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The impact of land transfer on food security: the mediating role of environmental regulation and green technology innovation

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Introduction: Food security is the lifeblood of national security and an important cornerstone for world 15 peace, stability, and development. In this context, the study of the impact of land transfer (TF) on food security (FS) provides a new perspective for land resource optimization.

Methods: Based on the empirical data of 30 provinces and regions in China from 2010 to 2022, this paper used the two-way fixed effect model to explore the causal relationship and the intermediary relationship between the two. Moreover, quantile regression is used to further explore the heterogeneity. In addition, the spatial Durbin model is used to analyze the spillover effect.

Results: First, land transfer has a significant promoting effect on food security. Secondly, land transfer has obvious heterogeneity to food security. Third, environmental regulation and green technology innovation play an intermediary role in land transfer to food security. Fourth, land transfer has a spatial spillover effect on food security.

Discussion: This paper not only enriches the theoretical research on the impact of land transfer on food security, but also provides empirical evidence. It provides an important reference for deepening China's land transfer policy system, optimizing land transfer resources and ensuring the safety of grain industry.

KEYWORDS

land transfer, food security, environmental regulation, green technology innovation, land resource optimization

1 Introduction

Food security, as a crucial aspect of daily life, is central to economic and social stability as well as sustainable development. As a typical agricultural country, China has played a prominent role in ensuring the supply of agricultural products and providing food and nutrition (Li et al., 2025). By 2023, China's grain output has remained above 1.3 trillion kilograms for nine consecutive years, and its *per capita* grain consumption has reached 493 kg, far higher than the internationally recognized food security line, providing important support for preventing hunger and stabilizing social development (Liu et al., 2025). However, it is undeniable that China is still a country that relies on food imports, which undoubtedly brings major hidden dangers to China's food security in the context of unstable international trade (Subramaniam et al., 2024). As an important factor of production in the grain industry, land is not only an important resource to ensure social stability but also the core of food security. By the end of 2023, the transfer rate of contracted rural land management rights in China will be 36.73 percent, and the transfer area of farmland contracted by households will increase from 270 million mu to 565 million mu, accounting for 40 percent of the country's total farmland contracted by households from 22 percent. It is worth noting that although the scale of agricultural land transfer continues to expand, there are still problems such as cultivated land wastage, extensive use of cultivated land, reverse transfer, and low efficiency of agricultural land transfer (Pei et al., 2019). Although China's policy system of strengthening agriculture, benefiting farmers, and enriching farmers have been continuously improved, under the background of China's extensive agricultural economic model, the tight pattern of food supply and demand in China has not changed fundamentally (Li et al., 2023; Wei et al., 2024a). Therefore, studying the impact of land transfer on food security has important theoretical and practical value for formulating scientific land policy, optimizing land resource allocation, and promoting agricultural modernization.

At present, the research on land transfer mainly focuses on three aspects. First, from the perspective of farmers' income, promote rural labor transfer by exploring land transfer (Huo and Chen, 2021; Tian et al., 2021), Improving the education level of the rural labor force (Liu et al., 2023; Zhang, 2024), Improving land value (Wang et al., 2018), Promoting the transformation of Rural development (Qi and Yang, 2022; Li et al., 2023) and other ways to achieve farmers' income growth, and how to achieve agricultural modernization through these ways. Second, from the perspective of agricultural production efficiency, this paper analyzes how land transfer can be passed through the land policy system (Guo and Liu, 2021; Lv, 2023), Allocation of Agricultural Resources (Fei et al., 2021; Li et al., 2022), land asset structure (Kaletnik et al., 2020; Wang et al., 2020) and other methods to promote the comprehensive development of agriculture. Third, from the perspective of ecological environment impact, the green emission reduction through land transfer is analyzed (Song et al., 2021; Zhong et al., 2022), Green Technology Innovation and Progress (Lu et al., 2020; Lyu et al., 2022) Environmental Regulations (Li et al., 2022; Xu et al., 2022) and other methods to improve agricultural ecological efficiency, and how to achieve green and sustainable agricultural development by protecting the ecological environment.

Additionally, research on food security also emphasizes three key aspects: First, from the perspective of policy implementation, through environmental policy (Lang and Barling, 2012; Huang et al., 2024) Political Will (Prosekov and Ivanova, 2018), Land Policy (Cui and Shoemaker, 2018; Wu and Zhang, 2024) and other policy tools to ensure food security. Second, from the perspective of security risks, through the analysis of food quality risks (Umarjonovna and Gulomjonovna, 2022), food environmental risks (Gregory et al., 2005), food health risks (Havas and Salman, 2011) and other typical international food security risks, and respond to alleviate food security problems from the risk level. From the perspective of agricultural development, research on improving the level of food technology (Li et al., 2021; Zou and Mishra, 2024), food production and supply level (Barrett, 2010), economic development level (Lv, 2023), and other methods protect food security from achieving high-quality agricultural development.

While existing studies offer valuable insights into the relationship between land transfer and food security, few have directly investigated the direct impact of LT on FS. The effectiveness of land transfer is subject to external factors such as agricultural resource endowment conditions and grain production technology, so it is necessary to adopt local measures to improve land use efficiency. At the same time, from the perspective of top-level policy design and practical effects, grain production benefits and economic benefits are equally important, which serves as a crucial foundation for assessing the effectiveness of land transfer policies. However, most existing research is limited to theoretical research, not from the perspective of experience to explore, lacks broad representation, and the comprehensive evaluation effect is limited. Therefore, assessing the impact of LT on FS also requires careful consideration of a more scientific and broader perspective.

Due to the obvious differences in geographical conditions, resource endowment, ecological environment, and other aspects of different countries and regions, there are also differences in how to solve food security problems, especially in food production goals, food production capacity, and the adoption of new agricultural technologies (Gartaula et al., 2024). In this context, even with the implementation of the land transfer policy, regional topography can lead to variations in grain production efficiency and the sustainable development of the grain industry, landform, technology, ecology, and other problems, and thus the alleviation of food security problems will also show different levels. When the ecological environment and technological innovation in the region are consistent with the structure of grain production factors, the improvement of environmental benefits and the improvement of green technological innovation level will help grain enterprises make better use of the endowment advantages of the region and improve the production efficiency of grain enterprises. Redundancy of factor inputs can also be avoided (Robertson and Swinton, 2005). In addition, the implementation of environmental monitoring policies will make it easier to ensure land quality, help promote the implementation of land transfer policies, and further ensure that food production is not threatened by the environment. The introduction of advanced agricultural green technology not only improves the efficiency of land use, and reduces the cost of grain production, but also further improves the efficiency of grain output. In summary, environmental regulation and green technology innovation play a mediating role in the impact of LT on FS. Therefore, integrating environmental and technical factors into the food security research framework and exploring the mediating effects of different factors in land transfer policies is crucial for effectively ensuring food security.

