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The Sustainability of the Farm-level Impact of Bt Cotton in China

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Abstract

The short-run impact of Bt cotton adoption has been well documented; however, the sustainability of the impact remains unclear. In particular, pest resistance build-up and secondary pest outbreaks have caused concern regarding the sustainability of this benefit. This paper analyses the effects and impact dynamics of Bt cotton adoption in China. Using six unique waves of panel data collected between 1999 and 2007, we show that the benefits of Bt cotton continue 10 years after it has been commercialised, albeit with evidence of a decline in the benefit since the early adoption period. Importantly, we also show that the benefit has been shared by both Bt and non-Bt cotton adopters.

Keywords: *Bt cotton*; *China*; *farm-level*; *panel data*; *pesticide use and cost*; *sustainability*.

JEL classifications: *D13, O33, Q12*.

1. Introduction

The short-run impact of Bacillus thuringiensis (Bt) cotton has been well documented worldwide (e.g. Qaim, 2003; Shankar and Thirtle, 2005; Wossink and Denaux, 2006; Ali and Abdulai, 2010; Carpenter, 2010). These studies showed that Bt cotton adoption has led to reduced pesticide use and increased cotton yield. The reduction of pesticide use not only resulted in increased economic profit but also contributed to a cleaner environment and improved the health status of farmers (Hossain *et al*., 2004; Abedullah and Qaim, 2005; Kouser and Qaim, 2011).

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However, more studies are still needed to determine the sustainability of the impact. Because of the increasing pest resistance to cotton bollworm and/or the outbreaks of secondary pests, it was expected that the short-run impact of Bt adoption would be totally offset in the long run (Pemsl and Waibel, 2007; Wang *et al*., 2008). However, Qiao (2015) and Qiao and Yao (2015) showed that the impact of Bt cotton adoption continues even 15 years after the commercialisation of Bt cotton in China. Since both of these studies are based on national aggregate data, however, neither of them analysed the impact dynamics of pesticide use against different pests (i.e. cotton bollworm and mirids) and of pesticide use in Bt plots and non-Bt plots.[2]

To the best of our knowledge, there have been only three studies that focus on the sustainability of Bt cotton adoption based on farm-level data. Using four waves of household survey data, Kathage and Qaim (2012) and Krishna and Qaim (2012) estimated the economic impact and impact dynamics of Bt cotton in India. However, Bt cotton was first commercially released in India in 2002 and thus had been planted for only 7 years when their final survey was conducted in 2008. The third paper by Huang *et al*. (2010) focused only on pesticide use against the cotton bollworm and did not discuss pesticide use against secondary pests, which was expected to offset the benefit of Bt cotton adoption. Furthermore, Huang *et al*. (2010) did not analyse the impact dynamics of total pesticide use, which is the core of understanding the sustainability of Bt cotton adoption.

This study contributes to the existing literature by examining the sustainability of Bt cotton adoption and uses six waves of household survey data from between 1999 and 2007. First, we focus on the impact of Bt cotton adoption on the total pesticide use in a dynamic setting. By analysing the impact dynamics of total pesticide use, we identify whether the benefit of Bt cotton is stable or diminishing. Second, we divide total pesticide use into pesticide use for controlling the cotton bollworm and that for controlling secondary pests. By doing so, we can not only answer whether the efficiency of Bt toxin in controlling the cotton bollworm has decreased over time, but also identify whether Bt cotton adoption has led to the outbreak of secondary pests.

The rest of the paper is organised as follows. In the next section, we discuss the data used in this study. We then descriptively analyse the benefits of Bt cotton and its impact dynamics by comparing the cotton yield and pesticide use on Bt and non-Bt cotton fields over time. To isolate the impact of Bt technology and its impact dynamics, we set up econometric models and discuss the estimation results in the third and fourth sections. The final section concludes the paper.

2. Data Collection and Pesticide Use in Cotton Production

2.1. Data collection

A panel survey of China's cotton farmers was carried out in six waves between 1999 and 2007. The sample covers farmers in four different provinces – Shandong, Hebei, and Henan provinces in the Yellow River valley and Anhui province in the Yangtze River valley. These four provinces are the second-, third-, fourth-, and sixth-largest cotton production provinces in China, respectively (National Bureau of Statistical of

[2]Cotton bollworms have been considered as primary pests whereas mirids have been considered as secondary pests in China's cotton fields. In this study, unless otherwise specified, secondary pests are mirids.

China (NBSC), 2008).[3] The Yellow River and Yangtze River valleys are two of the three largest cotton production regions in China (the other is the Northwest). More importantly, they are also the regions where the infestation of the cotton bollworm is serious and Bt cotton is widely planted (Wu and Guo, 2005; Qiao *et al.*, 2009).

