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Farm size and pesticide use: evidence from agricultural production in China

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Abstract

Purpose – China is the world's largest consumer of pesticides. To increase the use efficiency and achieve more sustainable and environmentally friendly use of pesticides in China, it is crucial to understand why Chinese farmers use such a large amount of pesticides.

Design/methodology/approach – The relationship between farm size and pesticide use was investigated by using national household-level panel data from 1995 to 2016.

Finding – Farms that are small and fragmented lead to the use of large amounts of pesticides in China. For a given crop type, three factors contribute to a negative relationship between farm size and pesticide use: the spillover effect from the use of pesticides by other farmers in the same village, the level of mechanization and the management ability of farmers. The first two factors play important roles in the cultivation of grain crops, while the last factor is the main reason why farmers with larger plots of land use fewer pesticides in the cultivation of vegetables. In addition, the effect of agricultural machinery services on reducing the use of pesticides is currently limited, and the service system in China is still insufficient, which has been pointed out that it is also due to the prevalence of small and fragmented farms.

Originality/value – The authors investigate and compare the farm size–pesticide use relationship in both grain and cash crop production. Moreover, the authors systematically explore and explain how farm size is related to a reduction in pesticide use in the cultivation of grain crops and cash crops. These results can help to better understand the role of land scale in pesticide use, lay a foundation for the formulation of policies to reduce pesticide use and provide valuable knowledge about pesticide use for other developing countries around the world.

Keywords Farm size, Pesticide use, Land fragmentation, Mechanization, Agricultural machinery services

Paper type Research paper

1. Introduction

Chemical pesticides are widely used inputs in modern agricultural production and play a significant role in ensuring stable and high yields of agricultural products. However, their

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extensive use has resulted in various problems in many developing countries, such as threats to food safety and human health and environmental pollution, especially in China (Lai, 2017; Hu *et al.*, 2015; Liu *et al.*, 2012; Snelder *et al.*, 2008).

According to the FAO data, China has the largest pesticide consumption in the world, with a use level that is well above the global average. Unreasonable use (mainly overuse) and low use efficiency are commonly found in China (Zhang *et al.*, 2015). In recent years, the Chinese government has recognized these issues and has begun to try to reduce the use of pesticides. However, the national average usage was still 9.95 kg/hm^2 in 2017, which was 3.78 times the global average in the same period. To increase the use efficiency and achieve more sustainable and environmentally friendly use of pesticides in China, it is crucial to understand why Chinese farmers use such a large amount of pesticides.

Many studies have focused on the factors affecting farmers' use of pesticides. The risk preference of farmers is generally considered to play an important role in pesticide use decision-making (Gong *et al.*, 2016; Liu and Huang, 2013). Some research also indicates that pesticide use is associated with misperception, the price of agricultural products and pesticides, household income, labor input and even the gender of farmers (Zhang *et al.*, 2019a; Wang and Gu, 2013; Schreinemachers and Tipraqsa, 2012; Dasgupta *et al.*, 2007; Atreya, 2007). However, there seems to be no evidence that Chinese farmers are more risk-averse than farmers in other countries or that there are any significant differences in perceptions, labor inputs and other factors. In addition to these factors, certain policy tools, such as subsidies, have also been found to be related to pesticide use (Goodhue and Klonsky, 2010; Templeton and Jamora, 2010; Serra *et al.*, 2005). While the analysis by Huang *et al.* (2011) shows that agricultural subsidies in China do not distort farmers' input use decisions. Therefore, the above factors still do not fully explain the higher use of pesticides in China than in other countries. Besides these, one possible explanation is the relatively widespread occurrence of significantly small farms in China. A number of studies revealed that farm size is critically associated with lower agricultural production costs and different input choices (Sheng *et al.*, 2019; Zhang *et al.*, 2019b; Hiironen and Riekkinen, 2016). Wu *et al.* (2018) and Zhu and Wang (2021) show that farm size is a strong factor influencing the use of agricultural chemicals among producers of grain crops in China. However, it is still unclear whether the relationship between farm size and pesticide use differs between grain crops and cash crops and how farm size reduces pesticide use.

In this article, we investigate the relationship between farm size and pesticide use across five different crops, which includes three major grain crops (wheat, rice and maize) and two types of cash crops (vegetables and fruits), by using household-level data since 1995. Our interest is in understanding how the farm size affects farmers' pesticide use in the production of different crops in China. The data we used covers about 20,000 rural households in over 300 villages across 31 provinces in Mainland China each year. We use survey data from National Rural Fixed Observation Points (NRFOP), which contains abundant production information at the household level, allowing us to assess the impact and explore the mechanism after controlling for other variables as comprehensively as possible.

Our paper makes the following contributions to the existing literature. First, we further examine the farm size–pesticide use relationship in cash crop production. Second, we systematically explore and explain how farm size reduces pesticide use for grain and cash crops. Differences in the external influence of other farmers in the same village, mechanization and farmers' management abilities are found to explain the relationship. The first two contribute to the negative association between farm size and pesticide use in grain crop production. While for vegetables, the last one is the main reason, which leads to the negative relationship between farm size and pesticide use.

The rest of the paper is organized as follows. Section 2 is the data set description; Section 3 describes the basic facts about pesticide use and farm size in China; Section 4 introduces our theoretical framework and empirical strategy; regression results and the interpretation are presented in Section 5; Section 6 provides a further discussion of our findings; and Section 7 is the conclusion.

