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Original Research

The Impact of Non-Grain Production on Agricultural Ecological Efficiency: A Blessing or a Curse?

Lu Wang[1], Hailan Qiu[2], Ying Tan[1]*

[1]College of Economics and Management, South China Agricultural University
[2]School of Economics and Management, Jiangxi Agricultural University

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Abstract

Food security is crucial to a nation's survival and development, yet the shift of cultivated land toward non-grain crops has led to a reduction in both the area and quality of farmland, while also potentially exerting a negative impact on the agricultural environment. The increase in agricultural production and farmers' income has laid a solid foundation for ensuring food security. However, agricultural production methods that come at a high cost to resources and the environment have profound negative impacts on the ecological environment. Agricultural ecological efficiency (AEE) serves as a crucial indicator for assessing the efficiency of agricultural resource utilization and environmental pressure. Research on AEE can provide valuable insights for the government in formulating agricultural policies. As China's agricultural structure undergoes transformation, the phenomenon of non-grain production (NGP) is becoming increasingly prominent, posing challenges to the ecological environment. This paper aims to evaluate the ecological sustainability of China's agricultural sector and analyze the challenges posed by NGP to AEE. Based on field survey data from Jiangxi Province, this paper employs the super-efficiency SBM model, treating agricultural pollution as an undesirable output, to measure AEE. We construct an endogenous switching model and a mediation model to explore the impact of NGP on AEE. The average AEE of the sampled farmers was 0.363, indicating significant room for improvement. NGP significantly reduced AEE; farmers engaged in NGP exhibited a 40.90% decrease in efficiency compared to a hypothetical scenario of grain-oriented production. Mechanism analysis revealed that NGP led to reduced adoption of socialized services, increased agricultural labor input, and higher usage of agricultural pollutants, thereby lowering AEE. Therefore, mitigating the negative impacts of NGP requires systematic interventions, such as increasing the supply of socialized services, optimizing labor allocation, and reducing the application of chemicals.

Keywords: crop structure, ecological efficiency, agriculture, super-efficiency SBM model

*e-mail: tying@scau.edu.cn

Introduction

Food production and security are vital to national survival and development, making the utilization and protection of farmland critical. The decline in farmland quantity and quality is a widespread phenomenon globally [1]. During the processes of socioeconomic development and urbanization, large amounts of land are occupied, and non-agricultural construction encroaching on farmland is widespread. In response to this issue, China has implemented a strict farmland red line policy. This policy mandates a dynamic balance between the total amount of regional farmland and its stability, emphasizing that non-agricultural occupation of farmland must be compensated with an equivalent amount of replenishment – "replenishment determines occupation". Nevertheless, the area of farmland continues to decrease. The decline in both the quantity and quality of farmland has become a prominent issue threatening China's food security. In addition to the occupation of farmland by non-agricultural construction, the impact of a non-grain-oriented agricultural structure on farmland also warrants attention. While policies and academic circles have focused more on the encroachment of agricultural land by urban expansion, insufficient attention has been paid to the non-grain transformation of farmland resulting from agricultural structural adjustments. Data from the third national land survey, with 2019 as the reference point, show that China's farmland area decreased by 7.5333 million hectares over the past decade. The primary reasons for this reduction were agricultural structural adjustments and national land greening initiatives.

The non-grain production (NGP) adjustment of agricultural structure refers to the conversion of farmland originally used for growing grain crops to the cultivation of non-grain crops such as vegetables and fruits, poultry farming, or fallowing [2]. National land greening refers to the conversion of cropland into forests or grasslands. For instance, the Grain for Green Program, vigorously promoted in China, restores farmland unsuitable for cultivation or located in ecologically fragile areas to forests or grasslands. Although this reduces the amount of cropland, it enhances the resilience of ecosystems and promotes the improvement of ecological services. In recent years, numerous field studies have indicated that NGP on China's farmland has become a widespread phenomenon [3]. In many regions of China, NGP is cultivated on farmland to increase agricultural income, leading to a significant decline in the proportion of grain crop cultivation. Driven by economic interests, which are higher for non-grain crops, some areas have seen large-scale replacement of grain crops with cash crops. Varying degrees of non-grain conversion exist on China's cultivated land, showing an expanding trend [4]. The non-grain phenomenon is more pronounced on transferred land. With 25.3 million hectares of transferred land in China, the probability of non-grain cultivation on transferred land is 5-6 times higher than on non-transferred land [5]. NGP on farmland not only threatens food security but also has negative impacts on the agricultural environment. The reduction of farmland due to non-grain changes in agricultural structure may lead farmers to increase the application of agricultural chemicals. Moreover, cash crops require more fertilizers and pesticides, increasing the risks of soil degradation and water pollution, which in turn exacerbates farmers' use of agricultural chemicals.

China feeds 21% of the world's population using only 7% of its farmland. Given the scarcity of arable resources, China has long pursued an agricultural production model characterized by high input, high output, and high resource and environmental costs to ensure food security. From 1978 to 2021, the total output value of agriculture, forestry, animal husbandry, and fisheries in China surged from 139.7 billion yuan to 14701.34 billion yuan. However, this agricultural growth has led to the overexploitation of land resources and the excessive use of agricultural chemicals. During this period, fertilizer application surged from 8.84 million tons to 51.91 million tons, causing significant negative impacts on soil and water resources. This high-consumption agricultural production model is unsustainable, making the transformation of agricultural practices imperative. Agricultural green transition has thus become a critical goal for China's agricultural development. When agricultural structure transforms, it will inevitably affect the quantity, quality, and ecological environment of farmland. Therefore, it is essential to analyze the impact of NGP on agricultural green development.

Agricultural ecological efficiency (AEE) is a crucial indicator for assessing green development in agriculture. It not only measures the input-output efficiency of agricultural production but also incorporates environmental efficiency into consideration. Its essence lies in evaluating agricultural production efficiency while accounting for resource consumption and pollution, aiming to achieve maximum agricultural output with minimal resource use and environmental impact under given production factor inputs. Enhancing agricultural production efficiency, reducing agricultural pollution, and maintaining soil fertility contribute to improving the AEE and achieving sustainable agricultural development [6]. Improving AEE serves as a tool for realizing sustainable agriculture. One pathway to promoting green transformation in agriculture is to enhance AEE, shifting the focus from increasing yield and income to improving quality.

