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The impact of large-scale agricultural operations on the grain production resilience: a quasi-natural experiment based on land transfer policy

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Under the dual challenges of intensifying global food security crises and pressing demands for sustainable agricultural development, investigating the mechanisms through which large-scale agricultural operations affect the grain production resilience carries significant strategic importance. Using a quasi-natural experiment based on land transfer policy, this study assesses these mechanisms. The findings indicate that large-scale agricultural operations significantly enhances grain production resilience. This positive effect is mediated by increased income levels among rural residents and greater participation in farmers' professional cooperatives. However, labor outflow and underdeveloped rural financial systems constrain the beneficial impact of large-scale agricultural operations on grain production resilience. Furthermore, heterogeneity analysis reveals regional variations in these effects. Compared to Chinese southern regions, northern regions exhibit a stronger influence of large-scale agricultural operations on grain production resilience. Similarly, while main grain-producing areas experience less pronounced effects, grain-selling regions and those with a balance between production and consumption are more significantly affected by large-scale agricultural operations. These findings contribute to the theoretical foundation for advancing land transfer policy reforms and fostering the development of farmers' professional cooperatives. Additionally, they offer policy insights for strengthening grain production resilience and ensuring the stability of grain supply.

KEYWORDS

grain production resilience, land transfer policy, large-scale agricultural operations, quasi-natural experiment, agricultural sustainability

1 Introduction

Global population growth and economic development have led to a continuous increase in food demand, while global food security faces multiple challenges. The increasing frequency of natural disasters, resource shortages, and ecological degradation associated with climate change pose significant threats to the stability and sustainability of grain production (Ericksen et al., 2009; Misra, 2014; Wheeler and von Braun, 2013). Under the dual pressures of natural disasters and resource scarcity, a resilient grain production system must be capable of rapidly adjusting production strategies and restoring production capacity to maintain a stable food supply and meet basic societal needs (Pingali et al., 2005; Neupane et al., 2022). As a result, enhancing grain production resilience has become a critical topic in contemporary agricultural research. A deeper understanding of grain production resilience is essential for designing effective agricultural policies, advancing the transformation and modernization of agricultural production systems, and promoting the sustainable development of the agricultural sector.

With the advancement of agricultural modernization, large-scale agricultural operations has emerged as a significant trend in agricultural development (Li and Guo, 2022; Ren et al., 2009). In recent years, the pace of land transfer in China has accelerated, resulting in the steady expansion of large-scale agricultural operations areas. The proportion of contracted cultivated land under large-scale agricultural operations has continued to rise, facilitated by the growing presence of new agricultural business entities such as family farms, large specialized farming households, farmers' cooperatives, and leading agricultural enterprises (Wang et al., 2018; Zhu et al., 2024). However, the expansion of large-scale agricultural operations has altered resource allocation, rural industrial management structures, and crop production methods. These changes raise important questions regarding their impact on grain production resilience. Specifically, does large-scale agricultural Operations promote or inhibit grain production resilience, and what mechanisms drive this relationship? Addressing these questions is essential and serves as the primary focus of this study.

The land transfer policy was designed to facilitate the reassignment of rural land management rights, optimize land resource utilization, and promote large-scale agricultural operations (Feng and Chen, 2022; Cao and Jin, 2024). China's land transfer policy is grounded in Marxist rent theory and institutional change theory, originating from the household responsibility system implemented during the reform and opening-up period in the 1970s. The "collective ownership, household operation" model initially revitalized agricultural productivity. However, urbanization subsequently led to issues of land fragmentation and abandonment. In the 1980s, the Chinese government first legalized land use rights transfer through constitutional amendments, and further standardized transfer procedures with the Rural Land Contracting Law in 2003. A significant reform occurred in 2014 with the "separation of three rights" (ownership, contract, and management rights), which protected farmers' interests while facilitating large-scale farming. To enhance agricultural efficiency and urban–rural resource mobility, recent years have seen continuous policy refinements, including measures to safeguard farmers' land rights, promote orderly transfer of management rights, and develop diverse forms of moderate-scale operations (Zhang, 2022; Li et al., 2022). In this context, this study employs a quasi-natural experimental design based on the land transfer policy to assess the impact of large-scale agricultural operations on grain production resilience. The analysis categorizes samples into a treated group and a comparison group based on the degree of policy exposure, enabling a comparative assessment of grain production resilience before and after policy implementation.

Historical evidence reveals stark contrasts in the effectiveness of land transfer policies between developed and developing countries. In developed economies, these policies have generally yielded positive outcomes. Germany, for instance, mitigated land fragmentation and advanced large-scale agricultural operations through legislative measures encouraging multi-stakeholder participation, thereby boosting farm productivity. Japan accelerated agricultural modernization by establishing specialized land management institutions, while the Netherlands enhanced land-use efficiency through systematic land consolidation programs (Fan and Zhao, 2019). Conversely, developing nations often grapple with institutional barriers and equity concerns that undermine policy efficacy. India's Tenancy Reform Act inadvertently exacerbated land fragmentation and suppressed productivity by overprotecting tenant farmers (Ghatak and Roy, 2007), whereas Russia's post-privatization Agricultural Land Circulation Law led to widespread land abandonment or non-agricultural use due to weak oversight (Shagaida and Lerman, 2017). As a pivotal developing economy, China's land transfer policy merits critical examination. This study investigates its ripple effects—particularly the expansion of large-scale agricultural operations—on grain production, offering actionable insights for similar contexts in the Global South.

The potential marginal contributions of this study lie in several dimensions. Firstly, while existing literature predominantly focuses on the relationship between large-scale agricultural operations and production efficiency, there remains a notable research gap regarding how such operations influence resilience in grain production. Addressing this underexplored dimension, this study employs a quasi-natural experimental design centered on China's land transfer policy to investigate the impact of large-scale agricultural operations on grain production resilience. Our findings unveil, for the first time, a quantifiable linkage between scaled farming and production resilience, offering a novel perspective that partially fills this scholarly void. Secondly, beyond examining the direct effects, we systematically dissect the underlying mechanisms driving the complex interplay between large-scale agricultural operations and production resilience, enriching the theoretical framework in this field. Thirdly, utilizing a moderating effects model, we identify critical yet overlooked factors—such as labor migration and rural financial institution development—that modulate the relationship between large-scale agricultural operations and resilience. These insights provide actionable guidance for optimizing complementary conditions (e.g., labor allocation and financial support) to amplify resilience gains during agricultural scaling. Finally, this study contributes fresh empirical evidence for developing countries navigating land transfer challenges. By demonstrating the synergistic potential of large-scale agricultural operations and resilience enhancement, as well as the moderating roles of labor mobility and financial infrastructure, our findings underscore that agricultural scaling serves as a vital pathway to strengthen grain production resilience. However, achieving this requires not only legislative support for land consolidation but also systemic reforms integrating farmer cooperatives, socialized service networks, and coordinated "land-labor-finance" policies. Furthermore, heterogeneity analysis reveals context-specific implications, offering tailored insights for diverse agroecological zones and institutional settings across the Global South, thereby enhancing the global relevance of this research.

2 Literature review and research hypothesis

2.1 Literature review

Large-scale agricultural operations has emerged as a significant trend in modern agricultural development, drawing considerable academic attention regarding its economic consequences. Existing research presents three primary perspectives: positive effects, negative effects, and non-uniform effects. Studies highlighting the positive effects of large-scale agricultural operations indicate that it contributes to the optimal allocation of resources and enhanced production efficiency (Chu-zhi and Huang, 2007; Gai et al., 2023), improves environmental efficiency, and facilitates technological advancement (Li and Zi, 2020; Yi et al., 2022). Additionally, large-scale agricultural operations have been linked to increased farm income, reduced production costs, and progress in agricultural modernization, including adjustments in farming structures (Huang et al., 2016; Shi and Wang, 2021; Li et al., 2020; Yang and Ji, 2021). Conversely, some studies suggest that large-scale agricultural operations may have negative effects, particularly due to the increased use of machinery and fertilizers, which may contribute to environmental degradation (Ma X. et al., 2019; Baojing et al., 2021). Under certain conditions, large-scale agricultural operations have been found to limit per capita farm income and grain production efficiency, increasing the risks faced by smallholder farmers (Das and Ganesh-Kumar, 2018; Ali and Deininger, 2015; Zhang, 2023; Shunchen et al., 2021). In addition to these conflicting viewpoints, research suggests that the economic consequences of large-scale agricultural operations are context-dependent, with both positive and negative effects on different aspects of agricultural development. For instance, Liao and Ma (2023) and Shi and Wang (2021) found that while large-scale agricultural operations may improve resource efficiency and, in some cases, reduce per-unit carbon emissions through technological advancements, they can also lead to lower grain yield per unit of cultivated land. This decline in yield may result from changes in cropping patterns, soil fertility challenges, or a shift toward mechanization-intensive practices that prioritize efficiency over yield maximization. Additionally, while large-scale agricultural operations may increase output for certain crops, it can negatively impact the unit yield and total production costs of others, depending on land use strategies and input allocation (Shi and Wang, 2021; Liao and Ma, 2023). Similarly, Noack and Larsen (2019) reported that while large-scale agricultural operations increases farmers' income, it simultaneously reduces grain yields (Noack and Larsen, 2019). Zhang et al. (2019) observed that with the expansion of large-scale agricultural operations, allocation inefficiency costs decreased, whereas technological inefficiency costs increased (Zhang et al., 2019). Furthermore, some studies suggest that the impact of large-scale agricultural operations may be nonlinear. Yuan et al. (2023) and Luan and Han (2020) found that the effect of large-scale agricultural operations on farmers' income and grain yield follows an "inverted U-shaped" pattern, initially promoting growth but later inhibiting it. Similarly, studies by Chen and Zhou (2016) and Rada and Fuglie (2019) indicate that the technology-driven impact of large-scale agricultural operations varies by region and country, exhibiting a complex mix of both positive and negative effects.

