

Article

The Resilience Trilemma in Grain Supply Chain: Unpacking Spatiotemporal Trade-Offs Across Production–Consumption Zones from the Case of China

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Abstract

This study examines the spatiotemporal evolution of China's grain supply chain resilience and regional disparities from 2012 to 2022, employing provincial data and a multidimensional framework encompassing resistance capacity, adaptive adjustment capacity, and innovation-driven transition capacity, and utilizing entropy weight method, kernel density estimation, convergence models and barrier factor analysis with GIS (v10.8.2) visualization. The results reveal a fluctuating upward trajectory in the composite resilience index. However, spatial heterogeneity persists as Major Grain-Producing Areas demonstrate high resistance capacity but lag in transformation due to path dependency, Major Grain-Consuming Areas excel in innovation yet face vulnerability from import dependence, and Grain Self-Sufficient Areas display rapid adaptive capacity growth but spatial polarization intensifies. Theil index decomposition confirmed that inter-regional disparities dominated, reflecting uneven technological diffusion and institutional priorities. Key drivers include natural endowments, infrastructure investments, and digitalization, though threshold effects in policy regulation and path dependency paradoxes constrain convergence. This study advances a dynamic governance framework to balance resilience trade-offs and align supply chain modernization with sustainable food security goals.

Keywords: grain supply chain; resilience; spatiotemporal evolution; China

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1. Introduction

Food security is a fundamental pillar of national security, and the resilience of grain supply chains plays a decisive role in its preservation [1]. Contemporary grain supply chains face multifaceted challenges, including climate change, trade protectionism, and public health emergencies, leading to threats such as production declines, price volatility, and logistics disruptions. Enhancing supply chain resilience defined as the capacity of grain systems to rapidly recover from external shocks, ensure equitable access to nutritious food, and maintain economic viability for stakeholders that has thus emerged as a key research priority.

The United Nations' 2030 Agenda for Sustainable Development identifies “zero hunger” (SDG 2) as a primary objective, yet global food systems confront escalating systemic risks. The FAO's 2023 State of Food Security and Nutrition in the World reports that

the global population experiencing hunger surged from 618 million in 2019 to 735 million in 2022, which one of the main reasons is supply chain disruptions. According to World Bank estimates, 31 countries with populations exceeding 100 million collectively account for 72% of global food demand pressures [2]. The strategic imperative of enhancing supply chain resilience in densely populated regions, where systemic vulnerabilities pose significant risks to both food accessibility and socioeconomic stability.

As a responsible nation representing nearly 18% of the global population, China has long regarded grain supply chain resilience as a strategic pillar of national security. Despite maintaining annual grain output above 650 million metric tons for eight consecutive years, post-production losses remain high at around 35 million metric tons. Projections suggest that by 2035, losses across harvesting, storage, processing, and consumption could fall to 1–3%. These trends not only reflect China's domestic efforts but also offer broader insights into enhancing food system efficiency and resilience amid global uncertainties. Strengthening grain supply chain resilience through improved risk resistance, adaptive management, and rapid recovery is essential not only for China but also for other countries seeking to balance productivity, sustainability, and security in an interconnected global food system.

Leveraging provincial data from 2012 to 2022, this study constructs a comprehensive evaluation index system to assess China's grain supply chain resilience. Methodologies including the entropy weight method, kernel density estimation, and convergence models are employed to systematically analyze its spatiotemporal evolution and regional divergence mechanisms, with a focus on three core dimensions: resistance capacity, adaptive adjustment capacity, and innovation-driven transition capacity. The findings reveal that China's grain supply chain resilience has a "fluctuating upward" temporal trend under the synergistic effects of institutional provisioning, technological innovation, and market mechanisms. Spatially, development patterns demonstrate distinct heterogeneity: major production regions exhibit high-risk resistance, Major Grain-Consuming Areas display strong transformation capacities, and balanced regions show weak convergence. Regional disparity dynamic convergence analyses reveal threshold effects in policy regulation and path dependency paradoxes.

The marginal contributions of this study are fourfold. First, it introduces an innovative analytical perspective that extends beyond qualitative discussions of food system resilience [3,4]. By quantitatively assessing grain industrial and supply chain resilience, it proposes a "distribution pattern–dynamic mechanism–spatial response" paradigm, advancing methodological approaches and emphasizing the vital role of resilient systems in food security and economic stability [5]. Second, it addresses a global gap in comprehensive evaluation frameworks. Grounded in complex adaptive systems theory, the study develops a multidimensional model encompassing resistance, adaptation, and transformation capacities, allowing objective and comparable resilience assessments. Third, it integrates advanced methods—kernel density estimation, Theil index decomposition, and barrier factor analysis combined with GIS visualization—to reveal spatial disparities and systemic constraints consistent with global agri-food resilience research. Finally, it offers policy insights of global relevance. The proposed differentiated strategies and the shift from passive defense to adaptive governance contribute to international debates on building resilient and sustainable food systems under growing uncertainties.

1.1. Theoretical Evolution of Grain Supply Chain Resilience

The conceptual evolution of grain supply chain resilience is closely intertwined with shifts in global security paradigms. Early studies prioritized supply chain stability [6], defining resilience as a system's capacity to withstand shocks without failure. As globaliza-

tion amplified risks, Christopher and Peck [7] advanced the notion of resilience in supply chain risk management, emphasizing proactive adaptation and signaling a theoretical shift from passive defense to active adjustment. Subsequent work by complexity theorists further expanded conceptual boundaries. In a seminal contribution to nature sustainability, Béné [8] proposed a tripartite framework of robustness–recovery–transformability, positing resilience as a dynamic process through which systems achieve functional upgrades via structural reorganization under disruption. This paradigm shift resonated with international policy discourse, as evidenced by the FAO’s 2021 White Paper for the Food Systems Summit, which asserted that resilience-building necessitates transcending supply chain repair to embrace innovation-driven systemic reconfiguration.

Multidimensional theoretical frameworks have injected new dynamism into resilience research. Multidimensional theoretical frameworks have significantly advanced resilience research. Contributions span multiple fields such as resilience engineering underscores distributed decision-making [9], dynamic capability theory reveals the synergy of agility and redundancy in supply chains [10], spatial network analysis uncovers infrastructure-driven divergence [11], and Bayesian network models help consolidate fragmented metrics [12].

1.2. Multidimensional Deconstruction of Resilience Mechanisms

The literature identifies grain supply chain resilience as shaped by the interactive effects of natural, economic, and social stressors. First, there are natural factors. The IPCC’s Sixth Assessment Report [13] confirmed that global warming has increased the frequency of extreme weather events, directly increasing the coefficient of variation for grain yields [3,14]. Droughts impact resilience through nonlinear pathways: inventory buffer mechanisms abruptly collapse when precipitation falls below a certain level [15]. Pest infestations further threaten crops, with novel pests exhibiting rapid transmission and resistance to conventional control, increasing supply uncertainty. Second, there are economic drivers. Economic volatility reveals intricate transmission channels. Trade policy shifts disrupt cross-border grain flows, destabilizing the scale and direction of the supply chain. Price surge elevates smallholder exit probabilities [16], whereas multinational corporations reduce risk exposure via options hedging [17]. The third factor is social vulnerability. Public health crises restrict labor mobility and logistics, impeding production-distribution linkages. Regional conflicts and civil unrest damage infrastructure, distort markets, and escalate demand shocks, as evidenced by protracted crises across the Middle East and Africa [11,18].

Emerging geopolitical perturbations, exemplified by the Russia–Ukraine conflict, show that grain trade restrictions reduce supply chain resilience indices, with low-income nations suffering losses greater than those of high-income countries [19]. Spatial heterogeneity analyses further challenge deterministic geographic explanations. Alphonse [20] demonstrated that land transport reliance increases supply disruption risk landlocked states, highlighting the moderating role of institutional resilience: improvement in the Democratic Governance Index (DPI) enhances climate-impacted food accessibility [16].

