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Article

Economic and Environmental Effects Evaluation of Farmer's Green Production Behaviors: Evidence from Major Rice-Producing Areas in Jiangxi Province, China

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Abstract: Evaluating the economic and environmental effects of farmers' green production behaviors holds important reference value for promoting sustainable agricultural development, alleviating agricultural non-point source (NPS) pollution, and achieving the organic combination of environmental protection and economic development. This paper utilizes survey data from 1,345 farm households in the main rice production areas of Jiangxi Province, China, using the example of reduced fertilizer application (RFA) among rice farmers. By constructing a DEA—SBM model with undesirable outputs to measure environmental effects, and applying an endogenous switching model to test the economic and environmental effects of farmers' adoption of green production technologies. The study found that: (1)The behavior of RFA by farmers has a significant positive impact on their net profit per mu (NPPA), helping farmers increase their income, with the increase ranging from 2.05% to 6.54%. (2)The behavior of RFA by farmers has a significant positive impact on agricultural green productivity (AGP), contributing to the improvement of the environment, with the improvement ranging from 44.09% to 45.35%. (3)Heterogeneity analysis found inconsistencies in the income-enhancing and environmental-enhancing effects at different quantiles of NPPA and AGP. Therefore, attention should be placed on improving the agricultural product quality supervision system under the market circulation mechanism, creating land scale conditions conducive to the promotion and application of fertilizer reduction technologies, and promoting the implementation of externality internalization compensation systems.

Keywords: farmers' green production behaviors; reduced fertilizer application; economic effects; environmental effects; endogenous switching model

1. Introduction

Promoting green agricultural development and improving agricultural ecological efficiency are essential pathways to achieving the organic integration of environmental protection and economic development. They are also crucial for advancing supply-side structural reforms in agriculture, and implementing the strategies of green agriculture and quality agriculture. For the past few years, China's agricultural economy has developed rapidly, with fertilizers playing an indispensable driving role as a key agricultural input [1]. However, fertilizer input has surpassed the optimal level, that balances economic returns and ecological efficiency [2]. According to the law of diminishing marginal returns to factor inputs, as fertilizer application exceeds the optimal level, its marginal output declines [3,4]. Over-reliance on fertilizers suppresses agricultural economic growth and induces severe ecological crises, such as soil fertility decline, water pollution, and increased greenhouse gas emissions. Which threaten the safety of agricultural products and constrain sustainable agricultural development [5]. Under the dual pressures of economic slowdown and

tightening resource and environmental constraints, the Chinese government highlights the importance of comprehensive prevention and control of agricultural NPS pollution. It calls for strengthening rural ecological civilization construction, and solid promotion of fertilizer and pesticide reduction and efficiency actions. Agricultural production must shift from over-reliance on resource consumption to an environmental friendly, and sustainable development model, striving to achieve the integrated goals of improving agricultural product quality, increasing agricultural output, and enhancing the ecological environment.

Under the context of the new era, farmers' green production behaviors, which are crucial for improving agricultural product quality, preventing agricultural NPS pollution, and ensuring food safety, serve as a key driving force for achieving sustainable agricultural development. The RFA is a typical green agricultural production behavior and has received widespread attention from the government and academia [6]. Many farmers actively cooperate with national agricultural reduction-related work and social development goals, vigorously implementing RFA. Existing research on RFA mainly focuses on viewing this behavior as an outcome variable, exploring the obstacles to achieving RFA. The research scope primarily involves individual-level behavioral inertia changes, technical cognition, and risk preferences of farmers [7]; the allocation of production factors (land, capital, labor) at the household level [8]; and socialized services, technical training, and subsidies for green production technologies at the agricultural production level [9]. Although RFA are influenced by many factors, farmers only adopt fertilizer reduction technologies if the net profit exceed those of traditional fertilization methods [10]. Thus, whether the goal of maximizing farmers' economic benefits can be met is key to the successful promotion of RFA. Meanwhile, under the increasingly severe trend of agricultural NPS pollution, whether RFA can address ecological environment shortcomings is also a matter of concern.

So, can RFA successfully achieve both economic and environmental goals? In the context where the contradiction between economic rationality and ecological rationality cannot be effectively reconciled, the debate on this goal continues. From the perspective of natural sciences, most studies based on field experiments, RFA plays an important role in increasing agricultural yield and improving the environment situation. For example, reducing fertilizer use by 10% in the wheat production drought-drought model, and by 24% in the dry-wet rotation mode, which can produce a certain "reduction and efficiency enhancement" effect. Remarkable differences in farmers' economic benefits under different fruit tree irrigation and fertilization modes [**Error! Reference source not found.**]. Some studies point out that the yield improvement effect of RFA is not significant in the initial year, but yields increase with the years of adoption [11]. Additionally, RFA helps improve soil fertility, increase soil biodiversity, enhancing soil health, ensuring crop yields, improving agricultural product quality, controlling agricultural NPS pollution, and reducing greenhouse gas emissions [13]. From an economic perspective, adopting green production technologies can reduce fertilizer use by 11.97%-20.98%, and increase agricultural operating income by 8.15%-9.07%. RFA decreases farmers' reliance on chemical inputs, thus lowering agricultural chemical input costs [14]. Moreover, RFA can effectively promote the standardization of crop production, enhance the safety of agricultural products, increase the market competitiveness of agricultural products, and achieve a premium for green agricultural products, thereby increasing farmers' income [15,16]. The application of soil testing and formulated fertilization technologies can increase agricultural product yields and have considerable economic benefits [17]. Green inputs can drive agricultural economic growth, achieving the goal of increasing production without increasing pollution [18]. However, some scholars argue that although RFA can reduce inputs, the current imperfect green agricultural product certification system in China, leads to insufficient premiums for green production, making it difficult for farmers to directly gain additional profits from FRA [19], which hindering farmers' income growth goals.