The first wave of the field survey was implemented in winter 1999, only 2 years after Bt cotton was officially commercialised in China. During pre-tests and interviews with local officers, we found that the adoption rate of Bt cotton varied significantly. Because adoption rates of Bt cotton in the Yangtze River valley and Northwest were very low at that time, we choose two provinces, Shandong and Hebei, in the Yellow River valley where Bt cotton was first introduced in 1997. Two counties in Hebei province and three counties in Shandong province where cotton was intensively planted were selected. After county selection, we randomly selected two villages in each county and 15–20 farmers within each village.

Follow-up waves were conducted in 2000 and 2001, 2004, 2006 and 2007. During the survey in 2000, we not only revisited the households in Shandong and Hebei provinces but also extended the survey to Henan, another important cotton production province in the Yellow River valley (NBSC, 2008). In 2001, we further extended the survey to another province, Anhui, in the Yangtze River valley. The households and plots sampled are shown in Appendix Table A1.

We continued to extend our sample sites for at least three reasons: (i) with the rapid spread of Bt cotton, it was becoming difficult to find non-Bt cotton plots in the Yellow River valley after the early 2000s; (ii) to increase the representativeness of our households to China's cotton production;[4] (iii) to compensate for the respondent attrition that occurred in progressive surveys. Some sampled farmers had stopped cotton cultivation during the period, mostly by turning to other crops, such as wheat and corn, or renting out all their land and migrating to cities. We randomly selected new sample respondents in the same village to replace those who dropped out. The priority was given to their relatives (e.g. brothers, sons or father) or neighbours.

In each of the six waves, farmers were asked to provide detailed information about their cotton production, households and each individual. The survey questionnaire was designed to collect basic socio-economic information and included several blocks. First, there was a section on basic household characteristics, such as farm size and labour endowments, production assets and housing. A second section recorded demographic information of each individual in the household (such as gender, age, education and marital status).

Our questionnaire also included a long section to record the cotton production of each cotton plot in the sampled households.[5] Information collected in this section forms the core of this paper's data for analysis. For each cotton plot, detailed information about yield and all inputs, such as seed (whether the variety was Bt, seed price,

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[3]Xinjiang is the largest cotton production province in China. However, owing to the hot and dry climate, the cotton bollworm in Xinjiang is not as serious as in the Yellow River valley and the Yangtze River valley. Hence, Bt cotton was first commercialised in the Yellow River valley and then spread into the Yangtze River valley.

[4]The climate in Northwest China is hot and dry, which is unsuitable for the cotton bollworm. Hence, the adoption rate of Bt cotton in the Northwest was low until the mid-2000s (Qiao, 2012).

[5]The average household has approximately 5 plots of land with a total area of 0.73 ha in our study area, of which 3.4 plots were allocated to cotton production in 2007.

etc.), irrigation cost, fertiliser use (quantity of and expenditure on), and labour use were recorded. For pesticide use, enumerators first asked the total number of times that farmers sprayed during the entire season. For each pesticide spray, a few follow-up questions were asked, for example: When did you spray? What pesticides did you spray? How much pesticide did you spray? What are the target pests and/or diseases?

Following Kathage and Qaim (2012), for the purpose of these mean value comparisons between Bt cotton plots and non-Bt cotton plots, we combine observations from three consecutive rounds, resulting in data for two periods – namely, 1999–2001 (early adoption period) and 2004–2007 (late adoption period).

2.2. *Bt cotton adoption and its impact on pesticide use*

Table 1 compares selected variables between Bt and non-Bt cotton plots. During the early adoption period, there are 218 non-Bt cotton plots and 1,093 Bt cotton plots (row 1). However, in the late adoption period, only 48 plots are planted with non-Bt cotton, whereas 2,106 plots are planted with Bt cotton.[6] Table 1 also shows that the yield of Bt cotton during 1999–2001 is approximately 25% higher than that of non-Bt cotton (2,593 kg/ha vs. 3,239 kg/ha, row 2). This difference increases to more than 40% during the late adoption period. In addition, even though there are some worries that the quality of Bt cotton is inferior to that of non-Bt cotton (e.g. Wang, 2009), our data show that Bt cotton and non-Bt cotton have very similar prices in both periods (row 3).

We classified total pesticide use into three different groups according to the target pests or diseases: (i) pesticide use against cotton bollworms, (ii) pesticide use against mirids, and (iii) pesticide use against other pests and/or diseases. If the pesticide spray was for two or more targets, questions regarding the shares of each target were asked, and pesticide use for each target was calculated based on these shares. Disaggregating into these three categories is of interest, because Bt technology is effective in controlling the cotton bollworm but is ineffective in controlling other pests and diseases. Beyond physical quantities, we also analysed the pesticide cost per hectare because there is a wide variety of chemical pesticides, which differ considerably in terms of formula concentrations and prices.