1.3. Practical Paths to Enhancing Resilience

The literature proposes concrete strategies for improving grain supply chain resilience, spanning technological innovation, collaborative governance, and policy interventions. First, technology-driven innovation has dual effects. Agricultural advancements in breeding, cultivation, and irrigation technologies enhance yield and quality, strengthening production resilience [21]. Empirical analyses reveal that IoT adoption reduces cold chain logistics losses, yet significant scale economies exist [22]. Blockchain technology improves food recall efficiency but perpetuates data poverty traps for SMEs [23]. Emerging resilience

digital twin models demonstrate faster post-disaster recovery by integrating machine learning with supply chain simulation [24]. Second, collaborative governance innovations are gaining policy traction. The supply chain is a collaborative chain [25]. Collaborations can help supply chains respond and recover from a disruption [26,27]. For example, cross-national evidence validates the effectiveness of public-private partnerships (PPPs): the integration of government reserves with commercial inventories reduces shortage risk [28]. The collaborative supervision between government departments on the upstream and downstream entities of the supply chain directly affects the resilience and development of the supply chain through the information sharing mechanism and cooperative governance mechanism [29]. Third, policy safeguards provide foundational support. Subsidies and insurance schemes stabilize production incentives and mitigate operational risks [30]. Vertically integrated cooperation frameworks with risk-sharing clauses and dynamic revenue-sharing mechanisms are highly important for a supply chain's stable and sustainable development [31]. Standardized contract templates incorporating ex ante risk allocation provisions improve supply chain coordination efficiency, particularly under price volatility scenarios [32,33].

1.4. Critical Research Evaluation

A synthesis of the literature reveals three critical limitations. First, insufficient modeling of temporal dynamics persists. Most studies rely on cross-sectional data [34], failing to capture time-variant characteristics, threshold effects, and path dependence in China's grain supply chain resilience. Second, spatial analyses operate predominantly at overly aggregate national scales, neglecting subnational heterogeneity and interactions [35]. This oversight undermines the precision of policy targeting, particularly in addressing spatially asymmetric vulnerability. Third, the proposed resilience-enhancing pathways disproportionately emphasize unidirectional technological fixes, overlooking the coevolutionary mechanisms among institutions, technological systems, and market structures. To address these gaps, this study develops an innovative three-dimensional framework (resistance-adaptation-transformation) coupled with spatial econometric models. This approach disentangles multiscale interactions while quantifying nonlinear resilience dynamics, offering granular decision support for food security governance.

2. Materials and Methods

2.1. Index System Development

Grain supply chain resilience refers to the capacity of a grain supply chain to rapidly recover and adjust its operational state following disruptions or to optimize its configuration toward peak performance. Enhancing this resilience has emerged as a critical imperative for alleviating hunger and safeguarding global food security. Building upon the operational resilience framework proposed in recent studies [14], we construct a multi-dimensional evaluation index system for China's grain supply chain resilience, anchored in three systemic capabilities: resistance capacity, which is the ability to withstand and buffer shocks through resource redundancy, and risk diversification. Adaptive adjustment capacity refers to the ability to reconfigure logistics, inventory, and pricing strategies under stress. Innovation-driven transition capacity refers to structural upgrading via digitalization, green technologies, and institutional innovation. The hierarchical index system integrates 22 quantifiable indicators across these dimensions tailored to China's provincial administrative units. Detailed indicator definitions, measurement protocols, and weighting schemes are presented in Table 1.

Table 1. Evaluation index system of the resilience level of China’s grain supply chain.

First-Order Dimension	Second-Level Dimension	Specific Indicators	Attribute	Weight
Resistance Capacity	The grain supply chain stability ability	Grain production per capita (tons/capita)	+	0.04659
		Arable land per capita (ha/capita)	+	0.04614
		Agricultural production price index	+	0.04995
	The grain supply chain coordination ability	Rural labor force level	+	0.00122
		Grain yield per unit area (kg/ha)	+	0.02793
		Foreign trade dependence (%)	—	0.05031
		Rural road access rate	+	0.04812
	Adaptive Adjustment Capacity	The grain supply chain disaster resilience ability	Crop damage rate	—
Strength of agricultural plastic film			—	0.05024
Fertilizer intensity			—	0.05022
Pesticide application intensity			—	0.05009
Agricultural diesel fuel intensity (tons/ha)			—	0.05009
The grain supply chain adjustment ability		Value added of primary industry in GDP (%)	+	0.04878
		Agricultural Insurance (Premium) Payout (million yuan)	+	0.04671
		The multiple crop index	+	0.04915
		Grain yield fluctuation rate	—	0.05018
Innovation-Driven Transition Capacity		The grain supply chain innovation ability	Planting construction of the crops	+
	Number of organic food certificates (PCS)		+	0.04643
	The grain supply chain transformation ability	Per capita disposable income of rural residents	+	0.04863
		Output value of grain	+	0.04696
		Number of grain industry enterprises (PCS)	+	0.04691
		Profit of grain industry enterprises (100 million yuan)	+	0.04575

2.2. Data Sources

To balance data availability and timeliness, this study utilizes panel data spanning 2012 to 2022 from 30 Chinese provinces (excluding Tibet, Hong Kong, Macau, and Taiwan). The datasets are derived from official statistical yearbooks and repositories, including the China Statistical Yearbook, China Statistical Yearbook on Science and Technology, China Yearbook of Grain and Material Reserves, China Rural Statistical Yearbook, China Population and Employment Statistical Yearbook, China Agricultural Machinery Industry Yearbook, National Bureau of Statistics (NBS) portal and provincial statistical yearbooks.

2.3. Methodology

Conceptualizing the Resilience Trilemma: A Constrained Optimization Perspective

In the process of enhancing the resilience of the food supply chain, the optimal levels of three core capabilities of the system—resistance, adaptive adjustment, and innovation-driven transformation—are difficult to reach simultaneously. There exists a fundamental trade-off relationship where an increase in one capability may lead to a decrease in the others. This “trilemma” does not imply that the three goals are completely mutually exclusive. Instead, it emphasizes that under the constraints of limited resources, policy attention, and time, overemphasizing the development of one or two capabilities may result in the deficiency of the others, thereby creating systemic weaknesses that restrict the

overall improvement of resilience. This study focused on different production and sales regions in China (Major Grain-Producing Areas, Major Grain-Consuming Areas, Grain Self-Sufficient Areas), vividly revealing the specific manifestations of this tripartite paradox in the temporal and spatial dimensions.

This study positions its three-dimensional resilience framework within the broader theoretical landscape. While existing frameworks like the robustness–recovery–transformation triad [8] offer valuable evolutionary perspectives, they often treat capacities sequentially and do not explicitly model their inherent trade-offs. Similarly, supply chain-oriented frameworks acknowledge trade-offs but are not designed to capture the deep-seated, spatially heterogeneous constraints inherent to agri-food systems. Our resistance-adaptation-transformation framework advances this discourse by formalizing the simultaneous and often conflicting nature of these capacities—the resilience trilemma, that as a central, measurable phenomenon, thereby offering a diagnostic tool for spatially targeted governance.

To formalize the “Resilience Trilemma”, we conceptualize it not as a problem with a single optimal solution, but as a constrained optimization challenge. The core proposition is that a grain supply chain system cannot simultaneously maximize its Resistance Capacity (R), Adaptive Adjustment Capacity (A), and Innovation-driven Transition Capacity (T) due to finite resources, path dependencies, and spatial-institutional constraints.

