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Toward a sustainable agricultural system in China: exploring the nexus between agricultural science and technology innovation, agricultural resilience and fiscal policies supporting agriculture

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Introduction: This study delves into the intricate dynamics between fiscal policies supporting agriculture and the non-linear influence of agricultural science and technology innovation on enhancing agricultural resilience. We conducted research across 31 provinces (including autonomous regions and municipalities) in China from 2007 to 2021.

Method: By constructing the evaluation index system of agricultural resilience, the entropy value method is used to measure the value of agricultural resilience, and then standard deviation ellipse and center of gravity migration analysis, benchmark regression model, heterogeneity analysis, threshold regression model are used to analyze the relationship between agricultural science and technology innovation, fiscal policies supporting agriculture and agricultural resilience.

Result: (1) The analysis of the spatio-temporal evolution trend shows that the overall development of China's agricultural resilience is relatively stable, the resilience range is expanding, and the geographical area with the southeast as the center of gravity presents a stronger pulling effect; (2) The benchmark regression model shows that agricultural science and technology innovation has a significant positive effect on agricultural resilience; (3) Agricultural science and technology innovation plays a nonlinear role in increasing agricultural resilience when fiscal policies supporting agriculture are used as a threshold variable. (4) Heterogeneity analysis highlights stronger promotion of agricultural resilience through science and technology innovation in non-main producing areas and economically underdeveloped regions.

Discussion: To address this, policymakers should leverage the resilience of the Southeast, boost innovation capacity, tailor innovation to local needs, and reinforce fiscal policies supporting agriculture. These insights provide valuable direction for policymakers in crafting effective measures to enhance agricultural resilience.

KEYWORDS

agricultural resilience, science and technology innovation, fiscal policies, threshold effect, spatiotemporal analysis

1 Introduction

In the contemporary landscape of agriculture, both at global and local scales, myriad challenges pose significant threats to the sustainability of the agricultural sector (Gouel and Guimbard, 2019). On the one hand, the demand for food and other essential ecosystem services provided by agriculture is on the rise, creating a complex scenario exacerbated by the mounting pressure on underlying agricultural production potential. On the other hand, factors such as climate change and soil degradation exacerbate pressures on agricultural systems, making the provision of private and public goods increasingly difficult and costly (Borrelli et al., 2020; Ortiz-Bobea et al., 2021; Elsner et al., 2023). At the same time, societal factors such as market shocks, pandemics, and wars intertwine to create a situation of uncertainty and instability that weakens the resilience of the agricultural sector.

Recent policy goals, as demonstrated by initiatives within the Kunming-Montreal Global Biodiversity Framework and the Farm to Fork strategy of the European Union, set ambitious environmental targets that must be achieved within short time frames (Schebesta and Candel, 2020). To mitigate the environmental impacts of agri-food systems, urgent action is needed to address the overuse of resources, environmental pollution from fertilizers and pesticides, greenhouse gas emissions, and biodiversity loss (Kanter et al., 2020; Wuepper et al., 2023). In tandem, concerns related to social sustainability and animal welfare underscore the urgency for comprehensive action in these areas. To navigate these combined challenges, the agricultural sector faces the imperative of delivering more with substantially smaller footprints, all while contending with reduced resources. This complex balancing act can give rise to conflicts, such as the tension between food production, profits, and environmental protection (Wuepper et al., 2023). Striking this delicate balance necessitates innovative approaches and breakthroughs conducive to sustainable development.

As a large agricultural country, the study of China's agricultural resilience is of great significance to the sustainable development of agriculture in other countries. In response to the global imperative for resilient agricultural practices, the 20th National Congress of the Communist Party of China outlined a visionary roadmap. The proposal emphasizes the acceleration of constructing a robust agricultural country, with a foundational guarantee of enhancing industrial resilience. In the face of escalating uncertainties in global development, bolstering agricultural resilience emerges not only as a means of stabilizing the agricultural foundation but also as a critical contributor to ensuring the stable operation of the national economic system. It acts as a metaphorical "ballast stone" for agriculture, providing stability in the face of evolving challenges. However, the agricultural sector confronts the escalating impacts of climate change and the recurrent incidence of extreme weather events. The convergence of natural and market risks further complicates the landscape, leading to a growing number of unpredictable events confronting the agricultural sector. This necessitates the exploration of breakthroughs conducive to sustainable development, with science and technology emerging as the fundamental solution for modern agricultural progress.

The strategic direction outlined by the United States in 2018 for the next decade of agriculture explicitly advocates technological innovation as the key to enhancing the resilience and recoverability of the food and agriculture system (Wan et al., 2023). The substantial progress in American agriculture is attributed to the pivotal role played by technology. Consequently, advancing agricultural resilience through technological innovation represents a crucial focal point for China in fortifying the construction of a robust agricultural nation. Yet, the public welfare attribute of agricultural technology places the onus on the government to assume the responsibility of the primary investor. This underscores the critical importance of government fiscal policies supporting agriculture, creating the necessary conditions for research and development in agricultural technology, and the transformation and application of its outcomes. Then, in the new development stage, how to scientifically assess the level of China's agricultural resilience, how to reveal the role of fiscal policies supporting agriculture in the process of the impact of agricultural science and technology innovation on agricultural resilience of the role of the mechanism, how to clarify the agricultural science and technology innovation, fiscal policies supporting agriculture on agricultural resilience to enhance the countermeasures and suggestions, and so on, these issues need to be further in-depth study.

This paper aims to provide evidence of the actual change in agricultural resilience in China and to explore the relationship between agricultural science and technology innovation, fiscal policies supporting agriculture for agriculture, and agricultural resilience from the perspective of sustainable agricultural development. To do so, we use data on China's agricultural resilience from 2007 to 2021 to show its spatiotemporal evolution. Additionally, we use heterogeneity analysis to explore how different regions influence the relationship between agricultural science and technology innovation and agricultural resilience through fiscal policies supporting agriculture. By achieving these objectives, this paper aims to contribute valuable insights into the intricate dynamics of agricultural resilience and inform policymaking for sustainable agricultural development.