As shown in Table 1, even though pesticide use is substantially higher in non-Bt plots than in Bt plots in the early adoption period, the difference becomes much smaller in the late adoption period. During the early adoption period, the total quantity of pesticides applied in Bt cotton fields was 19.7 kg/ha, which is approximately one-third of the total pesticide use in non-Bt cotton fields (row 4). However, this difference becomes much smaller in the late adoption period: total pesticide use in Bt cotton fields is approximately two-thirds of pesticide use in non-Bt cotton fields (22.7 kg/ha vs. 38.5 kg/ha).

These findings suggest that the relative advantage of Bt cotton decreased substantially. However, this impact dynamic might be caused by the positive spillover effects of Bt cotton. Previous research showed that the widespread adoption of Bt cotton had successfully suppressed the pest population density, and farmers had substantially reduced their pesticide applications even in their non-Bt cotton fields (Wu *et al*., 2008;

[6]Because of the small numbers of non-Bt plots in 2006 and 2007, the estimated relative advantage of Bt cotton over non-Bt cotton might be unrepresentative.

Table 1
Comparison of yield and inputs of Bt and Non-Bt cotton plots

	1999–2001				2004, 2006–2007			
	Non-Bt		Bt		Non-Bt		Bt	
	Mean	Std. dev.	Mean	Std. dev.	Mean	Std. dev.	Mean	Std. dev.
Number of observations	218		1,093		48		2,106	
Seed cotton yield (kg/ha)	2,593.15	807.01	3,239.71	721.42	2,204.24	946.44	3,155.32	918.16
Cotton price (yuan/kg)	3.70	0.60	3.62	0.58	4.43	0.61	4.37	1.00
Total pesticide use quantity (kg/ha)	58.34	44.34	19.74	19.11	38.49	33.72	22.73	17.21
Against cotton bollworms	44.57	37.62	9.92	14.18	16.26	13.49	7.80	9.31
Against secondary pests	0.07	0.49	0.13	0.92	9.04	15.02	6.00	6.78
Pesticide cost (yuan/ha)	1,210.19	878.68	416.01	364.98	859.95	641.33	627.57	449.08
Against cotton bollworms	929.80	775.44	196.65	258.29	373.15	311.52	197.98	233.11
Against secondary pests	1.16	7.71	2.49	15.07	171.27	192.43	146.22	161.45
Seed quantity (kg/ha)	46.29	38.46	53.78	45.21	57.73	41.62	57.31	45.33
Seed cost (yuan/ha)	149.60	156.55	442.24	346.69	258.47	244.17	547.44	435.76
Labour use (days/ha)	510.11	155.78	477.09	151.72	346.25	132.33	285.45	144.51
Irrigation cost (yuan/ha)	58.87	67.15	84.89	117.39	85.67	176.89	132.36	197.01
Fertiliser quantity (kg/ha)	430.15	197.41	433.19	201.81	420.62	162.79	434.56	272.61
Age of household head (year)	45.12	9.05	43.61	8.75	46.40	8.53	49.10	8.53
Education of household head (year)	6.84	2.63	7.53	2.71	7.17	2.21	7.47	2.80
Household head is cadre (1 = yes)	0.06	0.25	0.09	0.29	0.10	0.31	0.13	0.34
Land owned per household (ha)	0.63	0.26	0.79	0.38	0.72	0.33	0.76	0.40
Cotton area (ha)	0.55	0.23	0.52	0.27	0.62	0.34	0.64	0.37

Krishna and Qaim, 2012). Consistently, our data show that total pesticide use in non-Bt cotton fields decreased from 58.3 kg/ha in the early adoption period to 38.5 kg/ha in the late adoption period (row 4). Similar results are shown for pesticide cost (row 7).

However, the use of pesticides on mirids, the secondary pest, increased significantly in both Bt and non-Bt fields from the early to late adoption periods (row 6), and also for costs (row 9). We also find that even though the infestation level of secondary pests in the late adoption period is much higher than in the early adoption period, it seems that there is no difference between Bt and non-Bt cotton fields (rows 6 and 9).

Hence, Table 1 seems to show that Bt cotton successfully outperformed non-Bt cotton both in the early and the late adoption periods. Even though the pesticide usage on secondary pests has increased in the late adoption period, the pesticide reducing effect of Bt technology is still much larger than the increasing effect of secondary pests. Nevertheless, controlling for potentially confounding factors and isolating the impact of Bt technology requires multivariate regression analysis.

3. Regression Models

To estimate the unbiased treatment effects of Bt adoption on chemical pesticide use and cotton yield, we develop and estimate two types of models: a cotton yield model and a pesticide use (pesticide quantity and pesticide cost) model. These models can generally be represented as:

$$Y_{it} = \boldsymbol{X}_{it}\beta + \varepsilon_{it} \quad (1)$$

where Y is the respective outcome variable (i.e. the yield, quantity of, and expenditure on pesticide use). $\boldsymbol{X}$ is a vector of the independent variables, including Bt adoption. β is the vector of parameters to be estimated. Subscript i denotes the ith plot, subscript t is the time (survey wave), and ε is the error term.

