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Leveraging agricultural production organizations to reduce fertilizer use: Evidence from China☆

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ABSTRACT

Smallholder-dominated agriculture in China faces severe fertilizer overuse due to fragmented land, limited mechanization, and low adoption of advanced agricultural technologies. Agricultural production organizations (e.g., family farms, agricultural cooperatives, and agricultural enterprises), characterized by their relatively large scale and advanced agricultural practices, are considered potential solutions for promoting more sustainable practices. This study investigates whether and how different agricultural production organization forms are associated with fertilizer use in China. Linking detailed business registry data with county-level panel data, we find that agricultural enterprises and cooperatives are associated with reductions in fertilizer use at the county level, while family farms do not show a significant relationship. Agricultural mechanization and land consolidation are potential channels through which agricultural enterprises and cooperatives are linked to these reductions. Further analysis with household survey data suggests associations between these two types of organizations and reductions in smallholders' fertilizer inputs through agricultural services. Heterogeneity analysis indicates that agricultural enterprises have a more pronounced effect in areas with extensive land transfer, advanced fertilization techniques, and in the eastern and plain regions of China. Agricultural cooperatives, benefiting from their unique governance structure, consistently show negative associations with fertilizer use regardless of land transfer, fertilization techniques, and topography constraints. Our findings provide insights into pathways for transitioning smallholder farming toward sustainable agriculture.

1. Introduction

Smallholder-dominated agriculture in China faces excessive chemical fertilizer use with severe environmental externalities. Smallholder farmers, who account for more than 98% of the main agricultural operators in China, typically have an average cropland size per household of approximately 0.5 ha, significantly smaller than the farming operations in Europe (>30 ha) or the United States (>150 ha) (Cui et al., 2018; Wu et al., 2018; Zhong et al., 2023). The characteristics of smallholder agriculture, such as land fragmentation, small scale, and limited mechanization and technology adoption, have resulted in high production costs and low production efficiency (Chen et al., 2022; Duan et al., 2021). These factors are the main barriers causing excessive use of chemical fertilizers (Deng et al., 2024; Ren et al., 2022; Zhang et al., 2020). While chemical fertilizers are essential for enhancing agricultural production, their overuse can cause severe non-point sources pollution with regard to water and air pollution, and greenhouse gas emissions (Chen et al., 2014; Diaz & Rosenberg, 2008; Guo et al., 2010; Wang et al., 2025; Yu et al., 2019). The pressure of agricultural production systems to sustain the livelihood of vulnerable smallholders and prevent environmental degradation necessitates a transition toward more sustainable practices.

Agricultural production organizations (APOs), such as family farms, agricultural cooperatives, and agricultural enterprises, have been considered by the Chinese government as a potential solution that facilitates the transition of smallholder farming to sustainable agriculture

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(Ren et al., 2023; Yu et al., 2022). Compared to conventional smallholder farming, these APOs mitigate productivity constraints by improving production efficiency and reducing chemical input use through land consolidation, mechanization, and advanced management practices (Ren et al., 2023). Additionally, they may influence smallholders to adopt environmentally friendly practices and technologies through agricultural services extension and knowledge exchange (Candemir et al., 2021; Wossen et al., 2017). However, it remains unclear to what extent these APOs are empirically linked to measurable improvements in agricultural sustainability outcomes, such as reduced chemical fertilizer use.

Existing studies have highlighted the positive impacts of APOs, particularly agricultural cooperatives, on various aspects of agricultural performance. These include improvements in agricultural productivity, smallholder farmers' welfare and behaviors (Houssou and Chapoto, 2015; Lin et al., 2022a; Ma and Abdulai, 2016; Obi, 2011; Yi et al., 2019; Zheng, 2024). However, only a limited number of studies examine the relationships between these organizations and environmental pollution reduction (Ren et al., 2023; Yu et al., 2022; Zhou et al., 2018), and these studies are limited in scope. Zhou et al. (2018) investigate the influence of agricultural cooperatives on pesticide use among smallholder vegetable farmers. Ren et al. (2023) project that APOs, including family farms, agricultural cooperatives, and agricultural enterprises, could potentially reduce fertilizer inputs by 2–7% by 2100 in China. Another study by Yu et al. (2022), based on a survey in the Tai Lake watershed, find that family farms, agricultural cooperatives, and agricultural enterprises collectively are associated with an 8% reduction in fertilizer use, compared to smallholder farming. However, little evidence exists on the overall associations of APOs with fertilizer use when considering both the organizations' independent reduction patterns and their interaction with smallholders.

In this study, we investigate whether and how different agricultural production organization forms (family farms, agricultural cooperatives, and agricultural enterprises) are associated with county-level fertilizer use. We employ a panel dataset that couples the information on business registry data of three types of agricultural production organizational forms with the county-level dataset and the Chinese National Fixed-Point Survey data.

Results from the instrumental variable (IV) approach show that agricultural enterprises and agricultural cooperatives are associated with significant reductions in fertilizer use at the county level. Specifically, a 10% increase in the number of agricultural enterprises and agricultural cooperatives at the county level is linked to a 1.59% and 1.57% decrease in county-level fertilizer use, respectively. Extending our analysis to smallholder farmers, we find similar reduction patterns in nitrogen fertilizer use associated with these two organizational forms. However, we do not find a significant association between family farms and fertilizer reduction.

Further mechanism analysis suggests that agricultural mechanization and land consolidation are potential channels through which agricultural enterprises and cooperatives are linked to these reductions. Our heterogeneity analysis documents the agricultural and geographical conditions under which different APO forms exhibit these associations. The results reveal that agricultural enterprises have a more pronounced effect with reduced fertilizer use in areas with extensive land transfer, advanced fertilization techniques, and in the eastern and plain regions. Leveraging their governance structure advantage, agricultural cooperatives exhibit consistent associations with fertilizer reduction across diverse land transfer, fertilization techniques, and topography conditions.

Our study contributes to the literature in three aspects. Firstly, while existing studies focus on the relationship between APOs and agricultural performance, limited attention has been given to their contributions to agricultural sustainability. The few studies on agricultural sustainability have been limited to small-scale analysis or focus on future projection (Ren et al., 2023; Yu et al., 2022; Zhou et al., 2018). Moreover, constrained by micro-level data limitations, the above studies focus on identifying the collective effects of various APOs or differentiating the effects of APOs on smallholder farmers. Our study extends beyond this narrative by examining the overall associations of different types of APOs with fertilizer use at the county level when considering both the organizations' independent reductions and their interaction with smallholders.

Secondly, our study provides one of the first pieces of empirical evidence of the relationship between agricultural enterprises and agricultural sustainability. Previous literature on APOs mainly focuses on the role of agricultural cooperatives and family farms in influencing farmers' behaviors and welfare (Houssou & Chapoto, 2015; Obi, 2011; Yi et al., 2019). However, limited attention has been devoted to examining the influence of agricultural enterprises, an emerging organizational form of APO in China, with few studies relying on qualitative analyses due to data limitations (Brenya et al., 2023; Iyabano et al., 2022). In contrast, our study aims to bridge this gap by providing empirical insights on the role of agricultural enterprises.

Thirdly, our study also contributes to the broad literature on addressing fertilizer overuse in smallholder farming. Technological innovations and institutional arrangements are two critical solutions to tackling excessive fertilizer use and its associated environmental pollution (Wang et al., 2024; Wuepper et al., 2020). Technological advancements, such as integrated soil-crop management techniques and improved cultivation and irrigation technologies, have proven effective in enhancing nitrogen use efficiency and reducing fertilizer application (Chen et al., 2014; Cui et al., 2018; Zhang et al., 2015). At the national level, institutional and policy measures, such as fertilizer pricing policies and the strategy of "Zero Growth in Synthetic Fertilizer Use" in China, have also been successful in promoting fertilizer reduction (Lin et al., 2022b; van Wesenbeeck et al., 2021; Wang et al., 2022, 2023; Williamson, 2021; Wuepper et al., 2020). However, the implementation and widespread adoption of these technological and policy measures often face high costs and implementation barriers. This study offers a complementary perspective, highlighting how APOs help facilitate the transition toward a sustainable agricultural system through organizational transformation.

The remainder of the paper is structured as follows. We first introduce the background information on APOs and their potential mechanisms. Sections 3 and 4 describe our data and empirical strategy. Section 5 presents our results and robustness checks. Section 6 concludes this study.

2. Background and mechanism

2.1. Agricultural production organizations in China

The implementation of the Household Responsibility System in China since 1978, provided farmers with relatively stable land contracting rights, enhancing their productivity (Huang & Liang, 2018). However, this institutional change has also resulted in challenges in Chinese agricultural production, including small-scale operations, spatial dispersion, and low levels of organization and mechanization. These issues are extensively linked to the excessive application of chemical fertilizer and impede the adoption of environmentally sustainable farming practices.

Compared with traditional smallholders, APOs specialize in intensive and large-scale production, characterized by a significant level of mechanization and organization. As defined by the Chinese government, the organizational forms of APOs mainly include specialized households, family farms, agricultural cooperatives, and agricultural enterprises, with the last three being registered with local governments, which are also the focus of this study.

