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Exploring green grain production pathways: evidence from farmland and agricultural service scale operations in China

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To address the pressing issues caused by the excessive use of agricultural chemicals—such as farmland degradation, heightened ecological risks, and health hazards—and to promote green agricultural production, this study focuses on two key pathways of modern agricultural development: service-based scale operations supported by Agricultural Productive Services (APS), and farmland scale operations. It systematically investigates their respective impacts on the reduction of agrochemical inputs. Using panel data from China's Rural Fixed Observation Points and employing a system of simultaneous equations with a control function approach to address potential endogeneity, the study empirically examines how APS and farmland scale operations influence agrochemical input use. The results show that: (1) APS significantly reduce the intensity of chemical fertilizer and pesticide (CFP) application in grain production. Specifically, a 1% increase in APS usage is associated with an average decrease of 0.93 CNY per mu in fertilizer costs and 0.07 CNY per mu in pesticide costs. (2) Moderate-scale farmland operations significantly and positively contribute to reducing agrochemical use. (3) Crop-specific analysis reveals that both APS and moderate-scale operations reduce pesticide use in wheat, rice, and maize production. Regarding fertilizer use, APS is more effective for wheat, while farmland scale expansion proves more effective for maize. Both approaches contribute to fertilizer reduction in rice cultivation. These findings provide robust empirical evidence supporting the promotion of APS and appropriately scaled farmland operations as effective strategies to reduce agrochemical inputs and advance sustainable agricultural development.

KEYWORDS

agricultural productive services, farmland scale operation, fertilizer and pesticide reduction, control function approach, agricultural green production

1 Introduction

In the face of immense challenges such as climate change, ecological degradation, and food security concerns, modern agricultural development bears dual responsibilities: ensuring a continuous increase in grain output to meet the growing global demand while minimizing its adverse impact on the environment (Cui et al., 2018). Chemical fertilizers and pesticides (CFP), as fundamental inputs in agricultural production, have long been recognized for their pivotal role in boosting crop yields, stabilizing food supply chains, and advancing modern agricultural practices (Ahvo et al., 2023; Subedi et al., 2023).

However, the overuse and misuse of CFP in certain regions have led to serious ecological degradation and health risks (Sharma and Singhvi, 2017). These unsustainable practices have also degraded soil quality and posed threats to long-term food security, thereby attracting growing international concern (Brunelle et al., 2024). In response, governments around the world have implemented measures to reduce reliance on CFP. Nevertheless, global CFP consumption has continued to increase.

According to the Food and Agriculture Organization's "Statistical Yearbook 2024," the world's agricultural use of inorganic fertilizers per unit of cropland area increased by 32 percent between 2000 and 2022, reaching 113 kilograms of nutrients per hectare. Similarly, pesticide application rates per unit area of cropland rose by 37 percent during the same period (FAO, 2024). These figures reflect a concerning trajectory, underscoring the imperative to adopt sustainable practices that mitigate agrochemical overuse while ensuring food security and environmental protection.

China is one of the world's largest producers and consumers of CFP (Hu and Liu, 2024). Despite accounting for only 6.8% of the world's farmland, China consumes 23.32% of the global fertilizers (by nutrients) and 6.39% of the global pesticides (FAO, 2022a,b). Recognizing the severity of this issue, the Chinese government has prioritized reducing agrochemical inputs as a key aspect of promoting the green development of agriculture. Data from National Bureau of Statistics of China (2022) reveals that in 2022, the total application of chemical fertilizers in the country was 50.792 million tons (in pure nutrients), while pesticide usage was 236,000 tons, continuing a downward trend for seven consecutive years. Furthermore, the "2023 Report on the Green Development of Agriculture in China" highlights that the utilization rates of chemical fertilizers and pesticides for rice, wheat, and corn—the three major grain crops—dropped to 41.3 and 41.8%, respectively, in 2022. Compared to 2015, these figures represent decreases of 6.1 and 5.2 percentage points, respectively, showcasing significant progress in reducing agrochemical inputs in recent years. However, the question remains: How can China further promote the reduction of agrochemicals and the green development of agriculture while safeguarding food security? Beyond policy-driven efforts, the transformation of agricultural operation modes plays a critical role in achieving these objectives. This is a challenge that many nations striving to reduce agrochemical inputs must also address.

Smallholder farmers play a pivotal role in global food production, contributing approximately 70–80% of the world's food supply (Ricciardi et al., 2018; Touch et al., 2024). In China, data from the Third National Agricultural Census reveals that over 98% of agricultural business entities are smallholder farmers, with an average cultivated land area per household of less than 0.67 hectares (Wang and Mi, 2024). Compared with large-scale agricultural operations, smallholder farmers face significant challenges due to their limited access to knowledge, lack of professional agricultural training, and insufficient funds to invest in precision fertilization and pesticide application technologies. Their small-scale management also make it difficult to achieve economies of scale, further increasing the cost of adopting new technologies, which contributes to the persistently high intensity of chemical fertilizer and pesticide use (Jiao et al., 2019; Jin et al., 2021). Additionally, urbanization, industrialization, and marketization have driven significant rural labor migration to urban areas, exacerbating the aging of the agricultural workforce. Many smallholder farmers, particularly those engaging in part-time farming or nearing retirement, often lack the motivation to learn or adopt green production technologies (Li et al., 2021; Ren et al., 2022). This combination of small-scale, fragmented operations and aging labor poses significant challenges to advancing green agricultural production. To overcome these obstacles, it is imperative to explore and implement appropriate agricultural operation models that address the unique constraints faced by smallholder farmers while promoting sustainable and environmentally friendly agricultural practices.