Let R, A, and T represent the quantitative indices for resistance, adaptive adjustment, and innovation-driven transition capacities, respectively, as derived from our evaluation system. The ideal state of maximal resilience would be to maximize all three: $\max\{R, A, T\}$.

However, this is unattainable in practice. The system is subject to a feasibility constraint F that represents the total available resources (financial, natural, institutional, technological): $F(R, A, T|Z) \leq C$. Where Z is a vector of region-specific contextual factors (e.g., resource endowments, institutional quality, geographic location), and C is a system-specific capacity boundary.

This constraint manifests as a trade-off frontier, where enhancing one capacity often comes at the expense of at least one other. This can be represented as: $T = f(R, A|Z)$. Where the function f captures the opportunity costs and synergies between the capacities. The empirical patterns observed in our results reflect different regions’ positions relative to this frontier. The Resilience Trilemma in Grain Supply Chain shown as Figure 1.

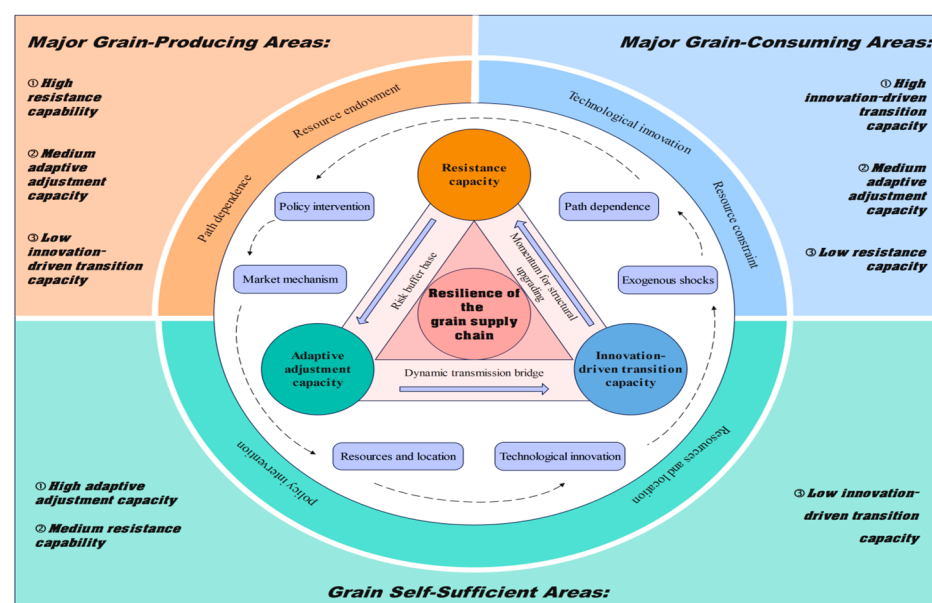


Figure 1. The Resilience Trilemma in Grain Supply Chain.

2.4. Entropy Weight Method

The entropy weight method (EWM) is adopted to evaluate the comprehensive resilience level of China's grain supply chain. The procedural steps are outlined as follows:

Data normalization. Given heterogeneous measurement units and directional distinctions (positive vs. negative indicators) in the selected variables, raw data are standardized via min–max normalization to confine values within [0, 1]. As shown in Table 1, the resilience evaluation system comprises 15 positive indicators and 7 negative indicators. The formulas are defined as follows.

$$\text{For positive indicators : } X_{ij} = \frac{x_{ij} - \min(x_{ij})}{\max(x_{ij}) - \min(x_{ij})} \quad (1)$$

$$\text{For negative indicators : } X_{ij} = \frac{\max(x_{ij}) - x_{ij}}{\max(x_{ij}) - \min(x_{ij})} \quad (2)$$

where X_{ij} denotes the standardized value of the j indicator for the i province; x_{ij} is the original value; and $\max(x_{ij})$ and $\min(x_{ij})$ represent the maximum and minimum values of the j indicator across all provinces, respectively. The data of item j of sample i are normalized, with n representative sample sizes.

$$P_{ij} = \frac{x_{ij}}{\sum_{i=1}^n x_{ij}} \quad (3)$$

Then, it is necessary to calculate the entropy, the difference coefficient and the weight of each index and finally calculate the comprehensive score of each region. The formulas are defined as follows.

$$e_j = -K \sum_{i=1}^n p_{ij} * \ln p_{ij}, K = \frac{1}{\ln n} \quad (4)$$

$$g_j = 1 - e_j \quad (5)$$

$$w_j = \frac{g_j}{\sum_{j=1}^n g_j} \quad (6)$$

$$S_i = \sum_{j=1}^n w_j p_{ij} \quad (7)$$

2.5. Kernel Density Estimation

Kernel density estimation (KDE) is a nonparametric method used to study the distributional dynamics of China's grain supply chain resilience and its subsystems across regions. It visualizes distribution patterns, location shifts, and extension characteristics through continuous density curves. Let independent and identically distributed observations from a continuous population with a density function be used. The kernel density estimator at any point is defined as follows.

$$f(x) = \frac{1}{Nh} \sum_{i=1}^n K\left(\frac{X_i - \bar{x}}{h}\right) \quad (8)$$

where n is the number of observations, K denotes the kernel function, X_i represents the observed values, $\bar{x}$ is the sample mean, and h is the bandwidth parameter.

2.6. Coefficient of Variation

To quantify regional disparities in grain supply chain resilience, the coefficient of variation (CV) is applied via the following formula.

$$V = \sigma_t / E(Y_t) \quad (9)$$

where V denotes the coefficient of variation in year, $E(Y_t)$ is the mean resilience value across regions in year t , and σ_t represents the standard deviation.

2.7. Theil Index

The Theil index decomposes regional differences in resilience into between-region and within-region components. Let the resilience score of a province, the national average resilience, and the total number of provinces be used. Provinces are categorized into groups (e.g., Major Grain-Producing Areas and Major Grain-Consuming Areas). The Theil index is calculated as follows.

$$T = \frac{1}{n} \sum_{i=1}^n \left(\frac{y_i}{\bar{y}} \right) \ln \left(\frac{y_i}{\bar{y}} \right) \quad (10)$$

$$T = T_b + T_w \quad (11)$$

$$T_b = \sum_{k=1}^k y_k \ln \frac{y_k}{n_k/n} \quad (12)$$

$$T_w = \sum_{k=1}^k y_k \left(\sum_{i \in g_k} \frac{y_i}{y_k} \ln \frac{y_i/y_k}{1/n_k} \right) \quad (13)$$

$$T_k = \sum_{i \in g_k} \frac{y_i}{y_k} \ln \frac{y_i/y_k}{1/n_k} \quad (14)$$

$$D_K = y_k \cdot \frac{T_k}{T} \quad (15)$$

$$D_b = \frac{T_b}{T} \quad (16)$$

where T is the Thiel index of China's grain supply chain resilience, and T_b , T_w , and T_k represent interregional differences, intraregional differences and intragroup gaps, respectively. y_i represents the comprehensive level of grain supply chain resilience of province i , $\bar{y}$ represents the average comprehensive level of China's grain supply chain resilience, and n represents the number of sample observations. The provinces are divided into groups of k according to their grain production and sales regions, and each group is $g_k (= 1, 2, \dots, 5)$; the number of municipalities included in group k is n_k . D_K and D_b represent the contribution rates of the intraregional gap and the intergroup gap, respectively.

2.8. σ -Convergence

To study the differences in Chinese grain supply chain resilience, this study aims to test whether regional resilience levels converge toward the national mean over time, and σ -convergence is assessed via the standard deviation. The formula is as follows.

$$V = \sqrt{\frac{1}{n} \sum_{i=1}^n (IGG_{it} - \overline{IGG_t})^2} \quad (17)$$

where IGG_{it} is the resilience score of region i in year t , and $\overline{IGG_t}$ is the national average in year t . If σ -convergence exists, it indicates reduced regional disparities.