These three types of APOs—family farms, agricultural cooperatives, and agricultural enterprises—differ in their production methods, governance structures (that is, decision-making processes), and interactions with smallholder farmers. Specifically, family farms, traditionally rooted in intergenerational practices, rely on manual labor with limited machinery. They often involve renting additional labor during busy seasons due to the extensive cropland they manage (Yu et al., 2022). Agricultural enterprises refer to large-scale, commercially-oriented farming operations that engage in intensive agricultural production. Their decision-making process is centralized to maximize their profit. Compared with other APOs, they typically employ advanced technologies, scientific management practices, and targeted marketing and sales strategies to optimize production and profitability (Zheng, 2024). Additionally, agricultural enterprises tend to attract young, highly educated farmers (Ren et al., 2023). They also interact with farmers through contractual agreements and provide a range of services to farmers throughout the pre-production, production, and post-production phases. Agricultural cooperatives are characterized as collaborative alliances formed by farmers sharing similar objectives. Within this collaborative structure, the cooperative serves as a central nexus of agreements through which farmers engage in collective efforts. Cooperatives are regarded as the bridge for linking smallholders and modern agriculture. By collaborating with smallholders, they can address the inefficiencies of traditional small-scale farming and promote sustainable agricultural development through shared benefits and risks. Unlike agricultural enterprises, cooperatives focus on the improvement of their members' welfare, not limited to profit maximization.

In our analysis, we focus on the development of APOs at the county level. Counties represent the third-tier administrative units in China's governance structure, positioned below the provincial and prefectural levels and above the townships. China has more than 2,800 county-level administrative units across 34 provinces/municipalities/autonomous regions. Counties serve as key agents in regional governance, functioning as the primary administrative tier for implementing agriculture policies. With a significant degree of financial and administrative autonomy, counties can tailor national policies to local conditions. This decentralized governance structure is critical for effectively managing agricultural resources, land use, and agricultural development programs, making counties a suitable unit for studying patterns related to APOs and fertilizer use.

2.2. Conceptual framework

In this section, we outline the mechanisms through which APOs may be associated with reductions in fertilizer use based on their above-mentioned operating characteristics. Two main channels are considered: (1) land consolidation combined with advanced technologies and mechanization, and (2) agricultural services provision and technical guidance to smallholders.

First, APOs are associated with improvements in fertilizer use efficiency and reduced fertilizer use through land consolidation and the adoption of advanced technologies and mechanization. Small, fragmented plots in China drive excessive fertilizer use, as smallholders often rely on manual application, which tends to be less efficient and less precise (Latruffe & Piet, 2014; Wu et al., 2018). Labor shortages, caused by rural-to-urban migration, exacerbate this issue, as millions of farmers leave rural areas in search of higher wages, resulting in the substitution of labor-intensive organic manure with chemical fertilizers to boost yields (Ebenstein et al., 2011; Li et al., 2023). According to Deng et al. (2024), fragmented croplands account for 15% of nitrogen fertilizer use but contribute only 8% of total crop production in China.

In contrast to smallholders, APOs manage large-scale farms through land consolidation. Duan et al. (2021) find that transitioning to large-scale farming could reduce nitrogen inputs by 24% compared to 2017 levels, leading to a substantial increase in nitrogen use efficiency from 44% to 52%. APOs typically lease fragmented plots from smallholders through contractual arrangements. This market-driven land consolidation further enables the adoption of advanced technologies, such as precision fertilization techniques and slow-release fertilizers, and complementary inputs, such as mechanization and irrigation systems (Deng et al., 2024; Wu et al., 2018), which improve the fertilizer use efficiency. For instance, precision fertilization techniques and mechanization ensure that fertilizers are applied accurately, only where and in the amounts required (Zhang et al., 2015).

Second, in addition to their internal operations, APOs could also provide agricultural services and technical guidance to smallholders,[2] influencing their fertilizer use. One pathway is through machinery rental services, which APOs can offer when machinery is underutilized (Huang et al., 2015; Yi et al., 2019). Access to such services lowers the barriers for smallholders to transition from manual fertilization to mechanized fertilization, leading to more efficient and precise application, which ultimately reduces fertilizer use (Zhong et al., 2023).

Another channel is through the promotion of nutrient management advisory services, which APOs provide through in-field knowledge training and guidance (Deng et al., 2010). These services have proven effective in reducing fertilizer use (Huang et al., 2008, 2012, 2015). While public agricultural extension services are a critical channel for farmers to access training and knowledge in China, these services often face constraints such as insufficient funding, limited personnel, and outdated infrastructure at the county and township levels (Lin et al., 2022). A large number of APOs can help fill these gaps by offering targeted technical training and field guidance to smallholders (Zheng, 2024). Training programs offered by APOs may cover practices such as site-specific fertilizer recommendations, fertilizer blend usage, and the application of high-efficiency fertilizers, such as slow-release or precision fertilizers, which improve nutrient use efficiency. Previous studies have shown that the involvement of agricultural cooperatives can help smallholders adopt environmentally friendly practices and agricultural technologies, thereby enhancing farm sustainability (Abebaw & Haile, 2013; Naziri et al., 2014).

In summary, APOs are expected to be associated with lower fertilizer use at the county level. Nevertheless, the magnitude of these associations may vary across different types of organizations based on their organizational structures and production characteristics.

3. Data

We compile a comprehensive dataset on APOs, fertilizer use, and socio-economic conditions across China for the years 2007–2015. Our analysis primarily employs three data sources: the business registry data on APOs; county-level data on fertilizer use, socio-economic, and agricultural conditions; and household-level survey data. Each data source is described in detail below.

3.1. Business registry data

We obtain the rural business registry data from the China Academy for Rural Development-Qiyan China Agri-research Database (CCAD) to

[2] The Chinese government encourages agricultural production organizations (APOs) to provide services and support the development of smallholder farmers. See *Opinions on Promoting the Organic Integration of Smallholder Farmers and Modern Agricultural Development* https://www.gov.cn/zhengce/2019–02/21/content_5367487.htm.

identify three types of APOs: agricultural enterprises, agricultural cooperatives, and family farms. APOs in the CCAD are classified based on business registry records using a combination of business registration type,[3] industrial classification,[4] keyword matching (e.g., business names containing "family farm"), and cross-referencing with officially issued lists of designated leading agricultural enterprises. The database contains information about the business registration date, business name, registered address, industry classification, and business closing date if applicable. This information enables us to construct the main independent variables—the number of each type of APO—at the county level. Data on agricultural enterprises and agricultural cooperatives have been recorded since 1953 and 2007, whereas data on family farms has been available since 2013. Fig. A1 presents the spatial distribution of the average number of agricultural enterprises, agricultural cooperatives, and family farms at the county level. In our main analysis, the number of agricultural enterprises includes both crop-based enterprises and crop-livestock enterprises. We also examine the robustness of results using only crop-based agricultural enterprises.

3.2. County-level data

County-level fertilizer data are sourced from the County-level Agricultural Database by the Ministry of Agriculture and Rural Affairs of China. The data was aggregated from surveys on farmers' agricultural production activities in local counties, covering the period from 1981 to 2015 (Chen & Gong, 2021; Wang et al., 2024). We use total fertilizer input calculated by the gross weight of nitrogen, phosphate, potash, and compound fertilizers per hectare in the main results. For heterogeneous analysis, disaggregated data on individual fertilizer types are employed.

3.3. Household-level data

Household-level data are used to examine the relationship between APOs and smallholder farmers' fertilizer use. These data are derived from the National Fixed-Point Survey, which is a rural household-level longitudinal survey collected by the Research Center for Rural Economy (RCRE) of the Chinese Ministry of Agriculture since 1986. We match household-level data with county-level APOs using village information. Specifically, we use information on farmers' nitrogen fertilizer use, the expenditure of nitrogen fertilizer use, the number of family members engaged in agriculture, cropland area, household income, and number of agricultural machines owned by households.

3.4. Control variables

We collect a range of control variables that are potentially related to both fertilizer use and the number of APOs at the county level. These variables include population, value added in the agriculture sector, value added in the industry sector, and fiscal expenditure, all sourced from the China County Statistical Yearbooks. Additional controls include the number of manufacturing agricultural enterprises, the number of agricultural enterprises in scientific research and technical services, and the number of technical cooperatives, based on the business registry data.

Meteorological controls, including precipitation and temperature data, are sourced from the Global Surface Summary of Day (GSOD), while sunshine duration data are obtained from the China Ground Climate Normal Value Dataset. We interpolate daily meteorological station observations to the county level using the inverse-distance weighting method and then calculate annual averages. For heterogeneity analysis, slope data is derived from the global digital elevation data jointly published by NASA and the Japanese Ministry of Economy, Trade and Industry (METI). Provincial-level statistics on land transfer, area for food crops and vegetables, and crop areas with deep fertilizer application technology are obtained from the China Rural Management Statistics Annual Report, the China Statistical Yearbook, and the China Agricultural Machinery Yearbook, respectively.

3.5. Sample construction and summary statistics

Because the three underlying databases overlap unevenly over time, we examine the associations between agricultural enterprises and cooperatives and fertilizer use over the nine annual rounds from 2007 to 2015. For family farms, which began to appear in the business registry in 2013, we focus on the three annual rounds from 2013 to 2015. Table 1 presents the summary statistics of the main variables. During our study period, the average number of agricultural enterprises per county was 58.73, alongside an average of 155.51 agricultural cooperatives and 47.80 family farms. The average total fertilizer use is 0.71 tons per hectare, which is more than three times the recommended safety limit of 0.225 tons per hectare. The average application amounts of nitrogen, phosphorus, potassium, and compound fertilizers are 0.32 tons per hectare, 0.10 tons per hectare, 0.08 tons per hectare, and 0.20 tons per hectare, respectively.

