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Fifteen Years of Bt Cotton in China: Results from Household Surveys

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Summary. — The short-run benefit of insect-resistant *Bacillus thuringiensis* (Bt) crops has been well documented, but its sustainability in the long run has not been well studied. On the other hand, pest resistance build-up and secondary pest outbreaks have caused concern regarding the sustainability of this benefit. Using seven unique waves of panel data collected during 1999–2012, we show that pesticide use against bollworms has not increased significantly over time, indicating that the buildup of pest resistance is still not a concern because of the existence of a large number of nature refuge areas. In addition, we show that Bt cotton adoption has not led to outbreaks of secondary pests. Finally, we show that the benefit has been shared by both Bt and non-Bt cotton adopters as the widespread adoption of Bt cotton has successfully suppressed the density of the pest population regionally. We conclude that the benefit of Bt cotton adoption continues 15 years after its introduction, albeit with evidence of a decline in the comparative advantage over non-Bt cotton in late adoption period. We believe that this contribution is theoretically and practically relevant because of the long length of our dataset and because we categorize pesticide use into that for controlling bollworms and that for controlling secondary pests.

Key words — pesticide use, benefit sustainability, household panel data, *Bacillus thuringiensis* cotton, China

1. INTRODUCTION

The long-term sustainability of the benefits of *Bacillus thuringiensis* (Bt) cotton adoption has become an important concern since the early 2000s even though its short-run benefits have been well documented (Areal, Riesgo, & Rodriguez-Cerezo, 2013; Brookes & Barfoot, 2014; Elbehri & Macdonald, 2004; Qaim, 2003; Qaim & Zilberman, 2003; Stone, 2011; Thirtle, Beyers, Ismael, & Piesse, 2003). Its opponents believe that the benefits are unsustainable for two major reasons. First, the widespread adoption of Bt crops can lead to the buildup of pest resistance (Gould, 1998). As a result of the lower efficiency of the Bt toxin in controlling pests, farmers' pesticide use is thus gradually restored to the level before Bt cotton adoption. Second, Bt cotton adoption can lead to outbreaks of secondary pests, which would offset its benefits (Pemsl & Waibel, 2007; Wang, Just, & Pinstrup-Anderson, 2008).

Concerns about the sustainability of Bt cotton adoption have significantly affected the development of Bt technology. In particular, after the outbreaks of secondary pests in Bt cotton fields in the early 2000s, the negative attitude toward Bt cotton was exacerbated in the news and media (Cleveland & Soleri, 2005; Kathage & Qaim, 2012; Qiao, 2015). Partly because of this reason, cotton varieties with a single Bt gene were replaced by varieties with double genes, although no field evidence has thus far shown that pests have developed resistance to the single Bt toxin. Further, the growing of Bt corn is still prohibited in most countries even though it has been successfully planted for decades. Similarly, Bt rice has not yet been commercialized even though the technology has been available for more than 10 years.

However, owing to data availability, no previous studies have provided empirical evidence of the sustainability of the long-term benefits of Bt cotton adoption. For example, by analyzing theoretical and simulation models, Qiao, Huang, Wilen, and Rozelle (2009), Qiao, Huang, Rozelle, and Wilen (2010) showed that pest resistance might not be an important concern as numerous nature refuges exist in China. However, these hypotheses need to be supported by field data. Huang *et al.* (2010) and Wang *et al.* (2009), using household data collected in rural China, empirically showed that outbreaks of secondary pests are more likely the result of short-term weather changes (i.e., temperature and rainfall variation) than Bt cotton adoption. However, their results must also be tested with long-term field data. Similarly, the empirical works of Qaim and colleagues have not provided a satisfactory answer to the sustainability of the benefits because Bt cotton had only been planted for seven years when they conducted their final survey in India in 2008 (Kathage & Qaim, 2012).

Based on the foregoing, this study estimates the sustainability of the benefits of farmed Bt cotton adoption, using seven-wave household data from China during 1999–2012. We believe that the presented findings provide a satisfactory answer to the issue of the sustainability of Bt cotton for two reasons. First, Bt cotton was first commercialized in 1997, while our last round of field surveys was conducted in 2012. In other words, this study assesses the benefit over 15 years. Second, we divide total pesticide use into pesticide use for controlling bollworms and that for controlling secondary pests. By analyzing the dynamics of pesticide use against bollworms, we thus determine whether the resistance buildup in the pest

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population has decreased the efficiency of the Bt toxin. Moreover, by analyzing the dynamics of pesticide use against secondary pests, we study whether Bt cotton adoption has caused outbreaks of secondary pests.

