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Assessing the impact of China's agricultural subsidy reform on fertilizer management: a county-level empirical analysis based on difference-in-difference model

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Agricultural subsidies are widely acknowledged to be a crucial cause in food security and environmental protection, with a substantial impact on fertilizer consumption. China is also attempting to promote the green transformation of agricultural subsidies and sustainable food production. Existing research has explored the impact of China's agricultural subsidies reform (ASR) on farmers' fertilizer application behavior at household level, but little is known about the overall effect of ASR at the regional level. This paper investigates the effect of on fertilizer inputs using the staggered difference-in-difference (DID) approach, based on county-level panel data for 723 counties in China's Main Grain Producing Area (MPA) from 2013 to 2020. The results show that the ASR obviously increases fertilizer consumption by 5–6% in MPA during the study period. An analysis of mechanism reveals that ASR boosts fertilizer input through increased grain output and on-farm employment, which both play a 13.83% and 6.42% partial mediator role. Conversely, the growth of planting scale is the primary conduit for fertilizer reduction, accounting for 11.78% of the total. Furthermore, this positive effect is significantly lower in counties with low farmer disposable income or high agricultural mechanization than in others. These findings offer valuable insights for other developing countries aiming to promote green transformation of agriculture.

KEYWORDS

agricultural subsidies, reform, fertilizer consumption, DID model, China's counties

1 Introduction

Chemical fertilizer management plays a crucial role in the formation of sustainable food systems in developing economies. On the one hand, fertilizer helps promote the global growth of grain production and provide sufficient food supplies (Zou et al., 2022). On the other hand, its excessive and inefficient consumption has contributed to ecological concerns such as the degradation of water resources, air pollution, greenhouse gas emissions, and climate change, which threatens public health and wellbeing (Khanna and Miao, 2022). Therefore, best management practices for farmers' fertilizer application are essential for reconciling food security with environmental protection. Farmers' decisions on fertilizer inputs are influenced by many factors (Beaman et al., 2013; Donkor et al., 2019; Lefebvre et al., 2020; Nakano and Magezi, 2020; Porteous, 2020; Weersink and Fulton, 2020; Tambet and Stopnitzky, 2021; Wang X. et al., 2021; Kebede, 2022), and existing studies generally believe that agricultural subsidies are important determinants of over-purchasing chemical fertilizer (Taheripour et al., 2008; Pe'er et al., 2019; Gazzani, 2021; Laborde et al., 2021). As a result, some developed countries have pledged to pursue a greener path for previous coupled agricultural subsidies, with the goal of encouraging farmers to use fewer agrochemical inputs and reconcile food production with sustainable tillage (Pe'er et al., 2019; Scown et al., 2020). For example, the United States, Canada, Australia, New Zealand, and the European Union have implemented numerous agri-environmental programs in the way of fund incentives to align food production with environmental sustainability (Baylis et al., 2022; Hasler et al., 2022; Pannell and Rogers, 2022).

In recent years, China, is also attempting to progressively adjust its agricultural subsidies with food security in mind to support the green transformation of agricultural production. The Chinese government has gradually established an agricultural subsidy system to ensure food supply and increase farmers' income since the abolition of agricultural taxes in 2006. From 2004 to 2015, this system consists of four main parts: subsidies for improved crop strains and seeds, direct subsidies for grain growers, comprehensive subsidies for agricultural material, and subsidies for agricultural machinery purchases. With the support of these subsidies, the planting area of grain increased from 101.61 million ha in 2004 to 117.46 million ha in 2014, and the grain output of China increased from 469.47 million tons in 2004 to 649.65 million tons in 2014. Meanwhile, the consumption of chemical fertilizers (effective weight) rose from 46.37 million tons to 59.96 million tons from 2004 to 2014. To facilitate moderate-scale operations and incentivize farmers to voluntarily adopt a range of conservation measures, such as incorporating straw back into the fields, implementing deep tillage practices, and reducing the application of chemical fertilizers and pesticides to enhance soil fertility, the Chinese government initiated an agricultural subsidy policy reform Specifically, the main reform is to combine the subsidy for improved crop strains and seeds, the direct subsidy for grain growers, and the comprehensive subsidy for agricultural materials into the subsidy for agricultural support and protection, which is known as the "three subsidies reform" (ASR). In 2015, the Ministry of Finance and the Ministry of Agriculture and Rural Affairs selected parts of counties in Anhui, Shandong, Hunan, Sichuan, and Zhejiang provinces of China as a pilot to carry out ASR. In 2016, the ASR was widely implemented in the remaining counties throughout China. The ASR has gone on for almost 8 years, and we have witnessed the growth of China's grain production. But it is not sure what impact ASR has had on fertilizer consumption due to the voluntary nature of conservation measures and the lack of monitoring of subsidized farmers (Liu et al., 2023). Three questions remain to be addressed: What is the impact of the ASR program on fertilizer input? What are the channels through which ASR plays a role in this? Will this impact be heterogeneous?

Therefore, a rising number of researchers have been engaged in an intensive discussion lately over the potential benefits of agricultural subsidies and reforms for the environment (van Beers et al., 2007; Helming and Tabeau, 2018). Their arguments fall into roughly three groups. Of them, two groups empirically investigate the impact of various agricultural subsidies on the input of fertilizer. But their opinions are different. One strand of the literature argues that Most of researchers found that agricultural subsidies in general helped farmers reduce fertilizer application (Laukkanen and Nauges, 2014; Luo et al., 2014), but the effect of agricultural subsidies on fertilizer application intensity varied significantly across farmers with different operation scales and planting structures (Mather and Jayne, 2018; Wu and Ge, 2019; Yang et al., 2021). The input-based policies are more cost-effective than their output-based counterparts in achieving a target reduction in fertilizer application (Sun et al., 2016). Liang et al. (2019) also point out that agricultural subsidies in China have generally brought about environmental co-benefits by applying life cycle assessment. However, the other strand of the literature held the opposite point of view. He et al. (2022) found that Wu et al. (2019) believed that agricultural subsidies for improved crop strains and seeds, the direct subsidy for grain growers, and the comprehensive subsidy for agricultural material increased farmers' fertilizer application. The third group analyzes the impacts of agricultural subsidies on the usage of fertilizer in terms of theory. There are three dimensions (Henderson and Lankoski, 2021; Lankoski and Lankoski, 2023) in which agricultural payments affect the use of chemical fertilizer: the *intensive margin*, *extensive margin*, and the *entry-exit margin* (Wang J. et al., 2021).