4. Empirical strategy

The main objective of this study is to examine the associations between different types of APOs and fertilizer use at the county level. Given the skewed distributions of fertilizer use and the number of APOs (Fig. A2), we use a log–log specification to mitigate the influence of extreme values and obtain elasticities for interpretation. To handle zero values in our independent variables, we add a small positive constant (set to 1) to the variables before applying the logarithm transformation. We include county fixed effects δ_c and year fixed effects θ_t to control for unobserved county-specific characteristics and time-varying common shocks. This yields the following two-way fixed effects model specification.

$$LogFert_{ct} = \beta_0 + \beta_1 LogAPO_{ct} + X'_{ct}\gamma + \delta_c + \theta_t + \varepsilon_{ct} \tag{1}$$

where the variable $LogFert_{ct}$ denotes the logarithms of fertilizer use per hectare in county c in year t. $LogAPO_{ct}$ represents the logarithm of the number of agricultural enterprises/agricultural cooperatives/family farms at the county level. The socio-economic controls X_{ct} consist of variables such as population, the value added in the agriculture sector, the value added in the industry sector, and fiscal expenditure, all of which may affect fertilizer use and the number of APOs. We also control for the number of manufacturing agricultural enterprises, the number of agricultural enterprises in scientific research and technical services, and the number of technical cooperatives. Additionally, government-led land consolidation efforts may spatially overlap with APOs, potentially confounding their effects. One important program is the Rural Land Contracting Law reform, which legalizes land transfers in rural areas since 2003. By providing more stable and secure property rights, this reform allows the land to be redistributed and consolidated toward large farms or more productive farmers, agricultural enterprises, and cooperatives through land rental markets (Bu & Liao, 2022; Chari et al., 2021; Cheng et al., 2019). To account for this potential confounding

[3] The registration type follows the official classification standard defined by the *Regulations on Statistical Classification of Market Entities*, issued by the National Bureau of Statistics and the State Administration for Market Regulation. See https://www.stats.gov.cn/sj/tjbz/gjtjbz/202302/t20230213_1902786.html for detail.

[4] The classification follows the *Industrial Classification for National Economic Activities (2017)* (see https://www.mca.gov.cn/n156/n187/n319/index.html for detail) and the *Statistical Classification of Agriculture and Related Industries (2020)* (see https://www.gov.cn/zhengce/zhengceku/2020–12/30/content_5575377.htm for detail), both issued by the National Bureau of Statistics of China.

Table 1
Summary statistics for key variables.

Variables	Units	N	Mean	S.D.	Min	Max
***A. County-level* variables**						
Key dependent variables						
Total fertilizer	t/ha	10,860	0.71	0.98	0.006	64.51
Nitrogen fertilizer	t/ha	10,860	0.32	0.49	0.001	32.50
Phosphorus fertilizer	t/ha	10,860	0.10	0.17	0.001	6.14
Potassium fertilizer	t/ha	10,860	0.08	0.13	0	5.23
Compound fertilizer	t/ha	10,860	0.20	0.31	0.001	21.07
Key independent variables						
Number of agricultural enterprises		10,860	58.73	53.48	0	254
Number of agricultural cooperatives		10,860	155.51	265.31	0	5,353
Number of family farms		2,902	47.80	123.90	0	1,999
Control variables						
Number of manufacturing agricultural enterprises		10,860	5.93	9.35	0	180
Number of agricultural enterprises in scientific research and technical services		10,860	3.58	8.64	0	178
Number of technical cooperatives		10,860	1.39	12.32	0	806
Population	10,00 people	10,860	52.95	34.86	2.58	232.57
Value added in the agriculture sector	million Yuan	10,860	1,997.93	1,580.39	41	13,995.16
Value added in the industry sector	million Yuan	10,860	6,435.90	11,517.66	32	169,568.00
Fiscal expenditure	million Yuan	10,860	1,804.45	1,603.06	35	27,434.06
Total power of agricultural machinery	10,000 kWh	10,737	37.99	38.91	1	1,512.00
Cropland area per capita	hectare/people	10,843	0.19	0.34	0.001	5.73
B. Household-level variables						
Nitrogen fertilizer	kg/mu	38,651	23.94	19.54	3.28	150
Expenditure of nitrogen fertilizer	Yuan/mu	38,651	45.14	36.65	5.71	255
Cropland area	mu	38,651	8.77	8.69	0.10	50
Number of family members engaged in agriculture		38,651	3.91	1.60	1	16
Number of machines owned by households		38,651	0.34	0.63	0	4
Household income	Yuan	38,651	33,927	22,034	400	122,027

Notes: A "mu" is a unit of land measurement in China, with 1 mu being equivalent to 0.0667 ha.

effect, we include a provincial-level policy implementation dummy as an additional control, following Li and Zhu (2023) and Chari et al. (2021). Furthermore, to estimate the individual associations of each type of agricultural production operator, we include the number of agricultural cooperatives and family farms as controls in the regression of agricultural enterprises, and vice versa. Standard errors are clustered at the county level to account for within-county correlation over time. Our parameter of interest, β_1, represents the elasticity of fertilizer use with respect to the number of APOs.

One major concern with a two-way fixed effects model is the endogeneity issue. This can be caused by omitted variables. While year fixed effects control for the country-wide trend in fertilizer use, and county fixed effects account for county-specific unobservable characteristics, such as geographical conditions, and agricultural production characteristics (e.g., terrain and cropping patterns), they do not account for time-varying differences within counties. Although we include a series of socio-economic control variables, unobserved factors may still exist that correlate with both the development of APOs and fertilizer use. For example, more efficient producers are more likely to join agricultural cooperatives and enterprises, and counties with more efficient producers would have larger shares of agricultural cooperatives and enterprises. This could introduce upward bias in the estimated associations between APOs and fertilizer use reduction. Additionally, counties with better agricultural conditions such as higher agriculture suitability and soil quality, may have more APOs than counties with less favorable conditions. When comparing counties with different numbers of APOs, those with better agricultural conditions may have a lower fertilizer use, potentially leading to an upward bias in the estimates between APOs and fertilizer use reduction. Moreover, unobserved investments or policy decisions at the county level are likely to influence both the prevalence of APOs and fertilizer use. For instance, counties that introduce subsidies to promote the development of APOs may also experience higher fertilizer use due to more intensive agricultural practices. This could create a downward bias in the estimated relationship between APOs and fertilizer use. Thus, the direction of bias from endogeneity issue remains uncertain. We further use an IV strategy to address other potential sources of bias.

We follow Acemoglu et al. (2019), Caselli and Reynaud (2020), and Chang et al. (2011) to construct an IV based on the province-wide average number of APOs (excluding the focal county). Our IV design is supported by evidence that institutional establishments often occur across geographical regions through imitation and peer effects (Caselli & Reynaud, 2020; Giuliano et al., 2013). Acemoglu et al. (2019), for instance, use regional waves of democratization as an instrument for democracy to examine its effect on GDP, arguing that regional patterns reflect the diffusion of democratic demand in areas with shared histories, political cultures, and networks. Similarly, Caselli and Reynaud (2020) apply this approach to the study of fiscal rules.

The IV captures exogenous variation in agricultural organizational development at the provincial level. We acknowledge the caution noted by Betz et al. (2018) that spatial instruments may introduce bias if spillover effects or interdependencies in outcome variables violate the exclusion restriction. Specifically, the IV may fail to identify the causal effect if neighboring regions directly influence the outcome in the focal county, for example, through the diffusion of agricultural practices or advisory services. Additionally, interdependence in outcome across regions could undermine the assumption that the instrument operates solely through the focal county if neighboring counties indirectly affect the outcome.

To mitigate the concern of potential spillover effects of neighboring counties, we exclude adjacent counties from the IV calculation, reducing the risk of spillover effects and ensuring our identification strategy uses variation in APO prevalence that is exogenous. Our IV strategy leverages the localized nature of APO services documented by Bizikova et al. (2020). These services including farming practices and fertilizer use are often tailored to county-specific agroecological conditions and exhibit limited spatial diffusion, as counties not adjacent to each other face heterogeneous production constraints. This modification reduces the risk of bias from neighboring counties, such as advisory services, which are unlikely to operate across long distances. In Equation (2), n denotes the total number of counties in the province where county c is located, while m denotes the number of its neighboring counties sharing borders with the focal county within the same province. N_c is the set of neighboring counties of c within the province, with $|N_c|=m$. $\sum_{k\in N_c} APO_{kt}$ is the sum of APOs over all neighboring counties of c. We denote $LogIV_{ct}$ as the IV and specify the first stage as Equation (3) and the second stage as Equation (4).

$$IV_{ct} = \frac{\sum_{k=1}^{n} APO_{kt} - APO_{ct} - \sum_{k\in N_c} APO_{kt}}{\mathrm{n}-1-\mathrm{m}} \tag{2}$$

$$LogAPO_{ct} = \alpha_0 + \alpha_1 LogIV_{ct} + X'_{ct}\lambda + \delta_c + \theta_t + \mu_{ct} \tag{3}$$

$$LogFert_{ct} = \beta_0 + \beta_1 Log\widehat{APO}_{ct} + X'_{ct}\gamma + \delta_c + \theta_t + \varepsilon_{ct} \tag{4}$$

The validity of the IV relies on meeting two key assumptions: relevance and exogeneity. For relevance, the average number of APOs across counties within the same province affects the number of such organizations in the focal county. The first-stage Kleibergen-Paap (KP) *F*-statistics (columns (3)–(4) in Table 3) exceed Stock and Yogo's 10% maximal bias threshold of 16.38, indicating that the IV is relevant. The validity of our approach could be threatened if other factors correlated with both IV and fertilizer use are omitted. The exclusion restriction assumes that conditional on the controls, the province-wide average numbers of APOs are associated with fertilizer use only via their correlation with the number of APOs in the focal county. One potential concern with the exclusion restriction is that APOs within the same province could provide machinery and technical services to the county, which could be related to fertilizer use in the focal county. However, this is unlikely to be the case, as our results remain robust after controlling for province-wide average machinery power[5] (Table 4, column (1)). Another concern is that the exclusion restriction might be violated through regional interdependence in fertilizer use (Betz et al., 2018). To address this, we incorporate provincial-level average fertilizer use[6] into our model to account for regional interdependence, and rule out this channel (Table 4, column (2)). Furthermore, the results are also robust to the inclusion of both controls for provincial-level average machinery power and fertilizer use (Table 4, column (3)).

