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Sustainability of the Economic Benefit of Bt Cotton in China: Results from Household Surveys

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ABSTRACT *In recent years, the sustainability of the economic benefit of Bacillus thuringiensis (Bt) crops has been subject to substantial debate. Using seven rounds of household survey data, this study shows that the economic benefit continued for 15 years after the commercialisation of Bt cotton in China. Owing to Bt cotton adoption, farmers have saved 8.46 billion US dollars on pesticide use during 1997–2012. This number is more than double if the benefits of increased yield, decreased labour use, and increased seed cost are considered. More importantly, the total quantity of pesticides used has been reduced by 2.19 million tons nationally during 1997–2012.*

1. Introduction

The short-term impact of *Bacillus thuringiensis*(Bt) cotton adoption has been well documented. Previous studies have shown that Bt cotton adoption led to a significant reduction in pesticide use and an increase in yield (Pray, Ma, Huang, & Qiao, 2001; Qaim, 2003). Studies in China have shown that Bt cotton adoption led to an increase in farmer benefits of 261–438 US$/ha, while the annual national benefit was 369 million US$ in the first few years of Bt cotton adoption (Fan, 2002; Pray, 2002). Consistent results were found in the following years (James, 2007). Similar benefits were also found in other countries where Bt cotton was planted (Brookes & Barfoot, 2005). These studies were usually based on household surveys conducted a couple of years after Bt cotton was commercialised in these countries.

However, the sustainability of the economic benefit of Bt cotton adoption has been subject to substantial debate. Those who oppose Bt technology are concerned that the short-term impact generated by Bt cotton will soon be completely offset due to increased pest resistance and secondary pest outbreaks (Pemsl & Waibel, 2007; Wang, Just, & Pinstrup-Anderson, 2008). In particular, since secondary pest outbreaks in approximately 2004, there has been widespread opposition to Bt technology in the media and public. The negative attitudes towards Bt technology have significantly affected consumers' attitudes, as well as governments' decisions on the scientific research and commercialisation of Bt crops (Qiao, 2015).

Despite the importance of this crop, no previous study has provided satisfactory information on the sustainability of the benefit of Bt cotton adoption. Based on household-level panel data, both Matin Qaim and his colleagues and Jikun Huang and his colleagues attempted to analyse the dynamics of

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the impact of Bt cotton adoption (for example, Huang et al., 2010; Kathage & Qaim, 2012; Krishna & Qaim, 2012; Qiao, Huang, & Zhang, 2016). These studies covered a medium-term time horizon of 7–10 years, but that looking at effects from a long-term perspective, as done here, is important, because changes in the technology's effectiveness can also occur after 7–10 years. Using aggregate provincial-level data, Qiao (2015) showed that the impact of Bt cotton adoption on pesticide use and yield did not diminish but continued. However, the results from this study might be misleading because of the usage of aggregate provincial-level data (Wooldridge, 2008). Using household-level data, Qiao, Huang, and Wang (2017a, 2017b) analysed the impact of Bt cotton adoption on the quantity and stability of pesticide use. However, these two papers focus only on pesticide use, while Bt technology also affects seed cost, labour use and cotton yield. Hence, the long-term comprehensive impact of Bt cotton adoption and its dynamics remain unclear.

The objective of this study is to fill this knowledge gap. Specifically, we 1) document the dynamics of pesticide use, labour input, seed cost, and cotton yield over time; 2) estimate the impact of Bt cotton adoption on inputs and outputs and their dynamics; and 3) summarise the national impact of Bt cotton adoption 15 years after its commercialisation in China. Bt cotton was commercialised in China in 1997, and our last field survey was conducted in 2012. Thus, our data cover a 15 year period after the commercialisation of Bt cotton. We believe that this study, based on long-term household panel data, should be able to provide satisfactory results to determine the sustainability of the economic benefit of Bt cotton adoption.

2. Data and the dynamics of pesticide use, labour, seed cost, and cotton yield

The data set is unique and includes seven rounds of household surveys conducted in rural China. We first discuss the sample selection and data collection and then analyse the data descriptively. Thus, we attempt to show the dynamics of pesticide use, labour use, seed cost, and cotton yield over time.

2.1. Data and samples

The panel data were collected in four provinces of China: Shandong, Hebei, and Henan provinces in the Yellow River valley, and Anhui Province in the Yangtze River valley; the Yellow River and Yangtze River valleys are two of the three major cotton-producing regions, while these four provinces are the second, third, fourth, and sixth largest cotton-producing provinces, respectively (National Bureau of Statistical of China [NBSC], 2008)[1]. Due to the warm and humid climate, bollworm infestations have been severe in these two regions (Wu & Guo, 2005). In particular, in the early 1990s, bollworm outbreaks caused substantial yield losses, and consequently, some farmers abandoned cotton production (Hsu & Gale, 2001; Huang, Hu, Pray, Qiao, & Rozelle, 2003).

The seven rounds of household surveys were conducted by the China centre for Agricultural Policy (CCAP). The first survey was conducted in winter 1999, two years after Bt cotton was officially commercialised in China. During pretests and interviews with local officers, we found that the adoption rate of Bt cotton in the Yangtze River valley and the northwest was very low at that time. Thus, we chose Shandong and Hebei, in the Yellow River valley where Bt cotton was introduced in 1997. Two counties in Hebei Province and three counties in Shandong Province where cotton was intensively planted also were selected. After county selection, we randomly selected two villages in each county and approximately 20 farmers within each village.

Follow-up surveys 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-producing 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 information on the sampled households and plots are shown in Table 1.[2]

We continually expanded our sample sites for three reasons: 1) to ensure we included non-Bt cotton because with the rapid spread of Bt cotton, it became difficult to find non-Bt cotton plots in the

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

Year	No. of farmers sampled	New farmers over previous round	Number of total plots	Number of Bt plots	Number 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

Yellow River valley after the early 2000s; 2) to increase the representativeness of our households to China's cotton production; and 3) to compensate for the respondent attrition that occurred in progressive surveys. Some sampled farmers had abandoned cotton cultivation during the period, mostly by turning to other crops, such as wheat and corn, or by renting out all their lands and migrating to cities. We randomly selected new sample respondents in the same village to replace those who we no longer part of the survey process. Priority was given to their relatives (for example, brothers, sons, or father) or neighbours.