The successful implementation of large-scale farmland operations in agriculturally developed countries like the United States, which is abundant in land resources, provides valuable insights for the rest of the world. However, in countries like China, where per capita land resources are limited, advocating for large-scale agricultural operations without considering the specific national context may not be entirely appropriate. In recent years, moderate-scale farming operations and agricultural productive services (APS) have developed rapidly in China and similar countries (Li et al., 2023a; Yan et al., 2021). APS refer to socialized services encompassing the entire agricultural production chain. These services are provided by family farms, farmers' cooperatives, industrialized management organizations, and socialized service organizations through either direct execution or assistance to farmers in completing operational tasks across pre-production, production, and post-production stages, such as agricultural input procurement, land improvement, fertilization, pesticide application, pest control, irrigation, and harvesting (Han et al., 2024). Research shows that APS have promoted the specialization of agricultural production, deepened the division of labor, and reshaped the traditional smallholder farming system (Shi et al., 2024; Gong, 2020). Service-scale operation refers to an agricultural production paradigm wherein farmers purchase APS from specialized providers for targeted production segments (e.g., mechanized harvesting, precision fertilization), thereby attaining scale economies and productivity gains without land transfer (Zhao et al., 2022). Farmland-scale operation refers to the practice of managing agricultural operations at a certain scale, typically through land consolidation and efficient use of land resources, aimed at improving productivity and operational efficiency. In China, Farmland-scale operation is primarily achieved through land transfers, enabling specialized large-scale farmers, family farms, and other entities to concentrate land resources at appropriate levels of operation. Currently, for countries like China, where per capita arable land resources are limited, the two modes of scaling agricultural operations are important pathways to achieving agricultural modernization. In conclusion, exploring the roles of these two agricultural scaling models—APS-backed service-scale operation and farmland-scale operation in reducing agrochemical use and promoting green agricultural development is of great significance.

The impacts of APS and farmland scale operation on agricultural development have long attracted scholarly attention and represent key trends in global agricultural transformation. A general consensus has emerged that both APS and farmland scale operation significantly contribute to improving agricultural productivity, efficiency, and farmers' income (Chen et al., 2022; Cai et al., 2023; Hou et al., 2023). In recent years, with growing global concerns over land resource constraints, ecological sustainability, and food safety, academic interest has increasingly turned to how APS and farmland scale operations contribute to green agricultural development. Existing research suggests that APS can promote the adoption of green technologies by providing farmers with professional, science-based services such as precision fertilization and targeted pest control (Huan et al., 2022; Cheng et al., 2022). By improving the allocation of agricultural inputs at the source, these services help curb the overuse of chemical fertilizers and pesticides, thereby facilitating environmentally sustainable production (Huan and Zhan, 2022; Li et al., 2023b). Nevertheless, several concerns persist. Scholars point out that the APS market is still underdeveloped in many regions, suffering from mismatches between supply and demand, fragmented service delivery, and inconsistent quality. As a result, even farmers willing to adopt green practices often face difficulties accessing reliable, high-quality services, limiting the transformative potential of APS (Zheng et al., 2022). The role of farmland scale operation in promoting green production is also subject to debate. Some studies affirm that expanding farmland scale helps reduce agrochemical inputs and supports green practices (Guo et al., 2022; Zhu et al., 2022; Song and Ye, 2022). However, other findings reveal that smallholder farmers, through intensive and meticulous farming methods, may achieve higher utilization efficiency of agrochemical than larger-scale operations, thus challenging the presumed environmental superiority of scale expansion (Hu et al., 2019; Qin and Lyu, 2020). Recent literature has started to explore the interplay between APS, farmland scale operation, and agrochemical input use. For example, Zhao et al. (2022) compare the individual impacts of APS and farmland scale on fertilizer application in rice cultivation, while Zhang et al. (2023b) examine how farmland scale moderates the effectiveness of APS in promoting green production. These studies provide a valuable foundation for understanding the potential synergies and tensions between these two operational dimensions. However, there are several shortcomings in the existing literature. Firstly, most studies analyze the impact of APS and farmland scale operation on the reduction of agrochemicals from a singular perspective, rarely considering their interaction within agricultural production. Secondly, few studies that explore the relationship between the two fully explain the mechanisms through which they influence agrochemical reduction. Additionally, existing research has not adequately addressed potential endogeneity issues when analyzing the impact of APS and farmland scale operation on agrochemical reduction, which could lead to biased estimations and affect the reliability of the conclusions.

The main contributions of this paper are threefold: First, against the backdrop of ongoing agricultural modernization, this study explores in depth the intrinsic relationship and underlying mechanisms between two forms of scale operation and the reduction of agrochemical inputs. It aims to uncover the effects of both APS-backed service-scale operation and farmland-scale operation on agrochemical reduction, thereby enriching the literature in this field and providing scientific evidence and decision-making references for policymakers to optimize scale operation policies and promote green agricultural development. Second, using large-scale, representative panel data covering agricultural producers in eastern, central, western, and northeastern China, this paper empirically examines the actual effects of both APS and farmland scale on reducing agricultural chemical inputs. The findings provide empirical support for a deeper understanding of how different scale operation paths contribute to green agricultural development, and offer a practical foundation for improving agricultural support policies and promoting input reduction. Third, the empirical analysis in this study not only systematically considers the interaction between APS and farmland scale operation but also fully identifies and addresses potential endogeneity issues. Specifically, a control function approach is employed to estimate a system of simultaneous equations, which overcomes the limitations of existing studies that separately examine the two types of scale operations, and effectively mitigates estimation bias caused by endogeneity—thereby enhancing the scientific rigor and credibility of the conclusions.

2 Theoretical analysis and research hypotheses

The field of agricultural production is undergoing profound transformations, with green and efficient development emerging as a critical imperative. Agricultural productive services and large-scale farmland operations serve as two pivotal driving forces in the complex process of reducing agrochemical inputs, directly influencing the ecological-economic balance. These factors are intricately interwoven, exerting mutual influence and creating a dynamic system that demands in-depth analysis to accurately map the pathways toward agricultural green transformation.

2.1 Service-scale operation and the reduction of agrochemical

The specialization of agricultural service providers enables the precise application of agrochemical. These professionals, trained in crop growth patterns, soil fertility, and pest control, can assess crop needs at various growth stages more accurately than ordinary farmers, reducing blind or excessive agrochemical use (Bongiovanni and Lowenberg-DeBoer, 2004; Zeng et al., 2022; Li and Zhu, 2023). This precision minimizes unnecessary inputs at the source (Huan et al., 2022; Lu et al., 2022). In addition, APS facilitate the scaling and standardization of agricultural production, enhancing agrochemical utilization efficiency. By integrating smallholder farmers into larger-scale management, APS overcome the limitations of fragmented farming and enable the use of professional machinery. Standardized equipment ensures uniform fertilization and pesticide application, reducing waste and preventing excessive localized usage (Cai et al., 2021; Zang et al., 2022; Li et al., 2023b). APS providers also play a vital role in disseminating agricultural knowledge and promoting green practices. Through close communication, they educate farmers on scientific fertilization, the risks of excessive agrochemical use, and the benefits of low-input, high-output practices. This gradually shifts farmers' production mindsets toward more sustainable practices (Teng and Lin, 2022).

