

The Impact of Land Management Scale on the Fertilizer Reduction Effect from the Perspective of Differences in Plot Characteristics

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Abstract:

In the context of severe agricultural non-point source pollution, this study seeks to investigate the mechanisms through which land management scale influences fertilizer use intensity, which is of both theoretical and practical significance for advancing green agricultural development in China. Utilizing micro-survey data from 615 rice farmers in Jiangxi Province, the research applies a two-stage least squares method with instrumental variables to explore the underlying relationship between land management scale and the reduction of fertilizer use intensity. The findings reveal a significant “U-shaped” relationship between land management scale and fertilizer use intensity, with an optimal land management scale of 8.62 acres. Furthermore, the degree of land fragmentation moderates the effect of land management scale on fertilizer reduction, with higher levels of fragmentation weakening this relationship. In contrast, the proportion of consolidated land strengthens the impact. Additionally, farmer age positively correlates with fertilizer use intensity, while education level and participation in agricultural technical training negatively influence it. Based on these results, the study concludes that improvements to the land transfer system are essential for promoting moderate-scale farming operations. It also advocates for the consolidation of farmland into contiguous plots and the enhancement of high-standard farmland infrastructure. Moreover, the study underscores the importance of elevating the overall quality of agricultural labor and fostering the development of new types of professional farmers.

Keywords:

Land Management Scale, Fertilizer Reduction Effect, Plot Characteristics, Farmer Differences, Jiangxi Province

1. Introduction

Fertilizers are a pivotal input in the agricultural sector, playing a central role in enhancing crop yields and driving the rapid development of the agricultural industry. However, the excessive use of fertilizers has engendered significant environmental

externalities, emerging as a formidable barrier to China's pursuit of sustainable agricultural development. As the world's largest consumer of fertilizers, China accounts for one-third of global fertilizer use intensity. Yet, fertilizer utilization efficiency is a mere 35%, markedly lower than the average levels observed in developed nations [1]. Since 2015, the "No. 1 Central Document" has consistently underscored the importance of reducing fertilizer use. As a result, the annual growth rate of fertilizer consumption has steadily declined. However, given the vast baseline of fertilizer use intensity in China, the reduction effects have yet to meet the initial policy expectations. Green development is the foundational principle of agriculture, with fertilizer reduction as an essential pathway to achieving sustainable agricultural progress. The shift toward large-scale land management as a transformative approach to agricultural operation is increasingly regarded as an effective means of addressing the problem of excessive fertilizer use. By actively promoting land circulation and large-scale farming, it is possible to reach fertilizer reduction targets, foster agricultural sustainability, and enhance the agricultural sector's competitiveness. With the advancement of urbanization, a significant migration of rural labor has occurred, and land transfer has become increasingly prevalent. Agricultural land is gradually concentrated in the hands of new types of large-scale operators, including professional farming households, family farms, and agricultural cooperatives [2]. This shift in agricultural management practices has created favourable conditions for the optimized allocation of production factors and presents a timely opportunity to address the issue of excessive fertilizer use. In China's pursuit of high-quality agricultural development, managing the overuse of fertilizers is critical to the country's ability to achieve its sustainable development strategy in agriculture. As such, investigating the impact of large-scale land management on fertilizer reduction has become an urgent priority.

The quality of arable land is intrinsically linked to a nation's food security and ecological stability. While fertilizers have significantly contributed to China's grain production, they have also precipitated soil degradation, eutrophication of water bodies, and the intensification of the greenhouse effect. Promoting a reduction in fertilizer use is not only a fundamental measure to strengthen the foundation of food security but also an imperative step in accelerating the green transformation of agriculture. This shift is paramount for China's food security and ecological well-being [3]. Moderate-scale farming can play a pivotal role in leading agricultural green development and is one of the key pathways for promoting fertilizer reduction. Therefore, it is essential to elucidate how land management scale influences fertilizer reduction, particularly in the context of variations in land parcel characteristics. This understanding will enrich domestic research on agricultural green development and provide valuable insights and evidence for further advancing fertilizer reduction efforts in Jiangxi Province.