Land transfer policies, widely implemented in modern agriculture to optimize land resource allocation and enhance agricultural efficiency, enable the orderly transfer of land through subcontracting, exchange, transfer, shareholding, and cooperative arrangements to facilitate agricultural transformation. Existing literature has revealed the multifaceted impacts of these policies on agriculture. On one hand, studies emphasize the strong linkage between land transfer policies and large-scale agricultural operations, with their synergistic effects recognized as a critical mechanism driving agricultural modernization. For instance, Liu and He (2024) argue that land transfer policies reshape land allocation logic through the clarification of property rights, establishing an institutional foundation for large-scale agricultural operations. Ye (2015) demonstrates that land transfer reforms enhance agricultural modernization by elevating the level of large-scale farming, while Huo and Chen (2024) further reveal that transfer-driven scale expansion significantly increases operational land area and promotes sustainable agricultural development. On the other hand, scholars have cautioned against potential adverse effects. Chen et al. (2024) warn that land transfer policies may trigger non-grain conversion of farmland and diminishing returns to scale, necessitating safeguards against compounded risks from management costs and market volatility. Haizhen et al. (2016), using an Interpretative Structural Modeling (ISM) approach, identify social risks such as unstable agricultural incomes, regional economic disparities, and ecological degradation linked to land transfers. Simultaneously, research has explored contextual factors influencing policy outcomes, including farmers' land attachment (Liu G. et al., 2022), social trust (Chen Y. et al., 2023), terrain characteristics, irrigation infrastructure, and land rental costs (Liu K. et al., 2022). Furthermore, studies highlight broader impacts beyond scale expansion, such as effects on rural incomes (Wang and Wang, 2017), farmland quality preservation (Sheng et al., 2025), and land-use efficiency (Ma and Chen, 2022) underscoring the policy's systemic ramifications.

The concept of resilience originates from physics, referring to an object's ability to absorb energy and withstand external forces. In the field other than physics, the word resilience was first applied to the study of ecology, and Holling (1973) defined it as the self-regulation and repair ability of ecosystem after external shocks. Aura et al. (2002) pioneered its application to economic systems, conceptualizing economic resilience as the ability to rebound swiftly post-shock. In recent years, scholarly attention has expanded to resilience within food systems. Tendall et al. (2015) define food system resilience as the capacity to maintain stability amid natural or anthropogenic shocks, while Béné et al. (2016) emphasize its multidimensional nature, spanning adaptive and transformative capabilities at individual, local, national, and global supply chain levels. Building on these foundations, this study conceptualizes "grain production resilience" as a composite of three interdependent capacities: resistance (withstanding shocks), recovery (post-shock restoration), and reconstruction (system reconfiguration for long-term sustainability). This tripartite framework acknowledges the inherent complexity of resilience in agricultural production systems, where external shocks—from climate extremes to market volatility—trigger cascading impacts. Consequently, the influencing factors of grain production resilience are inherently multifaceted. The existing literature has studied the influencing factors of grain production resilience from many angles. Jiang et al. (2023) used standard deviation ellipse and geographical detector model to study and found that urbanization rate, scientific and technological factors and price changes of agricultural means of production are the main factors affecting grain production resilience. Zhou et al. (2024) used two-way fixed effect model, IV-2SLS, moderating effect model and other empirical research results to show that agricultural insurance is an important factor affecting grain production resilience. Zeng and Cai (2024) took the panel data of China province as the sample, which showed that the labor transfer would significantly affect grain production resilience. Liu and Qin (2024) paid attention to the policy of high-standard farmland construction, and made an empirical test by using the multi-stage DID method, and finally came to the conclusion that farmland construction has an important impact on grain production resilience. Charatsari et al. (2022) paid attention to the factors of technological innovation in agricultural production, and the research showed that agricultural technological innovation also had an important impact on grain production resilience. Ma et al. (2024) and Zhu and Zhang (2024) respectively paid attention to technical training and agricultural productive services in agricultural activities from the perspective of farmers, and proved their important influence on grain production resilience. Recent research has also explored the role of digital empowerment (Hao and Tan, 2022; Zhang and Yong, 2025; Li et al., 2024a; Zuo et al., 2024) and climatic factors (Fan et al., 2024; Chen et al., 2024; Ma Y. et al., 2025), both of which have been found to significantly influence grain production resilience.

Existing literature provides evidence supporting both positive and negative economic consequences of large-scale agricultural operations. Meanwhile, the influencing factors of grain production resilience are indeed multifaceted. The literature on the economic implications of large-scale agricultural operations exhibits three salient limitations. Firstly, scholarly attention remains disproportionately skewed toward "economic efficiency," with resilience outcomes largely marginalized, while studies on large-scale agricultural operations predominantly focus on direct operational impacts rather than policy mechanisms or evaluative frameworks. Secondly, although the influencing factors of grain production resilience have been explored across economic, technological, and financial domains, the role of large-scale agricultural operations—particularly its systemic linkages to grain production resilience—remains under-theorized. Land transfer policies exert "systemic impacts" on grain production resilience through large-scale agricultural operations, spanning economic equity, social stability, and ecological sustainability, whereas singular factors like technology adoption or crop insurance yield context-bound effects confined to production or risk management. Crucially, the directional ambiguity—whether large-scale agricultural operations enhances or undermines grain production resilience—persists due to insufficient causal evidence, reflecting a critical knowledge gap. Thirdly, existing policy analyses, while addressing efficiency gains, social trade-offs, and environmental externalities of land transfers, overlook resilience as a latent systemic property. Methodologically, we find that most studies rely on linear regression or descriptive case analyses, lacking robust causal identification. Although quasi-natural experimental designs are pivotal for disentangling causality, their application to large-scale agricultural operations and the influencing factors of grain production resilience remains scarce. To address the existing research gaps, this study leverages China's land transfer policy as a quasi-natural experiment to rigorously investigate how large-scale agricultural operations shape grain production resilience. The innovations of this work are threefold. Theoretically, it pioneers a systemic analysis framework to capture the multidimensional impacts of agricultural large-scale operations under land transfer policies—spanning economic, social, and ecological interactions—contrasting sharply with reductionist single-factor approaches prevalent in the literature. Methodologically, it employs a staggered difference-in-differences (DID) design combined with mechanism analysis to overcome the causal identification limitations of prior studies reliant on linear models or descriptive case methods. Empirically, focusing on "resilience," it provides evidence for the persistent scholarly debate on whether large-scale agricultural operations enhances or undermines grain production resilience.

2.2 Research hypothesis

As a critical pathway for modern agricultural transformation, the impact of large-scale agricultural operations on grain production resilience not only finds robust support in the theory of economies of scale and the theory of agricultural technological progress but also receives profound explanation from the theory of increasing returns to land scale. Firstly, analyzed through the lens of "the theory of economies of scale," large-scale agricultural operations contribute to a substantial reduction in agricultural production costs by expanding the scale of production. This cost reduction is driven by the resource concentration effect and scale effect, which allow agricultural producers to acquire essential inputs—such as land, fertilizers, and pesticides—at lower costs (Sun et al., 2019; Zhang et al., 2024). Additionally, large-scale agricultural operations facilitates specialization and labor division in agricultural production, leading to significant improvements in production efficiency (Wang and Zhu, 2017; Song et al., 2020). The combined effects of cost reduction and efficiency gains strengthen the economic foundation of grain production, enhancing its resilience against external shocks such as natural disasters and market fluctuations. Secondly, analyzed through the lens of "the theory of increasing returns to land scale," in agricultural production, when the scale of land management is expanded to a certain extent, the efficiency of land output will increase, because agricultural producers can allocate production factors more rationally and realize the optimal combination of land, labor force, capital and other factors. For example, large-scale agricultural machinery can fully play its role in vast land to improve operating efficiency, and large-scale agricultural operations is also convenient to adopt advanced irrigation technology and management mode. They reduce the waste of resources per unit area, increase the output per unit land area and reduce the cost relatively, and further enhance the stability of grain production and the ability to cope with external shocks (Xiaoying et al., 2023). Thirdly analyzed through the lens of "the theory of agricultural technological progress," large-scale agricultural operations provides a favorable environment for the adoption and diffusion of advanced agricultural technologies. Large-scale production necessitates more efficient and technologically advanced equipment, driving innovation and research in agricultural science and technology (Shen et al., 2017; Xue et al., 2021). The integration of these advancements enhances the modernization and technological capacity of grain production systems, improving their ability to recover from disruptions and increasing overall resilience. Furthermore, technological progress has facilitated the transformation of grain production methods, promoting sustainable, intelligent, and environmentally friendly agricultural practices. These advancements contribute to the long-term stability and adaptability of grain production, ensuring a more resilient and sustainable agricultural sector.

