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Coupling of urbanization and grain production: patterns, processes, and mechanisms—a case study from China

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Food security is crucial for national stability and public welfare. Since the 21st century, China's grain production has been significantly influenced by the rapid process of urbanization. In this context, this paper systematically measures the multidimensional coupling patterns and dynamic coupling processes between urbanization and grain production from 2000 to 2022, and preliminarily summarizes the complex coupling mechanisms within the Chinese context. The goal is to provide scientific references for achieving high-quality coordinated development of urbanization and grain production in China. The study reveals the following key findings: (1) The coupling relationship between urbanization and grain production exhibits both regional heterogeneity and temporal variability, demonstrating specific levels of coupling and dynamic processes under distinct spatiotemporal conditions. (2) Between 2000 and 2022, both urbanization and grain production patterns in China underwent significant reconstruction, with the coupling coordination level displaying a long-term spatial pattern of "high in the north, low in the south; high in the east, low in the west." Although there is an overall upward trend in coupling coordination states, spatial imbalances and dimensional heterogeneity persist. (3) Since the beginning of the 21st century, the dynamic coupling processes between provincial urbanization and grain production have primarily manifested as two types: simultaneous increase (with urbanization outpacing grain production) and urban increase accompanied by grain production decrease. Various dynamic coupling types exhibit significant spatial clustering, and the multidimensional dynamic coupling processes reveal notable similarities. (4) The evolution of coupling states demonstrates an overall trend of optimization, with clear bidirectional migration trends observed in coupling dynamics, primarily transitioning from simultaneous increase (urbanization outpacing grain production) to urban increase with grain production decrease, and vice versa. (5) The formation of the complex coupling relationship between urbanization and grain production in the Chinese context is fundamentally influenced by changes in population quantity and structure between urban and rural areas, shifts in land use, economic transformation, regional specialization, technological interactions, and factor mobility. These influences exhibit significant negative effects in the domains of population, land, and economy, while showcasing notable positive effects in terms of technology and factor mobility.

KEYWORDS

urbanization, grain production, coupling, mechanisms, provincial level

1 Introduction

Food security is a key goal of the United Nations' sustainable development agenda. For China, a major developing nation, this issue has significant implications for global food stability and has garnered substantial attention from scholars. Since the founding of the People's Republic of China, the country's grain production capacity has increased dramatically, with a 420% rise in grain output from 1949 to 2022, strengthening its food security foundation. However, in the past two decades, China's grain production has faced serious challenges from various factors, including climate change (Semeraro et al., 2023), globalization (Bentham et al., 2020), geopolitics (Xu et al., 2024), marketization (Ma et al., 2020), industrialization (Ambikapathi et al., 2022), and urbanization (Gu et al., 2017). Among these, urbanization has profoundly shaped the overall landscape of China's grain production and influenced its evolution.

China's urbanization process features distinct phases and has undergone rapid development since the reform and opening-up, resulting in the gradual breakdown of the traditional urban–rural dual structure and a significant transformation in urban–rural relationships (Yang and Wang, 2022). As a crucial factor influencing grain production, urbanization has attracted considerable attention from scholars in geography, economics, sociology, and agricultural studies. Research in this field can be broadly categorized into two main areas. First, studies examining the impact of urbanization on grain production investigate whether it promotes or hinders agricultural output, presenting three primary perspectives: the "suppressive" view, which underscores urbanization's negative effects on essential production inputs like land and labor, leading to increased land scarcity (Huang et al., 2020); the "promotive" view, which emphasizes positive externalities such as technological spillovers and the return of resources, especially the multiplier effect of agricultural innovations (Mok et al., 2020); and the "complex effects" view, which considers regional geographic differences and various driving factors of grain production (Krugman, 1991), acknowledging that different spatial and temporal contexts result in diverse coupling models between urbanization and grain production (Zhu et al., 2021). Second, research on the mechanisms through which urbanization influences grain production can be summarized into six pathways: the transfer of agricultural labor (Yan et al., 2023), encroachment on high-quality arable land (Zhou B. B. et al., 2021), transformation of rural industrial structures (Zhu et al., 2018), advancements in agricultural technology (Benedek et al., 2023), return of rural-oriented resources (Zhu et al., 2023), and changes in agricultural policy (Yang and Zhang, 2021).

It is important to note that provincial regions play a crucial role in spatial governance for coordinating high-quality urbanization and food security in China (Meng et al., 2023). First, provinces exhibit stability, with relatively few changes to administrative boundaries since the founding of the People's Republic. Second, they represent relatively independent natural and cultural geographic units, characterized by noticeable differences in conditions across interprovincial borders, resulting in strong internal homogeneity. Third, provinces combine administrative and cross-administrative features; as political units, they experience significant competition and cooperation among various cities within their borders (Li E. K. et al., 2022). When focusing on the realities of urbanization and grain production, we see that, on one hand, as a vast continental nation, China has experienced rapid urbanization since this concept was integrated into the 10th Five-Year Plan as a national strategy. This has led to the creation of numerous single or dual-centered urban spatial systems at the provincial level, becoming vital engines for regional economic and social development (Chen et al., 2023). On the other hand, since the 21st century, new agricultural policies-such as the abolition of the agricultural tax, direct subsidies for grain, and the establishment of permanent basic farmland-have facilitated the transformation and specialization of agricultural production across provinces. This has emphasized the primary functions of provincial grain production and resulted in three types of grain functional zones: main producing areas, main selling areas, and balanced production-consumption areas (Wang et al., 2024).

After reviewing existing research and theoretical analyses, it is clear that while scholars have extensively examined the impact of urbanization on grain production, notable shortcomings remain. First, analyses of effects and mechanisms often fail to adequately decompose urbanization as a crucial driver of grain production, typically focusing only on the absolute level of population urbanization. Urbanization, however, includes multidimensional aspects of population, land, and economy that are fundamental to understanding its influence on grain production. Second, there is insufficient attention to the provincial spatial scale and a lack of support for decision-making applications. Provinces are essential for studying the relationship between urbanization and grain production, serving as vital governance scales for food security policy. Future research should conduct in-depth analyses of the static and dynamic coupling patterns between urbanization and grain production, delineating regulatory zones and tailored strategies based on major production areas, selling areas, and balanced production-consumption areas. Third, the scientific rigor and timeliness in selecting research periods are often inadequate. Many studies do not sufficiently justify their period selections, with the latest data ending in 2020. Both urbanization and grain production exhibit distinct phase characteristics, making the choice of research periods critical for explaining their coupling mechanisms and developing targeted optimization strategies.

Based on the aforementioned contextual background and research advancements, this paper will conduct an in-depth exploration of the coupling relationship between urbanization and grain production in China's provincial regions within the "Population-Land-Economy" framework. Specifically, the study aims to address the following questions: First, how can the research period be scientifically defined? Second, what complex coupling patterns have emerged between urbanization and grain production in China over the past two decades, and how has this coupling process evolved? Third, what are the objective principles governing the coupling of urbanization and grain production in China within the "Population-Land-Economy" framework? This research seeks to provide scientific support for the coordinated and high-quality development of urbanization and grain production in China during the new era.

2 Theoretical analysis

2.1 Coupling relationship analysis

2.1.1 Static coupling level

At a specific region and point in time, the coupling relationship between urbanization and grain production manifests as a static pattern that can be classified into various types based on the level of coupling coordination. This degree of coordination reflects the comprehensive and harmonious development of the urbanization subsystem and the grain production subsystem. The overall urbanization level within the "population-land-economy" framework indicates the stage of urbanization in the region (Figure 1) (Cai et al., 2021; Chen et al., 2014). In the early stages of urbanization, limitations in production technology and low resilience to agricultural disasters result in relatively weak grain production capacity, leading to a low-level coordinated state (Ayele and Tarekegn, 2020). During the mid-stages, urbanization advances more rapidly than grain production, with the first-generation technological revolution enhancing grain production capabilities, resulting in a moderate developmental imbalance (Follmann et al., 2021). In the later stages, although urbanization continues to progress, its growth rate slows. At the same time, the second-generation technological revolution fosters rapid advancements in agricultural productivity, promoting a new integrated urban–rural relationship that facilitates the bidirectional flow of resources. This enhances grain production capacity, achieving a high-level coordinated state between urbanization and grain production (Zeng and Chen, 2023).

2.1.2 Dynamic coupling process

Over time, urbanization and grain production systems evolve synergistically through their coupling. In this dynamic relationship, urban areas wield greater influence than rural areas, making urbanization the primary factor affecting grain production, while the latter has only a limited feedback effect on the former (Liu Y. S. et al., 2020). This relationship manifests in changes in grain production levels—whether increases or decreases—corresponding to shifts in urbanization levels, which can be classified into five categories: simultaneous growth (urbanization outpacing grain production), simultaneous growth (grain production outpacing urbanization), urban growth with declining grain production, declining urbanization with increasing grain production, and simultaneous decline (Figure 2). Regions demonstrating simultaneous growth exhibit a mutual reinforcement between grain production capacity and urbanization. In areas with strict resource and environmental constraints, more resources are typically allocated to urbanization, leading to urban growth outstripping grain production. Conversely, in regions where these constraints are less severe, development can ensure sufficient investment in grain production, allowing it to grow faster than urbanization. Regions experiencing urban growth but declining grain production show a negative trend in grain production capacity, indicating an imbalance between urbanization and grain production. This imbalance increases reliance on external food sources and poses food security risks (Ben Hassen et al., 2020). The scenarios of declining urbanization with increasing grain production and simultaneous decline occur within the context of de-urbanization. In this process, the return of skilled urban populations to rural areas promotes the rapid adoption of professional, capitalized, and technological family farming models, significantly enhancing regional grain production capacity (Wang et al., 2021a). However, de-urbanization may also signal an overall decline in regional development, adversely affecting rural areas due to urban downturns, which threatens grain production capacity (Yang et al., 2019). Given the current trends in urbanization in China, it is unlikely that most regions will experience declining urbanization alongside increasing grain production or simultaneous decline.

2.2 Coupling stage division

Since the establishment of the People's Republic of China in 1949, the relationship between urbanization and grain production has shown a coordinated and mutually beneficial progression, which can be divided into three main stages (Figure 3). The first stage (1949–1978) is characterized by slow growth, with urbanization increasing by

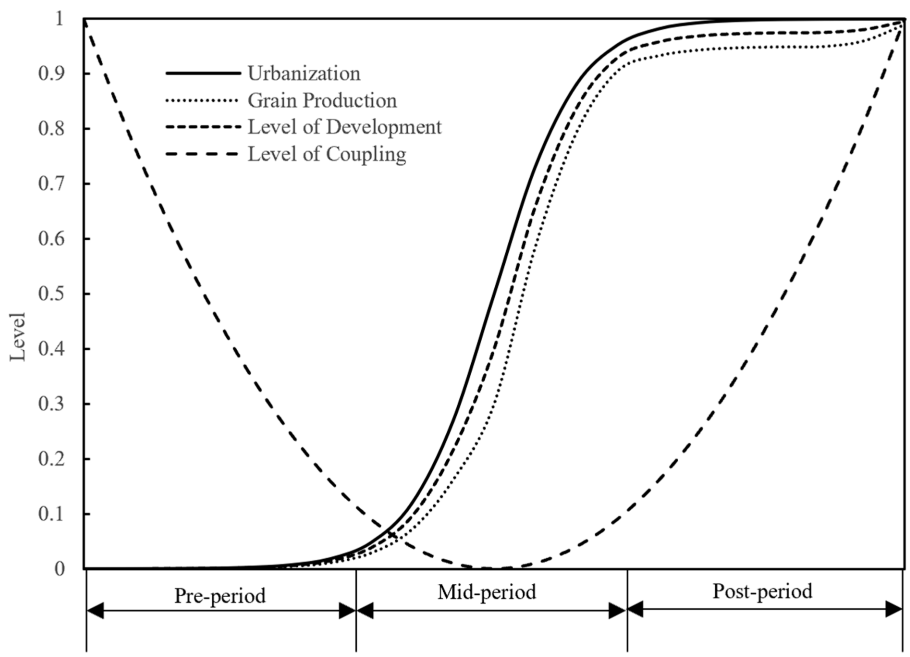

FIGURE 1
Static coupling pattern of urbanization and grain production.