As seen, there is still controversy whether subsidies reform can reduce fertilizer inputs. To reveal the reasons underlying these mixed findings, the two papers most closely related to our study investigated the impact of China's agricultural subsidy reform on fertilizer inputs at the farm household level. For example, Guo et al. (2021) analyzes the impact of agricultural subsidies on chemical fertilizer use by rice farmers using data from a household survey over the period of 2014 to 2018, based on Control Function (CF) approach and Heteroskedasticity-based identification strategy. Fan et al. (2023) assess the impacts of China's new agricultural subsidy on chemical fertilizer use, heterogeneity effect, and mechanism using data from the 2015 and 2017 China Rural Household Panel Survey (CRHPS). However, there are still research gaps to fill. First, these two studies have only focused on the impact of subsidies on fertilizer practices of farmers in a micro perspective, and the former pays attention to the marginal effect of the subsidization amount but not the ASR's policy effects. Actually, what is not yet clear is the impact of ASR on fertilizer input at a macro county level. Second, the latter's research period includes only 2015 (the year of ASR pilot) and 2017 (the first year after ASR implementation), which is difficult to identify the long-term effect of ASR. Third, they neglected the comparability between samples participating in ASR (the treatment group) and those not participating in ASR (the control group), and this will lead to estimation bias.

To fill these gaps, this study takes China's reform of three agricultural subsidies (ASR) as a policy shock and utilize the staggered difference-in-difference approach to estimate the effect of ASR on counties' fertilizer consumption, mechanism, and heterogeneity effect by using county-level panel data covering 723 counties in China's Main Grain Producing Area from 2013 to 2020.

This research makes three marginal contributions to the current research. First, compared with literatures that perform only empirical analysis, this study uses a theoretical model to propose hypotheses about how ASR affects fertilizer input and then employ a causality identification strategy to verify the hypotheses above. It combines theory and empirical evidence to enrich the literature on the assessment of agricultural subsidies' environmental effects. Furthermore, this study specifically examines the influence of ASR on fertilizer inputs at a county level, encompassing data from 2013 to 2020. This work will facilitate the comprehensive assessment of ASR's long-term impact at a regional level, thereby providing valuable insights for policymakers to optimize policies. Finally, its focus is directed toward the counties situated in China's Main Grain Producing Area, as these counties exhibit similarities and comparability in terms of geographic location and food production conditions. Moreover, they are directly and visibly impacted by shocks to ASR. By ensuring comparable treatment and control groups during causal inference, it can effectively mitigate estimation bias resulting from sample selection. Thus, this research should be of keen interest to regulators and policymakers seeking to promote food production and, at the same time, the management of fertilizer consumption.

In the next section, the analytical framework and research hypotheses on how ASR affects fertilizer spending are discussed. Section 3 introduces the empirical methods to be used in this study and describes the data processing for all variables. Section 4 discusses the empirical results. Finally, Section 5 summarizes conclusions and puts forward some policy recommendations.

2 Conceptual framework

In this section, this study draws on a partial static equilibrium model developed by Eli and Bui (2001) to clarify the mechanism underlying the effect of agricultural subsidy reform (ASR) on counties' fertilizer spending. Considering counties as the essential fields for fulfilling rural revitalization strategies in China and ensuring food provision, we focus on the county as the farming production unit. Within the PSE framework, we assume a cost-minimizing county producing food in perfectly competitive markets for inputs and outputs. In production, this county plants grain, Y, using labor, L, land, H, and fertilizer, F. Output is strictly increasing for all inputs, and we assume that the marginal productivity of all inputs is strictly positive and decreasing, as is customary. The cost of inputs takes the following form:

$$C = M\left(Y, L, H, F, w_l, w_h, w_f\right) \quad (1)$$

where w_l, w_h, and w_f are the prices of labor, land, and fertilizer, respectively. According to the Shepard lemma, we obtain demand for the fertilizer input F as a function of grain output, quantities of the other inputs, and prices, which we approximate by the linear equation:

$$F\left(Y, L, H, w_l, w_h, w_f\right) = \rho_0 + \rho_1 Y + \eta_1 L + \eta_2 H + \sum_j \varsigma_j w_j \quad (2)$$

The following is a simplified version of the ASR on fertilizer spending:

$$F\left(Y, L, H, w_l, w_h, w_f\right) = \psi + \phi ASR \quad (3)$$

Based on Equations (2) and (3), we seek first-order differentiation to acquire the mechanism through which the ASR influences fertilizer demand:

$$\frac{dF}{dASR} = \rho_1 \underbrace{\frac{dY}{dASR}}_{\text{Grain Output Channel}} + \eta_1 \underbrace{\frac{dL}{dASR}}_{\text{Labor Allocation Channel}} + \eta_2 \underbrace{\frac{dH}{dASR}}_{\text{Cultivation Structure Channel}} + \sum_j \varsigma_j \frac{dw_j}{dASR} = \phi \quad (4)$$

As shown in Equation (4), the marginal effect of ASR on fertilizer inputs (left side of the equation) is decomposed into four components on the right side of the equation. Next, we shed light on each component in detail and propose hypotheses to be examined in this paper.