2. Data

We use the data from NRFOP, which are collected by the Research Center of Rural Economy (RCRE) of the Chinese Ministry of Agriculture and Rural Affairs. This tracking survey began in 1986 and included both village-level data and household-level data. It covers about 20,000 rural households in over 300 villages across 31 provinces in Mainland China each year. The sample households were all randomly selected as the fixed observation points and surveyed subsequently until household members could not be tracked because of immigration, death or other reasons (Xu *et al.*, 2012). The survey collects comprehensive information on their economic activities. Benjamin Brandt and Giles (2005) provide a detailed discussion of the data and show evidence that the data are of high quality by comparing it to the agricultural census from the National Bureau of Statistics (NBS). Due to these advantages of wide coverage, large sample size and abundant indicators, NRFOP data are considered to be relatively representative and thus have been used in various empirical studies (Chari *et al.*, 2021; Yang *et al.*, 2016; Glauben *et al.*, 2012; Giles and Yoo, 2007; Yao, 2006). The particular advantage of the data for our study is the detailed information on agricultural inputs and outputs for continuous years at the household-crop level, which allows us to perform a more specific analysis. In this paper, we use household-level panel data from 1995 to 2016. Since the production data of different crops began in 2003, the time period of relevant analysis is from 2003 to 2016. After dropping the outliers and missing values, the final unbalanced sample includes approximately 10,000 households per year.

3. Pesticide use and farm size in China

From 2003 to 2008, the average pesticide use per hectare by Chinese farmers increased from 23.10 kg to 27.60 kg and then remained relatively stable until 2015 (Table 1). The usage was 26.85 kg/ha in 2016, which was slightly less than that in previous years. However, it was still larger than the global average, which was only 2.58 kg/ha for the same year (FAO, 2016). The average price of pesticides continued to rise, increasing by 70.46% in 2016 from 2003. Moreover, the pesticide input to cropland per hectare for cash crops was clearly greater than that for grain crops.

As shown in Table 2, the average farm size across rural households in China was approximately 0.60 ha between 1995 and 2016. Although there has been an increase in farm

Year	Total (kg/ha)	Wheat (kg/ha)	Rice (kg/ha)	Maize (kg/ha)	Vegetables (kg/ha)	Fruit (kg/ha)	Price (yuan/kg)
2003	23.10	8.70	20.10	10.35	35.55	52.95	19.84
2004	24.45	9.30	21.60	10.35	34.20	51.15	21.56
2005	26.25	9.15	24.00	10.20	35.25	59.55	22.90
2006	27.15	9.60	24.45	11.25	35.85	67.50	24.01
2007	27.45	9.75	25.20	11.10	37.35	69.00	25.65
2008	27.60	10.05	25.80	11.40	37.80	68.25	27.99
2009	27.60	10.05	24.75	12.00	38.10	72.75	28.34
2010	27.75	10.50	25.50	12.45	38.85	74.25	29.79
2011	27.30	10.65	25.65	12.30	39.75	76.05	30.97
2012	27.75	12.00	26.10	13.65	41.40	82.95	32.08
2013	27.30	12.30	26.55	13.50	42.00	81.15	33.08
2014	27.60	12.30	27.45	13.50	43.20	81.60	33.75
2015	27.45	12.75	27.15	14.10	44.40	83.70	34.33
2016	26.85	13.20	27.60	13.80	44.70	85.35	33.82

Note(s): Price is the average price of pesticide bought by farmers
Source(s): NRFOP dataset (2003–2016)

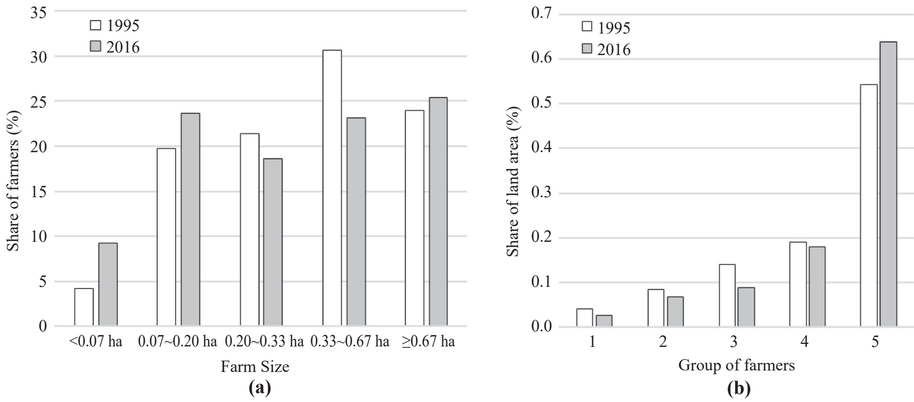
Table 1.
Pesticide use and price in China