2 Literature review

In recent years, agricultural resilience has emerged as a prominent research topic, with a primary focus on three key dimensions:

2.1 Connotation and measurement of agricultural resilience

The term "resilience," is rooted in the Latin word "resilio" meaning to return to the initial state. In different research fields, resilience has been given its specific meaning (Wang R. et al., 2023). Systems ecologist Holling (1973) applied the concept of resilience to the field of ecology, indicating the resilience and sustainability of ecosystems in the face of environmental change. In the field of economics, the use of resilience provides an effective tool for the explanation and illustration of economic phenomena (Fujita et al., 2002); Reggiani et al. (2002) explored resilience in the field of spatial economics; Martin et al. (2016) provided a more standardized definition of economic resilience and used the sensitivity index to measure the economic resilience of the city. The application of resilience at the city level aims to promote the sustainable development of cities. Tang and Tan (2022) argued that urban resilience emphasizes the organizing and coordinating power within the urban system and constructed an evaluation index system from four urban subsystems, namely, economy, society, ecology, and engineering. With the transformation of social lifestyles and living environments, the industrial system realizes the digital transformation while combining human capital, machines, and technology are combined to seek sustainability (Aheleroff et al., 2022). In the field of agriculture, Folke (2006) argue that agricultural resilience refers to the ability of an agricultural system to ensure that the main functions of the original system are not violated in the face of shocks such as natural and market shocks. Meuwissen et al. (2019) argue that agricultural resilience refers to the capacity to ensure that the system can perform the main functions of the original system in the face of complex economic, social, environmental, and institutional shocks, ensuring that the system can adapt and transform. Yu and Zhang (2019) defines it as the resistance and recovery ability of agricultural systems, measured across dimensions like production, ecological, and economic resilience. Hao Aimin et al. (2022) view agricultural resilience as the ability to withstand uncertainty shocks, involving adjustment, recovery, and continuous transformation. Measurements by Jiang et al. (2022) and Zhang and Hui (2022) encompass economic foundation, production conditions, technological progress, and ecological governance, using multidimensional indicators. Other scholars, like He and Yang (2021), approach agricultural resilience from the industrial chain perspective, viewing it as driven by modern technology, capable of effectively resisting shocks, and ensuring rapid recovery.

2.2 Influencing factors of agricultural resilience

In the context of global warming and price volatility, the future of agricultural systems faces uncertainty (Urruty et al., 2016). With society's increasing demand for agricultural products and the use of large quantities of chemical inputs such as fertilizers and pesticides, this kind of production at the expense of nature deprives environmental systems of resilience and sustainability (Bennett et al., 2021). Agriculture, as a weak industry, requires policy support from the government to guarantee the continued and stable operation of the agricultural economy (Wang J. et al., 2023). Diversity is key to food system resilience (Bisoffi et al., 2021). Diversified agricultural practices are conditions for food system resilience (Calo et al., 2021). Traditional elements such as agricultural infrastructure, communication technology, social capital, and transportation facilities are generally considered to be important factors influencing the level of agricultural resilience (Crespo et al., 2014; Chacon-Hurtado et al., 2020; Chaudhuri and Kendall, 2021; Tang and Chen, 2023). Hao Aimin et al. (2022) emphasize the significance of integrating agricultural industries under external shocks, highlighting its impact on enhancing resilience. Attention to intermediate media, including industrial structure optimization and agricultural industry integration, is underscored by Zhao and Xu (2023) and Zhou et al. (2023). Jiang et al. (2022) propose an inverted relationship between agricultural resilience and regional economic development, particularly noting strong regional linkages in major grain-producing areas. Song and Liu (2023) and Wang L. et al. (2023) identify the digital economy and innovation capacity as key factors in bolstering agricultural resilience.

2.3 Pathways for enhancing agricultural resilience

Alam et al. (2023) identified information and communications technology as a key factor in increasing the resilience of agri-food systems in developing countries and the need to ensure the resilience and sustainability of agricultural systems by facilitating the marketing of products, access to production inputs, and assisting stakeholders in adapting to the agri-food systems network. Zhang and Long (2023) highlight the constraint posed by weak agricultural research and development capabilities on agriculture's development, advocating for technology as the driving force for cultivating resilience. Wang Y. et al. (2023) argue that localized support for digital financial development and effective regulation are key to realizing an enhanced path to agricultural resilience. He and Yang (2021), based on the complex environmental conditions faced by the agricultural system at home and abroad, put forward the forging path of the resilience of China's agricultural industry chain in six dimensions, such as strengthening the advantages, extending the chain, expanding the scope, making up for the short boards, creating the joints, and backing up the industry chain, based on the systematic analysis and attempts to deconstruct the situation. Scholars such as Cao and Zhao (2017), Guo and Zhang (2023), and Yu et al. (2023), explore potential pathways for enhancing agricultural resilience through digitalization, green technology innovation, and industrial structure upgrading, respectively.

In summary, while existing research on agricultural resilience has yielded significant results, there is room for further expansion. The current literature predominantly examines factors affecting resilience from the perspectives of digital technology, facilities, and industry, with a limited focus on the direct impact of agricultural science and technology innovation. Additionally, the existing research results reveal a linear relationship between agricultural science and technology innovation and agricultural resilience but have not yet paid attention to the non-linear mechanism of agricultural science and technology innovation in the process of agricultural resilience enhancement. Consequently, this paper adopts the perspective of fiscal policies supporting agriculture, utilizing the panel threshold regression model to systematically explore the impact of agricultural science and technology innovation on agricultural resilience from both linear and nonlinear dimensions.

3 Theoretical analysis and research hypotheses

In the global competition in agriculture, technological advancement is the crux. Agricultural science and technology is the endogenous driving force for deepening the structural reform of the agricultural supply side and promoting the high-quality development of agriculture (Hua and Pan, 2022). With the structural adjustment of China's economic development strategy from the original exogenous economic growth model dominated by factor inputs such as capital and labor to the endogenous economic growth model dominated by knowledge and technology factors (Lv and Cai, 2020), agricultural science and technology innovation fosters agricultural resilience not only by promoting changes in agricultural production and operation and its management but also by facilitating the transformation of agricultural economic growth (Jiang et al., 2021). On the one hand, agricultural science and technology innovation can promote the rational allocation of agricultural resource elements, realize the transformation of agricultural production from rough to intensive, enhance the efficiency of agricultural production, and then enhance the resilience of agriculture. On the other hand, the agricultural system can also gather knowledge, technology, and other emerging enabling elements through the application of modern production technology, modern equipment technology, and other technologies, promote the horizontal expansion and vertical extension of the agricultural industry chain (He and Yang, 2021), extend the agricultural industry chain, increase the added value of agricultural products, promote the optimization and upgrading of the structure of the agricultural industry, achieve the connotative development of agriculture, and then enhance the agricultural resilience. Finally, technology is more sustainable than inputs of material factors and can make up for the shortcomings of traditional factors, to achieve the purpose of cost saving, improving efficiency, and enhancing the competitiveness of agricultural products in the market. The fundamental purpose of agricultural science and technology innovation is to apply the results of agricultural science and technology innovation in the agricultural pre-production, production, post-production, and many other links, so that it is transformed into real productivity, thereby enhancing the market competitiveness of agricultural production and management subjects, to achieve the purpose of agricultural resilience cultivation. Forming the foundation on these premises, we propose Hypothesis 1:

> *H1:* Agricultural science and technology innovation has a positive impact on agricultural resilience.