Existing literature has extensively explored the characteristics and causes of the shift away from grain production in agricultural structures. However, less attention has been paid to the environmental impacts of this shift, particularly its effects on AEE. Against the backdrop of labor migration and livelihood transformation, the transition of farmers to NGP is an inevitable trend. It is essential to clarify the impact of NGP on the agricultural environment. A scientific analysis of how NGP affects AEE can provide essential policy and technical support during their cultivation of cash crops, helping them avoid agricultural pollution and maintain soil fertility. This paper will also assist governments in formulating policies to support farmers' livelihood transformation while preventing excessive NGP from undermining food security.

Based on survey data from Jiangxi Province, this study utilizes a super-efficiency SBM model to measure AEE, while constructing an endogenous switching regression (ESR) model to analyze the impact of NGP in the planting structure on AEE. Existing research has analyzed AEE related to planting industries at both provincial and municipal levels. However, studies utilizing micro-level farmer survey data remain relatively limited. The innovations of this paper are as follows: First, farmers, as micro-level agents in agricultural production, make the study of their planting structure and AEE highly practically significant. Second, farmers' choices regarding planting structure and their agricultural input-output behaviors involve simultaneous decision-making. By applying an ESR model and counterfactual analysis, we address this issue of simultaneous decision-making, thereby making the analysis more reasonable. Finally, this paper evaluates the impact of NGP in agricultural planting structure on AEE, aiming to provide policy references for promoting agricultural green transformation.

Literature Review

Measurement and Influencing Factors of AEE

With the development of the social economy, resource consumption and environmental pollution have followed. Economic development achieved at the expense of the environment is unsustainable. The same holds true for agricultural development: the traditional agricultural production model characterized by high input and high consumption has led to resource overexploitation and environmental damage. Increasing attention is being paid to agricultural environmental benefits. The AEE is one of the valuable indicators for assessing efficiency in agricultural resource utilization and environmental pressure [7].

Scholars have incorporated resource and environmental factors into the analytical framework of agricultural production efficiency. By treating agricultural pollution as undesirable output in agricultural production, the evaluation of the AEE becomes more scientific. Research on AEE has yielded fruitful results, with studies measuring the AEE across different scales and agricultural structures in Asia, Europe, Africa, and other regions. Methods for measuring the AEE primarily include life cycle assessment [8], data envelopment analysis (DEA), and stochastic frontier analysis [9]. Among these, the DEA method is the most widely applied. As a non-parametric method, DEA avoids the influence of technical factors on the frontier production function and is used to evaluate the AEE with multiple inputs and outputs. Coluccia et al. [7] assessed the AEE of various regions in Italy and found it to be 0.778. Although it showed an increasing trend, there remains significant room for improvement. Stępień et al. [10] studied the AEE of small-scale farms in Poland, calculating an average AEE of 0.7, with the largest proportion of farms having efficiency values between 0.4 and 0.59. Liu et al. [11] used provincial-level data and applied the Super-SBM model to measure China's AEE from 1978 to 2017.

Scholars have conducted research on the impact of agricultural macro-policies, socio-economic development, agricultural structure, agricultural production conditions, and natural resource endowments on AEE. The paper by Czyżewski et al. [12] suggests that decoupled subsidies and labor-intensive agricultural expansion may reduce AEE, while investment subsidies and environmental subsidies can enhance it. Both subsidies and the proportion of agricultural income significantly affect AEE. Zhou et al. [13] point out that environmental regulations influence the AEE by increasing rural residents' health investments, thereby promoting it. Bonfire et al. [14] argue that participation in environmental protection can serve as an important indicator for measuring AEE, and agricultural environmental subsidies may be an effective means to guide farmers toward sustainable farming practices. Sintori et al. [15] used olive cultivation as an example, employing truncated regression to analyze the factors influencing AEE. The results show that subsidies, farmers' education levels, and the proportion of agricultural income all have significant effects on AEE. Shen et al. [16] studied grain crops to explore the factors affecting AEE in 31 provinces of China. They found that economic development level, agricultural production structure, and the urban-rural income gap all have significantly positive effects on AEE. Driven by market forces and economic incentives, the shift of farmers from growing grain crops to non-grain crops is a natural selection. The literature analyzes the factors influencing AEE using different crops as study subjects, while the structure of agricultural cultivation also affects AEE.

Non-Grain Production of Farmland

Rising grain production costs, coupled with persistently low grain prices, have driven changes in farmers' crop selection. The utilization of farmland in China is undergoing significant transformation, with large areas being diverted from grain production to NGP. This includes conversion to construction land or adjustments within agricultural structures, such as shifting to cash crop production, aquaculture, and poultry farming. The definition of NGP of farmland can be interpreted in both broad and narrow senses. Broadly, it refers to the reduction of farmland due to non-agricultural construction, agricultural restructuring, and damage from disasters. For instance, farmland in the North China Plain, the Northeast Plain, and the Loess Plateau has been encroached upon by construction land [17]. In a narrow sense, NGP refers to adjustments in agricultural planting structures, where land originally used for growing grain is repurposed for cash crops or other agricultural uses. With urban development, agricultural production types have shifted from grain to NGP, particularly in peri-urban areas [18]. The mechanism behind the shift from grain to NGP lies in the low economic returns of grain production, stable but low grain prices, and rising costs of labor and agricultural inputs. As "rational actors", agricultural producers weigh the pros and cons and opt for NGP to enhance economic benefits [19]. The proportion of NGP initially increases with the expansion of farm scale but eventually decreases [20].

Numerous studies indicate that the growing trend of NGP on farmland poses a threat to food security. Over the past decade, the sown area of grain production has decreased by approximately 13.33 million hectares. This large-scale reduction in grain production could lead to shortages in grain supply, driving up international grain prices and exacerbating hunger among impoverished populations. With improvements in living standards and growing nutritional awareness, Chinese residents are increasingly demanding diversified food options, including vegetables, fruits, meat, and dairy products, rather than relying solely on grains for nutrition [21]. Influenced by economic interests and consumption trends, a significant portion of China's farmland has been converted from grain production to cash crop production. Although China's self-sufficiency rate for grains was 98.32% in 2020, long-term food security challenges remain [22]. NGP of farmland may not only pose risks to food security but also present challenges to the agricultural environment.