In each of the seven rounds of surveys, farmers were asked to provide detailed information about their cotton production, households, and each individual in the household. The survey questionnaire was designed to collect basic socioeconomic information and included several sections. The first section was on basic household characteristics, such as farm size and labour endowments, production assets, and housing. The second section was designed to collect the 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. Information collected in this section forms the core of this paper's data that were used for analysis. For each cotton plot, detailed information regarding yield and all inputs, such as seed (whether the variety was Bt, seed price, and so forth), fertiliser use (quantity of fertiliser and expenditure on fertiliser), and labour use were recorded.

2.2. Spread of Bt cotton

Due to severe bollworm infestation, Bt cotton was first commercialised in the Yellow River valley in 1997. Because of the significant comparative advantage over traditional varieties, Bt cotton soon spread from the Yellow River valley to the Yangtze River valley. In the middle of the 2000s, only a few years after Bt cotton was first commercialised, almost all cotton fields were planted with Bt cotton.

Figure 1 shows the rapid spread of Bt cotton in our samples. The spread of Bt cotton in the Yellow River and Yangtze River valleys was so rapid that it was difficult to find non-Bt cotton fields in our subsequent field surveys. Thus, when we conducted the second round of surveys in 2000, we extended our samples to Henan Province, the second largest cotton-producing province at that time (NSBC, 2001). However, the share of Bt cotton in Henan was almost 80 per cent when we conducted another round of surveys in 2001. We then extended our samples into the Yangtze River valley. After the early 2000s, the adoption rate of Bt cotton was almost 100 per cent in both the Yellow River and Yangtze River valleys. As shown in Table 1, even though we continued expanding the reach of our samples, the number of non-Bt plots was still much smaller than that of Bt plots for the last three rounds of field surveys. Due to the small number of observations of non-Bt cotton plots, the comparison between Bt cotton and non-Bt cotton might not be representative, especially in 2012.

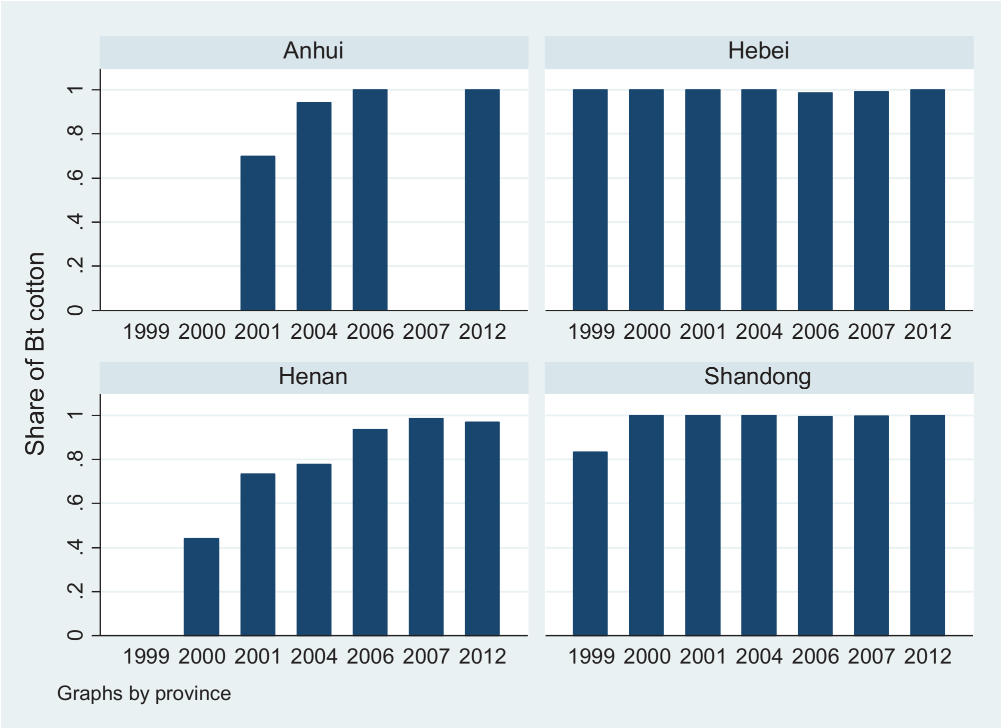

Figure 1. Bt cotton share in the sampled provinces.

2.3. Dynamics of pesticide use, labour use, seed cost, and cotton yield

Figure 2 shows the average pesticide use in Bt and non-Bt cotton fields during 1999–2012. Following previous studies, as an alternative, we used the quantity of pesticides used and expenditures on the pesticides used. As shown in Figure 2, both the quantity of pesticides used and expenditures on pesticides used for Bt fields is, on average, significantly smaller than the quantity and expenditures used for non-Bt fields (Up panel).

However, further calculations show that the comparative advantage of Bt cotton over non-Bt cotton diminished in subsequent years. In this study, we used the difference in pesticide use on Bt fields and that on non-Bt fields to measure the comparative advantage of Bt cotton. Table 2 shows that the advantage of Bt cotton was very significant in the early years but diminished in the subsequent years. For example, the pesticides used on Bt fields totaled 11.48 kg/ha, which is only 14.82 per cent of the amount used on non-Bt fields in 1999. The pesticides used on Bt fields were approximately one-third of that used on non-Bt cotton fields in 2000–2001. However, the difference in pesticide use on Bt fields and non-Bt fields disappeared between 2007 and 2012. A similar trend was observed for expenditures on pesticide used (3rd and 4th columns).