Based on the above analysis, this paper puts forward the research hypothesis H1: Influence of large-scale agricultural operations on grain production resilience is promotion.

Income distribution theory posits that equitable income allocation mechanisms are pivotal for enhancing household consumption capacity and productive investments, serving as a cornerstone for rational socioeconomic resource distribution and profoundly shaping economic behaviors and welfare. Within the context of land transfer policies driving large-scale agricultural operations, scaled farming entities leverage economies of scale and operational efficiency to generate higher economic returns, thereby elevating rural household incomes. This income redistribution operates through dual pathways. On the one hand, guided by production factor theory, scaled operations optimize the allocation and utilization of land, capital, and labor, reducing production costs and amplifying efficiency. The resultant profit expansion enables income streams—such as land rents and wages—to flow back to farmers, augmenting their property and wage incomes, which epitomizes the rationalized mobility and remuneration of production factors (Ao et al., 2021). On the other hand, scaled farming catalyzes agricultural value chain diversification and emerging agribusiness models, creating off-farm employment opportunities and broadening income channels. This reflects the spillover effects of income redistribution across broader economic sectors (Li and Guo, 2022), ultimately fostering inclusive rural development through structural economic transformation.

Rooted in human capital theory, income growth empowers farmers to enhance living standards and invest in education and skill development, fostering human capital accumulation that incentivizes proactive engagement in production management (Wang and Ding, 2011). This human capital upgrading not only elevates production efficiency but also bolsters risk-coping capacities against market volatility and operational uncertainties. Concurrently, rising incomes enable farmers to adopt advanced equipment, high-quality inputs, and improved irrigation infrastructure. Aligned with risk resilience theory, such investments optimize factor allocation, strengthening systemic capacity to withstand climatic shocks and price fluctuations, thereby safeguarding production stability (Girão et al., 1974). Moreover, higher income levels mitigate agricultural labor outmigration by enhancing sectoral attractiveness, ensuring sustained labor inputs to reinforce resilience foundations. Obviously, the improvement of rural residents' income level can promote grain production resilience.

Based on the above analysis, this paper puts forward the research hypothesis H2: Large-scale agricultural operations exert a positive mediating effect on grain production resilience by enhancing rural residents' income level.

Social network and organizational theories emphasize the critical role of interactions and cooperation among individuals and organizations within social networks in facilitating resource acquisition, information dissemination, and problem-solving. In the context of large-scale agricultural operations driven by land transfer policies, farmer professional cooperatives—functioning as key nodes within social networks and vital organizational entities—play a pivotal role. While the consolidation of agricultural production factors and market resources under scaled operations enhances efficiency, individual farmers often remain ill-equipped to cope with complex market dynamics and production risks. By organizing scattered individual farmers into cohesive social networks, these cooperatives enable members to share information, techniques, and resources, thereby fostering synergistic collaboration through the mutual reinforcement of strengths. This collective approach not only mitigates systemic vulnerabilities but also amplifies adaptive capacities in response to socioeconomic and environmental uncertainties.

Specifically farmer cooperatives provide members with comprehensive technical training and guidance, disseminating advanced cultivation techniques and management practices to enhance farmers' technical literacy and production competencies. This institutional support elevates the technology adoption rate and stabilizes crop yields through knowledge-driven agricultural intensification (Dong et al., 2019). In response to abrupt disruptions such as natural disasters, cooperatives mobilize collective disaster response mechanisms, enabling rapid resource coordination for post-disaster recovery and significantly mitigating livelihood vulnerabilities (Zhou and Liu, 2021). Furthermore, cooperatives exhibit comparative advantages in aggregating, analyzing, and operationalizing market intelligence. By establishing real-time information-sharing platforms, they empower members to navigate market dynamics strategically, optimize production portfolios, and hedge against price volatility—effectively decoupling smallholders from systemic market risks that threaten grain production sustainability. Obviously, the improvement of farmers' professional cooperation level can promote grain production resilience.

Based on the above analysis, this paper puts forward the research hypothesis H3: Large-scale agricultural operations exert a positive mediating effect on grain production resilience by enhancing farmers' professional cooperation level.

3 Data and methodology

3.1 Sample selection and data source

The revised Land Contract Law, enacted in early 2019 in China, strengthened farmers' land contract management rights by extending contract durations, ensuring the legal right to transfer land, and further refining the regulatory framework for land contract management. Under this revised law, land transfer mechanisms have become more diversified, transfer periods more flexible, and regulatory oversight more standardized. As a result, the policy reform represents a significant measure aimed at promoting the large-scale agricultural operations of rural land in China.

Given this context, this study examines the impact of large-scale agricultural operations on grain production resilience, using the 2019 revision of the Land Contract Law as an exogenous policy event in a quasi-natural experimental design. To assess changes in grain production resilience before and after the policy implementation, the study utilizes panel data from 30 provincial-level administrative regions in China, covering the period from 2007 to 2022. The data sources include: the CSMAR database from Taian, the China Agricultural Management Annual Report, the China Rural Statistical Yearbook, the China Population and Employment Statistical Yearbook, and the Chinese government network.

3.2 Variable selection and explanation

3.2.1 Explained variable

The measurement of grain production resilience (Y) in this study follows the approach proposed by Zheng et al. (2024), Wei et al. (2025), and Zheng and Zhao (2025). Using the entropy method, grain production resilience is assessed comprehensively across multiple dimensions, allowing for a systematic evaluation through a structured index system. Grain production resilience is categorized into three primary dimensions: resistance, recovery, and reconstruction.

Resistance: Represents the ability of the system to withstand external shocks and is measured through production base supportability and production capacity stability.

Recovery: Captures the system's ability to restore agricultural production following disruptions, assessed through ecological coordination and environmental recoverability.

Reconstruction: Reflects the capacity for long-term adaptation and innovation, incorporating diverse collaboration and production innovation.

To quantify grain production resilience, we have constructed a comprehensive evaluation index system, comprising six subsystems and 23 specific indicators. The specific indicators are detailed in Table 1, and the formula for calculating grain production resilience using the entropy method is presented as follows:

$$Z_i = \sum_{j=1}^{n} \left(W_j * S_{i,j} \right) \left(i = 1,2,\ldots,m; j = 1,2,\ldots,n \right) \quad (1)$$

$$S_{i,j} = X_{i,j} - \min\left(X_j \right) / \max\left(X_j \right) - \min\left(X_j \right) \quad (2)$$

$$S_{i,j} = \max\left(X_j \right) - X_{i,j} / \max\left(X_j \right) - \min\left(X_j \right) \quad (3)$$

Equation 1 calculates the comprehensive evaluation score of grain production resilience across different provinces (autonomous regions or municipalities). The variables in the formula are defined as follows:

- Z_i represents the comprehensive evaluation score for the *i-th* province (autonomous region or municipality).
- $S_{i,j}$ represents the standardized value of the *j-th* index for the *i-th* province (autonomous region or municipality).
- W_j represents the index weight of the *j-th* indicator.
- *m* represents the number of provinces (autonomous regions or municipalities) included in the evaluation.

Equations 2, 3 standardize the values of positive and negative indicators, respectively, ensuring comparability across different provinces. The variables are defined as follows:

- $X_{i,j}$ represents the raw value of the *j-th* indicator in the *i-th* province (autonomous region or municipality).
- $\min\left(X_j\right)$ represents the minimum value of indicator *j* across all provinces.
- $\max\left(X_j\right)$ represents the maximum value of indicator *j* across all provinces.

3.2.2 Explanatory variable

Large-scale agricultural operations refers to the consolidation of fragmented land holdings through land transfer, resulting in a more efficient and large-scale agricultural production model. The land transfer policy serves as the primary mechanism for facilitating large-scale agricultural operations. In this study, a quasi-natural experimental approach is employed to examine the impact of large-scale agricultural operations on grain production resilience, using the land transfer policy as an exogenous policy intervention.

To quantify large-scale agricultural operations, the explanatory variable is represented by an interaction term:

$$\left(\text{Treat}_{i,t} \times \text{Time}_t \right)$$

where,

- Time_t is a time dummy variable, assigned a value of 1 if the period is after policy implementation and 0 otherwise.
- $\text{Treat}_{i,t}$ is a policy dummy variable, assigned a value of 1 for regions significantly affected by the land transfer policy and 0 otherwise.

A region is classified as significantly affected by the land transfer policy if it meets both of the following conditions:

1. The average land transfer rate in the 4 years following the policy implementation is higher than in the 4 years preceding the policy.
2. The post-policy land transfer rate is at least 2 percentage points higher than the pre-policy rate.

3.2.3 Mechanism variables

The theoretical framework of this study suggests that large-scale agricultural operations influences resource allocation in grain production, leading to changes in production costs and efficiency. These changes, in turn, affect the income levels of grain producers, ultimately impacting grain production resilience. Relevant research supports that farmers' income affects agricultural production (Evans and Ngau, 1991; Ladd, 1957), which also supports that large-scale agricultural operations are beneficial to the improvement of farmers' income (Peng et al., 2020; Li G. et al., 2023). Meanwhile, shifts in resource allocation alter specialization and labor division, further influencing resilience outcomes. Relevant studies have proved that large-scale agricultural operations affect the level of farmers' professional cooperation (Zhang et al., 2025; Zang et al., 2022), which also proves that farmers' professional cooperation is closely related to agricultural production (Liang et al., 2023; Li et al., 2024b).