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

2. DATA COLLECTION AND PESTICIDE USE OVER TIME

(a) *Data collection*

Our data include seven waves of field surveys in 1999–2001, 2004, 2006, 2007, and 2012. Since Bt cotton was first commercialized in China in 1997, as noted in the Introduction, we believe that this is the largest amount of field survey data focused on the performance of Bt cotton. The sample covers farmers in four provinces—Shandong, Hebei, Henan, and Anhui—in North China Plain, China's largest cotton production region. These four provinces are the second-, third-, fourth-, and sixth-largest cotton production provinces in China, respectively (National Bureau of Statistics China, hereafter NBSC, 2008).

The first wave of the field survey was implemented in winter 1999, only two years after Bt cotton was officially commercialized in China. During pretests and interviews with local officers, researches, and farmers, we found that the adoption rate of Bt cotton varied significantly among major cotton production regions at that time. Because adoption rates of Bt cotton in the Yangtze River valley and Northwest were very low, 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 countries in Shandong province where cotton was intensively planted were selected. After county selection, we randomly selected two villages in each county and about 20 farmers within each village.

Follow-up waves were conducted in 2000–2001, 2004, 2006–2007, and 2012. 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.

We continued to extend our sample sites for at least three reasons: (1) 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; (2) to increase the representativeness of our households to China's cotton production;[1] (3) to compensate for the respondent attrition that occurred in later 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 farmers in the same village to replace those who dropped out. The priority was given to their relatives (e.g., brothers, sons, or father) or neighbors.

In each of the seven-wave surveys, farmers were asked to provide detailed information about their cotton production, households, and each individual. The survey questionnaire was designed to collect basic socioeconomic information and included several blocks. First, there was a section on basic household characteristics, such as farm size and labor 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.[2] 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 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?

As shown in Table 1, the final sample includes 4,127 cotton plots, from 627 households, in 20 villages.[3] Considering the wide and rapid spread of Bt cotton, it was hard to find non-Bt cotton plots that have existed since the early 2000s. As shown in the last column of Table 1, the numbers of non-Bt plots in later years (i.e., 2006, 2007, and 2012) are relatively small. Because of these small numbers of non-Bt plots, the comparison between Bt and non-Bt cotton might be unrepresentative in later years.

(b) *Pesticide use in Bt and non-Bt plots over time*

In China's major cotton production regions, bollworm is the primary pest (Guo, 1998). However, there is no consensus about secondary pests. Since this study aims to understand the impacts of Bt cotton adoption on bollworms *and* other pests over time, we grouped all pests except for bollworms together. In the rest of this study, unless otherwise specified, secondary pests mean all other pests except for bollworms. The secondary pest question arose when the infestation of mirids became a serious problem. In fact, mirids have been considered as the only secondary pests in some studies. Hence, we also analyzed the impact of Bt cotton adoption on pesticide use against mirids.

Table 2 shows the dynamics of the quantity of and expenditure on pesticide use per year. As shown in the first row of Table 2, total pesticide use has no clear monotonic increasing or decreasing trend over time. It increased in 1999–2001 but fell thereafter. This conclusion holds regardless of whether we check the quantity of or expenditure on total pesticide use.

To show the impact of Bt cotton adoption, we compare pesticide use in Bt fields with that in non-Bt fields. As shown in the second and third rows of Table 2, pesticide use in Bt fields always outperforms that in non-Bt fields irrespective of measurement using quantity or cost. In other words, the comparative advantage of Bt cotton over non-Bt cotton has remained over time. However, the comparative advantage of Bt cotton over non-Bt cotton, measured as the difference between pesticide use in Bt plots and in non-Bt plots, reduces in later years.

More interestingly, while there is no significant change in pesticide use in Bt cotton plots, pesticide use in non-Bt cotton plots presents a clear decreasing trend over time (see the third row of Table 2). Hence, the reduction in pesticide use in non-Bt plots leads to the diminishing comparative advantage of Bt cotton in later years. Wu, Lu, Feng, Jiang, and Zhao (2008) showed that the widespread adoption of Bt cotton has successfully suppressed the density of the pest population in both Bt and non-Bt cotton fields. Consistent with this finding, the pre-

Table 1. *Number of farms and plots sampled in the seven survey rounds. Data are from authors' survey*

Year	No. of farmers sampled	New farmers over previous round	No. of total plots	No. of Bt plots	No. of non-Bt plots
1999	218	218	310	279	31
2000	303	151	486	382	104
2001	244	87	526	435	91
2004	202	43	495	455	40
2006	320	23	945	931	14
2007	240	3	814	808	6
2012	310	102	551	548	3
Total	1837	627	4127	3838	289