In summary, by leveraging professional expertise, enabling large-scale and standardized operations, and fostering knowledge dissemination, APS effectively reduce agrochemical inputs and lay a solid foundation for agricultural green transformation.

Based on analysis above, we propose the first hypothesis of this paper (H1).

> *H1*: Agricultural productive services have a positive impact on reducing the use of agrochemical in agricultural production.

2.2 Farmland-scale operation and the reduction of agrochemical

As farmland operations expand, the specialization of agricultural production and management becomes more feasible.

Larger agricultural operators have the financial resources to hire experts who guide production with precise knowledge of crops, soil, and pests, enabling a shift from extensive to precise fertilization and spraying. This improves input efficiency and reduces the overuse of agrochemical (Zheng et al., 2020). Additionally, their stronger economic capacity and long-term production goals motivate them to prioritize agricultural sustainability, focusing on soil quality preservation and minimizing agrochemical use to prevent soil degradation (Mao et al., 2021; Hu et al., 2022). Larger farms also adopt advanced machinery, such as high-precision fertilizing and spraying equipment, which ensures even distribution of inputs, further reducing waste compared to manual or lower-precision methods used by small-scale farmers (Michels et al., 2020; Lyu et al., 2022). Moreover, larger operators benefit from better access to information and training, enabling them to adopt sustainable practices, such as integrated pest management systems that reduce reliance on agrochemical (Wu et al., 2018; Zheng et al., 2018).

However, expanding farmland beyond a certain threshold presents challenges. Managing very large areas increases operational complexity, making it harder to allocate resources efficiently. This may lead to over-application of agrochemical to compensate for yield losses caused by mismanagement. Diminishing marginal returns on inputs also incentivize farmers to use more fertilizers and pesticides to sustain productivity (Liang et al., 2020). Furthermore, excessive expansion may surpass the farmer's management capacity, reducing the feasibility of precision agricultural practices and leading to a reversion to traditional, input-intensive methods (Zhao et al., 2021). These challenges highlight the delicate balance required to optimize farmland scale for both economic and environmental sustainability.

On the basis of analysis mentioned above, we propose hypothesis (H2).

> *H2*: Moderate-scale farmland operation has a positive impact on the reduction of agrochemical inputs in grain production.

It is important to recognize the interaction between farmers' use of APS and their farmland scale. On one hand, as farmland scale expands, the demand for APS may decline. Larger-scale farmers often invest in their own machinery and equipment to meet production needs, thereby reducing their reliance on external services (Huan and Zhan, 2022). On the other hand, the widespread adoption of APS may suppress the incentive for scale expansion. The accessibility and convenience of APS reduce the marginal benefits of large-scale farming. For instance, smallholders can access mechanized operations and technical support through APS, diminishing the comparative advantage of scale farming and encouraging them to maintain their current farmland size (Ren, 2023). Furthermore, as marketization and specialization progress, the transaction efficiency of APS increasingly surpasses that of land operation rights, resulting in a substitution effect between APS and large-scale land farming (Luo, 2017). This dynamic indicates that APS and farmland scale are not only complementary in certain cases but also potentially competitive. Therefore, when analyzing the impact of APS and farmland scale on agrochemical input, it is crucial to account for the interaction between these two factors to avoid overlooking their complex and interdependent relationships.

3 Data and methods

3.1 Data sources

The data used in this study were obtained from the National Rural Fixed Observation Points Farm-Household Survey in China. This survey system annually collects data from over 20,000 farming households, spanning more than 300 administrative divisions across all 31 provinces, autonomous regions, and municipalities. The survey provides comprehensive information on the production, management, and consumption activities of farming households and their family members, serving as a reliable data source for this study. The study period covers 2004 to 2020, and a total of 85,964 household observations were included after excluding farmers who did not cultivate the three main grain crops and those with incomplete or abnormal data. The resulting dataset is an unbalanced panel at the micro level. To control for the influence of price fluctuations, total income, capital input, and costs of fertilizers and pesticides for the three main grain crops were adjusted to constant 2004 prices using deflation techniques.

3.2 Variables selection and description

3.2.1 Dependent variable

In this study, the dependent variables are "fertilizer application intensity" and "pesticide application intensity" measured using three indicators: average fertilizer (pesticide) expenditure per mu, fertilizer (pesticide) expenditure per unit of output value, and average amount of fertilizer (pesticide) applied per mu. While most existing research on CFP reduction uses CFP input per unit of farmland area as a measure of intensity, this approach may not accurately reflect actual application intensity due to variations in the effective element content across different types of CFP. Furthermore, farmers are typically more aware of the costs associated with CFP inputs than the exact quantities applied. Therefore, this paper refers to existing research (Zheng et al., 2020; Li and Zhu, 2023) and measures CFP application intensity primarily through average fertilizer (pesticide) input costs per mu for the three main grain crops, providing a more practical and reliable metric. These measures are employed as dependent variables in the baseline regression analysis.

3.2.2 Independent variable

The two independent variables in this study are agricultural productive services (APS) and farmland operation scale. Farmland operation scale is measured by the sown area of the three main grain crops. Existing literature typically measures the use of APS by whether it is purchased or by the number of agricultural tasks using APS (Han et al., 2024; Cai et al., 2023). In contrast, this study refers to existing research (Shi et al., 2023) and quantifies the use of APS through the cost of purchasing these services, represented as the proportion of APS expenditure relative to total production costs. This indicator reflects the extent to which farmers rely on APS in their agricultural operations.

3.2.3 Control variable

To address potential biases in model estimations caused by omitted variables, this study selects relevant control variables based on existing research (Zhu and Wang, 2021; Guo et al., 2022) that influence agricultural productive services, farmland operation scale, and fertilizer and pesticide application. The control variables include individual characteristics of household heads, such as gender, age (and its squared term), and education level. Family characteristics encompass household size, the ratio of farming labor, and the ratio of non-labor. Land conditions and production management variables include the number of plots, planting structure, the ratio of irrigable land, the replanting index for the three main grain crops, and village topography. The definitions and descriptive statistics of these variables are presented in Table 1.