In other words, a simple comparison of pesticide use on Bt fields and non-Bt fields seems to indicate that the comparative advantage of Bt cotton diminished over time. Because a reduction in pesticide use is the major benefit of Bt cotton adoption, a reduction in the comparative advantage in pesticide use causes those who oppose Bt technology to believe that the benefit of Bt cotton is only a short-term impact, rather than a sustainable, long-term impact. However, a further study shows that the reduction in the comparative advantage of Bt cotton seems to come from the non-Bt cotton fields. As shown in Table 2, pesticide use levels remained low on Bt plots throughout the 15 years (columns 2 and 4), while pesticide use on non-Bt plots decreased over time (columns 1 and 3). Hence, the diminishing difference between Bt and non-Bt cotton fields decreased over time due to a decrease in

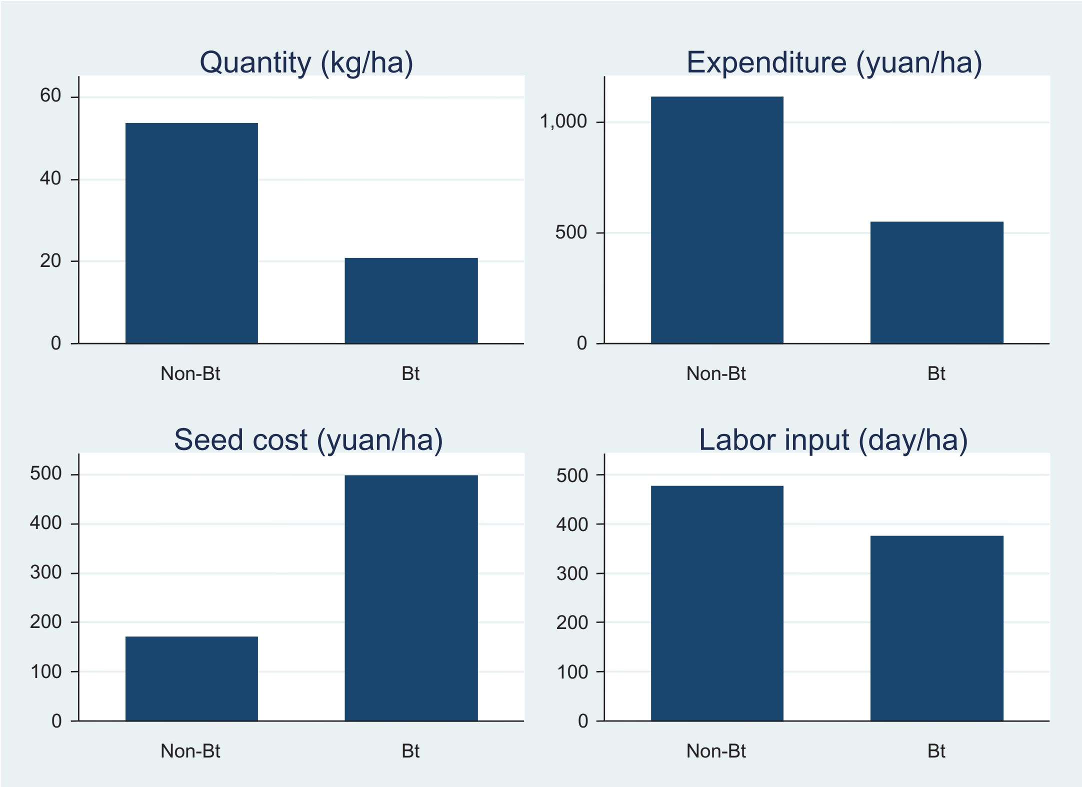

Figure 2. Average pesticide use, seed cost and labour inputs in Bt and non-Bt fields during 1999–2012.

Table 2. Pesticide use, labour input, seed cost and yield in Bt and non-Bt fields, 1999–2012

	Pesticide use									
	Quantity (kg/ha)		Expenditure (yuan/ha)		Labour (day/ha)		Seed cost (yuan/ha)		Yield (kg/ha)	
	Non-Bt	Bt	Non-Bt	Bt	Non-Bt	Bt	Non-Bt	Bt	Non-Bt	Bt
Total	53.51	20.73	1113.51	548.15	475.61	373.94	169.89	497.70	2524.38	3178.09
1999	77.47	11.48	1878.54	252.54	546.69	450.93	287.68	477.29	3512.66	3350.01
2000	47.30	20.76	955.99	441.46	480.03	513.43	134.14	392.79	1928.76	2993.67
2001	64.11	24.11	1241.50	491.30	523.74	460.57	111.05	458.48	2980.80	3383.33
2004	37.84	23.42	770.85	518.78	399.83	380.57	191.09	411.23	1990.64	2912.97
2006	45.44	24.51	1031.15	667.02	274.04	332.11	278.48	493.26	2475.00	3378.19
2007	19.26	19.68	447.26	468.26	236.78	182.28	311.06	537.88	2685.00	3014.08
2012	14.75	15.62	1072.11	758.39	557.07	516.87	905.85	632.41	2650.00	3142.72

non-Bt cotton pesticide use. If this scenario is true, then the benefit of Bt technology is not only sustainable but also is shared by non-Bt cotton adopters. We will develop econometric models and conduct estimations to test the hypothesis.

A similar trend was observed for labour use as that for pesticide use on Bt and non-Bt cotton fields. As shown in the 5th and 6th columns of Table 2, on average, the decrease in labour use was 21.38 per cent (373.94 days/ha on Bt plots vs. 475.61 days/ha on non-Bt plots). However, the advantage varied across years. In some years (for example, in 2000 and 2006), the average labour use on Bt plots was higher than that on non-Bt plots. This result is surprising because the reduction in pesticide use caused by Bt cotton adoption should have led to a reduction in labour use. However, some non-Bt cotton varieties are labour-saving varieties that do not involve branch pruning. As branch pruning is one of the most labour-intensive activities in cotton production, the decrease in labour use that occurred by the adoption of special non-Bt cotton varieties might have been higher than the decrease in labour use caused by Bt cotton adoption. Consequently, labour use on Bt cotton plots was higher than that on non-Bt plots in some years.

As expected, the seed cost for Bt fields was much higher than that for non-Bt fields. As new cotton varieties, the average seed price of Bt cotton was much higher than that of non-Bt cotton varieties. As shown in the 7th and 8th columns of Table 2, the seed cost of Bt cotton was two or more times that of non-Bt cotton for most of the years except for 2012. In 2012, the seed cost of Bt cotton was 632.41 yuan/ha, which was similar to that in the last round of the surveys (that is 2007). However, the seed cost of non-Bt cotton was 905.85 yuan/ha in 2012, which was much higher than that in the last round of the surveys and higher than that of Bt cotton. Thus, why was the seed cost of non-Bt cotton so high in 2012? As shown in Table 1, there were only three areas of non-Bt plots in the 2012 survey, which might have been special cotton varieties (for example, labour-saving varieties without branch pruning) and hence have had a higher price.