The existing literature reveals several key points: First, many conclusions about the economic and environmental effects of RFA are based on natural science experiments. There is a relative lack of empirical research at the micro-farmer level using econometric models. Because the internal and external environments of natural science experiments are strictly controlled, it is difficult to effectively reveal the impact of individual farmer heterogeneity in real-world settings. Second,

existing studies have a narrow scope in evaluating the effects of green agricultural production behaviors. They typically focus on the impact on crop yield or fertilizer use alone, lacking a dual evaluation system for both economic and environmental effects. Third, research from a micro-farmer perspective that measures agricultural environmental effects, mainly focuses on the actual amount or cost of fertilizers and pesticides, making it difficult to effectively identify the extent, which farmer behaviors impact the ecological environment. In view of the above, our study is based on a sample survey of 1,345 rice farmers in 30 counties (cities, districts) in Jiangxi Province, China in 2022. From a micro perspective, we construct a DEA—SBM model with undesirable outputs to measure environmental effects, and use an endogenous switching model to explore the potential economic and environmental effects of RFA in rice cultivation. This study aims to further expand existing research, and provide necessary policy references for the broader promotion of agricultural input—reduction production.

2. Theoretical Framework

2.1. *Economic Effects of Farmers' RFA*

As rational economic agents, maximizing household income is the key intrinsic motivation for farmers to adopt agricultural input-reduction production practices. Therefore, the positive expectations of the economic benefits from RFA drive farmers to implement their behaviors. This paper begins by exploring the economic effects on rice farmers, analyzing the potential economic effects of RFA from three aspects: cost savings, yield increases, and product premiums.

Firstly, adopting green agricultural production methods can help farmers avoid over-reliance on chemical inputs. By reducing the amount and frequency of fertilizer applications, the input cost of fertilizers can be lowered [20]. Additionally, compared to traditional fertilization methods, farmers who use soil formulators and precision fertilizer appliances can improve fertilization efficiency. This method not only reduces the amount of fertilizer used, but also allows farmers to gain a price advantage in the market through bulk purchasing of fertilizers, thereby reducing production costs [21].

Secondly, according to the law of diminishing marginal returns on factor inputs, the relationship between fertilizer input and marginal output in agricultural production shows an "inverted U-shaped" trend [22]. When the amount of fertilizer input reaches its maximum limit, the marginal output decreases as the application amount increases. Thus, under the current agricultural production technology conditions or farming habits, blindly increasing fertilizer input, does not significantly enhance yield. Moreover, studies have shown that compared to small-scale farmers, large-scale farmers use less fertilizer but achieve higher yields [23]. This indicates that scientific and appropriate fertilization methods can increase agricultural product yields [24].

Finally, RFA can promote the standardization of crop production, improve the quality and safety of agricultural products, effectively avoid excessive fertilizer residues, increase market competitiveness, and achieve a premium for green agricultural products, thereby increasing farmers' income. As the quality of agricultural products improves, farmers gain stronger market competitiveness and a price premium advantage in the trading market [25]. Thus, appropriate RFA provide a foundation for stable crop income, improve the commercial value of crops, and increase farmers' economic returns [26]. Thus, the following research hypotheses is proposed:

H1: Farmers' RFA significantly increases the NPPA in rice production.

2.2. *Environmental Effects of Farmers' Fertilizer Reduction Behavior*

Considering agricultural economic growth, it is also necessary to address the environmental issues arising from agricultural production processes. In recent years, scholars have begun to focus on the positive effects of green production technologies on the ecological environment. They have gradually incorporated agricultural pollution (such as agricultural carbon emissions, pesticide residues, and excessive fertilizer use) as undesirable outputs of agricultural production, put it into

the framework for evaluating agricultural productivity [27]. By analyzing the relationship between factor inputs, economic outputs, and the ecological environment in agricultural production, the environmental effects of agriculture can be measured. AGP is a key indicator of environmental effects, representing the ability to achieve maximum agricultural output with minimal resource consumption and environmental pollution, under a certain combination of agricultural input factors [28,29]. The environmental effects of farmers' RFA are specifically reflected in the following ways: RFA can reduce agricultural NPS pollution. Unreasonable fertilizer application methods are a major cause of agricultural NPS pollution, affecting water, soil, and air. In rice production, excessive and inefficient use of chemicals leads to numerous fertilizer residue in the soil, disrupting the soil's pH balance, causing soil acidification and compaction, and hindering sustainable agricultural development [30]. Excessive fertilizer use leads to phosphorus accumulation in the topsoil and excessive heavy metals [31], which, in eutrophic water environments, impede crop survival and severely impact the agricultural ecological environment. Soil respiration produces carbon dioxide, and over-fertilization increases the emissions of carbon dioxide, nitrogen oxides, and other gases, thus leads to atmospheric pollution [32]. RFA alleviate these environmental pollution issues and improve agricultural environmental efficiency. Thus, the following research hypotheses is proposed:

H2: Farmers' RFA significantly enhances AGP.

3. Data Source, Variable Selection, and Model Setting

3.1. Data Source

The sample data used in this study, were obtained from a micro-survey conducted by the research team on rice farmers in Jiangxi Province, China, from November 2022 to August 2023. The selection of samples and regions was considered based on the following: China ranks among the top in the world in rice production and consumption, with the planting area and output of rice accounting for 20% and 33% of the world's total, respectively. According to existing research, nitrogen fertilizer in rice production contributes about 50% of the total carbon emissions in the entire production process, primarily due to improper fertilizer application [33]. Therefore, this study focuses on the fertilizer input in rice production, from the perspective of rice farmers' production behaviors. Jiangxi Province is a traditional agricultural province and a major rice-producing area in China. For a long time, Jiangxi has promoted agricultural supply-side structural reforms, adhering to the principles of industrial agriculture, green agriculture, quality agriculture, and brand agriculture. The province has achieved a negative growth rate in fertilizer use for five years, with a reduction of 18.57% in 2022, compared to 2016. Thus, selecting rice farmers in Jiangxi Province as the research subjects, to explore the economic and environmental effects of farmers' RFA is representative, data-supported, and practically significant.