Impact of NGP on AEE

Existing literature presents divergent views on the impact of NGP on AEE. The first perspective suggests that the expansion of NGP has a negative effect on AEE. An increase in the proportion of NGP may lead to higher agricultural pollution [23]. The cultivation of cash crops can stimulate excessive use of fertilizers and pesticides, resulting in environmental pollution [24]. Contaminated soil, water, and air accumulate in the human body through the food chain, triggering various diseases [25]. Labor migration and crop diversity exhibit an inverted U-shaped impact on agricultural output and agricultural non-point source pollution. Agricultural output and non-point source pollution initially increase and then decrease with rising crop diversity. Diversified planting requires farmers to select fertilizers and pesticides based on different crops and land conditions, demanding more labor and resources [26]. Another perspective holds that NGP has a positive impact on AEE. With the rapid development of leisure agriculture and tourism agriculture, the issue of landscape homogenization in traditional grain production has been transformed. This expansion enhances the landscape and cultural functions of farmland and increases the diversity of farmland ecosystems [27, 28]. Intensive crop production benefits grain yield, but overly homogeneous landscapes can weaken the ecological functions of farmland. The production of non-grain crops, such as nursery stock, contributes to air purification, water conservation, and carbon sequestration [29].

Existing research has made significant contributions to understanding NGP and AEE, as well as the environmental impacts of NGP. However, the literature has not sufficiently addressed the effects of NGP on AEE. In particular, rigorous causal inference methods (such as ESR) to examine these effects remain scarce, and in-depth mechanism analysis is lacking. Existing research on the effects of NGP on AEE has not reached consistent conclusions, and studies from a micro perspective based on individual farmers remain limited.

Research Hypothesis

The conversion of high-quality grain farmland to other agricultural uses, such as seedling cultivation and aquaculture, leads to the loss of farmland resources. Changes in farmland functions affect soil quality and ecological balance. The impact of different types of non-grain crops on food security and the environment cannot be overlooked. Perennial non-grain shrubs, such as fruit trees and herbaceous plants, continuously absorb soil nutrients, resulting in soil degradation. Frequent human activities during cultivation, tillage, and harvesting accelerate soil compaction and reduce farmland quality. Strip-till NGP activities, such as seedling cultivation and farming, cause irreversible damage to agricultural production and severely affect the sustainable use of farmland resources [30]. The conversion to NGP leads to complex changes in land use patterns, impacting land sustainability and the long-term effectiveness of ecosystems, potentially causing land degradation, changes in hydroecological environments, and intensified agricultural pollution [31]. Simultaneously, NGP alters the intensity of factor inputs and farmland utilization methods [27]. The high-input, high-return, and high-risk production model of cash crops stimulates the excessive use of fertilizers and pesticides, leading to environmental pollution [24]. To meet the growth demands of cash crops, continuous high-intensity inputs of production factors are required, resulting in environmental issues such as soil degradation, groundwater pollution, and soil erosion, which negatively affect agricultural production and ecosystems [32, 33]. The expansion of NGP damages the soil tillage layer, exacerbates agricultural non-point source pollution, and increases carbon dioxide emissions, which are detrimental to food security and environmental protection in the long run [34-36]. Based on this, the first research hypothesis (H1) of this paper is proposed:

H_1: The shift in planting structure toward NGP has a significant negative impact on AEE.

Materials and Methods

Research Methods

Measurement of AEE Based on the Super-SBM Model

In agricultural production, human capital and material inputs not only generate agricultural products but also produce undesirable outputs, such as agricultural non-point source pollution. Traditional measurements of agricultural production efficiency only consider agricultural inputs and outputs while neglecting the role of agricultural pollution. The SBM model proposed by Tone incorporates undesirable outputs in the agricultural production process, making it more aligned with real-world conditions. Therefore, we employ the super-SBM model to calculate AEE. Crop farming is selected as the research subject, with the gross agricultural output value – including the output value of food crops such as rice, wheat, and potatoes, as well as cash crops – serving as the desirable output, and agricultural non-point source pollution as the undesirable output. Land input, labor input, and capital input are chosen as the input variables. The AEE in this paper is calculated using MaxDEA 8 Ultra software. The construction of the super-SBM model is as follows:

$$\rho = \min \frac{\frac{1}{m}\sum_{i=1}^{m}\overline{x_i}/x_{ik}}{\frac{1}{S_1+S_2}\left(\sum_{r=1}^{S_1}\overline{y_r^g}/y_{rk}^g+\sum_{q=1}^{S_2}\overline{y_r^b}/y_{rk}^b\right)}$$

$$s.t.\begin{cases} \overline{x} \ge \sum_{j=1,j\ne k}^{n}\theta_j x_j \\ \overline{y}^g \ge \sum_{j=1,j\ne k}^{n}\theta_j y_j^g \\ \overline{y}^b \ge \sum_{j=1,j\ne k}^{n}\theta_j y_j^b \\ \overline{x} \ge x_0, \overline{y}^g \le y_0^g, \overline{y}^b \ge y_0^b, \overline{y}^g \ge 0, \theta \ge 0 \\ i=1,2,\cdots m; j=1,2,\cdots n; r=1,2,\cdots S_1; q=1,2,\cdots S_2 \end{cases} \quad (1)$$

where n is the number of decision-making units (DMUs). Each DMU consists of inputs (m), desirable outputs (S_1), and undesirable outputs (S_2). Here, x, y^g, and y^b represent the input matrix, desirable output matrix, and undesirable output matrix, respectively. S_1 and S_2 denote the efficiency values of the evaluated units.

Impact of NGP Structure on AEE

This paper categorizes agricultural planting structures into non-grain production and grain-oriented production. An ESR is employed to examine the effect of farmers' NGP on AEE. The advantage of the ESR model lies in its ability to address selection biases caused by both observable and unobservable variables. The ESR model consists of two stages: the first stage is the selection equation, which estimates whether farmers adopt NGP; the second stage is the outcome equation, which estimates the impact of NGP on agricultural AEE.