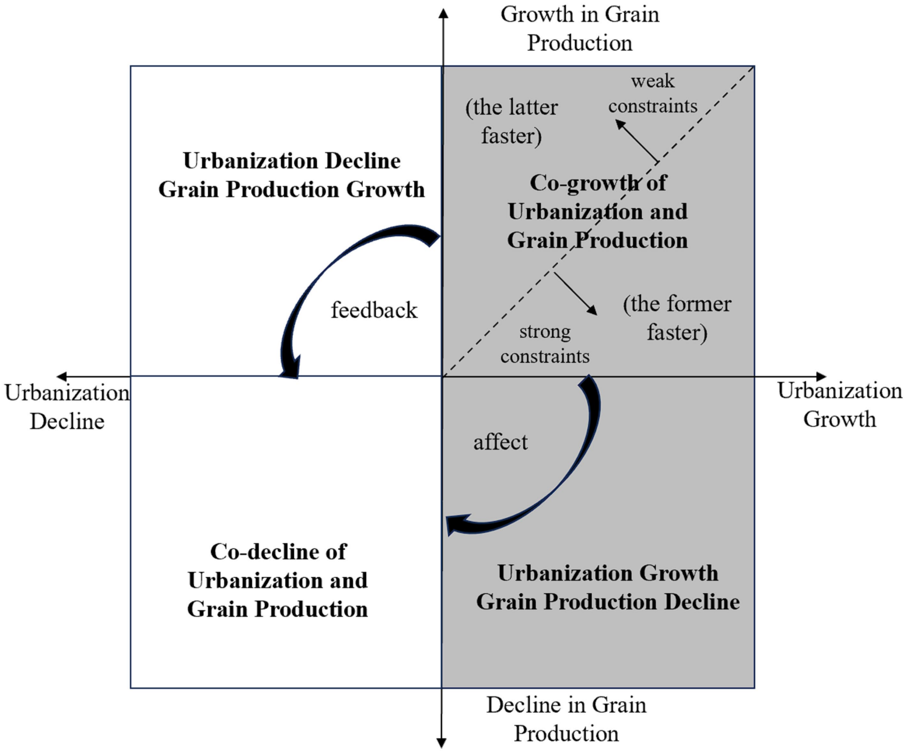

FIGURE 2
Dynamic coupling process of urbanization and grain production.

an average of 0.25 percentage points per year and grain production rising by an average of 6.61 million tons annually. The second stage (1978–2000) represents a period of moderate growth, during which urbanization averaged an increase of 0.83 percentage points per year, while grain production grew by an average of 7.16 million tons each year. The third stage marks a period of rapid growth, with urbanization averaging an increase of 1.32 percentage points annually, and grain production rising by an average of 10.2 million tons per year. This study focuses on the third stage for several reasons: First, China's rapid urbanization process began around 2000, when the urbanization rate was only 36%, indicating it was still in its early stages. Since then, China has progressed through the initial and mid-stages and is now in the later stage of urbanization. Second, during this rapid urbanization phase, cities have significantly exerted a depriving effect on rural resources, making the period since 2000 a time of intense interaction and conflict between urbanization and grain production. Third, despite potential conflicts, China has achieved twelve consecutive years of growth in grain production from 2000 to 2022, with growth rates far exceeding those of the previous two stages. This raises important questions about how these conflicts have been resolved and managed.

3 Data and methods

3.1 Indicator selection

Based on the earlier theoretical analysis, urbanization is a complex process that involves significant changes in population structure, spatial configuration, and economic dynamics. Therefore, this study measures urbanization from three perspectives: population, land, and economy (Table 1). In the population dimension, urbanization reflects important changes in aspects such as urban population size, spatial density, and employment structure. As a result, indicators selected include the urbanization rate, urban population density, and the proportion of non-agricultural workers (Cai et al., 2021). For the land dimension, urbanization is characterized by the expansion of urban built-up areas and the enhancement of urban infrastructure, alongside the growth of green spaces. Relevant indicators include the ratio of built-up area to total land area, per capita urban road area, and the green coverage rate within urban built-up areas (Li et al., 2020). In the economic dimension, urbanization encompasses the transformation of urban industrial structures, regional economic growth, and improvements in citizens' well-being. Consequently, indicators such as the proportion of non-agricultural output, per capita GDP, and disposable income of urban residents are chosen (Liang and Yang, 2019).

The level of grain production refers to the output capacity of the grain production system under specific temporal, natural, economic, and social conditions, as well as varying levels of input factors (Liu and Zhou, 2021). Scholars have conducted extensive research on measuring grain production levels and their spatial–temporal patterns, primarily using two approaches: representative indicators and composite indicators (Liu J. et al., 2020; Liu and Zhou, 2021). This study selects three key indicators—total grain production, yield per unit, and production structure—to characterize grain production capacity (Table 1). There are two main reasons for this selection. First, focusing on total production, yield, and production structure allows us to represent grain production levels from the output perspective,

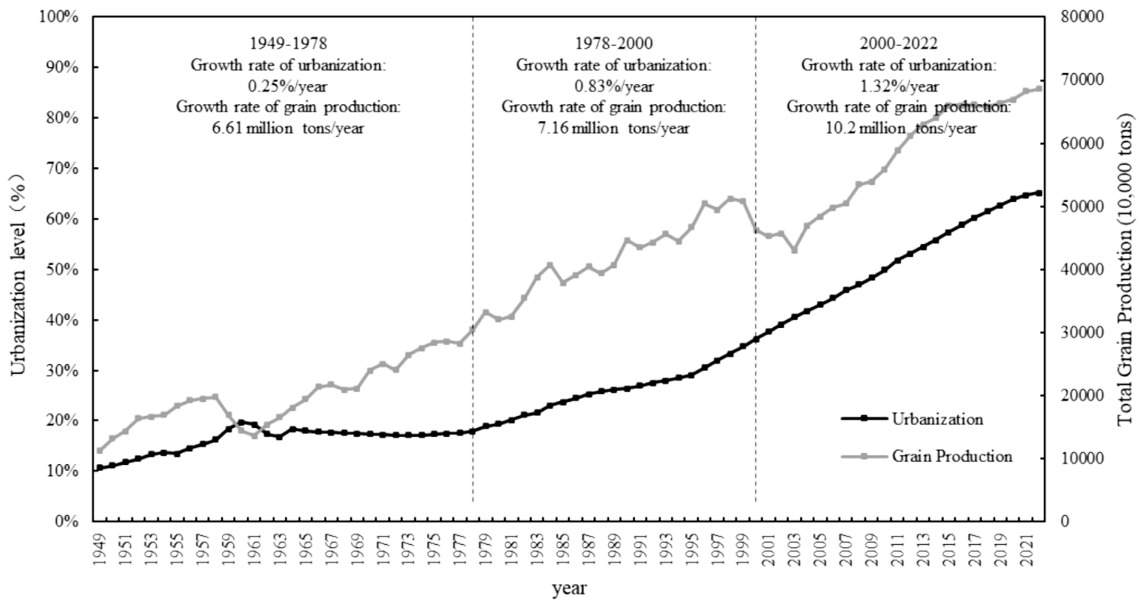

FIGURE 3
Time series evolution of China's grain production and urbanization since 1949.

providing a multidimensional and intuitive view of production characteristics. This method is more scientifically accurate and practical than approaches based solely on input factors. Total grain production serves as a central variable in food security research, reflecting overall output characteristics (Bene et al., 2020). Yield per unit indicates the quality of grain production, which is particularly important for a country like China, where per capita arable land is relatively scarce. In such cases, enhancing yield levels is often more effective than expanding land inputs in an extensive grain production model (Yang et al., 2020). The production structure illustrates the structural characteristics of grain production, especially in the context of urbanization, where the shift towards non-grain agricultural production significantly impacts food security (Liu and Zhou, 2021). Second, calculating grain production levels based on input factors can introduce causal confusion. Factors such as population, land, labor, and technology are causes of grain production levels, and urbanization itself is also a closely linked factor.

3.2 Research methods

3.2.1 Hierarchical combination weighting method

To ensure that weight measurements reflect both the objectivity of the data and the insights of experts, we employ a hierarchical combination weighting method. The indicator system consists of three levels: the goal level, the criterion level, and the indicator level. Based on the nine-point scale principle proposed by Saaty, the weights at the criterion level are generally simpler compared to those at the goal level; thus, we use the Analytic Hierarchy Process (AHP) to calculate these weights (Bene et al., 2020). In contrast, the weights at the indicator level are more complex, so we apply an improved entropy method for their calculation (Zhu et al., 2021). The specific weight results can be found in Table 1, with the relevant formulas outlined below (Equations 1–4):

$$W^{(2,1)} = \left[w_1^{(2,1)}, \ldots, w_n^{(2,1)} \right]^T \tag{1}$$

$$W_k^{(3,2)} = \left[w_{k,1}^{(3,2)}, \ldots, w_{k,m}^{(3,2)} \right]^T, k = 1, 2, \ldots, n \tag{2}$$

$$W^{(3,2)} = \left[W_1^{(3,2)}, \ldots, W_n^{(3,2)} \right] \tag{3}$$

$$W^{(3,1)} = W^{(3,2)} * W^{(2,1)} \tag{4}$$

In this context, $W^{(2,1)}$ represents the weight matrix of the criterion level relative to the goal level, calculated using the Analytic Hierarchy Process (AHP). Here, n denotes the number of variables at the criterion level, and m represents the number of variables at the indicator level. $W^{(3,2)}$ is the weight matrix of the indicator level relative to the criterion level, determined using the improved entropy method, and $W^{(3,1)}$ is the weight matrix of the indicator level relative to the goal level.

3.2.2 Static coupling measurement

The coupling coordination degree reflects the strength of interaction between two systems and their level of coordinated development. However, traditional coupling coordination indices have several shortcomings in practical applications. These include the uneven distribution of the coupling degree C within the [0, 1] range, computational biases resulting from the geometric weighting of the system's development level T, and an excessive dependence of the coupling coordination degree D on T. To address these issues, this paper employs the latest improved coupling coordination index (Wang et al., 2021b). The formula is as follows (Equations 5–7):

TABLE 1 Measurement index system of urbanization and grain production level.

Goal Level	Criterion level	Code 1	AHP weight	Indicator level	Code 2	Entropy weight	Combined weight
Urbanization	Population urbanization	x1	0.3393	Urban population rate (%)	x1_1	0.3385	0.1149
				Urban population density (people/km^2)	x1_2	0.4539	0.154
				Proportion of Non-agricultural employment (%)	x1_3	0.2077	0.0705
	Land urbanization	x2	0.3178	Proportion of urban built-up area to total land Area (%)	x2_1	0.4473	0.1422
				Per capita urban road area (m^2/capita)	x2_2	0.4093	0.1301
				Urban green space coverage rate (%)	x2_3	0.1434	0.0456
	Economic urbanization	x3	0.3429	Proportion of non-agricultural output (%)	x3_1	0.0508	0.0174
				Per capita GDP (Yuan/capita)	x3_2	0.4776	0.1637
				Per capita disposable income of urban residents (Yuan)	x3_3	0.4716	0.1617
Grain production	Total	y1	0.4203	Total grain production (10,000 tons)	y1_1	1.0000	0.4203
	Yield	y2	0.3235	Grain yield per hectare (tons/hectare)	y2_1	1.0000	0.3235
	Structure	y3	0.2562	Proportion of non-grain crop area (%)	y3_1	1.0000	0.2562

$$C = \sqrt{\left[1 - \frac{\sum_{i>j,j=1}^{n}\sqrt{\left(S_i - S_j\right)^2}}{\sum_{m=1}^{n-1} m}\right] \times \left(\prod_{i=1}^{n} \frac{S_i}{\max S_i}\right)^{\frac{1}{n-1}}} \quad (5)$$

$$T = \sum_{i=1}^{n} \alpha_i \times S_i, \sum_{i=1}^{n} \alpha_i = 1 \quad (6)$$

$$D = \sqrt{C \times T} \quad (7)$$

In this context, S represents the score of the subsystem, C is the coupling degree, T is the overall system score, D denotes the coupling coordination degree, and n indicates the number of subsystems. Since this paper focuses solely on the two subsystems of Urbanization and Grain Production, we have $n = 2$. Additionally, based on prior studies, the weights for both systems are set at 0.5. The improved coupling coordination model ensures a more even distribution of C within the [0, 1] range, resulting in higher overall validity of the model. Following the research of Li X. et al. (2022), the values of the coupling coordination degree are categorized into different types based on their magnitude (Table 2).

3.2.3 Dynamic coupling measurement

The dynamic coupling between urbanization and grain production is characterized by their synergistic evolution over a defined time period. By calculating ΔU and ΔF, it is possible to determine the rates of change for both urbanization and grain production. The formula is as follows (Equations 8, 9):

$$\Delta U_{it} = \frac{U_{it} - U_{i0}}{U_{i0}} \times 100\% \quad (8)$$

$$\Delta F_{it} = \frac{F_{it} - F_{i0}}{F_{i0}} \times 100\% \quad (9)$$

In this context, ΔU_{it} and ΔF_{it} represent the rates of change in urbanization and grain production, respectively, for region i in year t. U_{it} and F_{it} denote the levels of urbanization and grain production for region i in year t, while U_{i0} and F_{i0} indicate their levels in the base year for region i. Based on the rates of change, several types of dynamic coupling can be identified.

- When $\Delta U > \Delta F > 0$, this indicates that urbanization is increasing more rapidly than grain production, classified as Type B1.
- When $\Delta F > \Delta U > 0$, it signifies that grain production is increasing more rapidly than urbanization, classified as Type B2.
- Conversely, when $\Delta U > 0 > \Delta F$, it indicates a situation where urbanization is rising while grain production is declining, classified as Type B3, reflecting a disordered developmental relationship.
- When $\Delta F > 0 > \Delta U$ describes urbanization in decline while grain production is increasing, this is classified as Type B4, indicating a disordered relationship characterized by urban decline.
- Lastly, when $\Delta U < 0 \,\&\, \Delta F < 0$, this represents the type characterized by simultaneous declines in both urbanization and grain production, classified as Type B5.