To ensure the scientific and rational selection of survey regions and samples, the research team first divided the per capita GDP of 100 counties (cities, districts) in Jiangxi Province into three different regions: high, medium, and low. Using random sampling, 10 counties were selected from each region. Then, from each county, two townships were randomly selected, and from each township, two villages were randomly selected. Finally, 5-15 rice farming households were randomly selected from each village. The distribution of sample counties is drawn by ArcGIS as shown in Figure 1. The survey was conducted through face-to-face interviews between the interviewers and the respondents. A total of 1,500 questionnaires were distributed, with 1,410 questionnaires actually recovered, questionnaire validity rate of 94%. After excluding invalid indicators as required by the study, 1,345 valid samples were selected for analysis.

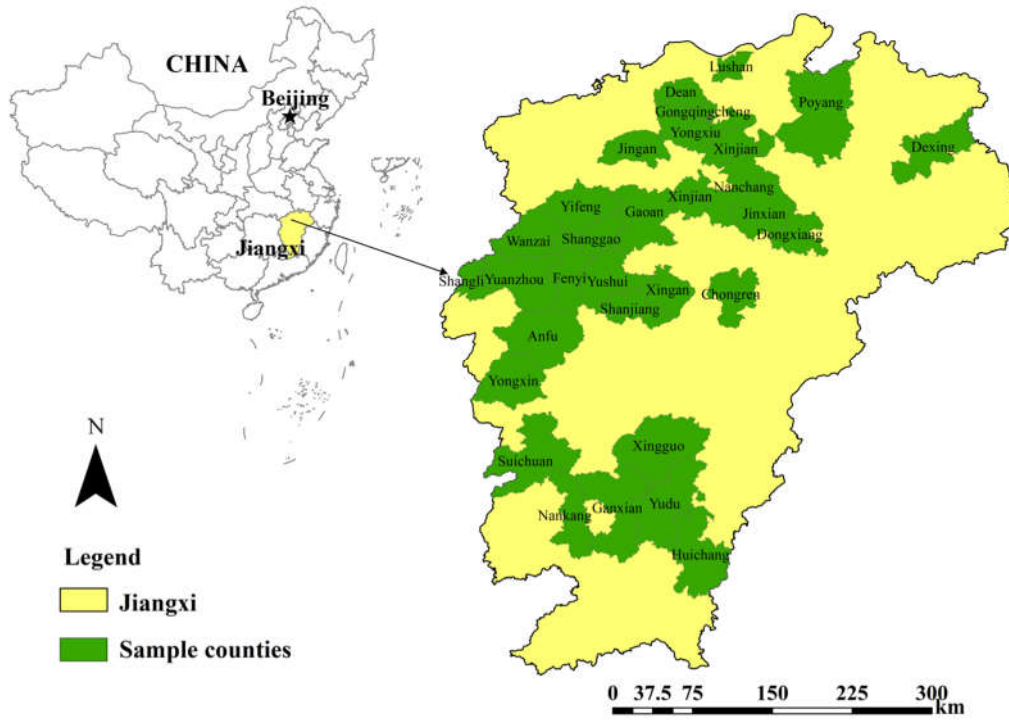


Figure 1. Distribution of Sample Counties. The map data in Figure 1 are from DataV. GeoAtlas. https://datav.aliyun.com/portal/school/atlas/area_selector, accessed on 27 05 2024.

3.2. Model Setting

Considering that whether rice farmers have RFA is a non-random event, this can lead to sample selection bias. Additionally, non-random controlled trials can't obtain information about the "counterfactual" making it difficult to identify causal relationships. Without correction, biased estimates may result. Therefore, considering the probability of rice farmers adopting RFA, estimating the treatment effects of this behavior on economic and environmental effects becomes crucial. In view of this, we employ an endogenous switching model to overcome sample selection bias caused by unobservable variables. This model can fit the effect decision equations and "counterfactual" equations, for both adopters and non-adopters of RFA, compensating for the shortcomings of previous research methods.

First, we establish the decision equation for rice farmers' RFA as follows:

$$D_i^* = \gamma Z_{ij} + \mu_i, \quad D_i = \begin{cases} 1, & D_i^* > 0 \\ 0, & D_i^* \leq 0 \end{cases} \quad (1)$$

D_i^* represents the unobservable variable for the decision to adopt RFA. Z_{ij} represents the observable factors influencing the adoption of RFA. γ represents the parameters to be estimated. μ_i represents the random disturbance term. The impact effect equation for adopting RFA is given by:

$$Y_{li} = \sum_{j=1}^n \beta_{lj} X_{lij} + \varepsilon_{li}; \quad D = 1 \quad (2)$$

$$Y_{oi} = \sum_{j=1}^n \beta_{oj} X_{oj} + \varepsilon_{oi}; \quad D = 0 \quad (3)$$

Y_{li} and Y_{oi} represent the economic and environmental effects produced by rice farmers who have adopted and those who have not adopted the RFA, respectively. X_{ij} represents other variables influencing these effects. This variable can overlap with Z_{ij} in Equation (1), but there must be at

least one identifiable variable not included in Z_{ij} . This variable only affects rice farmers' decision of whether adopt RFA, and does not affect the economic and environmental effects. Therefore, the average adoption of the RFA by other farmers in the village, excluding the farmer in question, is selected as the identifiable variable. It should be noted that due to the "herd effect," farmers' decisions to adopt the RFA are influenced by other farmers, meeting the requirement of correlation. Meanwhile, other farmers' decisions to adopt the RFA do not directly affect the NPPA and AGP of the farmer in question, meeting the requirement for exogeneity. β_i is the parameter to be estimated; ε_i is the random disturbance term.

The conditional expectations of rice farmers under the two scenarios of whether they adopt the RFA:

$$E(Y_{1i}|D_i = 1) = \beta_{1j}X_{1ij} + \sigma_{\mu 1v}\lambda_{1i} \quad (4)$$

$$E(Y_{0i}|D_i = 0) = \beta_{0j}X_{0ij} + \sigma_{\mu 0v}\lambda_{0i} \quad (5)$$

$\sigma_{\mu 1v} = cov(\mu_1, v)$, $\sigma_{\mu 0v} = cov(\mu_0, v)$, v is a random disturbance term with an expected value of 0.