2.9. β Convergence

β -convergence examines whether lagging regions catch up with advanced regions. Absolute β -convergence assumes homogeneous steady states, whereas conditional β -convergence accounts for region-specific factors. The regression model is specified as follows.

$$\ln\left(\frac{IGG_{i,t+1}}{IGG_{i,t}}\right) = \alpha + \beta \ln IGG_{i,t} + \gamma Z_{it} + \mu_i + \lambda_t + \varepsilon_{it} \quad (18)$$

where $\ln\left(\frac{IGG_{i,t+1}}{IGG_{i,t}}\right)$ measures convergence speed: a negative and significant value implies absolute convergence if no controls are included and conditional convergence if covariates are added. μ_i represents individual fixed effects, λ_t represents time fixed effects, and ε_{it} is the error term. If β convergence is significantly negative, the change in China's grain supply chain resilience in different regions will converge.

3. Results

3.1. Variation Characteristics of China's Grain Supply Chain Resilience Composite Index

3.1.1. Temporal Features of the Composite Index

The temporal evolution of China's grain supply chain resilience composite index from 2012 to 2022 is presented in Figure 2. The composite index exhibited an overall fluctuating upward trend during this period, driven by a compound mechanism of policy intervention–technology adoption–market adaptation. Specifically, the index increased from 2012 to 2022, with an average annual growth rate of 4.23%. However, notable phase fluctuations were observed that two growth peaks emerged after 2017 and after 2021, whereas growth slowdowns occurred from 2014 to 2016 and in 2018. The resilient system demonstrated distinct shock-response adaptive dynamics.

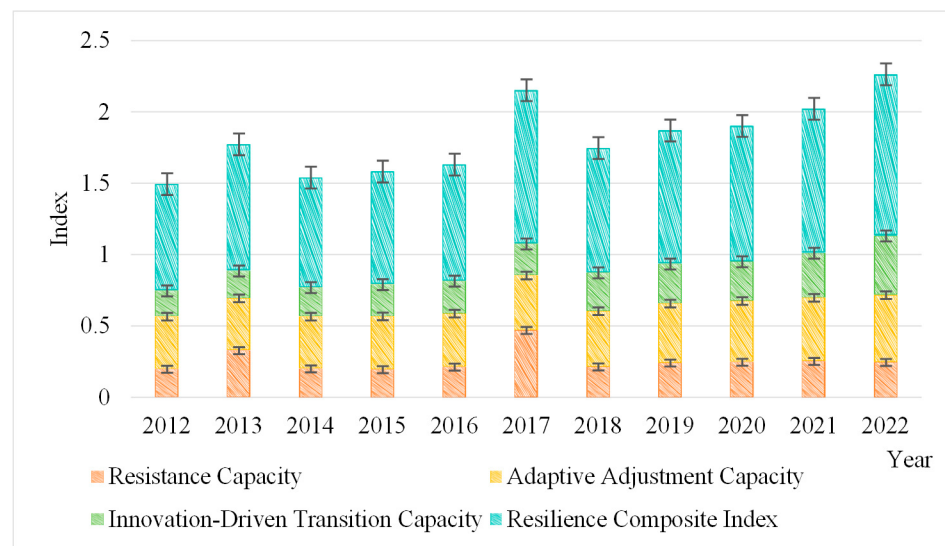


Figure 2. Temporal changes in the resilience level of China's food supply chain from 2012 to 2022.

For example, the 2018 China–US trade friction triggered a contraction in grain import channels, leading to decline in the composite index, which revealed vulnerabilities in external risk transmission mechanisms. Nevertheless, the supply chain system exhibited robust learning adaptability. Through diversified import strategies and expanded emergency processing capacity, the proportion of the grain trade under the Belt and Road Initiative rose to 37.2% (General Administration of Customs, 2021), and the number of emergency processing enterprises increased from 2017 to 2022. These adaptations facilitated supply chain reconfiguration, driving the composite index to a historic high in 2022. The findings

underscore that the enhancement of grain supply chain resilience reflects an adaptive cycle shaped by institutional supply, technological innovation, and market mechanisms. However, periodic fluctuations in risk resistance capacity highlight persistent systemic vulnerabilities. Balanced resilience development calls for building a comprehensive risk monitoring network and fostering deeper international production capacity cooperation.

From 2012 to 2022, the comprehensive index of grain supply chain resilience in all provinces showed an overall growth trend, but regional differentiation was obvious, as shown in Figure 3. Resource-based provinces such as Inner Mongolia, Xinjiang, and Jiangxi experienced growth, while eastern provinces like Shanghai and Zhejiang saw slower progress. In Yunnan, policy interventions in 2013 caused a temporary spike in the composite index, which normalized the following year, reflecting short-term volatility in policy-driven growth. Inner Mongolia's focus on the new energy industry has led to an average annual growth of 5.1% in the index, driven by the synergy between natural resources and technological innovation. Jiangxi's transformation capacity increased by 220% post-2020, supported by the green transformation of its nonferrous metal industry, with circular economy parks contributing over 35%. Tianjin's index surged by 45% in 2020 due to smart port upgrades and new infrastructure, but partially reversed in 2021 due to external market fluctuations. Technological progress and policy interventions are key factors in changes to resilience, while natural constraints (e.g., ecological limits in the Yellow River Basin) reinforce regional path dependence.

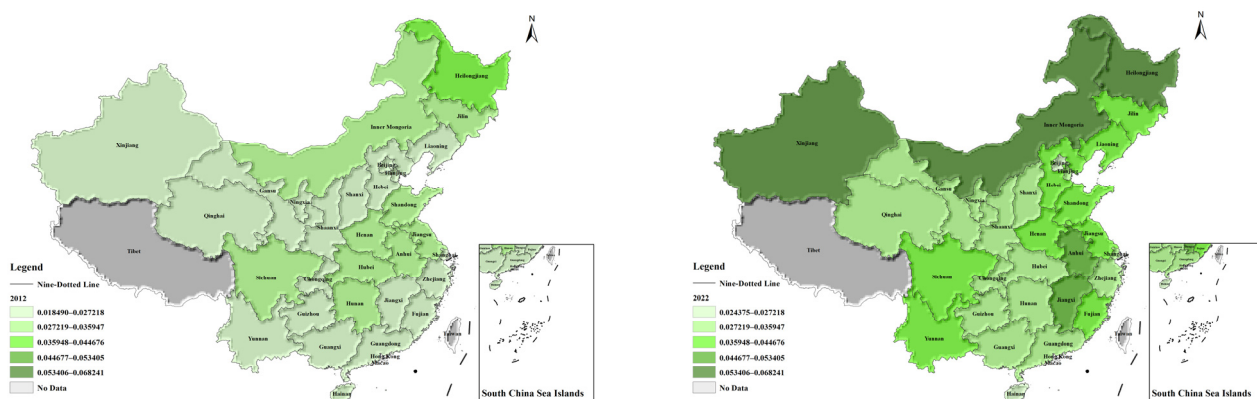


Figure 3. Spatio-temporal characteristics of China's food supply chain resilience in 2012 and 2022.

3.1.2. Evolution of Kernel Density in Grain Supply Chain Resilience Composite Index

Kernel density estimation, a nonparametric statistical method, is employed to estimate the probability density function of a random variable. By smoothing data distributions, it effectively visualizes positional shifts, peak morphologies, and distributional tails. This study applies kernel density estimation with Gaussian kernel functions and Silverman's adaptive bandwidth selection method to analyze the spatiotemporal evolution of China's SSC resilience composite index during representative years (2013, 2015, 2017, 2019, 2021). As shown in Figure 4, the rightward shift in the kernel density curves over the observation period corroborates the overall improvement in national grain supply chain resilience.