Year	Farm size(ha)	Total	Number of parcels of different sizes <0.07 ha	0.07–0.20 ha	0.20–0.33 ha	≥0.33 ha
1995	0.58	5.65	2.19	0.54	0.06	0.17
2000	0.57	5.35	1.99	0.46	0.07	0.16
2005	0.59	5.09	2.12	1.14	0.24	0.18
2006	0.58	5.10	2.07	1.12	0.25	0.18
2007	0.59	5.00	2.00	1.09	0.25	0.18
2008	0.60	4.88	1.89	1.06	0.25	0.18
2009	0.60	4.84	1.80	1.05	0.25	0.17
2010	0.59	4.81	1.79	0.99	0.25	0.17
2011	0.62	4.81	1.77	0.99	0.26	0.17
2012	0.65	4.67	1.60	0.96	0.25	0.17
2013	0.65	4.63	1.56	0.91	0.24	0.17
2014	0.67	4.60	1.45	0.85	0.24	0.17
2015	0.67	4.55	1.41	0.81	0.24	0.15
2016	0.67	4.60	1.39	0.81	0.23	0.15
Total	0.60	5.09	1.88	0.82	0.18	0.17

Source(s): NRFOP dataset (1995–2016)

Table 2. Farm size and the number of parcels at the household level

size since 2011, it was still only 0.67 ha in 2016. Specifically, as shown in Figure 1a, the share of farmers who held land areas greater than 0.67 ha increased during the 22-year period (from 23.96% in 1995 to 25.39% in 2016), which exceeded that of farmers holding land areas of 0.33–0.67 ha in 2016. However, the share of farmers with less than 0.20 ha also increased substantially, reaching 32.90% in 2016. In particular, 9.25% of farmers still held land areas less than 0.07 ha. This share increased by 120.24% compared to 1995. In addition, the share of the total land area held by the top 20% of farmers with the largest land area increased from 54.36% in 1995 to 63.74% in 2016, while the remaining 80% of farmers' share of the land decreased significantly in the same time period (Figure 1b). Therefore, the size difference between Chinese farmers' land areas is increasing significantly. Overall, the farm size among rural households in China is still too small. Chinese cropland is still dominated by smallholder farms. Almost three-quarters of the farmers' land size was less than 0.67 ha.



Note(s): Each group in panel B represents 20% of farmers ranked by farm size; for example, group 5 represents the top 20% of farmers by land area
Source(s): NRFOP dataset (1995-2016)

Figure 1. Farm size and distribution of cropland in 1995 and 2016

Table 2 also illustrates the annual average number of land parcels held by a sample household. Land fragmentation in China has decreased slightly during these years. However, the average number of parcels per household was still 4.60 in 2016, and most parcels were less than 0.07 ha. The average number of parcels larger than 0.33 ha per household remained roughly unchanged from 1995 to 2016, when the latest number was only 0.15. For farmers who held land areas greater than 0.67 ha, their land was also fragmented, as shown in Table 3. They had 5.84 plots on average in 2016. Most of the parcels were less than 0.20 ha. Specifically, we focused on two typical provinces with totally different geographical characteristics, Guizhou Province (GZ) and Jiangsu Province (JS) [1]. It is obvious from the data that even in JS, the number of parcels within large-scale farms (having a total land area of more than 0.67 ha) was also quite large, and the majority of their land parcels were small in size. Therefore, these data indicate that the fragmentation of cropland is still prevalent in China. Even for farmers with relatively larger farm sizes, their land was still "large but fragmented."

Figure 2 plots the relationship between the intensity of pesticide use and farm size by percentile. There is an obvious negative correlation between them. This phenomenon suggests that the use intensity of pesticides in China may be reduced by enlarging the land scale of smallholders. We then further empirically examine the impact of farm size on farmers' pesticide use and the mechanism in the following section.

4. Methods

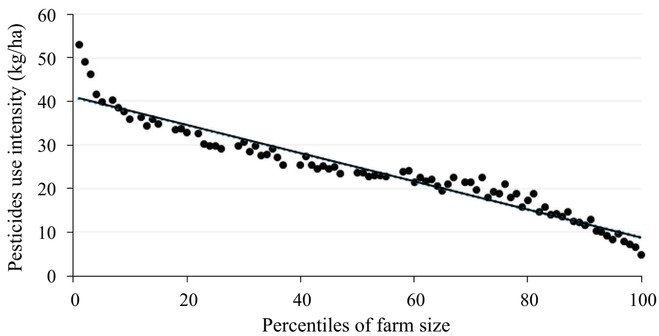
4.1 Theoretical framework

Many studies (Fox and Weersink, 1995; Pannell, 1990; Lichtenberg and Zilberman, 1986) have shown that pesticides act through an indirect mechanism on farm output, and it is better to use the damage-abatement production function, which represents a two-stage process in

Year		1995			2016	
Region	NW	JS	GZ	NW	JS	GZ
Total	6.12	4.88	10.96	5.84	4.98	7.82
Less than 0.07 ha	1.17	1.38	8.20	1.16	1.72	4.82
0.07–0.20 ha	1.29	0.88	0.71	1.62	2.10	2.18
0.20–0.33 ha	0.23	0.35	0.00	0.96	0.84	0.40
More than 0.67 ha	0.72	0.35	0.00	0.84	0.49	0.09

Note(s): NW, JS and GZ represent nationwide, Jiangsu Province and Guizhou Province, respectively
Source(s): NRFOP dataset (1995–2016)

Table 3. The number of parcels for large-scale farmers



Source(s): NRFOP dataset (1995-2016)

