Determinants and overuse of pesticides in grain production

A comparison of rice, maize and wheat in China

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Abstract

Purpose – The negative externalities of pesticide overuse increasingly concern the public. However, little empirical evidence has been provided for pesticide overuse and the relationship between the governmental agricultural extension system reforms and pesticide use in grain production from a nationwide perspective. The purpose of this paper is to estimate the productive effect and overuse of pesticides, and it also investigates the effect of the governmental agricultural extension system reforms on pesticide expenditure in rice, maize and wheat production in China.

Design/methodology/approach – A two-equation system model consisting of an exponential-specific damage-control production function and a pesticide use function is applied to the provincial-level data during the period 1985–2016.

Findings – While pesticide expenditure significantly increases grain productivity, the actual pesticide expenditure exceeds the economically optimal level. The commercialization reform of the governmental agricultural extension system contributed to the increase in pesticide expenditure. Moreover, the de-commercialization reform of the governmental agricultural extension system plays a limited role in pesticide reduction. Price fluctuations for grain and pesticide also impose significant effects on pesticide expenditure.

Originality/value – This study has two important policy implications for pesticide reduction in China. It is urgent to specify the functions of the governmental agricultural extension system, and encourage the development of the socialized agricultural technology service. More efforts should also be made to remove the bureaucratic intervention on the pricing mechanism of grain product and pesticide.

Keywords Grain production, Agricultural extension system reform, Damage-control production function, Pesticide overuse

Paper type Research paper

1. Introduction

China is the largest producer and user of chemical pesticides worldwide (Huang *et al.*, 2001; Qiao *et al.*, 2012; Zhang, Hu, Shi, Jin, Robson and Huang, 2015; Sun, Hu, Zhang and Shi, 2019). During the period 1991–2016, the production quantity of chemical pesticides in China has dramatically increased from 0.26 to 3.21m metric tons (Figure 1). Meanwhile, the quantity of pesticides used increased from 0.77m metric tons in 1991 to 1.74m metric tons in 2016 (Figure 1). Estimate indicates that per hectare pesticide use in China was about 2.5–5 times that of the world average (Qiu, 2011).

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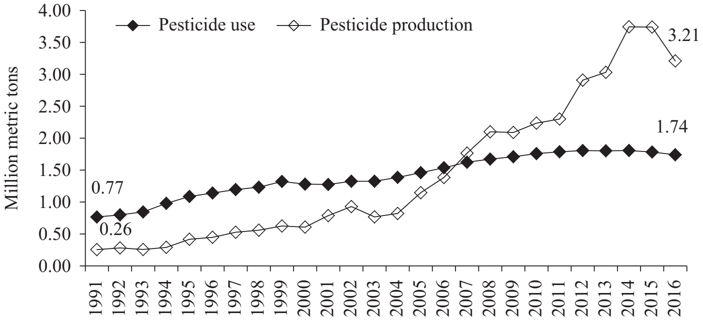


Source: China Rural Statistical Yearbook and China Industry Statistical Yearbook (National Bureau of Statistics of China, 1992–2017)

Figure 1.
Quantity of pesticide use and production (active ingredient) in China (1991–2016)

While there is evidence that pesticide use has made a great contribution to reducing crop yield loss, the overuse of chemical pesticides becomes a challenge to the sustained development of agriculture in China (Zhang, Shi, Shen and Hu, 2015). Popp *et al.* (2013) pointed out that the ratio of the actual grain crop yield to theoretical level increased from merely 42 percent in 1965 to 70 percent in 1990. In China, about 86.9m metric tons of grain output loss were recovered mainly by pesticide use in 2016 (Ministry of Agriculture of China, 2017). However, there is growing concern about the overuse of chemical pesticides in China. Huang *et al.* (2002) indicated that about 10–40 kg of chemical pesticides were overused in the production of both Bt and non-Bt cotton in China. Zhang, Shi, Shen and Hu (2015) also argued that the actual amount of pesticides used in rice and maize production in China was 2.3 and 1.2 times higher than the optimal level. Some recent studies further illustrate that farmers in China overuse pesticides in the production of not only grain crops but also vegetable and fruit (Jiang *et al.*, 2017; Li *et al.*, 2017; Guo and Wang, 2018; Wang *et al.*, 2018).