As the most populous country in the world, China has a huge demand for food and plays a key role in ensuring food security in the international community. However, with resource constraints and changes in grain consumption structure, grain demand is still facing a situation of unbalanced supply. At the same time, China's agricultural resources are unevenly distributed, especially in backward areas, where there are problems such as poor land and limited ecological conditions, leading to huge challenges in grain production. For most developing countries, agricultural production relies heavily on the production level of the rural labor force. However, with the continuous advancement of urbanization, rural labor forces continue to transfer to cities and towns, resulting in an increasingly high degree of arable land wastage, which in turn leads to a decrease in food output (Benton and Bailey, 2019). As the traditional agricultural development model becomes unsustainable, land transfer has become essential for enhancing the efficiency of rural labor and land in the process of agricultural modernization. In this context, although China implemented the land transfer policy relatively late, it has achieved significant improvement in land use, quality, transfer, and management, and its development momentum is obvious. In addition, by learning from the land and grain enterprises of developed countries, China constantly attaches importance to agricultural technology innovation, agricultural policy support, and agricultural professional personnel training, which not only effectively alleviates the domestic food security problem, but also provides reference experience for the development of the global food industry. Thus, using China as a case study, examining the impact of LT on FS can offer a scientific foundation for the high-quality, modern, and sustainable development of China's grain industry, while also providing valuable insights for other developing countries.

In summary, the marginal contribution of this paper to the existing literature is as follows: First, explore the impact of LT development on FS, and provide new empirical evidence for verifying the optimization of land resources from the perspective of food security. Second, considering the differences between different geographical and quantile, the heterogeneity analysis of LT on FS is deepened. Thirdly, by introducing environmental regulation and green technology innovation as intermediary variables, this paper systematically analyzes how LT acts on FS through these mechanisms, thereby enriching theoretical models and application practices in the field of land and food. By deepening the knowledge of the application of land circulation in the field of food, this paper provides ideas for optimizing the allocation of land resources, solving the problem of food security, and realizing the sustainable and modern development of agriculture.

2 Theoretical mechanism

2.1 Policy background

Promoting land transfer is an important measure for the government to vigorously develop agriculture, aiming at improving land use efficiency, improving agricultural productivity, ensuring food security, and promoting sustainable agricultural development. As previously stated, many developed countries have realized that to improve agricultural productivity and sustainable development, land transfer is indispensable. In China, agriculture and the food industry play a fundamental role in the national development process. However, for a long time, the traditional farming methods of crops in China have been inefficient, and the grain infrastructure has been relatively backward, leading to major challenges in grain production. Therefore, promoting land transfer and ensuring food security is not only of great significance but also has a distinct policy development trajectory.

For land transfer, in 1978, China introduced the household contract responsibility system, which created the foundation for land transfer. This reform separated land ownership from contracted management rights and laid the foundation for the reform of rural land management forms (Lin, 1991). In 1988, restrictions on the transfer of contracted rural land management rights were relaxed, providing a solid policy foundation for land transfer. In 2010, land transfer began to enter the stage of deepening development, further consolidating the basic rural management system, providing specific operations for rural land transfer, and greatly enhancing the rationality and standardization of the transfer market. In 2019, it was emphasized to strengthen the management and service of land management rights transfer, promote the optimal allocation of land resources, and provide a solid guarantee for agricultural efficiency, farmers' income increase, and rural revitalization. In addition, the fundamental principle that the land transfer system will be protected by law has been clarified, and relevant rules have been improved to promote the efficient and reasonable allocation of land resources (Zhou et al., 2020). By 2024, the land transfer policy further emphasizes the need to strengthen and improve the formation mechanism of land transfer prices, explore effective strategies, and prevent unreasonable increases in transfer costs.

In terms of food security, in 1974, the Food and Agriculture Organization of the United Nations defined the goal of food security as "everyone can get enough food for survival and health at any time", and obtaining enough food to meet the needs of food security is the only consideration (Chen and Kates, 1994). In 1983, the price factor was introduced, and food security was not only about food but also about affordability. In 1996, the goal of food security was further expanded, and the food obtained should meet the requirements of food hygiene, health standards, and nutritional balance (Maxwell, 1996). In 2001, the International Food and Agriculture Organization (FAO) revised its definition of food security. With the worsening of the ecological environment, the risks to future food security have significantly increased. Therefore, the International Food and Agriculture Organization (FAO) proposed that food security means that "all people in need of food have access to sufficient, safe and nutritious food at the physical, economic and social levels at any time." To further meet people's needs for a healthy diet and people's different food preferences (Lang and Barling, 2012; Liu et al., 2025). By 2024, FAO believes that ensuring food security requires eliminating hunger and malnutrition and providing adequate funding for food security and nutrition.

2.2 Influence mechanism of land transfer on food security

From a dynamic perspective, any policy and regulation introduced by the government aims to ensure the stable operation of society and meet the needs of the people. As a key policy, land transfer not only supports large-scale farming but also plays a vital role in ensuring the safety and growth of the food industry. From a practical perspective, it is the most fundamental logic in economics to expand the economic scale to maximize food income. As the key to achieving agricultural economic scale, land transfer policy provides the possibility to promote LT to ensure FS (Liu et al., 2018). First of all, land transfer has a factor allocation effect. Land and transfer facilitate the redistribution of agricultural land to those with higher production capacities, concentrating land in the hands of those capable of achieving greater grain output, this helps align land with production capacity, optimize the allocation of land resources, and ultimately enhance land use efficiency and grain production. Secondly, land transfer has the effect of scale management. The land transfer makes agricultural land concentrate from the hands of small farmers with dispersed management to large-scale and specialized growers and agricultural enterprises, which is conducive to the realization of moderate-scale management of agriculture, which can not only reduce agricultural production costs and obtain economies of scale. Finally, land transfer has an output effect. By promoting the optimal allocation of factors and the appropriate scale operation of the grain industry, land transfer can not only improve the efficiency of grain production but also protect the interests of farmers and increase the total agricultural output, thereby ensuring the sustainable development of agriculture. Therefore, this paper proposes the first hypothesis:

Hypothesis 1: LT has a promoting effect on FS.