3.3 Econometric model

To analyze the impact of agricultural productive services and farmland operation scale on farmers' fertilizer and pesticide inputs in grain production, while accounting for the potential interaction between participation in agricultural productive services and farmland operation scale, this study establishes the following system of simultaneous equations:

$$\begin{cases} CFP_{it} = \beta_0 + \beta_1 Scale_{it} + \beta_2 Scale_{it}^2 + \beta_3 APS_{it} + \partial X_{it} + \gamma_t + \varepsilon_{it} \\ APS_{it} = \delta_0 + \delta_1 Scale_{it} + \mu Y_{it} + \gamma_t + w_{it} \\ Scale_{it} = \varphi_0 + \varphi_1 APS_{it} + \theta Z_{it} + \gamma_t + v_{it} \end{cases} \quad (1)$$

Where CFP_{it} represents application of chemical fertilizers or pesticides of farm-household i in year t. APS_{it} represents agricultural productive services, while $Scale_{it}$ represents the farmland operation scale of farm-household i in year t. They serve as the primary independent variables in the first equation and become dependent variables in the second and third equations, respectively. X_{it} is the other control variables affecting the application of CFP. The second and third equations, respectively, use agricultural productive services and farmland operation scale, which are mutually influential, as the dependent variable and are affected by the controlled variables set, Y_{it} and Z_{it}, in each respective equation. The year fixed effect is represented by γ_t, which is introduced to control the impact of time trends. β_0, δ_0 and φ_0 are constant terms, and the coefficients of independent variables are parameters to be estimated. ε_{it}, w_{it} and v_{it} are the random error terms.

TABLE 1 Definition of variables and their descriptive statistics.

Variables	Description	Mean	SD
Dependent variable			
Fertilizer application intensity (FAI_cost)	Average fertilizer input costs per mu for the three main grain crops (CNY)	79.063	33.917
Pesticide application intensity (PAI_cost)	Average pesticide input costs per mu for the three main grain crops (CNY)	16.896	15.636
Fertilizer use efficiency (FUE)	Fertilizer input costs per 10,000 CNY output for the three main grain crops (CNY)	1589.941	727.164
Pesticide use efficiency (PUE)	Pesticide input costs per 10,000 CNY output for the three main grain crops (CNY)	322.671	281.615
Fertilizer application intensity (FAI_usage)	Average fertilizer usage per mu for the three main grain crops (kg)	69.356	48.722
Pesticide application intensity (PAI_usage)	Average pesticide usage per mu for the three main grain crops (kg)	1.227	3.329
Independent variable			
Agricultural productive services (APS)	The proportion of expenditure on APS relative to total production costs (%)	22.552	11.930
Farmland operation scale (Scale)	Sown area of the three main grain crops (mu)	9.357	15.629
Control variable			
Gender	The gender of household head (1 = male, 0 = female)	0.963	0.188
Age	The age of household head (year)	52.249	10.575
Age2	The square of the age of the household head divided by 100	28.418	10.998
Education	Education level of household head (year)	7.014	2.498
Household size	Number of household members (person)	4.124	1.528
Ratio of farming labor	Ratio of labor engaged in agricultural production	0.614	0.338
Ratio of non-labor	Ratio of non-labor among household members	0.195	0.209
Number of plots	The number of farmland plots in operation (piece)	5.545	4.874
Planting structure	The proportion of the sown area of wheat, corn, and rice	0.760	0.245
Ratio of irrigable	Ratio of irrigated farmland area to the total operated farmland area	0.772	0.305
Replanting index	Ratio of sown area to the total operated farmland area	1.548	0.509
Topography	Topography of the village (1 = plains, 2 = hills, 3 = mountains)	1.692	0.768
Instrumental variable			
IV_Scale	The average rent of farmland transfer in this village (CNY/mu)	334.586	288.413
IV_APS	The mean proportion of APS expenditure of other farm-households in the same village to their total production cost (%)	22.786	8.151

1 hectare = 15 mu.

To address endogeneity arising from interdependence and omitted variables in the model and to identify genuine causal relationships, this study employs the control function approach proposed by Wooldridge (2015) to estimate the simultaneous equations model. The control function approach utilizes a joint quasi-maximum likelihood function, integrating the estimation results of the second and third equations where endogenous variables are treated as dependent variables with the first equation for simultaneous estimation (Rios-Avila and Canavire-Bacarrezam, 2018). By accounting for the correlation between equations, this method effectively addresses endogeneity issues in simultaneous equation models, thereby providing more reliable and accurate estimation results.

The control function method requires the identification of suitable instrumental variables to estimate the model. Based on existing research (Liu and Wu, 2022; Zhang et al., 2023a), this study employs the mean proportion of APS expenditure by other farm households in the same village relative to their total production costs as an instrumental variable for APS in the second equation of Equation 1. Similarly, the average farmland rental price in the village is used as an instrumental variable for farmland operation scale in the third equation of Equation 1. Theoretically, the utilization of APS by other households in the same village can influence a household's decision to adopt APS but does not directly affect that household's farmland operation scale or CFP usage. Conversely, farmland rental prices primarily affect land transfer and farmland operation scale without directly influencing the household's use of APS or CFP. These two instrumental variables thus satisfy both the relevance criterion (correlation with the endogenous explanatory variable) and the exogeneity condition (no correlation with the disturbance term), indicating their suitability as instrumental variables.

4 Empirical results and analysis

4.1 Baseline regression results and analysis

The relevant test results of estimating the three equations in the simultaneous equation model using the control function approach are shown in Table 2. Firstly, the results of estimating the simultaneous equations with the dependent variables being fertilizer application intensity, agricultural productive services, and farmland operation scale, respectively, are presented in columns (1)–(3). The estimated coefficients of the connection parameter g_{12} between the fertilizer application intensity equation and the APS equation and the connection parameter g_{13} between the fertilizer application intensity equation and the farmland operation scale equation are all significant at the 1% statistical level. This indicates that there is a significant interaction between APS and farmland operation scale, and both have a significant impact on fertilizer application intensity, suggesting that the model setup is reasonable. Moreover, whether it is "Scale, Scale^2, and APS" in column (1), "Scale" in column (2), "APS" in column (3), or the instrumental variables "IV_APS" and "IV_Scale," their estimated coefficients are all significant at the 1% statistical level. Meanwhile, the estimated coefficients of most of the control variables in the three equations are significant at the 5% statistical level. This shows that it is appropriate to estimate the simultaneous Equations 1 using the control function method, the data fitting is good, and the model has well examined the impact of APS and farmland operation scale on fertilizer application intensity.