To examine these mechanisms, two key mechanism variables are selected:

- Rural residents' income level, measured by the average disposable income of rural residents in each region.
- Farmers' professional cooperation level, measured by the number of farmers' professional cooperatives per thousand primary industry employees.

3.2.4 Moderator variables

Labor and capital are fundamental production factors in grain production. Research shows that rural finance plays an important role in the large-scale agricultural operations (Song et al., 2025), and it is an important factor to promote agricultural development (Li H. et al., 2023). At the same time, the labor force is also a factor that cannot be ignored in the process of large-scale agricultural operations (Li et al., 2021), and it is even more indispensable for agricultural development (Ma L. et al., 2019). To explore their moderating effects

TABLE 1 Construction of the grain production resilience index system.

Primary index	Secondary index	Tertiary index	Index attribute
Resistance	Production base supportability	Effective irrigation area (1,000 hectares)	+
		Grain cultivated area (1,000 hectares)	+
		Number of employees in primary industry (10, 000)	+
		Total power consumed of agricultural machinery (10,000 kilowatts)	+
	Production capacity stability	Grain yield fluctuation index (%)	–
		Per capita grain possession (kg)	+
		Grain output per unit cultivated area (kg/ha)	+
Recovery	Ecological coordination	Pesticide use per unit grain planting area (kg/ha)	–
		Diesel oil for agricultural use per unit grain planting area (kg/ha)	–
		Fertilizer use per unit grain planting area (kg/ha)	–
		Plastic film for agricultural use per unit grain planting area (kg/ha)	–
		Water for agricultural use per unit grain planting area (10,000 cubic meters/ha)	–
	Environmental recoverability	Disaster/disaster area (%)	–
		Soil erosion control area (1,000 hectares)	+
		Multiple cropping index (%)	+
		Value added of total agricultural output value (RMB100 million)	+
Reconstruction	Diverse collaboration	Crop diversification (%)	+
		Ratio of feed grain cultivated area to grain cultivated area (%)	+
		Proportion of service industry in output value of agriculture, forestry, animal husbandry, and fishery (%)	+
	Production innovation	Investment in agricultural fixed assets (RMB100 million)	+
		Fiscal expenditure on agriculture, forestry and water affairs (RMB100 million)	+
		Expenditure on agricultural scientific research (RMB100 million)	+
		Agricultural science and technology personnel (10,000)	+

on the relationship between large-scale agricultural operations and grain production resilience, two moderator variables are selected:

- Rural financial institutions, measured by the number of business outlets of rural financial institutions in a given region.
- Labor outflow, measured by the number of migrant workers.

3.2.5 Control variables

Grain production systems are influenced by economic development, fiscal support, industrial structure, and agricultural product prices. Referring to Zeng and Cai (2024), the following control variables are included:

- Economic development, measured by regional per capita GDP.
- Fiscal support for agriculture, measured by the proportion of fiscal expenditure allocated to agriculture, forestry, and water affairs.
- Industrial development, measured by the added value of the primary industry.
- Agricultural production price levels, measured by the agricultural production price index, which compares the weighted average price of agricultural products in the current period to a base period (set at 100).

Table 2 provides a detailed description of all variables.

3.3 Model specification

3.3.1 Baseline regression model

To examine the impact of large-scale agricultural operations on grain production resilience, a DID model was constructed. The baseline regression model is specified as follows:

$$Y_{i,t} = \alpha_0 + \alpha_1 \left(Treat_{i,t} \times Time_t\right) + \alpha_2 \sum Control_{i,t} + \varphi_i + \delta_i + \varepsilon_{i,t} \quad (4)$$

where,

- $Y_{I,t}$ represents grain production resilience in province i at time t.
- $Treat_{i,t}$ is a policy dummy variable, which equals 1 if province i is significantly affected by the land transfer policy and 0 otherwise.

- $Time_t$ represents the implementation time of the land transfer policy, which equals 0 for the period before the implementation of land transfer policy, and 1 otherwise.
- $\sum Control_{i,t}$ represents a series of control variables. φ_i indicates the province-fixed effect. δ_i indicates the year-fixed effect. $\varepsilon_{i,t}$ indicates the error term.

3.3.2 Mediation effect model

To investigate the mechanism through which large-scale agricultural operations influences grain production resilience, a mediation effect model was constructed by introducing mechanism variables into the baseline regression. The model consists of the following equations:

$$Y_{i,t} = \alpha_0 + \alpha_m Mechanism_{i,t} + \alpha_2 \sum Control_{i,t} + \varphi_i + \delta_i + \varepsilon_{i,t} \quad (5)$$

$$Mechanism_{i,t} = \alpha_0 + \alpha_1 \left(Treat_{i,t} \times Time_t\right) + \alpha_2 \sum Control_{i,t} + \varphi_i + \delta_i + \varepsilon_{i,t} \quad (6)$$

where,

- $Mechanism_{i,t}$ represents the mechanism variable in the i-th province at time t.
- Equations 5, 6, together with Equation 4, form the mediation effect model, allowing for an empirical examination of whether changes in income levels or farmers' cooperatives mediate the relationship between large-scale agricultural operations and grain production resilience.

3.3.3 Moderation effect model

To analyze the moderating effects of key external factors on the relationship between large-scale agricultural operations and grain production resilience, the following moderation effect model was constructed (Equation 7):

$$Y_{i,t} = \alpha_0 + \alpha_w Moderator_{i,t} + \alpha_g TTM + \alpha_1 \left(Treat_{i,t} \times Time_t\right) + \alpha_2 \sum Control_{i,t} + \varphi_i + \delta_i + \varepsilon_{i,t} \quad (7)$$

where,

- $Moderator_{i,t}$ represents the moderator variable for province *i* at time *t*.
- $TTM = Treat_{i,t} \times Time_t \times Moderator_{i,t}$ is the interaction term between the moderator variable and the core explanatory variable.

4 Results and discussion

4.1 Descriptive statistics

The descriptive statistics for the key variables in the model are presented in Table 3. The mean value of grain production resilience is approximately 0.429, with a standard deviation of 0.081. The difference between the maximum (0.625) and minimum (0.229) values is 0.396, indicating substantial variation in grain production resilience levels across the sample.

The mean value of large-scale agricultural operations, as measured through policy exposure under the land transfer policy, is 0.117, suggesting that 11.7% of the sample regions were significantly affected by the policy intervention.

Furthermore, the control variables, mechanism variables, and moderator variables exhibit considerable variation, reflecting heterogeneous economic, financial, and labor conditions across different regions. These variations provide a robust data foundation for the subsequent empirical analysis.

4.2 Analysis of baseline regression results

The baseline regression results examining the impact of land transfer policy on grain production resilience are presented in Table 4.

- Column (1) reports the regression results without control variables. The estimated coefficient for large-scale agricultural operations is 0.058, which is statistically significant at the 1% level. This suggests that large-scale agricultural operations has a positive and significant effect on grain production resilience.
- Columns (2) and (3) present the results after incorporating control variables and accounting for province-fixed effects and year-fixed effects separately. The estimated coefficients for large-scale agricultural operations in these models are 0.038 and 0.028, respectively, both of which remain significant at the 1% level.
- Column (4) introduces both province-fixed effects and year-fixed effects simultaneously, making it the most rigorous specification. The estimated coefficient for large-scale agricultural operations is 0.015, which, while slightly lower than in previous specifications, remains positive and statistically significant at the 1% level.

The declining coefficients from 0.058 to 0.015 demonstrate the effectiveness of omitted variable correction in model refinement. Year fixed effects absorbed approximately 37% of the interference from macroeconomic fluctuations and climatic variability, indicating substantial systemic uncertainties embedded in economic conditions and climate patterns. Provincial fixed effects further accounted for 63% of the heterogeneity attributable to geographical endowments, aligning with China's pronounced regional disparities in agroecological characteristics. Across Models (2)–(4), both fiscal support and industrial development exhibited statistically significant impacts on the dependent variable ($p < 0.05$). While economic development level showed significance prior to controlling provincial and year fixed effects, its influence became statistically indistinguishable after their inclusion. Notably, agricultural producer price levels at the micro-scale emerged as significant predictors post-adjustment, confirming the appropriateness of control variable selection. Throughout Models (1)–(4), although the economic effect magnitudes attenuated compared to initial estimates, they remained statistically significant at the 1% level ($\beta = 0.122$–0.187). It can be seen that large-scale agricultural operations may indeed have resource concentration effect and scale effect, allocate production factors more reasonably, or support the grain production resilience through mechanization and technology diffusion. This result confirms hypothesis H1.

TABLE 2 Definition and description of variables.