2.3 Impact mechanism of land transfer on food security

At present, food security is facing severe challenges. For a long time, the development of China's grain industry has been subject to the influence of the agricultural ecological environment, and the development of grain enterprises relies more on agricultural policy support and lacks innovation awareness. As an important part of ensuring stable output of the grain industry, land transfer needs to strengthen government environmental control and agricultural green technology innovation in order to give full play to the promoting role of LT on FS (Wani et al., 2023). The land transfer policy itself has environmental benefits. On the one hand, with the expansion of the land management scale, environmental regulation and control will ensure food security from the root of food production. Moderate environmental regulation can not only directly reduce agricultural non-point source pollution emissions, but also guide and encourage more grain enterprises to switch from diversified planting to more efficient specialized planting, thus ensuring food quality and health issues. On the other hand, expanding the scale of land management can also lower the per-unit cost of agricultural green technology, thereby encouraging farmers to adopt more sustainable agricultural practices. It helps break the fragmentation and decentralization of small farmers' land management. Further enhancing the efficiency of sustainable grain production. In addition, the expansion of the land management scale, is conducive to the implementation of environmental regulations and the improvement of the level of green technology innovation, reducing the green production cost of grain enterprises, thereby improving the grain output capacity and output efficiency, and achieving the green and sustainable development of the grain industry. Therefore, this paper proposes the second hypothesis:

Hypothesis 2: Environmental regulation and green technology innovation play a mediating role in the influence of LT on FS.

2.4 Regional heterogeneity of land transfer on food security

Due to regional variations in economic development, resource distribution, and the ecological environment, the importance of land transfer and food security differs across China. Therefore, the actual effect of LT on FS will be different in different regions and at different levels (Gartaula et al., 2024). First of all, in areas with developed economic conditions, government departments pay more attention to land transfer policies and food security issues, the implementation cost of land transfer policies is relatively low, and the implementation obstacles are relatively few, which can better improve the productivity of grain enterprises and help alleviate inter-regional food security problems. Secondly, in economically backward areas, due to external factors such as relatively backward agricultural technology and a relatively poor ecological environment, it is difficult to implement land transfer policies in backward areas, and the food security problem cannot be alleviated. However, in the long run, the economically backward areas may have a "learning effect", learn from the experiences of economically developed regions and their land transfer policies, and then apply these lessons to address food security challenges. Finally, in areas with a higher degree of implementation of the land transfer policy, the land use efficiency is higher, which can give full play to the advantages of different land cultivation, effectively reduce the cost of grain cultivation, promote the improvement of grain production capacity, and effectively alleviate the problem of food supply. Based on these considerations, the paper proposes a third hypothesis.

Hypothesis 3: The effect of LT on FS has regional heterogeneity.

2.5 Spatial spillover effect of land transfer on food security

In the grain industry, in addition to the government as a promoter of the grain market, the transfer of agricultural land is also a very important market participant. As the basic link of grain production and management activities, local grain enterprises are likely to mimic the land transfer practices of neighboring areas to maximize their benefits, leading to an "imitation effect." (Zhang et al., 2024a). On one hand, in the grain and land transfer market, neighboring enterprises observe and replicate each other's practices. Which not only ensures that technical exchanges are not affected by administrative boundaries, this also fosters the growth and expansion of both the land transfer and grain markets. On the other hand, the institutional guarantees and financial subsidies provided by government departments in the region will provide strong help to land transfer and grain market. Local governments will learn from their previous experience in implementing agricultural land transfer policies, and based on the learning effect between neighboring governments, learn and follow the behaviors of neighboring local governments in agricultural land transfer policies and food security policies. In addition, the spillover effect is one of the important characteristics of technological innovation (Jaffe, 1986). The research development and application of new agricultural technology in a region can have a demonstration effect on the land and grain market in neighboring areas, which helps the phenomenon of "free riding" in neighboring areas and enables grain enterprises to better enjoy the dividends brought by the spillover of technological innovation. To better alleviate the problem of food security. Therefore, this paper proposes a fourth hypothesis.

Hypothesis 4: The spatial spillover effect of local LT on FS in adjacent areas.

3 Methods

3.1 Model setting

3.1.1 Benchmark model

Based on the above analysis, the bidirectional fixed effect model will be used in this study to verify the impact of land transfer on food security. The bidirectional fixed-effect model can accurately evaluate panel data, limit the source of bias to variables that change over time, and estimate the coefficient of the regression variable more accurately. The specific formula is as follows:

$$FS_{i,t} = \alpha + \beta_1 LT_{i,t} + \beta_2 X_{i,t} + \mu_i + \lambda_t + \varepsilon_{i,t} \quad (1)$$

In model (1), FS is the explained variable, representing food security, and LT is the core explanatory variable, representing land transfer; X is the set of control variables, i and t respectively represent the i province, the t period, μ_i represents the fixed effect of the region, λ_t represents the fixed effect of the year, and $\varepsilon_{i,t}$ represents the random disturbance term.

3.1.2 Mechanism model

In addition, investigate the possible mediating effect of land transfer on food security, we further added environmental regulation and green technology innovation into the benchmark model (1), and obtained model (2):

$$FS_{i,t} = \alpha + \beta_1 LT_{i,t} + \beta_2 Z_{i,t} + \beta_3 X_{i,t} + \mu_i + \lambda_t + \varepsilon_{i,t} \quad (2)$$

In model (2), $Z_{i,t}$ representative intermediate variable, environmental regulation and green technology innovation are the intermediate variables of this paper, and other symbols have the same meanings as in model (1).

3.1.3 Spatial model

To further examine the spatial spillover effect of land transfer on food security, model (1) is extended to spatial panel Durbin model (SDM):

$$FS_{i,t} = \alpha + \rho W FS_{i,t} + \beta_1 LT_{i,t} + \beta_2 X_{i,t} + \mu_i + \lambda_t + \varepsilon_{i,t} \quad (3)$$

In model (3), ρ is the spatial autoregressive coefficient and W is the spatial weight matrix. The other symbols have the same meaning as model (1).

3.2 Variable selection

3.2.1 Explained variables

Food Security (FS). Food security is a key indicator of agriculture's sustainable development capacity, the goal is to safeguard the entire food chain from external threats at a lower cost during agricultural production. Specifically, FS is measured as follows.