The first component labeled "*grain output channel*" reflects the effect of ASR on the purchase of fertilizer through its effect on grain output. This effect of ASR is widely believed to be positive. As is well known in the majority of the literature, after the reform of the agricultural subsidy system, all farmland farmers will receive a constant income, which encourages their motivation to specialize in planting and thus improves the efficiency of grain production. This has contributed to the growth in grain yield and fertilizer input ($\rho_1 \frac{dY}{dASR} > 0$).

The second component, which is labeled "*labor allocation channel*," has two subcomponents. The subcomponent $\frac{dL}{dASR}$ measures changes in the agricultural labor input due to the implementation of ASR. Numerous studies have been conducted to examine the effects of various agricultural subsidies on various aspects of farming (Bojnec and Ferto, 2020), with the majority of them discovering a positive impact on farm employment (Olper et al., 2014; Garrone et al., 2019). Li et al. (2022) also argued that as the agricultural subsidy system improves, farmers' willingness to engage in cultivation increases while their intentions to participate in non-agricultural sectors decrease ($\frac{dL}{dASR} > 0$). The sign of the η_1, which reflects whether labor and fertilizer input are complements or substitutes, is not known a priori. Tian et al. (2020) find that fertilizer appears to be a net complement to labor. Thus, we assume $\eta_1 > 0$.

The third component, which is labeled "*cultivation structure channel*," also consists of two subcomponents. On the one hand, the subcomponentreflects changes in the crop planting area resulting from ASR. Actually, one of the aims of ASR is to promote the optimum-scale management of grain, which probably entails an expansive sown area for the crop ($\frac{dH}{dASR} > 0$). On the other hand, subcomponent η_2 represents the relationship between crop size and fertilizer expenditure. Some studies believe that farm size has a negative effect on chemical fertilizer use (Ju et al., 2016; Yu et al., 2023). Therefore, we assume $\eta_2 < 0$.

As for the last term ($\frac{dw_j}{dASR}$) of the right side of the equation, we assume that it equals zero. The reason is that agricultural subsidies after the reform are decoupled from production, which does not introduce distortions to factor markets and influence the input prices.

Based on the analysis above, we propose the following hypotheses, which would be verified in the next sections:

Hypothesis 1 The implementation of ASR either promotes or reduces fertilizer input in planting, depending on the magnitude of the three effects mentioned above.

Hypothesis 2 The ASR impacts fertilizer consumption through three channels:

H2a The ASR increases fertilizer usage by increasing the grain output.

H2b The ASR promotes fertilizer investment through on-farm employment.

H2c The ASR increases crop area, resulting in a scale effect that reduces fertilizer use.

3 Research design

3.1 Empirical model

3.1.1 Staggered DID model

To accurately explore the impact of the ASR on fertilizer input (Hypothesis 1), we construct the following typical staggered DID model, referring to Beck et al. (2010):

$$\ln TF_{it} = \alpha + \delta ASR_{it} + \beta_1 \ln X_{it} + \nu_i + \mu_t + \varepsilon_{it} \tag{5}$$

where TF_{it} denotes the total fertilizer input and the subscripts i and t represent time and county, respectively. ASR_{it} is a variable reflecting the reform of agricultural subsidies. X_{it} denotes a host of control variables. δ and β_1 are parameters to be estimated. Additionally, ν_i, μ_i and ε_{it} represent county fixed effects, year fixed effects, and the random disturbance term, respectively.

3.1.2 Mechanism test model

In order to validate the potential mechanisms of ASR affecting fertilizer inputs (***H2a–H2c***), we draw on the mediation model and construct models (6)–(7), following (Du and Li, 2022). The econometric model is as follows:

$$\ln Medium_{it} = \alpha + \lambda ASR_{it} + \beta_2 \ln X_{it} + \nu_i + \mu_t + \varepsilon_{it} \tag{6}$$

$$\ln TF_{it} = \alpha + \varphi ASR_{it} + \theta \ln Medium_{it} + \beta_3 \ln X_{it} + \nu_i + \mu_t + \varepsilon_{it} \tag{7}$$

where $Medium_{it}$ denotes the mediating variables, including grain output (*Grot*), cultivation structure (*Culstr*), and labor input (*Labor*). The settings of other variables in Equations (6) and (7) are consistent with Equation (5).

3.2 Research samples and processing

In order to stimulate farmers to voluntarily adopt conservation practices such as fertilizer reduction and nutrient management on cropland, the Ministry of Finance and the Ministry of Agriculture and Rural Affairs of the People's Republic of China jointly issued the "Guidance on the Reform and Improvement of the Three Agricultural Subsidies Policy" (ASR) in 2015, which is conducive to enhancing the precision of the payment and promoting the green transformation of agricultural subsidies. The policy announced that counties in the five provinces of Zhejiang, Anhui, Sichuan, Shandong, and Hunan would be the pilot regions to implement the reform of three agricultural subsidies. In 2016, the remaining counties on the mainland of China gradually introduced the reform. To this end, we treat this policy as a quasi-natural experiment to verify ***Hypothesis 1***. Considering the similarity and comparability in geographical location and food production conditions among counties, we focus the research samples on those counties located in the Main Grain Producing Area[1] (MPA) of China, which is also the region obviously shocked by agricultural payments. We begin by eliminating counties in Zhejiang Province because they are located in China's Main Grain-Sale Area. Next, we select the 244 pilot counties for reform within the MPA as the treatment group. And the rest of the 479 counties in the MPA served as the control group. After deleting samples with severely missing data, we finally obtained panel data for 723 grain-producing counties over the period 2013–2020.