Whether farmers choose NGP primarily depends on the utility derived from such practices. Assume that the utility a farmer gains from choosing NGP is denoted as $Grain^*_{1i}$, and the utility from choosing grain-oriented production is denoted as $Grain^*_{0i}$, if $Grain^*_i = Grain^*_{1i} - Grain^*_{0i} > 0$, then the farmer will choose NGP; otherwise, they will choose grain production. However, $Grain^*_i$ is an unobservable variable. In practice, the farmer's actual choice between NGP and grain-oriented production can be observed. Therefore, the selection equation for the farmer's planting structure is constructed as follows:

$$Grain_i^* = \alpha X_i + \varepsilon_i, \ (Grain_i = 1, \text{ if } Grain_i^* > 0; \ Grain_i = 0, \text{ if } Grain_i^* \le 0) \quad (2)$$

where $Grain_i$ is a binary variable, $Grain_i = 1$ indicates the farmer chooses NGP, X_i represents factors influencing the farmer's choice of NGP, ε_i is the random disturbance term.

Assuming AEE is an observable variable, a linear regression equation is constructed with the binary variable of planting structure, and the OLS method is used for estimation.

$$AE_i = \beta\varphi_i + \lambda U_i + \mu_i \quad (3)$$

where AE_i represents the value of AEE, φ_i represents the observed variables affecting AEE, β, λ are the coefficients to be estimated, μ_i is the random disturbance term. There is a possibility of "simultaneous decision-making" between farmers' choice of planting structure and agricultural input factors. The selection equation assumes that the choice of planting structure is exogenously determined. However, in reality, the choice of planting structure may be based on expected returns or path dependence, which could lead to a "self-selection" problem. To address this, a simultaneous equations approach is adopted using an ESR model, which effectively mitigates endogeneity issues and improves the inefficiency and bias of estimation results [37]. The ESR model transforms Equation (2) into Equations (4a) and (4b), representing the impact effect models of AEE for the NGP group and the grain-oriented group, respectively:

$$AE_{1i} = \beta_1\varphi_{1i} + \mu_{1i}, \text{ if } Grain_i = 1 \quad (4a)$$

$$AE_{2i} = \beta_2\varphi_{0i} + \mu_{2i}, \text{ if } Grain_i = 0 \quad (4b)$$

AE_{1i} in Equation (4a), and AE_{2i} in Equation (4b), represent the AEE of the NGP group and the grain-oriented group, respectively. β_1 and β_2 represent the parameters to be estimated. μ_{1i} and μ_{2i} represent the random error terms. When unobserved factors simultaneously influence both farmers' planting structure and AEE, there is a correlation between the residual terms of the selection equation and the result equation. Specifically, $\sigma_1\varepsilon = \cos(\mu_{1i}, \varepsilon)$ and $\sigma_2\varepsilon = \cos(\mu_{2i}, \varepsilon)$ represent the covariances of the error terms of the selection equation and the impact effect model. If their correlation is significant, it indicates the existence of "simultaneous decision-making" and "self-selection" problems, leading to biased estimation results when using the OLS method. Therefore, the ESR model introduces the inverse Mills ratio (λ) calculated from the farmers' NGP selection equation (Equation (1)) into the result effect model to address this issue, correcting the selectivity bias caused by unobservable latent variables and minimizing endogeneity issues due to omitted variables. At this point, the result effect models of AEE for the NGP group and the grain-oriented group can be transformed into:

$$AE_{1i} = \beta_1\varphi_{1i} + \sigma_{1\varepsilon}\lambda_{1i} + \mu_{1i}\text{, if } Grain_i = 1 \quad (4c)$$

$$AE_{2i} = \beta_2\varphi_{2i} + \sigma_{2\varepsilon}\lambda_{2i} + \mu_{2i}\text{, if } Grain_i = 0 \quad (4d)$$

In Equations (4c) and (4d), λ_1 and λ_2 represent the unobserved latent variables. Therefore, the estimation results obtained from Equations (4c) and (4d) are unbiased and consistent. The ESR model uses the full information maximum likelihood estimation method to estimate the selection equation (Equation (2)) and the result effect equation (Equations (4c) and (4d)). The results obtained are more efficient than those from the Heckman two-step method. The ESR model allows overlapping explanatory variables between the selection equation and the outcome equation, but for better estimation, the result equation typically has one fewer explanatory variable than the selection equation.

This paper conducts a counterfactual analysis of the impact of farmers' planting structure, comparing the differences in AEE under actual and counterfactual conditions for NGP and grain-oriented production, to accurately evaluate changes in AEE after farmers adopt NGP. The conditional expectations of AEE for the NGP group and the grain-oriented group can be expressed as:

$$E[AE_{1i} \mid Grain_i = 1] = \beta_1\varphi_{1i} + \sigma_{1\varepsilon_i}\lambda_{1i} \quad (4e)$$

$$E[AE_{2i} \mid Grain_i = 0] = \beta_2\varphi_{2i} + \sigma_{2\varepsilon_i}\lambda_{2i} \quad (4f)$$

The conditional expectations of AEE under counterfactual input for the NGP group and grain-oriented production groups can be expressed as:

$$E[AE_{2i} \mid Grain_i = 1] = \beta_1\varphi_{1i} + \sigma_{2\varepsilon_i}\lambda_{1i} \quad (4g)$$

$$E[AE_{1i} \mid Grain_i = 0] = \beta_2\varphi_{2i} + \sigma_{1\varepsilon_i}\lambda_{2i} \quad (4h)$$

The ESR model can calculate three average treatment effects of planting structure on AEE: the average treatment effect on the treated (ATT) for the treatment group (NGP group), the average treatment effect on the untreated (ATU) for the control group (grain-oriented production group), and the average treatment effect (ATE) for the overall sample. The most critical estimated parameter is the ATT [38]. The ATT can be expressed as the difference between Equation (4e) and Equation (4g):

$$\begin{aligned} ATT &= E[AE_{1i} \mid Grain_i = 1] - E[AE_{2i} \mid Grain_i = 1] \\ &= \varphi'_{1i}(\beta_1 - \beta_2) + \lambda_{1i}(\sigma_{1\varepsilon} - \sigma_{2\varepsilon}) \end{aligned} \quad (4i)$$

Mediating Effects

To investigate whether farmers' NGP influences AEE through the use of agricultural socialized services, agricultural labor input, and agricultural pollutant usage rates, this paper refers to the research methodologies of Baron and Kenny, Dippel et al., and Wen et al. [39-41] and employs the following strategy for mechanism analysis.

$$AE_{it} = \alpha_1 + \theta_1\text{Grain}_{it} + \chi_1 Z_{\text{it}} + \mu_{\text{i}} + \varepsilon_{it} \quad (5)$$

$$M_{it} = \alpha_1 + \theta_1\text{Grain}_{it} + \chi_1 Z_{\text{it}} + \mu_{\text{i}} + \gamma_{\text{t}} + \varepsilon_{it} \quad (6)$$

$$AE_{it} = \alpha_2 + \beta_1 M_{\text{ij}} + \theta_1\text{Grain}_{it} + \chi_1 Z_{\text{it}} + \mu_{\text{i}} + \gamma_t + \varepsilon_{it} \quad (7)$$

Here, AE_{it} represents the value of AEE, $Grain_{it}$ denotes the planting structure of households, and M_{it} indicates the mechanism variables: the adoption of agricultural socialized services (servicenum), agricultural labor input rate (laborrate), agricultural technical efficiency (efficiency), and agricultural pollutant usage (polluteuse). μ_i controls for regional effects, γ_t controls for time effects, and ε is the random disturbance term.