The key determinant of farmers' fertilizer use intensity behavior is the scale of their operations. Fully leveraging the leadership role of moderate-scale farming in agricultural green development has become a critical policy focus in the ongoing battle against agricultural non-point source pollution [2,4]. In recent years, research on the relationship between agricultural production scale and the effects of fertilizer reduction has attracted widespread attention from scholars, giving rise to a variety of viewpoints and propositions. The majority of scholars assert that expanding the scale of operations can effectively reduce fertilizer use per unit of land. Research has confirmed that for every 1% increase in the scale of agricultural operations in China, fertilizer use intensity decreases by approximately 0.3%. Some scholars [5] present an

opposing view, suggesting that when production goals are set to maximize profits, an expansion in land management scale may lead to a greater willingness among farmers to increase fertilizer use, with the aim of maximizing short-term profits. Some scholars [6] have found that the relationship between land management scale and fertilizer use intensity is nonlinear. Based on farmland transfer data, some researchers have confirmed that the fertilizer reduction effect of large-scale land management exhibits uncertainty. Additionally, some scholars have found that there is a threshold in farmland scale regarding fertilizer utilization, with the relationship between scale of operation and fertilizer use following a U-shaped curve. That is, before reaching the threshold of moderate-scale farming, an increase in operational scale effectively reduces fertilizer use intensity. However, once this threshold is surpassed, unchecked expansion of the farming scale may exacerbate fertilizer use intensity.

A review of the literature reveals that the research achievements of numerous scholars provide a solid theoretical foundation for this study. However, there are still areas that warrant further exploration. First, the academic community needs to have more consensus regarding the relationship between land management scale and fertilizer use intensity. Therefore, further clarification of the relationship between land management scale and fertilizer use intensity in Jiangxi Province will contribute to providing more scientifically grounded policy recommendations for the region. Second, land parcel characteristics have a significant impact on land use. This study introduces two additional parcel characteristics—land fragmentation and the proportion of land area transferred for cultivation—into the analysis, examining how these factors influence the effect of land management scale on fertilizer use intensity. Based on this, the study uses micro-level survey data from rice farmers in Jiangxi Province. It employs a two-stage least squares method with instrumental variables to test the impact of land management scale on fertilizer use intensity. This approach will help provide scientific evidence for policy-making on land use and sustainable development in Jiangxi, offering valuable insights into the sustainable use of similar land types.

2. Theoretical Analysis and Research Hypotheses

From the perspective of economies of scale, farmers engaged in large-scale operations are more inclined to adopt innovative agricultural technologies. The fixed costs associated with modern agricultural technologies remain unchanged regardless of land area. As the scale of operation increases, the fixed unit cost gradually decreases, enabling large-scale farming to reduce the per-unit cost of technological inputs effectively. Furthermore, the contiguous land management brought about by large-scale operations helps reduce the transaction costs of production inputs between parcels, creating favourable conditions for mechanized fertilization. Moreover, mechanized deep ploughing, tillage, and fertilization technologies have significantly enhanced soil fertility and fertilizer utilization, reducing fertilizer use intensity. However, it is worth considering that once a particular scale of operation is reached, blind expansion by farmers may lead to increased costs, resulting in the phenomenon of "diseconomies of scale." Based on this, the following research hypothesis is proposed:

Hypothesis 1: Within the range of moderate scale, an increase in land management scale contributes to a reduction in fertilizer use.

Jiangxi Province is characterized by relatively small-scale arable land and high land fragmentation. The dispersed nature of land parcels limits the effectiveness of input substitution, leading farmers to increasingly rely on agricultural chemicals as substitutes for labor, thus undermining efforts to reduce fertilizer use intensity. Additionally, the indivisibility of agricultural production infrastructure makes it difficult for fragmented land parcels to share the costs of production tools, thereby diminishing the benefits of economies of scale. This situation significantly increases production costs, such as those related to farmland management and the transportation of production inputs, and further hinders efforts to reduce fertilizer use intensity. Based on this, the following research hypothesis is proposed:

Hypothesis 2: The fragmentation of land parcels limits the effectiveness of fertilizer reduction, as it elevates operational costs and undermines economies of scale.