Due to the public goods attribute of agricultural technology, thus the government needs to assume the main responsibility, play the role of macro-control, through the development of induced technological innovation policy, and then increase the investment in technological innovation, and infrastructure, to enhance the level of technological innovation (Hu et al., 2018). The nuanced impact of agricultural science and technology innovation on agricultural resilience is intricately linked to the threshold effect of fiscal policies supporting agriculture. Liu and Song (2020) have demonstrated that fiscal policies significantly shape the outcome of agricultural science and technology innovation. On the one hand, when the government plays the function of macro-control, it directly invests agriculture-related financial funds into the key areas of agricultural development and weak links, and through the aggregation of funds to enhance the capacity of agricultural development, thereby enhancing the resilience of agriculture (Ni and Wei, 2022); on the other hand, the fiscal policies supporting agriculture can correct the externality of agricultural science and technology innovation, which is conducive to promoting the progress of cutting-edge technology and thus realizing technological breakthroughs in focus, simultaneously, it is also conducive to promoting the transformation and application of the results of agricultural technology and promoting the spillover effect of the results of agricultural scientific and technological innovations, which in turn promotes the cultivation of agricultural resilience. From practical experience, the implementation of fiscal policies supporting agriculture varies in strength, and the impact effect will also vary, so the agricultural industry system usually adopts the dynamic adjustment of relevant policies to cope with the changes brought about by this difference. Insufficient financial support for agriculture capital investment intensity will affect the agricultural science and technology research and development and its innovation results of transformation and application so that agricultural science and technology innovation dividend is difficult to effectively release, and thus affect the level of agricultural resilience enhancement. It is posited that only through a scientifically efficient fiscal support pattern, crossing a certain threshold, can the positive impact of agricultural science and technology innovation be effectively leveraged to enhance agricultural resilience. Thus, we propose hypothesis 2:

> *H2:* Fiscal policies supporting agriculture have a threshold effect on the impact of agricultural science and technology innovation on agricultural resilience. Agricultural resilience will significantly improve only beyond a specific threshold level of fiscal support for agriculture.

4 Research design

4.1 Calculation of agricultural resilience and spatiotemporal evolution analysis

The color-marked part of the figure is the study area of this paper, including 31 provinces (autonomous regions and municipalities directly under the central government) in China, and the blank area is the missing part of the data, which is not marked in the figure (see Figure 1). To establish a robust agricultural resilience evaluation framework, we draw upon existing literature, incorporating insights from Lu et al. (2021) and other relevant sources. The development of an indicator system forms the first step in this process. Subsequently, the entropy method is applied to assign weights to the identified indicators, facilitating the computation of numerical values representing agricultural resilience. This step ensures a comprehensive and nuanced assessment by considering the relative importance of each indicator in the overall resilience evaluation. Drawing inspiration from the research findings of Song and Liu (2023), the analysis then extends to the spatiotemporal evolution of China's agricultural resilience. Leveraging ArcMap 10.8 software, various techniques are employed, including the 68% standard deviation ellipse analysis, spatial center of gravity, azimuth, and standard deviation of the major and minor axes. These methods collectively provide insights into the spatial distribution and temporal dynamics of agricultural resilience, offering a holistic perspective on its agglomeration patterns.

4.2 Variable measurement

4.2.1 Dependent variable

Agricultural Resilience (Resi) is chosen as the dependent variable. Presently, there is no unified standard for measuring agricultural resilience in the academic community. Agriculture, being a complex system, encompasses resilience considerations across multiple levels. Therefore, its evaluation cannot rely on a single indicator. Considering the completeness of the agricultural resilience evaluation system and data availability, this paper constructs an agricultural resilience evaluation indicator system spanning three dimensions: production resilience, ecological resilience, and economic resilience. Production resilience pertains to the ability of agriculture to withstand destructive events during the agricultural production process, primarily including

FIGURE 1
Map of the study area.

indicators related to agricultural production factor conditions. Ecological resilience involves the ability of agriculture to respond to environmental changes, encompassing inputs such as pesticides, fertilizers, and indicators like carbon emissions. Economic resilience relates to the capacity of entities involved in agricultural production and management to respond to economic shocks, specifically focusing on the economic foundation and staffing of agricultural production and management entities. The specific indicators are detailed in Table 1.

4.2.2 Independent variables

The independent variable is gauged by agricultural science and technology innovation (Tech). This study employs three dimensions to assess the capability of agricultural science and technology innovation: input level, output level, and transformation level. The input of agricultural science and technology innovation encompasses the effective integration and utilization of agricultural resources, forming the foundation of agricultural science and technology innovation. It comprises two indicators: the number of agricultural research and development (R&D) personnel and internal expenditures on agricultural R&D funds. Notably, the substitution of internal expenditure on agricultural R&D funds is based on the research findings of Sun and Youyi (2020) and Xu et al. (2021). Output is manifested by the outcomes resulting from agricultural science and technology innovation R&D, providing a substantial reflection of the level of agricultural science and technology innovation. This dimension includes indicators such as the number of applications for new agricultural plant varieties and the count of Chinese scientific papers indexed by major foreign search tools. Transformation involves the application of agricultural science and technology achievements to the agricultural production and management process, thereby elevating the level of agricultural science and technology transformation into real productive forces through the promotion and diffusion of agricultural technology. Indicators for this dimension include the amount of technology market transaction contracts and the number of technology market transaction contracts. The specific indicators are detailed in Figure 2.

4.2.3 Threshold variable

This study employs fiscal policies supporting agriculture as the threshold variable, specifically gauged by the proportion of expenditures allocated to agriculture, forestry, and water affairs in total fiscal expenditures.

4.2.4 Control variables

To uphold the precision of the regression results, the following control variables are chosen based on a thorough review of related literature: (1) Market Size (Market): Represented by the proportion of total retail sales of consumer goods to the gross regional product. (2) Human Capital Stock (Labor): Measured by the number of the rural population. (3) *Per Capita* Economic Development Level (Agdp): Measured by the *per capita*

TABLE 1 Agricultural resilience evaluation index system.