Data Sources

This paper utilizes data from the "Thousand Households in Hundred Villages" survey database, which was jointly conducted by Peking University and Jiangxi Agricultural University in December 2018. Jiangxi Province is a major agricultural province in central China, making it representative for studying AEE. The sampling of farm households followed the stratified sampling principle: 12 counties were selected

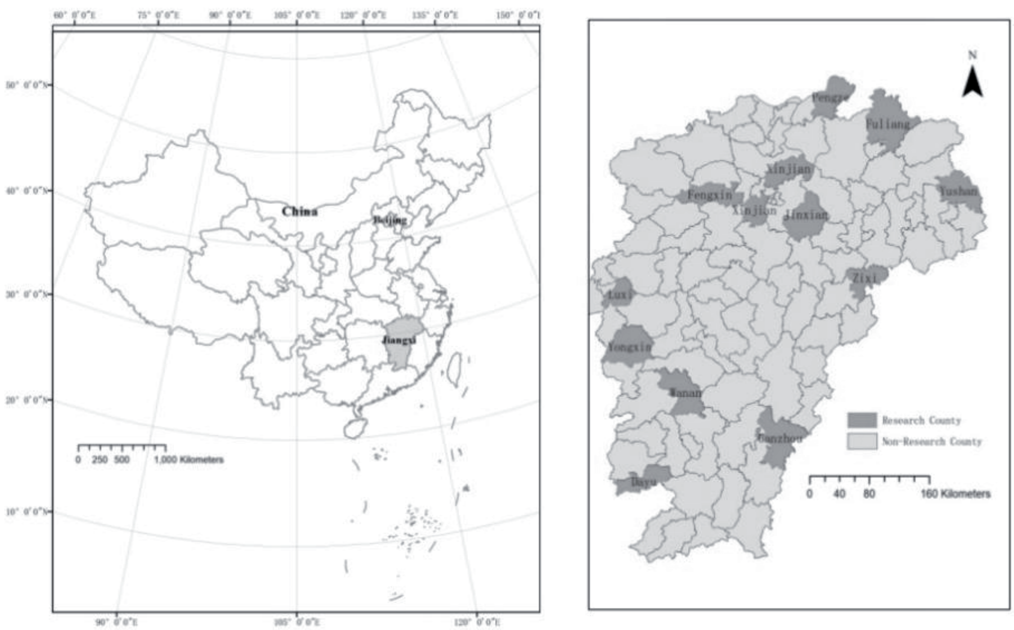

Fig. 1 Surveyed areas.

within the province, three townships were chosen from each county, three villages were selected from each township, and households were systematically sampled from each village to ensure randomness.

The selected households cover the northern, central, and southern regions of Jiangxi Province. A total of 1,080 farm household samples were collected in the survey. This paper focuses on the 743 households engaged in crop cultivation. After excluding samples with severe data gaps or logical inconsistencies, 711 valid samples were obtained. The surveyed areas are illustrated in Fig. 1.

Variable Selection

Dependent Variable. The dependent variable in this paper is AEE, which is estimated using the super-SBM model. The input variables selected include land input, labor input, and capital input. Specifically, land input is measured by the crop sown area, labor input is measured by the labor hours for crop planting, and capital input is measured by the costs of agricultural operations (e.g., seeds, pesticides, fertilizers). The desired output is the total agricultural output value, encompassing the output value of both grain crops and cash crops. It should be noted that self-used portions are valued at local market prices. The undesirable output is agricultural non-point source pollution. Agricultural non-point source pollution is measured by fertilizer loss and pesticide residue. Here, the fertilizer pollution amount is calculated as the fertilizer application amount multiplied by the fertilizer loss rate (similarly for pesticides). The pollutant loss rates refer to existing literature [42], with the fertilizer loss rate set at 65% and the pesticide pollution rate set at 50% (Table 1).

Core explanatory variable. The core explanatory variable in this paper is the planting structure. For research purposes, we classify farmers' planting structure into non-grain and grain-oriented. Some literature uses grain cropland area as the criterion for distinguishing non-grain and grain-oriented planting [43]. However, the area alone cannot adequately measure farmers' dependence on a particular industry. This paper adopts Cheng's classification criteria for transitioning

Table 1. Measurement indicators of AEE.

Category	Variables	Description	Mean	Std.
Input variables	Land input	Crop sown area (mu)	10.162	29.350
	labor input	labor hours for crops (hours)	203.404	392.238
	Capital input	Agricultural operating expenses (yuan)	5441.639	15097.510
Desirable output	Agricultural gross output	Total crop output value (yuan)	12973.900	37697.110
Undesirable output	Agricultural non-point source pollution	Fertilizer pollution (kg)	398.355	1267.816
		Pesticide pollution (kg)	20.817	88.092

farmers [44]. The planting structure is calculated as the ratio of the output value of cash crops to the total agricultural output value. If a farmer's cash crop output value ratio is 50% or higher, we define the farmer as engaging in NGP; if the ratio is 50% or lower, we define the farmer as engaging in grain-oriented production.

Identification variables. Referring to Yin et al.'s [45] method of setting instrumental variables, we selected NGP in the same village (nograiniv) as an instrumental variable. Due to information dissemination, technology sharing, and imitative learning among villagers within the same village, NGP behaviors among households in a single village are often highly correlated. This variable exerts a direct influence on the NGP behaviors of the study subjects, but does not directly affect the agricultural ecological efficiency of other sample households beyond the study subjects.

