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How Do Rising Farmland Costs Affect Fertilizer Use Efficiency? Evidence from Gansu and Jiangsu, China

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Abstract: As the farmland transfer market in China develops, moderate-scale operations increasingly grow but without much improvement in fertilizer use efficiency. This study theoretically analyzes the mechanism and effect of rising farmland costs on fertilizer use efficiency using multiple quadratic regression and mediating effects models. It empirically tests a micro-sample of 806 farmers in Gansu and Jiangsu provinces in China from two dimensions: the full samples and farmer heterogeneity. The results showed 0.544 as the average fertilizer use efficiency (hereinafter, *fe*) of farmers in Gansu and Jiangsu, highlighting the severe loss of *fe* caused by excessive fertilizer inputs. The multiple quadratic regression model further revealed an inverted U-shaped relationship between farmland costs and *fe*, with the U-shaped curve showing a remarkable inflection point at the USD 708/mu mark. When farmland costs are excessive (*cost* > CNY 708/mu), the increase in farmland costs inhibits the *fe*. An investigation of the corresponding impact mechanism for this scenario (i.e., *cost* > USD 708/mu) revealed that farmland costs directly suppress *fe* (−0.485) by distorting the fertilizer factor substitution effect and indirectly suppress *fe* (−0.037) by impeding the technology spillover effect of production specialization and production scale-up. We also found heterogeneity between two groups: ordinary farmers and new agricultural operators (e.g., large grain and family farmers), with the peak kernel density function of *fe* of new agricultural operators (0.85) being much higher than that of ordinary farmers (0.30). Moreover, the multiple quadratic regression between the groups revealed a lower inflection point for ordinary farmers (CNY 638/mu) than new agricultural operators (CNY 823/mu), highlighting that the *fe* of ordinary farmers was more likely to be inhibited by the excessive rise in farmland costs. To promote the sustainable development of China's agricultural production, we propose reducing the cost of farmland, promoting service-scale operations, and fostering new agricultural operators.

Keywords: farmland costs; fertilizer reduction; new agricultural operators; multiple quadratic regression model; mediating effect model

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1. Introduction

Since the founding of "New China", especially since the country's reform and opening-up, China's agricultural production methods have evolved—from relying mainly on traditional agricultural resources (labor) to capitalizing on chemical agricultural resources (chemical fertilizers) [1]. The rapid growth of chemical fertilizer application has greatly supported the stable supply of agricultural products in China [2]. However, negative environmental externalities such as the surface pollution caused by heavy fertilizer application have been highlighted [3–5], including soil acidification, the eutrophication of water sources, and increased greenhouse gas emissions [6,7], which have primarily impeded China's sustainable agricultural development. In response, the Chinese government has actively launched a zero-growth fertilizer campaign and enacted a series of policies to promote green agricultural development in recent years. Under the guidance of ecological civilization, China's zero fertilizer growth target has also been largely achieved, but the total base remains high. In 2020, the total fertilizer application in China was at 52.5 million tons, a unit area application rate of 390 kg/ha [8]. This is much higher than the internationally accepted fertilizer application limit of 225 kg/ha. At this stage, China's grain supply and demand remain in tight balance, with significant structural contradictions. Thus, the promotion of chemical fertilizer reduction has become an important link affecting food security and sustainable agricultural development, becoming the focus of academia.

In recent years, scholars in China and abroad have paid attention to fertilizer reduction [9–11], especially regarding the impact mechanisms, with different focuses in different periods. Based on the changing characteristics of the external environment of agricultural production in China, the existing literature provides an in-depth analysis of the influential factors concerning fertilizer reduction in three stages: labor off-farm transfer [12], farmland transfer market development [13], and agricultural production service market development [14]. Initially, in the context of the off-farm transfer of agricultural labor, there was growing concern that the ongoing wave of off-farm employment would hurt the agricultural environment, as measured by fertilizer use intensity, because rational smallholders tend to hedge output risks by over-applying fertilizers [15]. Using panel data from two representative mountainous and plain areas in Sichuan and Henan, Zhang et al. [12] found that non-farm employment in mountainous (plain) areas has an inverted U-shaped (positive) relationship with fertilizer inputs. As the market for farmland transfer continues to develop, academics have turned to analyzing the impact of farmland transfer on farmers' green production behavior [13,16]. Starting from the relationship between farmland operation scale and fertilizer inputs [17,18], scholars have focused on the positive impact of farmland transfer and the resulting farmland scale operation on fertilizer reduction. Zou et al. [19] found a suppressive effect of land transfer on the fertilizer use intensity of large-scale farmers. The area transferred and nongrain crop planted were also negatively associated with fertilizer application intensity. In contrast, the fertilizer reduction effect of farmland transfer in smallholder production was weaker or not significant [20,21]. To compensate for the negative impact of agricultural labor shortage and small-scale decentralized operation on agricultural production [22], China has rapidly developed agricultural production services in recent years, and some scholars have started to focus on the contribution of agricultural production services to fertilizer reduction. They concluded that agricultural productive services promote specialized division of labor and precision production and are an important option for fertilizer use reduction [23,24].

In contrast to domestic research, international studies focus on the influence of market factors on farmers' fertilizer application, such as consumption preferences [25], fertilizer prices [26,27], agricultural prices [28], and government intervention [29,30]. Goetzke [25] argued from an agricultural market supply and demand perspective that consumer preference for green agricultural products drives the reduction of chemical fertilizer inputs. Through a combination of theory and empirical evidence, Banerjee [26] found that the relative prices of fertilizer and output have a negative effect on fertilizer application by farm households. Additionally, international researchers have also focused on the influence of farmers' intrinsic characteristics on fertilizer application, mainly in terms of individual farmers' characteristics [31], land operation scale [32], social networks [33], and farmers' moral codes [34], to analyze the influence of production motivation and behavior on fertilizer application due to differences in farmers' intrinsic characteristics. International and domestic research also share commonalities, for instance focusing on the impacts of external factors such as farmland market development [35] and agricultural production service market development [36] on fertilizer application, and both disagree on whether land trading can contribute to fertilizer reduction. Conley and Udry [35] found that the scale of operation through agricultural land trading could improve fertilizer application efficiency. However, Bambio and Agha [36] showed that the expansion of land trade and the scale of operation intensified the short-term production behavior of farmers, which was not conducive to fertilizer reduction.

The literature above has explored the impact mechanism of fertilizer reduction based on the stage characteristics of the external environment of agricultural production in China, and the internal characteristics and external factors of farmers, providing an important reference for this study. However, what has been overlooked is that along with the continuous development of the farmland transfer market, farmland prices have increased, and the high farmland cost has become an important feature of China's agricultural production environment [37,38]. According to a Rural Land Management Rights Transfer Market Insight Series Report, the average cost of farmland in China was CNY 11,000/hm^2/year in 2020, and the average annual growth rate of farmland cost in China has exceeded that of agricultural production costs (i.e., material, labor, and land costs). Moreover, the share of land cost in the total output of Chinese agricultural production is, on average, 31.35%, which is much higher than that of the United States (21.00%), Brazil (16.92%), or the European Union (8.81%) [39]. Furthermore, farmland transfer has not brought about a fundamental change in China's fragmented household management pattern, nor has the application of organic fertilizer increased with the advancement of China's farmland transfer market [2]. The underlying problem is that given the rising farmland costs in China, farmland prices must be kept at a reasonable range for farmland transfers to lead to fertilizer reduction with excessive farmland costs, the allocation structure and degree of use of production factors by agricultural producers change or even get distorted. However, few studies have focused on the poor fertilizer reduction effect of farmland transfer from the perspective of farmland cost. For a deeper investigation of the classic proposition of fertilizer reduction in Chinese agriculture, the impact of farmland cost on fertilizer use efficiency to achieve sustainable agricultural development must be explored.