3.3 Data sources and descriptive statistics

3.3.1 Data sources

We construct a panel dataset covering 723 counties from 2013 to 2020 to estimate the impacts of ASR on fertilizer input in China's MPA, which is collected from publications issued by the China National Bureau of Statistics such as the China County Statistical Yearbook and the China City Statistical Yearbook. We also acquire the data needed in our research from various provincial, city, and county statistical bureau websites and people's government websites. In addition, the China Regional Economy Database in Easy Professional Superior is employed as a supplement, which gathers data from the National Bureau of Statistics and provides statistics of more than 400 prefecture-level and 2,000 county-level cities in 31 provinces, autonomous regions, and municipalities nationwide in terms of industry, agriculture, education, public health, the overall economy, capital construction, and social security, as well as the economic and social aspects in 10 major economic zones.

3.3.2 Descriptive statistics

Given that the purpose of this paper is to investigate the effect of ASR on fertilizer application, we take the consumption of chemical fertilizers (100 percent effective content equivalent) as the dependent variable.

The independent variable in this study is the agricultural subsidy reform, and the reform is set as a dummy variable, ASR_{it}. In fact, $ASR_{it} = Treat_i \times Time_t$ where $Treat_i$ indicates whether the county is classified as the treatment group for ASR. When $Treat_i = 1$, it means that the county is the treatment-group county

1 China's Main Grain Producing Area covers 13 provinces including Hebei, Heilongjiang, Jilin, Liaoning, Shandong, Jiangsu, Anhui, Jiangxi, Hubei, Henan, Hunan, Sichuan and Inner Mongolia.

TABLE 1 Variable definitions.

Variables	Definition
TF	The total consumption of chemical fertilizers (ton)
ASR	Dummy variable: treatment group=1; control group=0
Grot	Grain output (ton)
Culsrt	Ratio of grain crop area to the total sown area of farm crops
Labor	Number of rural employed persons in agriculture (ten thousand persons)
Income	Per capita annual disposable income of rural households (CNY)
Mech	Total power of agricultural machinery (kilowatt)
Er	Ratio of "environmental protection" to the total number of words in the government work reports of the prefecture-level municipalities to which each county is affiliated
Irga	Irrigated Area (thousand hectares)
Rain	Total annual precipitation in the county (millimeter)
Sun	Total annual hours of sunshine in the county (hours)

TABLE 2 Descriptive statistics.

Variables	Control group			Treatment group		
	Obs.	Mean	SD	Obs.	Mean	SD
Ln *TF*	1,925	9.9892	1.2384	3859	9.8267	1.3557
Ln *Grot*	1,925	12.4635	1.1883	3859	12.4016	1.2386
Culsrt	1,925	0.7661	1.9150	3859	0.8292	2.7147
Ln *Labor*	1,903	2.4053	0.8445	3793	2.3848	0.8593
Er	1,913	0.0035	0.0013	3839	0.0035	0.0013
Ln *Irga*	1,737	3.1493	1.1380	3511	3.1471	1.1715
Ln *Rain*	1,913	6.7727	0.3583	3839	6.8358	0.3443
Ln *Sun*	1,925	7.5406	0.2298	3859	7.5417	0.2639
Ln *Mech*	1,804	13.1313	0.9640	3539	13.017	0.9862
Ln *Income*	1,910	9.2362	0.3450	3830	9.5941	0.3068

within the policy pilot regions; when $Treat_i = 0$, it indicates that the county is assigned to the control group. In addition, $Time_t$ is the year dummy variable. If a county is established as a pilot in the year and after, it equals 1; otherwise, it is 0.

On the basis of the existing literature, we also controlled a group of variables to capture the influencing factors of fertilizer consumption. Tables 1, 2 present more details about the definitions and descriptive statistics of the selected variables.

4 Empirical findings

4.1 Baseline results

Following the empirical model described above, Equation (5) was estimated to assess the impact of ASR on the fertilizer input in Main Grain Producing Area of China. Table 3 (1)–(2) presents the baseline results. Column (1) shows the results without adding the control variables. As presented in Column (1), the coefficient of the ASR_{it} variable is 0.0606, which is positive and statistically significant at the 1% level. Column (2) presents the results after adding a series of control variables, the coefficient of the variable becomes 0.0531, and the significance level remains unchanged. This finding suggests that the ASR implemented in China has significantly increased fertilizer input.

4.2 Robustness checks

To further illustrate the robustness of the baseline result, a battery of sensitivity tests is conducted in this subsection.

4.2.1 Validity of the parallel trend assumption

The parallel trend is a crucial assumption for applying the DID framework to identify causality. Put differently, it means that there should have been no significant difference in the trends of the variables of relevance between the treatment and control groups if the agricultural subsidy reform had not occurred. In order to ensure that the results of the DID model are credible, we follow Jacobson et al. (1993) and Bertrand and Mullainathan (2003) to further construct a dynamic DID model to test the validity of the parallel trend assumption, and regard the first year prior to the implementation of the reform as the baseline period:

$$\ln TF_{it} = \alpha + \sum_{k\geq -3, k\neq -1}^{4} \delta_k ASA_{it}^{k} + \lambda \ln X_{it} + \nu_i + \mu_t + \varepsilon_{it} \quad (8)$$

where ASA_{it}^{k} denotes a list of dummy variables related to the year in which the ASR was implemented. When county$i$is in the k year before (after) being selected as a pilot county, it has the value 1 and otherwise has the value 0. For all other variables, the definitions are the same as in Equation (5). We exclude the first year (ASA_{it}^{-1}) before ASR implementation to avoid the noise of multicollinearity. Insignificant and δ_{-2} indicate that the parallel trend hypothesis is satisfied.