Next, we estimate the expected values of the economic and environmental effects in the two "counterfactual" scenarios: the effects for rice farmers who have adopted the RFA when they do not adopt it, and the effects for rice farmers who have not adopted the RFA when they do adopt it.

$$E(Y_{0i}|D_i = 1) = \beta_{0j}X_{1ij} + \sigma_{\mu 0v}\lambda_{1i} \quad (6)$$

$$E(Y_{1i}|D_i = 0) = \beta_{1j}X_{0ij} + \sigma_{\mu 1v}\lambda_{0i} \quad (7)$$

The average treatment effect on the treated (ATT) for the economic and environmental effects of rice farmers, who have adopted the RFA (treatment group) is represented by the difference between Equation (4) and Equation (6):

$$ATT = E(Y_{1i}|D_i = 1) - E(Y_{0i}|D_i = 1) = (\beta_{1j} - \beta_{0j})X_{1ij} + (\sigma_{\mu 1v} - \sigma_{\mu 0v})\lambda_{1i} \quad (8)$$

The average treatment effect on the untreated (ATU) for the economic and environmental effects of rice farmers, who have not adopted the RFA (control group) is represented by the difference between Equation (5) and Equation (7):

$$ATU = E(Y_{1i}|D_i = 0) - E(Y_{0i}|D_i = 0) = (\beta_{1j} - \beta_{0j})X_{0ij} + (\sigma_{\mu 1v} - \sigma_{\mu 0v})\lambda_{0i} \quad (9)$$

3.3. Variable Selection

3.3.1. Dependent Variables

(1) Economic Effect. From a "cost-benefit" perspective, this paper measures the economic effect of rice planting using the average NPPA for 2022. The calculation is based on the sales price of rice multiplied by the average yield per mu¹, minus the average cost per mu. The main costs include land rent, labor costs, agricultural input (fertilizers, pesticides, seeds, herbicides), machinery costs, and other costs (such as electricity) [34].

(2) Environmental Effect. The AGP measurement model accounts for input-output slack variables, effectively addresses the bias caused by slackness and radial and angular selection of inputs and outputs. It not only achieves the required efficiency, but also provides improvement targets and degrees for input factors and the distance from undesirable outputs in decision-making units [35]. Therefore, this paper uses the DEA—SBM model based on undesirable outputs to measure AGP,

¹ Note: 1 mu $\approx$ 667 m² or 0.067 ha.

which represents the agricultural environmental effect. The input indicators include land input (mu), labor input (workdays), agricultural inputs (fertilizers, pesticides, seeds, herbicides) (CNY), and machinery input (CNY). The output indicators include desirable and undesirable outputs, the desirable output is the total rice yield (in kilograms). The undesirable outputs include the emissions of nitrogen and phosphorus (in kilograms) during agricultural production. According to the material balance method [36], the emissions of nitrogen and phosphorus during rice production equal the pure content of nitrogen and phosphorus in fertilizers minus their content in the rice grains². If the calculated index is positive, it indicates a negative impact of agricultural production on the environment; if the index is negative, it indicates a positive impact. The specific input-output descriptions and statistics are shown in Table 1.

Table 1. Input-Output Indicators for Measuring the Agricultural Environmental Effects.

Typology	Indicator	Description of indicators
Input indicators	Land input	Crops sown (mu)
	Labor input	Including own-account and hired labor hours (hours)
	Seed input	Total cost of seeds purchased (CNY)
	Fertilizer input	Total cost of fertilizer purchases, including compost and fertilizer (CNY)
	Pesticides input	Total cost of pesticides purchase (CNY)
	Herbicides input	Total cost of herbicide purchase (CNY)
	Mechanical input	Total cost including owned and hired machinery (CNY)
Expected outputs	Output	Total crop production (catty)
Non-expected outputs	Nitrogen emissions	Nitrogen emissions from agricultural production (catty)
	Phosphorus emissions	Phosphorus emissions from agricultural production (catty)

3.3.2. Independent Variables

Currently, studies on RFA typically use the actual amount of fertilizer input for measurement [37]. Some studies identify the degree of fertilizer reduction by measuring fertilizer use efficiency [38]. With the continuous attention from the government and academia to the issue of agricultural NPS pollution, the methods for measuring fertilizer reduction have also been improved. Drawing on the measurement methods of fertilizer reduction effects by [39] and [40], this paper first calculates the optimal amount of fertilizer input in rice production by constructing a Cobb-Douglas production function. Then, by comparing the actual amount of fertilizer input by farmers with the optimal application amount, it determines whether the farmers have implemented RFA. Farmers whose actual fertilizer application amount is at or below the optimal level, are assigned a value of 1, indicating that they have RFA; otherwise, they are assigned a value of 0, indicating that they have not RFA.

² This research does not consider the nitrogen and phosphorus elements present in the soil and seeds. According to field surveys, farmers mainly use urea and compound fertilizers. Referring to the Reference Calculation Table for Pure Fertilizer Content:the nitrogen content in urea is 46%, the nitrogen and phosphorus contents in compound fertilizers are 15.18% and 27.43%, respectively (calculated based on the average standards of 14 main compound fertilizers).According to the Handbook of Agricultural Technology and Economics:The nitrogen content in every 100 kilograms of rice is 2.05 kilograms,the phosphorus content is 0.95 kilograms.

3.3.3. Control Variables

To reduce estimation bias caused by omitted variables, this paper controls the following variables:①Individual characteristics, including the age, education level, risk preference, training frequency, whether the village cadres, and work experience [41].②Household characteristics, including the number of laborers and total household income [42].③Agricultural production characteristics, including land management scale, degree of land parcel consolidation, soil fertility, and distance of the land plots [43,44].Descriptive statistical analysis of the variables is shown in Table 2.

The independent sample t-test results in Table 2, shows that the average NPPA of the farmers in the fertilizer reduction sample group (677.86 CNY), is significantly higher than the farmers in the non-reduction sample group (504.78 CNY); the AGP of the farmers in the fertilizer reduction sample group (0.51) is significantly higher than the farmers in the non-reduction sample group (0.27).

Table 2. Variable Definitions and Descriptive Analyses.