Figure 2. Distribution of pesticide use on different scale farms in China

which pesticides affect yields by killing pests. The model was widely used in later related studies (Wang and Gu, 2013; Skevas *et al.*, 2012; Huang, *et al.*, 2002). According to these studies and the actual production situation in China, our previous work (Gao and Shi, 2019) has extended the general form of the damage-abatement production function slightly to analyze the impact of some rural households and individual characteristics on their pesticide use. Based on these, our theoretical model is constructed as follows:

$$y_0 = f(x_1, x_2, \ldots) \tag{1}$$

$$y = (1-\lambda)y_0 + \lambda y_0[1 - D(Z)] \tag{2}$$

$$D(Z) = bZ, \; b \in (0, 1) \tag{3}$$

$$Z = Z_0[1 - C(T)] \tag{4}$$

$$C(T) = 1 - e^{-cT} \tag{5}$$

$$I = \theta p_y y - P_X X - p_t T, P_X = (p_1, p_2, \ldots), X = (x_1, x_2, \ldots)' \tag{6}$$

where y_0 is the output per unit area that would be obtained with no pest or other disease damage, and y is the actual production for a given pest density Z. λ is the probability of pest damage. $D(Z)$ is the damage function representing the lost proportion of output at damage level Z, which is a linear function with coefficient b for the sake of analysis. Z_0 is the pretreatment pest density. $C(T)$ is the control function for a given pesticide use level T, which is usually represented as an exponential form. Profit I is given by Eqn (6), where θ is the proportion of output for selling, p_y is the price of output and p_t is the pesticide price. X is the vector of input per unit area of x_1, x_2 and other production factors except land. P_x is the vector of the price of these input factors. Finally, the optimal pesticide use T^* can be measured by the following equation:

$$\theta p_y y_0 \lambda b Z_0 c e^{-cT^*} = p_t \tag{7}$$

With constant relative risk aversion, damage level and inputs, the theoretical study seems to imply that there is no direct relationship between farm size and the optimal pesticide use. However, the actual use of pesticides may be associated with farm size through several variables:

The first is λ, which is correlated with the crop type and then to farm size. This is because the incidence rates in grain crops are usually lower than those in cash crops, and large-scale cultivation is mostly for the former. The negative relationship between pesticide use and farm size found in the real case above may be partly due to this reason.

Second, Z_0 and p_y both have a direct positive effect on farmers' pesticide use for a given crop. A specific farmer's cognition and judgment of pest level Z_0 and the expected selling price p_y are affected by the pesticide use of other farmers in the same village. Thus, a farmer's pesticide use is affected by others' use. A previous study noted that there are input spillover effects among farmers' inputs (Guo and Marchand, 2019). Moreover, we think the influence may vary with the farmers' own farm size for two reasons. The first reason is based on the motivation for farmers to ensure their own yields. If others use a certain number of pesticides, the farmer who plants crops mainly for sale usually tends to overestimate Z_0 and then at least use a similar amount of pesticide to prevent his/her farm from becoming a "paradise for pests," thus suffering a greater yield loss than other farms. Hence, there may be a positive relationship between the pesticide use of farmers and other farmers in the same village. This external influence from others may decrease with the increase of a farmer's own farm size because the farmers' cognition and judgment of Z_0 are also closer to the objective facts about pest density at the same time.

However, for a farmer whose farm size is extremely small, he/she also has the possibility to be a free rider – use less or even does not use because the others have already sprayed the adjacent farmland with pesticides. Thus, the relationship between the external effect of others' pesticide use and farmers' own farm size may be an inverse U-shaped curve. The second reason is because of the motivation to ensure income. For crops planted in greenhouses, their pesticide use is not affected by the externality detailed above. However, the positive impact of others' use still exists because of farmers' expectations of their products' selling price p_y. If farmers use fewer pesticides than others, their product appearance may be relatively poor, resulting in a lower selling price. In this case, small-scale farmers are also more vulnerable due to the lack of market bargaining power and marketing channels. Therefore, compared to large-scale farmers, they have an incentive to use more pesticides to ensure their sales revenue. However, farmers whose farm size is extremely small may also use less pesticides because the produce is mainly for their own consumption rather than for sale. Thus, in this case, the relationship between the external effect and farm size may still be an inverse U-shaped curve.

Finally, the actual pesticide use of farmers T is often larger than the optimal value T^*. In the process of pesticide spraying, losses and waste inevitably occur, which cause farmers to apply pesticides beyond the optimal point. Utilization efficiency depends on the level of mechanization and farmers' ability (the management ability of farmers may also affect pesticide use by decreasing the incidence of pests λ). In this case, large-scale farmers are more able to adopt more advanced pesticide spraying technology (such as using agricultural drones) and are more knowledgeable, which can reduce pesticide use by increasing use efficiency. In fact, our field research found that smallholder farmers often use simple spraying equipment for single use or homemade equipment due to the cost constraints of purchasing. This equipment is inexpensive but will lead to considerable loss and waste, as well as an increase in pesticide use. Thus, due to the high level of mechanization and management ability, large-scale farmers' pesticide use may be relatively closer to T^* and less than that of small-scale farmers.