Previous studies have paid attention to the driving forces of pesticide use in China using farm- and household-level data. In terms of individual and family characteristics, age, gender, education level, income level, labor endowment and farm size are considered the potential factors influencing farmers' pesticide use (Rahman, 2003; Pemsl *et al.*, 2005; Huang *et al.*, 2008; Beltran *et al.*, 2013; Wang *et al.*, 2018; Wu *et al.*, 2018). Moreover, some studies provide evidence that farmers' knowledge and risk preference are important determinants of pesticide use (Hou *et al.*, 2012; Chen *et al.*, 2013; Liu and Huang, 2013; Khan *et al.*, 2015; Gong *et al.*, 2016; Jin *et al.*, 2017). A number of studies also argued that technology training and adoption may affect farmers' pesticide use (Tian *et al.*, 2015; Ying and Zhu, 2015; Xie *et al.*, 2017; Zheng *et al.*, 2019).

The reforms of the governmental agricultural extension system are considered to be closely related with the rapid increase in pesticide use in China (Hu *et al.*, 2009; Zhang, Hu, Shi, Jin, Robson and Huang, 2015). The commercialization reform of the governmental agricultural extension system since the late 1980s allowed the grassroots agricultural extension stations and agents to sell pesticides as well as other agricultural means of production to increase their expenses and income (Hu *et al.*, 2009; Babu *et al.*, 2015). Although the commercialization reform to some extent reduced the financial burden of local government, it in turn severely destroyed the functions of the governmental agricultural extension system (Huang *et al.*, 2001). In the context, roughly all the agricultural extension agents concentrated on the commercial activities rather than technology extension (Hu *et al.*, 2009). Recognizing the drawbacks, the government launched a new reform to prohibit the agricultural extension agents from engaging in the commercial activities in 2006 (Hu *et al.*, 2009). Although some positive outcomes have been obtained, several serious problems remained (Hu and Sun, 2018; Sun *et al.*, 2018).

While the previous studies have repeatedly analyzed pesticide overuse and determinants of pesticide use in China, two drawbacks remain. First, pesticide overuse by farmers in China has been studied mainly using farm- and household-level data, which might limit the interpretation of the results from a cross-regional and nationwide perspective. Moreover, little evidence is provided for the comparison of pesticide overuse among different grain crops from a nationwide perspective. Second, while some previous studies have analyzed the determinants of pesticide use or overuse from a micro perspective, little is known about how the governmental agricultural extension system reform affects pesticide use. Using the nationwide representative data, this study aims to estimate the productive effect and overuse of pesticides in grain production in China, and investigate whether and how the reform of the governmental agricultural extension system affects pesticide use in grain production. To address these two issues, this study is conducted in the case of three main grain crops, including rice, maize and wheat.

The rest of this study proceeds as follows. Section 2 introduces the damage-control production function, pesticide use model and estimation strategy. Section 3 describes the selection of study areas and data source. The regression results and discussion are presented in Section 4. This study concludes in the last section with some implications.

2. Methods

2.1 Damage-control production function

Since pesticide is a damage-control input, a damage-control production function has been frequently used to estimate the productive effect of pesticide use in agriculture (Huang *et al.*, 2001; Zhang, Shi, Shen and Hu, 2015). According to Lichtenberg and Zilberman (1986), the damage-control production function is developed as:

$$Y = AZ^{\beta}[G(X)]^{\gamma}, \tag{1}$$

where Y denotes crop yield; Z denotes a vector of productive inputs, such as labor and fertilizer; X denotes the expenditure of damage-control input, such as pesticide; and A denotes a constant. In general, γ is often assumed to be one.

$G(X)$ is defined as a function of non-decreasing in X with its value ranging in the interval [0, 1], and assumed to be subject to an exponential specification:

$$G(X) = 1 - e^{-\lambda X}, \tag{2}$$

where e denotes the natural constant. Hence, the marginal product of pesticide expenditure can be written as:

$$\frac{\partial Y}{\partial X} = \lambda AZ^{\beta}e^{-\lambda X}. \tag{3}$$

According to the principle of profit maximization, the economically optimal level of pesticide expenditure (X^*) adjusts to bring its marginal revenue and marginal cost into balance. The marginal revenue of pesticide expenditure at current price equals its marginal product multiplied by the current price of crop output in each year. Note that the marginal cost of pesticide expenditure in each year is set as one Chinese yuan measured at constant price in the base year. In the context, the marginal cost of pesticide expenditure at current price in each year equals its value at constant price in the base year (or 1 yuan) multiplied by the ratio of pesticide price in the current year to that in the base year. The economically optimal level of pesticide expenditure (X^*) can be written as:

$$X^* = \frac{1}{\lambda}\ln\left[\frac{P^y \cdot \lambda A(Z^*)^\beta}{P^x}\right], \tag{4}$$

where Z^* denotes the productive inputs corresponding to X^*, P^y denotes the price of crop output at current price, and P^x is the ratio of pesticide price in the current year to that in the base year.