Variable Name	Meaning and Assignment	Reduction		Non-reduction		Discrepancy
		Average Value	Standard Deviation	Average Value	Standard Deviation	
RFA	Fertilizer reduction application or not?0=no, 1=yes	n=1078		n=267		-
Economic effects	Farmer’s net return per mu from rice production in 2022(CNY)	677.86	13.51	504.78	7.00	173.08***
Environmental effects	The DEA – SBM model based on non-expected output measures AGP with values between 0 and 1	0.51	0.02	0.27	0.01	0.24***
Age	Actual age of farm householder (years)	51.54	0.49	55.01	0.28	3.47***
Education level	Educational attainment of farmers, 1 = primary school and below, 2 = junior high school, 3 = senior high school/vocation secondary school/technical school/vocational high school, 4 = post-secondary school, 5 = bachelor’s degree and above	1.87	0.05	1.87	0.03	-0.01
Risk preference	1 = risk aversion; 2 = risk neutrality; 3 = risk appetite	1.85	0.05	1.50	0.02	0.35***
Training frequency	Frequency of farmers’ participation in agricultural technology training, 1 = never; 2 = occasionally; 3 = often	1.43	0.04	1.32	0.02	0.12***
Whether the village cadres	Whether the farmer is a village cadre? 0=no, 1=yes	0.27	0.03	0.29	0.01	0.02
Work experience	1 = always farming, 2 = part-time farming, 3 = labor or business, 4 = other	0.27	0.03	0.29	0.01	0.02
Total household income	Gross farm household income (ten thousand)	9.03	0.95	5.95	0.19	3.07***

The number of laborers	Total number of agricultural laborers in farming households (person)	1.83	0.04	1.84	0.02	0.01
Land management scale	Total actual operating scale of rice production(mu)	98.57	7.19	77.39	2.82	21.18***
Degree of land parcel consolidation	1 = very scattered; 2 = more scattered; 3 = partially contiguous; 4 = all contiguous	3.11	0.05	2.43	0.03	0.69***
Soil fertility	Soil fertility status of the largest plots, 1=poor; 2=medium; 3=good; 4=excellent	3.21	0.04	2.87	0.03	0.25***
Distance of the land plots	Distance of largest plot from farmer's house(kilometre)	0.94	0.03	1.79	0.13	0.84***

4. Results and Discussion

4.1. Simultaneous Estimation Results and Analysis

To test the potential economic and environmental effects of farmers’ RFA, a simultaneous estimation was performed using the decision function of farmers’ RFA, along with the NPPA and AGP function of rice. The test results are shown in Table 3. The independence LR test for the two-stage equations, rejected the null hypothesis of mutual independence between the selection equation and the outcome equation at the 10% level. The Wald test rejected the null hypothesis, that mutual independence between the behavior equation and the outcome equation at the 5% level, indicating the model has strong significance. Additionally, the error term correlation coefficient ρ_1 was significant at the 5% statistical level, suggesting that unobservable factors influence farmers’ decisions on RFA, indicating the presence of selection bias, which validates the use of the ESRM. Moreover, the estimated values of the correlation coefficient ρ_1 in both sets of simultaneous equations, were significantly positive, indicating that farmers who adopted RFA, had higher NPPA and AGP than the average of the sample farmers, which is consistent with research hypotheses 1 and 2.

Regarding the selection equation, factors such as the farmer’s age, risk preference, whether the village cadres, total household income, degree of land parcel consolidation, and distance of land plots significantly influenced farmers’ RFA. In terms of the outcome equation, from the economic effect perspective, land management scale had a significant positive impact on the NPPA of rice production, indicating the presence of scale effects in rice production. The training frequency and the total number of laborers, significantly positively impacted the NPPA of farmers who have RFA, suggesting that participation in training, enhances farmers’ ability to acquire production and market information, thereby improving agricultural production benefits. Additionally, a higher number of agricultural laborers in a household, where income mainly comes from agricultural production, increases the likelihood of being exposed to and understanding green pest control technologies, resulting in greater economic effects. From the environmental effect perspective, the frequency of training participation and the number of agricultural laborers, had a significant positive impact on the AGP of farmers, further highlighting the importance of agricultural training and labor input in agricultural production. The land management scale significantly positively impacted the AGP of farmers who have RFA, indicating the presence of scale effects in green agricultural production. Soil fertility had a significant positive impact on the AGP of farmers who have RFA. For land with higher soil fertility, farmers tend to apply less fertilizer, resulting in higher environmental effects.

Table 3. Impact of Farmers’ RFA on NPPA of rice production.

Variable Name	RFA	NPPA of rice		AGP	
	Decision Models	Reduction	Non-reduction	Reduction	Non-reduction
Age	-0.026***	0.002	-0.003	-0.001	-0.004
	(0.006)	(0.002)	(0.002)	(0.001)	(0.002)
Education level	-0.036	0.019	0.022	0.004	0.016
	(0.063)	(0.017)	(0.025)	(0.005)	(0.025)
Risk preference	0.272***	-0.008	0.033	-0.012**	0.028
	(0.063)	(0.019)	(0.023)	(0.006)	(0.023)
Training frequency	0.080	0.006	0.068**	0.013*	0.083***
	(0.075)	(0.023)	(0.029)	(0.007)	(0.028)
Whether the village cadres	-0.185*	0.037	-0.064	0.019**	-0.056
	(0.111)	(0.030)	(0.044)	(0.009)	(0.044)
Work experience	-0.046	0.076***	-0.033	-0.005	-0.008
	(0.063)	(0.020)	(0.042)	(0.006)	(0.022)
Total household income	0.020***	0.006**	-0.002	0.001	0.001
	(0.007)	(0.002)	(0.002)	(0.001)	(0.002)
The number of laborers	0.022	-0.014	0.132***	0.019***	0.132***
	(0.073)	(0.020)	(0.029)	(0.006)	(0.029)
Land management scale	0.496***	-0.016	0.013	0.000	0.011
	(0.054)	(0.015)	(0.025)	(0.005)	(0.026)
Degree of land parcel consolidation	0.120**	0.010	-0.047	0.000	0.051*
	(0.054)	(0.014)	(0.029)	(0.004)	(0.027)
Soil fertility	0.001	0.001**	0.001**	-3.351	0.001*
	(0.001)	(0.000)	(0.007)	(0.000)	(0.000)
Distance of the land plots	-0.351***	-0.001	0.016	0.001	0.011
	(0.051)	(0.003)	(0.034)	(0.001)	(0.034)
Identifying Variables	3.798***				
	-0.335				
Constant term	-2.294***	6.155***	6.200***	0.266***	0.281
	-0.473	(0.131)	(0.208)	(0.041)	(0.206)
q0	-	-0.361***	-	0.102	-
		(0.096)	-	(0.134)	-
q1	-	-	0.180*	-	0.284**
		-	(0.107)	-	(0.118)
Wald test	-	30.63***		29.63**	
LR test	-	chi2(2) =14.09		chi2(2) =6.18	
		Prob > chi2 = 0.001		Prob > chi2 = 0.046	
Sample volume	1345	1078	267	1078	267