3.1. Yield model

The yield function used in our paper can be written as:

$$\begin{aligned} Yield_{i,t} = {} & \alpha_0 + \alpha_1 \times Bt_{i,t} + \alpha_2 \times Bt_{2004-2007i,t} + \alpha_3 \times Inputs_{i,t} + \alpha_4 \times Individual_{i,t} \\ & + \alpha_5 \times Province_i + \alpha_6 \times Year_t + e_{i,t}. \end{aligned} \quad (2)$$

In equation (2), Bt is a dummy variable, which equals 1 for a Bt plot, and 0 for a non-Bt plot. If the estimated coefficient of the Bt dummy variable in the yield function is positive and statistically significant, then the impact of Bt technology on cotton yield is positive, and *vice versa*.

In addition, we include a $Bt_{2004–2007}$ dummy variable, which is 1 if Bt cotton variety is planted in the late period (i.e. 2004, 2006 and 2007), and 0 otherwise. The *Bt* dummy variable is used to measure whether the technology has a positive net effect, whereas the $Bt_{2004–2007}$ dummy variable is used to capture the impact dynamics. For example, if the estimated coefficient of the *Bt* dummy variable is positive and the estimated coefficient of the $Bt_{2004–2007}$ dummy variable is statistically insignificant in the yield function, then the estimation results mean that the positive benefits of Bt technology is stable over time. A negative estimated coefficient of $Bt_{2004–2007}$ indicates that the benefit is shrinking, and *vice versa*.

The other input variables (*Inputs*) in the yield function include a hybrid dummy, seed cost, irrigation cost, fertiliser use, labour use, etc. As in Kathage and Qaim (2012), we also include the square of fertiliser use, square of pesticide use, and square of labour use to consider the non-linear relationships between them and the yield. To consider the interaction of the input variables, we also include the fertiliser–labour, fertiliser–pesticide and pesticide–labour variables in the estimation.

Characteristics of household heads (*Individual*), such as age and education, whether the household head is a cadre in the village, and whether the household head has attended any training programme on cotton production are also added into the yield function. Finally, provincial dummies (*Province*) and year dummies (*Year*) are added to control for the impact of location and time.

To control for the impact of all time-invariant factors that may affect the estimated relationships between Bt technology and yield (and the endogeneity problems that such unobserved heterogeneity can create), we take advantage of the panel nature of our data and estimate a fixed effect (FE) model (controlling the time-invariant fixed effects). Specifically, the FE model that we estimate is as follows:

$$\Delta Yield_{i,t} = \beta_0 + \beta_1 \times \Delta Bt_{i,t} + \beta_2 \times \Delta Bt_{2004-2007i,t} + \beta_3 \times \Delta Inputs_{i,t} + \beta_4 \times \Delta Cadre_{i,t} + \beta_5 \times \Delta Training_i + \beta_6 \times Year_t + \theta_{i,t} \tag{3}$$

where $\Delta Yield$, ΔBt, $\Delta Bt_{2004–2007}$, $\Delta Inputs$, $\Delta Year$, $\Delta Cadre$ and $\Delta Training$ are changes from their means of the variables defined above. In this version of the equation, we include only a subset of the variables (that is, only those variables that vary over time), so age (perfectly correlated with the time dummies), education and provincial dummies are excluded. θ is the error term.

3.2. Pesticide use model

Following Kathage and Qaim (2012) and Krishna and Qaim (2012), the FE models of pesticide use that we estimate can be written as:

$$\begin{aligned}\Delta Pesticide_{i,t} = {} & \gamma_0 + \gamma_1 \times \Delta Bt_{i,t} + \gamma_2 \times \Delta Bt_{2004-2007,i,t} + \gamma_3 \times \Delta Non - Bt_{2004-2007,i,t} \\ & + \gamma_4 \times \Delta Pesticide\_price_{i,t} + \gamma_5 \times \Delta Farm\_size_{i,t} + \gamma_6 \times \Delta Cadre_{i,t} \\ & + \gamma_7 \times \Delta Training_{i,t} + \gamma_8 \times \Delta Village\_Bt_{i,t} + \delta_{i,t}\end{aligned} \tag{4}$$

where $\Delta Yield$, ΔBt, $\Delta Bt_{2004–2007}$, $\Delta Cadre$, $\Delta Training$ are defined above. As we discussed in the above section, pesticide use is defined in terms of both quantity and cost. In addition to total pesticide use, we also consider pesticide use for controlling bollworms and pesticide use for controlling mirids as dependent variables.