4.2 Empirical model specification and variable definitions

The two most important variables used in our study are pesticide use per hectare and farm size. According to the theoretical framework and previous literature, the baseline empirical model is set in the following form:

$$\text{In}Q_{it} = \beta_0 + \beta_1 \text{In land}_{it} + \beta_2 \text{simpson}_{it} + \sum_{m=3}^{M} \beta_m \text{Controls}_{it} + \gamma_t + f_i + \varepsilon_{it} \quad (8)$$

where Q_{it} denotes pesticide use per cropland area here, and land_{it} denotes farm size as cropland area held by rural households. As previously mentioned, a high level of cropland fragmentation is prevalent in China. It affects the size of land parcels. To identify this effect on pesticide use, we add the Simpson land fragmentation index into the regression, which is denoted by simpson_{it}. This index is widely used to measure the level of land fragmentation (Knippenberg *et al.*, 2020; Ali *et al.*, 2019). Other variables to be controlled in the model include prices of pesticides and agricultural products, the share of off-farm household labor, fertilizer use intensity, the mode of product sales and land type. Considering that the share of off-farm household labor may affect the role of farm size, a decentralized interaction term was added into the regression to control for this. We also control for some farmers' characteristics that may affect their pesticide use, which include the social position, technical training background, education background and age of the household head [2]. The term f_i represents household fixed effects, which control for the other farm-specific characteristics that do not change over time, such as terrain. The term γ_t represents year fixed effects and is used to capture macrotechnological progress, weather variations and other time-variant factors. The descriptive statistics for all variables are presented in Table 4.

Variable	Mean	Std. dev
Pesticide use intensity (kg/ha)	23.85	1.75
Cropland area (ha)	0.60	12.65
Simpson land fragmentation index	0.65	0.26
Pesticides' price (yuan/kg)	24.93	17.30
Price index of agricultural products (1994 = 100)	138.47	41.83
Share of off-farm household labor	0.35	0.35
Fertilizer use intensity (kg/ha)	1547.10	83.63
Mode of product sales	0.95	0.21
Land type	1.66	0.49
Social position of household head	0.05	0.26
Technical training background of the household head	0.12	0.33
Education background of the household head (year)	7.49	2.64
Age of the household head	52.68	11.00

Source(s): Authors' estimation using the NRFOP data (1995–2016)

Table 4. Description of major variables

In addition, we tested whether the relationship between farm size and pesticide use differs across crops. We focus on three major grain crops (wheat, rice and maize) and two major types of cash crops (vegetables and fruits) and estimate each crop individually. In the new regression, the sowing area of each crop is used to measure farm size. Pesticide use is thus defined as the amount of pesticide use per sowing area here and in later regressions. Among the control variables, we use the actual selling price of each crop to replace the price index and the share of days that labor engages in off-farm work to replace the share of off-farm work labor. We also further include the proportion of each agricultural product sold into the baseline model [3], which is denoted by sales_{it}. The model specifications are as follows:

$$\text{In}Q_{it} = \beta_0 + \beta_1 \text{In}\,\text{sowing area}_{it} + \beta_2 \text{simpson}_{it} + \beta_3 \text{sales}_{it} + \sum_{m=4}^{M} \beta_m \text{Controls}_{it} + \gamma_t + f_i + \varepsilon_{it} \tag{9}$$

Then, we investigated the relationship between farm size and the external effect of other pesticide uses to explore the role of farm size on pesticide use. Based on the analysis above, farmers' pesticide use may be affected by the pesticide use of other farmers in the same village, and the potential relationship between this external effect and farm size may be nonlinear. To test these effects, we add three new variables into Eqn (9) [4]. The model specifications are as follows:

$$\begin{aligned}\text{In}Q_{it} = {} & \beta_0 + \beta_1 Q'_{it} + \beta_2 \text{In}\,\text{sowingarea}_{it} \times \text{In}Q'_{it} + \beta_3 (\text{In}\,\text{sowingarea}_{it})^2 \times \text{In}Q'_{it} \\ & + \beta_4 \text{In}\,\text{sowing area}_{it} + \beta_5 \text{simpson}_{it} + \sum_{m=6}^{M} \beta_m \text{Controls}_{it} + \gamma_t + f_i + \varepsilon_{it}\end{aligned} \tag{10}$$

where Q'_{it} denotes the pesticide use of other farmers in the same village in the form of weighted average use of pesticides per hectare [5].

Moreover, to better identify the two mechanisms by which farm size affects pesticide use through the level of mechanization and management ability of farmers, we follow Wu *et al.* (2018) and use the area of contracted land as an instrumental variable to extract the part that is not correlated with farmers' abilities and skills. This is because according to the household contract responsibility system in China, the size of the contracted land assigned is mainly determined by the household size and is not correlated with farmers' management ability and skills. Although farmers can theoretically expand their operating land area by the transfer of land use rights, in reality the transfer is limited by many factors (Ju *et al.*, 2016). Therefore, the actual cultivated area of farmers should be significantly positively correlated with their contracted land area. There may also be some doubt about whether the area of contracted land can be used as an instrumental variable in the regression of fixed effects (FE) due to a policy called "no change in contractual land size for 30 years" in China. This policy was put forward since the beginning of the second round of land contracting in 1998. However, it has been found that there is at least one minor adjustment or reallocation of contracted land size to solve contradictions between people and land caused by changes in village and household populations in many rural areas (Kong *et al.*, 2014). Therefore, the area of farmers' contracted land is not completely unchanged during the study time period in this paper, which can also be confirmed by the variance of related variables [6].