5. Results

5.1. Baseline

Table 2 reports the first-stage estimation results of the associations between the IVs and the number of agricultural enterprises/agricultural cooperatives/family farms at the county level. Column (1) shows the regression results without including control variables, while column (2) includes the control variables. All the regressions control for county and year fixed effects. Results in column (2) show that a one percent increase in the province-wide average number of agricultural enterprises, agricultural cooperatives, and family farms is associated with 0.65, 0.80, and 0.55 percent increases in the number of agricultural enterprises, agricultural cooperatives, and family farms at the county level. The KP *F*-statistics reported in Table 3 indicate that the province-wide average agricultural enterprises/agricultural cooperatives/family farms are strong predictors of their county-level counterparts.

Table 3 reports the estimated associations between APOs and fertilizer use. Panel A, Panel B, and Panel C show the estimation results of agricultural enterprises, agricultural cooperatives, and family farms, respectively. Columns (1)–(2) report the OLS estimates, while columns (3)–(4) report the IV estimates. The OLS estimates in Table 3, column (2), indicate a significant and negative association between agricultural cooperatives and fertilizer use after controlling for socio-economic and meteorological conditions as well as county and year fixed effects. In contrast, agricultural enterprises show a negative but statistically insignificant relationship, while family farms exhibit a positive yet insignificant correlation. However, the OLS estimates are subject to endogeneity biases, limiting their causal interpretation. Our preferred IV estimates (Table 3, column (4)) reveal that a 10% increase in the number of agricultural enterprises and cooperatives at the county level is associated with 1.59% and 1.57% reduction in fertilizer use, respectively, with no significant and negative association observed for family farms. The smaller and statistically insignificant OLS estimates relative to the IV estimates suggest that the sign of any unaddressed bias is positive. This is reasonable in light of the fact that some regions with a higher concentration of APOs are likely to have more intensive agricultural practices, which include higher fertilizer use. The IV approach corrects this bias, revealing a negative relationship between agricultural enterprises/cooperatives and fertilizer use.

Table 2
First-stage estimation.

Panel A: Agricultural Enterprise	(1)	(2)
Dependent variable	Log (#AgrEnterprise + 1)	
Log (IV)	0.6404***	0.6505***
	(0.0410)	(0.0428)
R^2	0.728	0.733
Observations	10,860	10,860
Panel B: Agricultural Cooperative	(1)	(2)
Dependent variable	Log (#Cooperative + 1)	
Log (IV)	0.8118***	0.7972***
	(0.0333)	(0.0329)
R^2	0.902	0.903
Observations	10,860	10,860
Panel C: Family Farm	(1)	(2)
Dependent variable	Log (#Farm + 1)	
Log (IV)	0.6115***	0.5496***
	(0.0557)	(0.0594)
R^2	0.664	0.684
Observations	2,902	2,902
Control Variables	NO	YES
County FE	YES	YES
Year FE	YES	YES

Notes: In Panels A, B, and C, log (IV) denotes the province-wide average number of agricultural enterprises, agricultural cooperatives, and family farms, respectively. Panels A and B report results for the period 2007–2015, while Panel C presents results for 2013–2015. Control variables in column (2) include log form of county-level population, value added of the agriculture sector, value added of the industry sector, fiscal expenditure, number of other two types of agricultural production organizations, number of manufacturing agricultural enterprises, number of agricultural enterprises in scientific research and technical services, and number of technical cooperatives, temperature, precipitation, and sunshine duration, and provincial level Rural Land Contracting Law reform dummy. Standard errors are clustered at the county level and are listed in parentheses. $^{***}p < 0.01$, $^{**}p < 0.05$, $^{*}p < 0.1$.

5.2. Robustness checks

We further conduct a series of robustness checks to validate our main results and address the potential concerns on the validity of the IV. We use several strategies, including incorporating additional controls, testing different measurements of the independent variables, and testing with different sample sets.

The validity of our approach (i.e. exclusion restriction) is threatened

[5] Here, to measure the machinery and technical services that could be provided by counties within the same province, we use the province-wide average machinery power, excluding the machinery power of the focal county itself and its neighboring counties, aligning with the IV construction.

[6] The provincial-level average fertilizer use refers to province-wide fertilizer use (excluding the focal county and adjacent counties), aligning with the IV construction.

Table 3
The associations between APOs and fertilizer use.

	(1)	(2)	(3)	(4)
	Log (Fertilizer)		Log (Fertilizer)	
	OLS	OLS	2SLS	2SLS
Panel A: Agricultural Enterprise				
Log (#AgrEnterprise + 1)	−0.0019	−0.0024	−0.1823***	−0.1591**
	(0.022)	(0.021)	(0.0668)	(0.0633)
Observations	10,860	10,860	10,860	10,860
Number of Clusters	1,393	1,393	1,393	1,393
KP Wald *F*-statistic			244.1	230.7
Panel B: Agricultural Cooperative				
Log (#Cooperative + 1)	−0.0399***	−0.0394***	−0.1619***	−0.1573***
	(0.013)	(0.013)	(0.0354)	(0.0355)
Observations	10,860	10,860	10,860	10,860
Number of Clusters	1,393	1,393	1,393	1,393
KP Wald *F*-statistic			594.9	588.4
Panel C: Family Farm				
Log (#Farm + 1)	−0.0009	0.0002	0.0276	−0.0090
	(0.008)	(0.009)	(0.0339)	(0.0381)
Observations	2,902	2,902	2,902	2,902
Number of Clusters	1,015	1,015	1,015	1,015
KP Wald *F*-statistic			120.4	85.68
Control Variables	NO	YES	NO	YES
County FE	YES	YES	YES	YES
Year FE	YES	YES	YES	YES

Notes: In Panels A, B, and C, Log (#AgrEnterprise + 1), Log (#Cooperative + 1), and Log (#Farm + 1) denote the logarithms of the number of agricultural enterprises, agricultural cooperatives, and family farms with an additional unit of 1, respectively. Panels A and B report results for the period 2007–2015, while Panel C presents results for 2013–2015. Control variables in columns (2) and (4) include log form of county-level population, value added of the agriculture sector, value added of the industry sector, fiscal expenditure, number of other two types of agricultural production organizations, number of manufacturing agricultural enterprises, number of agricultural enterprises in scientific research and technical services, and number of technical cooperatives, temperature, precipitation, and sunshine duration, and provincial level Rural Land Contracting Law reform dummy. Standard errors are clustered at the county level and are listed in parentheses. $^{***}p < 0.01$, $^{**}p < 0.05$, $^{*}p < 0.1$.

if other factors correlated with province-wide APOs are linked to fertilizer use. A violation of the exclusion restriction could occur if APOs within the same province provide cross-county mechanization and technical services that could be related to fertilizer use in the focal county. To mitigate this, we include province-wide average machinery power as a control variable in the model. The estimates of APOs remain largely unchanged, reinforcing the validity of our IV (Table 4, column (1)). Another concern with the exclusion restriction is the potential spatial interdependence of fertilizer use across counties. Province-wide APOs are associated with province-wide fertilizer use, which may indirectly relate to the fertilizer use in the focal county. We account for this by controlling for the provincial-level average fertilizer use to capture regional correlations. The results (Table 4, column (2)) indicate that while the estimated coefficients increase slightly, they remain consistent with the baseline estimates. Including both controls simultaneously (Table 4, column 3) also yields robust results. These robustness checks further support that our IV isolates plausibly exogenous variation in APO-driven organizational development.

We further test whether our results are sensitive to the transformation of the independent variable. In our baseline model, we use $\log(x+1)$ transformation to include the full sample for our elasticity estimation. Here, we conduct a robustness check using an inverse hyperbolic sine transformation, $log\left(x+\sqrt{x^2+1}\right)$, as proposed by Bellemare and Wichman (2020), which also retains zero-valued observations.

Table 4
The associations between APOs and fertilizer use, with additional controls.