Table 2. *Pesticide use in Bt and non-Bt cotton plots*

	Quantity (kg/ha)							Cost (1000 yuan/ha)						
	1999	2000	2001	2004	2006	2007	2012[a]	1999	2000	2001	2004	2006	2007	2012[a]
Total pesticide use														
All plots	18.07	26.44	31.03	24.59	24.82	19.67	15.62	0.42	0.55	0.62	0.54	0.67	0.47	0.76
Bt plots	11.48	20.76	24.11	23.42	24.51	19.68	15.62	0.25	0.44	0.49	0.52	0.67	0.47	0.76
Non-Bt plots	77.47	47.30	64.11	37.84	45.44	19.26	14.75	1.88	0.96	1.24	0.77	1.03	0.45	1.07
Pesticide use against bollworms														
All plots	12.57	18.94	15.03	4.67	8.67	8.71	4.53	0.29	0.38	0.29	0.09	0.21	0.19	0.26
Bt plots	6.29	14.23	8.49	3.82	8.46	8.71	4.54	0.13	0.28	0.16	0.08	0.21	0.19	0.26
Non-Bt plots	69.11	36.26	46.25	14.30	22.49	9.36	3.12	1.68	0.73	0.89	0.29	0.48	0.20	0.39
Pesticide use against secondary pests														
All plots	5.51	7.50	16.01	19.92	16.15	10.96	11.09	0.13	0.17	0.34	0.45	0.46	0.28	0.50
Bt plots	5.19	6.53	15.62	19.60	16.05	10.97	11.09	0.12	0.16	0.33	0.44	0.46	0.28	0.50
Non-Bt plots	8.36	11.04	17.86	23.54	22.95	9.91	11.63	0.19	0.23	0.35	0.49	0.55	0.25	0.68
Pesticide use against mirids														
All plots			0.30	7.22	6.59	4.88	1.43			0.01	0.15	0.15	0.11	0.09
Bt plots			0.33	7.12	6.47	4.89	1.42			0.01	0.15	0.15	0.11	0.09
Non-Bt plots			0.17	8.28	14.55	3.20	2.82			nd[b]	nd[b]	0.55	0.03	nd[b]

Data are from the authors' surveys in China's four major cotton-producing provinces. During the seven-wave surveys, 627 households were visited and most of them were revisited more than once. The statistics are from the 4,127 cotton plots, including those repeatedly visited.
[a] Due to rapid spread of Bt cotton, it was difficult to find non-Bt cotton plots in our sample sites in later years. As there are only three non-Bt cotton plots, the comparison in 2012 might be unrepresentative.
[b] No data.

sent study shows that non-Bt adopters have also substantially reduced their pesticide applications.

As noted earlier, we further classified total pesticide use into pesticide use against bollworms and pesticide use against secondary pests (and mirids). If the pesticide spray was for two or more targets, questions on the shares of each target were asked, and pesticide use for each target was calculated based on these shares. Such a categorization of pesticide use is of interest because Bt technology is effective at controlling bollworms but ineffective at controlling secondary pests.

The quantity of and expenditure on pesticide use against bollworms are shown in rows 4–6 of Table 2. Similar to total pesticide use, pesticide use against bollworms does not significantly change over time in Bt plots, but has a clear decreasing trend in non-Bt plots. Moreover, pesticide use against bollworms in Bt cotton fields is consistently smaller than that in non-Bt cotton fields, indicating that Bt cotton is still efficient at controlling bollworms.

The bottom part of Table 2 shows no difference between pesticide use against secondary pests and pesticide use against mirids in Bt and non-Bt plots. The quantity of and expenditure on pesticide use against secondary pests in Bt plots are similar to those in non-Bt fields (rows 8–9). Although expenditure on pesticide use against secondary pests increases over time, the increasing trend in Bt plots is similar to that in non-Bt plots. A similar story is repeated if we analyze pesticide use against mirids (rows 10–12).[4] In other words, Table 2 shows that Bt cotton adoption might not be responsible for the outbreaks of secondary pests.

3. REGRESSION MODELS

The results from the descriptive analysis are inconclusive because other factors might also affect pesticide use. To isolate the impact of Bt cotton adoption, we thus setup and estimate a general pesticide use model at the farm level in line with other studies (e.g., Huang, Hu, Pray, Qiao, & Rozelle, 2003; Pingali, Marquez, & Palis, 1994; Qaim & Zilberman, 2003).

We are specifically interested in three types of models: (1) pesticide use against bollworms, (2) pesticide use against secondary pests, and (3) pesticide use against mirids. For each model, pesticide use is measured in terms of either quantity or cost. In the following, we first discuss the functions used to estimate pesticide use against bollworms for two reasons. First, the pesticide use against secondary pests model and pesticide use against mirids model are similar. For simplicity, we discuss these two types of models together. Second, in both these models, endogenous pesticide use against bollworms is added as an explanatory variable.