3.2.4 Measurement of coupling type transition

The Markov chain is a statistical mathematical model that describes the transition of a system from one state to another across adjacent time periods, applicable to phenomena exhibiting "memorylessness." Existing research has demonstrated that both urbanization and grain production exhibit a strong degree of "memorylessness" (Yang et al., 2019). By employing a Markov chain, it is possible to quantitatively assess the evolution of the coupling relationship between urbanization and grain production at the provincial level, as well as to forecast their future coordinated development. The formula is as follows (Equations 10–13):

$$P\left\{\begin{array}{l}X_{t+1}=j \mid X_0=i_0, \\ X_1=i_1,\ldots,X_{n-1}=i_{n-1},X_n=i_n\end{array}\right\}=P\left\{X_{t+1}=j \mid X_n=i_n\right\} \quad (10)$$

$$P_{ij}=\frac{N_{ij}}{N_i} \quad (11)$$

$$N=\begin{bmatrix} N_{11} & \cdots & N_{1S} \\ \vdots & \ddots & \vdots \\ N_{S1} & \cdots & N_{SS} \end{bmatrix} \quad (12)$$

$$P=\begin{bmatrix} P_{11} & \cdots & P_{1S} \\ \vdots & \ddots & \vdots \\ P_{S1} & \cdots & P_{SS} \end{bmatrix} \quad (13)$$

In the equation, a total of S coupling states are defined. N_i represents the number of provinces in state i at time t, while N_{ij} indicates the number of provinces transitioning from state i at time t to state j at time $t+1$. P_{ij} denotes the frequency of this transition from state i at time t to state j at time $t+1$. N refers to the state transition matrix, and P represents the frequency transition matrix.

3.3 Data sources

The data for the indicators measuring grain production and urbanization utilized in this study are sourced from the National Bureau of Statistics of China, the China Statistical Yearbook, and various provincial statistical yearbooks. The completeness of the data exceeds 90%, and missing data for specific years were supplemented using linear interpolation. The sources for the driving factor data used in the analysis of driving mechanisms are provided in Table 3.

4 The coupling patterns of urbanization and grain production

4.1 The spatiotemporal evolution of urbanization and grain production levels

Between 2000 and 2022, China underwent a significant restructuring of both urbanization and grain production patterns. Overall, these processes demonstrated a mutually reinforcing relationship; however, notable spatiotemporal heterogeneities were present (Figures 4, 5). In terms of urbanization, all provinces in China showed substantial progress, although provinces in the Northeast, which have a historically earlier onset of urbanization, advanced at a relatively slow pace. Conversely, provinces in North and Northwest China experienced marked increases in urbanization, while the eastern regions—specifically the Beijing-Tianjin-Hebei area, the Yangtze River Delta, and the Pearl River Delta—emerged as leaders in China's urbanization efforts. Within this context of rapid urbanization, China's grain production levels underwent considerable spatial restructuring, primarily evident in the northward shift of the grain production center. Urbanization in southern provinces exhibited a certain negative impact on grain production levels, whereas urbanization in northern provinces did not appear to impede the enhancement of regional grain production. The disparities in grain production levels between northern and southern regions have increasingly amplified the contributions of northern provinces to China's food security. Data indicate that the Northeast's contribution to China's grain production rose from 11.5% in 2000 to 20.9% in 2022, with a peak contribution rate of 49.3% to China's grain production increase recorded between 2000 and 2011. According to the "National Medium- and Long-term Plan for Food Security (2008–2020)" issued by the Chinese government, the majority of key grain-producing areas are situated in northern regions. Due to the emphasis placed on food security functions by northern provinces, along with national policies favoring the elimination of agricultural taxes, the implementation of stringent land protection measures, and subsidies for grain production, China's grain production levels achieved a continuous increase for twelve consecutive years during this rapid urbanization period. Furthermore, significant improvements in grain yield per unit area were observed, regional disparities narrowed, and the excessive trend of non-grain cultivation was preliminarily curtailed, thereby reinforcing the foundations of food security.

4.2 Static coupling measurement

4.2.1 Overall coupling

Between 2000 and 2022, the coupling coordination degree between urbanization and grain production in China's provincial regions exhibited a spatial distribution characterized by the pattern of "higher in the north, lower in the south; higher in the east, lower in the west," with an overall upward trend in the coupling coordination status. In 2000, the development of urbanization and grain production across provinces was primarily marked by low to moderate coupling coordination, with low coupling coordination areas constituting the majority. Moderate coupling coordination zones were predominantly located in eastern coastal provinces as well as inland provinces such as Xinjiang, Heilongjiang, Shanxi, and Hubei. By 2011, high coupling

TABLE 2 Transition frequency matrix of static coupling relationship evolution of urbanization and grain production.

D Value	Coupling type	Type code	Description
(0,0.2]	Marginal coupling coordination	A1	Both urbanization and grain production are at low levels.
(0.2,0.4]	Low coupling coordination	A2	Urbanization is at a moderate level, while grain production remains low.
(0.4,0.6]	Moderate coupling coordination	A3	Urbanization is high, whereas grain production is low.
(0.6,0.8]	High coupling coordination	A4	Urbanization is high, with grain production at a moderate level.
(0.8,1.0]	Extreme coupling coordination	A5	Both urbanization and grain production are at high levels, promoting synergistic development.

coordination areas began to emerge in provinces such as Heilongjiang, Xinjiang, Jiangsu, Henan, and Jiangxi, while the number of moderate coupling coordination areas increased significantly, expanding into the central and southwestern regions. Low coupling coordination areas were found only in Qinghai Province. By 2022, the area of high coupling coordination regions had markedly increased, with regional coupling coordination types primarily consisting of moderate and high coupling coordination, and no extreme coupling coordination areas present. High coupling coordination zones were mainly distributed in the Northeast and central regions, while moderate coupling coordination areas were primarily found in South China and the western regions.

4.2.2 Dimensional coupling

Between 2000 and 2022, the coupling coordination degree among urbanization in terms of population, land, and economy, as well as grain production in China's provincial regions, exhibited significant spatial imbalance and dimensional heterogeneity (Figures 6–8).

(1) The coupling coordination pattern between population urbanization and grain production displayed clear spatial heterogeneity. In 2000, the predominant areas were characterized by moderate and low coupling coordination, with moderate coupling coordination zones mainly located east of the "Hu Huanyong Line," while low coupling coordination zones were primarily found west of this line. High coupling coordination areas appeared only in Guangdong Province. By 2011, moderate coupling coordination zones extended into the northwest, and high coupling coordination zones expanded into the central and northeastern regions. Guangdong, due to a significant influx of migrants and a marked decline in grain production capacity, transitioned from a high coupling coordination area to a moderate one. By 2022, the differentiation in coupling coordination between population urbanization and grain production became even more pronounced, exhibiting an "extreme-high-moderate-low" olive-shaped structure. Heilongjiang, owing to its solid foundation of urbanization and a significant enhancement in grain production capabilities since the 21st century, transformed into an extreme coupling coordination zone. The number of high coupling coordination zones increased significantly as moderate coupling coordination zones diminished, expanding into the northwest, while Qinghai remained in a state of low coupling coordination between population urbanization and grain production.

(2) The coupling coordination pattern between land urbanization and grain production underwent a spatial restructuring process from a "single-core-periphery" model to a "dual-core-periphery" model. In 2000, Heilongjiang served as the core area of high coupling coordination, with the central and eastern regions primarily exhibiting moderate coupling coordination as semi-peripheral areas. The western regions contained both low and moderate coupling coordination zones as peripheral areas. By 2011, the relationship between land urbanization and grain production in the central region showed significant improvement, with the east–west disparity in coupling coordination gradually surpassing the north–south gap. By 2022, the dual-core status of Henan and Heilongjiang was largely established, while the long-standing contradictions between land urbanization and grain production in the western regions, which remained peripheral, became increasingly prominent.

(3) The coupling coordination pattern between economic urbanization and grain production continued to stabilize and optimize. In 2000, with the exception of some western provinces classified as low coupling coordination zones, other regions were predominantly characterized as moderate coupling coordination areas. By 2011, the area of moderate

TABLE 3 Transition frequency matrix of static coupling relationship evolution of urbanization and grain production.

	a1. Population urbanization & grain production										a2. Land urbanization & grain production									
	a1-1.2000–2011					a1-2.2011–2022					a2-1.2000–2011					a2-2.2011–2022				
	A1	A2	A3	A4	A5	A1	A2	A3	A4	A5	A1	A2	A3	A4	A5	A1	A2	A3	A4	A5
A1	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
A2	0.00	0.18	0.55	0.27	0.00	0.00	0.50	0.50	0.00	0.00	0.00	0.13	0.88	0.00	0.00	0.00	1.00	0.00	0.00	0.00
A3	0.00	0.00	0.58	0.42	0.00	0.00	0.00	0.72	0.28	0.00	0.00	0.00	0.59	0.41	0.00	0.00	0.00	0.75	0.25	0.00
A4	0.00	0.00	1.00	0.00	0.00	0.00	0.00	0.00	0.91	0.09	0.00	0.00	0.00	1.00	0.00	0.00	0.00	0.10	0.70	0.20
A5	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

	a3. Economic urbanization & grain production										a4. Comprehensive urbanization & grain production									
	a3-1.2000–2011					a3-2.2011–2022					a4-1.2000–2011					a4-2.2011–2022				
	A1	A2	A3	A4	A5	A1	A2	A3	A4	A5	A1	A2	A3	A4	A5	A1	A2	A3	A4	A5
A1	0.00	0.50	0.50	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
A2	0.00	0.21	0.79	0.00	0.00	0.00	0.14	0.86	0.00	0.00	0.00	0.06	0.81	0.13	0.00	0.00	1.00	0.00	0.00	0.00
A3	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.50	0.50	0.00	0.00	0.00	0.80	0.20	0.00	0.00	0.00	0.56	0.44	0.00
A4	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.20	0.80	0.00
A5	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

FIGURE 4
Spatial evolution of provincial urbanization and grain production level in China from 2000 to 2022. **(a)** 2000. **(b)** 2011. **(c)** 2022.

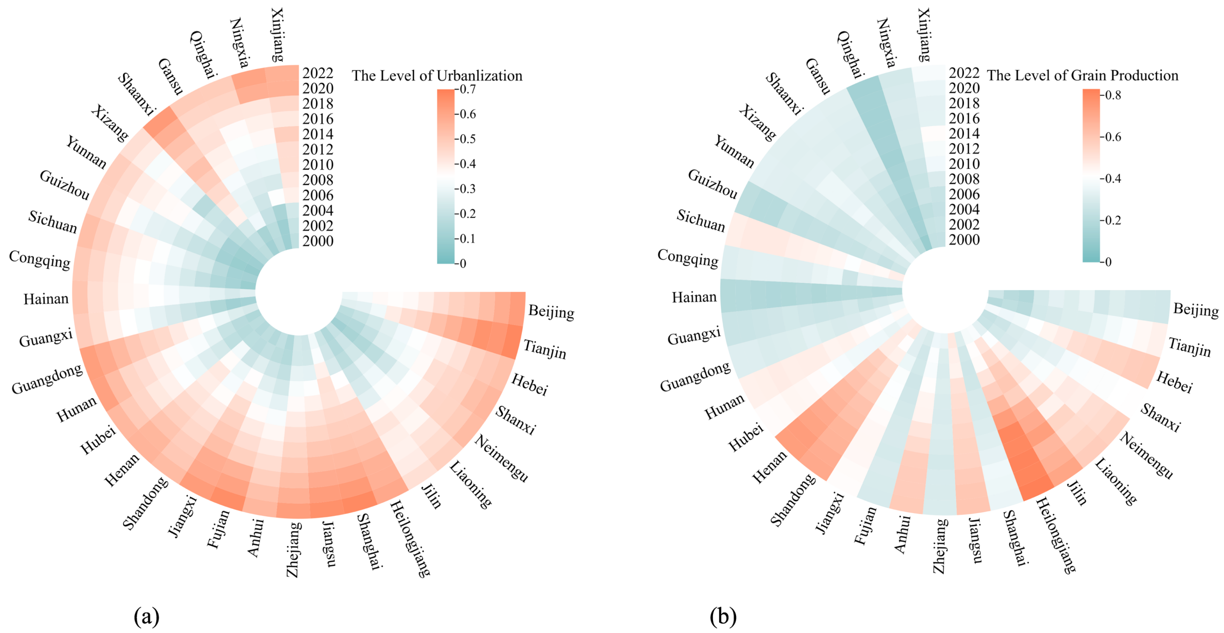

FIGURE 5
Time evolution of provincial urbanization and grain production level in China from 2000 to 2022. **(a)** Time series of urbanization level. **(b)** Time series of grain production level.

coupling coordination zones had further expanded, yet high coupling coordination zones had not yet emerged. By 2022, with the exception of Qinghai, classified as a low coupling coordination area, the coupling relationship between economic urbanization and grain production in other provinces showed significant improvement.