In the context, the empirical specification of the damage-control production function is constructed as:

$$\begin{aligned}\ln Y_{it} = {} & \alpha + \beta_1 \ln Fert_{it} + \beta_2 \ln Labor_{it} + \ln\left[1 - e^{-\lambda X_{it}}\right] + \rho_1 AESR_{it}^{1989-2005} \\ & + \rho_2 AESR_{it}^{2006-2016} + \rho_3 Drought_{it} + \rho_4 Flood_{it} + \rho_5 Trend_t + \mu_i + \upsilon_{it},\end{aligned} \tag{5}$$

where i and t denotes the ith province and tth year, respectively; *Fert* and *Labor* denotes per hectare fertilizer expenditure and labor input, respectively; Y and X are defined as above; $AESR^{1989-2005}$ and $AESR^{2006-2016}$ are two dummy variables denoting the commercialization and de-commercialization reforms of the governmental agricultural extension system during the period 1989–2005 and 2006–2016, respectively[1]; *Drought* and *Flood*, ranging from zero to one, denotes the share of areas affected by the drought and flood disasters, respectively; *Trend* denotes the time trend that accounts for technological progress; and μ denotes the provincial fixed effect. υ denotes the random error term. α, β_1, β_2, λ, ρ_1, ρ_2, ρ_3, ρ_4 and ρ_5 are the coefficients to be estimated.

Note that the severity of pest infestation may vary across years, and thus, the productive effect of a given level of pesticide expenditure may also differ. Thus, the coefficient λ is given as:

$$\lambda = \lambda_0 + \sum \lambda_{year} D_{year}, \tag{6}$$

where D_{year} are a group of dummy variables denoting all the years. In the context, λ_0 reflects the effect of pesticide expenditure on crop yield in the base year, and λ_{year} can capture the changes in the effect of pesticide expenditure on crop yield in each year compared with the base year.

2.2 Pesticide use function

As mentioned above, many previous studies have investigated the driving forces of pesticide use from a micro perspective using farm- and household-level data. This study, however, would be likely to the determinants of pesticide expenditure in grain production using the nationwide representative data. Hence, the selection of the independent variables would be distinct in the present study that focuses on whether and how the reform of the government agricultural extension system in China affects pesticide expenditure in grain production. In addition, both income level and price changes of crop output and pesticide are repeatedly considered as a main determinant of pesticide use in the literature (Huang *et al.*, 2001; Hou *et al.*, 2012; Chen *et al.*, 2013; Liu and Huang, 2013).

To analyze the impact of the governmental agricultural extension system reform on pesticide expenditure, a multiple linear model is constructed. Moreover, a time trend and provincial fixed effect are also included. Hence, the empirical specification is developed as:

$$\begin{aligned}\ln X_{it} = {} & \xi_0 + \xi_1 AESR_{it}^{1989-2005} + \xi_2 AESR_{it}^{2006-2016} + \xi_3 \ln Income_{i,t-1} \\ & + \xi_4 \ln IP_{it}^{y} + \xi_5 \ln IP_{it}^{x} + \xi_6 Trend_t + \vartheta_i + \varpi_{it},\end{aligned} \tag{7}$$

where *Income* denotes per capita rural income, and its one-year lagged value is used to mitigate the potential endogeneity; IP^y and IP^x denote the price indices of crop output and pesticide, respectively; and other variables are as defined above. ϑ denotes the provincial fixed effect; and ϖ denotes the random error term. ξ_0, ξ_1, ξ_2, ξ_3, ξ_4, ξ_5 and ξ_6 are the coefficients to be estimated.

2.3 Estimation strategy

It should be noted that an endogenous issue may emerge if Equations (5) and (7) are estimated separately. As pointed out by Huang *et al.* (2001), farmers' pesticide expenditure is a response to pest infestation. In other words, high level of pest infestation is likely to drive farmers to use more pesticides in crop production. Simultaneously, there exists a negative relationship between pest infestation and crop yield. In this context, per hectare pesticide expenditure may be an endogenous variable in Equation (5). To address this issue, a systematic estimation method is adopted to estimate the two-equation system model consisting of Equations (5) and (7) as done by Huang *et al.* (2001). In detail, Equation (7) is estimated first, and the predicted value of per hectare pesticide expenditure is then used to estimate Equation (5).

