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RESEARCH ARTICLE

The impact of Bt cotton adoption on the stability of pesticide use

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Abstract
Even though the impact of *Bacillus thuringiensis* (Bt) cotton on pesticide use has been well documented, all previous studies focus on the mean value of pesticide use. Using seven unique waves of panel data collected between 1999 and 2012 in China, we show that Bt cotton adoption has not only caused a reduction of the mean value of pesticide use, but also a reduction of the standard deviation of pesticide use. We conclude that Bt technology adoption has also contributed to the stability of pesticide use in cotton production. We believe that this contribution is theoretically and practically relevant because of the long length of our unique dataset.

Keywords: stability, pesticide use, Bt cotton, household panel data, China

1. Introduction

The economic benefits and its sustainability of *Bacillus thuringiensis* (Bt) cotton adoption have been well documented. For example, previous studies showed that pesticide use was reduced by more than two-thirds after Bt cotton adoption occurred in China (Pray *et al*. 2001; Huang *et al*. 2003). Similar results were found in other countries where Bt cotton was planted, such as the US, India, and Argentina (Frisvold and Tronstad 2002; Qaim 2003; Qaim and de Janry 2003). Further studies showed that the economic benefit that Bt cotton had generated is not only short-term but also is sustained over time (Kathage and Qaim 2012; Qiao 2015; Qiao *et al*. 2016). In addition, the reduction of pesticide use not only aroused increased economic profit but also contributed to a cleaner environment and improved the health status of farmers (Hossain *et al*. 2004; Kouser and Qaim 2011; Abedullah *et al*. 2015).

Concerns about the economic impact of Bt cotton adoption have important impact on public debate and government policies. In recent years, the negative attitude toward Bt technology was exacerbated in the news and media (Cleveland and Soleri 2005; Kathage and Qaim 2012; Qiao 2015). Affected by the rising voice against Bt technology, some consumers have changed their attitudes toward Bt crops, and some governments have slowed the speed of R&D related to Bt technology. In addition, realizing the negative impact of overuse of chemical pesticide and fertilizer, China targets zero growth in pesticide use by 2020. Hence, understanding the impact of Bt cotton adoption will influence the public debate and government policies.

However, all previous studies have focused on the impact

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of Bt cotton adoption on the dynamics of the mean value of pesticide use. Focusing only on the mean value might be misleading because a reduction of the mean value might be caused by some extra small observations (i.e., households with extreme low pesticide use). Consequently, yield loss might be significant because pest damage was not efficiently controlled. In addition, variation of pesticide use in a relatively small region (e.g., a village) is also an important indicator of technological efficiency (and hence economic benefit). Because environmental conditions (such as soil type and climate) are very similar or the same in a village, a small variation in pesticide use might indicate a higher technological efficiency and *vice versa*.

Despite its importance, however, no studies have focused on the impact of Bt cotton adoption on the variation in pesticide use and its dynamics over time. In other words, even though the impact of Bt cotton adoption on the mean value of pesticide use has been well-documented worldwide and dynamically, the impact on the standard deviation of pesticide use and its dynamics over time has not been well studied.

This study tries to fill the gap. To be specific, this study has two objectives. First, by analyzing the seven-wave household panel data collected in rural China, we will document the dynamics of the standard deviation of pesticide use over decades. Second, we will set up and estimate econometric models to isolate the impact of Bt cotton adoption on the standard deviation and its dynamics.

The rest of the paper is organized as follows. In the next section, we will set up a theoretical framework to discuss the relationship between pesticide use and pest population. By analyzing the framework, we will obtain the relationship between Bt cotton adoption and pest population, and that of Bt cotton and pesticide use (i.e., the mean and the standard deviation). The analytical results and hypothesis will be tested empirically on household panel data. Then we will discuss sample selection and data collection. Finally we will document the dynamics of the standard deviation of pesticide use over time in Bt and non-Bt fields. After the description, econometric models will be set up and estimated to isolate the impact of Bt cotton adoption. The estimation results and their implications will then be discussed in Sections 3 and 4, respectively. The final section concludes.

2. Data and methods

2.1. Theoretical framework

Previous studies analyzed the relationship between pest density at the current time period (T) and pest density at the next time period (T+1). For example, the widely adopted biological models assume that the pest population grows logistically (e.g., Clark 1976). In this study, for simplicity, we assume that pest density under nature (i.e., no control) has a normal distribution. In other words, the density of the pest population can be written as:

$$N \sim (\mu, \delta^2) \quad (1)$$

In eq. (1), N is the total pest population, and μ and δ are the mean and standard deviation of the distribution of the pest population, respectively.

We then assume that μ is larger than the economic threshold value in normal years; the marginal benefit of pesticide control (the damage abatement) is higher than the cost of pesticide use. Accordingly, farmers would like to spray pesticides to control pests to increase the benefit. This assumption is consistent with practices, because farmers sprayed pesticide every year. Lu *et al*. (2010) applied a linear relationship between pesticide use and Bt cotton adoption. Following this thought, we also assume that pesticide use has a linear relationship with pest population. In other words, pesticide use is proportional to pest population. Hence, the pesticide use function can be written as:

$$Pesticide \sim \alpha N \sim [(\alpha\mu), (\alpha\delta)^2] \quad (2)$$

In eq. (2), *Pesticide* is the pesticide use sprayed, while α is a positive coefficient (i.e., $\alpha>0$).

