SCIENCE CHINA
Life Sciences

• RESEARCH PAPERS •

August 2010 Vol.53 No.8: 981–991
doi: 10.1007/s11427-010-4036-y

A decade of *Bt* cotton in Chinese fields: Assessing the direct effects and indirect externalities of Bt cotton adoption in China

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Received October 13, 2009; accepted November 20, 2009

The objective of this study is to examine whether or not the gains from reduced spraying for bollworms are being sustained more than one decade after the initial adoption in 2007. Based on farm-level data collected by the authors in 1999–2007 in 16 villages from 4 provinces, this study shows that insecticides applied for controlling bollworms have declined. This analysis supports Chinese policy makers' decision to not require refuges of non-Bt cotton fields. It also suggests that past studies may have underestimated the benefits from adopting Bt technology.

biotechnology, Bt cotton, insecticide, sustainability, externalities, China

Citation: Huang J K, Mi J W, Lin H, et al. A decade of *Bt* cotton in Chinese fields: Assessing the direct effects and indirect externalities of Bt cotton adoption in China. Sci China Life Sci, 2010, 53: 981−991, doi: 10.1007/s11427-010-4036-y

The development of insect resistant crop varieties containing the *Bacillus thuringiensis* (Bt) gene has been a positive example of the application of agricultural biotechnology. In 2007 insect-resistant crop varieties were grown on a total of 42.1 million hectares, accounting for 37% of the world's total area of transgenic crops [1]. Countries that have introduced Bt crops have derived a number of significant benefits including increased yields, decreased production costs and, above all, a reduction of insecticide applications [2–8].

While the increased productivity of Bt cotton in the initial years of adoption is well-documented, less is known about its ability to sustain this productivity over a long time period. One of the major concerns about Bt crops is their potential vulnerability to the pests that develop resistance to the Bt toxin [9]. The spread of Bt cotton and other Bt crops could create selection pressure on the pest populations so that pests that are resistant would increase their share of the population. If too large of a share of the pests developed resistance to the Bt toxin, effectiveness of Bt crops in controlling pests would decline, farmers would apply more insecticide such that the benefits from utilizing Bt would be lost. It is also possible that the productivity of Bt could grow over time. There might be positive externalities associated with widespread adoption of Bt cotton. If the Bt cotton was able to eliminate a large enough share of the pest population, the population in a region might be reduced to

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the point where it was no longer a major threat to such crops as Bt cotton, non-Bt cotton, maize, or vegetables [10,11].

China provides a unique opportunity for studying the long-term benefits of Bt technology. Since commercial production began in 1997, millions of small farmers have adopted Bt varieties. The original Bt genes have not been replaced by the double gene construct which is used extensively in the US, and unlike many other countries there is no policy whereby farmers must maintain part of their cotton fields planted in non-Bt cotton to provide a refuge for pests that are susceptible to Bt. Another unique aspect about China is that we have been surveying cotton farmers and measuring the impacts of Bt cotton technology almost every year since 1999.

Early studies showed that Bt varieties increased crop yields and reduced insecticide use [5,12,13]. With the expansion of Bt varieties and more years of Bt in the field, some scholars were concerned about the long-term effects of Bt varieties [14,15]. It has been reported that the pests of cotton in the US (e.g., tobacco budworms and the American bollworm) began to build up resistance in less than 40 generations [16]. In China bollworms reproduce, on average, four times per year. Given that Bt varieties have now been planted for more than 10 years in some areas, it is an appropriate time to evaluate the long-term benefits (and costs, if any) of Bt cotton. A study of these issues also may give insight into the long-term effectiveness of Bt technology in developing countries in general.

Recent findings in the field of entomology give further impetus for our study. Wu *et al*. [11] showed that bollworm populations in China have evolved in a way in which Bt cotton may be able to be used on a long-term basis. Based on a dataset built on information collected during more than a decade of monitoring in experimental cotton fields in rural areas of northern China, their research found that the number of bollworms fell significantly with time. Many regional populations collapsed as Bt varieties expanded. It appears that the Bt toxins not only suppressed the insect populations in the fields with Bt varieties, but also populations on other crops which serve as hosts for bollworms. They concluded that after 10 years of use of Bt cotton varieties, resistance of bollworms to the Bt toxin had not yet emerged.

Despite the importance of understanding the sustainability of reducing insecticide use in Bt cotton, there are no household-level studies in China (or any other developing country) providing any evidence about the trends of insecticides in Bt cotton fields after more than a decade of use. In this study we want to understand whether the productivity gains associated with Bt cotton in China (measured as insecticide use for controlling bollworms) after 11 years of adoption have deteriorated, remained the same or been enhanced[1)].