Figure 1 depicts the time trend of δ_k within the 95% confidence interval. The coefficients before 2015 are insignificant and close to zero, with no consistent trend in fertilizer consumption until an ASR policy is in place, supporting the parallel trend hypothesis. Furthermore, the time trend of the coefficients from 2015 to 2017 indicates that the effect of ASR on fertilizer inputs is dynamically increasing. However, coefficient values began to decline after 2017, which demonstrates that the positive influence of ASR on fertilizer inputs started to diminish after 2017. The reason for this may be that the Chinese government has implemented a zero-growth fertilizer program.

4.2.2 Alternative measures

To test the robustness of the above results again, we take the fertilizer input intensity as the new dependent variable in the staggered DID model to estimate the coefficient. The estimation

TABLE 3 ASR's influence on fertilizer input.

Variables	Ln *TF*		Ln *FI*	
	(1)	(2)	(3)	(4)
ASR	0.0606*** (0.0177)	0.0531*** (0.0153)	0.0659*** (0.0161)	0.0555*** (0.0181)
Ln *Irrigation*		0.0908 (0.0558)		−0.0124 (0.0530)
Ln *Regulation*		0.0276*** (0.0099)		0.0226* (0.0121)
Ln *Machine*		0.0997*** (0.0314)		−0.0344 (0.0301)
Ln *Rain*		0.0073 (0.0263)		−0.0288 (0.0297)
Ln *Sun*		0.1215** (0.0522)		0.0935 (0.0593)
County FE	YES	YES	YES	YES
Year FE	YES	YES	YES	YES
Constant	9.8455*** (0.0102)	7.4349*** (0.7975)	5.6964*** (0.0107)	5.8142*** (0.7669)
Observations	5,784	4,831	5,784	4,831
R-squared	0.9858	0.9860	0.9296	0.9337

Values in parentheses are standard errors clustered at the county level. *, **, and *** indicate significance at the 10%, 5%, and 1% levels, respectively.

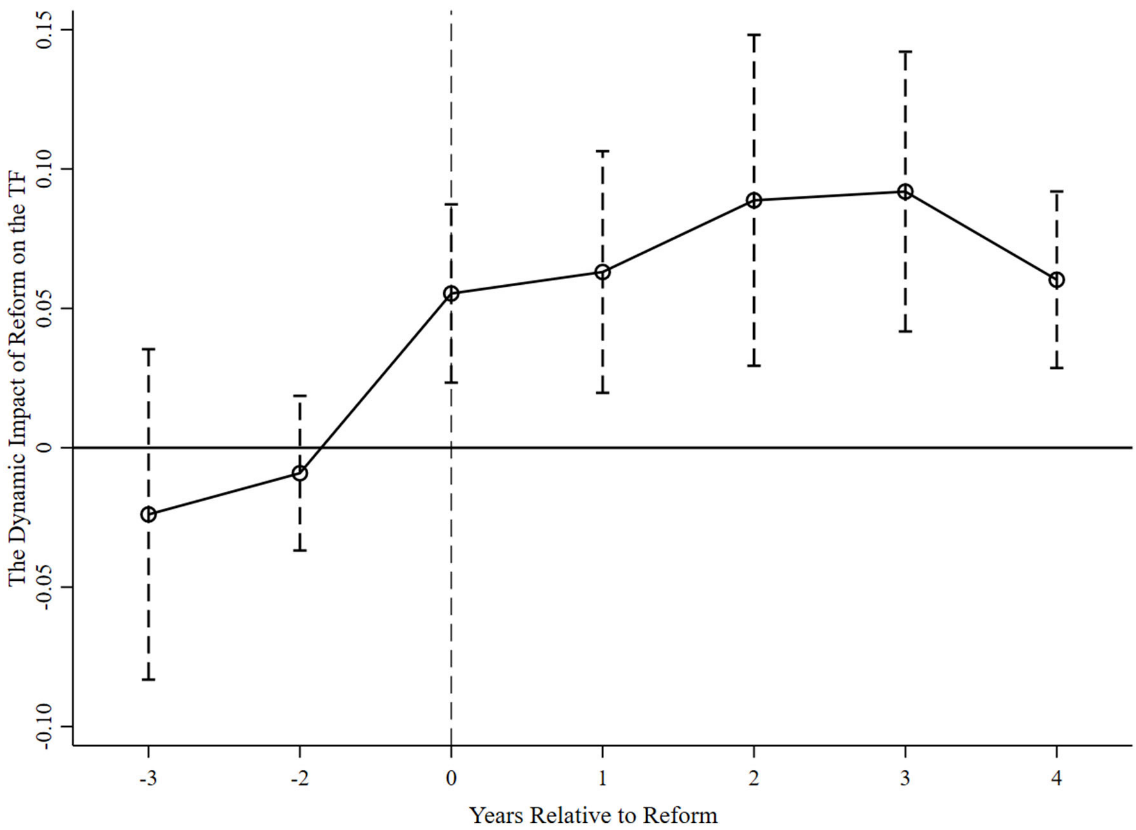

FIGURE 1
Results of the parallel trend test.

results are shown in Columns (3) and (4) of Table 3, which are similar to the sign and size of the coefficients of benchmark regression. In addition, the parallel trend test for this case is also conducted (Figure 2). It indicates that the outcomes are strongly robust if the explained variable is replaced.