As shown in previous studies, the pest population was successfully suppressed after the adoption of Bt cotton (Wu *et al*. 2008). Wu *et al*. (2008) showed that pest density has a linear relationship with Bt cotton adoption. Following this thought, the distribution of the pest population after Bt cotton adoption can be written as:

$$N_{new} = \beta N \sim [(\beta\mu), (\beta\delta)^2] \quad (3)$$

Where, N_{new} is the total pest population after Bt cotton adoption. β is a positive coefficient. We assume that $0<\beta<1$, because the pest population shrunk after Bt cotton adoption (Wu *et al*. 2008). In other words, we have $N_{new}<N$.

Accordingly, the pesticide use after Bt cotton adoption should be written as:

$$Pesticide_{new} \sim \alpha N_{new} \sim [(\alpha\beta\mu), (\alpha\beta\delta)^2] \quad (4)$$

In eq. (4), $Pesticide_{new}$ is the pesticide sprayed after Bt cotton adoption. According to eq. (4), we find that Bt cotton adoption not only lead to a reduction of the mean value of pesticide use (i.e., $\alpha\beta\mu<\alpha\mu$), but also lead to a reduction of the standard deviation of pesticide use (i.e., $\alpha\beta\delta<\alpha\delta$). This is also the hypothesis that we will test using panel household data collected in China. Because the impact of Bt cotton on the mean value of pesticide use has been well documented in previous studies, in this study, we will focus on testing the impact of Bt cotton adoption on the standard deviation of pesticide use.

2.2. Data

This study uses seven-wave panel household data collected in China. The first survey was conducted in 1999, two years after Bt cotton was commercialized in China. The most recent survey was conducted in 2012, 15 years after Bt cotton was commercialized in China. According to our knowledge, this is the longest panel household data focusing on the study of Bt cotton adoption.

The surveys were conducted in four major cotton production provinces in the Yellow River and Yangtze River valleys, which are two of the three major cotton regions in China. The first round survey was conducted in Shandong and Hebei provinces in the Yellow River Valley in 1999. According to the national statistics, in terms of sown areas, Shandong and Hebei provinces were the third and sixth largest cotton production provinces (NBSC 2000). During the second survey, conducted in 2000, we not only revisited the households in these two provinces, but also extended the survey to another important cotton production province in the Yellow River Valley, Henan Province. In 2000, the cotton-sown area of Henan Province was 733 thousand ha, and Henan was the second largest cotton production province (NBSC 2001). In 2001, we extended the survey to another province, Anhui, in the Yangtze River Valley. According to the statistics of NBSC (2002), the sown area of Anhui Province is 363 thousand ha, which makes Anhui the sixth largest cotton production province in 2001.

Two counties where cotton was intensively planted were randomly selected in each province. And in each county, usually two villages where cotton was intensively planted were randomly selected. In each village, about 20 households were selected and interviewed. For each household, all cotton plots were included. During our survey, some farmers abandoned cotton production. They either rented out their land and migrated to cities, or planted other crops (usually grain crops). Consequently, we had to replace these farmers by new samples in later years. The information of the sampled villages, households, and plots are shown in Table 1. More details about sample selection and data collection are shown in Qiao *et al*. (2016).

In each of the seven waves, farmers were asked to provide detailed information about their cotton production. When we conducted field surveys, we used recall survey techniques that are standard in economics literature. The survey questionnaire was designed to collect basic socio-economic information and included several blocks. First, there was a section on basic household characteristics. Information, such as farm size, labor endowments, and asset and housing value, was requested and recorded. Second, another section was designed to collect the demographic information of each individual in the household (such as gender, age, and education).

Our questionnaire also included a long section to record the cotton production of each cotton plot of the sampled households. In each round of field surveys, for each cotton plot, detailed information about cotton yield and all inputs, such as seed cost, fertilizer use, and labor use, was recorded. Because pesticide use is the most important variable of interest, detailed information was requested and recorded. Similar to other inputs variables, the pesticide use information is based on plot level. For each cotton plot, enumerators first asked the total number of times that farmers sprayed during the entire cotton-growing season. For each pesticide spray, a few follow-up questions were then asked (e.g., "When did you spray?"; "What pesticides did you spray?"; and "How much pesticide did you spray?"). Pesticide use in plot level is the core data used in this study.

2.3. Spread of Bt cotton

Due to the severe infestation of cotton bollworms, Bt cotton was first commercialized in the Yellow River Valley, the largest cotton production region in China, in 1997. Because of its significant comparative advantage over traditional varieties, Bt cotton soon spread from the Yellow River Valley to the Yangtze River Valley. In the early 2000s, only a few years after Bt cotton was first commercialized, almost all cotton fields were planted with Bt cotton in these two valleys.