Similar to the yield function, we include *Bt* and $Bt_{2004–2007}$ dummy variables to consider the impact of Bt technology on pesticide use and its impact dynamics. A significantly negative $Bt_{2004–2007}$ coefficient would indicate decreasing pesticide use (or increasing benefit), whereas a significantly positive coefficient would reveal increasing pesticide use (or shrinking benefit) over time.

In contrast to the yield equation, we also include a $Non\text{-}Bt_{2004–2007}$ dummy variable in pesticide use equations. This variable is 1 if the non-Bt variety is planted in the late period, and 0 otherwise. Previous studies have shown that the widespread adoption of

Bt cotton had successfully suppressed the cotton bollworm population density regionally; hence, those who planted non-Bt cotton varieties also reduced their pesticide applications (Carrière *et al.*, 2003; Wu *et al.*, 2008). A negative and significant *Non-*$Bt_{2004–2007}$ coefficient in the pesticide use functions indicates a pesticide use decrease for non-Bt cotton adopters, and *vice versa*.

Pesticide_price is the pesticide price. *Farm_size* is the land endowment of the household. To consider the impact of pest infestation over year, we also include a village full adoption variable (*Village_Bt*), which equals 1 if all the cotton in the village is Bt cotton, and 0 otherwise. δ is the error term.

4. Results

The results of the econometric estimation of equations (2) and (3) are shown in Table 2. In general, most of the regression results are consistent with the descriptive analysis in section 3. Most estimated coefficients of the control variables are of the expected signs and statistically significant in both the OLS model and the FE model. For example, the estimated coefficient of seed cost is significant and positive, indicating that plots planted with high-quality seeds (i.e. high seed cost) are more likely to have high cotton yield (row 4). At the same time, the estimation results also show that irrigation cost has a positive impact on cotton yield (row 5).

4.1. Impact of Bt technology on cotton yield and its impact dynamics

Importantly, the estimation results show that the adoption of Bt cotton has a positive net impact on cotton yield. As shown in Table 2, the estimated coefficient of the Bt dummy variable is positive in both the OLS and FE models and statistically significant in the FE model (row 1). According to the estimation results in the FE model, Bt cotton adoption increases the cotton yield by 155 kg/ha, which is equivalent to a 6% gain over the mean yield of non-Bt cotton plots.

More importantly, the estimation results tend to show that the positive net impact of Bt cotton adoption on cotton yield is stable. As discussed above, there are two Bt dummy variables in the models: the Bt dummy variable captures the impact of Bt cotton adoption in all years, whereas the additional $Bt_{2004–2007}$ dummy variable captures the impact of Bt cotton adoption in the late adoption period or the impact dynamics. The estimated coefficient of $Bt_{2004–2007}$ is positive but statistically insignificant in both OLS and FE models (row 2), indicating that the impact of Bt technology is stable over time.

Since Bt technology can only influence cotton yield through its impact on pest control or pesticide use, the impact of Bt technology on cotton yield must result from its impact on pest control, and consequently, on farmers' pesticide use. Similarly, the dynamics of the impact of Bt technology on yield must also result from the dynamics of its impact on pesticide use.

4.2. Impact of Bt technology on pesticide use and its impact dynamics

To assess the net impact of Bt cotton adoption on pesticide use and its impact dynamics, we estimate fixed-effect specifications of pesticide use functions. The results are shown in Table 3 (pesticide quantity equations) and Table 4 (pesticide cost equations). Because $Bt_{2004–2007}$, *non-*$Bt_{2004–2007}$ and the 3-year dummies (i.e. 2004, 2006

Table 2

Estimated coefficients of quadratic production (yield) function

	Dependent variable: yield (kg/ha)	
	OLS model	Fixed Effects model
Bt dummy	69.61	154.79
	(1.29)	(2.80)***
$Bt_{2004–2007}$ dummy	128.34	−12.71
	(1.23)	(0.12)
Hybrid dummy	9.06	74.67
	(0.27)	(2.16)**
Seed cost (yuan/ha)	0.26	0.17
	(9.31)***	(5.66)***
Irrigation cost (yuan/ha)	0.43	0.35
	(5.23)***	(4.12)***
Fertiliser (kg/ha)	0.12	-0.38
	(0.93)	(2.66)***
Square of Fertiliser	0.00	0.00
	(2.43)**	(4.38)***
Pesticide quantity (kg/ha)	17.78	14.38
	(10.67)***	(7.65)***
Square of Pesticide	−0.01	−0.01
	(2.06)**	(1.31)
Labour (day/ha)	1.17	1.01
	(4.07)***	(3.19)***
Square of labour	−0.00	−0.00
	(1.61)	(2.22)**
Fertiliser–labour interaction	−0.00	0.00
	(1.22)	(0.55)
Fertiliser–pesticide interaction	−0.01	−0.01
	(3.20)***	(2.95)***
Pesticide–labour interaction	−0.03	−0.02
	(8.85)***	(6.78)***
Age of household head	0.38	
	(0.29)	
Education of household head	−3.53	
	(0.86)	
Cadre dummy	91.09	27.67
	(2.71)***	(0.55)
Training dummy	64.87	128.12
	(2.67)***	(4.31)***
2000 year dummy	−148.60	−182.15
	(3.17)***	(3.85)***
2001 year dummy	193.69	201.90
	(4.00)***	(4.01)***
2004 year dummy	−515.17	−489.71
	(4.82)***	(4.51)***
2006 year dummy	−152.88	−57.92
	(1.40)	(0.53)
2007 year dummy	−307.23	−201.62
	(2.66)***	(1.72)*