	(1)	(2)	(3)
	Log (Fertilizer)		
Panel A: Agricultural Enterprise			
Log (#AgrEnterprise + 1)	−0.1425***	−0.2290***	−0.1528***
	(0.0545)	(0.0601)	(0.0520)
Observations	10,727	10,850	10,727
Number of Clusters	1,392	1,393	1,392
KP Wald *F*-statistic	389.3	294.8	397.3
Panel B: Agricultural Cooperative			
Log (#Cooperative + 1)	−0.1669***	−0.1476***	−0.1301***
	(0.0370)	(0.0341)	(0.0353)
Observations	10,727	10,850	10,727
Number of Clusters	1,392	1,393	1,392
KP Wald *F*-statistic	539.3	606.2	533.2
Panel C: Family Farm			
Log (#Farm + 1)	0.0000	0.0017	0.0009
	(0.0373)	(0.0376)	(0.0371)
Observations	2,879	2,899	2,879
Number of Clusters	1,009	1,014	1,009
KP Wald *F*-statistic	85.25	85.72	85.29
Province-wide Average Machinery Power	YES		YES
Province-wide Average Fertilizer Use		YES	YES
Control Variables	YES	YES	YES
County FE	YES	YES	YES
Year FE	YES	YES	YES

Notes: In Panels A, B, and C, Log (#AgrEnterprise + 1), Log (#Cooperative + 1), and Log (#Farm + 1) denote the logarithms of the number of agricultural enterprises, agricultural cooperatives, and family farms with an additional unit of 1, respectively. Panels A and B report results for the period 2007–2015, while Panel C presents results for 2013–2015. All model specifications including control variables and fixed effects are in line with the baseline. Standard errors are clustered at the county level and are listed in parentheses. $^{***}p < 0.01$, $^{**}p < 0.05$, $^{*}p < 0.1$.

Though the magnitudes of the estimated results in Table 5 column (1) are slightly smaller than those in the baseline, the signs and the significance are the same. We also directly use the logarithm of the number of agricultural enterprises/agricultural cooperatives/family farms as the independent variable to exclude the zero values. The results in Table 5 column (2) are in line with our baseline, which further verifies the robustness of our results.

While our main regressions are based on unbalanced panel data, we also use a balanced panel for robustness checks to rule out the possible concern of sample selection. Table 5 column (3) shows the estimated results of the number of agricultural enterprises and agricultural cooperatives are still significant at the 10% and 1% level, respectively, with similar magnitudes and signs to our baseline.

To examine whether the link between APOs and reduction in fertilizer use is driven by changes in crop portfolios, we include provincial-level shares of food crops and vegetable areas in our model specification. These provincial controls proxy for regional agricultural priorities, as county-level crop portfolio data are unavailable. Our results show that the magnitudes of APOs remain significant, although the coefficients are modestly attenuated compared to the baseline (Table A1, columns (1)–(3)). This suggests that the observed relationships between APOs and reduction in fertilizer use are independent of shifts in production portfolios. While provincial level data cannot fully capture localized crop choice, our analysis mitigates confounding from broader regional trends.

To account for the lagged effect of the number of APOs, we further include its lagged term as a control. The results presented in column (4) indicate that the coefficients for agricultural enterprises and cooperatives remain statistically significant, with a larger magnitude compared to the baseline. Moreover, to address the potential association

Table 5
Robustness checks of the associations between APOs and fertilizer use.

	(1)	(2)	(3)	(4)	(5)	(6)
	IHS (X)	Log (X)	Balanced panel	Control lagged X	Exclude family farms as control	Crop-based agricultural enterprises
Panel A: Agricultural Enterprise						
Log (#AgrEnterprise + 1)	−0.1531**	−0.1513**	−0.1483*	−0.2651**	−0.1633**	−0.1589**
	(0.0614)	(0.0616)	(0.0845)	(0.1055)	(0.0640)	(0.0631)
Observations	10,860	10,851	6,795	9,430	10,860	10,851
Number of Clusters	1,393	1,393	755	1,378	1,393	1,393
KP Wald *F*-statistic	230.1	221.4	217.6	221.8	227.9	243.3
Panel B: Agricultural Cooperative						
Log (#Cooperative + 1)	−0.1268***	−0.1812***	−0.1587***	−0.3818***	−0.1580***	
	(0.0306)	(0.0396)	(0.0477)	(0.1074)	(0.0356)	
Observations	10,860	10,371	6,795	9,430	10,860	
Number of Clusters	1,393	1,388	755	1,378	1,393	
KP Wald *F*-statistic	591.9	393.7	362.3	135.5	586.3	
Panel C: Family Farm						
Log (#Farm + 1)	−0.0047	0.0002	−0.0079	−0.0043		
	(0.0380)	(0.0801)	(0.0380)	(0.1726)		
Observations	2,902	2,155	2,882	1,744		
Number of Clusters	1,015	814	1,010	872		
KP Wald *F*-statistic	66.23	17.50	86.36	10.64		
Control Variables	YES	YES	YES	YES	YES	YES
County FE	YES	YES	YES	YES	YES	YES
Year FE	YES	YES	YES	YES	YES	YES

Notes: In Panels A, B, and C, Log (#AgrEnterprise + 1), Log (#Cooperative + 1), and Log (#Farm + 1) denote the logarithms of the number of agricultural enterprises, agricultural cooperatives, and family farms with an additional unit of 1, respectively. Panels A and B report results for the period 2007–2015, while Panel C presents results for 2013–2015. All model specifications including control variables and fixed effects are in line with the baseline, unless otherwise stated. Standard errors are clustered at the county level and are listed in parentheses. *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$.

of family farms with the estimation of agricultural enterprises and cooperatives, we fill in data on family farms prior to 2013 as the control variable. Since family farms do not exhibit a significant association with fertilizer use, we excluded them as a control variable from the baseline to mitigate any biases introduced during data filling. The results in Table 5 column (5) show that the associations between agricultural enterprises and cooperatives and fertilizer use remain consistent with the baseline.

To assess the robustness of our main analysis across different temporal scopes, we conducted a series of checks by progressively narrowing the sample to overlapping shorter periods. As shown in Appendix A Table A2, the negative associations between agricultural enterprises and cooperatives and fertilizer use remain robust across all subsamples ranging from 2008–2015 to 2012–2015. However, when the analysis is restricted to the period 2013–2015, during which family farm data are available, the results diverge: the association for agricultural enterprises becomes statistically insignificant, while the coefficient for cooperatives turns significant and positive. This divergence may reflect reduced statistical power due to the shorter time window, with limited variation in the expansion of APOs and fertilizer use. Additionally, this period coincides with policy changes affecting agricultural cooperatives, such as the implementation of the "Interim Measures for the Evaluation and Monitoring of Demonstration Agricultural Cooperatives".[7] This policy may induce compositional shifts, influencing the share of officially designated demonstration cooperatives relative to regular cooperatives within counties, thereby changing subsidy eligibility and operational patterns. Because the family farm analysis relies on the same short 2013–2015 period and cannot be extended to earlier years, these findings indicate that its estimates should be interpreted with caution. Longer panels, once available, will be useful for confirming whether the patterns for family farms align with those observed for agricultural enterprises and cooperatives.

Finally, since some agricultural enterprises engage in both crop cultivation and animal husbandry, we specifically analyze the association of the pure crop-based agricultural enterprises by segregating out

Table 6
The mechanisms that link APOs to fertilizer use.

	(1)	(2)
	Log (Machine power)	Log (Cropland area per capita)
Panel A: Agricultural Enterprise		
Log (#AgrEnterprise + 1)	0.1327***	0.1668***
	(0.0290)	(0.0457)
Observations	10,737	10,843
Number of Clusters	1,392	1,391
KP Wald *F*-statistic	225	231.4
Panel B: Agricultural Cooperative		
Log (#Cooperative + 1)	0.0960***	0.1386***
	(0.0188)	(0.0285)
Observations	10,737	10,843
Number of Clusters	1,392	1,391
KP Wald *F*-statistic	540.7	588.9
Panel C: Family Farm		
Log (#Farm + 1)	0.0014	−0.0201
	(0.0286)	(0.0135)
Observations	2,882	2,894
Number of Clusters	1,010	1,012
KP Wald *F*-statistic	86.36	85.67
Control Variables	YES	YES
County FE	YES	YES
Year FE	YES	YES

Notes: In Panels A, B, and C, Log (#AgrEnterprise + 1), Log (#Cooperative + 1), and Log (#Farm + 1) denote the logarithms of the number of agricultural enterprises, agricultural cooperatives, and family farms with an additional unit of 1, respectively. Panels A and B report results for the period 2007–2015, while Panel C presents results for 2013–2015. The cropland area per capita in column (2) is measured by dividing the total cropland area by the agricultural labor. All model specifications, including control variables and fixed effects are in line with the baseline. Standard errors are clustered at the county level and are listed in parentheses. *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$.

[7] In 2013, China implemented the *Interim Measures for the Evaluation and Monitoring of Demonstration Agricultural Cooperatives*, formally establishing a system for assessing and monitoring demonstration cooperatives, which played a significant role in the formalization of cooperatives.

Table 7
The associations between APOs and smallholder farmers' fertilizer use.