(a) *Models to estimate pesticide use against bollworms*

Factors affecting pesticide use against bollworms include Bt cotton adoption, refuge intensity, price of pesticides for controlling bollworms, and the characteristics of farmers. The empirical model used to estimate pesticide use against bollworms can be written as

$$Q\_bollworm_{ijt} = \alpha_0 + \alpha_1 * Bt_{ijt} + \alpha_2 * Bt_{ijt} * Year_t + \alpha_3 * non - Bt_{ijt} * Year_t + \alpha_4 * Refuge_{ijt} + \alpha_5 * Price\_B_{ijt} + \alpha_6 * Land_{it} + \alpha_7 * Household_i + \varepsilon_{ijt} \quad (1)$$

In Eqn. (1), subscript *i* is the *i*th household, *j* is the *j*th cotton plot, *t* is the *t*th year, and ε is the error term.

The dependent variable, *Q_bollworm*, is pesticide use against bollworms. This variable has two specifications: the quantity of and expenditure on pesticide use to control bollworms. The quantity of pesticide use is widely used to measure pesticide use (e.g., Huang, Hu, Rozelle, Qiao, & Pray, 2002; Huang *et al.*, 2003; Pray, Ma, Huang, & Qiao, 2001) and is also the core variable in our analysis. Expenditure on pesticide use is included since we also want to know whether the quality of pesticides matters.

The first independent variable of interest is the Bt dummy (*Bt*), which equals 1 for a Bt plot and 0 for a non-Bt plot. This variable is added to consider the general impact of Bt cotton adoption on pesticide use. A negative and significant coefficient of this variable means that Bt cotton adoption leads to a reduction in pesticide use and vice versa.

The second independent variable of interest is the interaction terms of the Bt dummy and year dummies (*Bt** Year*). These six interaction variables are created by multiplying the Bt dummy variable by each year dummy (for 2000, 2001, 2004, 2006, 2007, and 2012, with 1999 as the base year). These interaction variables are included to estimate whether the impact of Bt cotton on pesticide use varies over time. In other words, these six variables are used to account for the impact dynamics of Bt cotton in Bt plots.

Similarly, the interaction terms of the non-Bt dummy and year dummies (*non-Bt** Year*) are added to measure the dynamics of pesticide use in non-Bt fields. These six interaction terms are added to account for the spillover effect of Bt cotton. Because the six interaction terms of the Bt dummy variable and year dummies (*Bt** Year*), the six interaction terms of the non-Bt dummy variable and year dummies (*non-Bt** Year*), and six year dummies (*Year*) are perfectly multicollinear, we exclude the year dummies from the equation.

Refuge is a vector of variables included to capture the impacts of those refuge crops, including non-Bt cotton and other non-Bt crops (e.g., corn, soybean). In this study, we use two refuge variables. The first variable is the Bt cotton full adoption dummy, which is 1 if the village has completely adopted Bt cotton and 0 if there remains a share cultivated in non-Bt cotton. Following Huang *et al.* (2010), the second refuge variable is nature refuge intensity, which is the share of farm size planted in wheat (times 0.25) and other crops (e.g., maize, soybeans, non-Bt cotton, rapeseed, and vegetables). These crops are also important host crops for bollworms (Qiao, Huang, Wilen, & Rozelle, 2009).

Finally, *Price_B* is the unit price of the pesticides used to control bollworms and *Land* is the household's farm size. Taking advantage of the panel data dataset, we add household dummies (*Household*) to capture the impact of those time-invariant characteristics of households. After adding these dummy variables, we estimate a household fixed effect model.

(b) *Models to estimate pesticide use against secondary pests and mirids*

Outbreaks of secondary pests are considered as one of the largest threats to the sustainability of the benefits of Bt cotton adoption. After such outbreaks, farmers have to spray more pesticides compared with before Bt cotton adoption (Wang *et al.*, 2008). To isolate the impact of Bt cotton adoption on pesticide use against secondary pests (and specifically mirids), we set up and estimate econometric models. Since the model used to estimate pesticide use against secondary pests is similar to that used to estimate pesticide use against mirids, we first discuss the former in detail and then the latter in a simple way.

Following Wang *et al.* (2009), the model used to explain pesticide use against secondary pests is

$$Q\_secdonary_{ijt} = \gamma_0 + \gamma_1 * Q\_bollworm_{ijt} + \gamma_2 * climate_{it} + \gamma_3 * Price\_S_{ijt} + \gamma_4 * Land_{it} + \gamma_5 * Household_i + \phi_{ijt} \quad (2)$$

where *Q_secondary* is pesticide use against secondary pests. Similar to the specification of pesticide use against bollworms, pesticide use against secondary pests also has two specifications: quantity and cost.