Other explanatory variables. This paper controls for other factors affecting AEE, including land scale, agricultural management characteristics, and household characteristics, to minimize bias in the estimation process (Table 2). Household head characteristics include age, health status (health), education level (education), whether the householder is a village official (official), and whether agricultural technical training has been received (agritech). Household characteristics including degree of pluriactivity (pluriactivity) and labor force size (labor). Agricultural management characteristics include planting structure (structure), planting area (croparea), value of agricultural production equipment (equipment), and land transfer (transfer).

Results

Calculation Results of AEE

The agricultural AEE calculated in this paper is presented in Table 3. The AEE can be further decomposed into pure technical efficiency and scale efficiency. The results show a slight improvement compared to the AEE value of 0.339 for Jiangxi Province from 2004 to 2015 [46]. However, the mean value remains at a low level. As shown in Table 3, there are significant differences in AEE among farmers, indicating substantial potential for improvement in Jiangxi Province's AEE, thereby continuously promoting the green transformation of agriculture.

Given the considerable variation in AEE among farmers, for better illustration, this paper categorizes farmers into three groups based on their AEE scores: high-efficiency (≥1), medium-efficiency (>0.8 and ≤1), and low-efficiency (<0.8). The results reveal that the mean comprehensive ecological efficiency and pure technical efficiency are relatively low. Among the comprehensive efficiency and pure technical efficiency categories, the proportions of farmers in the high-efficiency group are 4.22% and 5.77%, respectively, while the proportions in the medium-efficiency group are 1.55% and 3.38%. This indicates significant potential for expanding the number of farmers in the medium- and high-efficiency groups and improving AEE. In contrast, the low-efficiency group accounts for 94.2% and 90.9% of the total, respectively (Table 3).

Table 2. Definitions of main explanatory variables and descriptive statistics.

Variables	Variable Definition	Mean	Std.
NGP	Whether the farmer engages in non-grain planting, yes = 1, no = 0	0.148	0.355
Nograiniv	Planting structure in the same village	0.148	0.224
Croparea	Agricultural planting area (mu)	5.921	6.269
Landinflow	Land inflow area (mu)	3.464	15.004
Aserices	Whether the farmer uses agricultural socialized services, yes = 1, no = 0	0.748	0.434
Price	Service price, yuan/mu	104.763	50.960
Servicecost	Service cost, yuan	821.709	1257.376
Equipment	Value of agricultural machinery owned by the farmer, thousand yuan	31.58	40.76
Agritech	Whether the farmer has received agricultural technical training, yes = 1, no = 0	0.091	0.288
Pluriactivity	Proportion of non-agricultural labor in the household (%)	0.373	0.484
Labor	Number of labor force in the household	2.848	1.165
Age	Actual age of the household head (years)	57.461	9.878
Official	Whether the household head is village Party secretary, village head, or a village committee member, yes = 1, no = 0	0.210	0.407
Education	Actual years of education of the household head (years)	8.051	6.559

Table 3. Calculation results of farmers' AEE.

Group	Comprehensive Efficiency		Pure Technical Efficiency		Scale Efficiency	
	Number	Mean	Number	Mean	Number	Mean
High efficiency	30	1.321	41	1.928	3	1.498
Medium efficiency	11	0.847	24	0.927	562	0.929
Low efficiency	670	0.312	646	0.342	146	0.591
Total	711	0.363	711	0.453	711	0.862

Determinants of NGP and AEE

This paper employs an ESR model to analyze the impact of NGP on AEE, with the results presented in Table 4. The $\ln\sigma_{1\mu}$ and $\ln\sigma_{0\mu}$ are significant at the 1% level, indicating that unobservable factors influence the relationship between NGP and AEE. The null hypothesis that NGP selection is independent of the result equation for AEE is rejected. Selection bias needs to be corrected, justifying the use of the ESR model. The selection equation reports the factors influencing farmers' choice of NGP. It can be observed that agricultural planting scale, agricultural socialized services, and the price of such services inhibit farmers from adopting grain-oriented production. Larger agricultural planting scales help overcome the limitations of fragmented management, promoting grain-oriented planting. Agricultural socialized services facilitate economies of scale in agricultural services through horizontal division of labor. Grain production typically requires large-scale planting, and mechanized services reduce labor demands in agricultural management, making farmers more inclined to choose grain-oriented production. The planting structure within the same village positively influences farmers' planting decisions, indicating a peer effect. If other farmers in the village adopt grain-oriented or non-grain planting, the individual farmer is also likely to follow suit.

The result equation in Table 4 reports the determinants of AEE for both the grain-oriented production and NGP groups. For the grain-oriented group, agricultural planting scale, land inflow, agricultural socialized services, and agricultural production equipment have significant positive effects on AEE. Agricultural socialized services act as a conduit for advanced technologies. Intelligent and precise fertilization and pesticide application reduce the input of agrochemicals, minimize undesirable outputs, and enhance the AEE of farmers engaged in grain-oriented planting. For the grain-oriented group, agricultural socialized services and land inflow improve AEE. Larger agricultural planting scale and land inflow facilitate contiguous planting, support mechanization, and enhance agricultural technical efficiency. Grain crops such as rice and wheat are suitable for mechanized operations. Farmers who own agricultural machinery can reduce labor input and improve production efficiency. However, the cost of agricultural socialized services has a significant negative impact on the AEE of the grain-oriented production group. Small-scale farmers lack bargaining power, and excessively high service costs increase their financial burden, reducing agricultural production efficiency and thereby negatively affecting AEE.

For the NGP group, agricultural socialized services still have a significant positive impact on AEE. Although services for non-grain crops developed later than those for grain crops, non-grain crops offer higher economic returns. Specialized services for specific types of cash crops help reduce excessive chemical usage due to farmers' lack of experience. Additionally, agricultural socialized services promote green certification, encouraging farmers to adopt eco-friendly production practices. However, the degree of household pluriactivity has a significant negative impact on AEE. Compared to grain crops, non-grain crops require more labor input and cannot be fully mechanized during planting and harvesting. Thus, a higher degree of household pluriactivity reduces AEE.