(1) Index system. Referring to previous studies (Wang et al., 2024; Wei et al., 2024b), constructed an indicator system including "food supply security, food production security, food access security, and food sustainable security". These indicators form a comprehensive system for measuring food security. Unlike most studies, this research considers the entire food industry chain as a key measure of food security, and evaluates the possible threats to the safety of the food industry before, during, and after production, which not only helps to improve the environment of the food industry but also realizes the sustainable development of the food industry and promotes the sustainable development of agriculture. The specific measurement indicators of FS are shown in Table 1.

(2) Measurement model: The entropy method, known for its efficiency and accuracy, is widely used in academic research due to its scientific and practical advantages. This study also employs this method to measure FS.

Figure 1 illustrates the changes in food security levels in China from 2010 to 2022. As shown, there are significant differences in FS between different regions. Specifically, the FS level in the eastern and central regions is at the leading level compared with the western region, which may be due to the better grain production conditions, storage conditions, and technical conditions in the eastern and central regions, which also indicates that the western region still has greater room for progress in ensuring FS. On the whole, the development of food security in China shows positive progress, but there is still a need to further optimize agricultural resource allocation, improve resource utilization efficiency, and achieve sustainable food industry development to ensure long-term FS.

3.2.2 Explanatory variables

Land transfer (LT), refers to the process of transferring, leasing, or jointly managing rural household-contracted farmland for a specified period, aiming at improving the efficiency of land use, optimizing the allocation of agricultural resources, and ensuring the security of agricultural development. Refer to previous studies (Yang et al., 2021; Zhang et al., 2024b) determined the specific measurement index of land transfer as the ratio of the area of cultivated land under household contract to the total area of cultivated land under household contract. By calculating this ratio, the relationship between the area transferred and the total area of cultivated land under household contracts can be understood. A higher ratio indicates a greater degree of land transfer, while a lower ratio indicates a smaller degree of land transfer. This index not only reflects land use efficiency, farmers' operational scale, and land resource allocation but also provides a scientific basis for formulating and implementing rural land transfer policies. The LT results, shown in Figure 2, indicate a fluctuating yet upward trend from 2010 to 2022, highlighting China's increasing focus and efforts on LT.

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TABLE 1 System of indicators of the level of food security.

Target level	Primary indicators	Secondary indicators	Tertiary indicators (units)	Weights	Quality
FS	Food supply security	Volatility of total food production	(Total food production in the current year - average of total food production in the last 5 years)/total food production in the current year (%)	0.012	-
		LT mobility	Cultivated LT *per capita* (mu/person)	0.047	+
		Grain reserves	Total grain production (tons)	0.054	+
		Resilience of crops to disasters	Area affected by crops/area sown with crops (%)	0.004	-
		Food supply stability	Grain purchases (tons)	0.102	+
		Food Circulation	Grain sales (tons)	0.064	+
	Food production security	Stability of food production	Grain sown area (millions of hectares)	0.050	+
		Agricultural financial support level	Grain sown area/Total sown area (%)	0.016	+
		Agricultural innovativeness	Total power of cropLT machinery (10,000 kW)	0.050	+
		Level of human capital	Qualified food workers (persons)	0.079	+
		Agricultural productivity	Gross agricultural output/primary sector employment (yuan/person)	0.296	+
		Infrastructure development	Number of agricultural water conservancy facilities constructed (units)	0.076	+
	Food access security	Rural Engel coefficient	Rural food consumption expenditure/total consumption expenditure (%)	0.005	-
		Food price volatility	(Current year food price index - previous year food price index)/Current year food price index (%)	0.004	-
		Food share	Total food production/resident population (tons/person)	0.044	+
		Road density	Length of transport routes (rail, road, waterway)/Urban area (km/sq km)	0.053	+
	Sustainable food security	Pesticide application rate	Pesticide application per unit of food sown area/Crop sown area (%)	0.004	-
		Fertilizer application rate	Fertilizer application per unit of food sown area Crop sown area (%)	0.008	-
		Agricultural film use	Agricultural film use per unit of food sown area/Crop sown area (%)	0.004	-
		Quality assurance	Effective irrigated area/crop sown area (%)	0.030	+

All indicators are calculated by the authors themselves.

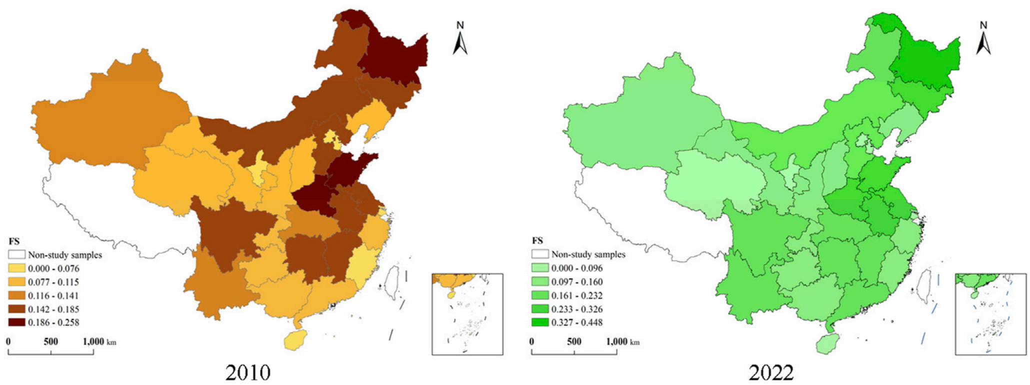

FIGURE 1
FS level.

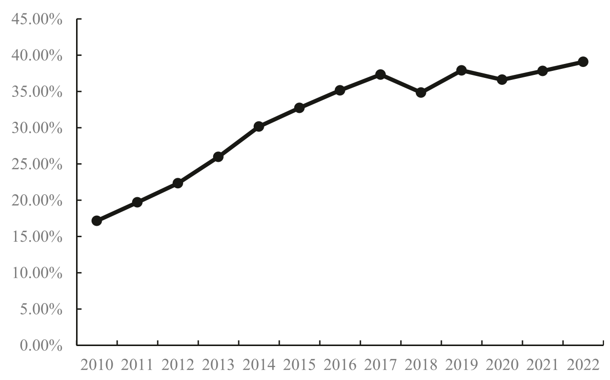

FIGURE 2
Land transfer level from 2010 to 2022.