The expansion of operational scale is typically achieved through land inflow. Farmers tend to acquire land adjacent to their own, reducing land fragmentation and creating contiguous, modern agricultural operations. Alternatively, they may acquire fertile land to decrease the overall use of fertilizers. From the perspective of large-scale farmers, who typically manage larger plots and derive a higher proportion of their income from agriculture, there is often a greater focus on agricultural production. Their increased motivation to adopt specialized agricultural techniques enables them to acquire scientific knowledge and management skills, thereby facilitating more rational and efficient fertilizer use intensity. Based on this, the following research hypothesis is proposed:

Hypothesis 3: The proportion of land inflow moderates the effect of land management scale on fertilizer reduction, enhancing the overall impact.

3. Data Sources, Variable Selection, and Model Specification

3.1. Data Sources

The data used in this study were obtained from a survey conducted during the summer of 2021 and the winter of 2022 in Jiangxi Province, covering eight counties (cities)—Wannian, Nanchang, Xinjian, Xingzi, Jiujiang, Lianhua, Xihu District of Pingxiang, and Xingguo—and spanning 32 townships and 62 natural villages. The survey employed a combination of stratified sampling and random sampling methods. Initially, based on regional distribution, one county (district) was selected from each of the four East, West, South, and North Jiangxi regions, with one county representing higher and lower economic development levels. Then, four townships from each county were selected based on their economic development and grain production conditions. Within each township, 1-3 villages were chosen, and 10-20 households were randomly selected for questionnaire distribution within each town. In total, 820 questionnaires were distributed. During data processing, samples with missing data in core variables were excluded, and extreme values were trimmed by winsorizing continuous variables to ensure the smoothness of the research data. Ultimately, 615 valid samples were obtained.

Jiangxi Province is surrounded by mountains east, west, and south, while the northern region borders the Yangtze River and Poyang Lake. A mix of hills and river valley plains characterizes the central part of the province. This strategic geographic location and abundant ecological resources have led to a diversified and efficient utilization of arable land in Jiangxi, making it one of China's twelve major grain-

producing regions and a key focal point in the Yangtze River Protection initiative. Therefore, studying the impact of land management scale on fertilizer reduction in Jiangxi Province is essential for promoting the region's high-quality, green, and low-carbon agricultural development.

3.2. Variable Selection

In this study, the dependent variable is fertilizer use intensity. The calculation method determines the average fertilizer input per mu of land, adjusted for purity, for rice-growing farmers. This study's core explanatory variable is the land management scale, measured by the rice cultivation area per farmer. Given the potential non-linear relationship between land management scale and fertilizer use intensity, the square of land management scale is also included as an additional core explanatory variable. The key variables selected for land characteristics include the degree of land fragmentation and the proportion of land inflow. These variables, along with their interaction term with the scale of land management, are included as core explanatory variables in the regression model. This study follows existing research to mitigate potential biases in the regression model estimates due to omitted variables. It includes the following control variables: age, education level, participation in agricultural technical training, total agricultural income, and whether the farmer has purchased agrarian insurance. This study uses the proportion of land transfer area, excluding that of a specific farmer, to the total arable land area in the same county as the instrumental variable for the land management scale.

Table 1. Descriptive Statistics.

Variable	Variable Names	Variable Descriptions	Mean	Standard Deviation
Dependent Variable	Fertilizer Use Intensity	Adjusted Fertilizer Input per Farmer	49.49	4.95
Core Explanatory Variables	Land Management Scale	Farmer's Rice Cultivation Area	4.43	3.51
	Square of Land Management Scale	Square of Farmer's Rice Cultivation Area	31.93	60.50
	the Degree of Land Fragmentation	Number of Cultivated Plots per Total Cultivated Area	0.62	0.38
	the Proportion of Land Inflow	Proportion of Inflow Land Area to Total Cultivated Area	0.46	0.20
Control Variables	Age	Farmer's Actual Age	55.31	11.09
	Education Level	Years of Education	6.42	2.82
	Participation in Agricultural Technical Training	Yes=1; No=2	1.15	0.35
	Total Agricultural Income	Natural Logarithm of Household Total Agricultural Income	8.78	1.19
	Whether Purchased Agricultural Insurance	Yes=1; No=2	1.34	0.48
Instrumental Variables	Ratio of Land Transferred by Other Family Farms in the Same County to Total Managed Land Area (%)		0.57	0.32

3.3. Model Specification

Considering the issue of endogeneity, this study follows the approach of Zhihui Liang [7] and employs an instrumental variable two-stage least squares (IV-2SLS) model. The specification is as follows in Equation (1):

$$F_i = \beta_0 S_i + \beta_1 S_i^2 + \gamma X_i + \varepsilon_i \quad (1)$$

Where F_i represents the fertilizer use intensity of the i -th farmer. Where S_i represents the land management scale of the i -th farmer. Where S_i^2 represents the square of the land management scale for the i -th farmer. Where X_i represents the control variables. Where β_0 , β_1 and γ are the coefficients to be estimated in the model. Where ε_i represents the error term.