4.3 Dynamic coupling measurement

4.3.1 Overall coupling

Since the beginning of the 21st century, the dynamic coupling process between urbanization and grain production in China's provincial regions has primarily manifested in two types: simultaneous increases in urbanization and grain production (with urbanization outpacing grain production) and urbanization increases coupled with grain production declines. From 2000 to 2011, China's urbanization process accelerated significantly, entering a rapid phase since the reform and opening-up period. The dynamic coupling types exhibited a distinct clustered distribution pattern. Provinces such as Sichuan, Yunnan, Guizhou, and southern coastal provinces like Guangxi, Guangdong, Fujian, and Zhejiang fell into the category of urbanization increasing while grain production declined, while the remaining provinces experienced simultaneous growth in both urbanization and grain production (with urbanization growing faster than grain production). From 2011 to 2022, the pace of urbanization slowed slightly compared to the previous eleven years, resulting in a further decentralization of the spatial distribution of provinces characterized by urbanization increases and grain production declines. Transformations in the dynamic coupling relationship emerged in various regions. For example, Qinghai and Tibet, with their limited agricultural production conditions due to their plateau geography, saw rapid urbanization advancements driven by national strategies such as the Western Development Program. In the Beijing-Tianjin-Hebei region, Tianjin's level of food security for Beijing improved significantly, with grain production capacity increasing by 49%.

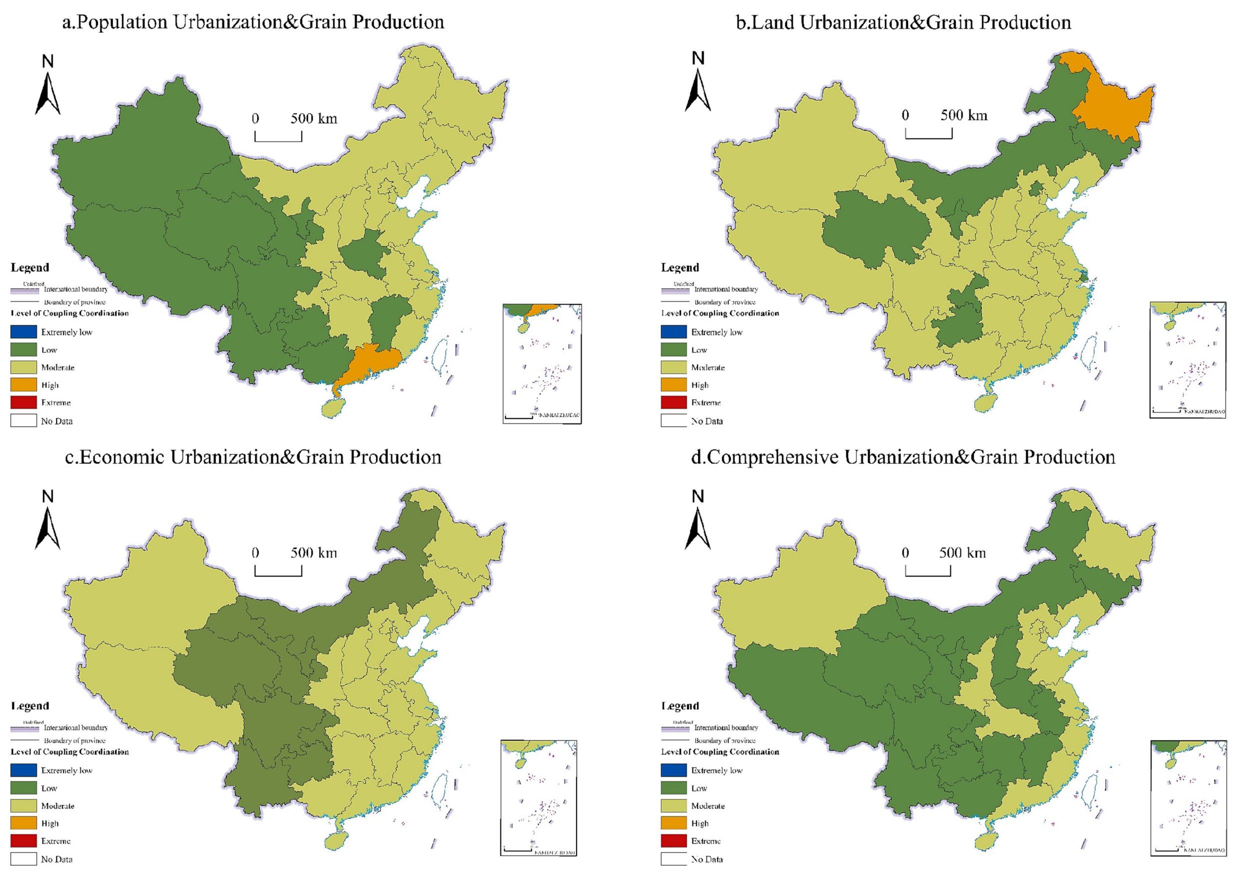

FIGURE 6
Multidimensional coupling pattern of urbanization and grain production in 2000. **(a)** Population Urbanization & Grain Production. **(b)** Land Urbanization & Grain Production. **(c)** Economic Urbanization & Grain Production. **(d)** Comprehensive Urbanization & Grain Production.

4.3.2 Dimensional coupling

From 2000 to 2022, the dynamic coupling processes of grain production with population urbanization, land urbanization, and economic urbanization in China's provincial regions exhibited significant spatial clustering and dimensional similarity (Figures 9, 10).

(1) The dynamic coupling process between population urbanization and grain production displayed four types: simultaneous increases (with urbanization outpacing grain production), simultaneous increases (with grain production outpacing urbanization), urbanization increases with grain production declines, and urbanization declines with grain production increases, with spatial clustering gradually weakening. From 2000 to 2011, the spatial clustering characteristics of dynamic coupling types were pronounced. Provinces in Northeast China, such as Inner Mongolia, Jilin, and Liaoning, were categorized as simultaneous increases (with grain production growing faster than urbanization), where grain production outpaced urbanization. Western provinces such as Xinjiang, Qinghai, Gansu, and Shaanxi, along with provinces in North and Central China, were classified as simultaneous increases (with urbanization growing faster than grain production), where grain production lagged behind urbanization but both exhibited coordinated promotion. Provinces in Southwest China, including Sichuan, Yunnan, and Guizhou, as well as southern provinces like Guangxi, Guangdong, and Fujian, fell into the category of urbanization increasing while grain production declined, indicating a negative effect of urbanization on grain production growth. Notably, Beijing in the Beijing-Tianjin-Hebei region exhibited an urbanization decline with grain production increase type, primarily due to the deconcentration of the population in the central urban area, where the population density decreased from 2,557 people per square kilometer in 2000 to 1,428 people per square kilometer in 2011, while grain production levels increased by 28%. In comparison to the previous eleven years, the spatial clustering of dynamic coupling types weakened from 2011 to 2022, with the emergence of simultaneous increases (with grain production growing faster than urbanization) in Henan and a shift of the urbanization increases with grain production declines type towards the western and central regions.

(2) The dynamic coupling process between land urbanization and grain production closely mirrored that of comprehensive urbanization, although some exceptional provinces were noted. From 2000 to 2011, Tibet exhibited a coupling coordination pattern of urbanization declines with grain production increases, primarily due to the reduction of per capita urban construction land area resulting from the substantial influx of population into cities. In Heilongjiang, grain production increased by 84%, compared to a 67% increase in land urbanization, resulting in a simultaneous increase (with grain production growing faster than urbanization) classification. From 2011 to 2022, the majority of provinces demonstrated simultaneous increases

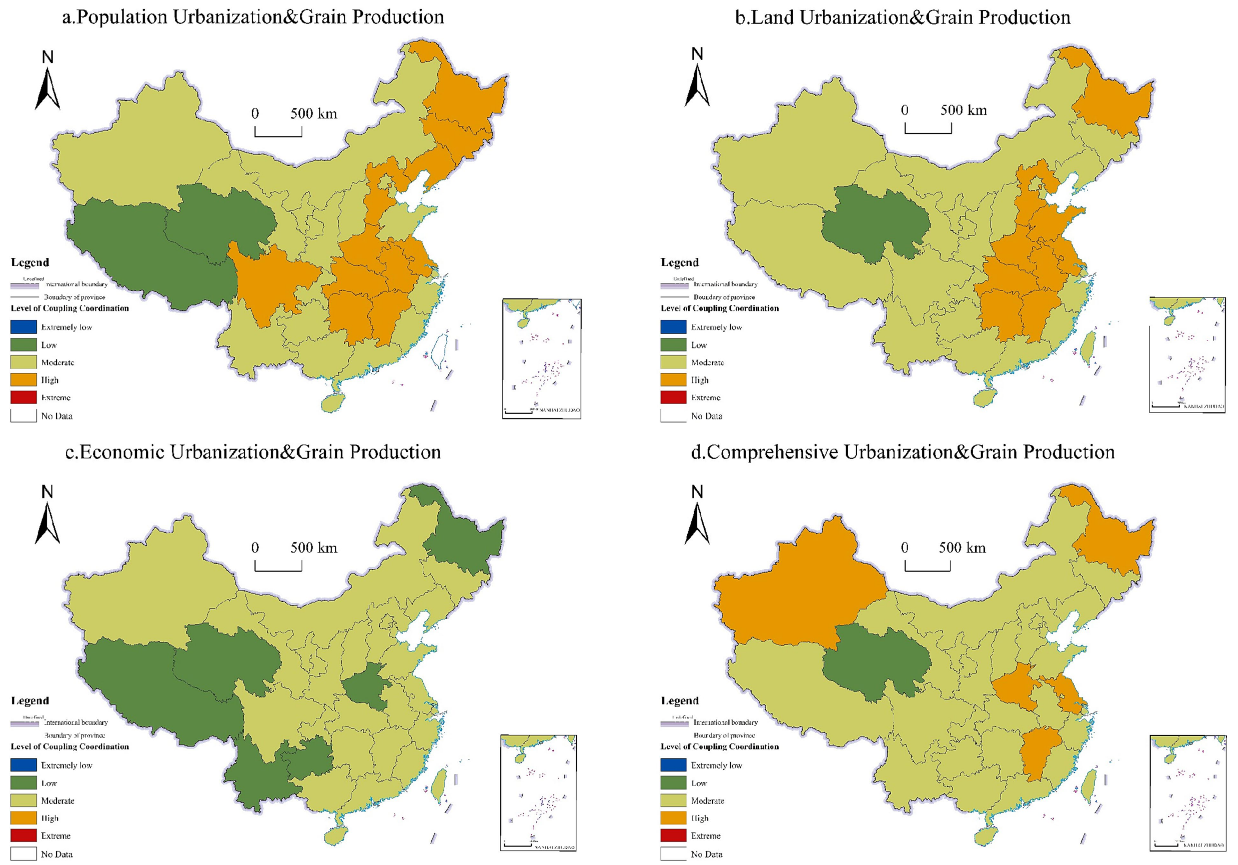

FIGURE 7
Multidimensional coupling pattern of urbanization and grain production in 2011. **(a)** Population Urbanization&Grain Production. **(b)** Land Urbanization&Grain Production. **(c)** Economic Urbanization&Grain Production. **(d)** Comprehensive Urbanization&Grain Production.

(with urbanization outpacing grain production), with only Tianjin exhibiting a simultaneous increase (with grain production outpacing urbanization). This was largely attributed to Tianjin's rapid increase in grain production per unit area and a decline in the trend of non-grain cultivation, with data indicating that grain production in Tianjin rose by 49% while land urbanization increased by only 24%.

(3) The dynamic coupling process between economic urbanization and grain production closely mirrored that of comprehensive urbanization, primarily characterized by simultaneous increases (with urbanization growing faster than grain production) and urbanization increases coupled with grain production declines.

5 The coupling process between urbanization and grain production

5.1 Evolution of static coupling types

The evolution of static coupling types displays an overall "rightward shift," characterized by dimensional heterogeneity and temporal phases (Table 3).

(1) From a dimensional perspective, on one hand, the static coupling relationships among population urbanization, land urbanization, and grain production have experienced varying degrees of degradation, particularly between population urbanization and grain production. From 2000 to 2011, this relationship saw a notable decline, coinciding with a period of extensive quantitative growth in urbanization, marked by a significant influx of agricultural migrant populations into urban areas. For instance, in Guangdong Province, the level of population urbanization increased by 0.17, while grain production levels decreased by 0.06 during the same period. On the other hand, the coupling coordination between economic urbanization and grain production has shown continuous improvement, with no significant negative trends, reflecting the robust development of non-agricultural industries and a complementary division of labor between urban and rural sectors.