3. Data

3.1 Study area

This study was conducted based on a provincial-level dataset with regard to grain production in a total of 22 provinces in China. Note that rice, maize and wheat are three types of major grain crops produced in China. Due to the data availability, the data of rice production covered 14 provinces, namely Liaoning, Jilin, Heilongjiang, Jiangsu, Zhejiang, Anhui, Fujian, Jiangxi, Hubei, Hunan, Guangdong, Guangxi, Sichuan and Yunnan. In terms of maize production, the data came from 13 provinces, including Hebei, Shanxi, Inner Mongolia, Liaoning, Jilin, Heilongjiang, Jiangsu, Shandong, Henan, Sichuan, Yunnan, Shaanxi and Xinjiang. As for wheat production, there were also 13 provinces, including Hebei, Shanxi, Heilongjiang, Jiangsu, Anhui, Shandong, Henan, Hubei, Sichuan, Yunnan, Shaanxi, Gansu and Xinjiang. Note that the selected provinces are the major-producing regions for the three crops correspondingly. According to the China Statistical Yearbook, during this period, the proportion of the rice output of the selected 14 provinces ranged from 88.6 to 93.8 percent; the proportion of the maize output of the selected 13 provinces ranged from 83.0 to 90.7 percent; and the proportion of the wheat output of the selected 13 provinces ranged from 89.8 to 96.4 percent (National Bureau of Statistics of China, 1986–2017). Hence, the selection of these provinces is nationwide representative in China. Due to the poor availability of data before 1985, in addition, the present study collected data during the period 1985–2016.

3.2 Data source

In this study, data for crop yield (Y) were from *China Statistical Yearbook* (National Bureau of Statistics of China, 1986–2017). The metric unit of crop yield is kilograms per hectare (kg/ha).

Three main inputs were considered in this study, including pesticide expenditure (yuan/ha), fertilizer expenditure (yuan/ha) and labor input (day/ha). The data for these three variables were all from *Compiled Materials of Costs and Benefits of Agricultural Products in China* (National Development and Reform Commission of China, 1986–2017)[2]. Note that the current value of both pesticide and fertilizer expenditure was deflated by the price indices of pesticide and fertilizer, respectively. In the context, both pesticide and fertilizer expenditure is measured at 1985 constant price. The price indices of pesticide and fertilizer were collected from *China Rural Statistical Yearbook* (National Bureau of Statistics of China, 1986–2017).

Both the price indices of grain (IP^y) and retail price indices of pesticide (IP^x) were included to reflect the impact of price changes of grain and pesticide on pesticide expenditure. To facilitate the estimation, this study made 1985 as the base year. Apart from the price indices of pesticide, the retail price indices of grain were collected from *China Statistical Yearbook* (National Bureau of Statistics of China, 1986–2017).

Per capita rural income (yuan), in this study, is measured by per capita disposable income of rural residents. The original data were collected from *China Statistical Yearbook* (National Bureau of Statistics of China, 1985–2016).

Drought and flood disasters were considered to control for the impact of natural disasters on crop output. Specifically, the share of areas affected by drought and flood disasters in the total sown areas in each province by year was calculated. The original data for these two variables were collected from *China Rural Statistical Yearbook* (National Bureau of Statistics of China, 1986–2017).

Table I summarizes the variables used in the study.

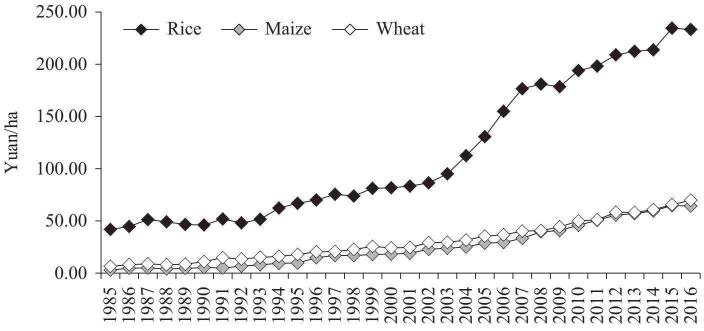
3.3 Changes in pesticide expenditure in grain production

During the period 1985–2016, the level of pesticide expenditure in grain production has experienced a dramatic increase. At 1985 constant price, per hectare pesticide expenditure in 2016 was 233.29 yuan/ha, 64.29 yuan/ha and 69.83 yuan/ha in rice, maize and wheat production, respectively, while in 1985 it was only 41.83 yuan/ha, 2.88 yuan/ha and 6.46 yuan/ha, respectively (Figure 2). In other words, the level of pesticide expenditure in