Impact of NGP on AEE

The differences in NGP and the determinants of AEE in Table 4 cannot reflect the specific impact of NGP on AEE. After eliminating selection bias, we calculated the impact of NGP on AEE (Table 5). The ATT on the AEE of farmers engaged in NGP is -0.4090. This indicates that for farmers who have already shifted to NGP, if they were to engage in grain production instead, their AEE per unit would increase by 40.90%. Conversely, the ATU for farmers engaged in grain-oriented planting was -0.2488, suggesting that for farmers currently producing grain, if they were to switch to NGP, their AEE per unit would decrease by 24.88%. The results show that NGP by farmers has a significant inhibitory effect on AEE. NGP leads to changes in input structure and resource allocation. The cultivation of cash crops can bring economic benefits, but due to the volatile market, farmers tend to choose cash crops with short production cycles, increasing the input of chemicals such as fertilizers and pesticides, which causes environmental damage and reduces AEE. Comparing the values of ATT and ATU reveals that when farmers who have already shifted to NGP return to

Table 4. ESR Model of the impact of planting structure on AEE.

Variables	Selection Equation		Result Equation			
	(1) whether to choose non-grain production		(2) non-grain production group		(3) grain-oriented production group	
Croparea	-0.0342**	(0.0166)	-0.0070	(0.0054)	0.0043**	(0.0017)
Landinflow	0.0235	0.0168	0.0253**	0.0117	0.0015**	0.0007
Aserices	-0.4123***	0.0753	0.1183*	0.0696	0.0359**	0.0164
Price	-0.0031**	0.0013				
Servicecost			-0.0287	0.0217	-0.0094*	0.0057
Equipment	-0.0139	0.0193	0.0052	0.0099	0.0070***	0.0027
Agritech	0.1197	0.2482	-0.1254	0.1219	0.0682*	0.0359
Pluriactivity	-0.0142	0.1572	-0.1449*	0.0816	0.0093	0.0231
Education	0.0048	0.0091	0.0001	0.0045	-0.0012	0.0016
Age	0.0009	0.0076	0.0001	0.0037	-0.0009	0.0012
Official	-0.0004	0.1735	0.0487	0.0782	0.0914***	0.0257
Nograiniv	2.1396***	0.2570				
Constant	-0.5898	0.5261	0.4773*	0.2700	0.3543***	0.0771
$\rho_{Y\varepsilon 1}/\rho_{N\varepsilon 1}$			-1.1371***	0.0736	-1.4076***	0.0296
$\chi^2(2)$	57.51***					

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

grain production, the increase in AEE exceeds the loss in AEE experienced by farmers who shift from grain production to NGP. NGP households require specific comparative advantages – such as specialized skills, greenhouses, and irrigation facilities – which result in lower AEE when cultivating non-grain crops. However, when these households transition to grain production, these resources and technologies become more versatile, leading to enhanced AEE.

Agricultural planting scale, agricultural socialized services, and the price of socialized services have a negative impact on farmers' choice of NGP. A larger agricultural planting scale is more conducive to the use of agricultural machinery, reducing labor input. Under the influence of non-agricultural employment and an aging labor force, a larger agricultural planting scale is more favorable for farmers to choose grain production. Socialized services centered on grain production are more mature, providing diverse options for small farmers. Agricultural socialized service organizations improve production efficiency by unifying the purchase of production materials and implementing large-scale mechanized operations. Services for cash crops require more precision and specialization, and small-scale demands are insufficient to induce the supply of professional services.

Mechanism Analysis

This section examines the pathways through which NGP affects AEE using OLS regression, estimating the impact of NGP on the following key variables: the adoption of agricultural socialized services (servicenum), agricultural labor input rate (laborrate), agricultural technical efficiency (efficiency), and agricultural pollutant usage (pollutrate) (Table 6). The adoption of agricultural socialized services is measured by the number of such services utilized by farmers. Agricultural labor input rate is defined as the labor time per unit area on the household's own land.

Table 5. Estimation results of treatment effects of farmers' planting structure on AEE.

Category	Decision Stage		Treatment Effect
	Non-grain production	Grain-oriented production	
Non-grain group	0.0505 (0.0048)	0.4596 (0.0167)	-0.4090*** (0.0192)
Grain-oriented group	0.0631 (0.0058)	0.3120 (0.0056)	-0.2488*** (0.0110)

Table 6. Mechanism analysis results

Variables	Servicenum	Laborrate	Efficiency	Pollutrate
NGP	-0.6505***	0.7722***	-0.0619***	0.3461***
	(0.1016)	(0.1141)	(0.0202)	(0.1292)
Control	Yes	Yes	Yes	Yes
Number	711	711	711	711

Agricultural technical efficiency is calculated using the DEA method, resulting in pure technical efficiency. This is derived by considering land, labor, and capital as input variables and gross agricultural output value as the output variable. Agricultural pollutant usage is measured by the amount of chemical fertilizers applied per unit of cultivated area. Column (1) shows that NGP reduces the probability of farmers using agricultural socialized services. Thus, NGP influences AEE by altering the adoption of agricultural socialized services. NGP negatively affects farmers' adoption of socialized services because mechanical services for grain crops are more well-established, and contiguous planting is more conducive to mechanized operations. Mechanization replaces manual labor, alleviating labor scarcity and high costs caused by aging and labor migration. Moreover, cash crops are more diverse, and only when a region develops a competitive industry for a specific crop can the demand for technical, sales, and other services generate the establishment of relevant service providers. Small-scale, scattered cultivation of cash crops struggles to create effective demand for socialized services, leading to a lack of suitable service providers.

Column (2) reports the mechanism test results for agricultural labor input. It can be observed that NGP increases agricultural labor input, thereby reducing AEE. Compared to grain production, cash crops have higher value but also require more meticulous care and maintenance, necessitating more labor time. The increase in labor input affects agricultural production efficiency, consequently impacting AEE. Column (3) presents the mechanism test results for agricultural technical efficiency. NGP has a significant negative impact on agricultural technical efficiency, as shifting to non-grain crops often requires more complex management, different inputs, and new technologies. Poor management can lead to inefficient input use. Column (4) reports the mechanism test results for the usage rate of agricultural pollutants. It can be seen that NGP increases the usage rate of agricultural pollutants. NGP is often market-driven and involves higher risks. Farmers' concern about market volatility encourages increased input of fertilizers and pesticides to shorten planting time and boost yields.