The estimation results of the first equation in columns (1) and (4) of Table 2 show that all coefficients of "APS" are significantly negative. After controlling for farmland operation scale, household head characteristics, family characteristics, and village characteristics, the findings indicate that increased use of APS significantly reduces the intensity of CFP application in grain production. In other words, APS have a positive impact on reducing CFP use, thereby preliminarily validating research hypothesis H1. Specifically, a 1 percentage point increase in the proportion of APS expenditure relative to total production costs leads to a reduction of 0.93 CNY in average fertilizer input cost per mu and 0.07 CNY in pesticide input cost per mu for the three main grain crops.

Additionally, the coefficient for "Scale" is significantly negative, while the coefficient for "Scale2" is significantly positive, both passing the 1% statistical significance test. This supports the presence of a U-shaped relationship between farmland scale and CFP application intensity. Initially, expanding farmland scale reduces CFP intensity, but beyond a certain threshold, CFP intensity begins to increase. Based on the estimated coefficients in columns (1) and (4), the calculated turning points of the U-shaped curve are farmland operation scales of 349.63 mu and 379.50 mu, respectively. Since most farmers operate on scales smaller than 300 mu, this suggests that expanding farmland operation scale is an effective strategy to reduce CFP application intensity up to the threshold scale. These findings preliminarily confirm research hypothesis H2.

The coefficients of "Scale" in columns (2) and (5) of Table 2 are significantly negative at the 1% statistical level, indicating that farmland operation scale has a significant negative impact on APS. Similarly, the coefficients of "APS" in columns (3) and (6) of Table 2 are significantly negative, indicating that APS have a significant negative impact on farmland operation scale.

4.2 Robustness test

4.2.1 Replace dependent variable

The low efficiency of CFP usage is a key factor driving their over-application in agricultural production. CFP utilization efficiency is measured as consumption per unit output, which accounts for both application intensity and the economic efficiency of agricultural production. To test the robustness of the baseline regression, the dependent variable was replaced with CFP utilization efficiency, and robustness tests were conducted. The results of the impact of agricultural productive services and farmland operation scale on CFP utilization efficiency are presented in columns (1) and (2) of Table 3.

Since the specifications and results of the two equations, with APS and farmland operation scale as dependent variables, remain largely unchanged, detailed results are omitted due to space constraints. A comparison of the regression results for CFP application intensity in Table 2 with CFP utilization efficiency in Table 3 shows that the coefficients and significance levels of the independent variables estimated using the control function approach are relatively consistent. This consistency underscores the robustness of the positive impacts of APS and farmland scale on reducing CFP inputs in grain production. Specifically, a 1 percentage point increase in the proportion of APS expenditure relative to total production costs reduces fertilizer input costs per 10,000 CNY output by 9.02 CNY and pesticide input costs by 0.82 CNY. Based on the coefficients of "Scale" and "Scale^2" in

TABLE 2 The impact of APS and farmland operation scale on the application intensity of CFP.

Variable	Fertilizer application intensity			Pesticide application intensity		
	FAI_cost (1)	APS (2)	Scale (3)	PAI_cost (4)	APS (5)	Scale (6)
Scale	−2.797*** (0.130)	−0.054*** (0.003)	–	−0.759*** (0.052)	−0.054*** (0.003)	–
$Scale^2$	0.004*** (0.001)	–	–	0.001*** (0.000)	–	–
APS	−0.927*** (0.019)	–	−0.045*** (0.002)	−0.074*** (0.008)	–	−0.045*** (0.002)
Gender	5.812*** (0.709)	−0.051 (0.170)	2.182*** (0.106)	2.246*** (0.315)	−0.051 (0.170)	2.182*** (0.106)
Age	0.401*** (0.097)	−0.024 (0.023)	0.094*** (0.020)	0.384*** (0.038)	0.094*** (0.020)	0.384*** (0.038)
Age^2	−0.490*** (0.095)	0.013 (0.023)	−0.135*** (0.020)	−0.403*** (0.037)	0.013 (0.023)	−0.135*** (0.020)
Education	0.078 (0.057)	0.016 (0.013)	−0.120*** (0.011)	−0.292*** (0.024)	0.016 (0.013)	−0.120*** (0.011)
Household size	1.383*** (0.128)	−0.082*** (0.023)	0.663*** (0.020)	−0.055 (0.051)	−0.082*** (0.023)	0.663*** (0.020)
Ratio of farming labor	13.189*** (0.888)	−0.470*** (0.102)	6.281*** (0.087)	−0.560 (0.362)	−0.470*** (0.102)	6.281*** (0.087)
Ratio of non-labor	−7.514*** (0.800)	−0.093 (0.178)	−2.701*** (0.155)	(0.248) (0.331)	−0.093 (0.178)	−2.701*** (0.155)
Number of plots	0.880*** (0.066)	−0.066*** (0.008)	0.443*** (0.008)	0.486*** (0.026)	−0.066*** (0.008)	0.443*** (0.008)
Planting structure	42.156*** (1.769)	2.490*** (0.145)	13.442*** (0.122)	4.797*** (0.725)	2.490*** (0.145)	13.442*** (0.122)
Ratio of irrigable	−6.224*** (0.790)	1.177*** (0.118)	−4.915*** (0.122)	5.009*** (0.295)	1.177*** (0.118)	−4.915*** (0.122)
Replanting index	−3.463*** (0.300)	−0.350*** (0.067)	−0.780*** (0.056)	2.815*** (0.132)	−0.350*** (0.067)	−0.780*** (0.056)
Topography (hills)	−13.862*** (0.571)	0.586*** (0.076)	−4.145*** (0.073)	2.788*** (0.241)	0.586*** (0.076)	−4.145*** (0.073)
Topography (mountains)	−21.981*** (0.812)	−0.355*** (0.102)	−5.692*** (0.094)	−1.297*** (0.321)	−0.355*** (0.102)	−5.692*** (0.094)
IV_Scale	–	–	−0.004*** (0.000)	–	–	−0.004*** (0.000)
IV_APS	–	0.925*** (0.004)	–	–	0.925*** (0.004)	–
Constant	62.218*** (2.824)	0.904 (0.670)	−4.338*** (0.581)	−2.452** (1.120)	0.904 (0.670)	−4.338*** (0.581)
Year FE	Yes	Yes	Yes	Yes	Yes	Yes
lns1	3.476*** (0.003)	–	–	2.677*** (0.004)	–	–
lns2	–	2.188*** (0.003)	–	–	2.188*** (0.003)	–
lns3	–	–	2.129*** (0.009)	–	–	2.129*** (0.009)
g12	0.199***(0.022)			−0.046***(0.009)		
g13	2.322***(0.126)			0.592***(0.052)		

(Continued)

TABLE 2 (Continued)

Variable	Fertilizer application intensity			Pesticide application intensity		
	FAI_cost (1)	APS (2)	Scale (3)	PAI_cost (4)	APS (5)	Scale (6)
Wald chi2	5050.88***			16074.37***		
Observations	85,964			85,964		

***, **, and, * refer to the 1%, 5%, and 10% significance levels, respectively. Robust standard errors for the parameters are in parentheses.

columns (1) and (2), the threshold farmland operation scales are calculated as 286.83 mu and 184.52 mu, respectively. Before reaching these thresholds, expanding farmland operation scale significantly lowers CFP input costs per unit output for the three main grain crops. In summary, after controlling for farmland operation scale and other variables, increased APS use in the production of the three main grain crops reduces CFP consumption per unit output, supporting hypothesis H1. Similarly, farmland operation scale expansion below the threshold effectively lowers CFP consumption per unit output, affirming hypothesis H2. These findings confirm the robustness of the baseline regression results.