Note: *, **, and *** indicate significant at the 10%, 5%, and 1% levels, respectively, with robust standard errors in parentheses. Also to attenuate the heteroskedasticity of the data in the model, the NPPA of rice in the model was treated as logarithmic.

4.2. Analysis of the Economic Effects of Farmers’ RFA

To reflect the impact of farmers’ RFA on their NPPA and AGP, the expected values of NPPA for non-reduction households and reduction households, adjusted for sample bias, were calculated using

equations (4) and (5). Additionally, the NPPA and AGP of the reduction group and non-reduction group under two "counterfactual" scenarios, were calculated using equations (6) and (7). Finally, the treatment effects of farmers' RFA on NPPA and AGP, ATT and ATU were calculated using equations (8) and (9). The estimated average treatment effects of RFA on NPPA are shown in Table 4. The ATT value is 0.437, indicating that if farmers adopting fertilizer reduction technology did not adopt this technology, their NPPA from rice production would decrease. The ATU value is 0.131, indicating that for farmers who have not implemented fertilizer reduction, adopting this technology would increase their NPPA from rice production.

To more clearly reflect the economic effects of farmers' RFA, the probability density distribution graphs of NPPA for reduction and non-reduction households were described separately. As shown in Figure 2 (left), if farmers who reduced fertilizer use chose not to reduce it, the probability density distribution curve of their NPPA, would shift significantly to the left. In the "counterfactual" scenario that reduction households do not reduce fertilizer, their NPPA would significantly decrease by 6.54%. Conversely, the ATU in Figure 2 (right) indicates that in the "counterfactual" scenario, non-reduction households choose to reduce fertilizer, the probability density distribution curve of their NPPA would shift to the right, suggesting that if non-reduction farmers chose RFA, their NPPA would increase by 2.05%. Hence, the fertilizer reduction behavior of sample farmers could increase their NPPA by 2.05%-6.54%. Based on the above analysis, it can be concluded that research hypothesis H1 is validated.

Table 4. Mean treatment effect of farmers' RFA on NPPA.

Groups	Fertilizer reduction	No fertilizer reduction	ATT	ATU
Fertilizer reduction	6.677	6.239	0.437***	-
No fertilizer reduction	6.526	6.396	-	0.131***

Note: *, **, and *** indicate significant at the 10%, 5%, and 1% levels, respectively, with robust standard errors in parentheses.

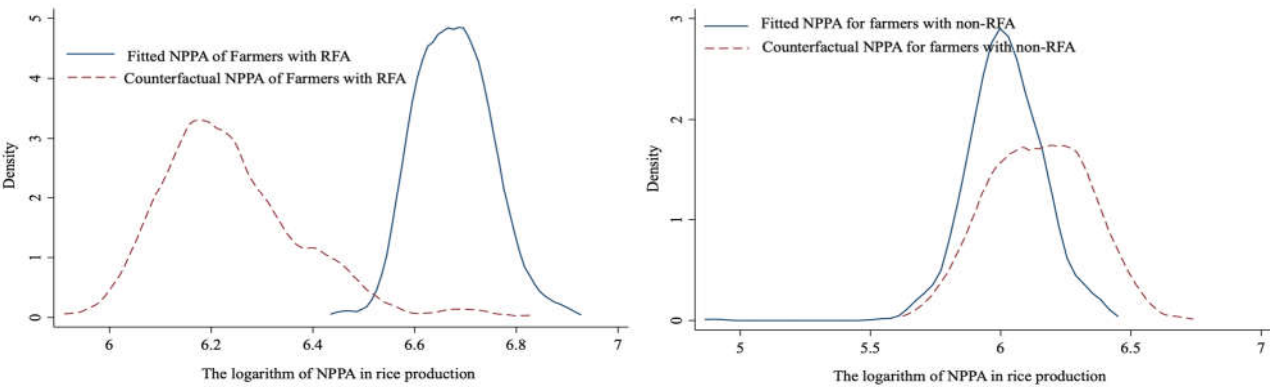


Figure 2. Probability density of farmer's NPPA in two scenarios.

4.3. Analysis of the Environmental Effects of Farmers' RFA

Table 5 presents the average treatment effects of farmers' RFA on AGP. The results show that adopting RFA has a significant positive treatment effect on farmers' AGP. The ATT value is 0.224, indicating that if farmers who adopted RFA did not adopt this technology, their AGP would decrease. The ATU value is 0.122, indicating that for farmers who have not implemented fertilizer reduction, adopting this behavior would increase their AGP.

To more clearly reflect the environmental effects of farmers' RFA, the probability density distribution graphs of AGP for reduction and non-reduction households were described separately.

As shown in Figure 3 (left), if farmers who reduced fertilizer use chose not to reduce it, the probability density distribution curve of their AGP would shift significantly to the left. In the "counterfactual" scenario where reduction households do not reduce fertilizer, their AGP would significantly decrease by 44.09%. Conversely, the ATU in Figure 3 (right) indicates that in the "counterfactual" scenario that non-reduction households choose to reduce fertilizer, the probability density distribution curve of their AGP would shift significantly to the right, suggesting that if non-reduction farmers chose RFA, their AGP would increase by 45.35%. Therefore, the RFA of sample farmers could increase their AGP by 44.09%-45.35%. Based on the above analysis, it can be concluded that research hypothesis H2 is validated.