Finally, Table 2 shows that the average yield of Bt cotton plots was also higher than that of non-Bt cotton plots. On average, the yield of Bt cotton plots was 3178.09 kg/ha, which was 25 per cent higher than that of non-Bt cotton (row1). Furthermore, the average yields of Bt cotton fields were consistently higher than those of non-Bt cotton fields in each year except for 1999 (last two columns).

3. Regression models

The above results might be misleading owing to the presence of confounding factors. For example, cotton yield is affected not only by Bt varieties but also by other factors, such as fertiliser use, labour use, and pesticide use. To address this issue, in the following paragraphs, we set up and estimate econometric models to isolate the impact of Bt cotton adoption.

In contrast to traditional inputs, such as fertiliser and labour, Bt technology and pesticide use are special inputs. As traditional inputs contribute to an increase in yield, Bt technology and pesticide use are used to reduce yield losses. To accurately describe the relationship between these inputs and yield, Headley (1968) and Lichtenberg and Zilberman (1986) suggested incorporating a damage abatement function into traditional models of agricultural production. This method has been routinely used in previous studies, such as Huang et al. (2003) and Qaim and de Janvry (2005). Following this methodology, we assumed a Cobb-Douglas production function and a Weibull or exponential specification for the damage abatement function. Thus, the framework of the yield function can be written as follows:

$$\begin{aligned} Yield_{i,t} &= \alpha_0 \prod_{j}^{n} X_{j,i,t}^{\alpha_i}\left(1 - e^{-pesticide_{i,t}^{m}}\right) \qquad \text{(Weibull)} \\ Yield_{i,t} &= \beta_0 \prod_{j}^{n} X_{j,i,t}^{\beta_i}\left(1 - e^{-c*pesticide_{i,t}}\right) \qquad \text{(Exponential)} \end{aligned} \tag{1}$$

In Equation (1), each function includes two parts. The first part (terms outside the parentheses) represents the traditional Cobb-Douglas production function, while the second part (terms in the parentheses) represents the damage abatement function. *Yield* represents the cotton yield (measured in kilograms per hectare), while X_j denotes the vector of the input variables. In this study, we considered three important traditional inputs: *fertiliser, labour*, and *seed*.[3]

Taking advantage of the panel data dataset, we added household dummies (*ID*) to capture the impact of those time invariant characteristics of households. After adding these dummy variables, we estimated a household fixed effect model. To capture the impact of plot heterogeneity, we added a plot size variable (*Plot*) in the production equation. Then, the yield function in Equation (1) can be rewritten as:

$$Yield_{i,t} = \left(\alpha_0 + \alpha_1 * Plot_{i,t}\right) * Fertilizer_{i,t}^{\alpha_2} * Labor_{i,t}^{\alpha_3} * Seed_{i,t}^{\alpha_4} * \left(1 - e^{-pesticide_{i,t}^{m}}\right) + \sum_{i}^{N} ID_i + \mu_{i,t} \qquad \text{(Weibull)}$$
$$Yield_{i,t} = \left(\beta_0 + \beta_1 * Plot_{i,t}\right) * Fertilizer_{i,t}^{\beta_2} * Labor_{i,t}^{\beta_3} * Seed_{i,t}^{\beta_4} * \left(1 - e^{-c*pesticide_{i,t}}\right) + \sum_{i}^{N} ID_i + \eta_{i,t} \qquad \text{(Exponential)} \tag{2}$$

In the Weibull function form, m is the coefficient to be estimated to capture the impact of pesticide use on cotton yield. In this study, we have two scenarios to define m, which can be written as:

$$m = m_0 + m_1 * Bt_{i,t}$$
$$m = \lambda_0 + \lambda_1 * Bt_{i,t} + \sum_{t=2}^{7} \lambda_t * Bt_{i,t} * Year_t + \sum_{t=8}^{13} \lambda_t * Year_t \tag{3}$$

where *Bt* is a dummy variable with a value of 1 for the Bt variety and 0 otherwise. *Year* is a vector of year dummies for 2000, 2001, 2004, 2006, 2007, and 2012, with 1999 as the base year. In the first scenario, the impact of Bt cotton adoption on the yield and its dynamics were assumed to be the same over time. In the second scenario, we considered the difference in the impact of Bt cotton adoption on the yield over time, which is captured by the interaction terms of Bt dummy and year dummies (Krishna & Qaim, 2012).

Similarly, the coefficient c in the exponential function form can be defined as:

$$c = c_0 + c_1 * Bt_{i,t}$$
$$c = \theta_0 + \theta_1 * Bt_{i,t} + \sum_{t=2}^{7} \theta_t * Bt_{i,t} * Year_t + \sum_{t=8}^{13} \theta_t * Year_t \tag{4}$$

Finally, estimating Equation (2) separately might cause bias, as Bt technology adoption also affects the input variables (that is pesticide use, seed cost, and labour use). To resolve this issue, we needed to simultaneously estimate the yield model in Equation (2) with the following input use models:

$$Pesticide_{i,t} = \gamma_0 + \gamma_0 * Bt_{i,t} + \sum_{t=2}^{7} \gamma_i * Bt_{i,t} * Year_t + \sum_{t=8}^{12} \gamma_i * non - Bt_{i,t} * Year_t + \gamma_{13} * Pesticide\_price_{i,t} + \gamma_{14} * Plot_{i,t} + \sum_{i=1}^{N} ID_i + \xi_{i,t}$$
$$Labor_{i,t} = \psi_0 + \psi_0 * Bt_{i,t} + \sum_{t=2}^{7} \psi_i * Bt_{i,t} * Year_t + \sum_{t=8}^{12} \psi_i * non - Bt_{i,t} * Year_t + \psi_{13} * Labor\_price_{i,t} + \psi_{14} * Plot_{i,t} + \sum_{i=1}^{N} ID_i + \varepsilon_{i,t} \tag{5}$$
$$Seed_{i,t} = \phi_0 + \phi_0 * Bt_{i,t} + \sum_{t=2}^{7} \phi_i * Bt_{i,t} * Year_t + \sum_{t=8}^{12} \phi_i * non - Bt_{i,t} * Year_t + \phi_{13} * Plot_{i,t} + \sum_{i=1}^{N} ID_i + \upsilon_{i,t}$$

where *Pesticide_price* represents the average price of the pesticides sprayed, while *labour_price* denotes the wage rate. All the other variables are as discussed above.