3.2.3 Control variables

Considering that there are many factors affecting the level of food security, this paper refers to the published literature (Zhou et al., 2022; Wang et al., 2023). The following control variables are set in this paper, as shown in Table 2.

3.2.4 Mechanism variables

Environmental regulation. With the increasing emphasis on the environment in China, environmental regulation is an important means to affect land transfer and food security. Refer to the published literature (Zou and Wang, 2024; Zhou et al., 2021). First, this paper will choose the logarithmic form of the completed investment in industrial pollution control to measure environmental regulation (IPI). Secondly, the ratio of gross regional product to total energy consumption is used to measure environmental regulation (EG). Overall, industrial pollution control and energy consumption are important factors in China's environmental governance. Higher investment in pollution control and a greater share of green energy consumption reflects the effectiveness of government environmental regulations. Therefore, a higher ratio indicates a stronger environmental regulatory capacity.

Green technology innovation. Referring to previous studies (Xu and Lin, 2024; Yu et al., 2024) Two different ways are adopted to measure green technology innovation. First, the logarithmic form of the ratio of regional technology market turnover to GDP is selected as green technology innovation capability (TMT). Secondly, the ratio of R&D expenditure of regional industrial enterprises to GDP is used to measure green technology innovation capability (R&DE). Overall, regional technology turnover and industrial enterprise R&D funds are important inputs to promote green technology innovation. Technological innovation will reduce industrial production costs, and the reduction of production costs is the best reflection of green technology innovation. Therefore, the greater the ratio, the stronger the ability of green technology innovation in the industry.

3.3 Data sources

This paper is based on the reality of land transfer and food security in China, but there is a certain lack of statistical data in Xizang, Hong Kong, Macao, and Taiwan in China, to take into account the availability and operationalization of LT and FS data, and to obtain as much as possible a more complete data resource as well as to reflect the latest situation of LT and FS in China, this paper sets the time interval of the sample data as 2010–2022, and The sample cities are selected from 30 provinces in China. The sources of data are the China Land Statistics Yearbook, China Grain and Material Reserve Yearbook, China Statistical Yearbook, China Rural Statistics Yearbook, and provincial development work reports. In addition, for individual missing data problems, this paper will use linear interpolation to fill in the part. The results of the expressive statistical analysis are shown in Table 3.

4 Results

4.1 Baseline regression results

Before the baseline regression, the differential inflation factor was evaluated first. The results indicated that the average variance inflation factor (VIF) of the regression equation was 2.94, significantly lower than the critical value of 10, indicating that there was no obvious multicollinearity problem between the independent variables. This paper first investigated the regression results without introducing control variables, as shown in column (1) of Table 4. It was found that without adding control variables, the regression coefficient of land transfer (LT) was significantly positive, and LT had a positive impact on the improvement of the FS level. To

TABLE 2 Control variables.

Variable	Code	Definition	Unit
Industrial structure	IS	The proportion of the added value of the primary industry in the GDP of each province	%
Degree of agricultural mechanization	DAM	Logarithmic form of the total power of agricultural machinery in each province	Megawatt
Foreign direct investment	FDI	Logarithmic form of actual utilization of foreign direct investment by each province as a share of each province's GDP	%
Human capital	HC	Average years of schooling = (illiterate ×1+ number of primary school education ×6+ number of junior high school education ×9+ number of senior high school and secondary school education ×12+ number of college and bachelor's degree or above ×16)/total population over 6 years old	%
Urbanization rate	URBAN	The proportion of the urban population to the permanent population in each province	%

TABLE 3 Descriptive statistics of variables.

Variable	N	Average	SD	Min	Max
Food security	390	0.155	0.077	0.039	0.464
Land transfer	390	0.313	0.171	0.001	0.958
Industrial structure	390	0.098	0.053	0.002	0.258
Degree of agricultural mechanization	390	3417.614	2924.189	93.970	13,353.020
Foreign direct investment	390	11.935	59.559	0.770	833.705
Human capital	390	9.341	0.891	7.607	12.698
Urbanization rate	390	0.585	0.132	0.226	0.895
Industrial pollution investment	390	199,739.500	200,984.700	476	1416464
Proportion of energy consumption	390	0.105	0.071	0.030	0.409
Technology market turnover	390	0.017	0.028	0.001	0.192
R&D expenditure	390	0.110	0.060	0.017	0.324

TABLE 4 Baseline regression results.

Variable	(1)	(2)	(3)	(4)	(5)	(6)
LT	0.058*** (2.890)	0.060*** (3.080)	0.065*** (3.420)	0.062*** (3.270)	0.064*** (3.370)	0.053*** (2.680)
IS		0.497*** (4.500)	0.513*** (4.770)	0.509*** (4.75)	0.506*** (4.730)	0.476*** (4.400)
DAM			0.032*** (4.503)	0.033*** (4.710)	0.034*** (4.850)	0.038*** (5.150)
FDI				−0.005* (−1.700)	−0.005* (−1.780)	−0.005* (−1.81)
HC					0.106 (1.580)	0.110 (1.640)
URBAN						−0.114* (−1.730)
Year	Control	Control	Control	Control	Control	Control
Region	Control	Control	Control	Control	Control	Control
R^2	0.409	0.442	0.473	0.478	0.482	0.486
N	390	390	390	390	390	390

Note: The t statistic is in parentheses; *, **, *** are significant at the level of 10%, 5%, and 1% respectively, the following tables are the same.

further improve the accuracy and reliability of the study. In this paper, Model 1 is used to add different control variables to paragraphs (2) to (6) in order to carry out regression again, to more accurately capture the indirect impact of these potential influencing factors on the regression results. The results show that the coefficient of LT remains positive and significant at the 1% level, confirming that increased land transfer plays a crucial role in enhancing FS. It is important to note that the size of the LT coefficient remains largely unchanged with the inclusion of control variables, suggesting that the findings of this study are relatively robust, and further prove hypothesis H1.