The equations for the models including interaction terms are as follows in Equation (2) and Equation (3):

$$F_i = \beta_0 S_i + \beta_1 S_i^2 + \beta_2 T_i \times S_i + \gamma X_i + \varepsilon_i \quad (2)$$

$$F_i = \beta_0 S_i + \beta_1 S_i^2 + \beta_2 Q_i \times S_i + \gamma X_i + \varepsilon_i \quad (3)$$

Where T_i represents the degree of land fragmentation for the i -th farmer. Where Q_i represents the proportion of land inflow for the i -th farmer. To mitigate heteroscedasticity, the natural logarithm of total agricultural income is applied. To address potential multicollinearity induced by the interaction terms, these terms are mean-centered.

4. Results Analysis

In this study, Stata 17.0 software was used to test for multicollinearity among the explanatory variables. The results show that the variance inflation factor (VIF) ranges from a maximum of 1.45 to a minimum of 1.02, with an average VIF of 1.11, all well below the threshold of 10. This indicates no significant multicollinearity among the explanatory variables, and the variable selection is reasonable.

4.1. Comparative Analysis of Regression Results

As shown in Model (1), Model (2), and Model (3), the direction of the regression coefficients in OLS and IV-2SLS is consistent, with the linear term coefficient being negative and the quadratic term coefficient being positive. This indicates a significant "U"-shaped relationship between land management scale and fertilizer use intensity, thus validating Hypothesis 1. Further comparison of the coefficients for the land management scale reveals that the absolute value of the coefficient for the land management scale in the OLS model (0.440) is much smaller than the absolute value of the coefficient in the second stage of the IV-2SLS model (2.356). This suggests that neglecting endogeneity leads to underestimating the regression results, thereby exaggerating the impact of land management scale on fertilizer use intensity. The coefficient for the squared term of the land management scale also shows a similar pattern. This indicates that the IV-2SLS results are robust and stable. Subsequent analysis is based on the IV-2SLS regression results, and due to space limitations, only the second-stage results of the IV-2SLS model will be presented in the following sections.

Table 2. The Impact of Land Management Scale on Fertilizer Use Intensity.

Variable	Model (1)OLS	Model(2)IV-2SLS-1	Model(3)IV-2SLS-2
Land Management Scale	-0.440**	—	-2.356***
	(-2.158)		(-5.312)
Square of Land Management Scale	0.016***	0.050***	0.111***
	(1.462)	(0.201)	(0.264)
the Degree of Land	-0.246***	-1.655***	-3.415***

Fragmentation	(-0.358)	(-0.119)	(-8.809)
the Proportion of Land Inflow	1.721**	0.153***	1.846**
	(1.692)	(0.221)	(1.134)
Age	0.019***	0.002**	0.017***
	(0.996)	(0.004)	(0.022)
Education Level	-0.111**	-0.101**	-0.109***
	(-0.475)	(-0.015)	(-0.080)
Participation in Agricultural Technical Training	-0.194*	-0.158**	-0.118***
	(-0.342)	(-0.113)	(-1.053)
Total Agricultural Income	0.107	0.166	0.213
	(0.086)	(0.036)	(0.008)
Whether Purchased Agricultural Insurance	-0.540	-0.113	-0.331
	(-0.273)	(-0.084)	(-0.033)
Instrumental Variables	—	-0.135***	—
		(0.134)	
Constant	49.866***	52.539***	54.738***
	(15.245)	(14.479)	(13.461)
R ²	0.332	0.324	0.371
Wald	—	—	13.910***
Number	615	615	615

Note: ① *, **, *** represent significance at the 10%, 5%, and 1% levels, respectively. ② The values in parentheses under the coefficients are the standard errors of your table or results section to avoid any ambiguity.