(2) From a temporal perspective, since the beginning of the 21st century, the static coupling relationship between urbanization and grain production in China has exhibited distinct temporal phases, which can be broadly divided into two stages. The first stage, from 2000 to 2011, is characterized by a transition from low coupling coordination levels to moderate levels. Provinces experiencing this transition include Shanxi, Inner Mongolia, Chongqing, Sichuan, and Yunnan, which have historically lagged in urbanization and grain production capacity. During this phase, both urbanization and grain production levels in

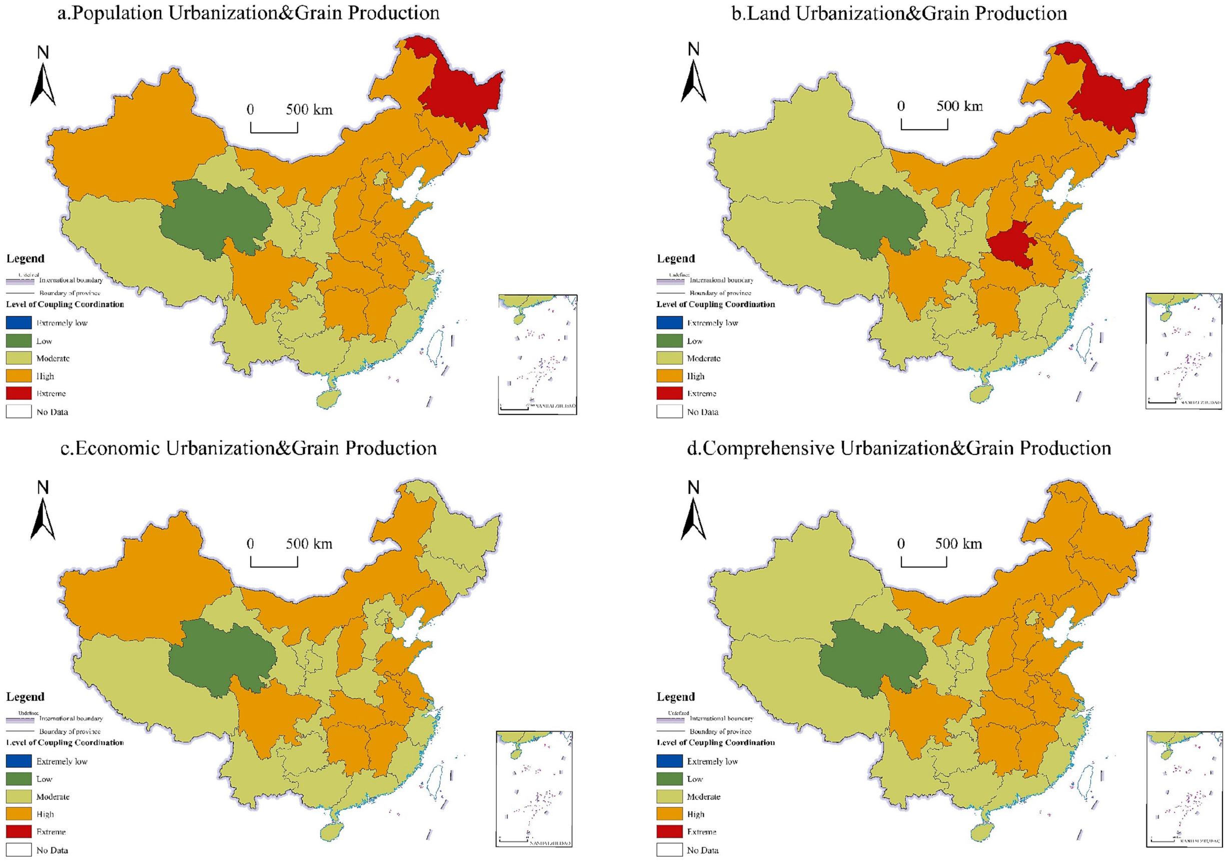

FIGURE 8
Multidimensional coupling pattern of urbanization and grain production in 2022. **(a)** Population Urbanization&Grain Production. **(b)** Land Urbanization&Grain Production. **(c)** Economic Urbanization&Grain Production. **(d)** Comprehensive Urbanization&Grain Production.

these provinces saw significant improvements. The second stage, from 2012 to 2022, is marked by an evolution from moderate to high coupling coordination levels. This transformation predominantly occurred in eastern provinces such as Tianjin, Hebei, and Shandong, where grain production levels ranked among the highest nationally and continuously progressed toward agricultural modernization. In this stage, urbanization processes also advanced rapidly, resulting in a high level of coordinated development between urbanization and grain production.

5.2 Evolution of dynamic coupling types

The evolution of dynamic coupling types exhibits a clear bidirectional trend, characterized by transitional tendencies and dimensional heterogeneity (Table 4).

(1) Overall, the dynamic coupling relationship between urbanization and grain production across multiple dimensions reveals two primary transition pathways: from B1 to B3 and from B3 to B1. The predominant trend is an improvement towards simultaneous increases in urbanization and grain production (with urbanization growing faster than grain production), accounting for approximately 71% of all provinces. This improvement arises from both originally well-coordinated provinces such as Jilin, Heilongjiang, Shandong, Henan, and Anhui in Central and Eastern China (73%) and provinces in Western China, such as Yunnan, Guizhou, and Sichuan, which transitioned from urbanization increases coupled with grain production declines (27%). The secondary trend is a decline towards urbanization increases accompanied by grain production declines, which accounts for about 26% of all provinces. This decline includes both originally disordered provinces, such as Zhejiang and Guangdong in Eastern China (38%), and remote provinces like Tibet and Qinghai experiencing deterioration (62%).

(2) Furthermore, from a dimensional perspective, the complexity of dynamic coupling type transitions exhibits significant variation, with the ranking of complexity across the three dimensions as follows: population urbanization & grain production (8 pathways) > land urbanization & grain production (6 pathways) > economic urbanization & grain production (4 pathways). Compared to the dynamic coupling relationship between economic urbanization and grain production, the first two dimensions show more internal structural adjustments within the simultaneous increases in urbanization and grain production type. Particularly in provinces like Heilongjiang and Henan, where population urbanization is relatively saturated and land urbanization is

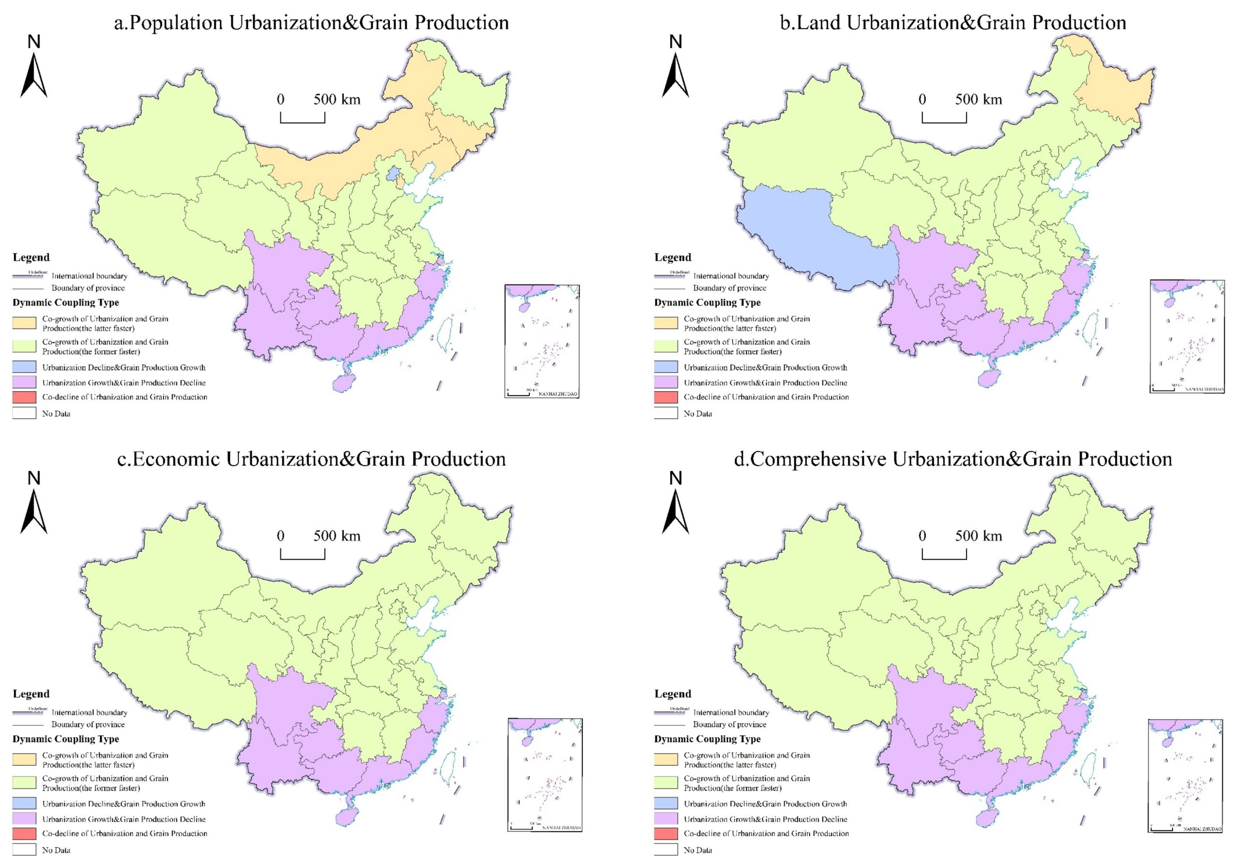

FIGURE 9
Multidimensional coupling process of urbanization and grain production from 2000 to 2011. **(a)** Population Urbanization&Grain Production. **(b)** Land Urbanization&Grain Production. **(c)** Economic Urbanization&Grain Production. **(d)** Comprehensive Urbanization&Grain Production.

overly aggressive, there is a gradual shift towards optimizing existing urbanization. This aims to enhance the efficient use of urban land resources in relation to population urbanization. The stagnation of expansive urbanization processes has allowed certain resources to be redirected towards grain production, resulting in a scenario where grain production growth outpaces urbanization growth.

6 The coupling mechanism between urbanization and grain production

6.1 Analysis of driving factors

Drawing on the theoretical and empirical analyses discussed earlier, this study identifies five driving factors—population, land, economy, technological advancement, and factor mobility—based on the principles of scientific rigor and feasibility to elucidate the coupling mechanism between urbanization and grain production (Table 5).

6.1.1 Population drivers

Two indicators are selected: the total rural population and the number of individuals employed in the primary sector. The former represents the absolute number of people in rural areas, while the latter reflects employment conditions in agriculture (Zhu et al., 2021).

6.1.2 Land drivers

Two indicators are utilized: the area of arable land in rural regions and the proportion of land allocated to grain crop cultivation. The first indicator indicates the total land available for grain production, while the second reflects the actual utilization of arable land (Zhou B. B. et al., 2021).

6.1.3 Economic drivers

This section includes two indicators: per capita agricultural output value and the share of crop output within the total agricultural, forestry, animal husbandry, and fishery sectors. The first indicator signifies labor productivity in crop production and is closely linked to labor earnings, while the second illustrates the role of crop production within the overall agricultural economy (Li X. et al., 2022).

6.1.4 Technological advancement

Two indicators are chosen: per capita total power of agricultural machinery and the application rate of chemical fertilizers per unit area. The first indicator reflects the level of agricultural mechanization, while the second indicates the extent of fertilizer use in agriculture (Zhu et al., 2021).

6.1.5 Factor mobility

This section also utilizes two indicators: reservoir capacity and investment in rural infrastructure. The former signifies investment in

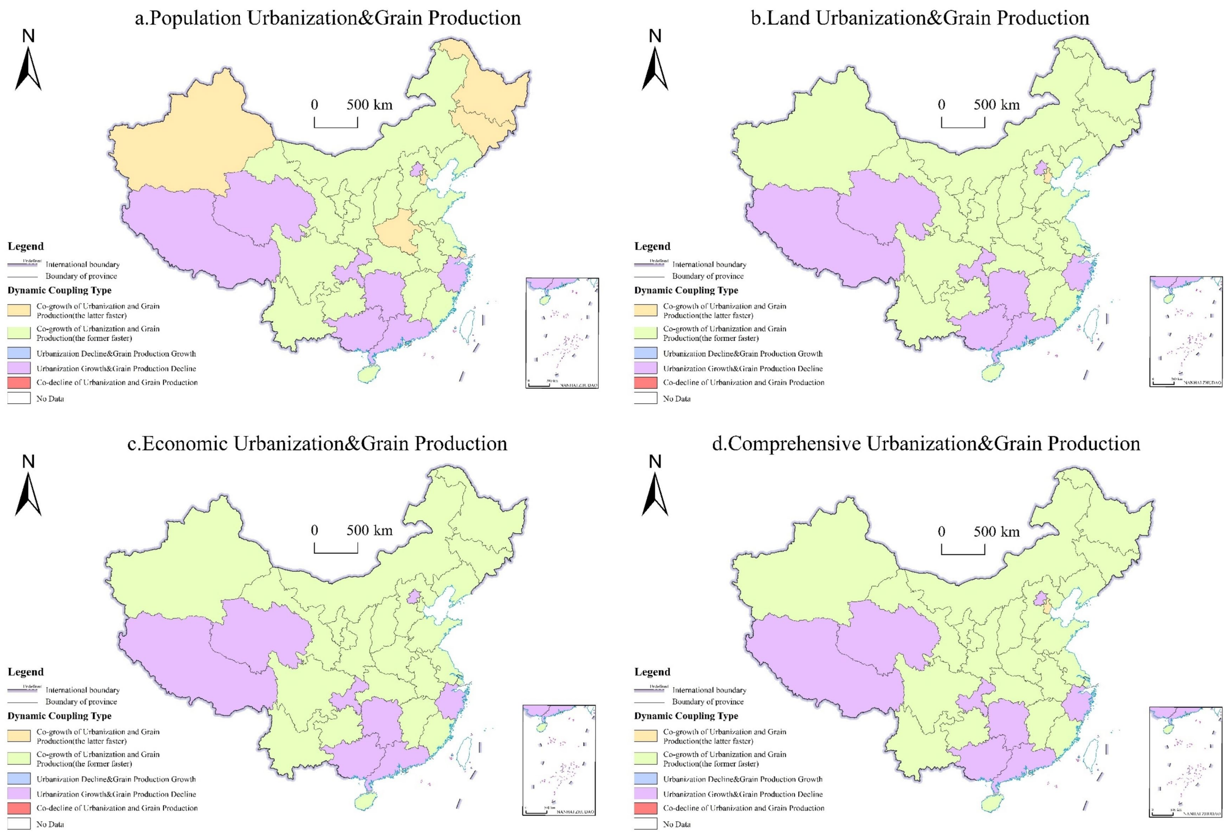

FIGURE 10
Multidimensional coupling process of urbanization and grain production from 2011 to 2022. **(a)** Population Urbanization&Grain Production. **(b)** Land Urbanization&Grain Production. **(c)** Economic Urbanization&Grain Production. **(d)** Comprehensive Urbanization&Grain Production.

agricultural facilities, while the latter represents financial contributions to agricultural development (Zhu et al., 2023).