4.2.3 Placebo test

To confirm that the inference in our research is not derived from a random chance, we perform a bootstrapping placebo test following Chetty et al. (2009), La Ferrara et al. (2012), and Huang et al. (2022). In particular, we randomly selected

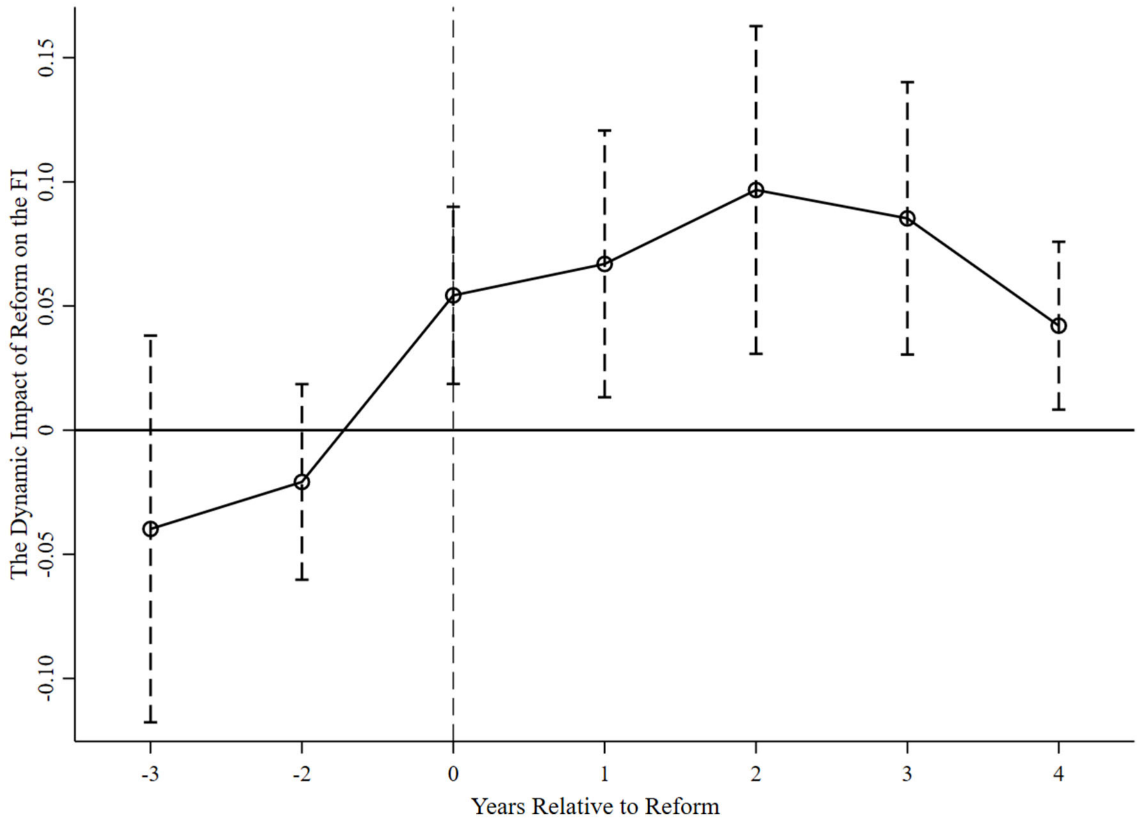

FIGURE 2
Robustness test results of the parallel trend test.

257 counties from the 723 total samples as the "false treatment group" and the rest of the counties as the "false control group". The baseline staggered DID regressions are then performed, and the process is repeated 500 times. Thus, we obtain 500 coefficients δ^{random} for the false dummy variables $FASA^{random}$ that were randomly constructed. Figure 3 presents the kernel density of δ^{random} and its *p*-value distribution. The distribution centers around zero with a mean value of 0.000, and the true estimate (0.0531, see column 2 of Table 2) falls outside the distribution. This result suggests that the DID-estimated results in the main regression are not purely the result of a coincidence.

4.3 Mechanism analysis: how ASR affects fertilizer inputs

Having found that ASR increased fertilizer inputs based on the previous empirical results, we now explore three potential channels analyzed in Part II to answer the question of how ASR works on fertilizer inputs. To this end, following Su et al. (2022) and Fan et al. (2023), we use seemingly unrelated regression combined with bootstrapping methods to estimate Equations (6) and (7) to verify ***H2a***, ***H2b***, and ***H2c***, respectively.

4.3.1 Evidence on the grain output channel

On the basis of the former theoretical analysis, the ASR may connect with fertilizer inputs through grain output. To provide an initial assessment of this channel, we regard the total grain yield as the output and then estimate the Equations (6) and (7). Columns (1) and (2) of Table 4 present the results. As reported in column (1), the coefficient of ASR in column (1) is 0.0415 and significant at the 1% level, indicating that the ASR leads to a significant increase in grain yield. The positive role of agricultural subsidies in increasing grain output has also been recorded in previous studies (Yu and Jensen, 2010; Just and Ropp, 2013; Garrone et al., 2019). Column (2) shows that the coefficients for *ASR* and *Grot* are 0.0532 and 0.1770, respectively, which are significant at the 1% level. This result demonstrates that the grain yield has a partially mediating effect on fertilizer input, and the contribution of this effect to the total effect is about 13.83%. Therefore, this result confirms ***H2a*** of the theoretical model.