4.2. The Impact of Land Management Scale on Fertilizer Use Intensity

As shown in Model (3), with the expansion of the land management scale, fertilizer use intensity initially decreases and then increases, exhibiting a "U"-shaped curve. The turning point occurs at 8.621 acres, indicating that the optimal land management scale is 8.62. The fundamental reason for this phenomenon lies in the trade-off between the costs of farming and the income derived from it. As the land management scale approaches the optimal scale, economies of scale in agricultural production begin to manifest. The costs of farm mechanization and the adoption of green agricultural technologies decrease while the efficiency of fertilizer use improves. Consequently, farmers no longer need to use large amounts of fertilizer, and the intensity of fertilizer use declines.

When the land management scale reaches the optimal level, there is an ideal match between the available labour, capital, and other production factors within the household, maximizing the profit from farming. However, agricultural production enters a more specialized phase as the land management scale expands. Due to the constraints of household resources, the marginal cost of production increases rapidly, especially as human capital demands rise significantly. At this stage, farmers are incentivized to adopt extensive farming practices and compensate for labor shortages by increasing fertilizer use, leading to a sharp rise in fertilizer use intensity.

Therefore, it can be concluded that expanding the land management scale only helps reduce fertilizer use intensity when the farm operates at an optimal scale, thus confirming Hypothesis 1. Some scholars argue that fertilizer use intensity decreases as land management scale increases, which contradicts the findings of this study. This discrepancy may be due to these scholars performing linear analyses without considering the square term of land management scale in their models.

4.3. The Impact of Plot Characteristics on Fertilizer Use Intensity

4.3.1. The Impact of the Land Fragmentation Degree on Fertilizer Use Intensity

As shown in Model (3), the coefficient of the land fragmentation degree is significantly negative, indicating that the land fragmentation degree is negatively correlated with fertilizer use intensity. In other words, an increase in the degree of land fragmentation reduces fertilizer use intensity. This is because the degree of land fragmentation increases the complexity of land management, prompting farmers to adopt more conservative fertilization practices to avoid waste. Additionally, land with a higher land fragmentation degree typically cannot achieve economies of scale, making it difficult for farmers to use large machinery and intensive techniques for efficient fertilization. Uneven fertilization and higher production costs encourage farmers to reduce fertilizer inputs, thus limiting fertilizer use intensity.

4.3.2. The Impact of the Proportion of Land Inflow on Fertilizer Use Intensity

As shown in Model (3), the coefficient for the proportion of land inflow is significantly positive, indicating that the proportion of land inflow is positively correlated with fertilizer use intensity. In other words, an increase in the proportion of land inflow leads to an increase in fertilizer use intensity. This is because, once an appropriate land management scale is achieved, if farmers continue to excessively pursue the expansion of their land management scale, fertilizer use intensity is likely to increase. Over-expansion of land management scale may lead farmers to depend more on fertilizers to increase yields, especially in large-scale production, where high-input, high-output farming models are standard. Although economies of scale may reduce some production costs, the excessive focus on yield often results in a substantial increase in fertilizer inputs to ensure crop growth and high yields. Furthermore, as the land management scale expands, farmers may encounter more significant difficulties in farm management, leading to uneven fertilization and inefficiency. As a result, they may increase fertilizer use intensity to compensate for management deficiencies, further increasing fertilizer use intensity.

4.4. The Moderating Role of the Land Fragmentation Degree and the Proportion of Land Inflow on Fertilizer Use Intensity

To examine how land management scale affects fertilizer use intensity, this study employs a moderating effect analysis, incorporating the land fragmentation degree and the proportion of land inflow into the model to test their impact on the relationship between land management scale and fertilizer use intensity.

4.4.1. Moderating Effect of the Land Fragmentation Degree

As shown in Model (4), the land fragmentation degree and land management scale significantly positively affect fertilizer use intensity at the 1% level, indicating that the land fragmentation degree weakens the land management scale effect on fertilizer use intensity. In other words, as the land management scale expands, the deeper the land fragmentation degree, the less conducive it is to reducing fertilizer use. The reason is that the expansion of the land management scale often accompanies an increase in the degree of land fragmentation. Although more significant agricultural production may lead to reduced fertilizer use, this effect is usually offset by the increased difficulty of managing fragmented land, prompting farmers to increase fertilizer use to cope with management challenges, ultimately increasing fertilizer use intensity. Thus,

Hypothesis 2 is supported. On the contrary, if the land plots are contiguous, land management scale and plot size will expand simultaneously. The economies of scale at the plot level form the basis of the farmer's economies of scale, and the benefits of contiguous land management facilitate fertilizer reduction. Therefore, as farmers expand their land management scale, they should aim to integrate inflowing land with their own, creating contiguous farming land.