In the pesticide equation, we added the interaction terms of Bt dummy and year dummies to capture the dynamics of the impact of Bt cotton on pesticide use over time. Previous studies have shown that Bt cotton adoption successfully suppressed the pest population regionally (Wu, Lu, Feng, Jiang, & Zhao, 2008). To consider the impact of Bt cotton on pesticide use in non-Bt fields, we also added the interaction terms of non-Bt dummy and year dummies. Since the interaction terms of Bt dummy and year dummies and those of non-Bt dummies and year dummies are perfectly collinear, year dummies and interaction terms of non-Bt dummy and year dummies were added into the functions alternatively. Finally, because there are only three areas of non-Bt plots in 2012, adding the interaction terms of non-Bt dummy and 2012 year dummy will cause similar issues. Hence, the interaction terms of non-Bt dummy and 2012 year dummy were excluded.

In the labour and seed cost equations, year dummies were added to consider the impact of those variables that vary from year to year. Similarly, the 2012 year dummy was dropped in labour and seed cost equations to avoid the collinearity problem. Finally, labour price (*labour_price*) was added to the labour equation to consider the impact of the increase in wage rate in recent years (Qiao & Yao, 2015).

4. Results and discussion

The results of the econometric estimation of the input equations are shown in Tables 3–5, while the estimation results of the cotton yield equation are shown in Table 6. In general, most of the regression results are consistent with the descriptive analysis in Section 3. Most estimated coefficients for the control variables have the expected signs and are statistically significant. In the following paragraphs, we first discuss the estimation results of the input equations and then that of the yield equation.

4.1. Impact of Bt cotton adoption on pesticide use, labour use, and seed cost and their dynamics

The estimation results show that the adoption of Bt cotton has significantly decreased pesticide use. As shown in the first column of Table 3, the estimated coefficient of the Bt dummy variable is 57.53, indicating that the average pesticide use in Bt cotton fields was 57.53 kg/ha less than that in non-Bt plots (77.47 kg/ha) in 1999. Thus, the pesticide use in Bt cotton plots was reduced by 74.26 per cent (57.53/77.47*100% = 74.26%). Similarly, the reduction in the average expenditure on pesticide use was 1459.86 yuan/ha, or 77.71 per cent of the pesticide use in non-Bt fields in 1999 (row 1).

More importantly, the estimation results show that the comparative advantage of Bt cotton over non-Bt cotton did not diminish in subsequent years. As shown in Table 3, all the estimated coefficients of the interaction terms of Bt dummy and the year dummies were positive and significant in both the quantity and the expenditure functions, indicating that the (quantity of and expenditure on) pesticide use increased in the subsequent years. However, the magnitudes of the estimated coefficients of all six interaction terms were much smaller than the absolute value of the estimated coefficient of the Bt dummy variable. In other words, the net impact of Bt cotton in subsequent years was still positive and substantial in terms of magnitude. For example, the reduction in the quantity of pesticide use in 2012 was 51.14 kg/ha (−57.53 + 6.39 = −51.14). Similarly, the reduction in expenditure was 1098.94 yuan/ha in 2012. This result is clearly contradictory to the expectation of those who believe that increases in pest resistance and secondary pest outbreaks would completely offset the economic benefit that Bt technology had generated.

Another important finding is that the non-Bt adopters also benefited from Bt cotton adoption. As shown in Table 3, the estimated coefficients of all interaction terms of non-Bt dummy variables and the year dummies were significant and negative, which implies that pesticide use in non-Bt cotton fields decreased significantly in the subsequent years compared to that in 1999 (the base year).This result is consistent with the findings of entomological studies that have shown that the widespread adoption of Bt cotton successfully suppressed cotton bollworm population density regionally (Wu et al., 2008).

Table 3. Impact of Bt cotton on pesticide use

	Pesticide use	
	Amount (kg/ha)	Cost (yuan/ha)
Bt	−57.53***	−1,459.86***
	(−17.50)	(−20.38)
Bt * year 2000	8.93***	237.82***
	(6.65)	(8.13)
Bt * year 2001	7.05***	189.42***
	(5.09)	(6.27)
Bt * year 2004	7.90***	236.05***
	(5.73)	(7.86)
Bt * year 2006	9.92***	334.00***
	(8.01)	(12.38)
Bt * year 2007	7.09***	225.26***
	(5.63)	(8.20)
Bt * year 2012	6.39***	360.92***
	(4.48)	(11.62)
Non-Bt * year 2000	−19.25***	−607.74***
	(−5.27)	(−7.63)
Non-Bt * year 2001	−11.19***	−537.77***
	(−3.04)	(−6.72)
Non-Bt * year 2004	−29.25***	−856.33***
	(−6.91)	(−9.29)
Non-Bt * year 2006	−31.02***	−770.30***
	(−5.70)	(−6.50)
Non-Bt * year 2007	−51.86***	−1,263.35***
	(−7.03)	(−7.86)
Pesticide price (yuan/kg)	−0.31***	1.73***
	(−16.49)	(4.19)
Plot size (ha)	−6.78***	−145.28***
	(−4.43)	(−4.36)
Household dummies	Yes	Yes
Constant	82.25***	1,726.71***
	(25.43)	(24.50)
Observations	4,127	4,127
R-squared	0.313	0.245
Number of households	627	627

Notes: z-statistics in parentheses, $***p < 0.01$, $**p < 0.05$, $*p < 0.1$.

Hence, all farmers, including those who planted non-Bt cotton varieties, reduced their pesticide applications. The reduction in total pest population density caused a reduction in pesticide use and thereby increased the net economic benefit of Bt cotton adoption in the long term.