Variable type	Variable name	Variable symbol	Definition and measurement
Explained variable	Grain production resilience	*Y*	Measured using the entropy method, capturing resistance, recovery, and reconstruction dimensions.
Explanatory variable	Large-scale agricultural operations	$Treat_{it} \times Time_t$	Policy exposure interaction term: $Treat_{it} = 1$ if the region is significantly affected by the land transfer policy, otherwise 0. $Time_t = 1$ after policy implementation, otherwise 0.
Control variables	Economic development	*Economy*	Per capita GDP of the region (RMB10,000 per year)
	Fiscal support	*Fiscal*	Proportion of fiscal expenditure allocated to agriculture, forestry, and water affairs (%).
	Industrial development	*Industry*	Added value of the primary industry (RMB100 billion)
	Agricultural production price level	*Price*	Agricultural production price index
Mechanism variables	Farmers' professional cooperation level	*Cooperation*	Number of farmers' professional cooperatives per 1,000 employed individuals in the primary industry.
	Rural residents' income level	*Income*	Average disposable income of rural residents (RMB10,000 per year).
Moderator variables	Labor outflow	*Outflow*	Number of migrant workers (millions)
	Rural financial institutions	*RFI*	Number of business outlets of rural financial institutions (in 10,000 units).

TABLE 3 Descriptive statistics of main variables.

Variables	*N*	Mean	SD	Min	Max
Y	480	0.429	0.081	0.257	0.653
$Treat_{i,t} \times Time_t$	480	0.117	0.321	0	1
Economy	480	5.257	3.106	0.692	19.031
Fiscal	480	11.034	3.301	2.869	20.384
Industry	480	1.922	1.408	0.083	6.299
Price	480	104.831	6.121	87.5	141.88
Cooperation	480	6.580	6.076	0.037	32.553
Income	480	1.186	0.667	0.255	3.973
Outflow	480	7.500	5.929	0.076	28.376
RFI	480	2.433	1.553	0.003	6.11

4.3 Parallel trend test

The parallel trend assumption is a fundamental prerequisite for the DID model, ensuring that, prior to the implementation of the land transfer policy, the trends in grain production resilience were similar between the treated group and the comparison group. This validates the comparison group as an appropriate counterfactual for estimating the causal effect of large-scale agricultural operations.

To test this assumption, an event study approach is employed. Specifically, the policy implementation variable ($Treat_{i,t} \times Time_t$) is replaced with year-specific dummy variables for the 5 years preceding the policy implementation, the year of implementation, and the 3 years following the policy.

The results, presented in Figure 1, indicate that:

- In the 5 years prior to policy implementation, the regression coefficients remained stable within the 95% confidence interval, suggesting that the grain production resilience trends of the treated and comparison groups were similar, with no statistically significant differences. This confirms that the parallel trend assumption holds.
- After policy implementation, the regression coefficient becomes significantly positive, indicating a substantial improvement in grain production resilience in areas more strongly affected by the policy.
- Over time, grain production resilience in the treated group exhibits a sustained upward trend, reinforcing the conclusion that large-scale agricultural operations effectively enhances resilience.
- These findings confirm that the DID model used in this quasi-natural experiment satisfies the parallel trend assumption, further validating the robustness of the baseline regression results.

4.4 Placebo test

To ensure that the observed effects of the land transfer policy on grain production resilience are not driven by random factors or unobserved shocks, a placebo test was conducted. This test assesses whether the estimated policy effect is due to chance rather than a true causal relationship.

The placebo test was implemented by randomly resampling the data 500 times to generate a pseudo-policy dummy variable, which serves as a fictitious treatment assignment unrelated to actual policy implementation. The regression model was then re-estimated using this pseudo-policy variable, and the distribution of the estimated coefficients and *p*-values was analyzed.

The results, presented in Figure 2, show that:

- The mean regression coefficient of grain production resilience on the pseudo-policy dummy variable is close to 0, and it is substantially different from the benchmark regression coefficient.

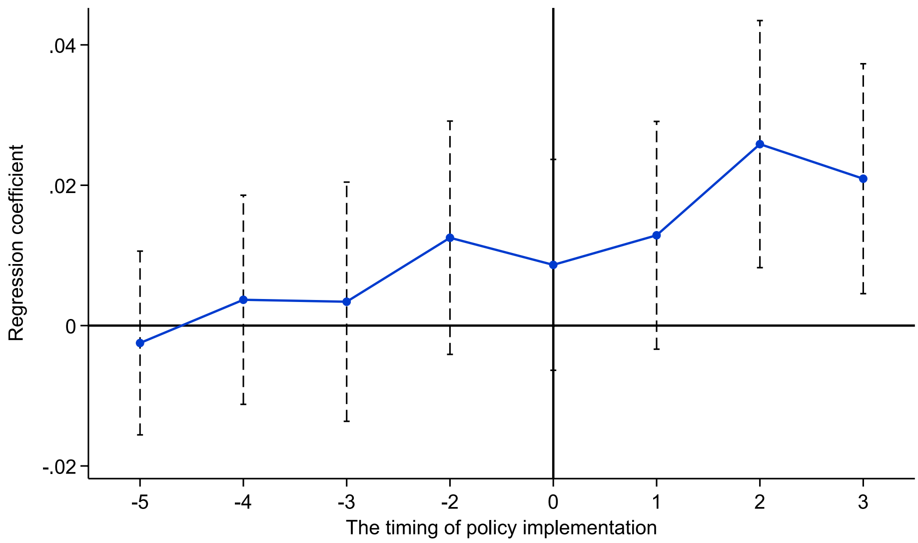

FIGURE 1
Parallel trend diagram.

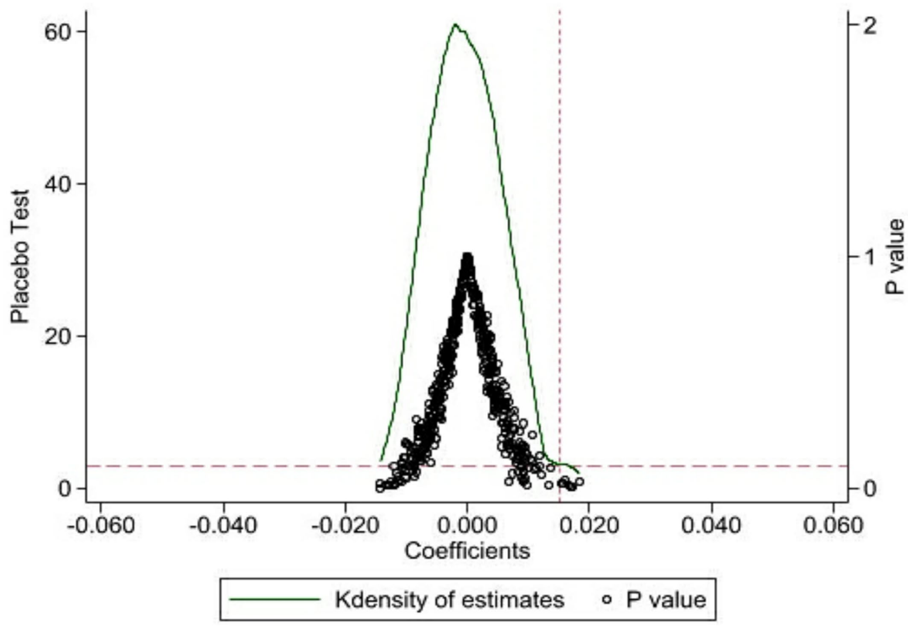

FIGURE 2
Placebo test diagram.

- The distribution of the estimated coefficients closely follows a normal distribution, indicating that the placebo treatment does not generate systematic effects.
- The *p*-values of the estimated coefficients are predominantly greater than 0.10, meaning that they do not reach statistical significance at the 10% level.

These findings confirm that the observed impact of large-scale agricultural operations on grain production resilience is not driven by random factors. Therefore, the results of the study remain robust and reliable.

4.5 Endogeneity test

To address potential endogeneity issues in the model—such as reverse causality, measurement errors, and omitted variable bias, a series of robustness tests were conducted based on established methodologies.

4.5.1 System GMM estimation

Following Ma Y.-f. et al. (2025), the system generalized method of moments (GMM) approach was applied to estimate parameters while addressing potential endogeneity issues. This method uses moment

TABLE 4 Results of baseline regression.

Variables	(1)	(2)	(3)	(4)
	Y	Y	Y	Y
$Treat_{i,t} \times Time_t$	0.058***	0.038***	0.028***	0.015***
	(0.011)	(0.009)	(0.003)	(0.003)
Economy	–	−0.003**	0.002**	−0.002
	–	(0.001)	(0.001)	(0.001)
Fiscal	–	0.004***	0.002***	0.002**
	–	(0.001)	(0.001)	(0.001)
Industry	–	0.044***	0.028***	0.022***
	–	(0.002)	(0.002)	(0.002)
Price	–	−0.000	0.000	−0.000**
		(0.001)	(0.000)	(0.000)
Constants	0.422	0.339***	0.324***	0.419***
	(0.004)	(0.070)	(0.018)	(0.025)
Province-fixed	–	No	Yes	Yes
Year-fixed	–	Yes	No	Yes
N	480	480	480	480
R^2_adj	0.052	0.651	0.959	0.967

***, **, and * indicate that the regression coefficient is significant at a level of 1, 5, and 10%, respectively. It is the same in the following table.

conditions, allowing for the consideration of both level and first-difference values of the dependent variable, thereby improving estimation efficiency.