To achieve this goal, we analyzed data that we collected in 1999, 2000, 2001, 2004, 2006 and 2007 from 16 villages in Hebei, Shandong, Henan and Anhui provinces. The results provide no evidence of rising insecticide use. Rather it was found that the amount of insecticide applied to control bollworms declined over time. The findings suggest that there may be positive externalities associated with the expansion of the Bt cotton area as the area of Bt cotton expands in a region, the amount of pesticides used by farmers on non-Bt crops falls, ceteris paribus. Our results are consistent with the study by Wu *et al*. [11] that the bollworm population has significantly declined over the past 10 years in the northern China cotton production zone.

The rest of the paper is organized as follows. The next section discusses the data used in the study. In the following section the record of Bt cotton production in China and the study areas is reviewed. A descriptive analysis of insecticide use by farmers in their Bt and non-Bt cotton-producing fields is presented. Section 3 introduces our multivariate, statistical model and provides the results of our econometric analysis of whether or not there is a declining or increasing trend of insecticides used to control bollworms in farm fields. The last section summarizes the results and draws out some possible lessons for regulators.

1 Data and samples

The data used in this study is from a database collected by the Center for Chinese Agricultural Policy (CCAP). The data from the first three years of data collection was used by researchers to assess the efficiency of *Bt* cotton relative to conventional cotton varieties in China [5–7,12–13]. The data herein is from six years of intensive farm household surveys which focused on *Bt* cotton production—1999, 2000, 2001, 2004, 2006 and 2007. Each year the CCAP survey team increased the sample size and coverage as the use of Bt cotton spread throughout China. By 2007 the surveys covered 44 villages in 6 provinces, Hebei, Shandong, Henan, Anhui, Jiangsu, and Hubei.

The villages and households included in the study were randomly selected. In each village about 20 to 30 farm households (the number varying with the size of the village) were selected by the survey team from a comprehensive list of all farming households in the village that was provided by the local household registration office. The selected

1) Impacts of Bt cotton on insecticide uses by farmers in long run might include insecticide use to control both target insects (e.g., bollworm) and non-target insects (e.g., mirids). For non-target insects, the results have been reported in Wang *et al.* [17]. This study shows that there was a rise in insecticide use to control secondary insects, particular mirids. However, that the rise in mirids between 2000 to 2006 in insecticide use for the control of secondary insects is far smaller than the reduction in total insecticide use due to Bt cotton adoption. Further econometric analyses show that rise and fall of mirids is largely related to local temperature and rainfall.

farmers were interviewed by trained enumerators from CCAP's survey team for about 2 to 3 h using recall survey techniques that are standard in economics literature. Information about Bt and non-Bt cotton production and inputs was collected on a plot-by-plot basis. Enumerators also asked farmers a number of questions about their perceptions of bollworm infestations as well as the losses that would have occurred had they not taken action to curb the infestations.

To assess the changing pattern of insecticide use over time and the correlates of these changes, the analysis required sample households that were surveyed in at least 2 periods. As a result, the analysis does not consider data from the 26 villages that were visited once. It also excludes two villages from Shandong that were not visited in 2006 and 2007. Hence, 16 villages from 4 provinces Hebei, Shandong, Henan and Anhui—are included in this study. Between 1998 and 2007, the four sample provinces accounted for more than 65% of China's total Bt cotton area in each year. In total, the sample includes information from 525 household observations that planted Bt and non-Bt cotton on 3576 plots. Descriptive statistics about the sample households are included in Appendix Table 1.

2 Bt cotton production and insecticide use to control bollworms in China

2.1 The intensity of Bt cotton cultivation

According to a national survey of Bt cotton adoption conducted by CCAP, the area planted in Bt cotton by China's farmers has spread rapidly since its initial adoption in 1997 (Table 1). Limited to a handful of villages in Hebei and Henan provinces in the first year of adoption, farmers in almost all provinces in the northern and central cotton zones rapidly adopted the crop—although the speed of adoption greatly varied by province. In Hebei and Shandong the level of adoption had already reached more than 95% by 2001 while the diffusion was slower in Henan and Anhui provinces. Across China, our recent survey showed that 3.89 million of the 5.93 million hectares of cotton planted in 2007 were planted with Bt cotton. In the four study provinces adoption reached 100% in two (Hebei and Shandong) and more than 80% in the other two (Henan and Anhui). Although not shown in Table 1, cultivation of Bt cotton has steadily expanded outside of the study areas to more southern provinces, e.g. Jiangsu and Hubei.