Level 1 indicators	Secondary indicators	Indicator properties	Indicator weights
Production resilience	Effective irrigated area/sown area	Positive	0.089
	Total agricultural machinery power/sown area	Positive	0.098
	Original value of rural household productive fixed assets	Positive	0.156
	Disaster-affected area/disaster area	Negative	0.005
Ecological resilience	Water usage for agricultural production per unit of sown area	Negative	0.009
	Amount of fertilizer used (pure equivalent) per unit of sown area	Negative	0.021
	Amount of diesel fuel used per unit of sown area	Negative	0.011
	Amount of pesticide used per unit of sown area	Negative	0.010
	Amount of agricultural plastic film used per unit of sown area	Negative	0.011
	Carbon emissions	Negative	0.027
Economic resilience	Added value of agriculture, forestry, animal husbandry, and fishery/number of employees in these industries	Positive	0.090
	Added value of agriculture, forestry, animal husbandry, and fishery/sown area	Positive	0.103
	Value of intermediate consumption goods in agricultural production/sown area	Positive	0.133
	Operating income from agricultural product processing/sown area	Positive	0.237

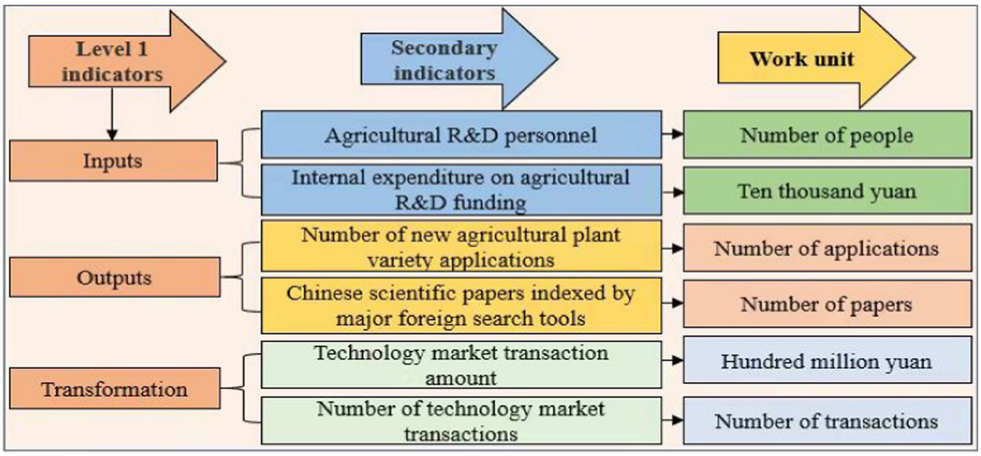

FIGURE 2
Evaluation indicator system for agricultural technological innovation.

gross regional product at the end of the year. (4) Ecological Environment (Envir): Measured by the ratio of the area affected by soil and water loss to the total area of the province or city. A detailed overview of the related variables and their descriptions is presented in Table 2.

4.3 Model setup

4.3.1 Baseline model

To scrutinize the direct impact of agricultural science and technology innovation on agricultural resilience, we construct the following two-way fixed effects model, see Equation 1:

$$\mathrm{Resi}_{it} = \alpha_0 + \alpha_1 \mathrm{Tech}_{it} + \alpha_2 X_{it} + \xi_i + \gamma_t + \varepsilon_{it} \quad (1)$$

In the presented model, where i represents provinces, t denotes time, Resi signifies agricultural resilience, Tech stands for agricultural technological innovation, X encompasses various control variables, ξ represents the province fixed effect, γ denotes the time fixed effect, and ε denotes the random error term.

4.3.2 Threshold effect model

The influence of fiscal policies supporting agriculture holds significant sway over agricultural resilience. As the intensity of policy support increases, the effect of agricultural science and technology innovation on agricultural resilience might display a nonlinear growth pattern. To capture this nonlinearity, we adopt a model inspired by Hansen (1999) nonlinear panel threshold model, and the results are presented in Equation 2:

TABLE 2 Definitions and descriptions of related variables.

Variable category	Variable symbol	Variable name	Explicit explanation
Dependent variable	Resi	Agricultural resilience	Calculated using the comprehensive evaluation indicator system (see Table 1) and entropy method
Independent variable	Tech	Agricultural technological innovation	Calculated using the comprehensive evaluation indicator system (see Table 2) and entropy method
Control variables	Market	Market size	Total retail sales of consumer goods/Gross regional product
	Labor	Human capital stock	Rural population (in tens of millions)
	Agdp	*Per capita* economic development level	Gross regional product/year-end permanent population
	Envir	Ecological environment	Area of soil and water loss/Provincial area
Threshold variables	Policy	Fiscal policies supporting agriculture	Expenditures on agriculture, forestry, and water affairs/Total fiscal expenditure

TABLE 3 Descriptive statistics of variables.

Variable name	Mean	Standard deviation	Minimum value	Maximum value	VIF
Dependent variable					
Resi	0.229	0.091	0.099	0.634	–
Independent variable					
Tech	0.086	0.124	0.000	0.934	3.83
Control variables					
Market	1.572	1.257	0.314	7.497	2.32
People	0.195	0.137	0.021	0.615	1.64
Agdp	0.398	0.235	0.078	1.387	3.40
Envir	1.125	1.320	0.000	6.942	1.46
Threshold variables					
Policy	0.112	0.034	0.029	0.204	3.83
Observations			465		

$$\begin{aligned}\text{Resi}_{it} &= C+\theta_1\text{Tech}_{it}\cdot I\left(\text{Policy}_{it}\le\sigma_1\right)+\theta_2\text{Tech}_{it}\cdot I\left(\sigma_1<\text{Policy}_{it}\le\sigma_2\right)\\ &\quad+\ldots+\theta_n\text{Tech}_{it}\cdot I\left(\text{Policy}_{it}>\sigma_n\right)+\beta X_{it}+\varepsilon_{it}\end{aligned} \tag{2}$$

Within this model, Policy_{it} functions as the threshold variable, delineated as the proportion of expenditures allocated to agriculture, forestry, and water affairs in total fiscal expenditures. The variable σ symbolizes a specific threshold value, with I(·) representing an indicator function. The parameters θ_1, θ_2, θ_n denote the threshold effects, estimating the impact coefficients of agricultural technological innovation on agricultural resilience when the threshold variable is below or above the threshold value σ. The coefficients β and C represent the estimated coefficients for control variables and the constant term, respectively.