Distributional Shifts: The kernel density curves exhibit significant rightward movement, with the mean composite index increasing from 0.026 in 2013 to 0.035 in 2021, whereas the standard deviation expands from 0.008 to 0.012. This reflects a policy-driven increase in resilience, accompanied by growing regional heterogeneity. Key factors include infrastructure investments, agricultural modernization, and emergency response capacity building. Disparities are further influenced by uneven infrastructure development and the varied growth of new agricultural business entities.

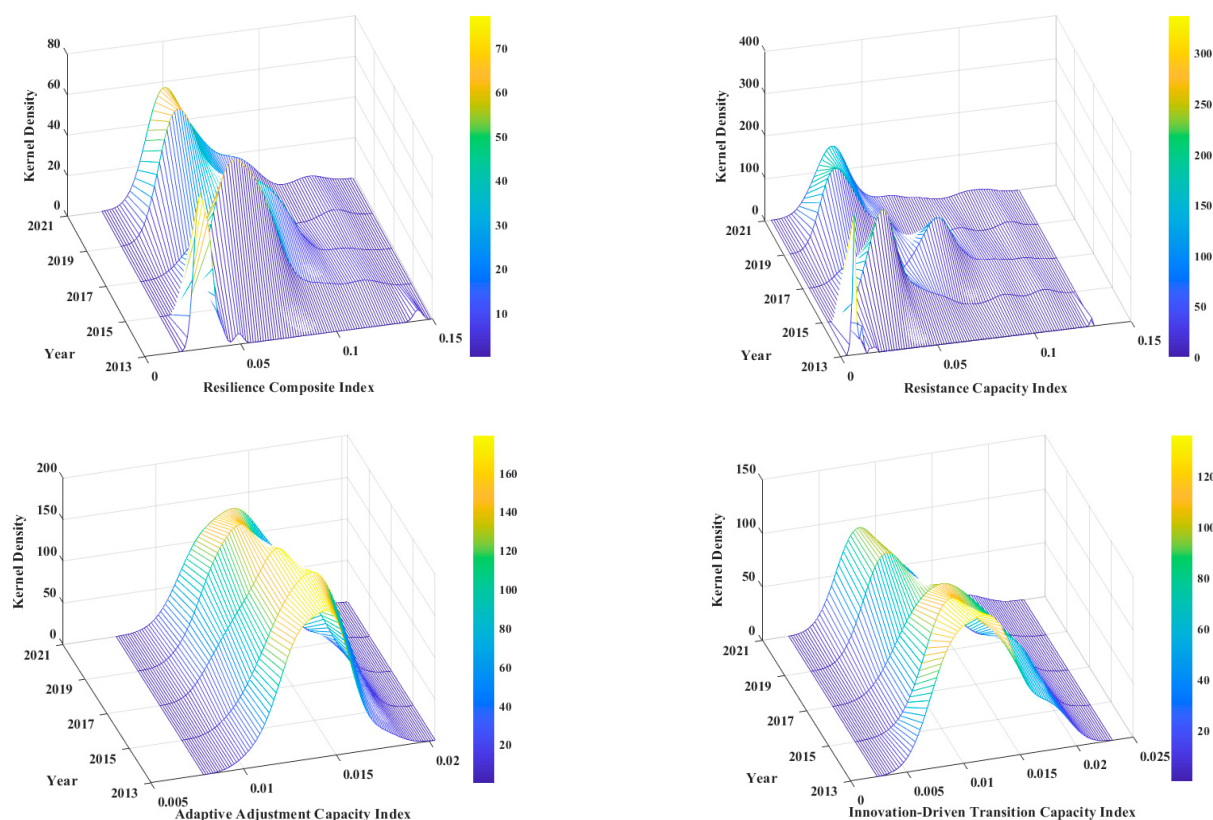


Figure 4. Evolution of kernel density in China's grain supply chain resilience.

Peak morphology transition: To formally assess the presence of multiple modes in the kernel density distributions, we applied Silverman's test and Hartigan's dip test. The distribution evolves from a unimodal right-skewed pattern (2013–2015), to a weakly bimodal structure after 2017. The dual peaks indicate increased regional polarization. High-resilience clusters (e.g., Heilongjiang, Inner Mongolia, Jiangxi) are likely influenced by favorable resources, technological innovations, and policy support, which contribute to resilience growth. In contrast, low-resilience regions (e.g., Hainan, Chongqing) face challenges due to geographical constraints, limited mechanization, and monoculture economies.

Tail Dynamics Analysis: The distribution's right tail thickens, whereas the left tail narrows. The resilience range expanded from 0.031 in 2013 to 0.043 in 2021. Notably, the range for high-resilience provinces (Heilongjiang, Inner Mongolia) widened from 0.03 in 2013 to 0.04 in 2021, driven by digital transformation initiatives such as the Smart Granary Project and Precision Agriculture. In contrast, low-resilience regions show range contraction, which may be associated with policy interventions such as targeted poverty alleviation and cross-provincial collaboration under the Grain Security Industrial Belt program, potentially narrowing foundational capability gaps.

Dynamic Evolution of Subsystem Indices in China's Grain Supply Chain Resilience Weight Structure of the Subsystem Indices

As shown in Table 1, China's grain supply chain resilience evaluation system, which is grounded in complex adaptive systems theory, employs a multitiered indicator framework to systematically deconstruct core stability determinants and their interaction mechanisms. This system integrates a capacity-building—problem-solving dual orientation, aligning with the dynamic evolutionary principles of complex systems while addressing multidimensional challenges to China's food security. Empirical analysis reveals three primary dimensions with distinct weight allocations: resistance capacity (28.17%), adaptive

adjustment capacity (43.87%), and innovation-driven transition capacity (27.97%). The dominance of adaptive adjustment capacity underscores its pivotal role in sustaining systemic resilience. To assess the robustness of the indicator weights derived from the Entropy Weight Method (EWM), a sensitivity analysis was conducted using the CRITIC (Criteria Importance Through Intercriteria Correlation) method. A Pearson correlation analysis between the original EWM-based indices and the new CRITIC-based indices yielded a correlation coefficient exceeding 0.95 for all years, indicating a very high level of agreement.

Adaptive adjustment capacity operates through a dual-driver mechanism comprising disaster resilience and adjustment ability, prioritizing responsiveness to natural disasters and market volatility. High-weight tertiary indicators such as the crop damage rate and agricultural diesel fuel intensity empirically validate the critical role of mechanization and chemical inputs in mitigating natural risks. However, this also reveals the ecological strain caused by technological path dependency, signaling trade-offs between short-term risk buffering and long-term sustainability. The subdued weight of agricultural insurance payouts highlights institutional gaps in market-driven risk dispersion mechanisms.

Resistance capacity reflects balanced weights between stability ability and coordination ability, emphasizing parity between optimizing baseline production conditions and enhancing collaborative governance. Foundational indicators such as arable land per capita and the rural road access rate constitute the material foundation of resilience. Notably, the high weight assigned to foreign trade dependency mirrors systemic vulnerabilities in import security under globalization. The agricultural production price index indicates that price fluctuations are directly transmitted to the production end, and its high weight is in line with the market imbalance risk caused by the supply lag in the spider web theory, which needs to regulate and stabilize expectations through price signals. The rural labor force level has a very low weight, or its marginal contribution has been weakened by mechanized substitution under the trend of the rural population hollowing out.

Innovation-driven transition capacity differentiates between innovation ability and transformation ability components, delineating endogenous drivers of agricultural modernization. High-weight indicators such as the planting of crops verify the importance of superior products and superior yields in the structural reform of the agricultural supply side. The per capita disposable income of rural residents is in line with the income-investment transmission mechanism whereby income increases to production modernization incentives. The relatively high weight of the number of organic certifications and the profit of grain industry enterprises highlights that consumption upgrading forces the green development of the industrial chain, and the grain industry needs to overcome the trap of low added value and strengthen the integration of the whole industrial chain. Future policy should prioritize dual objectives: optimizing technical pathways for high-weight indicators and institutional reinforcement for low-weight indices, thereby achieving holistic resilience enhancement.