The concern about the need for refuges has intensified because of the high levels of adoption by the mid-2000s (Table 1, bottom row). In the United States, the Environmental Protection Agency (EPA) adopted a refuge strategy for managing the evolution of Bt resistance in 1996 when Bt crops were first introduced [18]. During the 1990s cotton farmers in the southern United States had to leave either a "pure" refuge of non-Bt cotton and no pesticides for insect control that equaled 5% of their land or a "partial" refuge of 20% non-Bt cotton on which the farmer was allowed to spray conventional pesticides to control pests. Other countries, e.g. Canada, Australia and India, adopted similar refuge policies for Bt crops [19].

The other strategy to reduce the possibility of resistance that most countries have used is to adopt a double gene construct utilizing two Bt genes with different mechanisms for killing the pests. These double gene conscripts—the first of which was introduced in the US in 2002 and in India in 2006—are intended to increase the difficulty for bollworms to develop resistance.

China does not require farmers to plant refuges and the double Bt gene constructs have not been commercialized in China. This apparent lack of measures to prevent the development of resistance should not be taken to mean that

Table 1 Bt cotton adoption in China and sample provinces, 1997–2008[a)]

Year	Cotton area (×1000 ha)		Bt cotton adoption (%)					4 provinces' share of Bt cotton area in China (%)
	Total	Bt cotton	China	Hebei	Shandong	Henan	Anhui	
1997	4491	34	1	3	0	1	0	63
1998	4459	261	6	55	11	2	2	94
1999	3726	654	18	85	66	17	7	94
2000	4041	1216	30	97	88	31	20	91
2001	4810	2158	45	98	97	68	45	87
2002	4184	2156	52	99	99	77	56	86
2003	5111	2996	59	99	99	84	65	83
2004	5693	3533	65	100	100	84	70	79
2005	5062	3174	63	100	100	85	75	75
2006	5816	3700	64	100	100	85	85	69
2007	5926	3893	66	100	100	88	85	65
2008	5667	3831	68	100	100	90	85	66

a) Data source is based on CCAP's annual survey of Bt cotton adoption.

Chinese officials and scientists are not concerned about this issue. The prevailing view among scientists in China is that because such crops maize, wheat, rice and peanuts serve as alternative hosts of the bollworm, China's cotton producing region has sufficiently large "natural" refuges [20,21]. The practical difficulty of trying to enforce a Bt cotton refuge policy with millions of small farmers has been noted [22].

There is another group of scholars who believe that the bollworm is evolving resistance to the Bt toxin [23]. They argue that if the bollworm population rapidly developed resistance to Bt toxins, it would mean that farmers would have no choice but to return to their heavy reliance on conventional insecticides.

The levels of adoption by farmers in the 16 villages in our sample in Hebei, Shandong, Henan and Anhui (Table 2, rows 3, 6, 9 and 12) were higher than in the country as a whole. Farmers in the study villages in Hebei (by 1999) and in Shandong (by 2002) had achieved 100% levels of adoption. The levels of adoption by farmers in the study villages in Henan reached 94% by 2007; those in Anhui had reached 99% by 2006. This suggests that our sample effectively tests whether or not resistance (and corresponding rises in insecticide use) is related to the intensity of Bt cotton adoption.

Although the rates of Bt cotton adoption are high as a share of the total cotton area, in all of the study villages (even though the villages are in the heart of one of China's main cotton producing regions), cotton is far from being a mono-cultured crop. In Hebei between 1997 and 2007 the share of cotton in the total cultivated area ranged between 19% and 54%. The shares of cotton in the total cultivated area in the other sample villages ranged between 26% and 74%. Hence, unlike the cropping patterns of other nations, China's cotton crop is nearly always grown alongside a diversified set of other crops. A number of crops that are known to be a host of the bollworm. According to Wu and Guo [22], bollworms in China not only infest cotton during northern China's cotton growing season, they also live and breed in fields of wheat, maize, soybeans, rapeseed (or canola), vegetables and other minor crops. In the rest of the paper, these crops are designated as *refuge crops*.