4.4 Data sources and descriptive statistical analysis

This study utilizes national data from 31 provinces (autonomous regions and municipalities) spanning the years 2007 to 2021 as the research sample. Data sources encompass the "China Statistical Yearbook," "China Rural Statistical Yearbook," "China Science and Technology Statistical Yearbook," and the EPS database, among others. To address missing data, mean imputation and linear interpolation methods are employed. Additionally, to account for the impact of price inflation, relevant economic indicators are deflated using the Gross Regional Product (GRP) index, with the base year set as 2007. Drawing from the work of Hao and Tan (2023), the estimation formula for the original value of agricultural productive fixed assets after 2013 is as follows: the current year's original value of rural households' agricultural productive fixed assets = the previous year's original value of rural households' agricultural productive fixed assets × (current year's total power of agricultural machinery/previous year's total power of agricultural machinery). The descriptive statistical results for all variables are presented in Table 3. Notably, the Variance Inflation Factor (VIF) for each explanatory variable is below 5, satisfying the criterion for the absence of multicollinearity among the factors. Consequently, there is no issue of multicollinearity among the explanatory variables.

5 Results and discussion

5.1 Analysis of the spatiotemporal evolution trend of agricultural resilience

5.1.1 Temporal distribution and evolution trend of agricultural resilience

To analyze the spatiotemporal evolution of agricultural resilience, this study categorizes the data samples based on the

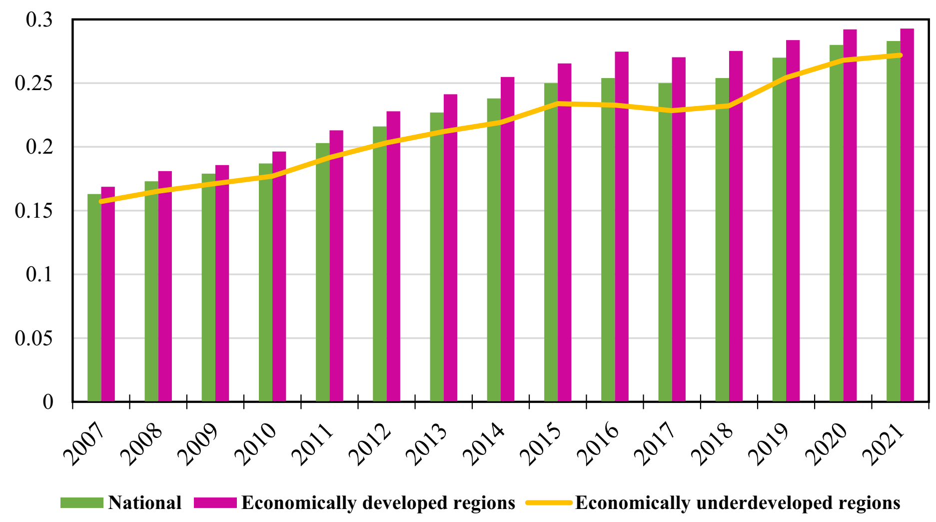

FIGURE 3
Trends in the temporal evolution of agricultural resilience by region, 2007–2021.

TABLE 4 Agricultural resilience standardization, 2007–2021 Parameters related to the standard deviation ellipse.

Year	Centroid coordinates	Centroid city	Centroid migration distance (km)	Major axis (km)	Minor axis (km)	Orientation angle (degrees)	Area (10,000 km^2)
2007	(111.479, 34.4022)	Luoyang, Henan province	–	3686.396	584.926	76.158	441.92
2012	(111.847, 34.3209)	Luoyang, Henan province	63.12	3679.463	618.699	71.375	446.08
2017	(112.024, 34.12)	Luoyang, Henan province	107.08	3657.961	636.294	66.900	451.00
2021	(112.402, 34.411)	Luoyang, Henan province	178.51	3693.207	668.038	54.536	448.44

economic development level of different regions. The division distinguishes between economically developed and underdeveloped areas using the median of the GDP averages from 2007 to 2021. Regions with a GDP average above the median are classified as economically developed areas, while those below are labeled as underdeveloped areas. Divided in this way, there is no evolution over time of economically developed and economically underdeveloped regions. In this paper, the temporal distribution and evolution trend of agricultural resilience are examined at three levels: nationwide, economically developed areas, and economically underdeveloped areas. Overall, the findings reveal a growth trend in agricultural resilience across China. Economically developed areas demonstrate a relatively stable growth trend, marked by a slowdown in the growth rate, potentially indicative of agriculture reaching a state of relative saturation. Conversely, agricultural resilience in economically underdeveloped areas exhibits fluctuations, likely influenced by traditional agricultural production methods in the early stages of development. This trend later accelerates, possibly attributed to the implementation of agricultural policies and the adoption of advanced technologies. These nuanced patterns shed light on the intricate dynamics of agricultural resilience at different economic development levels, emphasizing the multifaceted nature of factors influencing resilience trends in Figure 3.

5.2 Spatial distribution and evolution trend of agricultural resilience

To explore the spatial evolution trend of agricultural resilience in China from 2007 to 2021, this study employs the standard deviation ellipse and center of gravity migration analysis. Detailed parameters and migration trajectories are provided in Table 4 and Figure 4 (given space constraints, only data for the years 2007, 2012, 2017, and 2021 are included). Observations reveal the following trends: Firstly, the center of gravity of China's agricultural resilience demonstrates a tendency to shift towards the south-eastern part. Over the period from 2007 to 2021, the center of gravity of China's agricultural resilience was notably concentrated around Luoyang City, Henan Province. During this period, it began to evolve south-eastward, indicating a pronounced influence and pull of agricultural resilience by the south-eastern provinces. Secondly, the overall development of China's agricultural resilience remains relatively stable. From 2007 to 2021, the area covered by the 68% standard deviation ellipse expanded by approximately 6.52 thousand square kilometers, signifying robust agricultural resilience. Changes in key parameters such as azimuth angle, major axis, and minor axis indicate a shift in the orientation of agricultural resilience. While the range has expanded, the overall stability is evident, with a concentration in the northeast-southwest direction.