Table I.
Descriptive characteristics of the main variables

	Rice ($n=443$)		Maize ($n=405$)		Wheat ($n=414$)	
Variables	Mean	SD	Mean	SD	Mean	SD
Yield (kg/ha)	6,237.16	1,101.57	5,043.69	1,132.18	3,643.26	1,150.25
Pesticide expenditure (yuan/ha)	114.05	84.04	25.73	23.94	30.27	25.62
Fertilizer expenditure (yuan/ha)	326.68	95.35	311.35	109.27	321.91	134.55
Labor input (day/ha)	208.62	101.40	171.15	85.09	144.36	79.42
Per capita rural income (yuan)	981.17	718.23	955.26	681.15	867.05	641.87
Share of areas affected by drought	0.06	0.08	0.10	0.10	0.08	0.08
Share of areas affected by flood	0.05	0.06	0.04	0.05	0.03	0.05
Price indices of grain (%)	614.86	373.70	540.35	319.14	552.23	333.98
Price indices of pesticide (%)	270.62	71.05	307.04	101.73	297.80	92.51

Notes: SD, standard deviation. The price indices of grain and pesticide are measured with 1985 as the base year



Note: Pesticide expenditure is measured at 1985 constant price

Figure 2.
Per hectare pesticide expenditure in rice, maize and wheat production (1985–2016)

2016 was roughly 5.58-, 22.32- and 10.81-fold higher than that in 1985 in rice, maize and wheat production, respectively (Figure 2).

However, pesticide expenditure greatly differs across the three grain crops. In 2016, for example, pesticide expenditure in rice production was about 3.63- and 3.34-fold higher than that in maize and wheat production, respectively (Figure 2). In comparison, the level of pesticide expenditure in maize production was the lowest among the three main grain crops.

4. Results and discussion

4.1 Productive effect of pesticide expenditure on grain production

Table II summarizes the estimation results of Equation (5). Since the damage-control production function in this study is in an exponential specification, the ordinary least squares method cannot work. In the context, the feasible generalized nonlinear least squares approach was adopted to estimate the equations, as suggested by Chen and Lian (2013). The adjusted R^2 ranges from 0.78 to 0.81, which demonstrates a high explanatory power of the model in this study (Table II).

This study focuses on the effect of pesticide expenditure on crop yield. As shown in Table II, the estimated coefficients with regard to pesticide expenditure (λ_0) for the base year are all positive and statistically significant, which illustrates that pesticide use plays an important role in reducing yield loss due to crop pest infestation. This finding is consistent with the previous studies (Huang *et al.*, 2001, 2002, 2003; Zhang, Hu, Shi, Jin, Robson and Huang, 2015). However, it was also found that the productive effect of pesticide expenditure varies across years. In the case of rice production, the annually estimated λ_{year} for some years is statistically significant, and most of them are negative. Similar situations are also observed in maize and wheat production. Such findings may imply that the marginal effect of pesticide expenditure on crop yield decreases as pesticide expenditure expands.

The effect of fertilizer expenditure and labor input on grain yield differs across crops. As shown in Table II, the coefficients of fertilizer expenditure in rice and maize production are not significant. As argued by Sun, Hu and Zhang (2019) and Huang and Jiang (2019), this may suggest an overuse of fertilizer. In contrast, the coefficient of fertilizer expenditure in wheat production is significant, but the production elasticity is only 0.12 (Table II). In addition, the coefficients of labor input in both rice and wheat production are not significant, which means that the increase in labor input hardly induces growth in rice and wheat yield (Zhang, Shi, Shen and Hu, 2015). Although the coefficient of labor input for maize is significant, the production elasticity remains at a low level.

The impact of governmental agricultural extension system reforms seems mixed. As shown in Table II, almost all coefficients of reform dummy variables are not significant, except for that of $AESR^{1989–2005}$ in rice and maize production. However, all the coefficients of two disaster dummy variables are negative and significant, which illustrates that the occurrence of drought and flood disasters can sharply reduce grain yield. In addition, the estimated coefficients of time trends imply that technological progress contributes to the increase in grain yield.

4.2 Measuring pesticide overuse

Using the estimated coefficients as shown in Table II, and the average value of grain prices and other inputs, the economically optimal level of pesticide expenditure is calculated according to Equation (4). The data of grain prices were collected from *Compiled Materials of Costs and Benefits of Agricultural Products in China* (NDRC, 1986–2017). The change in the overuse of pesticide in rice, maize and wheat production is shown in Figure 3.