If only 25% of wheat area is counted (because part of cotton's growing season overlaps with wheat), the share of the sample village's total cultivated area that is planted in refuge crops is relatively large (Table 2, rows 2, 5, 8 and 11). In no province does the share of the refuge crop fall below 15%. In Hebei, Henan and Anhui the share of refuge crops exceeds 39%. In each of the 16 sample villages (not shown), the share of the refuge crops is never lower than 10%. On average the refuge area share in the sample villages was 46% in 2007. According to the advocates of China's natural refuge policy the existence of the refuge crops, which grow alongside China's Bt cotton, is enough to maintain the susceptibility of the bollworm population to the Bt toxin of Bt cotton. As mentioned above, in addition to the possible build-up of resistance to the Bt toxin that might be associated with intensive adoption of Bt crops, there could also be positive externalities. It is possible that as the area of Bt cotton has risen, there could have been a dampening effect on the growth of the entire bollworm population. If the entire level of population of pests fell enough, farmers (in all crops, including non-Bt cotton) may be able to reduce their levels of insecticides and reduce the

Table 2 Bt cotton, refuge crops and the role of cotton in Northern China's cropping patterns, 1997–2007[a)]

	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007
Hebei:											
Cotton area share (%)	19	23	32	42	42	43	43	54	33	34	31
Refuge crops share (%)	79	67	57	48	48	46	46	50	56	56	60
Bt cotton adoption (%)	77	98	100	100	100	100	100	100	100	100	100
Shandong:											
Cotton area share (%)	43	49	55	58	60	59	58	65	62	67	74
Refuge crops share (%)	89	55	38	30	27	24	26	21	23	19	15
Bt cotton adoption (%)	19	65	87	94	96	100	100	100	100	100	100
Henan:											
Cotton area share (%)	50	50	43	46	48	46	42	38	30	26	27
Refuge crops share (%)	100	94	62	43	39	43	44	47	56	63	62
Bt cotton adoption (%)	0	8	55	79	84	81	85	89	95	94	94
Anhui:											
Cotton area share (%)	35	35	38	39	41	41	42	40	42	42	-
Refuge crops share (%)	100	97	92	72	50	50	46	46	42	42	-
Bt cotton adoption (%)	0	19	27	50	85	85	92	98	99	99	-

a) Cotton area share is the share of the cotton area in the total crop area. Refuge crops include wheat, maize, soybeans, rapeseed, vegetables, and other minor crops. The refuge crops' share is calculated as the area of refuge crops as a percentage of the total cropped area during the cotton season. Bt cotton adoption is the share of Bt cotton in the total cotton area. Data source is from the authors' survey.

use of Bt cotton. Such a phenomenon is not without precedent. For example, in the US state of Arizona the population of pink bollworm almost disappeared a number of years after the commercialization and comprehensive spread of Bt cotton [10].

2.2 Insecticide use trends in China's cotton fields

Previous work regarding Bt cotton in China (e.g., Huang *et al*. [5]) found that one of the most significant outcomes for farmers who adopt Bt cotton was the sharp reduction of insecticide used relative to non-Bt cotton farmers (Table 3). With the exception of the differences between 1999 and 2000 and the villages in Hebei Province, insecticide use to control bollworms in both Bt and non-Bt cotton fields shows a falling pattern (Table 3). For example, in the two Henan sample villages (Henan-Taikang) and two Shandong sample villages (Shandong-Liangshan) for which there was data for all years between 2000 and 2007, insecticide use to control bollworms dropped from more than 14 kilograms per hectare to less than 4 kilograms per hectare (rows 2 and 4). Insecticide use to control bollworms also fell after 2000 in the four Anhui villages (rows 8 and 9).

The falling level of insecticide use to control bollworms is consistent with the hypothesis that there is a positive externality (e.g., there is a decrease in the size of the bollworm population) from farmer's adoption of Bt cotton area. Such a finding, however, must be interpreted with care. There are many other possible reasons for the decline in insecticide use. For example, it may be due to the learning effects of farmers who become confident that Bt is effective and they therefore do not need to spray so much insecticide for insurance purposes. Descriptive data about the level of insecticide use for controlling bollworms on non-Bt cotton helps isolate part of the effect of Bt in several ways. First, the patterns of insecticide use on non-Bt cotton fields do not show any sign that there was an increase in resistance (Table 3, rows 10 to 18). In fact, the level of insecticide used on the non-Bt cotton fields also fell. In the two Henan-Taikang villages, for example, the use of insecticides for bollworms fell from 33.2 kilograms per hectare in 2000 to 4.7 kilograms per hectare in 2007. Because non-Bt cotton has no way to protect itself against the bollworm, the falling use of insecticide to control bollworms may be an indication that the total population of bollworms in northern China is falling. This suggests the existence of a factor that affected both Bt and non-Bt crops (such as a falling pest population) and not a learning effect which would exclusively affect the Bt crop.