Furthermore, in the current literature on the factors influencing fertilizer reduction, most scholars still characterize the degree of fertilizer application directly by the amount of fertilizer input per unit area. Notably, the marginal output of fertilizers will vary under different factor allocation structures and even utilization levels. The key to whether fertilizer input is excessive lies in the relative difference between the actual versus optimal input amount of fertilizer. Therefore, some scholars have used the Cobb–Douglas production function to characterize the degree of fertilizer application from the perspective of fertilizer use efficiency based on the principle that the marginal product value of fertilizers equals the price of fertilizers [40,41]. Hence, we also investigate fertilizer use efficiency to reveal its changing characteristics from the perspective of rising farmland costs and explore the mechanism of how rising farmland costs affect fertilizer use efficiency. The empirical test is conducted using survey data of 806 farmers in the Gansu and Jiangsu provinces, and multiple quadratic regression and mediating effect models from two dimensions: the full sample and farmer heterogeneity. It is important in curtailing the adverse effects of fertilizers on the environment such as soil acidification, eutrophication of water sources, and increased greenhouse gas emissions, among others.

The remainder of this paper is structured as follows. Section 2 discusses the structural effect of rising farmland costs on fertilizer use efficiency and the impact mechanism. Section 3 presents the study area, data resources, and basic model. Section 4 provides the empirical analysis and main findings. In Section 5, we discuss the limitations of the study and policy recommendations. Section 6 presents the conclusions.

2. Theoretical Analysis

2.1. Impact Pathways of Rising Farmland Costs on Fertilizer Use: Direct Versus Indirect Effects

With the transfer of surplus agricultural labor and the reform of China's farmland system, the development of the farmland transfer market has accelerated, leading to a continuous rise in the cost of farmland. This situation has profoundly changed farmers' behavior toward fertilizer application, which can be summarized as direct and indirect effects of the rise in farmland cost (Figure 1a).

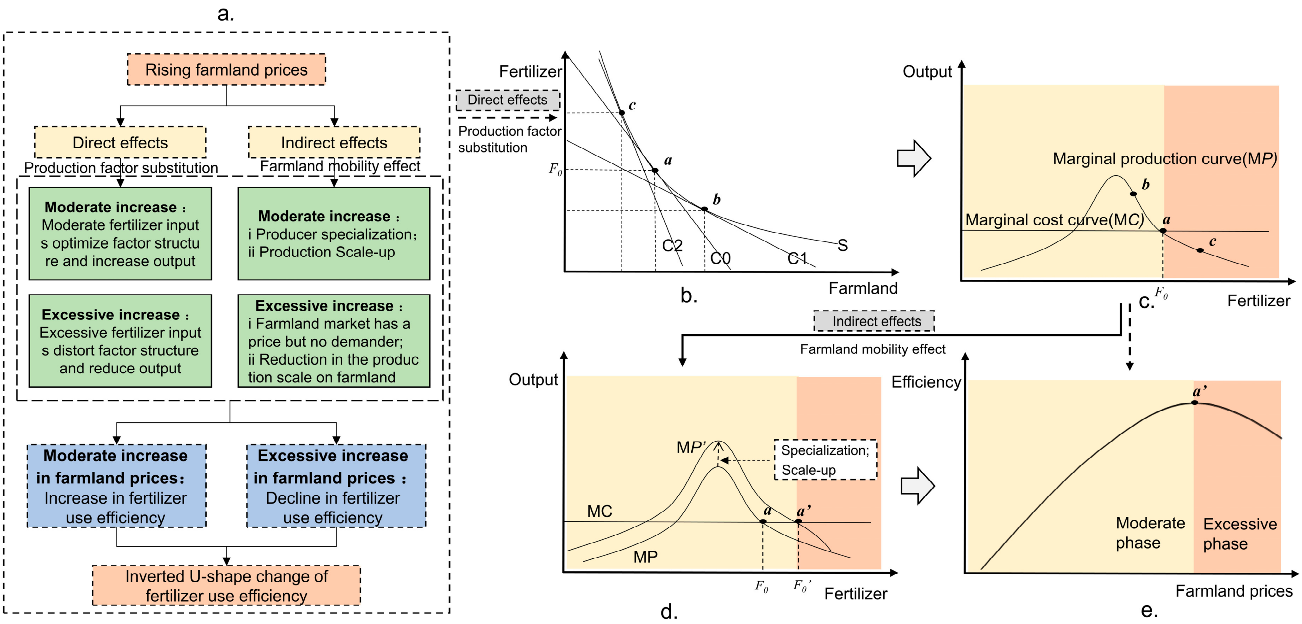

Figure 1. Mechanisms of the impact of rising farmland costs on fertilizer use efficiency. (**a**) illustrates the path of the impact of rising farmland costs on fertilizer use efficiency. (**b**) illustrates the substitution of fertilizers on farmland. (**c**) illustrates the effect of fertilizer input quantity on farmland output. (**d**) illustrates the effect of fertilizer input quantity on farmland output under the effect of indirect pathways. (**e**) illustrates the relationship between rising farmland costs and fertilizer use efficiency.

(1) Direct path based on the substitution effect of production factors

To maximize income, farmers restructure the input of each factor of production according to the changes in their relative prices, and the inputs of those that are relatively low-priced are increased to replace those that are relatively high-priced. In the case of fertilizer substitution for land, the substitution process is essentially influenced by the relative prices of production factors. The theory of induced technological innovation in agricultural development suggests that farmers will choose the appropriate technological innovation based on the relative prices of production factors. Moreover, fertilizer, as an agricultural production technology that involves biology and chemistry, is a land-substituting factor of production [42]. The increase in the farmland transfer price has caused the relative price of fertilizers to fall. The increased use of fertilizers, which is an input factor to promote crop growth, can partly replace farmland inputs that are higher-priced. Therefore, choosing to increase the amount of fertilizer applied per unit area to reduce the cost of farmland inputs is a rational choice for farmers.