Fig. 1 shows the rapid spread of Bt cotton in our samples. As shown in Fig. 1, the diffusion of Bt cotton was so rapid that it was difficult to find non-Bt cotton fields in

Table 1 Number of farms and plots sampled in the seven survey rounds

Year	Number of villages	Number of farmers	New farmers over previous round	Number of total plots	Number of Bt plots	Number of non-Bt plots
1999	8	218	218	310	279	31
2000	12	303	151	486	382	104
2001	12	244	87	526	435	91
2004	10	202	43	495	455	40
2006	16	320	23	945	931	14
2007	12	240	3	814	808	6
2012	18	310	102	551	548	3
Total	88	1 837	627	4 127	3 838	289

Data source: authors' survey.

our subsequent field surveys. When we conducted the second round of surveys in 2000, there were no non-Bt cotton fields in Shandong and Henan provinces, where we visited in 1999 (Fig. 1). Consequently, we had to extend our samples to Henan Province. The share of Bt cotton in Henan was almost 80% when we conducted another survey in 2001. We then extended our samples to the Yangtze River Valley. Only a few years later, after it was commercialized, Bt cotton was almost 100% planted in both the Yellow River Valley and the Yangtze River Valley. As shown in Table 1, even though we kept extending our samples from the Yellow River Valley to the Yangtze River Valley, the number of non-Bt plots is still significantly smaller than that of Bt plots in the last three rounds of field surveys. Due to the small number of observations of non-Bt cotton plots, the comparison between Bt and non-Bt cotton might not be representative in later years, especially in 2012.

2.4. Dynamics of the mean and standard deviation of pesticide use

As shown in Wu *et al*. (2008), Bt cotton adoption has successfully suppressed the total pest population regionally. Additionally, Wu and Guo (2005) showed that moths, which are the mature stage of cotton bollworms, have the ability to fly at least a couple of miles. On the other hand, the village is the basic unit in China. In the North China Plain, where our sample sites are located, there are usually several hundred to a couple of thousand people in a village, with about 0.1 ha land per capita. Including residual area, the area of a village is usually less than 1 square mile. Accordingly, in this study we use the village as the basic unit. Means and standard deviations of pesticide use are also calculated based on the village. And they are calculated for Bt plots, non-Bt plots and all plots, respectively. Summary statistics for the main variables used in this study are provided in Table 2.

Table 2 also compares the mean and standard deviation of pesticide use between Bt and non-Bt cotton plots. Consistent with our expectation, both the means and the standard deviations of the pesticide use are substantially and consistently higher in non-Bt plots than in Bt plots. This conclusion holds for the frequency of spray, quantity and cost of pesticide use of both total pesticide use and pesticide use against cotton bollworms. As shown in Table 2, the mean value of the pesticide use decreased by about one half (for total pesticide use) to two-thirds (for pesticide use against cotton bollworms) after Bt cotton adoption. Similarly, the standard deviation of pesticide use decreased by 40–49% for total pesticide use and 52–59% for pesticide use against cotton bollworms, respectively.

To show the dynamics of pesticide use over time, we first classified the seven rounds of surveys into three time periods: early period (1999–2001), middle period (2004 and 2006–2007), and late period (2012). We then calculated the means and standard deviations of the frequency of sprays, the quantity and cost of pesticide use in each village in each year. Finally, the means and standard deviations of pesticide

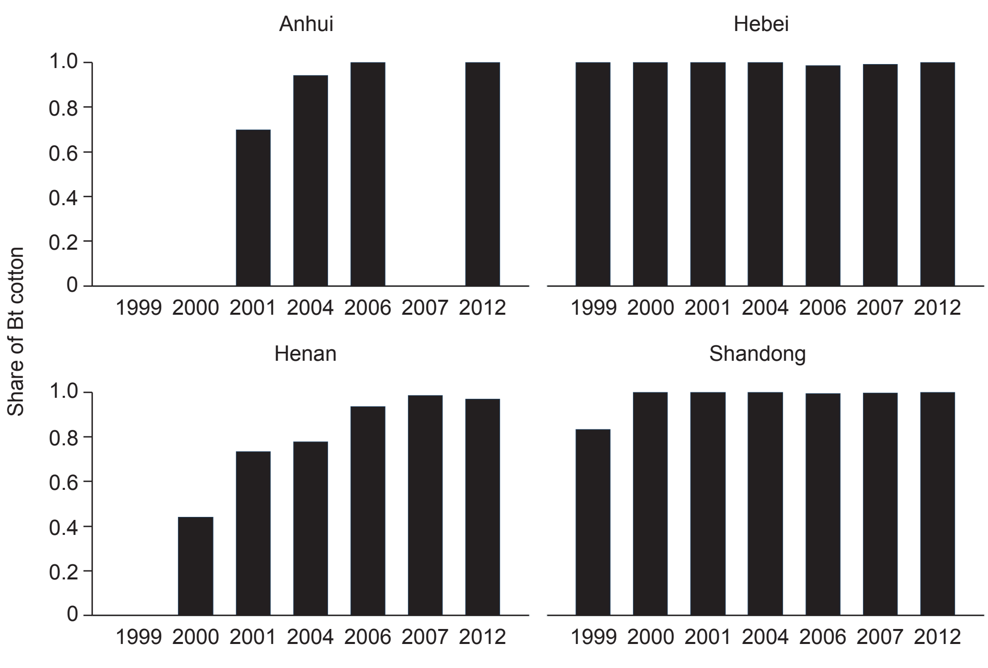

Fig. 1 The share of Bt cotton in the sampled provinces. Data source: authors' survey.

use were averaged over different time periods (i.e., early, middle, and late periods). The results are shown in Fig. 2.

As shown in Fig. 2, the means of pesticide use in Bt plots are always significantly smaller than those in non-Bt plots. This finding holds regardless of whether pesticide use is specified in terms of the frequency of pesticide sprays, the quantity or the cost of pesticide use (Panels A to C). This conclusion also holds in early, middle, and late periods.