Information from the farm household surveys in 2001 and 2007 about the level of infestations of bollworms supports the idea that the levels of infestation were falling over time. Figure 1 summarizes the responses of the sample farmers in our sample provinces. Farmers stated that between 1999 and 2007 the level of bollworm infestations fell (especially after 2001). The reported levels in the four sample provinces in 2003–2006 were the lowest of any year. This suggests that part of the reason for falling levels of insecticide use was the farmers' perception that the levels of infestations were falling.

Table 3 Insecticide use to control bollworms (in kilograms per hectare) in the sample villages in China for Bt cotton and non-Bt cotton plots, 1999–2007[a)]

	1999	2000	2001	2004	2006	2007
Bt plots	6.3	14.2	8.5	3.8	8.5	8.7
Henan-Taikang (2)	11.0	16.8	3.3	4.6	5.8	2.2
Henan-Fugou (2)	4.4	6.3	4.4	3.3	7.8	3.9
Shandong-Liangshan (2)	8.5	14.5	8.2	3.2	5.3	3.6
Shandong-Xiajin (2)	11.4	23.9	-	-	9.9	6.3
Hebei-Shenzhou (2)	2.1	3.1	-	-	7.8	9.3
Hebei-Xinji (2)	2.0	14.7	9.8	2.9	19.4	25.1
Anhui-Dongzhi (2)	-	-	8.5	3.5	3.8	-
Anhui-Wangjiang (2)	-	-	17.5	8.2	8.0	-
Non-Bt plots	69.1	36.3	46.3	14.3	22.5	9.4
Henan-Taikang (2)	-	33.2	27.5	16.3	15.2	4.7
Henan-Fugou (2)	-	42.6	27.3	7.2	32.8	0.1
Shandong-Liangshan (2)	-	-	-	-	24.7	-
Shandong-Xiajin (2)	69.1	-	-	-	-	5.7
Hebei-Shenzhou (2)	-	-	-	-	-	-
Hebei-Xinji (2)	-	-	-	-	31.3	20.4
Anhui-Dongzhi (2)	-	-	68.3	34.8	-	-
Anhui-Wangjiang (2)	-	-	57.2	12.1	-	-

a) Henan-Taikang (2) refers to 2 villages in Taikang county. Data source: Authors' household surveys.

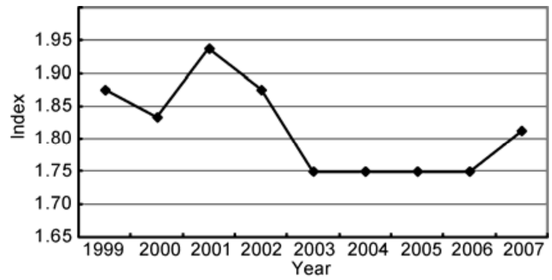

Figure 1 Degree of bollworm infestation as perceived by farmers in sample villages in China, from 1999 to 2007. The index created from the data was based on the question: Was bollworm infestation very serious (3) or normal (2) or light (1). Data source is from authors' surveys in 1999–2007.

3 Empirical model, hypotheses and multivariate results

The descriptive analysis in the previous section demonstrates the potentially complex patterns of insecticide use which were observed in the sample villages over time, across villages and between Bt cotton and non-Bt cotton plots. Bt cotton adoption has risen to high levels (as a share of cotton sown area). Cotton is not mono-cropped. In all sample villages it is cultivated alongside a substantial amount of refuge crops. There is no evidence that resistance is growing over time as shown by the fact that insecticide use to control for bollworms is falling in general (or at least not systematically rising). Somewhat unexpectedly, the data show that this falling trend is not only true for Bt cotton plots but also for non-Bt cotton plots. The descriptive data is consistent with the argument that the reason for the falling level of insecticide use to control bollworms is that there has been a systematic fall in the level of farmers' perception of an infestation .