Similar to input costs, the quantity of CFP used is a critical dimension for measuring the intensity of CFP application by farm households. Measuring intensity from a quantitative perspective enhances the clarity and intuitiveness of the analysis. To further test the robustness of the impact of APS and farmland operation scale on reducing CFP use, this study re-estimates the model using the quantity of CFP inputs as the dependent variable. It is worth noting that the data on fertilizer and pesticide usage from the rural fixed observation point survey is recorded at the household level rather than the crop level, with a significant number of missing values. To ensure data reliability, this study retains only households cultivating the three main grain crops without planting other crops, resulting in a reduced sample size of 20,020 households.

The estimation results of the first equation, presented in columns (3) and (4) of Table 3, indicate that the coefficients of "Scale^2" and "APS" are statistically significant at the 1% level, while the coefficients of "Scale" are significant at the 10% level. The signs of these coefficients are consistent with those in Table 2, confirming the robustness of the previous results. Specifically, a 1 percentage point increase in the proportion of APS expenditure relative to total production costs reduces fertilizer inputs per mu by 0.65 kg and pesticide inputs per mu by 0.01 kg. Additionally, the threshold farmland scale is calculated to be 109 mu for fertilizer inputs and 80 mu for pesticide inputs. Before reaching these thresholds, expanding farmland scale significantly reduces CFP inputs per mu.

In conclusion, the results demonstrate that increasing the use of APS significantly contributes to reducing CFP inputs, while farmland operation scale expansion effectively lowers CFP inputs per mu before reaching the threshold scale. These findings align with the baseline regression results, further confirming their robustness.

4.2.2 Excluding policy influence

In June 2017, the Chinese Ministry of Agriculture and Rural Affairs, in collaboration with the Ministry of Finance, introduced a pilot policy on agricultural production trusteeship subsidies. This policy involved substantial subsidy funds and significantly impacted China's agricultural productive services. To mitigate the potential influence of this policy on the estimation results, this study excluded data from 2017 onward. Consequently, the sample used for analysis includes households from 2004 to 2017, and the model was re-estimated accordingly. The re-estimation results, presented in columns (5) and (6) of Table 3, show that the coefficients, signs, and statistical significance of "Scale," "Scale^2" and "APS" remain consistent with the baseline regression results in Table 2. Specifically, a 1 percentage point increase in the proportion of APS expenditure relative to total production costs reduces fertilizer input costs by 0.87 CNY per mu and pesticide input costs by 0.07 CNY per mu. Additionally, the threshold farmland operation scales are calculated to be 364.10 mu for fertilizer inputs and 267.75 mu for pesticide inputs. These results align closely with the baseline regression findings in Table 2, further confirming the robustness of the effects of APS and farmland operation scale on CFP usage intensity.

4.2.3 Replacement of estimation method

To enhance the credibility of the results, a robustness test was performed by replacing the original control function method with the Three-Stage Least Squares (3SLS) method. The estimation results, presented in Table 4, show that the coefficients, signs, and statistical significance of "Scale," "Scale^2," and "APS" remain consistent with the baseline regression results in Table 2. This consistency further confirms the robustness of the baseline regression findings.

4.3 Heterogeneity analysis

Due to differences in farming practices, fertilizer demand, and risks of pests and diseases among the three main grain crops, the relationship between agricultural productive services (APS), farmland scale, and the intensity of fertilizer and pesticide use may vary. To examine these potential differences, the sample of farm households cultivating the three main grain crops was categorized into three groups: wheat, rice, and maize. The control function approach was then employed to estimate the impact of APS and farmland operation scale on the intensity of CFP use for each crop. The estimation results are presented in Table 5.

The study found that for the three main grain crops, the coefficient of APS in the CFP usage intensity equation was significantly negative at the 1% level, consistent with the comprehensive estimation results in Table 2. This indicates that APS have a significant positive effect on reducing CFP use for wheat, rice, and maize. Specifically, a 1 percentage point increase in the proportion of APS expenditure relative to total production costs decreases fertilizer input per mu by 1.04 CNY, 0.59 CNY, and 0.98 CNY for wheat, rice, and maize, respectively. Similarly, pesticide input per mu decreases by 0.24 CNY, 0.05 CNY, and 0.05 CNY for wheat, rice, and maize, respectively. These results suggest that the reduction in fertilizer usage due to APS is similar for wheat and maize but relatively smaller for rice. Additionally, the pesticide

TABLE 3 Results of the robustness check.

Variable	FUE (1)	PUE (2)	FAI_ usage (3)	PAI_ usage (4)	FAI_cost (5)	PAI_cost (6)
Scale	−47.613*** (3.010)	−8.857*** (0.913)	−0.436* (0.279)	−0.032* (0.021)	−3.796*** (0.188)	−1.071*** (0.073)
Scale^2	0.083*** (0.011)	0.024*** (0.003)	0.002*** (0.001)	0.0002*** (0.000)	0.005*** (0.001)	0.002*** (0.000)
APS	−9.018*** (0.421)	−0.821*** (0.139)	−0.651*** (0.076)	−0.014*** (0.005)	−0.872*** (0.021)	−0.074*** (0.008)
Constant	1472.678*** (61.018)	6.995 (19.921)	76.401*** (6.454)	−1.034** (0.437)	56.954*** (3.301)	−3.104** (1.270)
Control	Yes	Yes	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes	Yes	Yes
lns1	6.561*** (0.005)	5.569*** (0.004)	3.862*** (0.075)	1.189*** (0.058)	3.477*** (0.004)	2.678*** (0.004)
g12	−4.297*** (0.473)	−1.065*** (0.167)	0.133* (0.083)	0.003 (0.005)	0.153*** (0.023)	−0.045*** (0.010)
g13	43.043*** (2.941)	6.205*** (0.909)	−0.704** (0.307)	−0.003* (0.021)	23.273*** (0.183)	0.887*** (0.072)
Wald chi2	2266.04***	14000.00***	269.435***	346.868***	3976.897***	9892.056***
Observations	85,964	85,964	20,020	20,020	75,162	75,162

***, **, and, * refer to the 1%, 5%, and 10% significance levels, respectively. Robust standard errors for the parameters are in parentheses.