(2) Indirect path based on the effect of farmland mobility

The farmland mobility effect includes producer specialization and the scale-up of production methods, and farmland transfer prices indirectly affect fertilizer application through the technological spillover effects on producers and the production scale. Examples are provided below.

a. Producer specialization. Producer specialization refers to the allocation of land from inefficient growers to more efficient growers. In a period of moderate price increases, the farmland market promotes the efficient mobility of farmland, thus forming an exit (entry) mechanism for "weak" ("strong") operators. Farmland flows into the hands of capable operators, who usually have better agricultural knowledge, management skills, and ability to solve the technical constraints faced by green agricultural production. They have a greater chance of acquiring green agricultural production technologies, and the modern production methods they bring implicitly promote the reduction of agricultural fertilizer production. However, excessive farmland prices prevent these management experts from effectively solving the financial constraints caused by extreme cost increases, and the farmland transfer market becomes "price-less." When farmland is costly, it is difficult for operators to apply green production technologies effectively, and the fertilizer-reducing effect of farmland mobility is hampered [20].

b. Scale-up of production methods. Profit maximization theory suggests that when the marginal output of an input factor of production is greater than the marginal cost, producers are incentivized to increase the input of that factor. In a period of moderate increase in farmland prices, producers will still choose to flow into farmland because of the economic incentive of scale payoffs in agricultural production. Additionally, several studies have shown that scale production can reduce the unit area cost of new technology use [43] and promote the diffusion of new agricultural technologies [44,45]. For example, in the promotion of green production technologies such as soil testing formula fertilization and water–fertilizer integration, having a certain area of farmland to meet the scale criteria for promoting green production technologies [18,46] can help promote chemical fertilizer reduction. However, when the price of farmland is too high, especially when the marginal cost of farmland is greater than the marginal payoff generated by scale benefits, producers become less willing to purchase farmland and even choose to abandon farmland [47]. In this situation, scale production becomes difficult, thus hindering the fertilizer reduction effect [2].

2.2. Characteristics of Changes in Fertilizer Use Efficiency under Different Scenarios of Rising Farmland Costs

Here, fertilizer use efficiency refers to the ratio of the actual amount of fertilizer input to the potential minimum amount of fertilizer input that can be achieved under a condition where the output and other input production factors remain constant [48]. To reveal further the changing characteristics of fertilizer use efficiency from the perspective of rising farmland costs, it is assumed that (i) only land and fertilizer are considered as input agricultural factors of production; (ii) to maximize profits, producers achieve cost minimization under equal yields by adjusting the combination relationship between these two elements; and (iii) point A is the optimal point of fertilizer application, where the marginal output of fertilizer is equal to the marginal cost of fertilizer.

(1) Moderate increase scenario

As shown in Figure 1b, when land prices change, the equal cost line between fertilizer and land shifts for producers to realize their original expected returns. Specifically, when the farmland price is low, producers tend to invest in more land. At this time, the iso-cost line *C*1 is tangent to the iso-return curve *S* at point *b*. However, owing to the excessive input of farmland area, the amount of fertilizer input is insufficient, resulting in low fertilizer use efficiency. As the farmland price rises moderately, the producer realizes the expected return by increasingly substituting fertilizer for land, and the equal-cost line moves from *C*1 to *C*0. At this time, the equal cost line *C*0 is tangent to the equal return curve *S* at point *b*. The structure of production factors is optimized, and the amount of fertilizer input is gradually matched with the farmland area. As shown in Figure 1c, the equilibrium point moves from point *b* to point *a* as the iso-cost line *C*1 shifts to *C*0, at which time the marginal output of fertilizer equals the marginal cost of fertilizer, and the efficiency of fertilizer use reaches its peak.

Additionally, the specialization of producers and the scale of agricultural production change the constraints of family agricultural production technology, causing a shift in the marginal output curve of fertilizers. As shown in Figure 1d, *MP* shifts upward to *MP*′, facilitated by the farmland mobility effect. At this point, the fertilizer marginal output curve intersects with the marginal cost curve at point *a*′; the fertilizer use efficiency reaches the maximum, and the optimal input quantity of fertilizer expands to $F_0{}'$. Therefore, when the amount of fertilizer input resulting from the increase in farmland price is lower than F_0', the cost of farmland and fertilizer use efficiency show a positive relationship (Figure 1e).

(2) Excessive rise scenario

As shown in Figure 1b, as the farmland prices rise further, the equal cost line moves from *C*0 to *C*2, and the equilibrium point moves from point *a* to point *c*. At this point, the amount of fertilizer input is excessive and exceeds the degree of matching with the other factors of production. As shown in Figure 1c, the marginal output of fertilizers at point c is smaller than the marginal cost of fertilizers, and the amount of fertilizer input at this point exceeds the optimal amount of fertilizer input. Additionally, because of the excessive increase in farmland prices, the specialization of producers and the scale of agricultural production are inhibited, and the decrease in fertilizer use efficiency intensifies. Therefore, when the amount of fertilizer input resulting from the increase in farmland prices is greater than F_0', the cost of farmland and the efficiency of fertilizer use show a negative relationship (Figure 1e).

In summary, we propose the following hypothesis: the rising farmland cost—through the substitution effect of production factors, specialization of producers, and scale of agricultural production generated by the farmland mobility effect—leads the fertilizer use efficiency to exhibit an inverted U-shaped change with the rising farmland cost; in particular, the excessive rise in farmland cost hinders the improvement of fertilizer use efficiency.

3. Materials and Methods

3.1. Study Area

China is vast and varies greatly by region. We chose Gansu Province in northwestern China and Jiangsu Province in eastern China as the study areas to obtain representative results considering different farmland resource endowments, farmland prices, and fertilizer application rates (Figure 2), as explained in the following. First, Gansu is a typical inland mountainous region, where farmland resources are relatively poor; by contrast, Jiangsu is a flatter coastal province with high-quality farmland resources. Second, as the market development in Gansu Province is slow, the farmland transfer rent is relatively low—only 485 RMB/mu, while the farmland market in Jiangsu Province is well developed, and the farmland transfer rent is high—up to 920 RMB/mu. Moreover, in Gansu, where the fertilizer reduction policy is well implemented, fertilizer application is relatively low at approximately 800,000 tons. In Jiangsu Province, one of the major grain-producing provinces in China, the pollution is rather serious [40], and the fertilizer application is highly excessive from a nationwide perspective—up to 2.8 million tons. These facts are essential for determining the relationship between farmland cost and the fertilizer use efficiency in these regions.

3.2. Data Processing

Data were obtained from a survey of grain-growing farmers in the study area conducted in 2020. First, applying random sampling, 16 county-level administrative districts were selected as sample counties from these 2 provinces. Then, within each county, different types of towns were randomly selected considering factors such as resource endowment, geographical location, and economic development level. All villages within each selected town were divided into high- and low-income groups, with one of each income type being selected separately. Finally, in each village, no fewer than 10 households of different business types were randomly selected (large grain growers refer to households with more than 3.33 hectares of arable land; family farms refer to farmers identified and registered by the government as “family farms”, and all others are ordinary farmers). Using this sampling strategy, we surveyed a total of 845 households (64 villages in 32 towns in 16 counties).