Q_bollworm is added to capture the impact of Bt cotton adoption. If Bt cotton adoption led to a rise in the infestation of secondary pests, the estimated coefficient of *Q_bollworm*is negative and significant and vice versa. Similarly, an insignificant estimated coefficient of the *Q_bollworm* variable indicates that Bt cotton adoption, via pesticide use against bollworms, has no significant impact on pesticide use against secondary pests.

However, *Q_bollworm* is endogenous. Ignoring the endogeneity of this variable might thus yield estimation bias. To eliminate this possible source of bias, an instrumental variable approach is used in a two-stage least squares estimation framework. As shown in Eqn. (1), the Bt dummy, interaction terms of the Bt dummy and year dummies, interaction terms of the non-Bt dummy and year dummies, and price of pesticides for bollworms are used as instrumental variables in this study.

Following Wang *et al.* (2009), 10 climate variables (*Climate*) are added to capture the impact of climate on pest density and hence pesticide use to control secondary pests. These 10 climate variables include five temperature variables (*Temperature*) and five rainfall variables (*Rainfall*). The five temperature variables are the maximum daily temperatures in May, June, July, August, and September. The five rainfall variables are average rainfall in each of these months. These five months are selected since the cotton-growing season in the sampled sites runs from May to September. *Price_S* is the average price of all pesticides sprayed to control secondary pests. Similarly, as in Eqn. (1), taking advantage of the long panel dataset used, we estimate household fixed effect models by adding a set of household dummy variables (*Household*) into the model.

Next, we set up the following model to estimate pesticide use against mirids:

$$Q\_mirid_{ijt} = \theta_0 + \theta_1 * Q\_bollworm_{ijt} + \theta_2 * Climate_{it} + \theta_3 * Price\_M_{ijt} + \theta_4 * Land_{it} + \theta_5 * Household_i + \zeta_{ijt} \quad (3)$$

where *Q_mirid* is pesticide use to control mirids and *Price_M* is the average price of all pesticide use to control mirids. All the other variables are as above.

4. RESULTS AND DISCUSSION

The estimation results are shown in Tables 3–5. In general, most of the regression results are consistent with the descriptive analysis in Section 3. Most estimated coefficients of the control variables show the expected signs and are statistically significant. For example, the sign of the price of pesticide use is negative in the quantity function and positive in the cost function. In other words, the estimation results show that when the price of pesticides rose, farmers sprayed less pesticide and total expenditure on pesticide use increased. In the following, we discuss the estimation results in detail.

(a) *The dynamics of pesticide use to control bollworms*

Importantly, the estimation results show that the benefit of Bt cotton adoption, on average, is positive during the 15 years after Bt cotton was commercialized in China. As shown in Table 3, the estimated coefficient of the Bt dummy variable is negative and significant, indicating that pesticide use against bollworms in Bt fields is significantly smaller than that in non-Bt fields. On average, farmers spray 30.14 kg/ha of pesticides (or 78.49%) less in Bt cotton fields than in non-Bt cotton fields. The general benefit of Bt cotton adoption over 15 years is consistent with the short-run impact shown in previous studies (e.g., Huang *et al.*, 2003; Pray *et al.*, 2001). The consistency of the short- and long-term impacts provides the first clue for the sustainability of the benefit of Bt cotton adoption.

More importantly, the estimation results show that the benefit is sustainable over time. As shown in the second column of

Table 3. *Estimated parameters using a household fixed-effects model for estimating the effect of Bt cotton on the pesticide use against bollworms*