In contrast to maize and wheat, pesticide overuse performs much severer for rice (Figure 3). Except for the year 1985, the actual pesticide expenditure in rice production for

Table II.
Estimated results of the damage-control production function

	Rice ($n = 443$)		Maize ($n = 405$)		Wheat ($n = 414$)	
Dependent variable: $\ln Y_{it}$	Coefficient	t-value	Coefficient	t-value	Coefficient	t-value
$\ln Fert_{it}$	0.04	1.41	0.05	1.17	0.12**	2.57
$\ln Labor_{it}$	0.03	1.08	0.15***	3.52	0.04	1.11
λ_0	0.12***	3.93	2.28***	5.58	0.90***	5.22
λ_{1986}	0.12	0.36	−0.98*	−1.83	0.69	1.45
λ_{1987}	0.12	0.31	−0.42	−0.62	0.01	0.02
λ_{1988}	0.07	0.42	−0.05	−0.07	0.12	0.34
λ_{1989}	0.05	0.54	−0.57	−0.87	−0.36	−1.63
λ_{1990}	0.07	0.64	−0.81	−0.44	−0.26	−1.04
λ_{1991}	0.04	0.36	0.26	0.31	−0.51**	−2.09
λ_{1992}	0.04	0.45	0.49	0.27	−0.34	−1.19
λ_{1993}	0.02	0.15	1.25	0.02	−0.29	−0.70
λ_{1994}	0.04	0.14	−0.15	−0.16	−0.40	−1.11
λ_{1995}	0.05	0.10	0.17	0.17	−0.53**	−1.97
λ_{1996}	0.12	0.01	1.64	1.28	−0.54	−0.93
λ_{1997}	5.44***	> 50.00	−1.41***	−2.67	11.65	0.00
λ_{1998}	1.36	0.00	18.03	0.00	−0.49	−0.46
λ_{1999}	0.30	0.00	−0.92	−0.49	−0.50	−0.35
λ_{2000}	0.01	0.03	−1.11	−1.33	−0.69***	−3.53
λ_{2001}	−0.05	−1.17	−1.61***	−3.46	−0.61**	−2.35
λ_{2002}	−0.05	−1.32	−1.51***	−3.11	−0.66**	−2.34
λ_{2003}	−0.05	−1.00	−1.60***	−3.35	−0.70***	−3.35
λ_{2004}	−0.02	−0.42	−1.80***	−3.89	−0.60***	−2.89
λ_{2005}	−0.04	−0.51	−1.69	−1.63	−0.64***	−2.89
λ_{2006}	−0.07*	−1.69	−1.77***	−3.13	−0.59**	−2.17
λ_{2007}	−0.07	−1.47	−1.79	−1.24	−0.68***	−3.09
λ_{2008}	−0.06	−1.24	−1.89***	−2.66	−0.68**	−2.18
λ_{2009}	−0.07	−1.60	−2.01***	−4.69	−0.70***	−2.65
λ_{2010}	−0.07	−1.57	−2.10***	−5.03	−0.77***	−4.26
λ_{2011}	−0.07	−1.18	−2.12***	−5.03	−0.75***	−4.12
λ_{2012}	−0.08**	−2.11	−2.13***	−4.86	−0.78***	−3.95
λ_{2013}	−0.08**	−2.38	−2.06	−0.83	−0.81***	−4.62
λ_{2014}	−0.09***	−2.66	−2.15***	−4.99	−0.80***	−4.45
λ_{2015}	−0.09**	−2.56	−2.16***	−5.04	−0.79***	−4.43
λ_{2016}	−0.09***	−2.82	−2.16***	−5.13	−0.79***	−4.32
$AESR_{it}^{1989\text{–}2005}$	0.06***	3.09	0.07**	2.58	0.04	1.03
$AESR_{it}^{2006\text{–}2016}$	0.03	1.12	0.07	1.54	0.03	0.54
$Drought_{it}$	−0.12*	−1.87	−0.68***	−9.34	−0.58***	−4.98
$Flood_{it}$	−0.32***	−4.16	−0.44***	−3.34	−0.79***	−4.12
$Trend_t$	0.01***	5.06	0.01***	5.69	0.01***	4.36
Intercept	8.09***	38.86	7.44***	24.64	7.24***	25.36
Adjusted R^2	0.80		0.78		0.81	

Notes: The provincial dummy variables are included but not reported. *,**,***Significant at 10, 5 and 1 percent, respectively.

the other years was higher than the optimal value to different content. On average, more than 45 yuan/ha of pesticide expenditure in rice production was excessive during the period 1985–2016, which averagely accounted for about 40 percent of the actual pesticide expenditure (Figure 3). Similarly, the excessive pesticide expenditure in maize production was about 10.7 yuan/ha, accounting for roughly 42 percent of the actual level (Figure 3). In contrast with that in rice and maize production, pesticide overuse in wheat production seems relatively milder. As shown in Figure 3, both the level of excessive pesticide expenditure and its proportion in the actual pesticide expenditure are lower than that in rice and maize production.