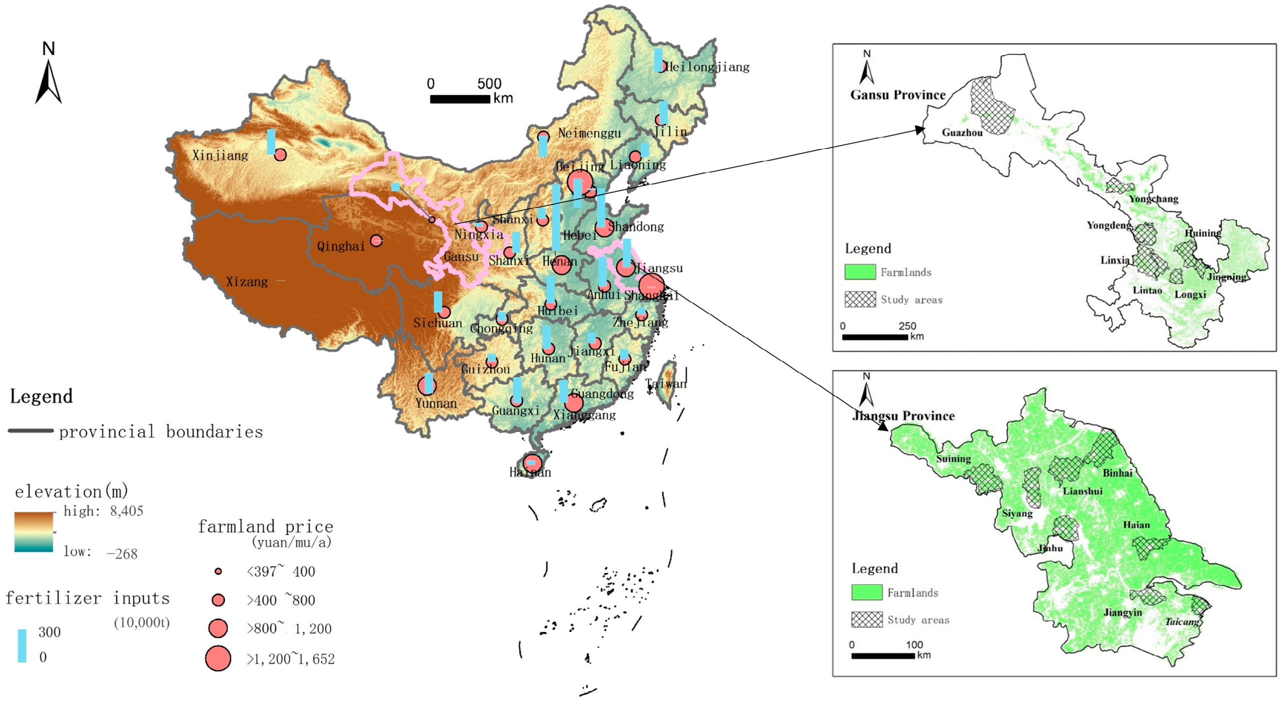

Figure 2. Profile of study areas. Note: Farmland price data were obtained from 41,452 sample sites surveyed by the Ministry of Natural Resources by letter; fertilizer input data were obtained from the Compilation of Information on Costs and Benefits of Agricultural Products in China.

For the specific survey of the data, we first trained the surveyors in a uniform manner and followed the steps of design, pre-survey, and finally revising the questionnaire. Secondly, in terms of survey content, we made detailed inquiries mainly about the production information of farmers, including basic data related to farmland transfer, fertilizer use, household characteristics, farmland characteristics, etc. However, since some farmers did not transfer their farmland, and some were not willing to disclose their specific agricultural production and operation information, they were excluded from our study. Finally, for the sake of data availability, we used 806 samples for this study by excluding samples who did not meet the needs of the study as well as outliers.

3.3. Methods

3.3.1. Measurement Method of Fertilizer Use Efficiency

Academics usually measure production efficiency or single-factor input efficiency through data envelopment analysis and stochastic frontier production function analysis (SFA) [49–51]. Considering that agricultural production is susceptible to stochastic factors such as weather and natural disasters, we use an SFA method that can effectively distinguish between stochastic perturbations and technical inefficiencies for estimation. The ratio of optimal quantity of the potential fertilizer input to the actual fertilizer input can be observed while keeping the technical efficiency fully effective. The specific steps are described as follows. First, we determined the formula for measuring fertilizer use efficiency (*fe*) based on the definition of *fe* in the theoretical analysis section. Second, we determined the production function under the condition of optimal amount of potential fertilizer inputs versus the production function under the condition of actual fertilizer inputs. We replaced the calculation of *fe* using polynomial substitution again. Finally, we substituted the actual output and input factor data of farmers into Equation (2) and used Stata to find out the α_1 and μi of each farmer, measuring the *fe* of each farmer in the calculation.

Specifically, we first characterized the fertilizer utilization efficiency with the following equation based on the definition:

$$fe_i = \frac{EFI_i}{AFI_i}, \tag{1}$$

where i denotes farmer; fe_i, fertilizer use efficiency; AFI_i, actual fertilizer input quantity; and EFI_i, optimal quantity of the potential fertilizer input.

Moreover, because we focus on measuring efficiency rather than examining the specific form of production, a simple C-D function is sufficient to support our study. Therefore, as with the majority of the literature (Shi et al., 2019), the C-D function is chosen as the specific form of the frontier production function, such that the efficiency frontier function can be expressed as follows:

$$lny_i = \alpha_0 + \alpha_1 lncf_i + \alpha_2 lnland_i + \alpha_3 lnlabor_i + \alpha_4 lnother_i + v_{1i} - \mu_i, \tag{2}$$

where y_i is the total output; and cf_i, $land_i$, $labor_i$, and $other_i$ represent fertilizer, land, labor, and other inputs, respectively. v_i is a random error term in the traditional sense, representing the random factors present in production (e.g., measurement errors and various uncontrollable random factors like weather and luck), which are assumed to follow a standard normal distribution. μ_i is a nonnegative technical efficiency term that reflects the deviation of the farmer's production from the frontier and is assumed to follow an exponential distribution with mean λ. It is also assumed that μ_i and v_i are independent of each other and both are uncorrelated with the explanatory variables.

In the selection of indicators, fertilizer input (in CNY), land operation area (in mu), farm labor (by person) and other agricultural production inputs other than fertilizers (specifically, land cost, labor cost, seedling fee, machine labor fee, etc.) are used to represent cf_i, $land_i$, $labor_i$, and $other_i$. y_i is characterized by agricultural production income (in CNY).

After estimating all the parameters of Equation (2) using the maximum likelihood method, the fertilizer use efficiency (*fe*) of the i_{th} farmer can be measured by Equation (3):

$$fe_i = \exp\left(\frac{-\mu_i}{\alpha_1}\right). \tag{3}$$

3.3.2. Multiple Quadratic Regression Model

Based on the theoretical analysis in part 2, we reasoned that the rising farmland cost has an inverted U-shaped effect on fertilizer use efficiency. To investigate the structural changes in the impact of rising farmland costs on fertilizer use efficiency, a multiple quadratic regression model is designed, and the quantitative relationship between farmland costs and fertilizer use efficiency for 806 farmers is examined using the following model:

$$fe_i = a \times cost_i + b \times {cost_i}^2 + \sum_{j=1}^{n} \partial_j X_{ij} + \beta_0 + v_{2i}, \tag{4}$$

where i denotes farm households; fe_i is fertilizer use efficiency; $cost_i$ is farmland cost, and ${cost_i}^2$ is the squared term of farmland cost. a, b, and β_0 are the parameters to be estimated. v_{2i} is a control for unobservables that vary by individual unit. X_{ij} is the control variable, and ∂_j is the regression coefficient of the control variable.