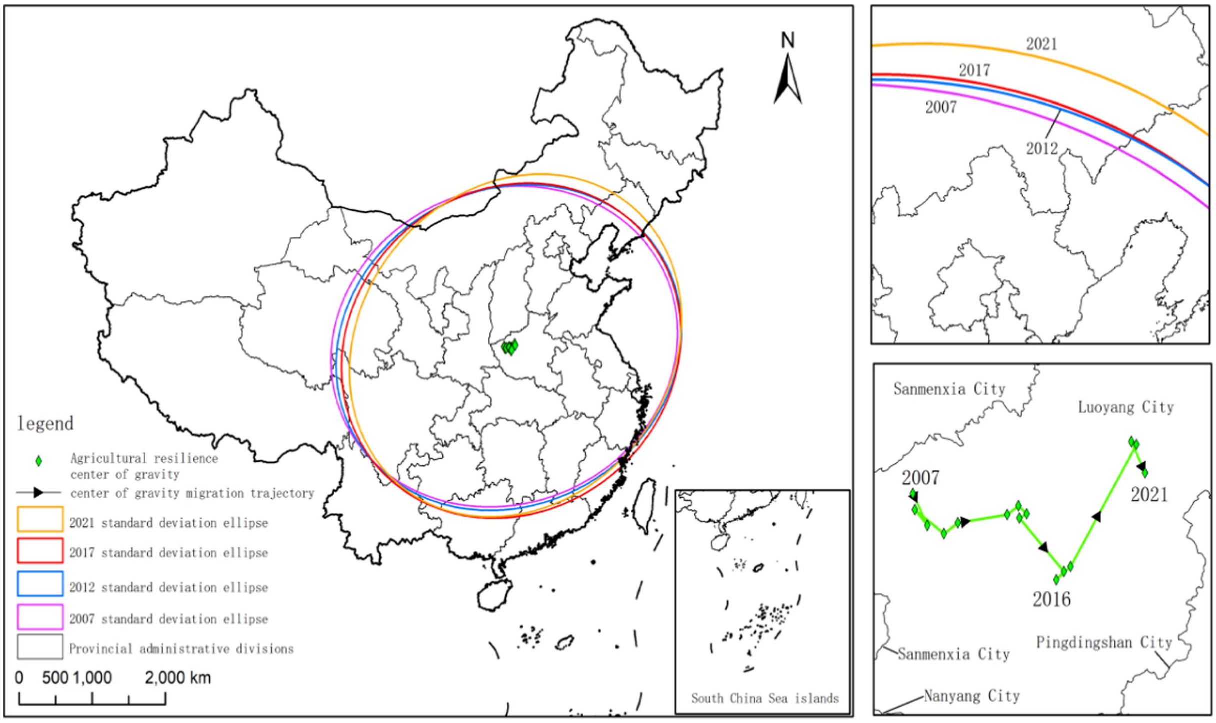

FIGURE 4
Standard deviation ellipse of agricultural resilience and the centroid migration trajectory.

TABLE 5 Results of the impact of agricultural STI on agricultural resilience.

Variables	Model 1	Model 2	Model 3
Tech	0.460*** (0.0508)	0.226** (0.0985)	0.168** (0.0804)
Market	—	—	0.0183*** (0.00442)
Labor	—	—	0.455*** (0.154)
Agdp	—	—	0.155*** (0.0526)
Envir	—	—	0.0140** (0.00581)
Constant term	0.189*** (0.0107)	0.156*** (0.00701)	−0.0235 (0.0416)
Province fixed effects	No	Yes	Yes
Year fixed effects	No	Yes	Yes
R^2	0.4603	0.711	0.795
Observations	465		

Robust standard errors in parentheses; ***, **, and * denote passing 1, 5, and 10% significance levels; if not otherwise noted, same below.

These findings underscore the dynamic and stable nature of agricultural resilience across China, offering valuable insights into the spatial patterns and evolution of this critical aspect of the agricultural landscape.

5.3 Baseline regression results

The baseline regression results, illustrating the impact of agricultural science and technology innovation on agricultural resilience, are presented in Table 5. Model 1 displays the regression outcomes without fixed effects for provinces and years. In Model 2, the core explanatory variable is included in a two-way fixed effects model, while Model 3 further introduces control variables into a two-way fixed effects model. Model 3, with an R2 of 0.795, exhibits the highest fit after incorporating control variables, indicating a substantial level of explanatory power. Across all models, agricultural science and technology innovation exhibit a significant positive correlation with agricultural resilience. Specifically, the significance is observed at the 1% level in Model 1, at the 5% level in Model 2, and remains significant at the 5% level in Model 3 after adding control variables. This consistent significance underscores the substantial promotional effect of agricultural science and technology innovation on agricultural resilience.

Upon analyzing the control variables in Model 3, Market Size (Market), Human Capital Stock (Labor), and *Per Capita* Economic Development Level (Agdp) show significance at the 1% confidence level, each with positive coefficients. This suggests that expanding market size can meet the needs of farmers and consumers, fostering positive interaction and enhancing agricultural resilience. Human capital stock proves to be a crucial foundation for rural agricultural transformation, as quality rural labor provides a source and momentum for agricultural resilience, with a significant impact on its stock. Higher *per capita* economic development levels contribute to increased investment in agricultural technology R&D, elevating the level of agricultural science and technology innovation and improving the capacity to resist external risks. The Ecological Environment (Envir) is significant at the 5% level with a positive coefficient, indicating that a favorable ecological environment promotes the enhancement of agricultural resilience to some extent.

5.4 Robustness tests

To ensure the reliability of the regression results, four robustness testing methods were employed: the instrumental variable method, lagging the core independent variable by one period, trimming 1%, and sub-sample regression. The results, presented in Table 6, are summarized as follows:

5.4.1 Instrumental variable method

To address potential endogeneity in the two-way fixed effects model, the instrumental variable method was utilized. The lagged one-period agricultural science and technology innovation variable served as the instrument, exhibiting a strong correlation and exogeneity to agricultural resilience. Rejection of the null hypothesis of "weak instruments" and "insufficient instrument variable identification" through the Kleibergen-Paap rk LM statistic and Kleibergen-Paap rk Wald F statistic validated the model's construction.

5.4.2 Lagged core independent variable

A one-period lag of the impact of agricultural science and technology innovation on agricultural resilience was considered. The results for the lagged core independent variable indicated significance at the 5% confidence level with a positive coefficient.

5.4.3 Trimming 1%

To mitigate the influence of outliers on regression results, a 1% data sample trim was applied. The results remained consistent with the above discussion.

5.4.4 Sub-sample regression

Considering economic shocks from the 2008 financial crisis and the 2020 pandemic, data for 2008 and 2020 were excluded, and regression analysis was rerun. Agricultural science and technology innovation continued to show significance at the 5% level. In summary, the robustness tests using the instrumental variable method, lagging the core independent variable, trimming, and sub-sample regression all support the strong robustness of the baseline regression results.