4.3 Determinants of pesticide use

The estimation results of the pesticide use function are presented in Table III. Note that the adjusted R^2 terms are all above 0.86, which means that the model used to analyze the factors influencing pesticide expenditure has relatively strong explanatory power. More importantly, the signs of the estimated coefficients are well consistent with our expectations.

Pesticide expenditure in rice, maize and wheat production during the period 1989–2005 was about 26, 52 and 78 percent higher than that before 1989 (Table III), which once more provides evidence that the commercialization reform of the governmental agricultural extension system significantly increased pesticide expenditure in China (Hu *et al.*, 2009; Zhang, Hu, Shi, Jin, Robson and Huang, 2015; Sun, Hu, Zhang and Shi, 2019). With the implementation of the de-commercialization reform since 2006, however, pesticide expenditure changed in different directions in rice, maize and wheat production. As for rice, the coefficient of $AESR^{2006–2016}$ is significantly larger than that of $AESR^{1989–2005}$ (Table III), which illustrates a further increase in pesticide expenditure from the period 1989–2005 to the period 2006–2016. As for maize and wheat, both coefficients of $AESR^{2006–2016}$ are significantly smaller than that of $AESR^{1989–2005}$ (Table III). Such a situation may be related with farmers' different degrees of dependence on pesticides across crops. Given that the level of pesticide expenditure in rice production has been more than three times that in maize and wheat production, which demonstrates that Chinese farmers' dependence on pesticide use is much higher in rice production than in maize and wheat production (Zhang, Hu, Shi, Jin, Robson and Huang, 2015; Zhang, Shi, Shen and Hu, 2015). As a result, the de-commercialization reform of the

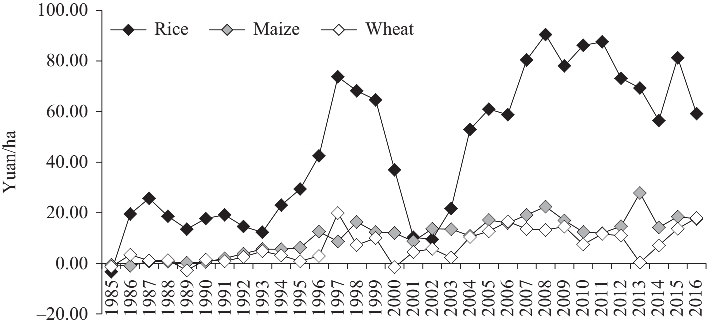


Figure 3.
The level of pesticide overuse in grain production in China (1985–2016)

Table III.
Estimated results for pesticide use model

	Rice ($n = 443$)		Maize ($n = 405$)		Wheat ($n = 414$)	
Dependent variable: $\ln X_{it}$	Coefficient	*t*-value	Coefficient	*t*-value	Coefficient	*t*-value
$AESR_{it}^{1989–2005}$	0.26***	2.59	0.52***	3.15	0.78***	6.83
$AESR_{it}^{2006–2016}$	0.55***	4.60	0.42**	2.06	0.71***	5.07
$\ln Income_{i,\ t-1}$	−0.08	−0.84	0.70***	4.06	0.44***	3.79
$\ln IP_{it}^{y}$	0.36***	6.38	0.36***	4.02	0.44***	6.18
$\ln IP_{it}^{x}$	−0.84***	−6.68	−0.65***	−3.16	−0.76***	−5.31
$Trend_t$	0.04***	5.13	0.05***	3.34	0.03***	2.62
Intercept	6.21***	7.81	−2.20	−1.42	0.59	0.55
Adjusted R^2	0.87		0.86		0.88	

Notes: The provincial dummy variables are included but not reported. ** and ***Significant at 5 and 1 percent, respectively governmental agricultural extension system could somewhat reduce pesticide expenditure in maize and wheat production with relatively lower pesticide use intensity. Meanwhile, pesticide expenditure in rice production would continue increasing due to farmers' excessive dependence on pesticide use (Rao and Ji, 2011). Anyway, it should also be noted that although pesticide expenditure in maize and wheat production during the period 2006–2016 was relatively lower than that during the period 1989–2005, it remained significantly much higher than the level before the commercialization reform of the governmental agricultural extension system (Table III). The fundamental reason for this situation may probably be that the de-commercialization reform played a limited role to improve the efficiency of the governmental agricultural extension service (Hu and Sun, 2018; Sun *et al.*, 2018).