Specifically, X_{ij} is selected mainly based on the existing literature on the factors influencing fertilizer use efficiency [52,53], and other possible influential factors are controlled for in three dimensions: household head, household, and region. At the household head dimension, age and educational attainmentare included. Additionally, an age squared term is included in the regression of on *fe*, given the life cycle theory. Among the household characteristics variables, fertilizer application is a tedious and labor-intensive part of agricultural farming, and the labor supply status affects the efficiency of fertilizer use; thus, the proportion of off-farm workers is chosen. In addition, the share of nonfarm income reflects the importance that farmers attach to land. Farmers with a higher share of nonfarm income have more sloppy production practices, often resulting in less efficient fertilizer use.

Therefore, the share of nonfarm income in total household income is chosen. Among the regional control variables, conditions such as economic environment and social development among regions also have a large impact on fertilizer use efficiency, and two variables, county GDP per capita and urbanization rate, are introduced in the model. Table 1 shows the descriptive analysis of each variable.

Table 1. Descriptive statistics of variables.

Type of Variable	Representation	Definition	Mean	Standard Deviation
Dependent variable	*fe*	Efficiency of agricultural production scale	0.54	0.24
Variables of fe measurement	*profit*	Agricultural production income (yuan)	15575.97	30193.28
	land	Land operation area (mu)	12.48	20.11
	labor	Farm labor inputs (person)	1.87	0.73
	fertilizer	Fertilizer inputs (yuan)	2198.94	3543.08
	capital	Other agricultural production inputs other than fertilizers (yuan)	9115.15	17778.89
Independent variable	*cost*	Transaction price (yuan)	565.91	239.01
Intermediate variables	*area*	Area of farmland inflow (mu)	11.04	19.66
Peasant variable	*age*	Age (year)	41.28	11.13
	age^2	Age × age (year)	1827.84	873.76
	edu	1 = illiterate, 2 = secondary school, 3 = middle school, 4 = high school, 5 = university and above	2.12	1.23
Family variable	*revenue*	Non-farm income/total revenue	0.46	0.22
	off-farm	Number of non-farm workers/total number	0.38	0.24
Regional variable	*pergdp*	GDP/population (10,000 yuan/person)	129.99	193.46
	urban	Urban population/total population (%)	55.36	11.59

3.3.3. Intermediary Effect Model

According to the theoretical analysis, both the producer's specialization and production scale-up are based on the farmland transfer. When the area of land transfer is small, both effects hardly come into play. Therefore, to test whether the farmland cost indirectly affects the efficiency of fertilizer use through the effect of farmland transfer, we further introduce the intermediate variable of farmland inflow area to form the following model:

$$fe_i = a_1 * cost_i + \sum_{j=1}^{n} \partial_{2j} X_{ij} + v_{3i}. \quad (5)$$

$$area_i = b_1 * cost_i + \sum_{j=1}^{n} \partial_{3j} X_{ij} + v_{4i}. \quad (6)$$

$$fe_i = c_1 * cost_i + d_1 * area_i + \sum_{j=1}^{n} \partial_{4j} X_{ij} + v_{5i}. \quad (7)$$

where fe_i, $cost_i$, and X_{ij} are the same as in Equation (4), and *area* is the inflow area of farmland. a_1, b_1, c_1, and d_1 are the coefficients to be estimated; ∂_{2j}, ∂_{3j}, and ∂_{4j} are the regression coefficients of each control variable, and ν_{3i}, ν_{4i}, and ν_{5i} are the individual effects. To enhance the comparability of the effect sizes of each path, the natural logarithms of the variables *cost*, *pergdp*, and *area* are taken in the mediating effect model.

Additionally, we split the intermediary effect analysis into two sets of multivariate primary model mediation effects analysis by classifying the sample groups using the inflection point values of the linear model, allowing us us to satisfy the requirements of existing mediated effects models while using binary regression and mediation model methods.

3.4. Description of Variables

Table 1 shows the descriptive analysis of each variable.

Dependent variable. The average fertilizer use efficiency of 806 households was found to be 0.544 using Equations (1)–(3), which is in general agreement with the current academic research [48]. Among them, the fertilizer use efficiency of 51% of the farmers was even lower than the average.

Independent variable. We found that the farmland cost obtained from the survey was consistent with the price level of samples surveyed by the Ministry of Natural Resources by letter in Section 3.1. The average of farmland cost obtained from the research was RMB 566/mu/year, of which more than 45% of farmers spend more than RMB 566/mu/year when transferring farmland.

Intermediate variable. We found that the average size of farmland transferred by farmers was 0.69 ha, but about 75% of them transferred farmland below the mean level. This indicates that most of the farmers' willingness to transfer farmland has yet to be further stimulated by government policies.

Control variables. At the individual level, we found that the average age of farmers in the sample group was 41.28 years and that 85.11% of them had not attended high school. From the household perspective, the average percentage of household non-agricultural income was 46%, and at least one-third of them were engaged in non-agricultural work. At the regional level, the economic development level and urbanization level of the districts and counties where the sample is located were high, including an average GDP per capita of 1.3 × 106 and an urbanization level of 55.36%.

4. Results

4.1. Fertilizer Use Efficiency in the Study Provinces

According to Equations (1)–(3), the average fertilizer use efficiency (hereinafter, *fe*) of the 806 households is 0.544. This indicates that nearly half of the inefficient fertilizer inputs are used in agricultural production in the study provinces, highlighting the severe inefficient fertilizer use caused by excessive fertilizer inputs. The maximum reduction rate of fertilizer input is 45.60% if technical inefficiency can be eliminated while keeping the quantity of other factor inputs and output levels constant. Furthermore, calculating the *fe* by farmer type, we see from the peak of the kernel curve in Figure 3 that the *fe* peak for the new agricultural operators is higher than that for ordinary farmers. This result indicates that under the current level of agricultural production technology and the market environment of production factors, it is easier for new agricultural operators to improve *fe* than it is for ordinary farmers. Moreover, this phenomenon is consistent with the current theoretical perceptions in academia: new agricultural operators usually have better agricultural knowledge and management skills and are better able to solve the technical constraints faced by agricultural green production [7,13].