5. Empirical results

5.1 Benchmark regression results

Table 5a reports the coefficients from estimating Eqn (8). It is obvious that there is a negative and statistically significant association between farm size and pesticide use, which implies that as the farm size increases, the use intensity of pesticides decreases. The effect holds and even increases slightly after we further control for the Simpson index. Statistically, a 1% increase in farm size is associated with a 0.21% decrease in pesticide use per hectare. This result is consistent with that reported by Zhu and Wang (2021). As previously mentioned, China is still dominated by a large number of smallholder farms; hence, the reduction effect based on the coefficients will remain large. To illustrate using the data in 2016, if the average farm size could be increased from 0.67 ha to 6.67 ha, the national average pesticide use might be reduced from 26.85 kg/ha to 16.51 kg/ha. In addition, we see that the level of land

(a): Total		
Cropland area	−0.194*** (0.005)	−0.211*** (0.006)
Simpson index	—	0.100*** (0.017)
Year FE	Yes	Yes
Household FE	Yes	Yes
R-squared	0.252	0.251
N	142,464	136,495

(b): Crops type	Wheat	Rice	Maize	Vegetables	Fruits
Sowing area	−0.173*** (0.012)	−0.180*** (0.010)	−0.192*** (0.009)	−0.190*** (0.010)	−0.269*** (0.017)
Simpson index	0.114*** (0.040)	0.161*** (0.034)	0.087*** (0.034)	0.099* (0.052)	0.073 (0.050)
Time FE	Yes	Yes	Yes	Yes	Yes
Household FE	Yes	Yes	Yes	Yes	Yes
R-squared	0.367	0.353	0.300	0.296	0.304
N	20,544	28,720	36,409	18,548	10,002

Note(s): Standard errors appear in parentheses; *$p < 0.10$, **$p < 0.05$, ***$p < 0.01$. Not reported: controls for pesticides' price, price index of agricultural productions, share of off-farm household labor, fertilizer use intensity, the interaction terms, the mode of product sales, land type, selling price of each crop, share of days that labor engages in off-farm work, proportion of each crop of products sold, the individual characteristics of household heads including the social position, technical training background, education background and age

Table 5.
Regression results of the farm size and pesticide use

fragmentation has a significant positive effect on pesticide use. Recalling the fragmentation of cropland in China, it can be inferred that integrating plots and reducing the number of household parcels will also reduce pesticide use. In other words, the effect of increasing the size of parcels is equivalent to increasing the farm size.

5.2 Regression results for different crops

The relationship between farm size and pesticide use was robust in the regression of different crops, as shown in Table 5B. We find that the negative effect of farm size on reducing pesticide use is still statistically significant for each crop, and the absolute value of the coefficient for most crops is smaller than that in the benchmark regression. This indicates that the negative effect of farm size is related to crop types but not entirely determined by them. In addition, the impact of land fragmentation is more significant in the production of three major grain crops. This is because grain crops are mainly grown in fields, while a certain percentage of vegetables are grown in greenhouses, which are less restricted by parcel size. For fruit production in China, farmers usually contract a large area for specialized cultivation; hence, their single gardens are usually a contiguous piece of land.

5.3 The impact of others' pesticide use intensity

As shown in Table 6, the pesticide use of others has significant and positive effects on a farmer's pesticide use in the production of different crops. This external effect is significantly greater in the crops planted in fields than in vegetables, where many are planted in greenhouses. For the crops planted in fields, the effect is due to the two reasons mentioned above in Section 4.1. For crops planted in greenhouses, the external effect is only caused by the expectation of selling prices.

Specifically, for grain crops, there is a significant inverse U-shaped relationship between the external effect and farm size. This implies that the impact of others' use intensity appears to initially increase with sowing areas. As the sowing area further increases, the impact declines when the area is more than the threshold value. The results indicate that the different spillover effects of others' use intensity are indeed one of the reasons that large-scale farmers use fewer pesticides in the cultivation of grain crops.

However, the relationship between the external effect and sowing area is a significant U-shaped curve for vegetables, and it increases monotonically when the land area is greater than zero. The coefficient for fruits is not significant. These results show that for cash crops, there is a significant positive correlation between the external effect and sowing area. This implies that in recent years, large-scale farmers in China have not been more powerful in marketing and selling than smallholder farmers. The market feedback mechanism by which agricultural products with lower pesticide use and fewer residues would have a higher price is not perfect. The price of agricultural products is still related more to the product's appearance, rather than to quality indicators such as pesticide residues. Therefore, large-scale farmers are more affected by other farmers' pesticide use.

5.4 Mechanization and management ability of farmers

We implement a two-stage least-squares (2SLS) estimation by instrumenting the sowing area with the area of contracted land [7] (denoted by contractual area) and compare the results with those from FE regression (Table 7). The coefficients of sowing area in FE reflect both the effect of mechanization and farmers' skills on the negative relationship between farm size and pesticide use, while the 2SLS results explain more of the former. For the grain crops, the estimated coefficients are consistent in sign and significance with the FE results. Comparing their magnitudes, we find that mechanization has a greater effect than farmers' management ability. Especially for maize, the absolute value of the coefficient in 2SLS is larger than that in