Table 4 shows that the adoption of Bt cotton led to a reduction of 76.76 day/ha, or 14.04 per cent of the total labour use in 1999 (first column). However, this benefit did not hold constant in the subsequent years. As shown in the second column of Table 4, the estimated coefficients of the interaction terms of the Bt dummy and the year dummies were positive and significant during 2001–2006, while they were nonsignificant in 2007 and 2012. Furthermore, the absolute values of the estimated coefficients of the interaction terms of the Bt dummy and the year dummies were larger than those of the Bt dummy during 2001–2006, indicating that the comparative advantage of Bt cotton over non-Bt cotton diminished.

Notably, this finding does not imply that the benefit of Bt cotton adoption, in terms of a decrease in labour use, disappeared. Except for 2012, the estimated coefficients of all the other year dummies were significant and negative, which implies that the labour use decreased in the subsequent years. We then reran the model by adding the interaction terms of non-Bt dummy and year dummies after

Table 4. Impact of Bt cotton adoption on labour input

	Labour input (day/ha)		
	(1)	(2)	(3)
Bt	−76.76***	−67.14**	−67.14**
	(−6.72)	(−2.46)	(−2.46)
Bt * year 2000		139.52***	53.37***
		(4.41)	(4.25)
Bt * year 2001		74.74**	−43.03***
		(2.37)	(−2.91)
Bt * year 2004		71.09**	−100.21***
		(1.98)	(−3.56)
Bt * year 2006		90.67**	−145.91***
		(1.98)	(−3.61)
Bt * year 2007		57.59	−262.91***
		(0.93)	(−6.81)
Bt * year 2012		10.42	10.42
		(0.07)	(0.07)
Non-Bt * year 2000			−86.15***
			(−2.80)
Non-Bt * year 2001			−117.77***
			(−3.70)
Non-Bt * year 2004			−171.29***
			(−4.04)
Non-Bt * year 2006			−236.58***
			(−4.04)
Non-Bt * year 2007			−320.50***
			(−4.49)
Year 2000		−86.15***	
		(−2.80)	
Year 2001		−117.77***	
		(−3.70)	
Year 2004		−171.29***	
		(−4.04)	
Year 2006		−236.58***	
		(−4.04)	
Year 2007		−320.50***	
		(−4.49)	
Wage rate (yuan/day)	−3.20***	−5.77	−5.77
	(−7.16)	(−0.90)	(−0.90)
Plot size (ha)	75.81***	−76.80***	−76.80***
	(5.06)	(−6.06)	(−6.06)
Household dummies	Yes	Yes	Yes
Constant	513.67***	702.40***	702.40***
	(34.70)	(5.90)	(5.90)
Observations	4,127	4,127	4,127
R-squared	0.040	0.374	0.374
Number of households	627	627	627

Notes: z-statistics in parentheses, ***$p < 0.01$, **$p < 0.05$, *$p < 0.1$.

excluding the year dummies due to complete collinearity. As shown in the third column of Table 4, the estimated coefficients of interaction terms of Bt dummy and the year dummies were still negative except for 2000, indicating that labour use decreased in Bt cotton fields in the subsequent years.[4] A similar reduction in labour use was also found in non-Bt cotton fields in subsequent years (that is the estimated coefficients of the interaction terms of non-Bt dummy and year dummies are also negative and significant).

Table 5. Impact of Bt cotton adoption on seed cost

	Seed cost (yuan/ha)		
	(1)	(2)	(3)
Bt	336.61***	311.18***	311.18***
	(11.31)	(3.54)	(3.54)
Bt * year 2000		−89.82	−57.68
		(−0.88)	(−1.61)
Bt * year 2001		120.96	26.10
		(1.19)	(0.71)
Bt * year 2004		−74.78	−48.90
		(−0.65)	(−1.34)
Bt * year 2006		−218.39	2.57
		(−1.48)	(0.08)
Bt * year 2007		−198.80	91.73***
		(−1.00)	(2.73)
Bt * year 2012		145.68***	145.68***
		(3.95)	(3.95)
Non-Bt * year 2000			32.14
			(0.33)
Non-Bt * year 2001			−94.86
			(−0.97)
Non-Bt * year 2004			25.89
			(0.23)
Non-Bt * year 2006			220.96
			(1.52)
Non-Bt * year 2007			290.53
			(1.47)
Plot size (ha)	−77.31**	−5.63	−5.63
	(−1.97)	(−0.14)	(−0.14)
Year 2000		32.14	
		(0.33)	
Year 2001		−94.86	
		(−0.97)	
Year 2004		25.89	
		(0.23)	
Year 2006		220.96	
		(1.52)	
Year 2007		290.53	
		(1.47)	
Household dummies	Yes	Yes	Yes
Constant	178.68***	156.54*	156.54*
	(6.05)	(1.84)	(1.84)
Observations	4,127	4,127	4,127
R-squared	0.036	0.058	0.058
Number of households	627	627	627

Notes: z-statistics in parentheses, ***$p < 0.01$, **$p < 0.05$, *$p < 0.1$.

The impact of Bt cotton adoption on labour use in the subsequent years was consistent with its impact on pesticide use. As shown in Table 3, Bt cotton adoption not only affected adopters but also non-adopters because Bt cotton adoption successfully suppressed pest populations regionally. As a result, pesticide use in both Bt and non-Bt fields decreased in subsequent years. As spraying pesticide and/or removing bollworms and other pests by hands were the most labour-intensive activities in cotton production, reductions in pesticide use and pest infestations might have led to the reduction in labour use in both the Bt and non-Bt fields in subsequent years.