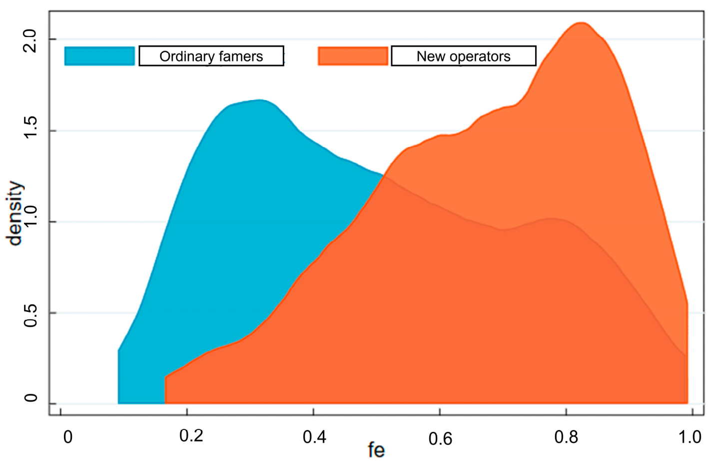

Figure 3. Kernel density distribution of farmers' *fe*.

4.2. The Effect of Rising Farmland Costs on Fertilizer Use Efficiency

Table 2 shows the regression results of the effect of rising farmland costs on fertilizer use efficiency. The table shows that both the primary term (*cost*) and squared term ($cost^2$) of farmland cost have a significant effect on fertilizer use efficiency (*fe*). The coefficient of the squared term is -3.72×10^{-7}, and the coefficient of the primary term is 5.27×10^{-3}. These results suggest the existence of a remarkable inflection value of the fitted function of the model, which indicates a nonlinear relationship between the farmland cost and the fertilizer use efficiency (Figure 4). Through the extreme value condition of a multivariate quadratic function in which $cost_0 = -2a/b$, the corresponding inflection point of farmland cost is calculated as RMB 708/mu. According to the inflection point measured by the model, the farmland cost is divided into two intervals: $cost \leq$ CNY 708/mu and $cost >$ CNY 708/mu, representing two stages of moderate and excessive increases in farmland cost, respectively.

Table 2. Estimation results of multiple quadratic regression model. Note: *** indicates significance at the levels of 1%.

Variables	Coefficient	T Statistic
cost	5.27×10^{-3} ***	8.63
$cost^2$	-3.72×10^{-7} ***	−4.15
age	0.048 ***	13.20
age^2	−0.001 ***	−12.80
edu	0.051 ***	10.86
revenue	−0.167 ***	−6.87
off-farm	−0.256 ***	−10.89
pergdp	0.001	−0.35
urban	0.002 ***	4.28
constant	−0.582 ***	−7.87
inflection point	708	
R^2	0.702	
N	806	

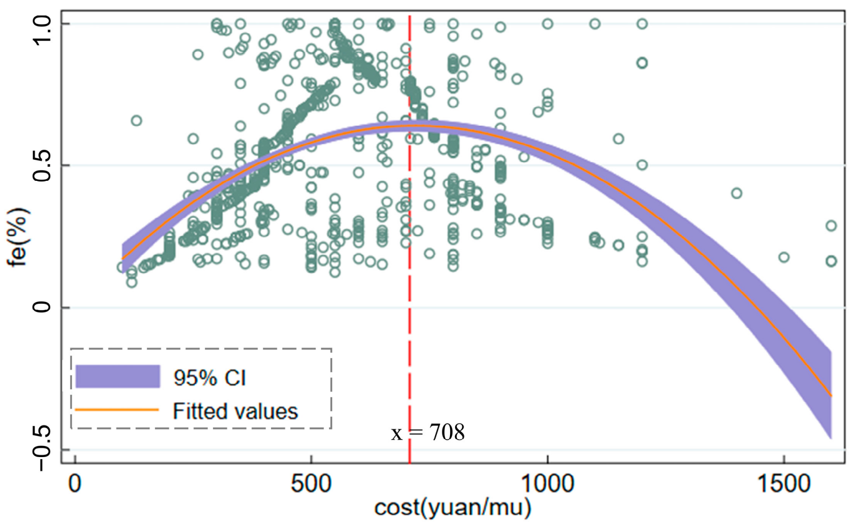

Figure 4. The inverse "U" shape relationship between *cost* and *fe*.

The inverted U-shaped effect of *cost* on *fe* is relatively consistent with the change curve of fertilizer use efficiency theoretically analyzed here, suggesting that the effect of farmland cost on fertilizer use efficiency changes from promotion to inhibition with the increase in farmland cost. Specifically, in the phase of moderate increase in farmland costs, the increase promotes the fertilizer use efficiency. This means that when the farmland cost is low, producers tend to buy relatively low-priced farmland, resulting in an input structure characterized by more farmland and less fertilizer among production factors, and the fertilizer use efficiency is at a low level owing to the relatively insufficient amount of fertilizer input. In the phase of moderate increase in farmland cost, producers increase the amount of fertilizer input and reduce the area of farmland input, as fertilizers act as a substitute production factor for farmland. Fertilizer use is gradually matched with the scale of farmland, technology level, and other factors; the input structure of production factors is optimized, and the efficiency of fertilizer use is continuously improved. In addition, the moderate rise in the farmland cost encourages market competition, leading to the gradual elimination of producers with poor operating ability and insufficient factor endowment from the market. As competent operators and large-scale households become the main agricultural producers, they improve at solving the technical constraints faced by agricultural green production, and fertilizer use efficiency is further improved. Therefore, the overall fertilizer use efficiency shows an increasing trend with the rising farmland cost.

However, as the farmland cost rises further to an excessive level, the impact on fertilizer use efficiency changes structurally to inhibit fertilizer use efficiency improvements. That is, when the farmland cost is relatively high, agricultural producers are financially constrained such that their willingness to purchase farmland and substitute fertilizers with relatively lower prices is reduced. The limited scale of farmland for production causes a structural distortion of less farmland and more fertilizer in production factor inputs, and fertilizer use efficiency is reduced because of excessive fertilizer inputs. In addition, an overpriced farmland destroys the original supply-and-demand balance in the market, causing the competitive mechanism of farmland market to fail. The production incentives for agricultural subjects—capable operators and large-scale households, the technical spillover of scale effect, and producer specialization—all suffer, further indirectly causing the reduction of fertilizer use efficiency.

From the regression results of the control variables, we see at the peasant level a significant inverted U-shaped relationship between *age* and *fe*, indicating that peasants of moderate age have richer management ability and production experience and can improve the efficiency of fertilizer use by optimizing the allocation structure of production factors. The significant positive correlation between *edu* and *fe* indicates that peasants who are relatively more educated have better agricultural knowledge and management skills and are more likely to improve fertilizer use efficiency through knowledge spillover and technology substitution. At the household level, *off-farm* significantly suppresses *fe*, indicating that off-farm labor leads to a reduction in agricultural labor, and growers tend to choose the more quantity, less frequency approach in fertilizer application to compensate for the lack of agricultural labor, which leads to inefficient fertilizer use. In addition, *revenue* significantly suppresses *fe*, suggesting that growers with a higher proportion of off-farm income have less funds dedicated to agricultural production; agricultural production is simpler and sloppy, and fertilizer efficiency tends to be lower. At the regional level, *pergdp*, *urban*, and *fe* are all positively correlated, but only *urban* passes the significance test. The results suggest that a higher level of urbanization may facilitate the effective flow of labor factors between agricultural production and nonagricultural work, resulting in an exit mechanism for weak business ability and an entry mechanism for strong business ability in agricultural production. Laborers who stay in rural areas for agricultural production usually have better agricultural knowledge and management skills and are better able to solve the technical constraints faced by green agricultural production, thus improving fertilizer use efficiency.