Additionally, Fig. 2 shows that the dynamic of the mean value of total pesticide use over time in Bt plots is different from that in non-Bt plots. On the one hand, the mean values of the total pesticide use in Bt plots seem to have no clear increasing or decreasing trend over time (Panel A–C, right side). On the other hand, the mean values of pesticide use in non-Bt plots show a clear decreasing trend from the early period to the middle period and late period (Panel A–C, left side). In other words, Fig. 2 seems to show that the mean value of the pesticide use in Bt plots did not change, while the mean value of the pesticide use in non-Bt plots decreased over time. From the perspective of the average amount of pesticide use, this finding seems to provide evidence that the benefit of Bt cotton adoption has been shared by non-Bt adopters (Qiao 2015; Qiao *et al*. 2016).

Unlike the dynamics of the mean values of pesticide use, the standard deviations have a clear decreasing trend over time in both Bt plots and non-Bt plots. This finding holds whether pesticide use is measured by the frequency of pesticide sprays or the quantity of pesticide use. The only exception occurs when the variation of pesticide use is measured by the standard deviations of the cost of pesticide use. Even though the decreasing trend of the standard deviation of the cost of pesticide use in non-Bt plots is clear, it seems to have no clear trend over time in Bt plots (Panel C).

Fig. 2 might be misleading because the total pesticide

Table 2 Mean and standard deviation (SD) of pesticide use[1)]

	All plots		Bt plots		Non-Bt plots	
	Mean	SD	Mean	SD	Mean	SD
Mean of						
frequency of spray (time)	14.05	4.83	13.43	4.81	19.47	5.24
quantity of total pesticide use (kg ha^{-1})	22.18	12.71	20.06	10.28	41.66	23.01
cost of total pesticide use (CNY ha^{-1})	581.15	275.56	536.81	254.36	945.71	473.95
quantity of pesticide use against cotton bollworms (kg ha^{-1})	9.66	9.26	7.69	6.27	24.38	19.68
cost of pesticide use against cotton bollworms (CNY ha^{-1})	232.12	181.53	190.29	129.71	525.17	394.13
Standard deviation of						
frequency of spray (time)	4.60	2.18	4.24	1.66	5.87	3.71
quantity of total pesticide use (kg ha^{-1})	14.55	9.91	12.48	7.01	24.37	19.42
cost of total pesticide use (CNY ha^{-1})	343.77	188.08	302.52	141.51	505.98	456.67
quantity of pesticide use against cotton bollworms (kg ha^{-1})	9.25	9.03	7.46	5.86	18.04	14.80
cost of pesticide use against cotton bollworms (CNY ha^{-1})	208.72	168.01	168.24	94.28	349.75	312.03
Unit value of total pesticide use (CNY ha^{-1})	28.58	11.71	28.53	11.66	25.12	13.76
Unit value of pesticide use against cotton bollworms (CNY kg^{-1})	28.73	17.41	28.43	17.33	29.41	36.90
Share of Bt cotton adoption	0.93	0.16	1.00		0.00	

[1)] In the first column, mean values and SD of the frequency, the quantity, and the cost of pesticide use are calculated within a village and then used as observations. Finally, we analyze these observations in Bt and Non-Bt plots over different time periods.
Data source: authors' survey.

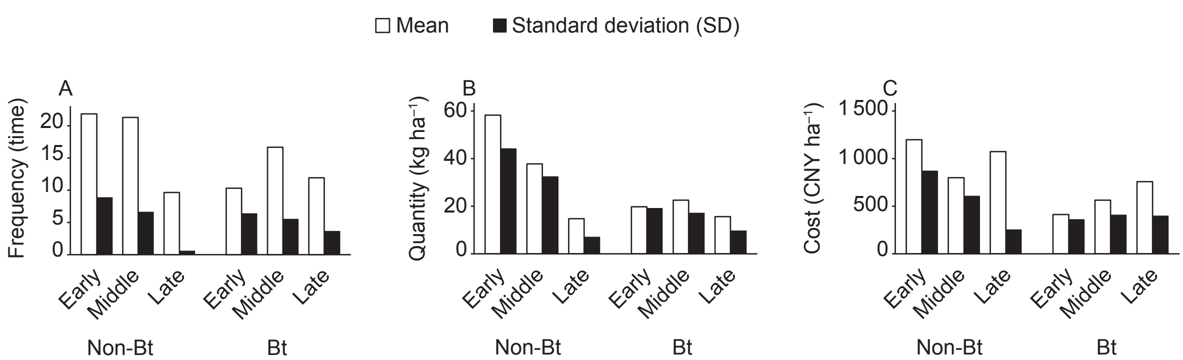

Fig. 2 Mean values and standard deviations (SD) of the frequency (A), the quantity (B), and the cost (C) of pesticide use. Early period, 1999–2001; Middle period, 2004, 2006–2007; Late period, 2012. Data source: authors' survey.

use includes pesticide use against pests and diseases other than cotton bollworms. In China's cotton fields, cotton bollworms are almost the only target pest of the Bt toxin. The Bt toxin has no effect on other pests, such as mirids and planthoppers, and diseases. To isolate the impact of Bt cotton adoption, we analyze the dynamics of the means and standard deviations of pesticide use against cotton bollworms over time. The results are shown in Fig. 3. However, it is not helpful to classify the spray times by different pests. Hence, Fig. 3 only reports the dynamics of the means and standard deviations of the quantity and cost of pesticide use.