4.2 Endogeneity test and robustness test

As demonstrated above, LT significantly promotes FS. To further validate the robustness of the baseline regression results, this paper will employ the following verification methods. In addition, in order to avoid endogeneity problems that may occur in regression, this paper will first conduct an endogeneity test and then conduct a robustness test. The specific methods are as follows:

First, is the instrumental variable method. Considering that the traditional bidirectional fixed effect evaluation model may have estimation bias and endogeneity problems, this paper chooses the stage lag of land transfer as the instrumental variable (Söderström and Stoica, 2002). The specific test results are shown in column (1) of Table 5. The value of the LM statistic is 298.823, which is far greater than the critical value of 10% significance level, indicating that there is no obvious problem of weak instrumental variables in the benchmark regression in this paper. In addition, the value of Wald F statistic is 1724.260, which is significant at a 1% level, rejecting the null hypothesis that the selected instrumental variables are not identifiable, which proves that the selection of instrumental variables is scientific and reasonable, and also proves that the baseline regression in this paper is robust.

Second, replace the model. Tobit regression model was adopted as an alternative model (Amemiya, 1984), and the results of Tobit regression were shown in column (2) of Table 5. The influence

TABLE 5 Robust regression of FS by LT.

Variable	(1)	(2)	(3)	(4)
LT	0.211*** (10.980)	0.083*** (4.440)	0.040* (1.940)	0.037* (1.870)
Control variable	Control	Control	Control	Control
Year	Control	Control	Control	Control
Region	Control	Control	Control	Control
LM statistic	298.823			
Wald F statistic	1724.260***			
N	360	390	360	390

coefficient of LT on FS remains significantly positive at the 1% level, further confirming the robustness of the baseline regression results in this paper.

Third, the control variable lags by one stage. According to Miao et al. (2024) research method, the robustness test selects the one-stage hysteretic method of control variables, this not only helps mitigate the endogeneity issue in estimating the benchmark model but also provides a scientific measure of its robustness The test results are shown in column (3) of Table 5. Although the significance level of the LT coefficient has slightly decreased, it remains significant, confirming the robustness of the baseline regression results in this paper.

Fourth, add a control variable. Economic development is an important factor affecting the level of local food security, which can not only provide the necessary capital input for agricultural production but also improve comprehensive agricultural efficiency (Bedasa and Deksisa, 2024). Therefore, this paper selects the logization of the GDP of each province as a measurement index to measure economic development and adds it to the benchmark regression model. The evaluation results in column (4) of Table 5 show that LT continues to have a significant positive effect on FS, further confirming the robustness of the baseline regression results.

4.3 Heterogeneity analysis

To further explore the effect of LT on FS, the study examines regional heterogeneity and uses quantile regression. This approach enhances the understanding of land transfer's impact and offers a more detailed perspective for policy formulation.

4.3.1 Geographical regional heterogeneity

Due to the significant differences in the level of economic development and soil type in different regions of China, the effect of LT may be affected to different degrees. Therefore, in order to better evaluate the performance of LT in different regions, we divided the sample into three regions: east, middle, and west. The results are shown in columns (1)–(3) of Table 6. The study found that LT had the most significant promoting effect on FS in the eastern region, and the influence coefficient was significantly positive at the 5% level. This is because the eastern region of China has a higher level of economic development and more advanced agricultural technology, making it easier to foster the high-quality development of the food industry. Additionally, the eastern region is primarily flat, and good ecological conditions can better promote LT to play its advantages in agricultural resource allocation. In contrast, the impact of LT on FS in the central and western regions is either insignificant or weak, highlighting the complex risks and challenges these regions face in implementing LT. For instance, the western region is predominantly characterized by hilly and mountainous terrain, and there are practical problems such as complex terrain and poor ecological conditions, and the economic development and agricultural frontier technology in the central and western regions are relatively backward. Therefore, the implementation cost of LT is high, and the improvement effect of grain production and acquisition efficiency is limited, which leads to the limited development of the grain industry.

TABLE 6 Regression of regional heterogeneity of FS by LT.

Variable	(1) Eastern	(2) Central	(3) Western
LT	0.037** (2.490)	−0.031 (−0.790)	−0.045 (−0.810)
Control variable	Control	Control	Control
Year	Control	Control	Control
Region	Control	Control	Control
N	143	104	143

4.3.2 Quantile regression

The advantage of quantile regression is that estimation conditions of different levels can be selected, and dependent variables can be captured through quantiles distributed under different conditions to more scientifically and accurately reflect the nonlinear relationship between LT and FS (Koenker and Hallock, 2001). Therefore, this paper selects nine quantiles, including 10%, 20%, 30%, 40%, 50%, 60%, 70%, 80%, and 90%, to study the potential impact of LT on FS under different quantile conditions. The results are shown in Table 7. On the whole, LT has a statistically significant effect on FS, and its influence shows a steady upward trend from low score to high score, indicating that LT can produce significant improvement effects. In addition, it is worth noting that at the decimal point near 80%, the influence coefficient of LT shows a “decrease followed by an increase” trend. This finding reveals that during the implementation of LT, the marginal utility of LT is not a purely linear increase, but may briefly decrease when the

TABLE 7 Quantile regression.

Variable	FS	FS	FS	FS	FS	FS	FS	FS	FS
	P10	P20	P30	P40	P50	P60	P70	P80	P90
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
LT	0.093***	0.120***	0.125***	0.131***	0.138***	0.155***	0.173***	0.156***	0.210***
	(4.870)	(9.550)	(12.300)	(12.900)	(9.520)	(9.610)	(9.040)	(6.270)	(5.480)
Control variables	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Year	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Region	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
N	390	390	390	390	390	390	390	390	390

marginal effect reaches the critical point, and then increases again after the critical point. This finding is significant for governments in developing countries, suggesting that government agencies should actively support LT initiatives, continuously optimize the allocation of land resources, improve the efficiency of land use, and maximize the land benefit. In addition, as an important guarantee for the development of the food industry, the higher the degree of circulation of LT, the better to ensure that FS is not threatened by land elements, and the better to promote the sustainable development of agriculture.

4.4 Mediation effect

4.4.1 Environmental regulation

First of all, the conclusion above proves that environmental regulation has a mechanism function. Therefore, this paper chooses environmental regulation as the first intermediate variable based on Model 2 and selected the completed investment in industrial pollution control (IPI) and the proportion of GDP and energy consumption (EG) to characterize environmental regulation respectively, and added them to the model (2) as mechanism variables for evaluation. The experimental results are shown in columns (1) and (2) of Table 8. The conclusion indicates that the effect of LT on FS remains significantly positive at the 5% level even when IPI and, EG are included, with both IPI and, EG showing positive correlations at various levels. The results show that environmental regulation plays an obvious mediating role in the impact of land transfer on food security. By comparing the two measures, it is found that the coefficient and significance of investment in environmental governance are not as significant as the ratio of energy consumption, which shows that only strengthening investment in the environment is not enough, but should also focus on the actual environmental governance, and promote the green production of food with the green use of land, so as to better reflect food security. Hypothesis 2 is proven.