	Amount (kg/ha)		Cost (yuan/ha)	
	(1)	(2)	(3)	(4)
Bt dummy (1 = yes)	−30.14***	−54.34***	−626.30***	−1,380.16***
	(−34.62)	(−22.33)	(−34.47)	(−27.58)
Bt dummy * 2000 year dummy		10.62***		218.24***
		(10.74)		(10.73)
Bt dummy * 2001 year dummy		3.05***		73.75***
		(2.99)		(3.51)
Bt dummy * 2004 year dummy		0.10		10.83
		(0.09)		(0.52)
Bt dummy * 2006 year dummy		5.61***		148.84***
		(6.14)		(7.92)
Bt dummy * 2007 year dummy		6.36***		141.62***
		(6.79)		(7.36)
Bt dummy * 2012 year dummy		2.88**		130.30***
		(2.45)		(5.41)
Non-Bt dummy * 2000 year dummy		−17.92***		−631.98***
		(−6.53)		(−11.19)
Non-Bt dummy * 2001 year dummy		−12.51***		−572.07***
		(−4.58)		(−10.18)
Non-Bt dummy * 2004 year dummy		−40.20***		−1,102.18***
		(−12.77)		(−17.02)
Non-Bt dummy * 2006 year dummy		−37.23***		−995.20***
		(−9.29)		(−12.08)
Non-Bt dummy * 2007 year dummy		−48.33***		−1,215.39***
		(−8.93)		(−10.92)
Pesticides (against bollworm) price	−0.06***	−0.06***	0.95***	0.99***
	(−6.67)	(−6.76)	(5.11)	(5.58)
Non-Bt refuge dummy(1 = no)	−5.17***	−4.32***	−108.91***	−85.21***
	(−6.20)	(−5.36)	(−6.26)	(−5.13)
Share of nature refuge crops	18.79***	14.20***	415.55***	275.88***
	(6.39)	(4.96)	(6.77)	(4.68)
Farm size (ha)	−0.22	−0.39	1.57	−3.64
	(−0.54)	(−1.03)	(0.19)	(−0.46)
Year Dummies	YES	NO	YES	NO
Constant	35.69***	59.28***	677.37***	1,411.58***
	(21.90)	(21.77)	(19.91)	(25.20)
Observations	4,127	4,127	4,127	4,127
R-squared	0.360	0.407	0.338	0.404
Number of households	627	627	627	627

Note: Figures in parentheses are absolute value of *z* statistics. The symbols *, ** and*** denote significance at 10, 5, and 1%, respectively. The number of observations used in regression was 4127. Data are from authors' survey.

Table 4. *Estimated parameters using a household fixed-effects model for estimating the effect of Bt cotton on the pesticide use against secondary pests*

	Quantity (kg/ha)	Cost (yuan/ha)
Quantity of pesticide use against bollworms (kg/ha)	−0.02	
	(−1.14)	
Cost of pesticide use against bollworm (yuan/ha)		0.00
		(0.07)
Price of pesticides against secondary pests (yuan/kg)	−0.14***	−0.02
	(−14.97)	(−0.07)
Max daily temperature in May (°C)	−1.10***	−25.12***
	(−6.20)	(−6.37)
Max daily temperature in June (°C)	−0.04	21.66***
	(−0.11)	(3.20)
Max daily temperature in July (°C)	0.16	15.75**
	(0.52)	(2.36)
Max daily temperature in August (°C)	3.04***	66.07***
	(9.25)	(9.08)
Max daily temperature in September (°C)	0.10	−17.72***
	(0.53)	(−4.24)
Average rainfall in May (mm)	−1.41***	−22.63***
	(−6.76)	(−4.92)
Average rainfall in June (mm)	1.15***	19.99***
	(6.74)	(5.30)
Average rainfall in July (mm)	−1.30***	−0.31
	(−11.63)	(−0.13)
Average rainfall in August (mm)	1.10***	18.13***
	(11.67)	(8.69)
Average rainfall in September (mm)	1.22***	48.83***
	(6.51)	(11.76)
Farm size (ha)	−0.72**	−37.84***
	(−2.36)	(−5.58)
Constant	−49.13***	−1,831.85***
	(−3.52)	(−5.96)
Observations	4,127	4,127
R-squared	0.549	0.595

Note: Figures in parentheses are absolute value of z statistics. The symbols *, ** and *** denote significance at 10, 5, and 1%, respectively. The number of observations used in regression was 4127. Data are from authors' survey.

Table 3, although the estimated coefficients of the interaction terms of the Bt dummy and year dummies are positive, their magnitudes are much smaller than the estimated coefficient of the Bt dummy. In other words, although the comparative advantage of Bt cotton over non-Bt cotton decreases in later years, the net benefit is still positive and substantial in absolute value. This finding implies that the Bt toxin is still efficient at controlling bollworms and that the buildup of the resistance of the pest population is not a concern 15 years after the introduction of Bt cotton in China.

The buildup of the resistance of the pest population is not a concern because of the existence of a large number of nature refuge areas. Although planting non-Bt cotton as a refuge crop is not mandatory, China's farming sector is composed of millions of small households in highly fragmented farms, which allows bollworms to find sufficient natural refuges such as maize, wheat, and soybean (Qiao *et al.*, 2009). As a result, the Bt toxin is still efficient at controlling bollworms overtime (i.e., pesticide use against bollworms has not increased significantly).

Interestingly, the estimation results also show that the benefit of Bt cotton adoption had been shared by non-Bt cotton adopters. As shown in the second column of Table 3, the estimated coefficients of all the interaction terms of the non-Bt dummy and year dummies are negative and statistically significant. In other words, pesticide use in non-Bt cotton fields in later years (i.e., 2000 and after) is much smaller than that in 1999, the base year. According to the estimation results, because of the reduction in pest density caused by the wide adoption of Bt cotton, the range of pesticide use reduction in non-Bt fields is from 12.51 kg/ha (or 18.10%) in 2001 to 48.33 kg/ha (or 69.93%) in 2007. These results indicate that the decrease in Bt cotton's comparative advantage in later years is determined by the reduction in pesticide use in non-Bt cotton fields.