	(1)	(2)
	Log (Farmers' N fertilizer use)	Log (Farmers' N fertilizer expenditure)
Panel A: Agricultural Enterprise		
Log (#AgrEnterprise + 1)	−0.0743**	−0.0786**
	(0.0375)	(0.0382)
Observations	38,651	38,651
Number of Clusters	240	240
KP Wald *F*-statistic	28.58	28.58
Panel B: Agricultural Cooperative		
Log (#Cooperative + 1)	−0.0896*	−0.0784*
	(0.0466)	(0.0475)
Observations	38,651	38,651
Number of Clusters	240	240
KP Wald *F*-statistic	32.97	32.97
Control Variables	YES	YES
Household FE	YES	YES
Year FE	YES	YES

Notes: In Panels A and B, Log (#AgrEnterprise + 1) and Log (#Cooperative + 1) denote the logarithms of the number of agricultural enterprises and agricultural cooperatives with an additional unit of 1, respectively. Panels A and B report results for the period 2009–2015. Columns (1) and (2) control for household fixed effects and year fixed effects. The county-level control variables are in line with the baseline. Household-level controls include the number of family members engaged in agriculture, cropland area, household income, and number of agricultural machines owned by households. Estimates of the impact of family farms on household-level nitrogen fertilizer use and expenditure are not reported, as they fail to pass the weak instrument test. Standard errors are clustered at the county level and are listed in parentheses. $^{***}p < 0.01$, $^{**}p < 0.05$, $^{*}p < 0.1$.

the combined crop-livestock agricultural enterprises. Table 5 column (6) shows a slightly lower magnitude than the baseline. One possible explanation for this finding is that integrated crop-livestock agricultural enterprises can boost the utilization of organic fertilizers through a crop-livestock farming cycle, thus facilitating a decrease in chemical fertilizer use. This may manifest in the model results showing a relatively larger negative association between fertilizer application and agricultural enterprises practicing integrated crop-livestock methods.

5.3. Mechanisms

As discussed in Section 2, APOs may be linked to fertilizer use through both direct channels (land consolidation combined with advanced technologies and mechanization) and indirect channel (smallholder farmers' fertilizer use).

We first examine whether these three types of APOs are associated with county-level agricultural mechanization and land consolidation. Using the total power of agricultural machinery as the dependent variable, we find that agricultural enterprises and cooperatives show significant and positive associations with mechanization (Table 6, column (1)). Specifically, a 10% rise in the number of agricultural enterprises is linked to an average 1.33% increase in the total power of agricultural machinery, while a similar increase in agricultural cooperatives is associated with a 0.96% average increment. Family farms, however, show no significant association. These outcomes imply that enhancing agricultural mechanization levels could serve as a potential channel through which agricultural enterprises and cooperatives are associated with reduced fertilizer use.

Due to data limitations, characterizing the extent of land consolidation or the number of land parcels at the county level is challenging. Here we use cropland area per agricultural labor as a proxy for land consolidation. This metric reflects the movement of agricultural labor between agricultural and non-agricultural sectors, indicating the level of land consolidation aimed at facilitating more efficient large-scale operations. Results (Table 6, column (2)) show that both agricultural enterprises and cooperatives are positively associated with cropland area per agricultural labor, while family farms show a negative relationship. This finding suggests that agricultural enterprises may be linked to land outflows from smallholders by raising land rents, enabling surplus labor to transition to urban and non-agricultural sectors, especially for those with low productivity (Fu et al., 2022; Li & Zhu, 2023). Agricultural cooperatives, on the other hand, may help their membership scale up through shared services. Consistent with the literature unveiling the reduction effects of land consolidation or farm size on fertilizer use (Duan et al., 2021; Hu et al., 2021; Ju et al., 2016; Li & Zhu, 2023), the pathways we illuminate may explain why agricultural enterprises and cooperatives are associated with reduced fertilizer use. Moreover, the decrease in cropland area per agricultural labor associated with the development of family farms highlights the ongoing need for modern input factors within family farms.

We further leverage the household survey dataset to extend our analysis to smallholder farmers. To better examine the associations between APOs and smallholders' fertilizer use, we exclude observations with cropland areas exceeding 50 mu.[8] While some of the remaining households may also be affiliated with agricultural cooperatives, the inclusion of household fixed effects helps mitigate this concern by controlling for time-invariant unobservable characteristics. Our results show that both agricultural enterprises and agricultural cooperatives are associated with reductions in smallholder's fertilizer use. Specifically, a 10% increase in the number of agricultural enterprises at the county level is linked to a 0.74% decrease in smallholder's nitrogen fertilizer use, and a similar increase in agricultural cooperatives corresponds to a 0.90% reduction (Table 7, column (1)). We find similar reductions in nitrogen fertilizer expenditure for smallholders (Table 7, column (2)). These findings indicate that agricultural enterprises and cooperatives have the potential to influence smallholder farmers in reducing fertilizer use through the provision of agricultural services and knowledge exchange (Zhang et al., 2024). The results of agricultural cooperatives are consistent with the extensive literature on the significant role of agricultural cooperatives in enhancing the adoption of green technology and sustainable practices among smallholder farmers (Bizikova et al., 2020; Ma et al., 2018).

5.4. Heterogeneity

In this section, we investigate the heterogeneous associations of

[8] Large-scale agricultural operators are typically defined as farmers with land holdings of 50 mu or more in China, where 1 mu equals 0.0667 ha.

APOs with fertilizer use. Different types of APOs may be associated with varying outcomes conditional on agricultural, geographical, and topographical characteristics. We first examine whether the associations between APOs and fertilizer use vary by land transfer levels. Since APOs generally operate on large farm sizes compared with smallholder farmers, they face lower transaction costs of land consolidation in regions with formal institutional arrangements of land transfer. Here we measure the levels of land transfer using provincial level land transfer areas[9] in 2006. We categorize the samples into two groups depending on whether the provincial land transfer area in 2006 surpassed the provincial median. Estimation results in Table A3 column (1) show that in regions with more extensive land transfer, agricultural enterprises are associated with greater reductions in fertilizer use, whereas cooperatives exhibit no significant differential association. The finding aligns with the fact that agricultural enterprises are often linked with extensive land transfer. In contrast, leveraging their governance structure, agricultural cooperatives may facilitate land coordination through relational networks or member-based arrangements, potentially enabling similar outcomes across varying institutional contexts.

Next, we explore the role of historical adoption of fertilization technologies. We use the proportion of land with mechanized deep fertilizer application[10] at the provincial level to measure the regional adoption of advanced fertilization techniques. The sample is divided based on whether the regional level of fertilization techniques is above or below the provincial average. The results (Table A3, column (2)) show that agricultural enterprises are associated with reductions in fertilizer use in regions with higher adoption of advanced fertilization techniques. In contrast, the association for agricultural cooperatives does not differ significantly across regions with varying levels of adoption. This could be attributed to the role of agricultural cooperatives in bridging knowledge and information gaps among smallholder farmers by providing agricultural extension services, including guidance on chemical inputs, cultivation methods, and production systems. These efforts can facilitate the adoption of sustainable production practices among smallholder farmers even in regions with limited access to advanced fertilization techniques, thereby contributing to lower fertilizer use (Bizikova et al., 2020; Candemir et al., 2021; Ma et al., 2018).

We then investigate spatial heterogeneity by grouping the sample into eastern and central/western regions. Provinces/municipalities of Beijing, Tianjin, Hebei, Jiangsu, Shanghai, Zhejiang, Fujian, Shandong, Guangdong, Hainan, and Liaoning are classified within the eastern region, with the remaining provinces/municipalities/autonomous regions categorized as central and western region. We find significant spatial heterogeneity of agricultural enterprises and agricultural cooperatives, with stronger negative associations in the eastern region (Table A4, column (1)). One potential explanation is that excessive fertilizer use is more prevalent in the east, leading to greater marginal effects of reduction of APOs.

We also explore how the effect of APOs differs by topography. We classify samples with an average slope of less than 15 degrees as plains and those with a slope of 15 degrees or more as mountain areas. We find that agricultural enterprises are more strongly associated with reductions in fertilizer use in plain areas (Table A4, column (2)). This result is reasonable, as plain areas are physically suitable for large-scale farming with higher adoption of machinery and technology, which facilitates the reduction of fertilizer use. However, cooperatives show no significant heterogeneity between plains and mountainous regions, likely due to their capacity to integrate smallholders into modern agricultural practices even in less favorable terrains.

Finally, we examine the heterogeneous associations between APOs and the use of specific fertilizer types, including nitrogen, potassium, phosphate, and compound fertilizers. The results (Table 8, Panel A) show that every 10% rise in the number of agricultural enterprises at the county level, is associated with a 1.78% in nitrogen fertilizer use, and a 1.47% in compound fertilizer use. Agricultural cooperatives are associated with reductions across all fertilizer types, with a 10% increase linked to reductions of 1.36%, 1.47%, 1.82%, and 1.73% in nitrogen, phosphate, potassium, and compound fertilizer use at the county level, respectively (Table 8, Panel B). These associations emphasize the important role of agricultural enterprises and cooperatives in promoting more efficient fertilizer use across different fertilizer types.

6. Conclusion and policy implication

Smallholder farming in China, characterized by land fragmentation, limited mechanization, and low technology adoption, often leads to excessive use of chemical fertilizers. APOs have been proposed as potential solutions for transforming smallholder farming toward sustainable agriculture. While previous studies have provided evidence of the relationship between APOs and smallholders' welfare, little is known about the role of APOs in fertilizer use, especially when considering both their independent associations and their interaction with smallholders. This paper contributes to the understanding by examining whether and how different forms of APO are associated with fertilizer use at the county level.