4.4.2. Moderating Effect of the Proportion of Land Inflow

As shown in Model (5), the proportion of land inflow and land management scale has a significant negative effect on fertilizer use intensity at the 5% level, indicating that the Proportion of Land Inflow strengthens the impact of land management scale on fertilizer use intensity. In other words, as the land management scale expands, a higher proportion of land inflow is more conducive to reducing fertilizer use. The primary reason for this is that, on the one hand, an increase in total cultivated land area facilitates the formation of large-scale farming, improving agricultural production management, promoting mechanization, and applying precision fertilization techniques. This allows for precise fertilizer use intensity and optimized resource allocation, reducing fertilizer waste, improving fertilizer efficiency, and increasing land use efficiency, effectively reducing fertilizer use intensity. On the other hand, contiguous land breaks through the barriers of field ridges, making large-scale machinery operations possible, thereby promoting the reduction of fertilizer use and specialized farming practices. Furthermore, land consolidation encourages farmers to shift from a scattered, multi-plot mode to monocropping, improving land use and labor efficiency and avoiding the "tragedy of the commons." Therefore, Hypothesis 3 is supported.

Table 3. Moderating Effects of the Land Fragmentation Degree and the Proportion of Land Inflow.

Variable	IV-2SLS-2	
	Model (4) adds the interaction term between the Degree of Land Fragmentation and Land Management Scale	Model (5) adds the interaction term between the Proportion of Land Inflow and Land Management Scale
Land Management Scale	-4.720*** (-7.006)	-1.774*** (-5.070)
Square of Land Management Scale	0.255*** (0.372)	0.089*** (0.278)
the Degree of Land Fragmentation	-5.649*** (-10.904)	—
the Proportion of Land Inflow	—	1.678** (1.077)
the Degree of Land Fragmentation×Land Management Scale	1.181*** (1.079)	—
the Proportion of Land Inflow×Land Management Scale	—	-0.266** (-0.660)
Control Variables	Control	Control
Constant	56.591** (14.561)	53.736*** (13.587)

R ²	0.320	0.419
Wald	12.458***	14.234***
Number	615	615

Note: ① *, **, *** represent significance at the 10%, 5%, and 1% levels, respectively. ② The values in parentheses under the coefficients are the standard errors of your table or results section to avoid any ambiguity.

4.5. The Impact of Other Variables on Fertilizer Use Intensity

Among the control variables, farmer age has a positive effect on fertilizer use intensity, while the level of education and participation in agricultural technology training have negative effects. Specifically, older farmers tend to use more fertilizer, possibly due to traditional farming habits, lower adaptability to new technologies, and a greater need for yield stability. On the other hand, farmers with higher levels of education tend to use less fertilizer, as they are more likely to adopt modern agricultural technologies such as precision fertilization, which improves resource utilization efficiency and thus reduces fertilizer use intensity. Farmers who have participated in agricultural technology training also show significantly lower fertilizer use intensity, likely because they can more accurately assess soil needs and optimize fertilizer management, leading to reduced fertilizer use intensity. The impact of farmers' total agricultural income and whether they purchase agricultural insurance on fertilizer use intensity did not pass significance testing.

4.6. Robustness Test

To further ensure the reliability of the above results, this study conducts a robustness test using the variation estimation method. As shown in Table 4, the regression analysis was performed on both the model without interaction terms (Model 6) and the models with interaction terms (Models 7 and 8). The results were consistent with those previously presented, indicating that the findings are robust. The plot characteristics play a moderating role in the impact of land management scale on fertilizer reduction.

Table 4. Robustness Test.