Table 6. Impact of Bt cotton adoption on cotton yield using Weibull damage abatement function

	Without considering the dynamic over time		With considering the dynamic over time	
	Coefficient	t-value	Coefficient	t-value
fertiliser (yuan/ha)	0.0024	1.13	0.0066***	2.88
labour (day/ha)	0.0168***	2.83	0.0349***	4.40
Seed (yuan/ha)	0.0120***	3.52	0.0094***	3.06
Pesticide (kg/ha)	0.0050	0.64	0.0246*	1.65
Bt variety dummy	0.0243***	3.58	0.0240	1.52
Bt * year 2000			−0.0107	−0.58
Bt * year 2001			0.0231	1.28
Bt * year 2004			−0.0089	−0.41
Bt * year 2006			−0.0033	−0.12
Bt * year 2007			0.0161	0.36
Year 2000			−0.0365***	−2.19
Year 2001			−0.0101	−0.63
Year 2004			−0.0744***	−3.40
Year 2006			0.0062	0.24
Year 2007			−0.0121	−0.28
Year 2012			−0.0633***	−4.95
Plot size (ha)	166.0848***	2.11	294.1145***	4.15
Constant	4889.3820***	6.71	4393.0100***	6.51
Household dummies	Yes		Yes	
Observations	4127		4127	
Adjusted R-square	0.5417		0.5853	

Notes: ***$p < 0.01$, **$p < 0.05$, *$p < 0.1$.

Finally, as expected, the adoption of Bt cotton led to an increase in seed cost (Table 5). As shown in the first column, compared to non-Bt cotton plots, in Bt plots, seed cost was 336.61 yuan/ha higher and was 117.01 per cent of the seed cost of non-Bt cotton varieties in 1999. Thus, the seed cost more than doubled for Bt cotton adopters. The estimated coefficient of the interaction term of the Bt dummy and the year dummies were nonsignificant except for 2012 (2ndcolumn).[5] Similar results were shown in the third column when the interaction terms of non-Bt dummy and year dummies were added and the year dummies were excluded.

In summary, the estimation results of the input equations show that the economic benefit of Bt cotton adoption, particularly the reduction in pesticide use, did not diminish in subsequent years. Theoretically, the build-up of resistance in pest populations and the increasing damage caused by secondary pests may have partially offset the economic benefit of Bt cotton adoption (Qiao et al., 2018). However, as shown in Tables 2 and 3, pesticide use in Bt plots increased only during 1999–2000 but not in the subsequent year. On the other hand, regional reduction in pest population caused by the widespread usage of Bt cotton led to even larger economic benefits, which also benefited non-adopters. Thus, over the long term, the net impact of Bt cotton adoption depended on whether the positive side (that is reduction in pest population) or the negative side (that is pest resistance build-up and secondary pest outbreaks) was dominant. The estimation results in this study show that the positive side was larger than the negative side, 15 years after Bt cotton commercialisation.

4.2. Impact of Bt technology on cotton yield and its dynamics

The estimation results of the yield equation are presented in Table 6 (when the Weibull function form is used). When the exponential function form was used, we obtained similar results.[6] Most importantly, the functions that used the Weibull and exponential damage control functional forms showed similar results for the effect of Bt cotton, the variable in which we are interested. Thus, in the following paragraphs, we will focus our discussion on the estimation results using the Weibull function form.

As shown in Table 6, most of the coefficient estimates were as expected and statistically significant. For example, the estimated coefficients of fertiliser cost and seed cost were all positive and statistically significant, indicating that high fertiliser cost and/or high seed cost were associated with high cotton yield.

Importantly, the results show that the estimated coefficient of the Bt cotton dummy was positive and statistically significant under both scenarios (row 5, Table 6). According to the discussion in Section 3, the sign of the marginal impacts of pesticide use on cotton yield was the same as the sign of the Bt cotton dummy. Thus, the estimation results suggest that Bt cotton is effective in helping pesticides reduce the damage from pest infestations and in achieving higher yields than would have been achieved without Bt adoption. Therefore, Bt cotton increases the productivity of cotton production.

More importantly, the estimation results also show the dynamics of Bt cotton adoption on cotton yield. As shown in Table 6, none of the estimated coefficients of the interaction terms of Bt dummy and year dummies was statistically significant (rows 6–10). Thus, the estimation results show that the impact of Bt cotton adoption on cotton yield remained stable over time.

Further calculations show that Bt technology increased cotton yield by 6.03 per cent. Using the estimated coefficients shown in Table 6 and the inputs to Bt and non-Bt cotton plots, we predicted the cotton yield in Bt and non-Bt cotton fields in each year. According to our calculation, the average predicted yield of Bt plots is 6720.52 kg/ha, while the average predicted yield of Bt plots is 6339.88 kg/ha. The yield of Bt plots is 380.63 kg/ha, or 6.03 per cent, higher than that of non-Bt plots.

4.3. Economic benefit of Bt cotton adoption in China

After estimating the results of the impact of Bt cotton adoption on inputs and yield, we calculated the national impact of Bt cotton adoption. To calculate the national impact, we used cotton sown area data from the China Statistical Yearbooks (NSBC, various years). We classified all the cotton-producing provinces into three regions: the Yellow River valley, the Yangtze River valley, and the northwest.[7] Due to the hot and dry climate in the northwest, the degree of the bollworm infestation in the northwestern region was significantly different from those in the other two regions. Thus, we excluded the northwest region in the calculation, even though the share of Bt cotton increased rapidly and by more than 50 per cent in recent years in the northwest region. Thus, our calculation of the national impact of Bt cotton was underestimated. Data on labour price were obtained from the All China Data Compilation of the Costs and Returns of Main Agricultural Products (National Development and Reform Commission, various years). The data on the percentages of Bt cotton in the Yellow River and Yangtze River valleys were extracted from the CCAP. The yields of the Bt plots and non-Bt plots in a specific year were calculated as follows: First, for the seven years that we conducted field surveys (that is 1999–2001, 2004, 2006, 2007 and 2012), the yields in Bt cotton and non-Bt cotton plots were discussed above, while the impact of Bt cotton adoption on pesticide use, labour use and seed cost were determined from the estimation results that are shown in Tables 3–5. Second, we used the moving average method to determine the impact of Bt cotton for the years when no field survey was conducted during 1999–2012 (that is 2002, 2003, 2005, and 2008–2011). Third, for simplicity, we assumed that the impacts of Bt cotton in 1997 and 1998 were the same as that of 1999. The results of the calculation are summarised in Table 7.