Finally, our results for expenditure on pesticide use are similar (columns 3–4 in Table 3). The estimation results show that expenditure on pesticide use against bollworms decreases substantially after Bt cotton adoption. Although expenditure on pesticide use increases in later years, the net impact of Bt cotton adoption is still substantial. Similar to the findings in the quantity estimations, the results from the cost equations show that non-Bt cotton adopters also benefit substantially from Bt cotton adoption.

(b) *The dynamics of pesticide use to control secondary pests and mirids*

The estimation results of pesticide use against secondary pests are shown in Table 4. The first column shows the estimation results of the quantity equations, while the second column shows those of the cost equations. As shown in Table 4, the estimated coefficients of the quantity of and expenditure on pesticide use against bollworms are both

Table 5. *Estimated parameters using a household fixed-effects Tobit model for estimating the effect of Bt cotton on the pesticide use against mirids*

	Quantity (kg/ha)	Cost (yuan/ha)
Quantity of pesticide use against bollworm (kg/ha)	−0.06**	
	(−2.18)	
Cost of pesticide use against bollworms (yuan/ha)		0.04
		(1.38)
Price of pesticides against mirids (yuan/kg)	−0.00	0.06**
	(−0.93)	(2.56)
Max daily temperature in May (°C)	−0.31*	−3.48
	(−1.89)	(−0.97)
Max daily temperature in June (°C)	2.03***	48.89***
	(9.02)	(10.13)
Max daily temperature in July (°C)	−3.10***	−56.43***
	(−12.62)	(−10.85)
Max daily temperature in August (°C)	3.24***	55.22***
	(10.69)	(8.51)
Max daily temperature in September (°C)	2.93***	54.67***
	(11.73)	(10.50)
Average rainfall in May (mm)	1.68***	43.82***
	(9.47)	(11.91)
Average rainfall in June (mm)	−0.72***	−15.35***
	(−4.06)	(−3.93)
Average rainfall in July (mm)	−0.48***	−2.97
	(−4.83)	(−1.43)
Average rainfall in August (mm)	−0.31***	−5.98***
	(−3.40)	(−3.16)
Average rainfall in September (mm)	1.55***	33.46***
	(11.86)	(12.01)
Farm size (ha)	−1.21***	−30.96***
	(−5.87)	(−6.99)
Constant	−127.15***	−2,695.65***
	(−9.86)	(−9.82)
Observations	3,331	3,331

Note: Figures in parentheses are absolute value of z statistics. The symbols *, ** and *** denote significance at 10, 5, and 1%, respectively. The number of observations used in regression was 3331. Data are from authors' survey.

statistically insignificant (rows 1–2). In other words, pesticide use against bollworms owing to Bt cotton adoption has no impact on pesticide use against secondary pests. That is, the worry that Bt cotton adoption led to outbreaks of secondary pests is not supported by the evidence in this study.

The estimation results of pesticide use against mirids are shown in Table 5. Although mirids have been considered as the most important secondary pests, their infestation was not serious at all in 1999 and 2000. Because of nearly absent of mirids in cotton field, farmers did not separately record the pesticide use to control mirids in our first two years surveys. The pesticide use to control mirids was recorded in 2001 and farmers recorded pesticide uses to control each of all pests even the pesticide use to control a pest (e.g., mirids) was nearly zero with the updated questionnaire. Therefore, Eqn. (3) is estimated using the data collected in 2001, 2004, 2006, 2007, and 2012. The final sample includes 3331 plot observations of 547 households. In addition, as 25.58% of the observations are zero, we estimate Tobit models, rather than OLS models.

Table 5 shows that the reduction in pesticide use against bollworms, which is caused by Bt cotton adoption, leads to an increase in pesticide use against mirids (row 1). However, the impact is not substantial in terms of magnitude. According to the estimation results, pesticide use against mirids increases by 0.06 kg/ha if pesticide use against bollworms reduces by 1 kg/ha. As shown in Table 3, the maximum difference in pesticide use against bollworms between Bt fields and non-Bt fields is 38.78 kg/ha (in 2001). Hence, the maximum increase in pesticide use against mirids caused by Bt cotton adoption is 2.33 kg/ha (or 7.51% of total pesticide use). In addition, the estimated coefficient of the pesticide cost equation is insignificant, indicating that the cost of pesticide use against bollworms has no significant impact on that for mirids (column 2 of Table 5).