Variable	IV-2SLS-2		
	Model (6) without the interaction term.	Model (7) adds the interaction term between the Degree of Land Fragmentation and Land Management Scale	Model (8) adds the interaction term between the Proportion of Land Inflow and Land Management Scale
Land Management Scale	-2.356***	-4.720***	-1.774***
	(-5.312)	(-7.006)	(-5.070)
Square of Land Management Scale	0.111***	0.255***	0.089***
	(0.264)	(0.372)	(0.278)
the Degree of Land Fragmentation	-3.415***	-5.649***	—
	(-8.809)	(-10.904)	
the Proportion of Land Inflow	1.846**	—	1.678**
	(1.134)		(1.077)
the Degree of Land	—	1.181***	—

Fragmentation×Land Management Scale		(1.079)	
the Proportion of Land Inflow×Land Management Scale	—	—	-0.266**
			(-0.660)
Control Variables	Control	Control	Control
Constant	54.738***	56.591**	53.736***
	(13.461)	(14.561)	(13.587)
R ²	0.371	0.320	0.419
Wald	13.910***	12.458***	14.234***
Number	615	615	615

Note: ① *, **, *** represent significance at the 10%, 5%, and 1% levels, respectively. ② The values in parentheses under the coefficients are the standard errors.of your table or results section to avoid any ambiguity.

4.7. Heterogeneity Analysis

With the acceleration of urbanization, the generational differentiation of agricultural labor has become increasingly pronounced, leading to significant differences between the new generation and the older generation of farmers in terms of values, ecological awareness, and agricultural production practices. According to relevant research by scholars [2], the survey participants were divided into two groups: the older generation of farmers (born before 1965) and the new generation of farmers (born after 1966).

As shown in Table 5, among the sample farmers, the new generation accounted for the majority, with 358 households representing 58.21%, while the older generation had 257 households representing 41.79%. Comparing models (9), (10), and (11) reveals that even under the influence of generational differences, the relationship between land management scale and fertilizer use intensity remains a stable "U" shape, consistent with previous findings. The underlying reason lies in multiple factors, including technological level, environmental awareness, and economic incentives.

The new generation of farmers typically has higher levels of education and more substantial capabilities for adopting new technologies. Before reaching an optimal land management scale, they can fully utilize modern agricultural technologies to improve land resource efficiency and reduce fertilizer use intensity. Additionally, influenced by the popularization of the "ecological agriculture" concept and the goals of "sustainable development," the new generation of farmers places greater emphasis on environmental protection and food safety. They adopt "low input, sustainable" production methods, reducing excessive reliance on fertilizers. However, after reaching an optimal scale, the complexity of agricultural production management increases. In particular, fragmented land, crop diversification, insufficient labor, and technical support make precise fertilization more complex, increasing fertilizer use intensity. Furthermore, with the expansion of the agricultural production scale, the new generation of farmers often prioritizes production efficiency and market demand. In the absence of corresponding technological support, fertilizers, being a key factor in boosting crop yield, inevitably see an increase in usage.

The older farmers are more inclined to adopt conservation tillage techniques to maintain land sustainability. However, after reaching an optimal land management scale, the difficulty of land management and production complexity significantly

increase, especially as fragmented and dispersed land makes fertilizer management more challenging. Due to the lower level of technology adoption, the older generation of farmers, when facing land-scale expansion, needs more technical support and knowledge updates. As a result, they tend to rely more on increasing fertilizer input to ensure crop yields, leading to higher fertilizer use intensity.

Table 5. Heterogeneity Analysis.

Types of Farmers	Variable	IV-2SLS-2		
		Model (9) without the interaction term	Model (10) adds the interaction term between the Degree of Land Fragmentation and Land Management Scale	Model (11) adds the interaction term between the Proportion of Land Inflow and Land Management Scale
the Younger Generation of Farmers	Land Management Scale	-2.364***	-4.255***	-3.073***
		(-4.5753)	(-6.8517)	(-6.7314)
	Square of Land Management Scale	0.108***	0.222***	0.153***
		(0.220)	(0.347)	(0.354)
	the Degree of Land Fragmentation	-3.055***	-3.908***	—
		(7.822)	(10.063)	
	the Proportion of Land Inflow	1.789***	—	1.824**
		(1.917)		(2.071)
	the Degree of Land Fragmentation×Land Management Scale	—	1.164***	—
			(1.007)	
	the Proportion of Land Inflow×Land Management Scale	—	—	-0.385**
				(-0.853)
	Control Variables	Control	Control	Control
	Constant	57.377***	64.196***	57.026***
		(17.508)	(25.887)	(17.572)
the Older Generation of Farmers	R ²	0.271	0.352	0.369
	Wald	13.687***	13.558***	15.934***
	Number	358	358	358
	Land Management Scale	-3.130***	-3.765***	-2.396**
		(-3.422)	(-8.822)	(-7.754)
	Square of Land Management Scale	0.332***	0.241***	0.155***
		(0.678)	(0.557)	(0.478)
	the Degree of Land Fragmentation	-5.717**	-4.152***	
		(9.611)	(12.230)	
	the Proportion of Land Inflow	1.044***		1.820***
		(1.974)		(1.476)
	the Degree of Land Fragmentation×Land Management Scale	—	1.778***	—
			(1.205)	
	the Proportion of Land	—	—	-0.438***