Table 5. Mean treatment effects on the impact of farmers’ RFA on AGP.

Groups	Fertilizer	No fertilizer	ATT	ATU
	reduction	reduction		
Fertilizer reduction	0.508	0.285	0.224***	-
No fertilizer reductio	0.391	0.269	-	0.122***

Note: *, **, and *** indicate significant at the 10%, 5%, and 1% levels, respectively, with robust standard errors in parentheses.

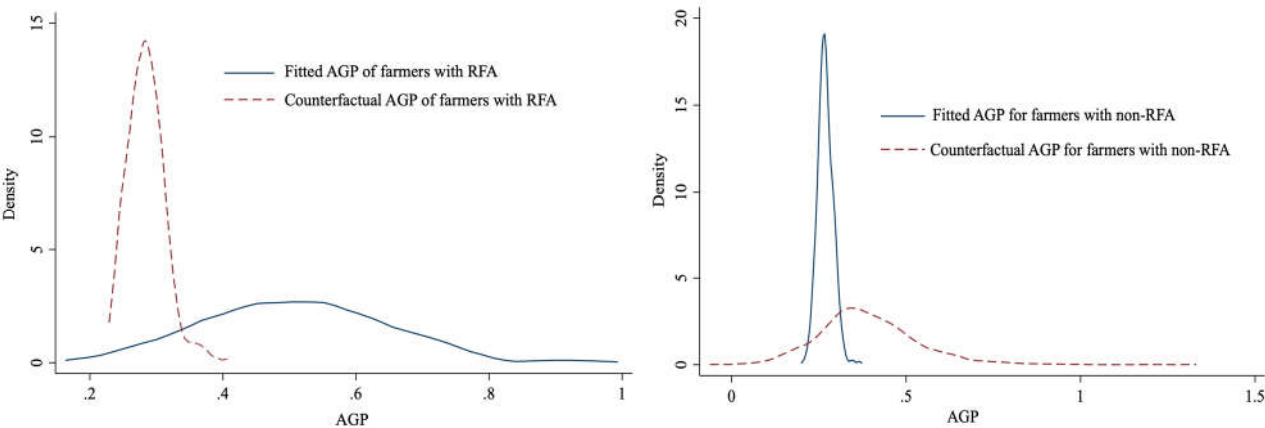


Figure 3. Probability density of AGP in two scenarios.

4.4. Robustness Test

To ensure the reliability of the above conclusions, robustness tests were conducted by replacing the estimation methods. The OLS model, Tobit model, and Propensity Score Matching (PSM) method, were used to examine the economic and environmental effects of farmers’ RFA. The specific test results are shown in Table 6. Table 6 presents the regression results using the OLS model and Tobit model. The results show that RFA have a significant positive impact on the NPPA and the AGP of rice farmers. Table 7 shows the impact results of farmers’ RFA on NPPA and AGP, estimated by the nearest neighbor matching, kernel matching, and caliper matching. It can be found that the average treatment effect (ATT), estimated by the three matching methods is significantly positive, indicating that farmers’ RFA can significantly improve their economic and environmental effects. The results of the OLS model, Tobit model, and the PSM method, are consistent with the results of the endogenous switching model, indicating that the model results are robust.

Table 6. Results of OLS and Tobit regressions on the economic effects of framers’ RFA.

Variable	Economic effects	Environmental effects
	(OLS)	(Tobit)
RFA	0.249***	0.234***

	(0.026)	(0.014)
Control variable	control	control
Constant term	6.192***	0.224***
	(0.113)	(0.037)
R2/Pseudo R2	0.091	-1.022
Cample volume	1345	1345

Note: *, **, and *** indicate significant at the 10%, 5%, and 1% levels, respectively, with robust standard errors in parentheses.

Column of Table 7 presents the average results of the three matching methods’ ATT. It can be found that farmers’ RFA can significantly improve the economic and environmental effects of rice production. After excluding other factors, RFA can increase the NPPA of rice farmers by an average of 0.23, with an increase of 3.49%; RFA can increase the AGP of rice farmers by an average of 0.24, with an increase of 47.06%. The results of the PSM test, whether it is the increase in net profit or the increase in AGP, are within the estimation range of the endogenous switching model, further verifying the robustness of the research conclusions.

Table 7. PSM regression results of economic and environmental effects of framers’ RFA.

Matching method	Economic effects (NPPA)		Environmental effects (AGP)	
	ATT	T	ATT	T
Nearest neighbor matching	0.239***	7.53	0.239***	10.87
Kernel matching	0.236***	8.46	0.242***	11.39
Caliper matching	0.223***	7.49	0.239***	11.08
Average value	0.233	-	0.240	-

Note: *, **, and *** indicate significant at the 10%, 5%, and 1% levels, respectively.

4.5. Analysis of Differences in Economic and Environmental Effects of RFA Among Farmers of Different Management Scales

To further analyze the heterogeneous effects of farmers’ RFA on economic and environmental outcomes at different quantiles, this study employs quantile regression to examine the effects at the 25th, 50th, and 75th quantiles of economic and environmental outcomes. The previous research conclusions, indicate that RFA have a significant positive impact on the NPPA and AGP. Quantile regression provides a clearer understanding, the differential impacts of RFA on various levels of NPPA and AGP. The test results are shown in Table 8. From an economic perspective, RFA have a significant positive impact across different levels of NPPA. The impact is highest at the lower net profit level (0.25 quantile), and decreases as the net profit level increases. This indicates that the economic effect of RFA diminishes, as the profit from rice production increases, suggesting that for farmers with higher profits, the economic benefits of RFA have reached an optimal level. Thus, RFA should not be a continuous practice, but should aim for the optimal application amount to maximize economic benefits. From an environmental perspective, RFA have a significant positive impact across different levels of AGP, with the impact increasing significantly as green productivity improves. This suggests that farmers with relatively low green productivity, have a stronger inertia towards high fertilizer application, and the path dependency of agricultural production limits the environmental benefits of RFA. Therefore, for farmers with relatively low AGP, improving environmental outcomes will also rely on additional collaborative measures beyond fertilizer reduction.