TABLE 4 Results of the robustness check: 3SLS.

Variable	Fertilizer application intensity			Pesticide application intensity		
	FAI_cost (1)	APS (2)	Scale (3)	PAI_cost (4)	APS (5)	Scale (6)
Scale	−4.040*** (0.268)	−0.172*** (0.004)	–	−1.074*** (0.108)	−0.172*** (0.004)	–
Scale2	0.033*** (0.003)	–	–	0.009*** (0.001)	–	–
APS	−0.993*** (0.020)	–	−0.101*** (0.004)	−0.089*** (0.008)	–	−0.101*** (0.004)
IV_Scale	–	–	−0.755*** (0.062)	–	–	−0.755*** (0.062)
IV_APS	–	0.912*** (0.004)	–	–	0.912*** (0.004)	–
Constant	62.785*** (2.931)	0.379 (0.665)	−3.537*** (0.629)	−2.263* (1.179)	0.379 (0.665)	−3.537*** (0.629)
Control	Yes	Yes	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes	Yes	Yes
R2	0.1891	0.2712	0.4343	0.0546	0.4343	0.2712
Wald chi2	10736.37***	68675.59***	32787.24***	13840.90***	68675.59***	32787.24***
Observations	85,964			85,964		

***, **, and, * refer to the 1%, 5%, and 10% significance levels, respectively. Standard errors for the parameters are in parentheses.

reduction effect is most pronounced for wheat, while it is relatively smaller for rice and maize. For the impact of farmland operation scale on CFP usage intensity in wheat production, the coefficient of "Scale" in the fertilizer usage intensity equation is not statistically significant, while the coefficient of "Scale^2" is significantly positive at the 1% level. This indicates that the threshold farmland operation scale for fertilizer usage intensity in wheat cultivation corresponds to zero, meaning that as the scale of wheat operations expands, fertilizer usage intensity increases. This finding aligns with Ji et al. (2016), who also observed a positive relationship between cultivated land area and fertilizer input intensity for wheat based on fixed observation point data. The increasing fertilizer usage intensity in wheat cultivation can

TABLE 5 Comparative analysis of different crops.

Variable	Wheat		Rice		Maize	
	FAI_cost	PAI_cost	FAI_cost	PAI_cost	FAI_cost	PAI_cost
Scale	−0.182 (0.294)	−2.121*** (0.109)	−6.438*** (0.291)	−1.251*** (0.122)	−3.143*** (0.229)	−0.926*** (0.055)
Scale2	0.022*** (0.005)	0.014*** (0.002)	0.019*** (0.002)	0.004*** (0.001)	−0.0003 (0.001)	0.002*** (0.000)
APS	−1.044*** (0.025)	−0.242*** (0.007)	−0.586*** (0.029)	−0.045*** (0.014)	−0.982*** (0.036)	−0.046*** (0.009)
Constant	95.856*** (3.593)	−5.711*** (1.137)	22.659*** (5.273)	−3.226 (2.308)	86.255*** (4.586)	8.141*** (1.119)
Control	Yes	Yes	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes	Yes	Yes
lns test	Yes	Yes	Yes	Yes	Yes	Yes
g test	Yes	Yes	Yes	Yes	Yes	Yes
Wald chi2	11000.00***	5252.12***	2364.27***	7179.15***	2285.75***	1931.97***
Observations	38,046	38,046	43,988	43,988	43,169	43,169

***, **, and, * refer to the 1%, 5%, and 10% significance levels, respectively. Robust standard errors for the parameters are in parentheses.

be attributed to the nutrient requirements of wheat across different growth stages. Timely fertilization at each stage is crucial for achieving high yields, and farmers operating larger farmland scales are more likely to perform timely fertilization, resulting in higher fertilizer input intensity. Therefore, for wheat cultivation, reducing fertilizer usage intensity through agricultural productive services may be a more effective approach.

The results of the impact of farmland operation scale on the intensity of CFP use for the three main grain crops reveal distinct patterns. In the fertilizer use intensity equations for rice, the coefficient of "Scale" is significantly negative, while the coefficient of "Scale^2" is significantly positive at the 1% statistical level. This indicates a significant U-shaped relationship between farmland scale and fertilizer use intensity for rice, with a threshold farmland operation scale of 169.42 mu. Expanding farmland operation scale below this threshold can effectively reduce CFP use in rice cultivation. For maize, the coefficient of "Scale" in the fertilizer use intensity equation is significantly negative, while the coefficient of "Scale^2" is not significant, suggesting a negative linear relationship between farmland scale and fertilizer use intensity. This indicates that expanding farmland operation scale can significantly reduce fertilizer use intensity for maize, a finding consistent with Guo et al. (2022). This may be attributed to maize's stronger adaptability, lower soil requirements, and simpler cultivation processes compared to wheat and rice, which reduce the need for excessive fertilizer inputs to manage operational risks on larger scales. In the pesticide use intensity equations for wheat, rice, and maize, the coefficients of "Scale^2" are significantly positive, indicating a U-shaped relationship between farmland operation scale and pesticide use intensity for all three crops. The threshold farmland operation scales associated with the lowest pesticide use intensity are 75.75 mu for maize, 156.38 mu for rice, and 231.50 mu for wheat. Given the current farmland operation scale in China, most farmers have not yet reached these thresholds. Therefore, moderately expanding farmland operation scale is conducive to reducing pesticide use for all three crops.