4.3. Analysis of the Impact Mechanisms: Direct and Indirect Effects

Based on the inflection point value of farmland cost, the sample group was first divided into moderate ($cost \leq 708$) and excessive ($cost > 708$) groups. Further, the mediating effect model was used to group the effect mechanism for empirical analysis. The regression results all indicated (Table 3) that farmland cost directly and, through mediating variables, indirectly influenced fertilizer use efficiency. To illustrate the mechanism of the effect of *cost* on *fe* under the excessive farmland cost scenario, we present the following analysis for the excessive farmland cost group.

Table 3. Estimation results of intermediary effects model. Note: *, **, *** denote reaching 10%, 5% and 1% significance levels, respectively; T-statistics in parentheses.

Variable	Model 1	Model 2	Model 3
lncost	−0.522 * (−9.28)	−1.202 *** (−3.51)	−0.485 *** (−8.53)
lnarea	–	–	0.030 *** (2.830)
lnage	0.073 ** (2.47)	0.520 *** (2.90)	0.057 * (1.93)
edu	0.069 *** (8.83)	−0.014 (−0.30)	0.069 *** (9.02)
revenue	−0.168 *** (−3.82)	−0.070 *** (−0.26)	−0.166 *** (−3.83)
off-farm	−0.157 *** (−3.81)	0.061 (0.24)	−0.159 *** (−3.92)
lnpergdp	0.015 (0.11)	0.122 (1.21)	0.012 (0.72)
urban	0.001 (0.11)	−0.003 (−0.31)	0.001 (0.17)
constants	3.576 *** (8.36)	6.927 *** (2.42)	3.384 * (7.93)
R^2	0.672	0.162	0.683
Sobel test	–	–	−0.037 ***
N	141	141	141

Indirect effects: As shown in Table 3, *cost* has a significant and negative coefficient on *fe* (Model 1). After adding the mediating variable *area* (Model 3), *cost* shows a significant negative effect on *fe*, while *area* also shows a significant positive effect on *fe*. The Sobel test results reveal that the mediating effect of *area* on *fe* is significant at −0.037 (Model 3). This indicates that in the high farmland cost scenario, it is impossible for the operators to effectively address the financial constraints caused by excessive cost increases. The farmland market is priced but not marketed, which makes it difficult for the operators to apply green production technology and indirectly inhibits fertilizer use efficiency. In addition, producers' willingness to purchase farmland decreases in the context of excessively rising farmland costs. The insufficient scale of farmland inputs in agricultural production makes it difficult to take advantage of the technological spillover effect of the scale effect of agricultural production, which further inhibits fertilizer use efficiency.

Direct effects: After deducting the mediating effect of *area* from the total effect, the remaining part then reflects the magnitude of the factor substitution effect. The parameter estimation results reported in Model 3, Table 3 show that in the excess group, after deducting the mediating effect of *area*, the effect of *cost* on *fe* remains significant at −0.485. This suggests that the high cost of farmland further increases the relative price of farmland and that fertilizers continue to play a substitution role for farmland. However, the limited scale of farmland inputs leads to the structural distortion of less farmland and more fertilizer, thus reducing fertilizer use efficiency due to excessive fertilizer inputs.

4.4. Estimations Results between Ordinary Farmers and New Agricultural Operators

After dividing the samples into groups of general farmers and new agricultural operators, the multiple quadratic regression of farmland cost on fertilizer use efficiency was rerun. The model estimation results (Table 4) show that both the primary and secondary terms of farmland cost in the two sample groups significantly affect the fertilizer use efficiency at the 1% level, and both have great inflection points, which are CNY 638/mu and CNY 823/mu. According to the two sets of inflection points, the farmland costs in the samples were classified into two stages: suitable and excessive. An inverted U-shaped relationship was found between *cost* and *fe* in both the general farmers' group and the group of new agricultural operators. This means that with the shift from moderate to excessive increase in farmland cost, the impact of farmland cost on fertilizer use efficiency structurally changes from promotion to an inhibition (Figure 5). In particular, the excessive increase in farmland cost hinders the improvement of fertilizer use efficiency, which further verifies our theoretical analysis and the empirical results for the full sample.

Table 4. Model estimation results of different growers Note: *** denotes reaching 1% significance levels.

Variables	Model 1 (Ordinary Farmers)		Model 2 (New Agricultrul Operators)	
	Coefficient	T Statistic	Coefficient	T Statistic
cost	8.10×10^{-3} ***	7.12	5.72×10^{-3} ***	8.63
cost^2	-6.35×10^{-7} ***	−7.00	-3.47×10^{-7} ***	−4.15
age	0.042 ***	11.21	0.066 ***	4.64
age^2	−0.001 ***	−10.82	−0.001 ***	−4.70
edu	0.054 ***	10.24	0.031 ***	3.19
revenue	−0.208 ***	−7.95	0.013	0.22
off-farm	−0.228 ***	−9.17	−0.273 ***	−4.40
pergdp	0.001	−0.87	0.001	0.98
urban	0.002 ***	4.31	0.001	0.27
constant	−0.547 ***	−7.24	−0.851 ***	−3.03
inflection point value	638		823	
R^2	0.719		0.599	
N	665		141	

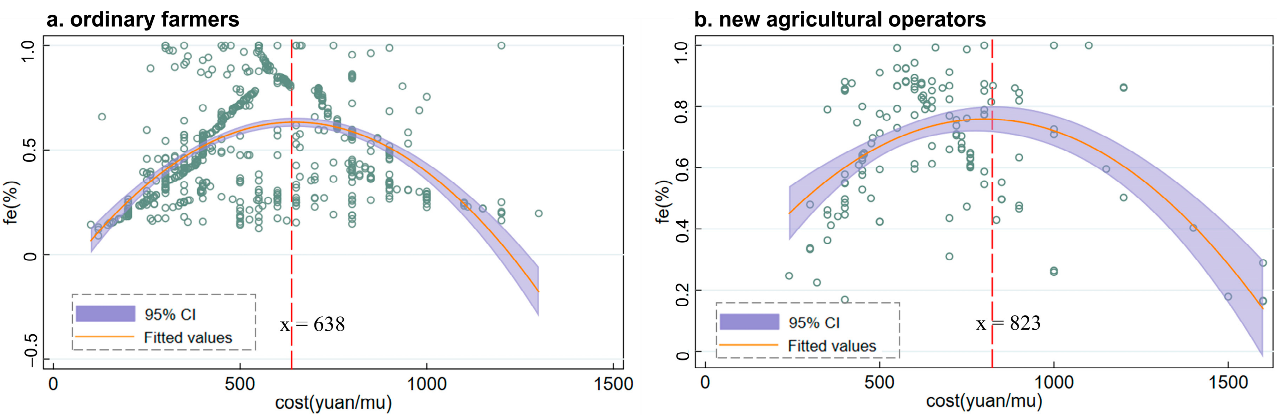

Figure 5. The scatter plots of *cost* and *fe* in ordinary farmers and new agricultural operators.