Additionally, acknowledging that grain production is significantly influenced by natural conditions, particularly climate change, this study includes four indicators: the area affected by agricultural disasters, the area undergoing flood control measures, annual average accumulated temperature, and annual average precipitation. The first two indicators capture the impact of disasters on agricultural production and the effectiveness of disaster management, while the latter two reflect the temperature and precipitation conditions favorable for agriculture (Semeraro et al., 2023). Details of the specific indicators selected are presented in Table 5.

The baseline model is configured as follows (Equation 14):

$$D_{it} = \sum_{j=1}^{10} \alpha_j z_{j,it} + \sum_{m=1}^{4} \beta_m k_{m,it} + u_i + \varepsilon_{it} \tag{14}$$

In this context, D_{it} denotes the degree of coupling and coordination between urbanization and agricultural production for province i at year t. The variable $z_{j,it}$ represents the j-th explanatory variable for province i at year t, with α_j as its corresponding coefficient. The variable $k_{m,it}$ signifies the m-th control variable for province i at year t, and β_m represents its coefficient. Additionally, u_i accounts for individual fixed effects, while ε_{it} is the random error term. To ensure the robustness of the regression results and facilitate comparisons of regression parameters, multiple regression models have been established. Specifically, Models 1 and 2 represent pooled ordinary least squares (POLS) regressions, with and without control variables, respectively. Models 3 and 4 indicate panel regressions with individual fixed effects, also conducted with and without control variables. Finally, Models 5, 6, and 7 examine the degrees of coupling and coordination between urbanization and agricultural production concerning population, land, and economic dimensions.

Initially, the panel data was treated as general cross-sectional data for the POLS regression. The regression coefficients for most variables in Models 1 and 2 were found to be significant, with an average variance inflation factor (VIF) of 4.06, indicating that the selected combination of explanatory variables does not exhibit significant multicollinearity (Figure 11). Subsequently, a panel model regression was performed. F-tests revealed that individual fixed effects are significant, while Hausman tests confirmed that fixed effects are more appropriate than random effects. The regression results indicate that, on one hand, the overall goodness of fit for the models is satisfactory, with R^2 values exceeding 0.5487. However, the goodness of fit for the panel models generally surpasses that of the cross-sectional models, and models that account for control variables exhibit better fit than those that do not, emphasizing the importance of regional heterogeneity and natural environmental factors in influencing agricultural production (Table 6). On the other hand, the driving factors for coupling and coordination between urbanization and agricultural production exhibit dimensional heterogeneity.

Focusing on specific regression results: in the population dimension, the reduction in the absolute rural population in China

TABLE 4 Transition frequency matrix of dynamic coupling relationship evolution of urbanization and grain production.

		b1. Population urbanization & grain production					b2. Land urbanization & grain production				
		2011–2022					2011–2022				
		B1	B2	B3	B4	B5	B1	B2	B3	B4	B5
2000–2011	B1	0.59	0.18	0.24	0.00	0.00	0.75	0.05	0.20	0.00	0.00
	B2	0.50	0.50	0.00	0.00	0.00	1.00	0.00	0.00	0.00	0.00
	B3	0.56	0.11	0.33	0.00	0.00	0.67	0.00	0.33	0.00	0.00
	B4	0.00	0.00	1.00	0.00	0.00	0.00	0.00	1.00	0.00	0.00
	B5	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

		b3. Economic urbanization & grain production					b4. Comprehensive urbanization & grain production				
		2011–2022					2011–2022				
		B1	B2	B3	B4	B5	B1	B2	B3	B4	B5
2000–2011	B1	0.77	0.00	0.23	0.00	0.00	0.73	0.05	0.23	0.00	0.00
	B2	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	B3	0.67	0.00	0.33	0.00	0.00	0.67	0.00	0.33	0.00	0.00
	B4	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	B5	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

has not hindered the coordinated development of urbanization and agricultural production. This observation aligns closely with the fundamental national context of "more people than land" in rural areas. More importantly, maintaining an adequate number of primary sector employees is crucial. In the land dimension, both the total area of arable land and the proportion of grain crop sowing significantly promote the coordinated development of urbanization and agricultural production. This is primarily because these are fundamental elements necessary for ensuring grain production. The central government of China has placed a strong emphasis on rural land protection and macro-control of economic crop cultivation in recent years. In the economic dimension, higher labor productivity in crop cultivation implies better economic returns for farmers, thereby increasing their willingness to plant. This significantly promotes the coordinated development of urbanization and agricultural production. In fact, Chinese farmers exhibit a high degree of mixed production characteristics, as economic crops generally yield higher returns than grain crops. Consequently, while ensuring grain production, farmers tend to choose economic crops, leading to a decrease in the proportion of agricultural output within the overall agricultural, forestry, animal husbandry, and fishery sectors. In terms of technological progress, advancements in mechanization and fertilizer application have significantly enhanced the coordinated development of urbanization and agricultural production, substantially improving the technological level of agricultural production in China and partially offsetting the negative impacts of urbanization on grain production. According to data from the National Bureau of Statistics of China, the level of agricultural mechanization increased by 110% from 2000 to 2022. In the dimension of factor flow, investments in water conservancy facilities and rural construction have also significantly promoted the coordinated development of urbanization and agricultural production. The water projects constructed and maintained by various levels of government in China are crucial for supporting grain production, especially in regulating the uneven temporal and spatial distribution of precipitation. Moreover, since the implementation of the New Rural Construction Policy in 2005, the Chinese government has allocated special funds annually for rural construction aimed at enhancing water supply, gas services, roads, and bridges. Investments in rural construction grew by 288% from 2005 to 2022. Additionally, amidst global climate change, fluctuations in temperature and precipitation conditions, as well as accompanying natural disasters, pose significant threats to grain production in China. However, the disaster response capabilities in agricultural production are continuously improving. Data from the Statistical Yearbook of China indicate that, in terms of disaster prevention, the area affected by agricultural disasters in 2022 was only 19% of that in 2000. Regarding disaster management, the area of agricultural disaster in 2022 was only 14% of that in 2000.

6.2 Multidimensional coupling mechanisms

Building upon the analysis of the driving factors, the intricate coupling relationship between urbanization and grain production is fundamentally influenced by demographic changes, land use dynamics, economic development, technological progress, and factor mobility. Specifically, population urbanization markedly alters the quantity and composition of agricultural labor; land urbanization exerts significant negative impacts on both the scale and quality of agricultural land; and economic urbanization creates a "push-pull" dynamic that drives transformations in agricultural industrial structures. Furthermore, technological advancements and the return of factors during the later stages of urbanization exert notable positive effects on grain production. However, in contexts characterized by inadequate technology and persistent outmigration, rural areas may continue to experience decline (Figure 12).

6.2.1 Population-driven urbanization and grain production

From a demographic perspective, urbanization is conceptualized as the transition of agricultural populations to urban populations. For

TABLE 5 Driving factors analysis variables.

Variable symbol	Variable description	Unit	Variable category	Variable connotation	Data source
D	Coupling coordination degree of urbanization and grain production	None	Dependent Variable	Coupling Status of Urbanization and Grain Production	Calculated data
D1	Coupling coordination degree of population urbanization and grain production				
D2	Coupling coordination degree of land urbanization and grain production				
D3	Coupling coordination degree of industrial urbanization and grain production				
z1	Rural population size	Ten Thousand	Independent Variable	Absolute number of rural population	China statistical yearbook
z2	Number of employees in the primary industry	Ten Thousand		Employment status in the agricultural sector	
z3	Area of arable land in rural regions	Thousand Hectares		Absolute quantity of arable land in rural areas	
z4	Proportion of arable land used for grain crop cultivation	%		Actual utilization of arable land in rural areas	
z5	Per capita value of crop production	Ten Thousand Yuan/Person		Labor productivity in crop production	
z6	Proportion of crop production value in the agricultural sector	%		Importance of crop production within the overall agricultural economy	
z7	Per capita total power of agricultural machinery	Kilowatt/Person		Level of agricultural mechanization	
z8	Application rate of chemical fertilizers per hectare	Ton/Hectare		Level of chemical fertilizer application in agriculture	
z9	Reservoir capacity	Hundred Million Cubic Meters		Investment in agricultural infrastructure	
z10	Investment in rural construction	Hundred Million Yuan		Financial input in agriculture	China urban–rural construction statistical yearbook
k1	Area affected by agricultural disasters	Thousand Hectares	Control Variable	Impact of disasters on agricultural production	Official website of the national bureau of statistics of China
k2	Area under flood control measures	Thousand Hectares		Agricultural disaster management	
k3	Average ANNUAL ACCUMULATED TEMPERATURE	Celsius		Temperature conditions for agricultural production	European centre for medium-range weather forecasts
k4	Average annual precipitation	Millimeters		Precipitation conditions for agricultural production	

urban areas, the influx of agricultural migrants not only provides a substantial labor force but also generates increased consumer demand, thereby facilitating the development of urban economies of scale. Conversely, this demographic shift poses governance challenges, complicating the provision of essential services such as housing, education, healthcare, and social security, which collectively influence the urbanization process (Zhang and Chen, 2024). In rural contexts, a moderate outflow of agricultural labor can create conditions conducive to large-scale agricultural production, particularly in resource-constrained areas characterized by high population density relative to land availability. This shift also synergizes with the application of modern agricultural technologies (Wang et al., 2021a). However, under an aggressive model of external urbanization, the substantial outmigration of quality young and middle-aged agricultural labor profoundly alters the demographic landscape of rural regions, leading to phenomena such as depopulation, aging, and declining birth rates, all of which pose significant threats to current and future labor supplies for grain production (Liu et al., 2021b; Liu and Zhou, 2021).

6.2.2 Land-driven urbanization and grain production

From the perspective of land use, urbanization is manifested as the expansion of urban land at the expense of rural land. Both urban development and agricultural production exert considerable demand on land resources, leading to significant land-use conflicts, particularly in flat and well-connected areas suitable for both uses (Sui and Lu, 2021). For urban areas, urban sprawl facilitates the expansion of

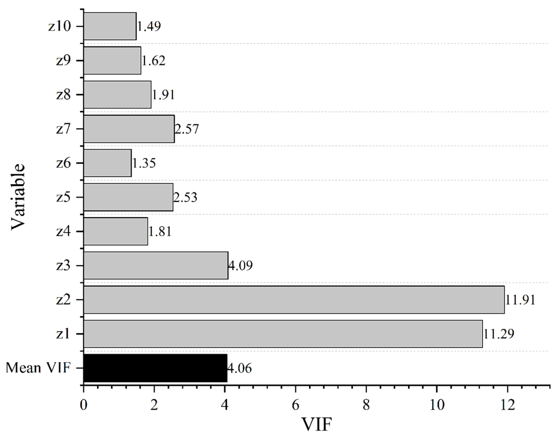

FIGURE 11
The test of multicollinearity.

developmental space and scale, while the marketization of land finance provides necessary funding for sustainable urban growth. Conversely, the encroachment of urban development on land resources diminishes agricultural production capacity, resulting in reduced availability and declining quality of agricultural land. Measures such as unequal compensation for land use fail to effectively counteract the systemic decline of agricultural land due to urbanization (Zhou Y. et al., 2021). Furthermore, in regions suffering from severe rural depopulation, the actual utilization rate of agricultural land is further diminished, resulting in substantial fallow land.