Table 2
(*Continued*)

	Dependent variable: yield (kg/ha)	
	OLS model	Fixed Effects model
Provincial dummies	Yes	
Constant	3,190.43	2,704.06
	(24.18)***	(25.07)***
Observations	3,465	3,465
R^2	0.511	0.155
No. of households		522

Note: Absolute value of *t* statistics in parentheses; *significant at 10%; **significant at 5%; ***significant at 1%.

and 2007) in the late adoption period are perfectly multicollinear, two scenarios were estimated. Under the first scenario, we added $Bt_{2004–2007}$ and $non\text{-}Bt_{2004–2007}$ dummy variables and excluded the 3-year dummies. Under the second scenario, we added $Bt_{2004–2007}$ and the 3-year dummies and excluded the $non\text{-}Bt_{2004–2007}$ dummy variable. As shown Tables 3 and 4 (columns (1)–(3) vs. columns (4)–(6)), estimation results under these two scenarios are very similar.[7]

As expected, Table 3 shows that the estimated coefficient of the Bt dummy variable is negative and statistically significant, indicating that Bt cotton adoption leads to the reduction of pesticide use. According to the estimation results, Bt cotton adoption reduces total pesticide use in the early adoption period by 37.4 kg/ha, a 64% pesticide use savings over non-Bt cotton. This finding is consistent with the short-run impact of Bt cotton adoption in previous studies, such as Huang *et al.* (2002, 2003) and Pray *et al.* (2001). However, the estimated coefficient of the $Bt_{2004–2007}$ dummy variable is positive and significant (Table 3, row 2). In other words, the estimation result shows that compared to that in the early adoption period, pesticide use in the late adoption period increased. However, the net savings of pesticide use due to Bt technology adoption in the late adoption period is still positive and substantial ($37.4 - 11.2 = 26.2$ kg/ha).

We also find that the decrease in the total pesticide use comes mainly from the decrease in the use of pesticides against the cotton bollworm. The results show that the use of pesticides against the cotton bollworm in Bt cotton fields is reduced by 35.6 kg/ha (columns (2) and (5)), reflecting the Bt's effect on cotton bollworm resistance.

However, entomologists have shown that the Bt cotton adoption had successfully reduced the total pest population in all cotton fields (e.g. Lu *et al.*, 2010). In other words, with the widespread use of Bt cotton, pest infestation has decreased not only in Bt cotton fields but also in non-Bt cotton fields. To consider the impact of this 'externality', we add another dummy variable, $Non\text{-}Bt_{2004–2007}$, to the equation. The estimated coefficient of this variable is -12.3 in the total pesticide use equation (column (1)), which is approximately one-third of the estimated coefficient of the Bt dummy

[7]It is worth noting that when the $non\text{-}Bt_{2004–2007}$ dummy variable is included, the Bt effects are relative to non-Bt cotton in the early period. When the $non\text{-}Bt_{2004–2007}$ dummy variable is excluded, the effects are relative to all non-Bt plots, regardless of the period.