Table 6.
The effect of others' pesticide use intensity

	Wheat	Rice	Maize	Vegetables	Fruits
The pesticide use intensity of other farmers in the same village	0.278*** (0.024)	0.432*** (0.027)	0.252*** (0.013)	0.153*** (0.012)	0.318*** (0.022)
Sowing area × Others' pesticide use intensity	0.204*** (0.024)	0.149*** (0.028)	0.147*** (0.010)	0.082*** (0.010)	0.040** (0.018)
Sowing area square × Others' pesticide use intensity	−0.020** (0.008)	−0.050*** (0.007)	−0.010*** (0.003)	0.023*** (0.005)	0.005 (0.007)
Sowing area	−0.089*** (0.015)	−0.192*** (0.010)	−0.118*** (0.009)	−0.254*** (0.011)	−0.325*** (0.020)
Simpson index	0.112*** (0.038)	0.169*** (0.032)	0.040*** (0.032)	0.091* (0.052)	0.027 (0.049)
R-squared	0.410	0.416	0.386	0.322	0.347
N	20,530	28,692	36,359	18,449	9,890

Note(s): Standard errors appear in parentheses; *$p < 0.10$, **$p < 0.05$, ***$p < 0.01$. Not reported: controls for pesticides' price, selling price of each crop, share of days that labor engages in off-farm work, fertilizer use intensity, the mode of product sales, land type, proportion of each crop's products sold, the individual characteristics of household heads including the social position, technical training background, education background and age, time and household fixed effects

Table 7. Two-stage least-squares (2SLS) regression of the farm size and pesticide use

	Wheat		Rice		Maize		Vegetables	
	FE	2SLS	FE	2SLS	FE	2SLS	FE	2SLS
Sowing area	−0.193*** (0.012)	−0.158*** (0.048)	−0.193*** (0.009)	−0.102** (0.043)	−0.189***	−0.321*** (0.043)	−0.194*** (0.010)	−0.072 (0.160)
Others' use intensity	0.519*** (0.013)	0.518*** (0.017)	0.510*** (0.011)	0.517*** (0.014)	0.453*** (0.008)	0.447*** (0.044)	0.199*** (0.011)	0.183*** (0.035)
First-stage								
Contractual area	–	0.440*** (0.019)	–	0.344*** (0.016)	–	0.368*** (0.016)	–	0.142*** (0.022)
N	20,530	18,117	28,692	25,435	36,359	32,725	18,449	15,913
Kleibergen–Paap rk Wald *F* statistic	–	523.134	–	472.601	–	502.715	–	40.952

Note(s): Standard errors appear in parentheses; $^{*}p < 0.10$, $^{**}p < 0.05$, $^{***}p < 0.01$. Not reported: controls for pesticides' price, selling price of each crop, share of days that labor engages in off-farm work, fertilizer use intensity, the mode of product sales, land type, proportion of each crop's products sold, the individual characteristics of household heads including the social position, technical training background, education background and age, time and household fixed effects

FE. This implies that maize producers' poor management ability does not match the current farm size and increases the overuse of pesticides. For vegetables, the coefficient of farm size in 2SLS is negative but not significant and much smaller than that in the FE estimate. This result indicates that the negative relationship between farm size and pesticide use in vegetable production is mainly caused by the high management ability of large-scale farmers. The role of mechanization is relatively small. The reason may be that many vegetables are planted in greenhouses, and the relatively closed and narrow space makes it difficult to use large and medium-sized spraying machinery. Pesticide spraying in the greenhouse still mainly relies on relatively backward equipment, such as a Knapsack Sprayer and a handheld spray gun (Liu *et al.*, 2017). Therefore, mechanization has no significant effect.

6. Discussion: the impact of agricultural machinery services

The results above show that machinery adoption, which is correlated with farm size, affects the farm size–pesticide use relationship for grain crops. Because large-scale farmers can upgrade production technology and adopt advanced machinery, the use efficiency of pesticides can be effectively increased, thereby reducing the use intensity. However, with the development of specialized divisions in agricultural production, farmers can purchase relevant agricultural services or rent instead of buy machinery. Thus, small-scale farmers also theoretically can increase their level of mechanization and then reduce pesticide use. Therefore, there are two different propositions about the development strategy of agriculture in China. One advocates realizing the "land-scale economy" through agricultural land transfer and consolidation, and the other advocates realizing the "service-scale economy" by promoting the specialized division of labor (Luo, 2017). In the study of this paper, we are interested in whether there is also a negative correlation between the use of agricultural machinery services and pesticide use. Based on the previous results, we mainly focus on the three major grain crops (wheat, rice and maize) but also test for the robustness of the results by further including cash crops (vegetables and fruit).

A dummy variable denoted by $service_{it}$ is added to model (9). If the farmer had rented others' machines or bought the machinery services, the variable equals 1; otherwise, it is zero. The empirical results are shown in Table 8. The coefficient of *service* is negative in the regression for the three major grain crops. However, only the result from wheat is statistically significant, and the coefficient is very small. In the regression results for vegetables and fruit, purchasing machinery services even has a positive effect, which means it may increase the use intensity of pesticides significantly. This result is consistent with previous results in Section 5.4, in which the lower use of pesticides on large farms for cash crop production is mainly attributed to the more knowledgeable and skillful large-scale producers rather than mechanization. Given that the farm size is generally small in China, it can be reasonably inferred that most farmers have limited farming knowledge and relatively low management ability. In this case, only increasing their level of mechanization by purchasing relevant services without the corresponding improvement of knowledge and skills cannot effectively improve the use efficiency of pesticides but may lead to an increase in the use intensity.