Discussion

Based on field survey data from Jiangxi Province, this paper empirically analyzes the impact of NGP on AEE and its underlying mechanisms. We find that the overall AEE in the sample regions is relatively low. This result indicates that agriculture in the study areas is inefficient in converting factors such as land, water, and fertilizers into economic output and positive environmental performance, exhibiting the coexistence of resource waste and environmental pollution. Some studies indicate that losses in land-use efficiency in rural areas far exceed those in urban areas [47]. This finding aligns with conclusions from national and various regional studies on AEE [48], highlighting the urgency of seeking a balance between ensuring food security and alleviating environmental pressures.

The core finding of this paper is that the shift to NGP leads to a decline in AEE. This conclusion reveals the significant risks present in the current agricultural transformation. It is consistent with results from studies focusing on the environmental consequences of NGP, such as those of Hao et al., Li et al., and Huang et al. [49, 50]. The expansion of cash crops often accompanies higher demands for water and fertilizers, as well as increased pesticide use intensity, thereby exacerbating agricultural non-point source pollution. Compared to the existing literature, our findings provide a more nuanced perspective. Some studies suggest that shifting from grain crops to cash crops can enhance the economic output per unit of land and, under efficient management, improve efficiency [51]. This paper, however, reveals the environmental costs associated with NGP from the perspective of AEE, which integrates both economic and environmental dimensions. Through rigorous causal inference methods, this paper confirms the existence of such negative effects, providing micro-level evidence from farm households to inform related debates.

This paper explores the key pathways through which non-grain production impacts AEE. First, the reduction in the adoption of socialized services is an important mechanism. Previous research suggests that agricultural socialized services promote scaling and specialization through the division of labor in agriculture, effectively improving resource utilization efficiency and thereby reducing pollution emissions [52]. Our mechanism analysis indicates that non-grain farmers may reduce their adoption of efficient and environmentally friendly socialized services due to the more complex production processes of cash crops, which require finer labor management, or because of the small and fragmented scale of cultivation. This finding explains how NGP inhibits the growth and popularization of the agricultural socialized services market, thereby indirectly hindering the improvement of AEE. China has over 200 million contracted farming households, with an average household size of just 7 mu (approximately 1.1 acres). This reality dictates that China cannot fully replicate the model of large-scale farms seen in Europe and the United States. In this context, agricultural socialized services serve as a crucial pathway to compensate for insufficient land management scale and guide smallholder farmers toward modernization, all without altering land contracting relations. This study reveals that socialized services are relatively limited in the production of cash crops, which precisely highlights the significant challenges faced in promoting the scaling, specialization, and socialization of cash crop production under smallholder dominance. It suggests that there is a mismatch between the current development of socialized service systems, primarily oriented toward grain production, and the production needs of cash crops characterized by high heterogeneity, high added value, and high risks. Second, the increase in agricultural labor input is another pathway. Non-grain crops (such as vegetables and fruits) often involve labor-intensive practices, requiring more meticulous operations and manual management. This high labor input implies lower resource allocation efficiency, thereby reducing AEE. This highlights how NGP may lead to a "reverse modernization" regression in the factor structure of agriculture. Finally, the increased use of agricultural pollutants is the most direct environmental impact pathway. The appearance and quality of cash crops are crucial factors for sales. Farmers have no choice but to increase pesticide and fertilizer inputs to ensure their crops remain free from pest and disease infestations, directly leading to an increase in undesirable outputs and thereby affecting the sustainable development of agriculture [36]. The highly fragmented usage practices among smallholder farmers make source oversight and technical guidance extremely costly.

The essence of land input-output has shifted from quantity to both quantity and quality [53, 54]. In the context of the expanding trend of NGP, how can we address its challenges to AEE? Cash crops offer higher profits than grain crops, and cultivating them can increase farmers' income. However, NGP should not occupy basic farmland. It is essential to first ensure the planting area of grain crops, avoid excessive non-grain conversion of cultivated land, and guarantee food security. Given the limited availability of cultivated land, optimizing land-use efficiency through methods such as intercropping, relay cropping, and vertical farming can enhance output per unit area. When cultivating cash crops, farmers can opt for high-value local specialty crops, such as unique fruits and vegetables, medicinal herbs, and edible fungi. By establishing agricultural cooperatives or partnering with local enterprises, these products can undergo deep processing, launch their own brands, or be incorporated into geographical indication systems. Sales can be boosted through e-commerce platforms or live-streaming marketing, thereby increasing income. Economic incentives can drive farmers to adopt green cultivation practices, meeting consumer demand for green and organic agricultural products.

Conclusions

With socioeconomic development and changes in residents' dietary and nutritional demands, the non-grain orientation of the agricultural planting structure has become an irreversible trend. Based on survey data from farmers in Jiangxi Province, this paper evaluates AEE and examines the impact of NGP on AEE using an ESR model. The findings are as follows: the average AEE of the sampled farmers is 0.363, indicating significant room for improvement. NGP significantly reduces AEE. Specifically, farmers engaged in NGP exhibit a 40.90% lower AEE compared to a hypothetical scenario where they engage in grain-oriented production. Mechanism analysis reveals that NGP reduces the adoption of socialized services, increases agricultural labor input and the use of polluting agricultural products, thereby lowering AEE.

Mitigating the negative environmental impacts of NGP is not merely a technical issue but a systematic undertaking involving policy, technology, market, and society. The government should provide scientific guidance and regulation through planning and policies. Permanent basic farmland and grain production zones should be spatially managed to prohibit non-grain activities such as digging ponds for fish farming, planting seedlings, and cultivating fruit trees. Local governments should restrict the cultivation of water-intensive and highly polluting economic crops in ecologically sensitive areas such as ecologically fragile zones and water source protection regions. Policy incentives and ecological compensation mechanisms should be strengthened by linking agricultural subsidies to environmentally friendly practices. For instance, farmers who actively adopt ecological planting methods should receive more subsidies, while those who sacrifice yield for environmental protection should be economically compensated. Developing deep processing of agricultural products and extending the industrial chain can help farmers gain higher returns, which can be reinvested in environmental technologies.

Author Contributions

LW: Conceptualization, methodology, software, formal analysis, investigation, resources, data curation, original draft, review, editing, visualization; HQ: Software, formal analysis, investigation, resources, data curation, review, editing, visualization; YT: Investigation, resources, original draft, review, editing, visualization

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Conflict of Interests

The authors declare no competing interests.

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