4.4.2 Green technology innovation

Secondly, according to the conclusions above, we choose green technology innovation as the second mediating variable in this paper. In addition, we selected the ratio of regional technology market turnover (TMT) and R&D expenditure (R&DE) to GDP respectively to measure green technology innovation capability and included it again as a mechanism variable in model (2) for regression. The test results are shown in Table 8 (3) and (4). The results showed that the coefficient of LT was positively significant at 1% and 5% levels, respectively, the coefficients of TMT and R&DE were also significantly positively correlated at the 1% level The results of the study verify that the use of green innovation technology can help to play the role of land transfer in promoting food security and prove the intermediary role of green technology innovation. By comparing the effect coefficients of the two types of technological innovation, it is found that R&D investment generates greater value, which directly indicates that in order to better guarantee food security, technological innovation has more far-reaching value in land transfer. Prove Hypothesis 2 again.

4.5 Space spillover effect

To further test the spatial spillover effect of land transfer on food security, this paper uses the spatial Durbin model (SDM) for spatial regression analysis of LT and FS, based on a geographic linkage matrix.

4.5.1 Moran index test

Before using a spatial model, it is necessary to verify the spatial correlation between explanatory variables and explained variables (Moran et al., 1994). In this paper, the Moran index test was conducted based on a geographic collar matrix, and the results are shown in Table 9. From 2010 to 2022, the global Moran index of LT and FS variables is significantly positive at 1% and 5% levels, respectively. From the perspective of the time dimension, the spatial correlation level of LT and FS in China presents an up-and-down amplitude, which may be due to the uneven development degree of LT and FS in different periods in China. Therefore, since both LT and FS have significant spatial autocorrelation, it means that the spatial correlation and spatial spillover can be further discussed in the regression analysis of LT to FS, which can prove that the use of spatial regression in this paper is scientific and reasonable.

TABLE 8 Mechanism test of FS by LT.

Variable	(1)	(2)	(3)	(4)
LT	0.052** (2.490)	0.044** (2.240)	0.045** (2.260)	0.056*** (2.830)
IPI	0.003* (1.820)			
EG		0.193*** (2.920)		
TMT			0.005** (2.260)	
R&DE				0.196*** (3.130)
Control variable	Control	Control	Control	Control
Year	Control	Control	Control	Control
Region	Control	Control	Control	Control
N	390	390	390	390

TABLE 9 Spatial correlation regression.

Year	LT	Z-value	FS	Z-value
	Moran's I		Moran's I	
2010	0.283***	2.742	0.189**	1.886
2011	0.287***	2.723	0.192**	1.915
2012	0.310***	2.899	0.217**	2.133
2013	0.333***	3.094	0.243***	2.371
2014	0.373***	3.439	0.264***	2.574
2015	0.349***	3.209	0.289***	2.885
2016	0.406***	3.685	0.306***	2.979
2017	0.420***	3.783	0.285***	2.803
2018	0.221**	2.324	0.295***	2.936
2019	0.430***	3.892	0.235**	2.342
2020	0.453***	4.120	0.216**	2.170
2021	0.416***	3.776	0.257***	2.565
2022	0.374***	3.392	0.207**	2.101

4.5.2 Spatial regression effect

Secondly, for the use of spatial models, after Wald, LM, Hausman, and other diagnostic tests, the optimal estimation method is the spatial-temporal dual fixed-effect SDM model, and the geographical connection and geographical distance are respectively adopted as the basic matrix, and the regression Model 3 is used to evaluate the results. The specific evaluation results are shown in Table 10. The results show that under various matrix conditions, the direct effect, spatial spillover effect, and total effect of LT on FS are all significantly positive, to varying degrees, which further proves hypothesis H4, which indicates that LT not only has a promoting effect on the development of FS in the local area but also has a significant promoting effect on neighboring areas. This indicates that LT has a regional spillover effect, promoting the positive development of FS within the region and also benefiting neighboring areas.

5 Discussion and policy implications

5.1 Conclusion

Through a detailed analysis of panel data from 30 provinces in China (excluding Xizang, Hong Kong, Macao, and Taiwan) from 2010 to 2022, this study deeply explores the impact of LT on FS, and draws the following four core conclusions:

First, the baseline regression results revealed a substantial and positive effect of LT on FS, a finding that persisted even after the inclusion of control variables. At the same time, robustness tests confirmed the reliability of these findings, and adjustments for various model specifications and control variables did not significantly change the conclusion that LT has a positive effect on FS. This conclusion highlights the critical role of increasing the frequency and efficiency of land use in protecting food security.

Second, the mediation effect test further revealed the specific mechanism of LT's influence on FS, in which environmental regulation and green technology innovation, as important intermediary variables, had a significant promoting effect on the improvement of FS. This indicates that LT can indirectly ensure food security and development by improving the intensity of environmental regulation and strengthening the development of green technology.

Thirdly, the results of heterogeneity analysis showed that there was heterogeneity of LT in different regions. LT significantly increased FS in eastern China, but had no significant effect on FS in central and western China. In addition, LT at higher points has a more obvious promoting effect on FS. This is due to the better economic conditions in eastern China, the higher comprehensive quality of the rural labor force, the higher degree of LT, and the higher degree of policy implementation, which can better promote the growth of FS.

Fourth, the spatial regression results show that LT has a spatial spillover effect on FS. This indicates that LT will promote FS geographically and spatially. This also indicates that the development in the local region can drive the development of FS in neighboring areas, which can have a learning effect and better promote the development of FS in the whole country.

To sum up, the practical contribution of this study is mainly reflected in that this study takes China as the experimental sample,

 10.3389/fenvs.2025.1538589

TABLE 10 Spatial spillover effect regression.

Geographical adjacency weight matrix	Geographic collar matrix			Geographic distance matrix		
	LR_Direct	LR_Indirect	LR_Total	LR_Direct	LR_Indirect	LR_Total
LT	0.035* (1.810)	0.185*** (3.850)	0.219*** (4.000)	0.059*** (3.070)	0.093** (2.230)	0.154*** (3.020)
Control variable	Control	Control	Control	Control	Control	Control
Area effects	Control	Control	Control	Control	Control	Control
Time effects	Control	Control	Control	Control	Control	Control
N	390	390	390	390	390	390

not only discusses the influence of LT on FS from the theoretical level but also verifies how LT affects FS from the empirical level, thus helping to enrich the research between LT and FS. On the one hand, it can provide ideas for China's land circulation and sustainable development in the future; On the other hand, it can also provide practical experience for other developing countries to further promote the high-quality development of the food industry by optimizing land resources, and provide important ideas for realizing the sustainable development of global land.