6.2.3 Economic-driven urbanization and grain production

Economically, urbanization reflects a transition in development modes, structural upgrades in industries, and changes in labor division. Regional economic development has shifted from a solely agricultural growth model to a diversified economic framework. Urban centers have established a variety of higher-tier non-agricultural industries, functioning as specialized service hubs for their respective regions. Within these regions, an objective division of labor has emerged between urban and rural areas, with variations in resource endowments leading to distinct labor divisions among different cities. For rural areas, the prosperity of urban economies juxtaposed with the low returns of traditional agricultural practices creates a "push-pull" effect that accelerates the migration of agricultural labor. Additionally, economic urbanization instigates a transformation in agricultural industrial structures, primarily characterized by a shift from low-value traditional grain crops to high-value cash crops, along with the emergence of agricultural ancillary sectors such as rural e-commerce, agricultural complexes, and agro-tourism (Schneider, 2017; Wang et al., 2023).

6.2.4 Technological progress-driven urbanization and grain production

The urbanization process, marked by the agglomeration of resources, objectively facilitates technological advancements in agriculture, significantly enhancing grain production capabilities. On one hand, urban areas benefit from rich human capital and efficient information networks, positioning them as key growth poles for regional technological innovation. During the mid-stages of urbanization, the interplay between urbanization and industrialization—particularly in machinery and chemical sectors—effectively promotes the mechanization of grain production and the application of fertilizers. In the later stages, the interrelation between urbanization and informatization fosters the development of advanced agricultural technologies characterized by automation, digitalization, and high spatial–temporal resolution (Radić et al., 2022). Conversely, agricultural technological advancements enhance the resilience of grain production systems, particularly in managing agricultural disasters, thus providing essential technical support for disaster preparedness, response, and recovery (Haji et al., 2024). Furthermore, modern agricultural technology is increasingly applied within large-scale agricultural production, where urbanization facilitates the emergence of large grain producers, cooperatives, and leading enterprises, creating critical practical avenues for the promotion of these technologies.

6.2.5 Urban–rural factor mobility-driven urbanization and grain production

From the perspective of mobility, the interaction between urban and rural areas is characterized by multidimensional factor flows, where the direction, intensity, and structure of these flows exert complex influences on regional urbanization and grain production. The scope of factor flows encompasses traditional production factors—such as land, labor, and capital—as well as emerging factors like data, technology, and ideas, continuously expanding the breadth of urban–rural interactions (Zhu et al., 2023). In the Chinese context, rural areas characterized by low population density, human capital, and environmental quality exhibit contrasting issues to urban areas suffering from high population density, overloaded infrastructure, and elevated governance costs, creating a symbiotic relationship between rural and urban challenges. The root cause of these issues lies in the excessive concentration of factors in urban areas and the impediments to the free and equitable exchange of resources between urban and rural settings (Fang, 2022). Notably, the impact of factor mobility on grain production is temporally phased; during the early and mid-stages of urbanization, classical economic theories—such as Lewis's dual economy structure theory and Perroux's growth pole theory—illustrate a trend towards unbalanced development (Lewis, 1954; Perroux, 1950), with rural populations and land rapidly concentrating in urban areas, thereby threatening grain production through the swift depletion of traditional rural production factors. In the later stages of urbanization, while urbanization continues to possess growth potential and remains a dominant trend in socio-economic development, traditional production factors such as labor and land are unlikely to fundamentally return to rural areas. However, the economic benefits derived from urbanization can effectively flow back to the agricultural sector; more crucially, the substantial maturation of emerging factors such as data and technology can foster the establishment of a smart agricultural technology system, enriching the qualitative dimensions of grain production. Emerging production factors significantly substitute for traditional factors, thereby amplifying the effects on grain production (Gao and Lyu, 2023). Thus, in the later stages of urbanization, leveraging financial resources to support agricultural revitalization, along with the integration of emerging production factors into agricultural industrialization, can promote the coordinated development of urbanization and grain production. In contrast, adherence to a traditional unidirectional flow of factors could precipitate negative declines in regional grain production levels, ultimately hindering the overall.

TABLE 6 Basic regression and sub-dimensional regression.

	Model1	Model2	Model3	Model4	Model5	Model6	Model7
z1	0.0683* (−1.73)	0.0513 (−1.29)	−0.8325*** (−13.10)	−0.7927*** (−11.96)	−0.6148*** (−8.04)	−0.5218*** (−7.51)	−0.9453*** (−10.49)
z2	−0.1347*** (−3.17)	−0.1074*** (−2.59)	0.1135*** (−2.67)	0.1182*** (−2.78)	0.1105** (−2.25)	0.0580 (−1.30)	0.1354** (−2.34)
z3	0.0026 (−0.10)	0.0192 (−0.63)	0.0883* (−1.73)	0.0960* (−1.87)	0.2613*** (−4.41)	0.1133** (−2.10)	−0.1627** (−2.33)
z4	0.1129*** (−7.36)	0.1089*** (−7.02)	0.1419*** (−6.91)	0.1413*** (−6.84)	0.1464*** (−6.14)	0.1705*** (−7.87)	−0.0377 (−1.34)
z5	−0.0096 (−0.22)	0.0106 (−0.25)	0.1352*** (−4.57)	0.1302*** (−4.37)	0.0733** (−2.13)	0.0933*** (−2.99)	0.3578*** (−8.84)
z6	−0.0171 (−1.16)	−0.0209 (−1.34)	−0.1244*** (−6.42)	−0.1199*** (−6.18)	−0.1286*** (−5.75)	−0.0840*** (−4.13)	−0.0430 (−1.63)
z7	0.2526*** (−10.18)	0.2283*** (−9.26)	0.2208*** (−9.50)	0.2174*** (−9.31)	0.1290*** (−4.79)	0.2584*** (−10.56)	0.3778*** (−11.90)
z8	0.0230 (−1.21)	−0.0279 (−1.35)	0.0895*** (−4.08)	0.0955*** (−4.29)	0.1062*** (−4.14)	0.0770*** (−3.30)	0.1578*** (−5.22)
z9	0.0060 (−0.34)	0.0303* (−1.71)	0.0376* (−1.83)	0.0466** (−2.23)	0.0847*** (−3.51)	−0.0569*** (−2.59)	0.0692** (−2.43)
z10	0.2870*** (−16.22)	0.2328*** (−12.15)	0.0513*** (−2.89)	0.0449** (−2.48)	0.0345* (−1.65)	0.0361* (−1.90)	0.1494*** (−6.08)
k1		−0.1273*** (−5.00)		−0.0126 (−0.66)	0.0102 (−0.47)	−0.0590*** (−2.98)	−0.0551** (−2.14)
k2		0.0664*** (−3.95)		0.1153** (−2.00)	0.0193 (−0.29)	−0.0528 (−0.87)	0.3166*** (−4.04)
k3		0.0712*** (−3.44)		0.0453 (−0.47)	0.1428 (−1.27)	−0.1090 (−1.07)	0.3396** (−2.57)
k4		−0.0510*** (−2.89)		−0.0385* (−1.96)	−0.0449** (−1.99)	−0.0610*** (−2.97)	0.0201 (−0.75)
_cons	0.3740*** (−27.83)	0.3889*** (−25.67)	0.5954*** (−22.26)	0.5514*** (−8.46)	0.4604*** (−6.12)	0.6239*** (−9.12)	0.3021*** (−3.41)
N	713	713	713	713	713	713	713
R-squared	0.5487	0.5822	0.7824	0.7854	0.6493	0.6968	0.8180
Fixed effects			yes	yes	yes	yes	yes
F	85.3544	69.4721	241.6770	174.5934	88.3318	109.6494	214.4554
F test: Prob>F			0.0000	0.0000	0.0000	0.0000	0.0000
Hausman: Prob>chi2			0.0000	0.0000	0.0000	0.0000	0.0000

*$p < 0.1$, **$p < 0.05$, ***$p < 0.01$.

7 Discussion and conclusion

7.1 Discussion

7.1.1 Complexity analysis of the coupled and coordinated development of urbanization and grain production in China

Unlike the "inhibitory effects" and "promoting effects" of urbanization on grain production (He et al., 2022; He et al., 2023; Huang et al., 2020; Mok et al., 2020), the complexity of their interaction is thoroughly demonstrated in this study (Liu and Zhou, 2021). The research on the coupling relationship between urbanization and grain production transcends simple studies of positive or negative effects. It accounts for the superimposition of both effects within specific spatial scales and reveals a spiral upward trend in their coupling and coordination over time (Zhu et al., 2021). This phenomenon has been particularly evident in regional empirical studies in China since the 21st century. Specifically, the complexity can be summarized in five key aspects: (1) the multidimensional interactions of coupling elements, (2) the complex spatial structures of coupling patterns, (3) the intricate evolutionary paths of coupling processes, (4) the multifaceted driving factors of coupling mechanisms, and (5) the regional heterogeneity observed in the study. The most critical aspect is the complexity of the driving factors behind the

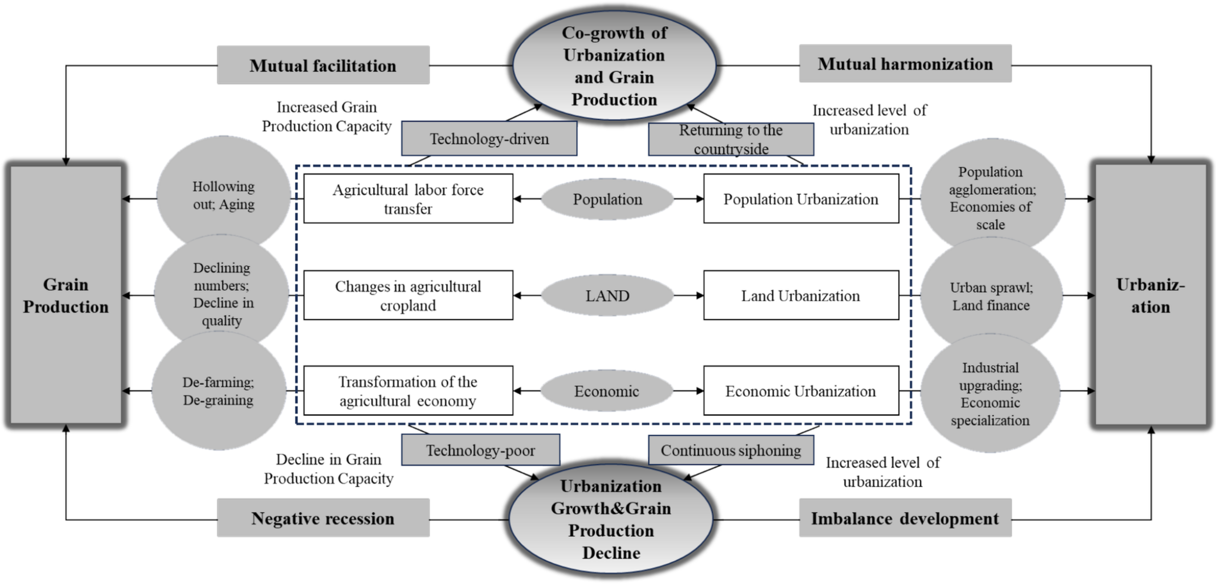

FIGURE 12
The multidimensional coupling mechanism of urbanization and grain production.

coupling mechanisms, which includes both "secondary natural factors" such as population, economy, technology, and the flow of factors, as well as "primary natural factors" such as land, climate, and natural disasters (Krugman, 1991). While the impact of climate change on China's grain production is both significant and complex, this is not the primary focus of the current study. From the perspective of other factors, elements such as population, land, and economy tend to reinforce the "inhibitory effects," while technological progress and the orderly flow of urban–rural factors contribute to the "promoting effects." At the macro level, the coupling and coordination relationship between urbanization and grain production in China continues to improve, revealing a gradual weakening of the "inhibitory effects" and a consistent strengthening of the "promoting effects."

7.1.2 Coupled and coordinated development of urbanization and grain production in the context of China's urbanization policy changes

Since the reform and opening-up period, China's urbanization has followed a clear phased pattern, as illustrated in Figure 3 of this study. The authors divide China's urbanization process over the past 70 years into three stages, each marked by distinct differences in the pace of development. These differences in urbanization speed are largely attributed to the Chinese government's strategic decisions regarding urbanization pathways, which have played a critical role in regulating the speed and stages of development (Chen et al., 2023; Liu and Zhou, 2021). In summary, based on the urbanization strategies and models chosen by the Chinese government, the coupled and coordinated development of urbanization and grain production since the reform and opening-up period can be roughly divided into three stages (Fang et al., 2017; Gu et al., 2017): First Stage (1978–1992): Against the backdrop of rural industrialization, small towns in China developed, albeit at a limited scale. During this period, rural residents could leave agriculture without leaving their hometowns, taking up factory jobs without migrating to cities. This allowed them to engage in industrial production to increase income while maintaining grain production activities. Consequently, the coupling and coordination between urbanization and grain production remained at a low level. Second Stage (1992–2013): As China gradually established its market economy and integrated into globalization, large cities saw rapid development. Agricultural labor migrated long distances to urban areas, which intensified the urban–rural divide. Meanwhile, the improvement of grain production capacity in rural areas was relatively slow, resulting in a medium-level coupling and coordination between urbanization and grain production (Liu and Zhou, 2021). Third Stage (2013–present): The Chinese government has actively promoted a new urbanization strategy, marking a shift away from the previously aggressive urbanization models. Measures have been taken to control the unregulated expansion of urban populations and land, balance urban–rural relations, and encourage the return of resources such as personnel, technology, and capital to rural areas. As a result, the coupling and coordination between urbanization and grain production has reached a medium-high level (Liu Y. S. et al., 2020). Thus, the coupling and coordinated relationship between urbanization and grain production is closely tied to the urbanization model. Through adjustments in national urbanization policies, the Chinese government is steering these two sectors toward a state of high-quality and coordinated development.