5.5 Threshold model regression results

To examine the nonlinear dynamic evolution of policy factors in the agricultural science and technology innovation's impact on agricultural resilience, this study employs the proportion of expenditures on agriculture, forestry, and water affairs in total fiscal expenditures as a threshold variable to gauge fiscal policies supporting agriculture. Drawing from Hansen (1999) methodology, a threshold effect test is conducted to explore the policy level at which agricultural science and technology

TABLE 6 Robustness test results.

Variable name	2SLS	Lagging the core independent variable by one period	Trimming 1%	Sub-sample regression
Tech	0.164*** (0.0416)	—	0.168** (0.0804)	0.170** (0.0823)
l. Tech	—	0.183** (0.0833)	—	—
Market	0.0185*** (0.00312)	0.0178*** (0.00491)	0.0183*** (0.00442)	0.0174*** (0.00433)
Labor	0.459*** (0.0747)	0.442*** (0.159)	0.455*** (0.154)	0.453*** (0.148)
Agdp	0.150*** (0.0222)	0.152*** (0.0462)	0.155*** (0.0526)	0.152*** (0.0551)
Envir	0.0137*** (0.00269)	0.0134** (0.00573)	0.0140** (0.00581)	0.0134** (0.00548)
Kleibergen-Paap rk LM statistic	30.021***	—	—	—
Kleibergen-Paap rk Wald F statistic	3165.201***	—	—	—
Critical value at 10% level of weak identification test	16.38	—	—	—
Province fixed effects	Yes	Yes	Yes	Yes
Year fixed effects	Yes	Yes	Yes	Yes
R^2	0.397	0.779	0.795	0.779
Sample size	434	434	465	403

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innovation transforms into a real productive force, exerting a promoting or inhibiting influence on agricultural resilience. The null hypothesis posits the existence of single, double, and triple thresholds. The test results, detailed in Table 7, reveal that both the single and double thresholds are significant at the 5% level, while the triple threshold does not pass the significance test. Consequently, the double threshold model is selected as the basis for estimating and analyzing the results.

The double threshold regression results and LR tests, outlined in Table 8 and Figure 5, categorize the sample into three intervals: (−∞, 0.0675], (0.0675, 0.1646], and (0.1646, +∞). In the first threshold interval, where the level of fiscal policies supporting agriculture resides, the estimated coefficient is negative and fails the significance test. This suggests that at this stage, possibly due to significant investments in agricultural public infrastructure, the application of agricultural technology in agricultural production encounters obstacles under limited fiscal support for agriculture funds, thereby impacting the improvement of agricultural resilience levels.

In the second threshold interval, when fiscal policies supporting agriculture are present, it is significant at the 1% level. This indicates that for each 1% increase in the intensity of fiscal policies supporting agriculture implementation, the impact of agricultural science and technology innovation on agricultural resilience increases by 0.158%. Upon reaching the third threshold interval, the role of fiscal policies supporting agriculture becomes increasingly evident, with the impact of agricultural science and technology innovation on agricultural resilience further increasing by 0.759 percentage points. In the second and third threshold intervals, fiscal policies supporting agriculture exhibit a significant positive effect in enhancing agricultural resilience through agricultural science and technology innovation, with the marginal effect continuously increasing.

Considering the lagging nature of fiscal policies supporting agriculture, the analysis also explores its impact with one and two periods lagged. As demonstrated in Table 9, under the conditions of one and two periods lagged, the estimated coefficient for the first threshold interval is positive but not significant, while for the second and third thresholds, it is significant at the 1% level with positive coefficients. Compared to current fiscal policies supporting agriculture, the effects of one and two periods lagged fiscal policies supporting agriculture are stronger. On one hand, due to the already improved agricultural public facilities, fiscal support for agriculture has shown a clear effect. On the other hand, to enable fiscal policies supporting agriculture to play a role in enhancing agricultural resilience through agricultural science and technology innovation, it is essential to increase the intensity of fiscal support for agriculture funds.

TABLE 7 Threshold effect test results.

Model	F-statistic	p-value	1% critical value	5% critical value	10% critical value
Single threshold	67.44	0.0360	105.2675	60.2678	45.3665
Double threshold	66.33	0.0220	85.7289	46.1321	34.4121
Triple threshold	18.41	0.6670	141.3979	89.7881	69.1613

p-values and critical values were obtained through 1,000 rounds of repeated sampling using the bootstrap method.

TABLE 8 Double threshold estimates and confidence intervals.

Threshold	Threshold estimate	95% confidence interval
First threshold	0.0675	[0.1583, 0.1679]
Second threshold	0.1646	[0.0626, 0.0693]

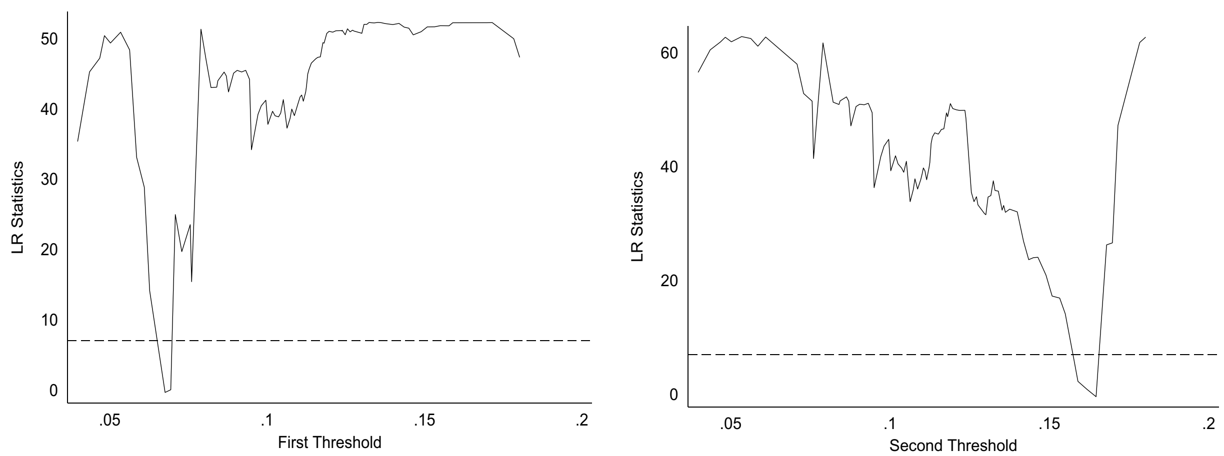

FIGURE 5
LR test graph.

TABLE 9 Parameter estimates for the double threshold effect model.