3.1.3. Temporal Characteristics of Subsystem Indices in Grain Supply Chain Resilience

The temporal evolution of subsystem indices reveals differentiated growth patterns and resilience drivers, as shown in Figure 3.

The resistance capacity index demonstrates significant cyclical volatility, fluctuating between 0.1959 and 0.4708. Peaking in 2017 before sharply retreating, this trajectory reflects periodic vulnerabilities to external shocks. The fluctuation correlates with policy intervention intensity: the 2017 No. 1 Central Document catalyzed agricultural supply-side reforms, optimizing reserve systems and production capacity regulation. Consequently, risk resistance has increased by 120.0% annually. However, the 2018 China-U.S. trade friction

exposed import dependency risks, triggering a 51.2% decline, indicating interactions between short-term policy efficacy and exogenous disruptions.

The adaptive adjustment capacity index exhibited sustained growth, increasing from 0.3685 in 2012 to 0.4711 in 2022. This trend reflects systemic optimization via institutional reforms. After the implementation of the 2015 Provincial Governor Responsibility System for Food Security, provincial grain reserves expanded annually by 12.7% (National Food and Strategic Reserves Administration, 2018), directly enhancing supply chain stability. Streamlined administrative governance further fortifies internal adaptive mechanisms.

Innovation-driven transition capacity grew most dynamically, increasing from 0.1809 in 2012 to 0.4150 in 2022, with accelerated growth after 2020. Dual drivers which technology iteration and policy incentives underpin this trajectory. The Ministry of Agriculture's Digital Agriculture and Rural Development Plan (2019–2025) elevated grain e-commerce penetration from 9.4% to 23.6% and deepening digital integration boosted end-to-end response efficiency.

The spatiotemporal evolution of resilience was significantly shaped by major external shocks, which acted as catalysts that exposed systemic vulnerabilities and triggered adaptive responses. The trade frictions demonstrated that high resistance in production zones could not insulate the system from vulnerabilities in consumption zones, underscoring the interconnectedness of the national system. Conversely, the COVID-19 pandemic revealed that pre-investments in innovation-driven transition capacity (e.g., digitalization) were critical for sustaining adaptive adjustment during unparalleled logistical paralysis. These observations provide empirical validation for our trilemma framework and highlight the nonlinear, shock-dependent nature of resilience trade-offs. This implies that building resilience requires a balanced portfolio of investments tailored to defend against both geopolitical and bio-logistical threats.

3.1.4. Kernel Density Evolution of Subsystem Indices in Grain Supply Chain Resilience

To elucidate the dynamic evolution of subsystem indices, kernel density estimation was applied to analyze the temporal characteristics of risk resistance, adaptive adjustment, and innovation transformation capacities between 2012 and 2022 (Figure 4). The findings indicate that the multiscale spatiotemporal coupling of China's grain supply chain resilience results from three distinct evolutionary pathways, namely gradient leapfrogging, collaborative optimization, and polarized restructuring. This dynamic is propelled by a sequential transmission chain encompassing policy intervention, technology diffusion, and market selection. This resilience trilemma underscores the need to transcend unidimensional optimization, pivoting toward a synergistic governance framework that integrates policy targeting, technological inclusivity, and market openness.

The resistance capacity subsystem exhibits pronounced core–periphery divergence, reflecting asymmetric resource allocation and institutional advantages. The kernel density estimation results for 2012 revealed that the provincial indices were concentrated in a low-level equilibrium. By 2022, the primary peak shifted rightward, accompanied by a secondary peak and a thickened right tail. This bifurcation mirrors the dual effects of the Grain Security Industrial Belt policy: frontier provinces such as Xinjiang and Inner Mongolia achieved increased resilience through national reserve depot expansion, whereas eastern provinces faced diminishing marginal returns due to arable land constraints and widening interprovincial disparity. Despite overall risk threshold enhancement, intensified spatial heterogeneity necessitates cross-regional fiscal transfers to counterbalance polarization.

The adaptive adjustment capacity subsystem demonstrates a transition from binary fragmentation toward coordinated convergence, validating the bridging effect of digital technology. In 2012, the left-skewed density curve featured a main peak and a left tail

formed by traditional agricultural bases (Hebei, Henan), highlighting infrastructure disparities. After the implementation of smart granaries and blockchain traceability systems (2022), the curve shifted right, with a sharpened main peak and thinner left tail. The trickle-down effect of 5G-driven warehousing upgrades shortened monitoring response times in central/western provinces, reducing the interprovincial. While digitalization mitigates spatial inequities, vigilance against “digital divide” exclusionary risks remains critical.

The innovation-driven transition capacity subsystem evolves through three distinct phases—fractured distribution, unipolar breakthrough and multipolar symbiosis. The 2012 multimodal distribution indicated fragmented development, with most provinces clustered in low-value ranges. Following supply-side reforms (2022), the density curve shifted right, forming a dominant peak encompassing 68% of the provinces. Market mechanisms reshaped spatial dynamics through two pathways, as e-commerce hubs such as Jiangxi and Chongqing enhanced agricultural circulation efficiency, while traditional agrarian provinces increased R&D intensity by advancing integrated reforms across supply, innovation, and capital chains.

3.1.5. Regional Disparities in China’s Grain Supply Chain Resilience Resilience Differentiation Features Based on Spatial Patterns of Grain Production–Consumption

As shown in Figure 5, China’s spatial structure of grain production–consumption, shaped by the historical interplay of resource endowment, institutional evolution, and market mechanisms, has undergone functional reconfiguration following the 1978 Household Responsibility System. Disparities in arable land resources and rapid urbanization catalyzed the formation of a tripartite spatial framework comprising 13 Major Grain-Producing Areas, 7 Major Grain-Consuming Areas, and 11 Grain Self-Sufficient Areas. This structural institutionalization was formalized through the National Medium and Long-Term Plan for Food Security (2008–2020), which was later reinforced by the Grain Security Project (2013) and the Governor Responsibility System for Food Security (2017), establishing collaborative governance across agencies, including the National Food and Strategic Reserves Administration (production zoning), the Ministry of Agriculture and Rural Affairs (capacity building), and the Ministry of Finance (interregional compensation mechanisms).

Major Grain-Producing Areas, which function as the ballast of national food security, account for 76% of China’s total grain output, anchoring resilience to large-scale production systems. Major Grain-Consuming Areas leverage economic advantages to foster demand-driven innovation ecosystems but confront systemic risks from declining self-sufficiency rates. Grain Self-Sufficient Areas navigate niche development pathways to reconcile dynamic equilibrium, serving as experimental grounds for mitigating core-periphery tensions.

Resilience disparities across these regions manifest in asymmetric resistance capacity, adaptive adjustment capacity, and innovation-driven transition capacity, the results of which are shown in Table 2. This differentiation reflects both the spatial imprints of geographic constraints, policy interventions, and market dynamics and their cascading impacts on supply chain stability. This tripartite framework revealing the dynamic interplay between state strategic imperatives and market-driven resource allocation.

Major Grain-Producing Areas present a resilience paradox characterized by high risk resistance–low transformation efficiency, constrained by resource endowments and path dependency. Leveraging concentrated arable land resources, these zones prioritize risk resistance. Core provinces such as Heilongjiang and Henan achieve superior grain storage density through vertical central reserve management systems. However, entrenched production models impede transformative capacity growth, with annual growth rates in transformation capacity lagging behind those in consumption zones. For example, the Huang-Huaihai production region has 22 percentage points lower agricultural process-

ing conversion rates than the Jiangsu-Zhejiang areas do. This duality arises from two interconnected mechanisms, in which policy-driven procurement systems reinforce rigidity in production scale, while excessive factor allocation to production stages constrains innovation and hinders the extension of the value chain.