7.1.3 Coupling and coordinated development of urbanization and grain production in China: regional patterns and optimization strategies

To facilitate the high-quality coordinated development of urbanization and grain production, it is essential to adopt strategies that are context-specific and temporally relevant (Liu et al., 2021a). This research delineates spatial patterns based on the levels of coupled coordination and the dynamic processes involved in the interaction between urbanization and grain production. Initially, by assessing the current levels of coupled coordination, two primary categories are identified: moderate coupled coordination and high coupled coordination. Further refinement of these categories is achieved by analyzing the trends in coupling dynamics, particularly referencing the changes in urbanization and grain production from 2011 to 2022. Specifically, if urbanization levels experience an upward trajectory while grain production levels decline, this scenario is classified as a grain production decline type. Conversely, if both urbanization and grain production exhibit simultaneous upward trends, with grain production growth outpacing urbanization, it is categorized as a grain production optimization type. In instances where urbanization progresses more rapidly than grain production, this situation is identified as an urbanization optimization type. Ultimately, the study classifies the 31 provincial units into five distinct types: (1) moderate coupled coordination with grain production decline, (2) moderate coupled coordination with urbanization optimization, (3) high coupled coordination with grain production decline, (4) high coupled coordination with urbanization optimization, and (5) high coupled coordination with grain production optimization (Figure 13). This classification underscores the diverse trajectories and interdependencies that characterize the relationship between urbanization and grain production across different regional contexts.

Based on the identified spatial patterns of coupled coordination between urbanization and grain production, a systematic optimization strategy can be formulated. This strategy aims to harmonize global and local considerations, integrate economic development with grain production, balance developmental levels with quality, and enhance regional specialization while leveraging complementary advantages.

7.1.3.1 Moderately coupled coordination—grain production decline type

This category includes seven provincial units: Beijing, Zhejiang, Guangdong, Guangxi, Chongqing, Qinghai, and Tibet. In this group, Beijing, Zhejiang, and Guangdong are experiencing a persistent decline in grain production levels despite a backdrop of relatively high urbanization. The optimization strategy for these regions should focus on mitigating excessive non-grain crop cultivation while ensuring adequate investments in agricultural technology, finance, and human resources to bolster grain production. Conversely, Guangxi, Chongqing, Qinghai, and Tibet require a coordinated approach to elevate both urbanization and grain production levels, with a particular emphasis on agricultural technological innovation aimed at improving yields in remote and challenging environments.

7.1.3.2 Moderately coupled coordination—urbanization optimization type

This category encompasses nine provincial units: Shanghai, Fujian, Hainan, Guizhou, Yunnan, Shaanxi, Gansu, Ningxia, and Xinjiang. Within this group, Shanghai, Fujian, and Shaanxi exhibit a trend of increasing urbanization alongside relatively low grain production levels, which may lead to new forms of dissonance between urbanization and grain production. Therefore, it is imperative to prioritize high-quality grain production and agricultural modernization within the high-quality urbanization agenda. Meanwhile, Hainan, Guizhou, Yunnan, Gansu, Ningxia, and Xinjiang demonstrate moderate levels of both urbanization and grain production; thus, the implementation of new-type urbanization initiatives could effectively foster high-quality coordinated development in these regions.

7.1.3.3 Highly coupled coordination—grain production decline type

This category is represented by Hunan, which showcases a high level of urbanization alongside moderate grain production levels. Over the period from 2011 to 2022, both total grain production and yield levels have experienced fluctuations, exhibiting an upward trajectory. Future strategies should concentrate on regulating excessive non-grain crop cultivation to stabilize and enhance grain production.

7.1.3.4 Highly coupled coordination—urbanization optimization type

This category includes thirteen provincial units: Hebei, Shanxi, Inner Mongolia, Liaoning, Jilin, Heilongjiang, Jiangsu, Anhui, Jiangxi, Shandong, Henan, Hubei, and Sichuan. Among these, provinces such as Jilin, Heilongjiang, Shandong, Henan, and Anhui are significant agricultural producers, where urbanization presents further opportunities for advancement. Future policies should aim to minimize urban encroachment on high-quality arable land, thereby ensuring the sustainability of grain production volumes and reinforcing their status as agricultural powerhouses, essential for national grain security. In other provinces, the constraints of resources and the environment during the high-quality urbanization phase diminish production advantages; hence, it is crucial to enhance the flow of rural–urban factors and implement technological empowerment initiatives to improve regional grain production levels.

7.1.3.5 Highly coupled coordination—grain production optimization type

This category is represented by Tianjin, which exhibits a high level of urbanization coupled with a moderate and consistently improving grain production level. Given the limited availability of arable land, Tianjin's scale advantages in grain production are not pronounced; however, it stands out in high-tech agricultural capabilities. In light of the current context of relatively subdued urbanization growth, Tianjin should focus on developing high-quality urban agricultural zones, positioning itself as a model for high-tech agricultural development and urban–rural integration in the Beijing-Tianjin-Hebei region.

8 Conclusion

This study utilizes China as a representative case from the 21st century to systematically empirically investigate the multidimensional coupling patterns and processes between urbanization and grain production across Chinese provinces from 2000 to 2022. The research aims to identify the driving factors and preliminarily summarize the coupling mechanisms between these two systems.

This study, departing from traditional research on the coupling relationship between urbanization and grain production, contributes novel perspectives and innovations in the following three aspects: (1) Research Perspective: Grain production and urbanization are conceptualized as systems comprising organically integrated multidimensional elements. Unlike prior approaches that treat urbanization as a single entity, this study deconstructs urbanization into three subsystems—population, land, and economy—and investigates the coupling states and interaction mechanisms not only between these two systems but also among the urbanization subsystems and the grain production system, thereby revealing their

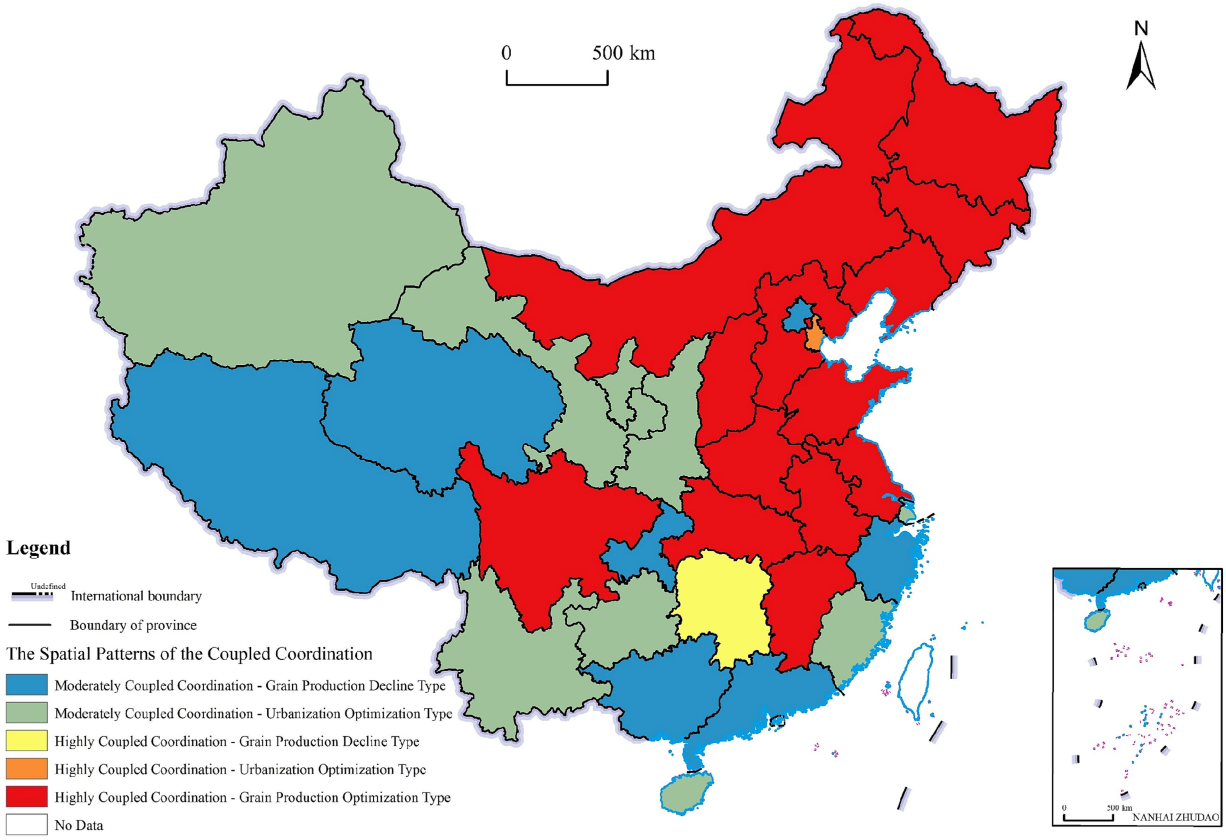

FIGURE 13
The spatial patterns of the coupled coordination between urbanization and grain production.

mechanisms of action more profoundly, building upon the foundational work of scholars such as Liu et al. (2021b) and Zhu et al. (2021). (2) Research Methodology: This study employs a combination of static and dynamic coupling methods to characterize the coupling patterns and processes between urbanization and grain production. This approach not only captures the static coupling state between the two systems but also elucidates the dynamic evolution of these coupling states. Moreover, the coupling coordination degree is calculated using the latest optimized models, ensuring robust applicability to this research (Cai et al., 2021; Zhu et al., 2021). (3) Selection of Research Period: The study selects a more representative period, the third phase (2000–2022), which spans the transition from the initial phase of rapid urbanization to the era of high-quality urbanization in China. This period represents the most significant and complex stage of the coupling relationship between urbanization and grain production (Li X. et al., 2022; Ma et al., 2020). By integrating innovative perspectives, methodologies, and the selection of a representative study period, this study produces findings that are scientifically robust, systematically comprehensive, and highly credible. It reveals the multidimensional, long-term coupling processes and mechanisms between urbanization and grain production in China. At the macro level, the coupling coordination between the two systems has generally improved, whereas at the provincial level, heterogeneous coupling states and differentiated evolutionary processes are evident. These findings highlight the necessity for region-specific and context-sensitive policy recommendations to promote high-quality coordinated development of urbanization and grain production in China. Furthermore, by taking China as a case study, this research offers valuable insights for international reference in similar contexts, systematically uncovering the coupling patterns between national urbanization and grain production in a populous developing country during a period of rapid urbanization (Ambikapathi et al., 2022).

Admittedly, certain aspects of this study require further refinement and exploration in future research. Firstly, this study adopts a narrow definition of “food security”—aligned with the consensus of the Chinese government and academia—that focuses on the production end of key grain crops, particularly total output (production scale), yield per unit area (production quality), and production structure. While emphasizing grain production is essential—particularly under the context of global geopolitical tensions and the substantial food demands of populous nations—the broader concept of “food security” proposed by the Food and Agriculture Organization of the United Nations (FAO), encompassing availability, accessibility, stability, and utilization, warrants further exploration (Erokhin et al., 2022; Xie et al., 2021). Future research will address these dimensions under the broader framework of food security. Secondly, urbanization and grain production should not merely be regarded as simple systems of multidimensional element integration; they embody complex organizational structures characterized by dual dynamics of self-organization and external influences, along with features such as adaptability, synergy, and volatility (Molajou et al., 2023). Future research should leverage the techniques, methods, and theories of complex systems science to better define the relational dynamics, system boundaries, and external interconnections between urbanization and grain production systems, thereby enhancing the understanding of their mechanisms of action while balancing developmental and security principles to promote orderly interactions. Thirdly, grain production is influenced not only by the complex drives of urbanization but also profoundly affected by global climate change as a natural force (Wheeler and von Braun, 2013). According to the IPCC's Fifth Assessment Report, global climate change represents the most significant environmental challenge facing humanity in the 21st century, with rising temperatures, abnormal precipitation patterns, and extreme climate events—such as droughts, floods, typhoons, and frost—posing major threats to global and regional food security. For developing countries like China, the challenges of food security become particularly complex and urgent within the dual context of rapid urbanization and climate change, necessitating systematic research within the framework of "urbanization-climate change-food security."

Author contributions

XC: Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Software, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing. ShW: Conceptualization, Formal analysis, Funding acquisition, Resources, Writing – review & editing. ZY: Conceptualization, Formal analysis, Project administration, Supervision, Writing – review & editing. KL: Conceptualization, Formal analysis, Project administration, Supervision, Writing – review & editing. SiW: Methodology, Software, Validation, Visualization, Writing – review & editing. MQ: Methodology, Software, Validation, Visualization, Writing – review & editing. XM: Methodology, Software, Validation, Visualization, Writing – review & editing.

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Conflict of interest

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