4.3.2 Evidence on the agricultural labor input channel

Labor input may play a mediating role in ASR influencing fertilizer input. To peer into these linkages, we conduct a mediation analysis by using labor invested in farming as a mediating variable. The influence mechanism test results on labor input effect are reported in columns (5) and (6) of Table 4. The results in column

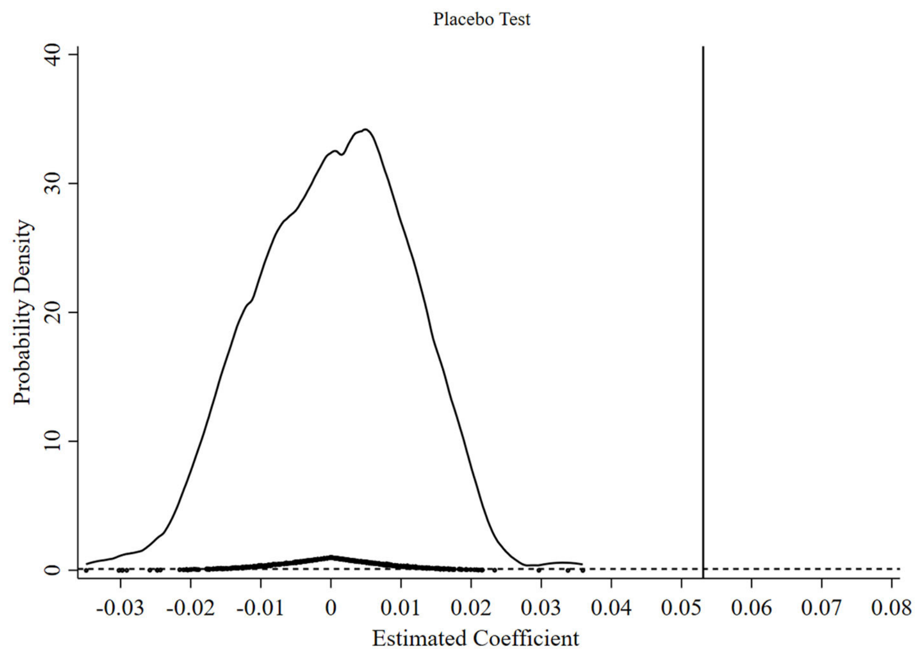

FIGURE 3
Results of placebo test.

TABLE 4 Results of mechanism test.

Variables	(1) Ln *Grot*	(2) Ln *TF*	(3) *Culstr*	(4) Ln *TF*	(5) Ln *Labor*	(6) Ln *TF*
ASR	0.0415*** (0.0151)	0.0532*** (0.0176)	0.0265** (0.0123)	0.0481*** (0.0158)	0.0333*** (0.0101)	0.0488*** (0.0154)
Ln *Grot*	-	0.1770*** (0.0546)	-	-	-	-
Culstr	-	-	-	−0.0236** (0.0115)	-	-
Ln *Labor*	–	–	–	–	–	0.1023** (0.0482)
Constant	9.3419*** (0.7571)	5.7818*** (1.0933)	0.1210 (0.5032)	6.7297*** (0.9057)	2.3695*** (0.0067)	9.5985*** (0.1141)
Control variables	YES	YES	YES	YES	YES	YES
County FE	YES	YES	YES	YES	YES	YES
Year FE	YES	YES	YES	YES	YES	YES
Constant	9.3419*** (0.7571)	5.7818*** (1.0933)	0.1210 (0.5032)	6.7297*** (0.9057)	2.3695*** (0.0067)	9.5985*** (0.1141)
Observations	4,831	4,831	4,743	4,743	5,696	5,696
R-squared	0.9852	0.9864	0.9915	0.9868	0.9611	0.9861

Values in parentheses are standard errors clustered at the county level. *, **, and *** indicate significance at the 10%, 5%, and 1% levels, respectively.

(5) show that the estimated coefficient on the *Labor* is significantly positive, indicating that the introduction of ASR has stimulated farmers to engage more labor in food production. In column (6), the estimated coefficients of both ASR and the *Labor* are significantly negative. Based on this, we further calculate the contribution of this effect to the total effect as 6.42%. This result indicates that the ASR can increase the fertilizer input through the labor allocation. The reasons for the labor input effect of the policy are the following. On the one hand, after the reform of agricultural subsidies system, the decoupled payment is only available to farmers who practically cultivate the land, and it is a stable income for rural residents. Thus, the subsidy could attract more agricultural employment (Nordin, 2014) and reduce the outflow of labor from agriculture. Huang et al. (2020) also found that agricultural subsidies truly reduced China's yearly labor reallocation from agricultural to non-agricultural sectors by 0.68 million people (about 5.7 per cent of the observed annual rural-urban migration). On the other hand, the reduction of off-farm employment means the decrease of farmers' off-farm income, which has a positive impact on the demand for purchased fertilizers (Pfeiffer et al., 2009; Ma et al., 2018). Thus, ***H2b*** is verified to be correct.

4.3.3 Evidence on the cultivation structure reform channel

To verify whether ASR affects fertilizer inputs through the reform of planting structure, we use the cropping structure as a mediation variable. The portion of grain sown area in the total planted land is applied to reflect the planting structure, and then Equations (6) and (7) are estimated again. The results presented in columns (3) and (4) of Table 4 confirm that changes in planting structure are indeed a significant mediating variable through which ASR reduces fertilizer input. The implementation of the ASR results in a 2.65% expansion of grain area sown, which in turn leads to a 2.36% reduction in fertilizer usage. The findings suggest that 11.78% of the total effect can be explained by the indirect effect of ASR through the reform of cultivation structure. Our results are consistent with a recent study by Guo et al. (2021). The reason for this is that the subsidy policy connected with arable land scale encourages farmers to expand their farmland scale. And more extensive arable land enables economies of scale to be exploited, which further curbs fertilizer adoption (Ju et al., 2016; Ren et al., 2021; Zhang et al., 2021). As a result, ***H2c*** is proven to be correct.

4.4 Heterogeneous analysis

The average effect of ASR on fertilizer input was demonstrated above. However, there are differences in the degree of agro-economic development and production facilities between counties within the Main Grain Producing Area of China, which probably cause heterogeneity in the responses to policy shocks among counties. Therefore, this study considers further disaggregated analysis to glean more granular insights into the differential effects of ASR on fertilizer input. Specifically, we examine whether the effects of ASR vary across the disposable income of farmers and the degree of agricultural mechanization.