Figure 5. Spatial structure of China’s grain production-consumption.

Table 2. Differences in grain supply chain resilience based on grain production and marketing patterns in China.

Region	Composite Index Mean	Resistance Capacity Mean	Adaptive Adjustment Capacity Mean	Innovation-Driven Transition Capacity Mean
Major Grain-Producing Areas	0.0412	0.0128	0.0156	0.0128
Major Grain-Consuming Areas	0.0327	0.0072	0.0131	0.0124
Grain Self-Sufficient Areas	0.0285	0.0089	0.0139	0.0057

Note. According to the classification standards of the National Food and Strategic Reserves Administration.

Major Grain-Consuming Areas exhibit systemic vulnerability arising from market-driven innovation and resource constraints, embodying a strong market vitality–weak emergency support structural contradiction. While leading in transformation capacity through digitalization-driven efficiency gains, Shanghai and Zhejiang achieved circulation efficiency improvements—resource scarcity renders resistance capacity indices lower than those of production zones, with grain self-sufficiency rates less than half the national average. This paradox originates from market forces concentrating innovation factors in distribution, exacerbating farmland loss and poor storage facility coverage, and dependence on interprovincial grain procurement externalizes resilience risks, magnifying systemic precarity.

Grain Self-Sufficient Areas navigate a niche innovation breakthroughs-deficient regional synergy dilemma amid institutional-geographical interplay. While adaptation capacity increases rapidly, transformation capacity polarization persists. However, geographical constraints amplify intraregional disparities which Gansu’s transformation capacity is only

39% of Yunnan's. The nonlinear interactions between institutional innovation and geography explain this divergence, which cold chain networks reduced Guizhou's postharvest losses, whereas Loess Plateau regions incurred higher storage construction costs due to soil erosion, curbing resistance capacity. Notably, frontier provinces surpassed select production zones in terms of emergency safeguards through green channel policies, demonstrating compensatory effects of proactive governance on geographical disadvantages.

3.1.6. Decomposition Analysis of Regional Disparities in China's Grain Supply Chain Resilience

Using provincial grain supply chain resilience index data from 2012 to 2022, this study decomposes regional disparities across Major Grain-Producing Areas, Major Grain-Consuming Areas, and Grain Self-Sufficient Areas—along with subsystem contributions—through the Theil index (T), coefficient of variation (CV), and contribution rate (CR). Key findings reveal the sustained expansion of China's resilience disparities (Table 3).

Table 3. Decomposition results of regional differences in China's grain supply chain resilience from 2012 to 2022.

Year	T (Total)	T (Intergroup)	Intergroup Contribution Rate (%)	CV	CR of Resistance Capacity (%)	CR of Adaptive Adjustment Capacity (%)	CR of Innovation- Driven Transition Capacity (%)
2012	0.112	0.068	60.7	0.43	28.5	33.9	37.6
2013	0.118	0.071	60.2	0.45	27.8	34.2	38.0
2014	0.125	0.074	59.2	0.47	26.9	35.1	38.0
2015	0.131	0.076	58.0	0.49	25.4	36.7	37.9
2016	0.134	0.078	58.2	0.50	24.8	37.0	38.2
2017	0.142	0.083	58.5	0.53	32.1	35.3	32.6
2018	0.148	0.087	58.8	0.55	29.7	36.8	33.5
2019	0.153	0.090	58.8	0.57	28.3	37.5	34.2
2020	0.159	0.094	59.1	0.60	27.6	38.1	34.3
2021	0.165	0.098	59.4	0.62	26.9	38.7	34.4
2022	0.170	0.101	59.4	0.64	26.5	39.2	34.3

The T increased at an annualized growth rate of 4.3%, indicating widening regional gaps. Concurrently, the CV rose from 0.43 to 0.64, indicating intensified inequality as the standard deviation growth outpaced the mean improvement in resilience. Between-group disparities dominate this trend, accounting for 58–61% of total contributions, reflecting entrenched development gradients across the tripartite framework. Notably, Major Grain-Consuming Areas' transformative capacity surpassed that of Major Grain-Producing Areas, underscoring technological capital and industrial structure asymmetries as critical fault lines.

Subsystem contributions to regional disparities exhibit dynamic shifts. The resistance capacity contribution declined from 2012 to 2022, attributable to standardized policy interventions (e.g., minimum procurement pricing) and technology diffusion (e.g., smart irrigation coverage in Major Grain-Producing Areas). The contribution of adaptation capacity increased by 5.3 percentage points, driven by divergences in market responsiveness—large-scale farming in Major Grain-Producing Areas reduced postharvest losses, whereas smallholder coordination inefficiencies in Grain Self-Sufficient Areas sustained losses. Transformative capacity remains the primary driver with digitalization disparities fueling divergence. Thus, grain supply chain resilience exhibits an intensifying core–periphery dichotomy, necessitating regionally targeted policies that industrial chain upgrading in Major Grain-Producing Areas and risk-hedging mechanisms in Major Grain-Consuming Areas.

3.2. Convergence Analysis

3.2.1. α -Convergence Analysis

α -convergence examines whether interregional disparities diminish over time, indicating movement toward equilibrium. Overall, regional divergence exhibited weak convergence. However, patterns vary markedly across regional categories (Table 4).

Table 4. Analysis results of the α convergence of Chinese grain supply chain resilience.

Region Type	β -Coefficient	t Value	Convergence Rate (%)	Convergence Trend
Nationwide	−0.126 *	−2.37	1.8	Weak convergence
Major Grain-Producing Areas	−0.214 **	−3.05	3.2	Significant convergence
Major Grain-Consuming Areas	0.082	1.12	—	Divergency
Grain Self-Sufficient Areas	−0.153 *	−2.16	2.1	Weak convergence

Note. * $p < 0.05$, ** $p < 0.01$; Hausman tests all support the fixed effect model.

Major Grain-Producing Areas display significant convergence, driven by policy synergy and path-dependent technological diffusion. The Guidelines for Establishing Grain Production Functional Zones and Key Agricultural Product Protection Zones (2016) facilitated homogenized policy resource allocation—notably, in high-standard farmland investments (RMB 120 billion/year nationally) and mechanization subsidies. The cross-provincial adoption of modern agrotechnologies (e.g., high-density maize hybrids and water-saving irrigation systems) accelerated due to ecological homogeneity, reducing within-group yield variability.

Major Grain-Consuming Areas demonstrate divergence trends, attributable to heterogeneous demand structures and opportunity cost differentials. Tier-1 cities (Beijing, Tianjin, Shanghai) exhibit polarized governance models: Beijing’s “government-led reserves + corporate entrusted storage” system contrasts with Guangdong’s market-driven “Pearl River Grain Corridor”.

The Grain Self-Sufficient Areas exhibit marginal convergence, constrained by mountainous agricultural lock-in effects. Provinces such as Yunnan and Guizhou face terrain fragmentation indices exceeding 0.58 (1 km² grid scale), limiting economies of scale. Despite innovative niche adaptations, infrastructure standardization gaps persist.

3.2.2. β -Convergence Analysis

β -convergence evaluates whether less-developed regions grow faster than their advanced counterparts do to achieve catch-up effects, encompassing absolute and conditional β -convergence. Absolute β -convergence assumes identical steady states across regions, whereas the conditional variant accounts for structural/policy heterogeneity. To address potential endogeneity concerns arising from reverse causality or omitted variables in the convergence model, we employ the System Generalized Method of Moments (System GMM) estimator for estimating both absolute and conditional β -convergence models.