	Inflow×Land Management Scale			(-1.567)
	Control Variables	Control	Control	Control
	Constant	53.634***	62.669***	42.397**
		(12.809)	(11.351)	(11.615)
	R ²	0.471	0.323	0.318
	Wald	13.487***	13.852***	13.734***
	Number	257	257	257

Note: ① *, **, *** represent significance at the 10%, 5%, and 1% levels, respectively. ② The values in parentheses under the coefficients are the standard errors of your table or results section to avoid any ambiguity.

5. Conclusion and Policy Implications

5.1. Conclusions

(1) The land management scale in Jiangxi Province significantly impacts fertilizer use intensity, exhibiting a "U"-shaped relationship. The optimal land management scale is 8.62 mu. Specifically, before reaching the optimal scale, an increase in the land management scale leads to a reduction in fertilizer use intensity; however, beyond the optimal scale, further expansion of the land management scale results in an increase in fertilizer use intensity.

(2) The degree of land fragmentation and the proportion of land inflow have different moderating effects on the relationship between land management scale and fertilizer reduction. The degree of land fragmentation weakens the fertilizer reduction effect of the land management scale, meaning that increased land fragmentation hinders the reduction in fertilizer use. Conversely, the proportion of land inflow enhances the fertilizer reduction effect of the land management scale, with a higher inflow of land area contributing to a more significant fertilizer reduction.

(3) Farmer age positively influences fertilizer use intensity, while education level and participation in agricultural technical training have a negative impact. Both younger and older generations of farmers significantly influence the fertilizer reduction effect of land management scale, maintaining a stable "U"-shaped relationship.

5.2. Policy Implications

(1) Improve the land transfer system and promote moderate-scale land management. Currently, most farmers in Jiangxi Province have land management scales (with an average of 4.43 mu) that do not reach the optimal scale of 8.62 mu. As a result, the benefits of economies of scale still need to be realized. Therefore, on the one hand, the government should improve the land transfer system, carry out land consolidation projects, and build high-standard farmland to facilitate concentrated and contiguous land management. On the other hand, the government should foster farmers with growth potential, guiding them towards modern agricultural business models. By leveraging cooperatives and service organizations, the government can help farmers expand their land management scales and increase support for agricultural development initiatives.

(2) Encourage the concentrated transfer of agricultural land and strengthen high-standard farmland construction. Encouraging the concentrated transfer of agricultural land helps achieve large-scale farming, enhances agricultural productivity, and reduces the resource waste caused by fragmented operations. Through land consolidation, the development of agricultural industries can be accelerated, and modern agricultural technologies and equipment can be introduced. Strengthening the construction of high-standard farmland is essential for enhancing land productivity. This includes improvements to irrigation systems, soil conservation, and basic agricultural infrastructure, which increase land-use efficiency, improve agricultural sustainability, and reduce fertilizer use.

(3) Enhance the overall quality of agricultural workers and cultivate new-type professional farmers. Improving the overall quality of farm workers and cultivating new-type professional farmers is crucial for promoting agricultural modernization and sustainability. By improving farmers' education and professional skills, it is possible to increase their acceptance of new technologies and environmentally-friendly practices. This transformation is essential for promoting changes in agricultural production methods, particularly in reducing fertilizer use intensity, and will play an active role in achieving sustainable agricultural development.

Conflicts of Interest

The authors declare that there is no conflict of interest regarding the publication of this article.

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