The results above indicate that the construction and development of agricultural socialized services systems in China are still insufficient. Hence, their effect on reducing pesticide use is currently limited. Cai and Wang (2016) showed that the main reason may still be that the average cropland area of rural households in China is relatively too small and fragmented, which hinders the development of socialized production services. Therefore, farmers' purchase and use of socialized services are limited. Although farmers who operate adjacent parcels could buy services together by negotiating and cooperating in theory, the communication cost would undoubtedly be large. In addition, farmers with multiple land parcels usually grow a greater diversity of crops, which may result in different crop varieties between adjacent parcels (Di Falco, *et al.*, 2010). This also reduces the likelihood of regional pest control.

Table 8. Effect of agricultural machinery services

	Wheat	Rice	Maize	Vegetables	Fruit
Service	−0.088*** (0.021)	−0.009 (0.010)	−0.010 (0.011)	0.094* (0.052)	0.065*** (0.020)
Sowing area	−0.172*** (0.012)	−0.180*** (0.010)	−0.191*** (0.009)	−0.195*** (0.010)	−0.271*** (0.017)
Simpson index	0.113*** (0.040)	0.161*** (0.034)	0.086** (0.034)	0.090*** (0.017)	0.065 (0.050)
R-squared	0.346	0.353	0.300	0.298	0.305
N	20,544	28,720	36,409	18,548	10,002

Note(s): Standard errors appear in parentheses; $^{*}p < 0.10$, $^{**}p < 0.05$, $^{***}p < 0.01$. Not reported: controls for pesticides' price, selling price of each crop, share of days that labor engages in off-farm work, fertilizer use intensity, the mode of product sales, land type, proportion of each crop's products sold, the individual characteristics of household heads including the social position, technical training background, education background and age, time and household fixed effects

These results do not necessarily suggest that the "land-scale economy" proposition should be encouraged over the "service-scale economy." We believe there is no contradiction or conflict between them. They are applicable to regions with different geographical characteristics. However, the key to realizing the "service scale economy" depends on the development of the horizontal division of labor and specialized planting in connected farmland (Luo, 2017). Due to the relatively small farm size and high levels of land fragmentation that are still prevalent in China, it is difficult to spontaneously generate specialized planting in a large contiguous area. Therefore, our estimated results show that the impact of agricultural machinery services on reducing pesticide use is currently limited. It can be reasonably predicted that with land transfer and consolidation, the service scale should also play a role in reducing pesticide use by improving the mechanization level of smallholders in major grain crop production. This has been confirmed by the results of small thematic field surveys (Ying and Xu, 2017).

7. Conclusion

Understanding why pesticide use is so high and how to reduce it are critical issues for the sustainable development of Chinese agriculture. We investigate the relationship between the farm size and pesticide use in China by using household-level panel data covering 31 provinces in mainland China from 1995 to 2016. We further discuss the specific mechanism of the effect of the farm size on the cultivation of different crops. In addition, we examine the role of socialized agricultural machinery services in China.

We show that there is a negative and significant association between farm size and pesticide use. Statistically, a 1% increase in farm size decreases the use intensity of pesticides by 0.21%. The result is still robust when we restrict our regression to different crop types. Three factors contribute to the negative relationship. The first factor is due to the pesticides use intensity of other farmers in the same village having an external effect on farmers' pesticides use, while farmers with different farm sizes are affected differently. For the three major grain crops (wheat, rice and maize), there is a significant inverse U-shaped relationship between the external effect and sowing area. For vegetables and fruit, the relationship tends to be U-shaped, and it increases monotonically when the land area is greater than zero. The second factor is the different level of mechanization introduced by different farm sizes. The third factor is that farmers who have large land holdings are more knowledgeable and skillful than those with small land holdings. The first two factors play important roles in the negative relationship between pesticide use and sowing area in the cultivation of grain crops, while the last factor is the main reason for the negative relationship in the cultivation of vegetables. In addition, we find that the effect of agricultural machinery services on reducing the use intensity of pesticides is quite limited, which indicates insufficient development. According to the existing research, the development of socialized services systems is also hindered by the prevalence of small and fragmented farmland.

Overall, our study suggests that small and fragmented farms are a strong factor that leads to the overuse of pesticides in China. Therefore, in the long term, land consolidation still needs to be promoted to increase the average farm size and reduce land fragmentation. However, the role that land fragmentation plays in moderating farmers' risk should also be considered. It is necessary to ensure that there are appropriate risk management alternatives in place before making land consolidation policies (Knippenberg *et al.*, 2020). In the short term, governments can subsidize small land holder farmers to upgrade their homemade pesticide spraying equipment, such as replacing the current nozzles with efficient nozzles. This can effectively reduce certain waste and losses in pesticide use, which has already been practiced and confirmed as being useful in Heilongjiang Province [8].

Notes

1. Jiangsu province is located in the plain, while Guizhou province is mostly mountainous. Therefore, the level of land fragmentation in Guizhou province is naturally higher than that in Jiangsu province.
2. Please refer to the supplementary appendix for a detailed definition of all variables.
3. The detailed definition of these variables can also be seen in the supplementary appendix.
4. Since the interaction between farm size and the share of off-farm labor is not significant in the regression above, we no longer control for it here and in the subsequent regressions.
5. See the supplementary appendix for details.
6. See Table S1 in the supplementary appendix for details.
7. Since the area of contracted land in the NRFOP dataset does not include the contracted area of orchard and other garden types, we do not implement the 2SLS regression estimation for fruit.
8. See https://heilongjiang.dbw.cn/system/2019/06/06/058212654.shtml for details (in Chinese).

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Appendix

The Supplementary material available online for this article

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