The above analysis is based on regression results at specific quantiles. This study further describes the marginal contributions and trends of RFA on economic and environmental outcomes across all quantiles (as shown in Figure 4). The results in Figure 4 indicate, that the coefficients of the impact of RFA on NPPA and AGP are generally greater than 0, confirming that RFA enhance both economic and environmental outcomes. These findings are consistent with the main conclusions presented earlier.

Table 8. Quantile regression of economic and environmental effects of framers’ RFA.

Variable	Economic effects (NPPA)			Environmental effects (AGP)		
	0.25 quartile	0.5 quartile	0.75 quartile	0.25 quartile	0.5 quartile	0.75 quartile
RFA	0.309*** (0.034)	0.224*** (0.030)	0.181** (0.181)	0.046*** (0.124)	0.182*** (0.054)	0.460*** (0.029)
Control variable	control	control	control	control	control	control
Constant term	5.885*** (0.187)	6.279*** (0.148)	6.577*** (0.129)	0.144*** (0.038)	0.181** (0.080)	0.304*** (0.059)
R ²	0.073	0.056	0.049	0.048	0.048	0.228
Sample volume	1345	1345	1345	1345	1345	1345

Note: *, **, and *** indicate significant at the 10%, 5%, and 1% levels, respectively, with robust standard errors in parentheses.

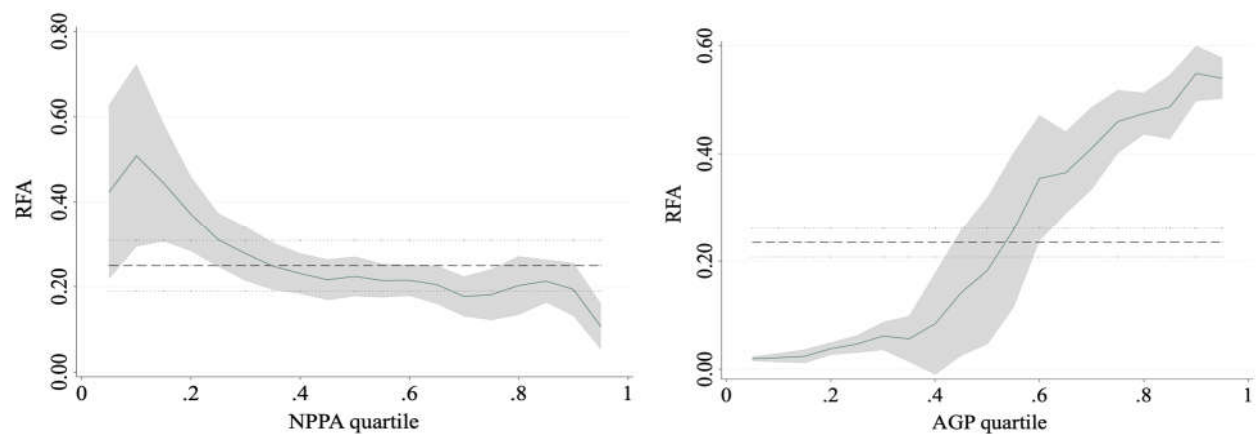


Figure 4. Interquartile regression coefficients and trends.

5. Conclusions

This study based on a sample of 1,345 rice farmers in Jiangxi Province, explores the economic and environmental effects of farmers’ RFA. The research results are as follows: In terms of economic effect, RFA have a significant positive impact on the NPPA, helping farmers increase their income. The increase in income ranges between 2.05% and 6.54%. In terms of economic effect, RFA significantly enhance AGP, improving the agricultural environment. The improvement ranges between 44.09% and 45.35%. The income-increasing effects and environmental improvement effects vary across different levels of NPPA and AGP. As NPPA increases, the economic effect of RFA decreases; conversely, as AGP increases, the environmental effect of RFA shows a significant upward trend.

Based on the above research conclusions, the following policy recommendations are proposed to promote green production behaviors among farmers, and effectively achieve fertilizer reduction: firstly, encourage RFA among low-profit farmers, encourage and guide low-profit farmers to adopt integrated green agricultural production technologies, to stimulate income potential. Improve the

quality supervision system for green agricultural products, within the market circulation mechanism. Promote the certification of agricultural product quality, based on the quality evaluation results from monitoring departments, implement differentiated pricing for agricultural products of different quality levels. Increase the development of green and organic agricultural products, on the basis of promoting green and organic agricultural products at high quality and good prices. Secondly, create favorable land scale conditions for fertilizer reduction technology promotion: research indicates that expanding farmers' operational scale is crucial for achieving RFA. In the context of the "three rights separation" reform in contracted land, actively promote property rights system reform, further activate the rural land management rights market, accelerating land transfer, expand farmers' operational scale. This will facilitate RFA through scale economies. Thirdly, implement externality internalization compensation system: RFA improve the environment and enhance social benefits, thus having the characteristics of public goods. Develop corresponding compensation policies for behaviors with positive externalities, to ensure the effective implementation of RFA. Governments should provide technical, financial, and other compensations to farmers who actively adopt fertilizer reduction technologies.

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Institutional Review Board Statement: This study was granted exemption by the Welfare Ethics Committee of Jiangxi Agricultural University (acceptance number: JXAULL-20221002). We certify that the study was performed in accordance with the 1964 declaration of HELSINKI and later amendments. Ethical review and approval were waived for this study due to REASONS: This study does not fall within the scope of ethical research. The authors use survey data from the research group at Jiangxi Agricultural University for analysis. The survey was conducted anonymously, and all participants were fully informed of the reasons for conducting the survey and the use of relevant data. No personal identity information was collected during the survey, and there were no conflicts of interest or potential risks for the rights holders.

Data Availability Statement: The raw data supporting the conclusions of this article will be made available by the authors on request.

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