The results, presented in Column (1) of Table 5, indicate that:

- The first-order autocorrelation test (AR(1)-P) is less than 0.1, while the second-order autocorrelation test (AR(2)-P) exceeds 0.1, suggesting that autocorrelation is limited to the first order, meeting the validity requirements of the GMM approach.
- The Hansen test for over-identifying restrictions (Hansen test-$p > 0.1$) fails to reject the null hypothesis, confirming that the selected instrumental variables are appropriate.
- The coefficient for the lagged dependent variable ($L.Y$) is significantly positive, indicating persistence in grain production resilience over time.
- After controlling for $L.Y$, the coefficient estimates for the explanatory variables remain consistent with the baseline regression results, further supporting the validity of the findings.

4.5.2 Double machine learning (DML) method

To further address potential endogeneity, the DML approach was employed, following He et al. (2022). This method integrates machine learning techniques with causal inference to estimate the relationship between large-scale agricultural operations and grain production resilience while controlling for confounding variables.

The DML process consists of two stages:

- Stage 1: A random forest algorithm was used to estimate predictive models for both large-scale agricultural operations and grain production resilience, incorporating relevant covariates.
- Stage 2: Regression analysis is conducted using the prediction residuals from Stage 1 to estimate the causal effect of large-scale agricultural operations on grain production resilience, reducing the influence of confounding variables.

The results, presented in Column (2) of Table 5, indicate that the estimated coefficient for large-scale agricultural operations remains significantly positive, confirming a robust causal relationship between large-scale agricultural operations and grain production resilience.

4.5.3 Oster coefficient stability test

Following Oster (2019), the Oster coefficient stability test was used to evaluate whether the results are biased due to unobserved omitted variables. This method estimates the true coefficient (β^*) using the following formula:

$$\beta^* = \beta^*\left(R_{\max}, \delta\right),$$

where,

- R_{max} represents the maximum goodness-of-fit (R-squared) that would be achieved if all unobservable variables were included.
- δ is the selection ratio, which quantifies the relative strength of association between observable and unobservable variables.

Two conditions were tested:

(1) If $\beta = 0$ and $R_{max} = 1.3R$, and the absolute value of the estimated coefficient exceeds 1, the endogeneity test is passed.
(2) If $\delta = 1$ and $R_{max} = 1.3R$, the estimated coefficient range of the endogenous variable β^* is examined. If this range does not include 0, the test is passed.

The results, presented in Table 6, confirm that both conditions hold, indicating that the regression estimates are not biased by unobservable omitted variables.

The results from the system GMM, DML estimation, and Oster stability test all provide strong support for the validity of the baseline regression findings. These tests confirm that the relationship between large-scale agricultural operations and grain production resilience is not driven by endogeneity concerns, further reinforcing the reliability of the study's conclusions.

4.6 Robustness test

In addition to the parallel trend test, placebo test, and endogeneity test, additional robustness checks are conducted to ensure the reliability of the research findings. The following methods are applied.

4.6.1 Influence of outliers

To eliminate the potential impact of outliers on the regression results, the original dataset was winsorized by truncating observations outside the 1st and 99th percentiles. The regression was then re-estimated using the adjusted dataset. The results, presented in Column (1) of Table 7, indicate that the positive impact of large-scale agricultural operations on grain production resilience remains

TABLE 5 Endogeneity test results of system GMM and DML.

Variables	(1) System GMM	(2) DML
	Y	Y
L.Y	0.716***	–
	(0.047)	–
$Treat_{i,t} \times Time_t$	0.006*	0.014***
	(0.003)	(0.005)
Constants	0.156***	−0.000
	(0.041)	(0.001)
Control variables	Yes	Yes
Province-fixed	Yes	Yes
Year-fixed	Yes	Yes
AR(1)-P	0.001	–
AR(2)-P	0.204	–
Hansen test-*p*	0.377	–
N	450	480

TABLE 6 Test results of Otser coefficient stability.

Test method	Criterion	Practical calculation results	Pass
(1)	$(\|\delta = 0, R_{max} = 1.3R\| > 1)$	$\delta = 3.393$	Yes
(2)	Value range does not contain 0.	[0.032, 0.040]	Yes

statistically significant. The coefficient direction and significance level remain unchanged, suggesting that the findings are robust to extreme values and not driven by outliers.

4.6.2 Propensity score matching-difference-in-differences (PSM-DID) approach

To further verify the reliability of the results, a PSM-DID method was applied. The process consists of two steps:

- PSM: A group of comparison regions with similar pre-policy characteristics was identified for the treated group.
- DID: The differences in grain production resilience between the treated and comparison groups were compared before and after policy implementation.

The results, shown in Column (2) of Table 7, indicate that grain production resilience significantly improved in the treated group after policy implementation, while no significant changes were observed in the comparison group. This further confirms that the positive effect of large-scale agricultural operations on grain production resilience is not driven by sample selection bias.

4.6.3 Controlling for confounding policy effects

Given that other agricultural policies may have influenced grain production resilience during the study period, additional policy dummy variables were introduced to control for their potential confounding effects. The following policies, which overlap with the implementation of the land transfer policy, were included: DID-1: Dummy variable for China's agricultural insurance subsidy pilot policy; and DID-2: Dummy variable for the agricultural socialized service pilot policy. These policies overlap with the implementation of land transfer policy and have a potential impact on grain production resilience.

TABLE 7 Robustness test results—PSM-DID estimation, winsorization, and exclusion of policy effects.

Variables	(1) Psm-did	(2) Tail-shrinng	(3) Excluding policy 1	(4) Excluding policy 2
	Y	Y	Y	Y
$Treat_{i,t} \times Time_t$	0.013***	0.015***	0.015***	0.015***
	(0.003)	(0.003)	(0.003)	
DID-1	–	–	−0.013***	
	–	–	(0.003)	
DID-2	–	–	–	0.009***
	–	–	–	(0.003)
Constants	0.423***	0.419***	0.425***	0.418***
	(0.024)	(0.025)	(0.024)	(0.024)
Control variables	Yes	Yes	Yes	Yes
Province-fixed	Yes	Yes	Yes	Yes
Year-fixed	Yes	Yes	Yes	Yes
N	457	480	480	480
R^2_adj	0.970	0.967	0.968	0.967

The regression results, presented in Columns (3) and (4) of Table 7, indicate that these two policies are significantly associated with grain production resilience. However, after controlling for their influence, the positive impact of large-scale agricultural operations on grain production resilience remains statistically significant. The coefficient magnitude and direction remain stable, demonstrating that the findings are not driven by the effects of other policies.

The results of multiple robustness checks—including outlier adjustment, PSM-DID estimation, and policy confounding controls—all confirm that large-scale agricultural operations significantly enhances grain production resilience. These findings reinforce the reliability and robustness of the baseline regression results.

5 Further discussion

5.1 Discussion of the influence mechanism

To further explore the mechanisms through which large-scale agricultural operations affects grain production resilience, this analysis focuses on two key factors: farmers' professional cooperation level and rural residents' income level. The mediation effect test method proposed by Chen J. et al. (2023) is applied to assess these relationships.

The results presented in Table 8 (columns 1 & 3) confirm this mediation effect. The relationship between large-scale agricultural operations and farmers' professional cooperation, as well as the

TABLE 8 Test results of mechanism analysis.

Variables	(1)	(2)	(3)	(4)
	Cooperation	*Income*	Y	Y
Treat $_{i,t}$ × *Time* $_t$	2.995***	0.214***		
Cooperation	(5.639)	(0.025)	0.001*** (0.000)	
Income				0.044*** (0.006)
Constants	9.212***	0.735***	0.343***	0.338***
	(3.541)	(0.142)	(0.021)	(0.020)
Control variables	Yes	Yes	Yes	Yes
Province-fixed	Yes	Yes	Yes	Yes
Year-fixed	Yes	Yes	Yes	Yes
N	480	480	480	480
R^2_adj	0.851	0.979	0.966	0.968

TABLE 9 Test results of moderating factors.

Variables	(1) Labor outflow	(2) Rural financial institutions
	Y	Y
Treat $_{i,t}$ × *Time* $_t$	0.025***	0.026***
	(0.005)	(0.006)
Outflow	−0.001**	
	(0.001)	
Treat $_{i,t}$ × *Time* $_t$ × *Outflow*	−0.001*** (0.000)	
RFI		0.005**
		(0.003)
Treat $_{i,t}$ × *Time* $_t$ × *RFI*		−0.004***
		(0.002)
Constants	0.362***	0.359***
	(0.021)	(0.021)
Control variables	Yes	Yes
Province-fixed	Yes	Yes
Year-fixed	Yes	Yes
N	480	480
R^2_adj	0.968	0.967

relationship between professional cooperation and grain production resilience, is statistically significant. The findings indicate that large-scale agricultural operations strengthens resilience by increasing professional cooperation among farmers. Obviously, the enhanced level of farmer professional cooperation facilitates intensive resource sharing and technology exchange, which accelerates organizational integration in grain production systems. This institutional consolidation generates dual mechanisms of economies of scale and synergistic effects, leading to a progressive reduction in production costs and enhanced market competitiveness—both critical drivers of production resilience. Concurrently, elevated cooperation provides structural support through market intelligence platforms and financial service networks, empowering producers to mitigate compound risks arising from price volatility and climatic shocks, grain production resilience is improved. The hypothesis H2 is verified here.