Notably, the inflection point of the ordinary farmers is smaller than that of the new agricultural operators. This indicates that the fertilizer use efficiency of ordinary farmers is more vulnerable to the excessive increase in farmland cost compared with that of new agricultural operators. The reason for this is that different types of producers have different factor allocation behaviors and factor endowments. Compared with ordinary farmers, new agricultural operators, such as large grain farmers and family farms, usually have better agricultural knowledge and management skills at the same factor input level and are better able to solve the financial constraints faced by agricultural production. With rising farmland costs, the new agricultural operators can maintain their profit margin in agricultural production in various ways such as technological substitution and factor structure optimization, which are more tolerant of the rising farmland costs. Therefore, fertilizer use efficiency is less affected by the farmland cost.

5. Discussion

5.1. Innovations and Outlooks for Future Research

High farmland costs have become an important feature of China's agricultural production environment. However, relatively little attention has been paid to the loss of fertilizer use efficiency caused by rising farmland cost. This study's contributions are summarized as follows: (1) We focus on fertilizer use efficiency from the perspective of rising farmland costs and identify key factors for the poor fertilizer reduction effect of farmland transfer; (2) the effect of rising farmland costs on fertilizer use efficiency is revealed, and the underlying mechanism and feasible strategies to promote fertilizer efficiency by reducing farmland costs are clarified; (3) by differentiating between ordinary farmers and new agricultural operators, this study reveals the differences in production behavior of different operators in the face of rising farmland costs, and provides a new policy logic for fertilizer reduction.

However, this study has its limitations. First, as revealed in previous studies, differences in crop type can lead to large variations in fertilizer use [19], and more fertilizers tend to be used in nongrain crops [7]. Moreover, another study suggested that rising farmland costs drive producers to prefer nongrain crops [54]. This suggests that fertilizer use efficiency and planted crop types may vary with the extent of rising farmland costs. Therefore, in the context of rising farmland costs in China, especially in the current environment of increasing cash crop acreage in China, there is an urgent need to further analyze the impact of rising farmland costs on fertilizer use efficiency from the perspective of changes in planted crop types in the future. Second, because of issues on the availability of microdata on farmers, some potential explanatory variables, such as soil conditions and degree of farmland use, were omitted in this study, and only cross-sectional microdata for 2019 were used. Additionally, there may be a mutual causal relationship between farmland cost and fertilizer use efficiency. As plots with higher fertilizer use efficiency tend to have higher output values that can further counteract farmland prices, this phenomenon should be further investigated. In future work, these issues can be adjusted and expanded through a combination of long time series and multiple cross-sectional data to provide a comprehensive understanding of farmland costs and fertilizer use efficiency. In addition, China is a large country with obvious geographical differences, and the selection of local cities in Gansu and Jiangsu may not provide sufficient evidence to reveal the whole picture and draw general conclusions. In future work, this study can be further improved by integrating more cities with different natural endowments and social development characteristics.

5.2. Policy Implications

This study shows that the high rise in farmland cost has become the main obstacle to sustainable agricultural production in China. Achieving the green development of Chinese agriculture requires both organic integration with the current farmland transfer market and the improvement of China's current fertilizer reduction policies.

First, the standardized management of the farmland transfer market should be strengthened, for example, through the development of land transfer information platforms, contract management, price evaluation, and other services to prevent excessive increases in farmland costs. The government should increase subsidies for the producers who use farmland, and especially for fertilizer reduction, establish a fertilizer reduction compensation system based on market price compensation, supplemented by government ecological compensation. In addition, a monitoring mechanism for farmland prices should be established, and fixed sample points should be selected nationwide to monitor farmland prices regularly.

Second, against the backdrop of the high farmland costs in China, the Chinese government should recognize the necessity of various forms of moderate-scale operations. Integrating smallholder production into the modern agricultural development track with the help of agricultural production services not only helps prevent the risk of high land costs but also ensures the sustainable development of agricultural scale operations. For example, the scale of agricultural services can realize contiguous scale economy by facilitating the mechanization of fertilizer application behavior to compensate for the indistinguishability of fertilizers.

Third, because new agricultural operators are more efficient in fertilizer use and less affected by excessive increases in farmland costs, the Chinese government should vigorously cultivate new agricultural operators in the future. For new agricultural business entities, the establishment of awards in lieu of subsidies can further encourage them to make long-term investments that are conducive to fertilizing the land and promote models and experiences of chemical fertilizer reduction technologies. Meanwhile, the government should encourage ordinary farmers to transform into new agricultural operators, for example, by increasing compensation for fertilizer reduction and actively guiding them to adopt new technologies (such as soil inspection and fertilizer application).

6. Conclusions

To identify the key factors that constrain farmland transfer in China and influence fertilizer reduction, in the context of high farmland costs in China, this study theoretically analyzed the mechanism and effect of rising farmland costs on fertilizer use efficiency. Accordingly, a multiple quadratic regression model and a mediating effects model were used to test empirically a microsample of 806 famers in Gansu and Jiangsu provinces of China and provide empirical support for the theoretical analysis in two dimensions: full samples and grower heterogeneity. We draw the following conclusions.

The lack of fertilizer use efficiency due to excessive fertilizer input is a serious problem in China, and we calculated the average fertilizer use efficiency of growers in Gansu Province and Jiangsu Province in China to be 0.544. The multiple quadratic regression model further revealed an inverted U-shaped relationship between farmland costs and *fe*, and the U-shaped curve showed a remarkable inflection point at the farmland cost of 708 Yuan/mu. The influence of rising farmland costs on *fe* showed a structural change from promotion to inhibition. Specifically, when the farmland costs were excessive ($cost > 708$ yuan/mu), the increase in farmland costs inhibited the *fe*. Then, we investigated the impact mechanism under the scenario of an excessive rise in the farmland costs ($cost >$ USD 708/mu). We found that farmland costs directly suppressed *fe* (−0.485) by distorting the fertilizer factor substitution effect and indirectly suppressed *fe* (−0.037) by impeding the technology spillover effect of production specialization and production scale-up. In addition, we found heterogeneity between ordinary farmers and new agricultural operators (e.g., large grain farmers, family farmers, etc.), with the peak kernel density function of *fe* of new agricultural operators (0.85) being much higher than that of ordinary farmers (0.30). Moreover, the multiple quadratic regression between the general farmers and new agricultural operators revealed that the inflection point value of the ordinary farmers (638 yuan/mu) was lower than that of the new agricultural operators (823 yuan/mu), indicating that the *fe* of ordinary farmers is more likely to be inhibited by the excessive rise in farmland costs. The reasons for this are that new agricultural operators usually have better agricultural knowledge and management skills, and they are better able to address the technical constraints faced by green agricultural production. In the face of rising farmland costs, they maintain profit margins in multiple ways such as through technological substitution and factor structure optimization. Therefore, new agricultural operators are more tolerant of the rising cost of farmland, and their fertilizer use efficiency is less affected by the cost of farmland.

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