Variable name	Current fiscal support for agriculture intensity	Lagged by one period	Lagged by two periods
Market	0.014*** (0.004)	0.015*** (0.004)	0.0105*** (0.00359)
People	0.473*** (0.110)	0.486*** (0.129)	0.506*** (0.134)
Agdp	0.185*** (0.052)	0.164*** (0.043)	0.149*** (0.0389)
Envir	0.009** (0.003)	0.009** (0.004)	0.00659** (0.00314)
Policy ≤0.0675	−0.003 (0.099)	0.059 (0.078)	0.0442 (0.0735)
0.0675 < policy ≤0.1646	0.158*** (0.054)	0.167*** (0.054)	0.158*** (0.0506)
Policy >0.1646	0.759*** (0.175)	0.762*** (0.159)	0.709*** (0.158)
R^2	0.837	0.821	0.806
Sample size	465	434	403

TABLE 10 Results of heterogeneity analysis.

Variable	Major grain-producing areas	Non-major grain-producing areas	Economically developed areas	Economically underdeveloped areas
Tech	0.0251 (0.103)	0.217** (0.0790)	0.106 (0.160)	0.791** (0.359)
Control variables	Yes	Yes	Yes	Yes
Provincial fixed effects	Yes	Yes	Yes	Yes
Yearly fixed effects	Yes	Yes	Yes	Yes
R2	0.839	0.799	0.822	0.833
Sample size	195	270	240	225

5.6 Heterogeneity analysis

5.6.1 Heterogeneity analysis based on major grain-producing areas

Due to resource endowment differences, regions adjust their agricultural development strategies based on local conditions. This implies potential variations in the impact of agricultural science and technology innovation on agricultural resilience between major grain-producing and non-major producing areas. Consequently, this paper conducts a heterogeneity analysis for both major grain-producing and non-major grain-producing areas, with results summarized in Table 10. Notably, the estimated coefficients of agricultural science and technology innovation are positive in both cases, indicating a positive effect on enhancing agricultural resilience. In terms of significance level, the impact of agricultural science and technology innovation on agricultural resilience in non-major grain-producing areas is significant at the 5% level, surpassing that in major grain-producing areas. This distinction is attributed to the resource endowment advantages of major grain-producing areas, where agricultural resilience is more influenced by natural resources, potentially diminishing the promotional effect of agricultural science and technology innovation outcomes. Conversely, for non-major grain-producing areas lacking such resource advantages, resilience enhancement through agricultural technology becomes particularly crucial.

5.6.2 Heterogeneity analysis based on different levels of economic development

Given the importance of agriculture in the national economy, regions with lower economic development levels often rely heavily on the agricultural sector to bolster overall economic growth. Consequently, the impact of agricultural science and technology innovation on enhancing agricultural resilience may differ across regions with varying economic strengths. As per the division standards for economic strength regions, the heterogeneity analysis results, outlined in Table 10, reveal a stronger and more significant impact of agricultural science and technology innovation on enhancing agricultural resilience in economically underdeveloped areas. Conversely, while economically developed areas show a positive estimated coefficient, it is not significant. This phenomenon may arise from the larger proportion of primary industries in economically underdeveloped areas, which emphasizes the construction of agricultural production infrastructure. In these regions, the stock of agricultural technology innovation outcomes may be relatively insufficient. Therefore, agricultural science and technology innovation plays a particularly prominent role in enhancing agricultural resilience in economically underdeveloped areas, resulting in higher significance compared to economically developed areas.

6 Conclusions, policy recommendations and limitations and future directions

6.1 Conclusion

The study has provided valuable insights into the state of agricultural resilience in China. Firstly, the overall development of agricultural resilience has exhibited positive growth, with a widening scope, particularly driven by the south-eastern regions. Secondly, the positive impact of agricultural technological innovation on resilience is significant, highlighting the crucial role of advancements in agricultural technology in fortifying the agricultural sector. Thirdly, the threshold variable analysis, considering the proportion of expenditures on agriculture, forestry, and water affairs to total fiscal expenditures, indicates that optimal enhancement occurs when this proportion ranges between 6.75 and 16.46%, with the most robust impact observed beyond 16.46%. Temporal analysis suggests varying strengths concerning fiscal policies supporting agriculture at the current, lagged by one period, and lagged by two periods. Lastly, the heterogeneity analysis reveals that the promotion effect of agricultural technological innovation is more pronounced in non-major grain-producing areas and economically underdeveloped regions.

6.2 Policy recommendations

Drawing from the conclusions, several policy recommendations emerge. Firstly, there is a need to leverage the role of high-resilience areas, especially in the southeast. Despite recent stabilization, focusing on dynamic trends and utilizing agricultural technological innovation can further enhance resilience, with high-agricultural resilience areas demonstrating agricultural technologies to low-agricultural resilience areas through modern agricultural demonstration parks, science and technology service extension stations, etc., and facilitating technological spillovers to low-agricultural resilience areas. Secondly, to enhance agricultural technological innovation capabilities, efforts should be made to strengthen support in human, material, and financial aspects. This involves investing in research and development, improving conditions for result transformation, and creating an environment conducive to innovation. Thirdly, increasing support for fiscal policies is crucial. Low-intensity fiscal policies hinder the full potential of agricultural technological innovation, and an increase in the intensity of fiscal support is recommended. Considering lagged effects, optimizing the allocation of fiscal support for agriculture funds is necessary to enhance fund utilization efficiency. Lastly, recognizing regional differences is essential in tailoring agricultural technological innovation to local conditions. This involves focused efforts to enhance resilience through technological innovation, with specific strategies for non-major grain-producing areas and economically underdeveloped regions.

6.3 Limitations and future directions

While providing valuable insights, this study has certain limitations that should be acknowledged. Firstly, the research focuses on China, and the generalizability of findings to other contexts may be limited. Additionally, the study primarily relies on quantitative methods, and the inclusion of qualitative approaches could offer a more comprehensive understanding of the complexities involved. Future research should explore the nuanced dynamics of agricultural resilience using mixed-methods approaches. Furthermore, the study primarily examines the impact of fiscal policies supporting agriculture and technological innovation on resilience, leaving room for investigations into other potential influencing factors. Addressing these limitations can contribute to a more robust understanding of agricultural resilience dynamics globally and guide effective policy interventions.

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

WQ: Writing – review & editing, Writing – original draft, Methodology, Formal analysis, Data curation, Conceptualization. CR: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Methodology, Formal analysis, Conceptualization. LJ: Writing – review & editing, Visualization, Validation, Supervision, Resources, Project administration, Investigation, Funding acquisition, Conceptualization. NK: Writing – review & editing, Validation, Investigation.

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Conflict of interest

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

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