5.2 Discussion

In this paper, the influence of LT in China on FS was discussed, and the conclusion showed that LT had a significant promoting effect on FS, which verified hypothesis H1 in this paper, which was consistent with the results of existing literature (Alamirew et al., 2015). This indicates that in China's current grain production and management activities, the allocation of land resources is insufficient, the emphasis on land circulation is insufficient, and the construction level of agricultural infrastructure is not good, so it is necessary to strengthen the use of land resources to achieve FS. Environmental regulation and green technology innovation have mediating effects on the influence of LT on FS, which verifies hypothesis H2 and is consistent with the results of Pei et al. (2024). On the one hand, the implementation of government environmental control can better strengthen farmers' awareness of ecological environmental protection in grain production. On the other hand, the application of green technology can promote the improvement of production efficiency and the reduction of production costs of grain enterprises. In the eastern region with more developed economic development and the region with higher LT levels, LT has a significant positive impact on FS, especially in the region with higher LT levels, which proves that hypothesis H3 is consistent with the research results of Peng et al. (2021). This indicates that in areas with sufficient funds and high management levels, land transfer and utilization should be increased to ensure land use efficiency, while in relatively backward areas, more advanced agricultural technologies can be introduced to optimize land resource allocation to improve food security. From a spatial perspective, this paper proves that LT has a spatial spillover effect on FS, which is consistent with the conclusion of hypothesis H4 and the results of existing literature (Petrescu-Mag et al., 2019). China should increase the situation of land in different regions, and give full play to the advantages of regional land and geography, better allocate agricultural land resources, reduce waste in the production process, accurately control grain planting and sales, and better improve the efficiency of land use. In addition, we should also pay attention to inter-regional technical exchanges and achieve cross-regional technical support to better ensure the development of the food industry. For other developing countries, exchanges and support between different regions should be strengthened to achieve better development of FS through inter-regional driving and learning effects.

5.3 Policy recommendations

First, we will strengthen the infrastructure of the grain industry. Perfect basic hardware facilities are an important guarantee to promote the efficiency of land transfer and the high-quality development of grain industry. Therefore, government departments should increase investment in infrastructure, improve the level of grain industry infrastructure construction, give play to the guiding role of land policies, implement and implement the implementation of land regulations in various regions, and build a complete land transfer and supervision system. In addition, it is necessary to give full play to the government's capital investment in the field of land and food, promote the deep integration of production, university and research led by land and food enterprises, take market demand as the guidance, and constantly promote the rational distribution of land resources, which not only provides the core driving force for the stable development of the food industry, but also provides an important idea for optimizing land resources.

Second, promote the deep integration of government environmental regulations and agricultural green technology innovation. Environmental regulations and agricultural green technology innovation are the key factors to optimize land resources and ensure food security. It is suggested that the government strengthen the ecological environment control of the food industry and investment in agricultural scientific research funds, and accelerate the improvement and implementation of agricultural ecological environment laws and regulations, which can not only better protect the ecological environment of agriculture and land resources, but also reduce pollution emissions in the process of food production, so that food quality can be guaranteed. At the same time, through the development and application of cutting-edge agricultural green technologies, promote the application of cutting-edge technologies such as smart agriculture and artificial intelligence in the land and food industry. While improving the efficiency of rural land use, it can also improve grain production capacity, help land resources be fully utilized, and further promote the sustainable development of the food industry.

Third, optimize the allocation of rural human capital and deepen the reform of the agricultural policy system. The comprehensive quality of the rural labor force is an important factor affecting the implementation and application of land transfer policy. It is suggested that the government strengthen the training of the comprehensive quality and comprehensive ability of the rural labor force, strengthen the learning of land use knowledge through reasonable guidance to farmers, cultivate agricultural land planting talents with professional skills, give full play to the advantages of land transfer, and optimize the utilization of land resources. On the other hand, the government should strengthen the implementation of agricultural policies, establish a sound land use and supervision system, reduce the cost of land use in the process of food production, improve farmers' land use efficiency, and give full play to the advantages of different land resources according to different land conditions, choose food planting methods according to local conditions, so as to ensure a steady increase in food output and better guarantee food security.

6 Research deficiencies and prospects

As a whole, this paper studies the impact of LT on FS from a provincial perspective, and confirms that LT plays an important role in promoting FS. However, it is undeniable that there are still shortcomings, and future research can be in-depth from the following three levels:

First, expanding the sample data. The data samples used in this study are at the provincial level, which can provide us with macro-level analysis, but more detailed and in-depth discussion of the impact of LT on FS in deeper geographical areas, future studies can refine the granularity of LT and FS data, and further expand the samples to prefecture-level and even county-level data. This will help us more accurately show the differences between LT in different geographical, and economic backgrounds and resource endowment conditions.

Second, deepen the evaluation of the effect of land policy implementation. Although the relationship between LT and FS is evaluated using a bidirectional fixed-effect model, the consideration of land policy application and implementation is still missing. Future studies should introduce land policy as an evaluation indicator and use a more comprehensive evaluation model to explore the long-term effects and potential impacts of LT on FS.

Third, take developed countries as research objects. Although this study takes China as an experience sample, it can provide some experimental basis for developing countries, but it can better show the advantages of LT policies in developed countries and the experience of land resource optimization in developed countries. Future research can choose developed countries as research objects, use developed countries' index data for evaluation and analysis, explore the development experience of developed countries' land and food industry, and put forward substantive suggestions for developing countries to optimize land resources and ensure high-quality development of the food industry.

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

MX: Conceptualization, Data curation, Formal Analysis, Investigation, Methodology, Software, Writing–original draft, Writing–review and editing. ZL: Conceptualization, Funding acquisition, Methodology, Project administration, Resources, Supervision, Validation, Visualization, Writing–review and editing. XW: Supervision, Validation, Visualization, Software, Writing–review and editing. GH: Writing–review and editing, Supervision, Validation, Resources, Visualization.

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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.

Generative AI statement

The author(s) declare that no Generative AI was used in the creation of this manuscript.

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