5 Discussion

The primary question this study addresses is whether, and in what ways, two pathways of scale operation—APS-backed service-scale operation and farmland-scale operation—contribute to reductions in agrochemical inputs. Our empirical results confirm Hypothesis 1, demonstrating that APS significantly reduce the intensity of both fertilizer and pesticide use in grain production. This finding is consistent with Huan and Zhan (2022), who, using 2018 cross-sectional data from 1,321 households across 132 villages in China, report similar input-saving effects. However, unlike Huan and Zhan (2022), which relies on a single-year snapshot, our analysis employs multi-year panel data from a broader range of regions, offering a more representative sample. Furthermore, whereas Huan and Zhan (2022) treat farmland-scale management as a mediating factor between APS and agrochemical use, we conceptualize service-scale and farmland-scale operations as endogenously interrelated and apply a simultaneous equation model to capture their mutual interactions, thereby extending the scope of existing research. Our empirical results also confirm Hypothesis 2: moderate-scale farmland operations exert a positive effect on CFP reduction in grain production. Within a certain range, enlarging farmland scale helps to curb CFP use, while further expansion beyond this threshold proves counterproductive. This outcome aligns with Liu et al. (2023), who, based on survey data from 769 rice farmers in China's Jiangxi Province, identified a U-shaped relationship between farm size and fertilizer intensity—fertilizer use declines with scale expansion up to an optimal point, then rises thereafter. Building on their findings, our study incorporates the interaction between service-scale and land-scale operations, revealing that both APS-supported service-scale management and appropriately scaled farmland operations independently contribute to agrochemical reduction. These dual pathways represent promising strategies for China's future agricultural development.

This study also possesses global relevance, as many countries worldwide are striving to ensure food security, reduce agrochemical inputs, and promote green agricultural development. The findings can offer valuable insights to nations currently undergoing or planning a green production revolution. For instance, Rahman and Connor (2022), using national survey data from Bangladesh—a country known for excessive fertilizer use—found that agricultural services contribute to fertilizer reduction. Alexandri et al. (2022) observed that in Romania, small farms incur higher fertilizer expenditures per hectare, whereas larger-scale farms apply relatively less fertilizer per unit of land. These results suggest that both agricultural service–based scaling and farmland-scale management are beneficial in many contexts. However, the pressures and challenges associated with reducing agrochemical use vary by country due to differences in geographical environments, levels of economic development, and agricultural practices. For example, in many sub-Saharan African countries, agrochemical inputs are relatively low, and related issues are not currently urgent (Falconnier et al., 2023).

This study also has several limitations. First, constrained by the existing database, we were unable to obtain indicators capable of finely examining the underlying mechanisms. Future research should use tailored surveys or more comprehensive data sources to explore these mechanisms in depth, thereby enhancing the rigor and depth of the analysis. Second, the panel data used in this study only cover up to 2020 and may not fully capture recent developments in agricultural policies and technologies. Although the dataset is highly representative—encompassing multiple provinces in eastern, central, western, and northeastern China and including various types of agricultural entities and farming practices—caution is warranted when extrapolating the findings to the post-2020 context. Revalidation using more up-to-date and longitudinal panel data is an important direction for future research. Finally, we measure APS by its share of total production costs but do not fully account for heterogeneity across different APS types, which may bias our estimates of their impact on CFP reduction. Future studies should disaggregate APS categories and explore their specific causal pathways, thereby providing more targeted empirical evidence for policymaking.

6 Conclusion and policy implications

Excessive use of fertilizers and pesticides remains a pervasive issue in agricultural production across many countries, resulting in severe environmental consequences such as soil degradation, water contamination, and harm to ecosystems. Reducing CFP use and achieving agricultural green development remain significant challenges. This study incorporates the interaction between Agricultural Productive Services and farmland operation scale into a unified analytical framework. Using a simultaneous equation model and data from China's national rural fixed observation points (2004–2020), the study explores the impact of APS and farmland scale on farmers' behavior in reducing agrochemical inputs through a control function approach. The results show that Agricultural Productive Services significantly reduce the use intensity of chemical fertilizers and pesticides in the production of the three main grain crops. At the same time, moderate-scale farmland operation also contributes to the reduction of agricultural chemical use. Expanding farmland scale reduces CFP use until a threshold scale is reached, beyond which further expansion increases CFP use. Importantly, most farmers currently operate on a scale far below this threshold. Robustness tests, including replacing dependent variables, excluding policy influences, and adopting alternative estimation methods, confirm the consistency and validity of the baseline regression results.

The study also finds that the relationship between APS and farmland operation scale is characterized by substitution. Specifically, the adoption of APS negatively impacts farmland operation scale expansion, while larger farmland scale reduces farmers' reliance on APS. Further analysis by crop type indicates that both APS and moderate-scale farmland operations significantly reduce pesticide use intensity for wheat, rice, and maize cultivation. However, the effects on fertilizer use reduction vary by crop. For wheat, APS is the preferred approach to reducing fertilizer use intensity. For maize, expanding farmland scale proves more effective. For rice, both APS and moderate-scale management contribute to fertilizer reduction, highlighting the need for crop-specific strategies in green agricultural development.

Based on these findings, the study proposes several policy implications. First, it is crucial to emphasize the role of APS in promoting green agricultural development by reducing agrochemical inputs. Developing the socialized service market, increasing financial support for APS providers, and incentivizing service providers that meet green production standards are essential steps. Additionally, training programs should be implemented to enhance the green production knowledge and skills of APS providers while fostering technological innovation to improve service quality. Second, moderate-scale farmland operations play a critical role in agricultural green production. Policies should encourage land transfers and support the development of various moderate-scale operation models. Education and training on green production practices should also be provided to management entities to promote the adoption of green technologies and further reduce CFP use. Third, strategies should consider the suitability of APS and farmland scale expansion for different crops. Combining APS with moderate-scale farmland operations tailored to specific crops can achieve better results, contributing to sustainable agricultural development.

In conclusion, this study deepens the understanding of how APS and farmland scale influence the reduction of agrochemical inputs and highlights feasible pathways for accelerating agricultural green development. The findings offer valuable insights for global agricultural policies, particularly in fostering sustainable farming practices and promoting green production technologies.

Data availability statement

The data analyzed in this study is subject to the following licenses/restrictions: The data used in this article are confidential and not publicly available. The original data can be obtained from the Rural Fixed Observation Points of the Ministry of Agriculture and Rural Affairs of the People's Republic of China. Requests to access these datasets should be directed to http://zdscxx.moa.gov.cn:8080/nyb/pc/index.jsp and the Corresponding Author.

Author contributions

GH: Conceptualization, Formal analysis, Methodology, Software, Visualization, Writing – original draft, Writing – review & editing. TL: Conceptualization, Funding acquisition, Methodology, Project administration, Resources, Supervision, Writing – review & editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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