Drawing on county-level panel data with detailed business registry data of three types of APOs, our IV estimates show that agricultural enterprises and cooperatives are associated with lower levels of fertilizer use at the county level. However, we do not find a significant and negative association between family farms and fertilizer use. The mechanism analysis suggests that these associations are linked to higher levels of agricultural mechanization, land consolidation, and influences on smallholders' fertilizer inputs. Heterogeneity analysis indicates that agricultural enterprises show stronger associations with lower fertilizer use in areas with more extensive land transfer, advanced fertilization techniques, and in the eastern and plain regions. Leveraging their governance structure advantage, agricultural cooperatives consistently show negative associations with fertilizer use regardless of land transfer, fertilization techniques, and topography constraints.

China is the largest consumer of chemical fertilizers globally, with average chemical fertilizer use per hectare of cropland significantly exceeding the recommended threshold of 225 kg/ha. Our results indicate that a 10% increase in the number of agricultural enterprises and cooperatives at the county level is associated with a 1.59% and 1.57% decrease in county-level fertilizer use, respectively. A reduction of this magnitude could make a significant contribution to China's national strategy of "Zero Growth in Synthetic Fertilizer Use" from 2015 to 2020 and the ongoing "Fertilizer Reduction Action Plan" for 2025.

Smallholder farming is prevalent worldwide, particularly in developing countries (Foster & Rosenzweig, 2022), where smallholder farmers may face challenges similar to those encountered in China. Our findings highlight the positive role of agricultural enterprises and cooperatives in reshaping smallholder farming toward green transformation, which provides insights for policymakers and practitioners seeking to address environmental issues related to smallholder farming. First, policy interventions such as subsidies and credit incentives, could be implemented to encourage greater participation of APOs in sustainable agricultural practices. These interventions should also take into

[9] Provincial level land transfer area refers to the total area of contracted farmland transferred by rural households under legal and voluntary principles. These land transfers occur primarily through rental agreements or equity arrangements (e.g., shareholding), where households transfer their agricultural management rights to other operators. The transfer area includes both government-led and market-driven land transactions. This data is sourced from the China Rural Management Statistics Annual Report.

[10] Here we use deep fertilizer application technique to measure advanced fertilization technique. Deep fertilizer application refers to applying a specified amount of fertilizer evenly at a depth of 6–10 cm below the soil surface, targeting areas where crop roots are most concentrated. This method enhances fertilizer use efficiency by promoting better absorption and minimizing volatilization and nutrient loss.

Table 8
Heterogenous associations in different types of fertilizer use.

	(1)	(2)	(3)	(4)
	Log (N fertilizer)	Log (K fertilizer)	Log (P fertilizer)	Log (Compound fertilizer)
Panel A: Agricultural Enterprise				
Log (#AgrEnterprise + 1)	−0.1782***	−0.0726	−0.0956	−0.1467**
	(0.0682)	(0.0668)	(0.0662)	(0.0651)
Observations	10,860	10,860	10,860	10,860
Number of Clusters	1,393	1,393	1,393	1,393
KP Wald *F*-statistic	230.7	230.7	230.7	230.7
Panel B: Agricultural Cooperative				
Log (#Cooperative + 1)	−0.1361***	−0.1469***	−0.1818***	−0.1727***
	(0.0387)	(0.0385)	(0.0374)	(0.0376)
Observations	10,860	10,860	10,860	10,860
Number of Clusters	1,393	1,393	1,393	1,393
KP Wald *F*-statistic	588.4	588.4	588.4	588.4
Panel C: Family Farm				
Log (#Farm + 1)	0.0212	−0.0897*	0.0029	−0.0779
	(0.0581)	(0.0503)	(0.0473)	(0.0602)
Observations	2,902	2,902	2,902	2,902
Number of Clusters	1,015	1,015	1,015	1,015
KP Wald *F*-statistic	85.68	85.68	85.68	85.68
Control Variables	YES	YES	YES	YES
County FE	YES	YES	YES	YES
Year FE	YES	YES	YES	YES

Notes: Log (N fertilizer), Log (K fertilizer), Log (P fertilizer), and Log (Compound fertilizer) represent the logarithms of nitrogen, potassium, phosphorus, and compound fertilizers, respectively. In Panels A, B, and C, Log (#AgrEnterprise + 1), Log (#Cooperative + 1), and Log (#Farm + 1) denote the logarithms of the number of agricultural enterprises, agricultural cooperatives, and family farms with an additional unit of 1, respectively. Panels A and B report results for the period 2007–2015, while Panel C presents results for 2013–2015. All model specifications including control variables and fixed effects are in line with the baseline. Standard errors are clustered at the county level and are listed in parentheses. ***$p < 0.01$, **$p < 0.05$, *$p < 0.1$.

account spatial differences and geographical characteristics. Second, our mechanism analysis implies the importance of the adoption of machinery and fertilization technologies in reducing fertilizer overuse. Investment in agricultural technology and innovation may therefore serve as potential policy instruments for sustainable agriculture. Additionally, our results also provide evidence that land consolidation may be conducive to agriculture sustainability. Institutional innovations that reduce the transition cost of land transfer could further facilitate APO development and promote large-scale farming, sustainable farming.

Finally, some limitations to this study should be noted. First, because regulatory oversight and the availability of financial subsidies are limited, some cooperatives may be established primarily to capture external financial support in China, raising concerns about the prevalence of so-called "fake" cooperatives (Michalek et al., 2018). Our empirical analysis does not explicitly address this issue due to the lack of a unified definition and the absence of data on "fake" cooperatives during our study period (2007–2015). Although recent studies have proposed identifying fake cooperatives using annual reports, regulatory sanctions, and operational irregularities (Zhong et al., 2023), such data are only available after 2014. Existing studies also suggests modest limited regional variation in their incidence (Liang et al., 2024). We therefore consider that the number of registered cooperatives can still serve as a reasonable proxy for APO development. Second, China's APOs are evolving and increasingly featured with hybrid organizational forms that combine agricultural enterprises, cooperatives, and family farms. However, data on these hybrid types are not yet available, preventing us from examining how such organizational forms related to fertilizer use. Future research should revisit this question when data become accessible.

CRediT authorship contribution statement

Meng Xu: Writing – review & editing, Writing – original draft, Visualization, Methodology, Formal analysis, Data curation, Conceptualization. **Xiaoxi Wang:** Writing – review & editing, Writing – original draft, Visualization, Methodology, Funding acquisition, Formal analysis, Data curation, Conceptualization, Validation. **Kevin Chen:** Writing – review & editing, Funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A

Table A1
Robustness checks with controlling for the crop portfolio changes.

	(1)	(2)	(3)
	Log (Fertilizer)		
Panel A: Agricultural Enterprise			
Log (#AgrEnterprise + 1)	−0.1385**	−0.1392**	−0.1583**
	(0.0650)	(0.0655)	(0.0657)
Observations	10,860	10,860	10,860
Number of Clusters	1,393	1,393	1,393
KP Wald *F*-statistic	220	200.4	238.7
Panel B: Agricultural Cooperative			
Log (#Cooperative + 1)	−0.1461***	−0.0306**	−0.1458***
	(0.0344)	(0.0128)	(0.0344)
Observations	10,860	10,860	10,860
Number of Clusters	1,393	1,393	1,393
KP Wald *F*-statistic	587.1	180.1	323
Panel C: Family Farm			
Log (#Farm + 1)	−0.0120	−0.0142	−0.0021
	(0.0350)	(0.0353)	(0.0371)
Observations	2,902	2,902	2,902
Number of Clusters	1,015	1,015	1,015
KP Wald *F*-statistic	98.69	84.55	76.29
Ratio of Provincial-Level Food Crops Area	YES	YES	NO
Ratio of Provincial-Level Vegetables Area	YES	NO	YES
Control Variables	YES	YES	YES
County FE	YES	YES	YES
Year FE	YES	YES	YES

Notes: In Panels A, B, and C, Log (#AgrEnterprise + 1), Log (#Cooperative + 1), and Log (#Farm + 1) denote the logarithms of the number of agricultural enterprises, agricultural cooperatives, and family farms with an additional unit of 1, respectively. Panels A and B report results for the period 2007–2015, while Panel C presents results for 2013–2015. All model specifications including control variables and fixed effects are in line with the baseline. Standard errors are clustered at the county level and are listed in parentheses. ***$p < 0.01$, **$p < 0.05$, *$p < 0.1$.

Table A2
Temporal robustness of the associations between agricultural enterprises and cooperatives and fertilizer use.