The results, as shown in Table 8 (columns 2 & 4), confirm that large-scale agricultural operations positively influences rural residents' income, which in turn contributes to greater grain production resilience. Obviously, the increase of income will enhance consumers' consumption ability and willingness. For agricultural producers, this means that they have more funds to improve production conditions, introduce new technologies and improve food quality, which not only helps to improve the stability and output of food production, but also enhances agricultural producers' resistance to natural disasters and market fluctuations, thus enhancing the resilience of food production. The hypothesis H3 is verified here.

5.2 Discussion of moderating factors

To further examine whether certain key factors influence the relationship between large-scale agricultural operations and grain production resilience, this study considers the effects of labor outflow and the number of rural financial institutions as moderating variables.

Labor outflow affects grain production resilience by reducing the availability of agricultural labor, which may limit the full advantages of large-scale agricultural operations. As rural workers migrate to urban areas in pursuit of higher incomes, their reduced engagement in agricultural activities can diminish the incentives for farmers to invest in agricultural technology and capital improvements. This shift constrains the ability of large-scale agricultural operations to enhance grain production resilience. Moreover, although migrating farmers may transfer their land to other farmers or agricultural enterprises, this process is often uneven and inefficient, leading to issues related to land quality variability and suboptimal resource allocation. These challenges can further weaken the resilience of grain production systems. These challenges are structurally exacerbated within China's unique institutional and socioeconomic contexts. Firstly, the household registration system (hukou) and entrenched urban–rural dualism have shaped a distinct pattern of labor migration—characterized as "physically detached from rural livelihoods while retaining land entitlements." This institutional hybridity creates path dependencies where migrant workers maintain contracted farmland rights despite urban employment, substantially constraining the effectiveness of land transfer policies and the realization of scale economies in agricultural operations. Secondly, the unbalanced development of economic space in China leads to more migrant workers being young workers. The outflow of labor accelerates the aging of agricultural groups, and the adoption rate of smart devices by elderly farmers is low, which weakens the technical efficiency potential of large-scale operations.

The results presented in Table 9, Column (1), indicate that labor outflow has a significantly negative effect on grain production resilience. Additionally, the interaction term between labor outflow and large-scale agricultural operations is also negative and statistically significant, suggesting that labor migration not only directly weakens resilience but also reduces the effectiveness of large-scale agricultural operations in enhancing grain production resilience.

While increased access to rural financial institutions is expected to strengthen grain production resilience by providing farmers with easier access to credit and financial support, its interaction with large-scale agricultural operations introduces complexities that may lead to unintended negative consequences. The expansion of rural financial institutions improves the accessibility and convenience of financial services, thereby supporting investment in agricultural activities. However, this benefit may not be evenly distributed across all farmers. Larger farms or agricultural enterprises often find it easier to secure financial support, while small-scale farmers may continue to face difficulties in obtaining loans due to high borrowing costs or collateral requirements. As a result, the potential benefits of financial access are unevenly distributed, weakening the overall improvement in grain production resilience. At present, there is still structural exclusion in the rural financial system in China: the average interest rate of loans from leading agricultural enterprises is significantly lower than that of small farmers, and large-scale entities obtain low-cost funds by mortgage of land management rights, while it is normal for small farmers to face financing constraints. Furthermore, financial resources from rural institutions are not always used effectively to enhance productivity or resilience. In some cases, funds may be diverted to non-agricultural investments or used to expand production scale rather than improve efficiency, which fails to enhance grain production resilience. At present, due to the high risk of agricultural production, the limited profitability of agricultural real economy and the relative lag of financial supervision, rural financial institutions and policy financial institutions in China have a tendency of "deviating from reality to emptiness" at the same time, showing a trend that financial resources flow more to non-agricultural fields. Additionally, as large-scale agricultural operations develops, the cost of production may rise, and the cost of financial services may increase, further exacerbating financial pressures on agricultural producers. These rising costs can counteract some of the benefits of financial access and lead to a net negative moderating effect. At present, the high coverage of digital finance in China and the weak use ability of elderly farmers aggravate the dilemma of the cost of financial services and agricultural production costs.

The results shown in Table 9, Column (2), suggest that while an increase in rural financial institutions positively influences grain production resilience, the interaction term between financial institutions and large-scale agricultural operations is negative and statistically significant. This finding indicates that although financial institutions independently contribute to resilience, their presence weakens the positive impact of large-scale agricultural operations on grain production resilience.

5.3 Heterogeneity discussion

5.3.1 Heterogeneity in grain functional areas

To examine whether the impact of large-scale agricultural operations on grain production resilience varies across different functional areas, this study classifies 30 provinces into three categories based on the grain functional area classification framework: main grain-producing areas, main grain-selling areas, and production-marketing balance areas. A fixed effects model was applied for empirical estimation, following the baseline regression methodology.

The results, presented in Table 10, indicate that large-scale agricultural operations exerts different effects on grain production resilience across these three regions. Column (1) reports the results for main grain-producing areas, Column (2) for main grain-selling areas, and Column (3) for production-marketing balance areas. In main grain-producing areas, the estimated coefficient is −0.002 and is not statistically significant, suggesting that large-scale agricultural operations does not have a meaningful impact on resilience in these regions. In contrast, in main grain-selling areas, the coefficient is 0.018, which is statistically significant at the 1% level, indicating a positive effect of large-scale agricultural operations on grain production resilience. Similarly, in production-marketing balance areas, the coefficient is 0.027 and is also significant at the 1% level, highlighting an even stronger positive effect. These findings suggest that grain production resilience in production-marketing balance areas and main grain-selling areas is more significantly influenced by large-scale agricultural operations, whereas no significant effect is observed in main grain-producing areas. Among the three groups, production-marketing balance areas exhibit the strongest positive response, followed by main grain-selling areas, with main grain-producing areas showing the weakest response.

Several factors may explain these regional differences. In main grain-producing areas, the oversupply of grain production results in

TABLE 10 Regional heterogeneity test results.

Variables	(1) Producing areas	(2) Selling areas	(3) Balance areas	(4) Northern provinces	(5) Southern provinces
	Y	Y	Y	Y	Y
$Treat_{i,t} \times Time_t$	−0.002	0.018***	0.027***	0.017***	0.008**
	(0.004)	(0.006)	(0.006)	(0.004)	(0.003)
Constants	0.369***	0.438***	0.407***	0.391***	0.444***
	(0.035)	(0.061)	(0.030)	(0.034)	(0.034)
Control variables	Yes	Yes	Yes	Yes	Yes
Province-fixed	Yes	Yes	Yes	Yes	Yes
Year-fixed	Yes	Yes	Yes	Yes	Yes
N	208	112	160	240	240
R^2_adj	0.962	0.884	0.944	0.967	0.973

relatively low profitability, reducing the economic incentives for resilience-enhancing investments. Additionally, non-grain land use is more prevalent in these regions, leading to inefficient land transfer that does not necessarily strengthen grain production resilience. The heavy reliance on agricultural labor further amplifies the negative impact of labor migration, making these regions more vulnerable to workforce shortages. Moreover, grain production in these areas often depends heavily on chemical fertilizers and other external inputs, which may negatively affect soil quality and long-term resilience.

In production-marketing balance areas, where grain supply and demand are relatively stable, large-scale agricultural operations facilitates a more efficient allocation of agricultural resources toward grain production. This improved efficiency strengthens grain production resilience by optimizing land use and resource distribution. Additionally, government policies in these areas may be more proactive in supporting grain cultivation, providing farmers with incentives to expand grain production. The balanced grain supply and demand dynamics also increase the strategic importance of grain production, thereby encouraging higher adoption of large-scale agricultural operations practices, which enhances resilience.

In main grain-selling areas, the government may place a stronger emphasis on encouraging grain production due to higher demand and greater reliance on external food supplies. The higher levels of urbanization in these areas lead to stricter land management policies, ensuring that agricultural land is effectively utilized. However, the economic structure in main grain-selling areas is often more diversified, reducing the relative importance of grain production as an economic pillar. While large-scale agricultural operations positively influences grain production resilience, its effect in these areas is less pronounced than in production-marketing balance areas, where grain cultivation plays a more central role.

5.3.2 Regional heterogeneity between Northern and Southern China

To examine whether the impact of large-scale agricultural operations on grain production resilience varies by region, this study classifies 30 provinces into northern and southern regions based on the north–south geographical boundary. The econometric estimation results are presented in Table 10, with Column (4) reporting results for northern China and Column (5) for southern China.

The findings indicate a stronger effect of large-scale agricultural operations on grain production resilience in northern China compared to the southern region. In northern China, the estimated coefficient is 0.017, which is statistically significant at the 1% level, suggesting a strong positive relationship between large-scale agricultural operations and grain production resilience. In contrast, in southern China, the coefficient is 0.008, which remains statistically significant but at the 5% level, indicating a weaker yet still positive effect.

Several factors may explain these regional differences. Geographical conditions play a key role in shaping the effectiveness of large-scale agricultural operations. In southern China, the prevalence of mountains and hilly terrain results in fragmented farmland, which limits the potential for large-scale mechanized farming. Additionally, the humid climate increases the risk of pests and diseases, further complicating large-scale production and reducing overall resilience. In contrast, northern China is characterized by fertile soil and expansive flatlands, which are highly suitable for mechanized farming and facilitate the efficient implementation of large-scale agricultural operations.