5. CONCLUSION

The sustainability of the benefit of Bt cotton adoption has been central to the debate between those who oppose Bt technology and those who support it. Taking advantage of the long household-level panel dataset collected in rural China, this study shows that pesticide use against bollworms has not increased significantly over time, indicating that the buildup of pest resistance is still not a concern 15 years after Bt cotton was commercialized in China. In addition, this study shows that Bt cotton adoption did not lead to outbreaks of secondary pests. Although Bt cotton adoption is associated with a rise in mirids, the magnitude of the increase is relatively small. Based on these seven-wave household data, this study thus provides solid evidence that the benefit of Bt cotton adoption is sustainable in China's cotton production regions.

We believe that the findings of this study have important implications. For years, those who oppose Bt technology have dominated the debate about its adoption. 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. For example, the technical part of Bt rice has been ready for more than a decade. However, it is still not commercialized in any countries. As rice is the largest crop and one that has high density pesticide use globally, not allowing the commercialization of Bt rice is a huge loss. Similarly, even though Bt maize had been successfully planted for two decades, the non-commercialization of Bt maize in China is also a huge loss. This study answered the two core questions that threaten the sustainability of Bt cotton under China's agricultural production system. This study with 15 years of Bt cotton adoption is consistent with the similar studies with 7 years of Bt cotton adoption in India (Kathage & Qaim, 2012; Krishna & Qaim, 2012). It is worth to note that our conclusions are based on China's current agricultural production system. Under different circumstances, the sustainability of Bt crops may differ. For example, there is evidence of resistance developed to the first generation of Bt strains in United States (Tabashnik, Brévault, & Carrière, 2013). Whether our results will be continued to be valid in China in the future is still worth for further study because China's agricultural production system is also undergoing significant change. But, we believe the results of this study will influence the debate about consumers' attitudes as well as the R&D of Bt technology worldwide.

NOTES

1. The climate and cotton production in Northwest China (mainly including Xinjiang Uyghur Autonomous Region and Gansu province) are significantly different from those in North China Plain.

2. The average household has approximately five 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.

3. For revisited households, each visit is counted as one observation. Similarly, each revisited plot is counted as one observation.

4. Although pesticide use against secondary pests and mirids increased significantly from the early to the mid-2000s, pesticide use against mirids only increased in some samples and in some years, and this did not continue in later years (see Table 6 for details). Further study confirms that the dynamics of pesticide use against other pests such as planthoppers, aphids, and red spiders showed a similar trend.

Table 6. *Amount of pesticide use against secondary pests and pesticide use against mirids in the sample villages in China for Bt cotton and non-Bt cotton plots, 1999–2012*

	Pesticide use against secondary pests (kg/ha)							Pesticide use against mirids (kg/ha)				
	1999	2000	2001	2004	2006	2007	2012	2001	2004	2006	2007	2012
Bt plots	5.19	6.53	15.62	19.60	16.05	10.97	11.09	0.33	7.12	6.47	4.89	1.42
Henan-Taik		7.21	9.97	22.96	14.10	13.48	7.00	1.05	11.40	6.41	4.58	1.21
Henan-Fugou		5.34	9.36	15.92	16.87	11.61	10.19	0.63	4.62	8.40	4.91	1.37
Shandong-Liangshan	6.97	6.43	10.79	7.61	5.85	5.92	9.49		3.71	2.63	3.10	1.08
Shandong-Xiajin	5.79	9.48			17.22	12.66	11.18			8.09	3.94	1.20
Hebei-Shenzhou	3.43	2.59			11.02	8.51	10.29			7.97	5.90	2.54
Hebei-Xinji	3.66	6.78	6.99	27.72	16.86	14.72	11.66		15.46	10.27	7.23	1.22
Anhui-Dongzhi			37.96	25.04	23.72		11.23	0.34	0.08	4.03		1.46
Anhui-Wangjiang			27.54	22.31	22.53		13.68	0.45	0.15	5.72		1.48
Non-Bt plots	8.36	11.04	17.86	23.54	22.95	9.91	11.63	0.17	8.28	14.55	3.20	2.82
Henan-Taik		11.49	10.19	26.34	19.90	12.48	16.48	0.40	12.32	9.44	3.94	5.50
Henan-Fugou		10.12	7.92	16.32	32.42	12.87	9.21	0.32	4.01	17.99	5.03	1.48
Shandong-Liangshan					8.79					5.25		
Shandong-Xiajin	8.36					14.18					3.33	
Hebei-Shenzhou												
Hebei-Xinji					33.18	3.72				30.38	1.48	
Anhui-Dongzhi			25.43	41.38					1.50			
Anhui-Wangjiang			25.39	18.45					0.19			

Note: Data are from authors' survey.

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APPENDIX A.