Per capita rural income is a factor influencing pesticide expenditure in maize and wheat production except for that in rice production. Each ten percent increase in the one-year lagged per capita rural income would lead to a 7.0- and 4.4-percent increase in pesticide expenditure in maize and wheat production, respectively (Table III). Note that a number of previous studies also reached the similar conclusions (Rahman, 2003; Beltran *et al.*, 2013).

Moreover, price fluctuation of grain and pesticide could significantly influence pesticide expenditure. Given that both price indices of grain and pesticide are measured using 1985 as the base year, each ten percent increase in grain price would cause pesticide expenditure to increase by 3.6–4.4 percent (Table III). In addition, each 10 percent increase in pesticide price would result in an 8.4-, 6.5- and 7.6-percent decrease in pesticide expenditure in rice, maize and wheat production, respectively (Table III). The findings in this study are highly consistent with that in the previous studies (Hou *et al.*, 2012; Chen *et al.*, 2013; Liu and Huang, 2013).

5. Conclusions and implications

This study investigates pesticide overuse and the relationship between the governmental agricultural extension system reforms and pesticide expenditure in rice, maize, and wheat production in China. To address the endogeneity issue, a two-equation system model is developed and applied to the provincial-level data during the period 1985–2016. Using the damage-control production function, the estimation results shows that while pesticide expenditure could exert a significant effect on grain productivity, the actual pesticide expenditure overall exceeds the economically optimal level in rice, maize and wheat production. Further estimation also reveals that the commercialization reform of the governmental agricultural extension system contributed to the increase in pesticide expenditure, and the de-commercialization reform of the governmental agricultural extension system plays a limited role in pesticide reduction. Price fluctuations for grain and pesticide also impose significant effects on pesticide expenditure.

In conclusion, the findings may have two important policy implications for pesticide reduction in China. First, the commercialization reform of the governmental agricultural extension system since the late 1980s contributed to the indiscriminate use and overuse of pesticides (Hu *et al.*, 2009). Although the de-commercialization reform since 2006 has obtained some desirable outcomes, its positive effect on pesticide reduction is extremely limited. In the context, it is urgent to deepen the reform of the governmental agricultural extension system through specifying the functions of the governmental agricultural extension institutions and agents. Moreover, some useful policies should be implemented to support and encourage the development of the socialized agricultural technology service. Second, it is crucial to strengthen agricultural supply-side structural reform, and push the price of grain and pesticide to be determined by the market. Given the largest population and relatively less arable land in the world, the Chinese government has implemented a policy mix to promote grain production so as to ensure the national food security during the past decades (Huang *et al.*, 2001). To stimulate and protect farmers' initiative in grain production, the government not only continually raised the minimum support prices for grain product, but also depressed the price of pesticides to reduce grain production costs (Ge and Zhou, 2012). According to the findings in this study, more efforts should be made to remove such bureaucratic intervention on the pricing mechanism of grain product and pesticide.

Notes

1. In 1989, the State Council released "Decision on Revitalizing Agriculture with the Support of Scientific and Technological Progress and Enhancing the Extension of Achievements in Agricultural Science and Technology" to improve agricultural extension services, permitting agricultural extension institutions to provide services combining technology with product. In the context, agricultural extension institutions successively established their own marketing department to sell agricultural means of production (Ministry of Agriculture and Rural Affairs of the People's Republic of China, 1999). Thus, 1989 is often regarded as the beginning of the commercialization reform of the governmental agricultural extension system. To address the problems caused by the commercialization reform, the State Council released "Opinions on Deepening the Reform to Enhance the Establishment of Grassroots Agricultural Extension System" in 2006, which no longer permitted the township-level agricultural extension institutions to engage in commercial activities. As a result, we regard 2006 as the end of the commercialization reform as well as the beginning of the de-commercialization reform of the governmental agricultural extension system.
2. From a historical perspective, the National Development and Reform Commission of China was formerly known as the State Planning Commission (1952–1998) and State Development Planning Commission (1998–2003).

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