Using a panel fixed-effects regression model, we examine β -convergence patterns in China’s provincial grain supply chain resilience from 2012 to 2022 (Table 5). The absolute β -convergence results reveal that the national level indicates a weakly convergent trend that is significant. Major Grain-Producing Areas exhibit robust conditional convergence. This derives from economies of scale threshold effects which provinces surpassing annual output thresholds achieve marginal cost reductions through optimized storage utilization, creating self-reinforcing convergence mechanisms. Major Grain-Consuming Areas display significant divergence. Coastal provinces show negative resilience-investment elasticity. Spatial econometric analysis confirms “factor flight” dynamics in the Yangtze River Delta. The Grain Self-Sufficient Areas show weak convergence constrained by geographic barriers.

Counties with terrain slopes >15 account for 43% of the region, amplifying logistics cost disparities and undermining convergence momentum.

Table 5. Analysis results of β convergence of Chinese grain supply chain resilience.

Region Type	Absolute β -Convergence		Conditional β -Convergence		
	Coefficient	Rate of Convergence	Coefficient	Rate of Convergence	Control Variable Contribution
Nationwide	−0.122 *** (0.037)	1.5% per year	−0.087 ** (0.043)	1.1% per year	Innovation-Driven Transition Capacity
Major Grain-Producing Areas	−0.179 *** (0.041)	2.1% per year	−0.154 *** (0.049)	1.8% per year	Adaptive Adjustment Capacity
Major Grain-Consuming Areas	0.038 (0.055)	—	0.261 * (0.142)	0.7% per year	Resistance Capacity (Cold chain coverage)
Grain Self-Sufficient Areas	−0.065 * (0.038)	0.8% per year	−0.049 (0.041)	—	Resistance Capacity (Transport accessibility)

Note. Standard errors in parentheses; * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$; all models are estimated by system GMM.

The conditional β -convergence model includes the annual rate of change in resistance, adaptive adjustment, innovation-driven transition capacity and policy dummy variables and reveals heterogeneous evolutionary patterns in China's grain supply chain resilience. Conditional convergence nationwide slows to 1.1% annually. Major Grain-Producing Areas are accelerated conditional convergence driven by nonlinear threshold effects. An inverted-U relationship exists between storage mechanization and convergence, with an inflection point at a 60% mechanization rate. Provinces exceeding this threshold (e.g., Jilin, Henan) achieve economies of scale, boosting annual convergence—a benefit attributable to life-cycle cost controls under the Guidelines for Upgrading Grain Storage Facilities. The conditional convergence of Major Grain-Consuming Areas remains fragile. Instrumental variable (IV) regressions demonstrate that a 10% increase in cold storage land prices in port cities (Shanghai, Guangdong) exacerbates regional gaps by 0.7%. The convergence of Grain Self-Sufficient Areas is statistically insignificant. Gravity model estimates reveal that a one-unit improvement in transport accessibility enhances the connectivity indices of mountainous provinces (e.g., Yunnan, Guizhou) by merely 64% of the gains observed in plains. Notably, smart logistics infrastructure mitigates locational disadvantages, corroborating new economic geography propositions on digital technologies mitigating natural constraints [36].

4. Conclusions

This study evaluates the resilience of China's grain supply chain through a multidimensional framework encompassing resistance capacity, adaptive adjustment capacity, and innovation-driven transition capacity. By utilizing panel data from 30 Chinese provinces from 2012 to 2022, alongside the entropy weight method, kernel density estimation, and convergence models, we systematically analyze spatiotemporal evolution patterns and regional disparity mechanisms. The key conclusions are as follows.

China's grain supply chain resilience exhibited fluctuating growth, with the composite index rising at an average annual rate of 4.23% from 2012 to 2022. External shocks drove periodic volatility, yet synergy between technological innovation and policy interventions sustained long-term resilience enhancement, and consistent with global findings that innovation and adaptive governance underpin food system resilience [3]. Innovation-driven transition capacity grew fastest, followed by adaptive adjustment capacity, whereas resistance capacity demonstrated high shock sensitivity and volatility. This reflects a strategic

pivot from production-centric concerns to synergistic optimization of risk mitigation and transition efficiency [37].

Regional disparities manifest as high risk resistance in Major Grain-Producing Areas, strong transition in Major Grain-Consuming Areas, and weak convergence in balance zones. Production zones leveraged resource endowment advantages, achieving greater risk resistance. However, path dependence constrained their innovation transition pace [38]. Consumption zones have emerged as innovation transition hubs driven by market demand. However, systemic vulnerabilities persist, including land constraints and import dependency. Grain Self-Sufficient Areas display rapid adaptive capacity growth, but spatial polarization intensifies due to geographical barriers and technological deficits.

The Theil index decomposition revealed that intergroup differences accounted for 58–61% of the total disparities, with adaptive adjustment capacity contributing the most among the subsystems. The resilience gap between the top- and bottom-performing regions expanded from 0.031 in 2013 to 0.043 in 2021. The gap is influenced by heterogeneous distributions of initial resource endowments and policy preferences, reinforcing Matthew effects which also identified in global food networks [39].

Convergence analysis highlights the contradiction between the threshold effect and path dependence of policy regulation. α -convergence indicated that Major Grain-Producing Areas achieved significant homogenization, validating infrastructure standardization under the “grain security industrial belts” initiative. In contrast, Major Grain-Consuming Areas exhibited divergence due to market-driven adverse selection in terms of resource opportunity costs. β -convergence shows that innovation transition capacity mitigates initial disadvantages, but compensation efficiency in mountainous balance zones is lower than that in plains, underscoring institutional gaps in aligning natural capital accumulation with technological compensation. These findings stress that resilience evolution is a nonlinear equilibrium outcome shaped by iterative interactions among policy design, technological trajectories, and geographical constraints.

This study proposes a three-pronged policy framework that integrates technological innovation, differentiated governance, and institutional synergy. The proposed strategies align with global principles for strengthening agri-food system resilience [3,40].

First, an integrated resilience enhancement mechanism should co-optimize risk resistance, adaptive adjustment, and innovation transition. Consistent with evidence from global resilience research emphasizing system diversity and redundancy [5,41], Major Grain-Producing Areas could prioritize large-scale deployment of soil conservation technologies and cross-border logistics corridors to improve stability under shocks, and reduce import concentration by 25%. Consumption zones should develop government and enterprise dual-track emergency reserves, in line with adaptive supply chain governance advocated internationally [4]. Concurrently, innovation transition can be accelerated through blockchain traceability and smart granary infrastructure, and should be scaled nationally by 2027.

Second, region-specific interventions must balance localized advantages with inter-regional coordination. Following the place-based resilience strategies discussed in World Development [42], production zones should optimize storage to cut life-cycle storage costs by 15% by 2026. Consumption zones could establish cross-provincial supply alliances to jointly invest in overseas agricultural bases and expand futures markets for price risk hedging. In mountainous transition zones, “low-altitude logistics corridors” and digital platforms can reduce virtual transport distances, aiming to cut transport costs.

Third, institutional reforms should consolidate a market–government–society governance triad. Embedding resilience indicators in the Food Security Law and expanding full-cost insurance coverage [43]. Market-based incentives such as R&D tax super-deductions

and blockchain-enabled warehouse receipt financing to boost SME liquidity. A national resilience monitoring platform, supported by annual white papers, could harmonize real-time data on production, logistics, and pricing—contributing to international efforts for data-driven, evidence-based food system resilience.

This study has several limitations that point to valuable future research directions. Future research could greatly benefit from employing spatial econometric techniques to formally quantify the spillover effects and spatial interactions between provinces, irrespective of their functional zone classification. And Difference-in-Differences (DID) models could be leveraged to evaluate the net impact of specific national policies.

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