Economic structure also contributes to these differences. The southern region has undergone rapid industrialization and urbanization, leading to a declining role of agriculture in the regional economy. Many farmers in the south are more inclined to seek employment in urban areas or engage in non-agricultural sectors, which reduces the available agricultural labor force and weakens production resilience. In contrast, northern China, particularly the northeast region, continues to rely heavily on agriculture as a pillar of the regional economy. Farmers in these areas maintain a stronger attachment to land, making it easier to establish stable large-scale grain production bases.

Differences in agricultural production models further influence resilience outcomes. The southern region is characterized by diverse crop cultivation, which, while beneficial for food security and crop rotation, may also introduce greater production instability in response to market fluctuations. In contrast, the northern region specializes in a narrower range of grain crops, which enables greater economies of scale and improves grain production efficiency and market competitiveness. This specialized planting model enhances resilience by stabilizing production processes and optimizing resource allocation.

6 Conclusions and policy recommendations

This study employs a quasi-natural experiment based on land transfer policy to analyze the impact of large-scale agricultural operations on grain production resilience. The findings indicate that large-scale agricultural operations significantly enhances grain production resilience, primarily through two mechanisms: increasing rural residents' income and strengthening farmers' professional cooperation. However, the results also highlight certain constraints. Labor outflow and the expansion of rural financial institutions, as moderating factors, weaken the positive effect of large-scale agricultural operations on resilience, emphasizing the critical role of labor availability and financial development in agricultural sustainability.

The heterogeneity analysis further reveals regional variations in the effects of large-scale agricultural operations. The northern region experiences greater improvements in grain production resilience compared to the southern region, likely due to more favorable geographic conditions and a stronger agricultural economic structure. Additionally, production-marketing balance areas and main grain-selling areas exhibit stronger improvements in resilience than main grain-producing areas, where structural challenges such as land transfer inefficiencies and over-reliance on external inputs (such as fertilizer, etc.) may hinder the benefits of large-scale agricultural operations.

These findings provide important enlightenment for countries with different agro-ecological regions and agricultural conditions in the world to cope with the challenges of climate change, market fluctuation and food security, especially for developing countries with serious land fragmentation and agricultural modernization transformation. Based on these findings, the following policy recommendations are proposed to further enhance grain production resilience.

6.1 Deepening land transfer policy reform

Empirical evidence confirms that large-scale agricultural operations significantly enhance grain production resilience. The government can deepen the reform of land transfer policy according to the actual situation and build an efficient and intensive agricultural management system. The specific measures are: focusing on land transfer, giving priority to the establishment of a trinity reform framework of "clear property rights-active market-institutional guarantee." Focus on improving three aspects: Firstly, strengthen the market mechanism, develop flexible modes such as cross-season circulation and contract management, establish a national land transfer trading platform, realize the digitalization of ownership registration, price evaluation and contract management through blockchain technology, and reduce transaction costs and default risks; Secondly, improve legal protection, clarify the property right of land management right, set up a special dispute arbitration institution, explore the mortgage financing system of management right, and enhance long-term investment confidence; The third is to optimize policy incentives, give targeted support such as tax relief and infrastructure facilities to the main body of continuous circulation for many years, and establish a linkage mechanism between transfer scale and ecological compensation to promote sustainable intensification. This kind of reform is especially suitable for areas with serious land fragmentation, such as Southeast Asia and Africa, and can release land integration dividends on a large scale.

6.2 Promoting the development of farmers' professional cooperatives

Empirical evidence confirms that farmers' cooperatives play an important mediating role in the process of large-scale agricultural operations promoting grain production resilience. The government can formulate relevant policies to strengthen the construction of farmers' cooperative organizations and activate the socialized service network. The specific measures are: promoting the transformation of cooperatives from "quantity growth" to "function upgrading," focusing on cultivating three types of capabilities: production and service capabilities (providing agricultural machinery sharing and popularizing smart agricultural technology), market docking capabilities (building a direct power supplier platform and developing order agriculture) and risk resistance capabilities (jointly insured with climate index insurance). Establish a grading certification system for cooperatives, and give priority to opening up resources such as government procurement and scientific research projects to high-level organizations. At the same time, cooperatives and scientific research institutions are encouraged to build a "technology diffusion center" to promote resilient technologies such as water-saving irrigation and stress-resistant varieties.

6.3 Increasing rural residents' income

Empirical evidence confirms that farmers' income play an important mediating role in the process of large-scale agricultural operations promoting grain production resilience. The government can design diversified income-increasing paths to enhance farmers' resilience against risks. The specific measures are: implementing the two-wheel drive strategy of "increasing efficiency in the main business and generating income by sideline business." In the agricultural field, we should promote the cooperative mode of "scale management subject+small farmers" and share intensive benefits through guaranteed purchase and profit sharing; in the non-agricultural field, develop county labor-intensive industries and establish an integrated employment support system of "skills training-job docking-social security connection." In addition, explore new income-increasing channels such as "agricultural carbon sink trading" and "realization of ecological product value," and include the improvement of grain production resilience in the scope of green financial support.

6.4 Implementing policies according to local conditions to promote grain production resilience

Spatially differentiated policies are essential due to heterogeneous impacts across agroecological zones. The government should formulate the policy of spatial adaptation and break the regional resource constraints. Specific measures should be based on agricultural ecological zoning and agricultural conditions to carry out differentiated support: In production-marketing balance areas, increase subsidies and the construction of farmland water conservancy facilities; In main grain-producing areas, guide the circulation of cultivated land and promote green agriculture, stimulate stable production through horizontal financial transfer payment; in main grain-selling areas, optimize the industrial structure, strengthen land management, and establish a "cultivated land protection compensation fund"; In the plain areas with contiguous land (such as North America and Eastern Europe), we should focus on developing fully mechanized super-large-scale farms; In hilly and mountainous areas with broken terrain (such as South Asia and Latin America), "service scale" (such as UAV plant protection and hosting services) should be promoted. By implementing region-specific policies, agricultural development can be better aligned with local environmental, economic, and structural conditions, ensuring targeted and effective resilience-enhancing interventions.

6.5 Promoting labor force retention and strengthening financial support for agricultural development

Based on the empirical results that the number of rural financial institutions and the outflow of labor force play a moderating role in the process of large-scale agricultural operation affecting the resilience of grain production, governments should optimize the factor flow system and ease the labor and financial constraints. It is a feasible scheme to implement the combination policy of "labor force return+financial innovation": on the one hand, pilot the "new professional farmers' housing project" in the main grain producing areas, provide targeted benefits such as housing subsidies and children's education, and attract young people to return home; On the other hand, we will develop financial instruments such as "special loans for scale operation" and "climate resilience insurance," and use satellite remote sensing and big data to build a credit evaluation model for business entities to lower the financing threshold. In international cooperation, we can learn from the rural development fund model of EU Common Agricultural Policy (CAP), and bind financial support with the adoption of green agricultural technology.

7 Research limitations and future directions

Although this study provides valuable insights on the relationship between large-scale agricultural operations and grain production resilience, some limitations should be acknowledged to guide future academic research. The main limitations are reflected in the following two aspects: (1) Limitations of methods. Although the quasi-natural experimental design based on the implementation of land transfer policy has solved the endogenous problems to some extent, it may still face selection bias due to the non-random introduction of policies in different regions. Although our research results have passed the endogenous test in many different ways, the unobserved heterogeneity in local governance capacity and informal institutional factors may still exist. In addition, although our resilience measurement framework contains multiple impact dimensions, it may not be able to fully capture the emerging challenges in climate change scenarios, such as compound extreme weather events. (2) Limitations of datas. The provincial group data structure limits our ability to analyze the micro-level mechanism, especially about the farmers' decision-making process and the ecological impact at the plot level. In view of the long adaptation period of agricultural system, the time range (2007–2022) may not be enough to reflect the long-term dynamic change of resilience. In addition, our proxy indicators of professional cooperation (such as the ratio of cooperative members) may oversimplify the complicated process of social capital formation.

There are four potential directions for future research: (1) vertical mechanism analysis. Through the implementation of mixed method, group investigation and process tracking are combined to reveal the time dynamic change of resilience index; (2) cross-scale integration. Develop a multi-level model to link family decision-making, village governance and macro-policy environment; (3) global comparative research. Establish an international research network to compare the institutional configuration of BRICS countries and Southeast Asian countries with similar agricultural transformation; (4) inclusion of emerging risks. Quantify the impact of new pressure factors (including cross-border grain market fluctuation and biofuel competition) on the resilience of grain production.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

Author contributions

DC: Writing – original draft, Methodology, Data curation, Investigation, Software, Conceptualization, Writing – review & editing, Validation, Resources, Formal analysis.

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Conflict of interest

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

Generative AI statement

The author declares that no Gen AI was used in the creation of this manuscript.

Supplementary material

The Supplementary material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fsufs.2025.1596449/full#supplementary-material

SUPPLEMENTARY TABLE S1
Empirical Analysis.

SUPPLEMENTARY TABLE S2
Measurement of Grain Production Resilience.

SUPPLEMENTARY TABLE S3
Heterogeneity Analysis.

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