Table 3
Fixed effect models of pesticide use

	Dependent variable: pesticides use (kg/ha)					
	Total (1)	Bollworms (2)	Mirids (3)	Total (4)	Bollworms (5)	Mirids (6)
Bt dummy	−37.42	−35.59	−1.83	−37.46	−35.59	−1.86
	(26.79)***	(34.38)***	(2.11)**	(26.85)***	(34.89)***	(2.17)**
$Bt_{2004–2007}$ dummy	11.21	3.55	7.66	23.03	24.73	−1.70
	(8.80)***	(3.76)***	(9.68)***	(7.75)***	(11.38)***	(0.93)
Non-$Bt_{2004–2007}$ dummy	−12.29	−23.53	11.23			
	(3.96)***	(10.22)***	(5.83)***			
Pesticide price	−0.24	−0.18	−0.05	−0.25	−0.20	−0.04
	(9.64)***	(10.12)***	(3.45)***	(9.99)***	(11.28)***	(2.84)***
Farm size	−2.82	−3.60	0.77	−2.91	−1.73	−1.18
	(2.25)**	(3.87)***	(0.99)	(2.19)**	(1.79)*	(1.44)
Cadre dummy	−0.60	−1.41	0.82	−0.28	−0.45	0.17
	(0.41)	(1.31)	(0.90)	(0.19)	(0.42)	(0.19)
Training dummy	−0.54	1.26	−1.80	−0.72	0.88	−1.61
	(0.62)	(1.96)**	(3.35)***	(0.84)	(1.39)	(3.02)***
Village Bt adoption	−10.13	−7.00	−3.13	−10.18	−7.73	−2.45
	(8.09)***	(7.54)***	(4.02)***	(8.09)***	(8.40)***	(3.17)***
2000 year dummy	8.61	6.81	1.80	8.51	6.62	1.89
	(6.19)***	(6.60)***	(2.09)**	(6.12)***	(6.51)***	(2.22)**
2001 year dummy	6.92	1.82	5.10	6.77	1.04	5.74
	(4.87)***	(1.73)*	(5.78)***	(4.75)***	(0.99)	(6.55)***
2004 year dummy				−13.57	−27.04	13.47
				(4.31)***	(11.76)***	(6.97)***
2006 year dummy				−10.62	−19.90	9.28
				(3.36)***	(8.61)***	(4.78)***

Table 3
(*Continued*)

	Dependent variable: pesticides use (kg/ha)					
	Total (1)	Bollworms (2)	Mirids (3)	Total (4)	Bollworms (5)	Mirids (6)
2007 year dummy				−12.28	−19.63	7.35
				(3.83)***	(8.36)***	(3.73)***
Constant	65.25	52.73	12.52	65.73	52.49	13.24
	(31.53)***	(34.38)***	(9.75)***	(31.51)***	(34.41)***	(10.34)***
R^2	0.26	0.37	0.06	0.27	0.39	0.08
Observations	3,465	3,465	3,465	3,465	3,465	3,465
No. of households	522	522	522	522	522	522

Note: Absolute value of *t* statistics in parentheses; *significant at 10%; **significant at 5%; ***significant at 1%.

Table 4

Fixed effect models of pesticide cost

	Dependent variable: pesticides cost (yuan/ha)					
	Total (1)	Bollworms (2)	Mirids (3)	Total (4)	Bollworms (5)	Mirids (6)
Bt dummy	−767.32	−750.61	−16.87	−768.70	−750.66	−18.19
	(25.24)***	(33.68)***	(0.91)	(25.46)***	(34.24)***	(0.99)
$Bt_{2004–2007}$ dummy	354.33	106.94	247.26	514.66	513.29	−4.36
	(12.77)***	(5.26)***	(14.61)***	(8.00)***	(10.99)***	(0.11)
Non-$Bt_{2004–2007}$ dummy	−191.42	−460.17	274.26			
	(2.83)***	(9.29)***	(6.65)***			
Pesticide price	2.13	1.85	0.28	1.58	1.38	0.20
	(4.00)***	(4.74)***	(0.87)	(2.95)***	(3.55)***	(0.61)
Farm size	−65.52	−67.30	1.75	−58.64	−24.32	−34.24
	(2.40)**	(3.36)***	(0.11)	(2.04)**	(1.17)	(1.96)*
Cadre dummy	−25.75	2.78	−28.55	−8.44	24.74	−33.16
	(0.81)	(0.12)	(1.47)	(0.27)	(1.07)	(1.71)*
Training dummy	−2.69	37.63	−40.33	−11.80	29.08	−40.89
	(0.14)	(2.73)***	(3.52)***	(0.63)	(2.14)**	(3.58)***
Village Bt adoption	−197.44	−143.46	−53.76	−203.29	−160.11	−42.99
	(7.24)***	(7.18)***	(3.23)***	(7.46)***	(8.10)***	(2.59)***
2000 year dummy	208.27	147.42	60.86	203.37	143.11	60.27
	(6.88)***	(6.64)***	(3.29)***	(6.76)***	(6.55)***	(3.28)***
2001 year dummy	155.72	49.46	106.31	145.76	31.43	114.34
	(5.03)***	(2.18)**	(5.63)***	(4.72)***	(1.40)	(6.07)***
2004 year dummy				−258.98	−540.19	286.58
				(3.81)***	(10.93)***	(6.90)***
2006 year dummy				−108.02	−377.68	275.29
				(1.58)	(7.61)***	(6.60)***

Table 4
(*Continued*)

	Dependent variable: pesticides cost (yuan/ha)					
	Total (1)	Bollworms (2)	Mirids (3)	Total (4)	Bollworms (5)	Mirids (6)
2007 year dummy				−169.83	−370.49	206.37
				(2.45)**	(7.35)***	(4.87)***
Constant	1,173.52	939.25	234.38	1,190.56	933.40	257.22
	(26.05)***	(28.45)***	(8.53)***	(26.37)***	(28.48)***	(9.34)***
R^2	0.22	0.34	0.12	0.23	0.36	0.13
Observations	3,465	3,465	3,465	3,465	3,465	3,465
No. of household	522	522	522	522	522	522

Note: Absolute value of *t* statistics in parentheses; *significant at 10%; **significant at 5%; ***significant at 1%.

variable (row 3). In other words, similar to what occurred in the Bt cotton fields, the results show that pesticide use in the non-Bt cotton fields also decreased significantly in the late adoption period.