As shown in Table 7, owing to Bt cotton adoption, Chinese farmers saved 8.46 billion on pesticide use during 1997–2012, with an average savings of 0.56 billion US$ per year (column 3).[8] The reduction is 50.88 per cent of the total expenditure on pesticide use in 1999. If the benefit from seed cost (which is negative since the seed cost of Bt cotton is higher than that of non-Bt) and yield increase are counted, then the annual benefit can be as high as 1.32 billion US$. Due to the increasing wage rate, after considering the reduction in labour use, the annual benefit of Bt cotton adoption more than doubled and reached 3.45 billion US$.

Table 7. The economic benefit of Bt cotton in China, 1997–2012

	Benefit in physical volume (million ton)		Pecuniary benefit (billion US$)[a]					
			Pesticide	Yield	Seed	labour	Total	
	Pesticide saved	Yield	(1)	(2)	(3)	(4)	(5) = (1)+(2)+(3)	(6) = (5)+(4)
Total (1997–2012)	2.19	16.88	8.46	13.34	−1.97	31.90	19.83	51.73
Annual	0.15	1.13	0.56	0.89	−0.13	2.13	1.32	3.45
(%)[b]	50.55	6.67	50.88	9.81	−111.32	53.22	39.43	37.85

Notes: All the cost and benefit are in 2012 year price; [a]According to China Statistics Yearbook (2013), 1 US$ = 6.31 yuan in 2012; [b]The percentage values are the change in comparison to 1999.

More importantly, the total quantity of pesticide use decreased by 2.19 million tons nationally during 1997–2012, with an annual reduction of 0.15 million tons. As shown in previous studies, a reduction in pesticide use benefits not only farmers by increasing their profits and improving their health but also agrobiodiversity, the environment and ecosystems (Hossain, Pray, Lu, Huang, & Hu, 2004; Krishna, Qaim, & Zilberman, 2016; Qiao, Huang, Zhang, & Rozelle, 2012; Veettil, Krishna, & Qaim, 2017).

5. Conclusions

In recent years, the sustainability of the economic benefit that Bt crops have generated has been subject to substantial debate. Those who oppose Bt technology believe that such economic benefit has only a short-term impact, which will gradually diminish in the long run due to increasing pest resistance and secondary pest outbreaks (Pemsl & Waibel, 2007; Wang et al., 2008). Due to data unavailability, however, none of the previous studies has provided satisfactory information on the sustainability of the economic benefit that Bt crops generate. On the one hand, the available national aggregate data do not include enough information to address this issue. On the other hand, the available household survey data sets only cover a short period of time; thus, they are also insufficient to answer the sustainability question. As a result, there has been strong opposition to Bt technology both in public and in the media, and this opposition has risen significantly in recent years.

Using seven sets of household survey data, we analysed the economic impact of Bt cotton adoption and its sustainability after its commercialisation in China. This study showed that even though the seed cost of Bt cotton is higher than that of non-Bt cotton, the positive benefit that Bt cotton has generated, in terms of reductions in both pesticide use and labour use as well as increases in yield, was still prominent. Consistent with its short-term impact, the benefit of Bt cotton adoption did not diminish but remained stable and continuous over time. In addition, consistent with the findings of entomologists who showed that general pest density reduced regionally after Bt cotton adoption, this study showed that Bt cotton adoption also led to a significant reduction in pesticide use in non-Bt cotton plots.

The findings of this study have important implications. First, undoubtedly, these findings will contribute to a wider public debate in China as well as in other countries where Bt crops are commercialised or are yet to be commercialised. Based on long-term panel household-level data, this study provides solid empirical evidence that the economic benefit of Bt technology is not limited to a short-term period but is sustainable over time. We believe that the estimation results from this study will help to decrease the current debate and affect public attitude.

Second, our results are helpful for policy makers in managing Bt crop adoption. Facing criticism from those who oppose Bt technology, some governments have stalled the commercialisation of available Bt crops (that is Bt rice) and reduced expenditures on research and the extension of Bt technology, which has caused and will cause substantial economic losses. We believe that the results of this study will contribute to the research and commercialisation of Bt crops worldwide. Specifically, there are some countries where farmers, due to credit constraints, are not able to control pests effectively. Moreover, there are some countries where farmer health is heavily affected by pesticide spraying due to lack of protection. There are other countries where food is insufficient due to the yield losses caused by pests. We hope that the results of this study will contribute to the spread of Bt crops, which will not only increase agricultural outputs and producer profits but also decrease the amount of pesticides used and contribute to improvements in the environment and farmer health.

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Notes

1. The other largest cotton-producing region is the northwest, which includes the Xinjiang Uyghur Autonomous Region, the largest cotton – producing province in China, and Gansu Province.
2. The data are available on request.
3. The correlation coefficient between seed cost and Bt dummy is 0.1889.
4. The absolute value of the estimated coefficient of the Bt dummy is greater than the estimated coefficients of the interaction term of the Bt dummy and 2000 year dummy, indicating that Bt cotton adoption led to a reduction in labour use in 2000 compared to that in 1999.
5. Further studies have shown that the three areas of non-Bt cotton plots in 2012 belonged to three households that had not been visited before. Hence, the estimated coefficient of the interaction term of Bt and 2012 year dummy also includes the impact of the year trend in 2012.
6. The most significant difference is the estimated coefficients of labour use and pesticide use. When the Weibull function form is used, the estimated coefficients of labour use and pesticide use are positive, while they are bounded when the exponential function form is used. This finding also occurs in similar studies (for example Huang et al., 2003).We re-ran the yield function when the exponential function form was used and found that dropping the labour use variable did not affect the estimated coefficients of the other variables. For simplicity, the estimation results when the exponential function form was used are not shown.
7. The Yellow River valley includes Beijing, Tianjin, Jilin, Liaoning, Neimenggu, Hebei, Henan, Shandong, Shanxi, and Shaanxi provinces; the Yangtze River valley includes Anhui, Fujian, Hubei, Hunan, Jiangsu, Jiangxi, Shanghai, Sichuan, Yunan, Guangxi, Guizhou, and Zhejiang provinces; the northwest includes Xinjiang and Gansu provinces.
8. According to NSBC (2013), 1 US$ = 6.31 yuan in 2012.

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