Similar to the findings in Fig. 2, the mean values of quantity of pesticide use against cotton bollworms in Bt plots are significantly smaller than those in non-Bt fields, indicating that the comparative advantage of Bt cotton over non-Bt cotton continued (Panel A, Fig. 3). Dynamically, the mean values of pesticide use against cotton bollworms show a clear decreasing trend in non-Bt fields, but no obvious trend in Bt fields, which is similar to that of total pesticide use. These findings hold if we specify the variable as cost of pesticide use against cotton bollworms (Panel B, Fig. 3).

On the other hand, in terms of standard deviations of the quantity of pesticide use against cotton bollworms, the decreasing trends are clear in both Bt and non-Bt fields (Panel A), which is the same as that of total pesticide use. Similar to the dynamics of the means, the standard deviations of the cost of pesticide use against cotton bollworms show decreasing trends over time in both Bt and non-Bt fields (Panel A).

In Fig. 4, we try to link the dynamics of pesticides, both means and standard deviations, to the spread of Bt cotton. From panel A (mean values and standard deviations of the frequency of sprays) to panel B (for the mean values of pesticide use) and panel C (for the standard deviations of pesticide use), there are clear decreasing relationships between pesticide use and the share of Bt cotton. In other words, Fig. 4 seems to show that both the mean values and the standard deviations of pesticide use (the total and that against cotton bollworms) decreased as the share of Bt cotton in a village increased.

In summary, Figs. 2–4 seem to show that, as the Bt cotton spread over time, both the mean values and standard deviations of pesticide use decreased. In other words, Bt cotton adoption not only led to a reduction of the mean values of pesticide use, but also the variation of pesticide use. The findings from the descriptive analysis in this section are consistent with the theoretical hypothesis in Section 2.1.

2.5. Econometric models

The above analysis might be misleading because factors other than Bt cotton adoption might also affect the means and the standard deviations of pesticide use. To isolate the impact of Bt cotton adoption, in this section we are going to setup and estimate pesticide use econometric models. Following the theoretical framework discussed in Section 2.1, the empirical model that we used to estimate the variation of pesticide use can be written as:

$$Pesticide_{jt}=\alpha_0+\alpha_1 Bt_{jt}+\alpha_2 Year_t+\alpha_3 Province_j+\varepsilon_{jt} \quad (5)$$

Where, j is the jth village; t is the tth year; and ε is the error term.

In eq. (5), the dependent variable, *Pesticide*, is pesticide use. As discussed above, this variable has three specifications: the frequency of pesticide spray (in number of times), the quantity of pesticide used (in kg ha^{-1}), and the cost of pesticide used (in CNY ha^{-1}). When pesticide use is measured by quantity or cost, we apply eq. (5) under two scenarios. In the first scenario, total pesticide use is the

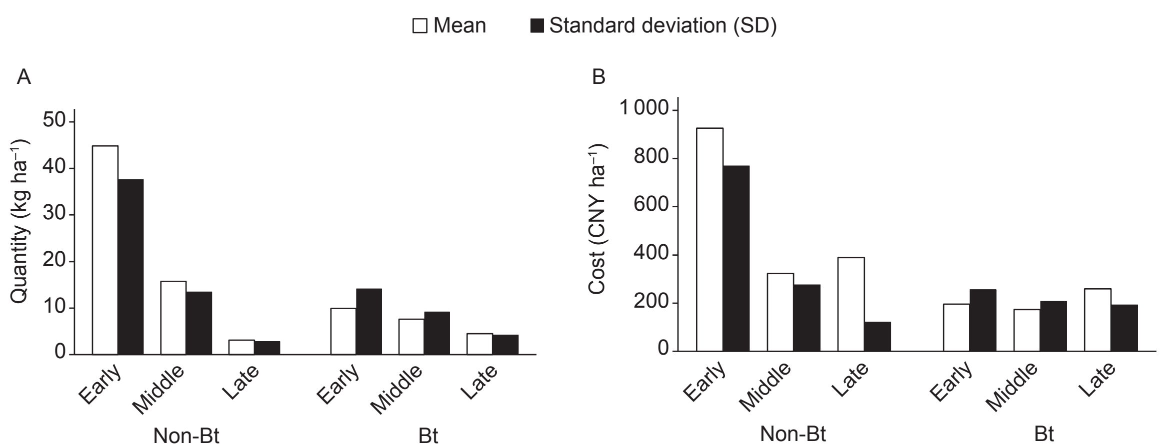

Fig. 3 Mean values and standard deviations (SD) of the quantity (A) and cost (B) of pesticide use against cotton bollworms. Data source: authors' survey.