	(1)	(2)	(3)	(4)	(5)	(6)
	Log (Fertilizer)					
Panel A: Agricultural Enterprise						
Log (#AgrEnterprise + 1)	−0.1469**	−0.1554***	−0.1549***	−0.2410***	−0.4580***	0.0160
	(0.0613)	(0.0592)	(0.0564)	(0.0666)	(0.1363)	(0.0791)
Observations	9,497	8,122	6,725	5,404	4,101	2,902
Number of Clusters	1,383	1,351	1,279	1,213	1,117	1,015
KP Wald *F*-statistic	215.7	200.5	170.8	127.8	52.29	93.87
Panel B: Agricultural Cooperative						
Log (#Cooperative + 1)	−0.2401***	−0.4664***	−0.4591***	−0.4631***	−0.3635***	0.3597***
	(0.0577)	(0.0833)	(0.0855)	(0.0996)	(0.1113)	(0.1023)
Observations	9,497	8,122	6,725	5,404	4,101	2,902
Number of Clusters	1,383	1,351	1,279	1,213	1,117	1,015
KP Wald *F*-statistic	281.4	239.4	220.5	183.7	176.1	146.7
Time Period	2008–2015	2009–2015	2010–2015	2011–2015	2012–2015	2013–2015
Control Variables	YES	YES	YES	YES	YES	YES
County FE	YES	YES	YES	YES	YES	YES
Year FE	YES	YES	YES	YES	YES	YES

Notes: In Panels A and B, Log (#AgrEnterprise + 1) and Log (#Cooperative + 1) denote the logarithms of the number of agricultural enterprises, and agricultural cooperatives with an additional unit of 1, respectively. All model specifications including control variables and fixed effects are in line with the baseline. Standard errors are clustered at the county level and are listed in parentheses. ***$p < 0.01$, **$p < 0.05$, *$p < 0.1$.

Table A3
Heterogeneity analysis with regard to land transfer and fertilization techniques.

	(1)	(2)
	Log (Fertilizer)	
	By land transfer	By fertilization techniques
Panel A: Agricultural Enterprise		
Log (#AgrEnterprise + 1)	−0.2296***	−0.1293**
	(0.0829)	(0.0609)
Log (#AgrEnterprise + 1)× Land Transfer	−0.1556**	
	(0.0702)	
Log (#AgrEnterprise + 1)× Fertilization Techniques		−0.1306***
		(0.0405)
Observations	10,860	10,860
Number of Clusters	1,393	1,393
KP Wald *F*-statistic	60.10	133.8
Panel B: Agricultural Cooperative		
Log (#Cooperative + 1)	−0.1650***	−0.1572***
	(0.0361)	(0.0380)
Log (#Cooperative + 1)× Land Transfer	0.0161	
	(0.0113)	
Log (#Cooperative + 1)× Fertilization Techniques		−0.0085
		(0.0125)
Observations	10,860	10,860
Number of Clusters	1,393	1,393
KP Wald *F*-statistic	291.6	289.9
Panel C: Family Farm		
Log (#Farm + 1)	−0.0758	−0.0081
	(0.0695)	(0.0417)
Log (#Farm + 1)× Land Transfer	0.0353	
	(0.0240)	
Log (#Farm + 1)× Fertilization Techniques		−0.0052
		(0.0199)
Observations	2,902	2,893
Number of Clusters	1,015	1,012
KP Wald *F*-statistic	19.35	33.95
Group Dummy Variables	YES	YES
Control Variables	YES	YES
County FE	YES	YES
Year FE	YES	YES

Notes: In Panels A, B, and C, Log (#AgrEnterprise + 1), Log (#Cooperative + 1), and Log (#Farm + 1) denote the logarithms of the number of agricultural enterprises, agricultural cooperatives, and family farms with an additional unit of 1, respectively. Panels A and B report results for the period 2007–2015, while Panel C presents results for 2013–2015. Group dummy variables represent the dummy variables of regions with large land transfer areas, and advanced fertilization techniques in the regressions. All model specifications including control variables and fixed effects are in line with the baseline. Standard errors are clustered at the county level and are listed in parentheses. ***$p < 0.01$, **$p < 0.05$, *$p < 0.1$.

Table A4
Heterogeneity analysis with regard to regions and topography.

	(1)	(2)
	Log (Fertilizer)	
	By regions	By topography
Panel A: Agricultural Enterprise		
Log (#AgrEnterprise + 1)	−0.2374***	−0.1720***
	(0.0726)	(0.0640)
Log (#AgrEnterprise + 1)× East	−0.2450***	
	(0.0753)	
Log (#AgrEnterprise + 1)× Plain		−0.1452***
		(0.0417)
Observations	10,860	10,860
Number of Clusters	1,393	1,393
KP Wald *F*-statistic	73.39	76.60
Panel B: Agricultural Cooperative		
Log (#Cooperative + 1)	−0.1618***	−0.1474***
	(0.0359)	(0.0377)
Log (#Cooperative + 1)× East	−0.0258*	
	(0.0152)	
Log (#Cooperative + 1)× Plain		−0.0165
		(0.0115)
Observations	10,860	10,860
Number of Clusters	1,393	1,393
KP Wald *F*-statistic	266.6	291.3
Panel C: Family Farm		
Log (#Farm + 1)	−0.0128	−0.0085
	(0.0378)	(0.0397)
Log (#Farm + 1)× East	−0.0336*	
	(0.0180)	
Log (#Farm + 1)× Plain		−0.0018
		(0.0152)
Observations	2,902	2,902
Number of Clusters	1,015	1,015
KP Wald *F*-statistic	44.29	47.28
Group Dummy Variables	YES	YES
Control Variables	YES	YES
County FE	YES	YES
Year FE	YES	YES

Notes: In Panels A, B, and C, Log (#AgrEnterprise + 1), Log (#Cooperative + 1), and Log (#Farm + 1) denote the logarithms of the number of agricultural enterprises, agricultural co-operatives, and family farms with an additional unit of 1, respectively. Panels A and B report results for the period 2007–2015, while Panel C presents results for 2013–2015. Group dummy variables represent the dummy variables of regions with east region, and plain area in the re-gressions. All model specifications including control variables and fixed effects, are in line with the baseline. Standard errors are clustered at the county level and are listed in parentheses. ***$p < 0.01$, **$p < 0.05$, *$p < 0.1$.

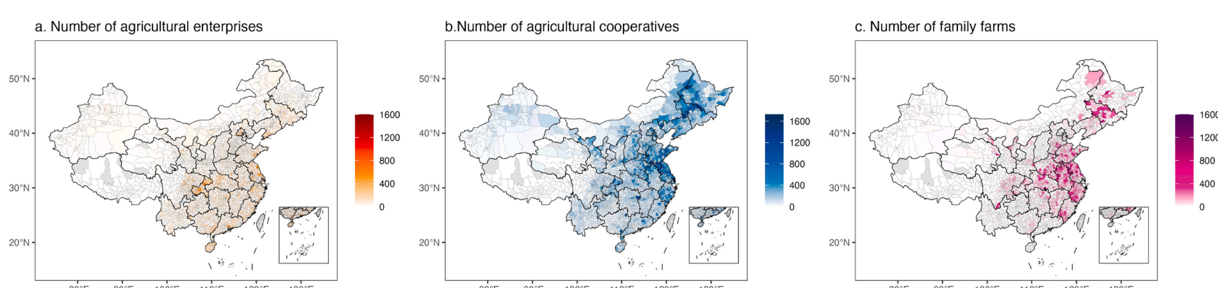

Fig. A1. Spatial distribution of the average number of agricultural enterprises, agricultural cooperatives, and family farms. *Notes*: Figures a and b show the average number of agricultural enterprises and cooperatives from 2007 to 2015, while figure c presents the average number of family farms between 2013 and 2015. Black polygons indicate provincial boundaries, and grey polygons mark county boundaries. Counties shaded in grey represent missing data, while counties shaded in white represent zero.

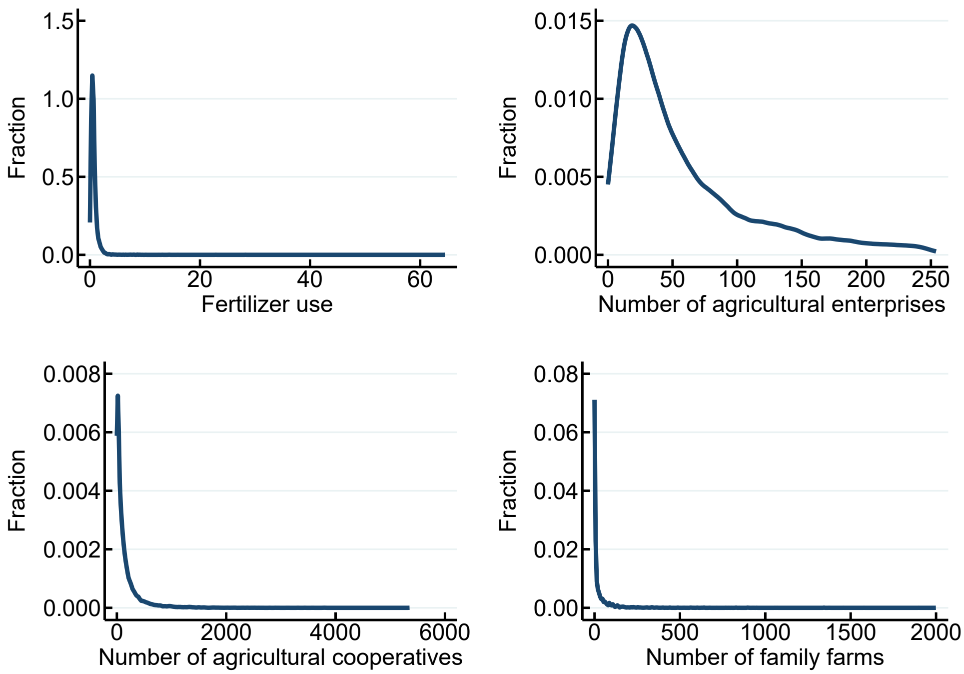

Fig. A2. Density plot of fertilizer use and the number of agricultural production organizations at the county level

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