Firstly, the disposable income of farmers can serve as an indicator of the development of the regional agricultural economy. When agricultural production thrives in a region, farmers experience increased disposable income, which subsequently alleviates their financial constraints and enables them to purchase more fertilizer (Veljanoska, 2022). To examine the heterogeneity of ASR among different income groups, we divide the overall sample into two subsamples based on the median value of farmers' disposable income—a high-income group and a low-income group. The regression results for these groups are presented in Table 5 (1)–(2). It is evident that the regression coefficient for high-income regions is significantly 0.0640, while it is statistically insignificant for low-income regions. This finding suggests that additional income from agricultural subsidies may further enhance fertilizer application in wealthier counties due to reduced financial constraints faced by farmers who have greater purchasing power.

Secondly, the impact of reforms varies depending on the level of agricultural mechanization. Similarly, we categorize the entire sample into a high-Mech group and a low-Mech group based on the median value of total power of agricultural machinery (*Mech*), followed by conducting heterogeneity analysis. According to columns (3) and (4) in Table 5, coefficients representing policy effects on fertilizer use are significantly 0.0325 for high-Mech subsamples and 0.0738 for low-Mech subsamples respectively. These results indicate that policy effects are much stronger in regions with lower levels of crop mechanization. A plausible explanation could be attributed to areas with advanced agricultural mechanization being equipped with state-of-the-art machinery and equipment throughout farming and harvesting processes which enable precise fertilization practices resulting in improved efficiency and savings.

5 Conclusion and recommendations

5.1 Conclusion

China's agricultural subsidies have contributed to an adequate food supply and improved farmers' wellbeing. However, they also encourage farmers to put more fertilizer into food production. In 2015, the Chinese government launched an reform of agricultural subsidies (ASR). How this reform will affect fertilizer consumption remains to be investigated. This study examines the impact of ASR policy on fertilizer inputs in farming and its intrinsic mechanisms by applying a staggered DID model based on county-level panel data on 723 counties in the Main Grain Producing Area of China over the period of 2013–2020. The research results are as follows:

(1) During the research period, ASR policy significantly increases fertilizer consumption by 5–6% in China's Main Grain Producing Area, but this positive effect tends to weaken in the light of the policy's dynamic analysis.
(2) The ASR increases fertilizer input by promoting grain output and on-farm employment, which play a partial mediator role of 13.83% and 6.42%, respectively. But the expansion of planting scale is the main channel for the fertilizer reduction, acting as a partial mediation for 11.78%.
(3) Finally, the heterogeneity analysis reveal that the ASR has a greater impact on fertilizer usage in counties with higher farmers' disposable income. Last but not least, the policy results in a much lower positive effects on fertilizer spending in counties with a higher level of agricultural mechanization.

5.2 Recommendations

Based on findings above, this paper suggests that the transformation of the agricultural subsidy system to a greener one is worth continuing. Although the main goal of merging the three subsidies into one is to foster food production, farmers should be encouraged to engage in green farming practices. The farmer is still potentially allowed to spend subsidies on fertilizers they over purchase due to the voluntary nature of conservation measures and the lack of a monitoring system. The specific policy recommendations are as follows:

(1) Specialized green payment programs for farmers should be prioritized and linked to environmentally friendly farming practices. Eligibility criteria for subsidies should include provisions related to green production measures, and stronger supervision mechanisms should be established.

TABLE 5 Heterogeneity of ASR on fertilizer consumption.

Variables	Farmers' disposable income		Agricultural mechanization	
	(1) High−income	(2) Low−income	(3) High−mech	(4) Low−mech
ASR	0.0640*** (0.0225)	0.0286 (0.0217)	0.0325** (0.0129)	0.0738** (0.0302)
Control variables	YES	YES	YES	YES
County FE	YES	YES	YES	YES
Year FE	YES	YES	YES	YES
Constant	9.9027*** (0.0152)	9.7949*** (0.0144)	10.4451*** (0.0086)	9.1476*** (0.0201)
Observations	2,886	2,832	3,096	2,662
R-squared	0.9808	0.9897	0.9790	0.9844

Values in parentheses are standard errors clustered at the county level. *, **, and *** indicate significance at the 10%, 5%, and 1% levels, respectively.

(2) Considering that subsidies can contribute to a reduction in fertilizer usage through an extension of planting areas, policies regarding land transfer and farm management at an agrarian scale need further improvement and coordinated promotion with green conservation projects. In the production process, farmers should receive guidance on scientifically applying fertilizers based on local conditions. Policies supporting new types of agricultural management entities with large-scale operations as well as small farmers with limited management capacity are necessary to improve fertilizer utilization efficiency.

(3) The government should pay more attention to the allocation of subsidy funds in high-income areas. Apart from the above, since the development of agricultural mechanization is favorable to the reduced consumption of chemical fertilizer, precision technologies such as accurate fertilizer equipment are necessary to be vigorously researched, developed, and spread. Gradually implement quota fertilization, integrated promotion of green prevention and control mode, build green planting system, reduce the amount of fertilizer input; technology such as low-tillage and no-tillage, green ecological cycle farming mode, deep tillage and fertilization by agricultural machinery should be promoted to replace the use of chemical fertilizers through technology.

5.3 Limitations and prospects of the study

This paper provides new evidence to promote the green transformation of agricultural subsidies and sustainable food production in China. However, some limitations remain to be broken in the future. Due to the availability of data, I only evaluated the effects of ASR at the regional level, and the data of my study is only updated to 2020. In future studies, I would try to gather more multi-period farm household survey data to accurately capture the medium and long-term, macro and micro impacts of subsidy policies.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

Author contributions

DF: Conceptualization, Data curation, Software, Formal analysis, Methodology, Visualization, Writing—original draft. FY: Supervision, Funding acquisition, Writing—review & editing, Validation.

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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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