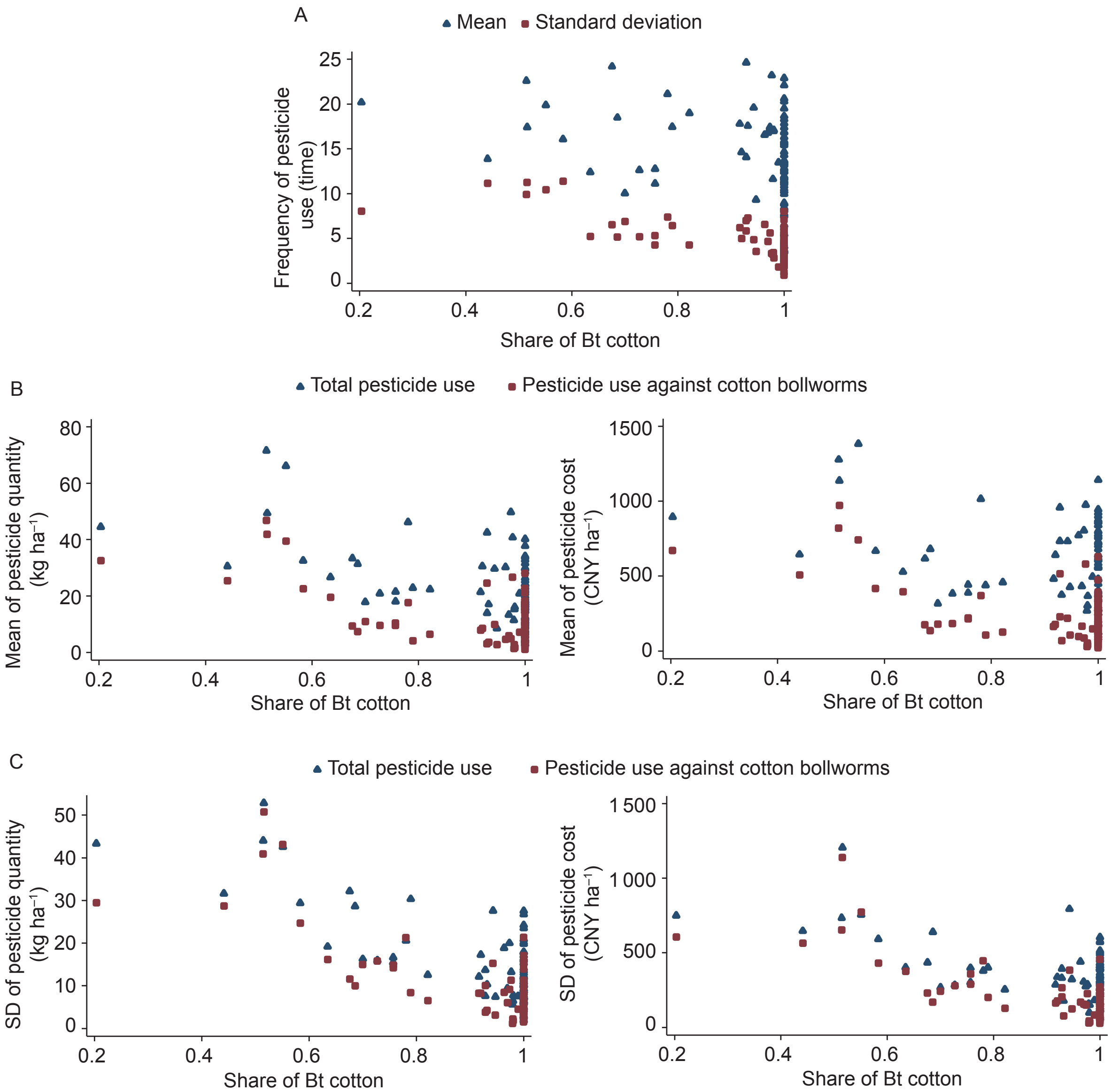

Fig. 4 Shares of Bt cotton and mean values and standard deviations (SD) of frequency, quantity and cost of pesticide use. Data source: authors' survey.

dependent variable. In the second scenario, pesticide use against cotton bollworms is the dependent variable. Finally, the means and the standard deviations of pesticide use (of the total and that against cotton bollworms) models are estimated, respectively. In addition, when the mean functions are estimated, the impact of pesticide price is considered and a new variable (*Price*) is added into eq. (5).

Bt is the share of Bt cotton in a village. As discussed above, the pesticide use variables (i.e., means and standard deviations) are measured based on village. Accordingly, we use the share of Bt cotton in a village to measure the impact of Bt cotton adoption. If the estimated coefficient of *Bt* in the mean values of pesticide use equation is significant and negative, we conclude that Bt cotton adoption led to a reduction of pesticide use. Similarly, a significant and negative coefficient in the equations of standard deviations indicates that Bt cotton adoption led to a reduction of stability of pesticide use, and *vice versa*.

Year is a vector of dummy variables. Because the data set used in this study includes seven rounds of household surveys, six-year dummies (for the years 2000, 2001, 2004, 2006, 2007, and 2012) are added in eq. (5). The first year, 1999, is the base. Adding year dummies captures the impact of those time-varying factors (such as temperature and rainfall).

Province is a vector of province dummies. Because the household panel data were collected in four major cotton production provinces, we added three province dummies (for Shandong, Hebei, and Anhui provinces, with Henan as the base province). With the addition of province dummies, eq. (5) considers the impact of provincial related factors.

3. Results

The results of the econometric estimation are shown in Table 3 (for the standard deviations of the frequency of pesticide spray and the quantity of pesticide use), Table 4 (for the standard deviations of cost of pesticide use), and Table 5 (for the mean values of frequency of pesticide spray and quantity of pesticide use). As discussed above, for both the quantity (i.e., the quantity of pesticide use) and the cost (i.e., the cost of pesticide use) equations, we estimated two scenarios (i.e., total pesticide use and pesticide use against cotton bollworms). In general, the regression results are consistent with the descriptive analysis above. In the following paragraphs, we first discuss estimation results for the amount of pesticide use equation and then for the pesticide cost equation.