The decrease of total pesticide use in the non-Bt cotton fields in the late adoption period also mainly comes from the decrease of pesticide use against the cotton bollworm. As shown in the second column, pesticide use against the cotton bollworm decreased by 23.5 kg/ha in non-Bt cotton fields in the late adoption period. With the widespread use of Bt cotton, the cotton bollworm population has been successfully suppressed (Lu *et al*., 2010). The resulting benefits were felt by not only farmers who planted Bt cotton but also those who planted non-Bt cotton.

However, the results also show that pesticide use against the cotton bollworm increased slightly in the late adoption period. As shown in the second column, the estimate coefficient of the $Bt_{2004–2007}$ dummy variable is positive and significant, indicating that the farmers used more bollworm pesticides in the late adoption period. Consequently, in the late adoption period, the difference between Bt fields and non-Bt fields decreases. This might be the reason why most of the farmers and observers believe that the relative advantage of Bt cotton is dying away or has completely disappeared in China. However, as shown in row 2, compared to the early adoption period, farmers sprayed 3.55 kg/ha more pesticides to control cotton bollworm in the late adoption period, which is only approximately 10% of the reduction in pesticide use led by Bt cotton adoption.

Finally, the pesticide usage against secondary pests increased in both Bt fields and non-Bt fields in the late adoption period. With the widespread use of Bt cotton, farmers used less pesticide than before, because most chemical pesticides are broad-spectrum pesticides that can control the cotton bollworm, mirids and other pests. Hence, because farmers sprayed less pesticide to specifically control the cotton bollworm, the mirid population increased. Consequently, farmers must spray more pesticide to specifically control mirids (column (3)).

Finally, our results for the expenditure of pesticides used produce similar results (Table 4). Both the total pesticide cost and the pesticide cost against the cotton bollworm decreased substantially after Bt cotton adoption (row 1). Although the total pesticide cost increased in the late adoption period, the net impact of Bt technology adoption is still very substantial (row 2). Moreover, with the decrease of pesticide use against the cotton bollworm, the expenditures of pesticide use against secondary pests (i.e. mirids) increased in both Bt and non-Bt cotton fields (column (3)). Similar to the findings in the pesticide quantity estimations, non-Bt cotton adopters also benefit substantially from Bt cotton adoption (row 3).

5. Conclusions

Using farm-level panel data collected via six waves in rural China, we analysed the impact of Bt cotton adoption and its sustainability. Consistent with its short-run impact, this study shows that the net positive impact of Bt technology continued after Bt cotton had been commercialised for more than 10 years in China.[8] Nevertheless,

[8]According to the data released by the National Development and Reform Commission (various years), the general decreasing trend of total pesticide use in China's cotton production, led by Bt cotton adoption, continued after we conducted the last wave of field surveys in 2007.

the impacts have clearly eroded over time, with more pesticides being used in the later adoption period (2004–2007) compared with the earlier period. Our study also shows that the benefit of Bt technology spills over to those who planted non-Bt cotton varieties, reflecting the effects of the technology on pest populations.

The findings of this study have important implications. Since the short-run benefit of Bt cotton adoption has been well documented, the concern regarding the sustainability of the benefit has become an issue that has plagued the public and policymakers in recent years (Kathage and Qaim, 2012; Qiao, 2015). Because of this concern, development of genetically modified technology decelerated significantly. This study, together with other studies based on farm-level data (such as Huang *et al.*, 2010; Kathage and Qaim, 2012; Krishna and Qaim, 2012) and studies based on nationally representative aggregate data (Qiao, 2015; Qiao and Yao, 2015), showed that the benefit generated by Bt cotton persists, although diminished from the early adoption period. These empirical results might mitigate some concerns and contribute to the development of GM technology worldwide.

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Appendix
Information on Sampled Households and Cotton Plots

Table A1

Number of farms and plots sampled in the six survey rounds.

Year	No. of farmers sampled	New farmers over previous round	No. of Bt plots	No. of non-Bt plots
1999	218	218	279	28
2000	302	150	379	96
2001	244	88	435	91
2004	177	38	400	36
2006	320	25	928	16
2007	231	3	778	8