As shown in the first column of Table 3, the estimated coefficient of the share of Bt cotton is negative and significant, indicating that the standard deviation of the frequency of pesticide spray decreased as the share of Bt cotton increased. In other words, the estimation results show that Bt cotton adoption led to a reduction of the variation of pesticide use (i.e., the reduction of the standard deviation of spray times) among farmers in a village. According to our estimation, if the share of Bt increase by 0.01, the standard deviation of the frequency of pesticide spray will reduce by 0.0868, which is 1.89% of the average of the standard deviation of the pesticide spray (0.0868/4.5995×100%=1.89%).

Importantly, the estimation results also show that the impact of Bt cotton adoption on the stability of pesticide use in a village holds. As shown in the first two columns in Table 3, most of the estimated coefficients of provincial dummies and year dummies are insignificant, while the absolute values of the significant ones are much smaller than that of the share of Bt cotton. In other words, the estimation results in Table 3 show that Bt cotton adoption has a negative impact on the variability of total pesticide use in all sampled villages and in all years.

A similar result occurs if we replace total pesticide use with pesticide use against cotton bollworms and re-run the models. As shown in the third column of Table 3, the estimated coefficient of the share of Bt cotton is still negative and statistically significant, indicating that Bt cotton adoption led to a reduction of the variation of pesticide use against cotton bollworms in a village. Similar to that of the total pesticide use, the absolute values of the Bt cotton adoption is larger than any of the provincial dummies and year dummies. In other words, the impact of Bt cotton adoption

Table 3 Impact of Bt cotton adoption on the standard deviation (SD) of pesticide use

	SD of total spray times	SD of total pesticide use	SD of pesticide use against cotton bollworms
Share of Bt cotton	–8.68***	–51.10***	–47.88***
	(–6.58)	(–9.45)	(–10.43)
Henan Province (1=Yes)	–0.27	–7.32***	–5.60***
	(–0.54)	(–3.58)	(–3.23)
Shandong Province (1=Yes)	0.36	–2.46	0.87
	(0.69)	(–1.15)	(0.48)
Hebei Province (1=Yes)	–0.64	–4.67**	–1.28
	(–1.20)	(–2.15)	(–0.69)
Year 2000 (1=Yes)	1.18*	0.66	0.02
	(1.77)	(0.24)	(0.01)
Year 2001 (1=Yes)	1.04	–0.06	1.55
	(1.50)	(–0.02)	(0.64)
Year 2004 (1=Yes)	1.27*	3.91	–4.12*
	(1.80)	(1.35)	(–1.68)
Year 2006 (1=Yes)	0.97	3.44	–1.54
	(1.48)	(1.29)	(–0.68)
Year 2007 (1=Yes)	–0.46	–1.90	–2.37
	(–0.68)	(–0.68)	(–1.01)
Year 2012 (1=Yes)	–0.11	–1.81	–3.45
	(–0.16)	(–0.68)	(–1.51)
Constant	12.25***	65.43***	56.90***
	(9.36)	(12.19)	(12.48)
Observations	88	88	88
R-squared	0.62	0.69	0.73

t-statistics are in parentheses. ***, P<0.01; **, P<0.05; *, P<0.1.
Data source: authors' survey.

Table 4 Impact of Bt cotton adoption on the standard deviation (SD) of the expenditure on pesticide use

	SD of the cost of pesticide use	SD of the cost of pesticide against bollworms
Share of Bt cotton	–925.94***	–965.71***
	(–7.49)	(–10.51)
Henan Province (1=Yes)	–112.88**	–110.42***
	(–2.42)	(–3.18)
Shandong Province (1=Yes)	–16.02	20.14
	(–0.33)	(0.55)
Hebei Province (1=Yes)	–65.51	–19.17
	(–1.32)	(–0.52)
Year 2000 (1=Yes)	–15.20	–28.19
	(–0.24)	(–0.61)
Year 2001 (1=Yes)	–44.73	–18.58
	(–0.69)	(–0.39)
Year 2004 (1=Yes)	34.10	–100.48**
	(0.52)	(–2.04)
Year 2006 (1=Yes)	122.10**	–2.97
	(1.99)	(–0.07)
Year 2007 (1=Yes)	–66.60	–70.93
	(–1.05)	(–1.51)
Year 2012 (1=Yes)	129.88**	13.43
	(2.11)	(0.29)
Constant	1 221.16***	1 160.34***
	(9.94)	(12.72)
Observations	88	88
R-squared	0.55	0.69

t-statistics are in parentheses. ***, $P<0.01$; **, $P<0.05$; *, $P<0.1$.
Data source: authors' survey.

on pesticide use against cotton bollworms continues over time and is universal over regions. This result is not hard to understand because the bollworm is the primary pest, and the target pest of Bt toxin is exclusively cotton bollworms in China's cotton fields.

Similarly, the estimation results when cost of pesticide use is the dependent variable show that Bt cotton adoption led to a reduction of the standard deviation of pesticide cost. As shown in Table 4, whether the dependent variable is the cost of total pesticide use or the cost of pesticide use against cotton bollworms, the estimated coefficient of the share of Bt cotton variable is always negative and significant. In other words, the estimation results show that the standard deviation of pesticide use, total or against cotton bollworms, decreased as the share of Bt cotton in a village increased. Consistent with its impact on the amount of pesticide use (as shown in Table 3), Table 4 shows that Bt cotton adoption also led to stability of the cost of pesticide use.

Finally, as expected, the estimation results show that Bt cotton adoption led to significant reduction of the mean values of pesticide use. As shown in Table 5, the estimated coefficients of the share of Bt cotton are negative and statistically significant in both the total pesticide use and the pesticide use against cotton bollworms equations. In other words, the estimation results show that Bt cotton adoption led to a reduction of the general average of pesticide use in a village. This finding is consistent with the hypothesis in Section 2.1 and the results of previous studies (for example, Qiao 2015, Qiao *et al*. 2016).

4. Discussion

Previous entomological studies show that Bt cotton adoption has successfully suppressed the pest population regionally (Wu *et al*. 2008). Consequently, pesticide use in non-Bt fields also decreased (Qiao 2015; Qiao *et al*. 2016). From another perspective, this study shows that variation of pesticide use also decreased after Bt cotton adoption. Reduction of the standard deviation of pesticide use shows that the benefit of Bt cotton adoption is not only enjoyed by those adopters, but also by non-Bt adopters. Stability of pesticide use led by Bt cotton adoption contributes to the stability of cotton yields and economic benefit as no farmers, especially non-adopters, spray too less or too much.

The findings of this study have important implications. First, the findings will contribute to a wider public debate in China as well as in other countries where Bt crops are planted. The economic impact of Bt crops has been and is still subject to a heated debate not only in the field of research but also in the news and media (Kathage and Qaim 2012; Qiao 2015). Even though studies show that economic benefit of Bt crops adoption is significant and sustainable,

Table 5 Impact of Bt cotton adoption on the means of the pesticide use

	Total pesticide use			Pesticide use against cotton bollworms	
	Frequency (time)	Quantity (kg ha^{-1})	Cost (CNY ha^{-1})	Quantity (kg ha^{-1})	Cost (CNY ha^{-1})
Share of Bt cotton	–15.79***	–52.76***	–1 117.79***	–49.16***	–1 026.77***
	(–5.13)	(–6.70)	(–6.20)	(–9.23)	(–9.17)
Pesticide price	–0.02	–0.37**	4.55	–0.11*	0.09
(CNY kg^{-1})	(–0.35)	(–2.12)	(1.14)	(–1.77)	(0.07)
Henan Province	–1.93*	–17.83***	–419.83***	–8.48***	–171.76***
(1=Yes)	(–1.67)	(–6.03)	(–6.21)	(–4.02)	(–3.88)
Shandong Province	–0.86	–10.54***	–244.18***	0.28	27.31
(1=Yes)	(–0.70)	(–3.34)	(–3.38)	(0.13)	(0.60)
Hebei Province	–0.25	–8.25**	–181.90**	0.50	36.72
(1=Yes)	(–0.20)	(–2.63)	(–2.53)	(0.22)	(0.79)
Year 2000 (1=Yes)	2.76*	5.96	143.22	5.38**	92.42
	(1.79)	(1.51)	(1.59)	(2.00)	(1.63)
Year 2001 (1=Yes)	4.70***	9.02**	173.83*	2.55	27.19
	(2.90)	(2.18)	(1.83)	(0.90)	(0.46)
Year 2004 (1=Yes)	9.22***	8.60**	211.88**	–3.12	–70.00
	(5.60)	(2.04)	(2.20)	(–1.09)	(–1.16)
Year 2006 (1=Yes)	10.97***	13.24***	361.35***	3.88	94.55*
	(7.30)	(3.44)	(4.11)	(1.47)	(1.71)
Year 2007 (1=Yes)	9.16***	10.13**	256.26***	4.28	85.09
	(5.87)	(2.54)	(2.80)	(1.57)	(1.48)
Year 2012 (1=Yes)	5.45**	12.87**	352.48***	4.61	153.02**
	(2.55)	(2.35)	(2.81)	(1.42)	(2.24)
Constant	23.79***	82.55***	1 486.08***	57.65***	1 144.81***
	(7.13)	(9.67)	(7.60)	(10.24)	(9.68)
Observations	88	88	88	88	88
R-squared	0.60	0.62	0.58	0.66	0.61

t-statistics are in parentheses. ***, $P<0.01$; **, $P<0.05$; *, $P<0.1$.
Data source: authors' survey.

it seems that the negative attitude toward Bt crops is dominating in the news and media. From a new perspective, the estimation results of this study provide empirical evidence that the economic benefit of Bt cotton adoption is not only enjoyed by those adopters, but also by non-Bt adopters, which will definitely help to calm down the public debate.

Our results are also helpful for Chinese policymakers in managing Bt crop adoption. The public debate in the news and media not only affected consumers but also the policy makers. At least partially for this reason, the Chinese government has stalled the commercialization of other Bt crops (such as Bt rice and Bt corn), even though billions of dollars have been spent on these crops and China leads the world in Bt rice technology. Results of this study are believed to contribute to the management of Bt crops by the Chinese government.

5. Conclusion

Even though the impact of Bt cotton adoption on pesticide use has been well-documented, all previous studies focus on the analysis of the general mean value of pesticide use. In this study, we show that Bt cotton adoption not only led to a reduction of the mean of pesticide use, but also to a reduction of the standard deviation of pesticide use. In other words, Bt cotton adoption also contributes to the stability of pesticide use among farmers.

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