3.1 Model specification

While the descriptive analysis suggests that there is a relationship between Bt adoption and the suppression of the bollworm population rather than rising populations due to resistance, it is possible (indeed probable) that other factors might affect insecticide use to control bollworms. Multiple regression analysis reduces any biases from these other factors to afford improved understanding of the underlying relationships. To isolate the effect of Bt cotton adoption on insecticide use to control bollworms, a general pesticide use model was used as the starting point for the analysis [6,24]. A number of modifications were made to the basic "determinants of insecticide use" framework: (i) the model was estimated for the level of insecticide used to control for bollworms not for total insecticide use (ii) on the right hand side of the equation, a measure was used to indicate whether or not the farmer's plot cultivated Bt or non-Bt (Bt) as there might be a difference given the fact that Bt cotton naturally expresses a toxin which partially controls bollworms and non-Bt cotton does not (iii) we included a set of five "Year" indicator variables (one for each year of our data, with 1999 dropped) and five "Bt*Year" interaction variables to measure the trend of insecticide use over time on both Bt and non-Bt cotton (iv) a measure of the intensity of Bt cotton adoption at the village level is included (full adopt) and (v) a measure of the share of the refuge crops planted in the village alongside the Bt cotton crop. We included the measures of the intensity of Bt cotton adoption and the share of refuges in the local cropping patterns in order to understand if there are any positive or negative externalities which may be associated with the production environment in our sample of China's cotton growing villages.

The conceptual model is specified as:

Insecticide use to control for bollworms (plot level)
= f (Bt cotton adoption (plot level); Year effects, Year times Bt adoption effects; Bt cotton adoption (village level), Refuge crop intensity (village level); Others factors), (1)

where "Insecticide use to control for bollworms" (henceforth, *Q_bollworms*) is the insecticide used to control for bollworms; *Bt* (at the plot level) is an indicator variable which is one if the plot is Bt cotton and zero otherwise; year effects are measured with two sets of variables-a set of year dummies (which are a set of five year dummies for 2000, 2001, 2004, 2006 and 2007, with 1999 as the base year) and a set of five interaction terms that are created by multiplying the Bt variable times each Year dummies (*Bt* Year_dummies*)[2]; Bt cotton adoption at the village level is measured as a dummy variable which is one if the village has completely adopted Bt cotton and zero if there remains a share that is cultivated in non-Bt (*Bt_full_adopt)*; *Refuge intensity* is the share of total sown area planted in wheat (times 0.25) and other crops (e.g., maize, soybeans, non-Bt cotton, rapeseed and vegetables) which are planted at the same time as the Bt cotton. There is a set of three interaction variables for measuring the effect of refuge areas in different provinces that are measured as the Refuge intensity variable times the provincial dummies with Hebei as the base province.

Taking advantage of the dataset (both its time dimension and the fact that information about production is available at the plot-level), the empirical version of the model in equation (1) that is to be estimated is:

$$\begin{aligned} \text{Q\_bollworm}_{ijt} &= \text{a}+\text{b Bt}_{ijt},+(\text{c}_0+\text{c}_1\text{ Bt}_{ijt})*\text{ Year\_dummies} \\ &+d\ Bt\_full\_adopt_{vt,} + e\ Refuge\ intensity_{vt} \\ &+ f\ Refuge\ intensity*province_{vt} + g\ Price_{it} \\ &+\text{h Farm\_size}_{it}+\text{r household dummies}+\text{u}_{ijt}, \qquad (2) \end{aligned}$$

2) Note that rising (falling) Q bollworm over time of the non-Bt cotton is measured by the coefficients of the Year dummies. The effect of Bt adoption over time of the Q bollworm on Bt cotton is measured by the sum of the coefficients of the Year dummies and Bt*Year dummies.

where i, j, v and t respectively index household, plot, village and time (or year). $Q\_bollworm_{ijt}$ is measured in one of two ways—either as the quantity of insecticide used to control for bollworms (in kilograms per hectare) on plot j of household i in year t or as the cost of the insecticide (in yuan per hectare), and where Bt, Year dummies, Bt*Year dummies, Bt_full_adopt, Refuge intensity, Refuge intensity*Province dummies are as defined in the previous paragraph.

In order to explain the net effect of *Bt*, the effect of Bt (and non-Bt) over time, the effect of *Bt_full_adopt* (or the intensity of Bt), and the effect of *Refuge_intensity* on *Q-bollworm*, other factors that influence insecticide use to control bollworms need to be accounted for. In this analysis three other variables (or sets of variables) are included. In particular, we include two variables that measure the profitability of insecticide use. The first is the price of pesticides (*Price*—measured as yuan per kilogram). The second is the size of the household's total area of cultivated land (or *Farm_size*). Third, 524 household dummies are also included to control unobserved fixed effects which come from household characteristics. The symbols *a, b, c, d, e, f, g, h* and *r* are parameters to be estimated.

Equation (2) is estimated by the Ordinary Least Squares (OLS) method if it is assumed the error term, u_{ijt}, follows a normal distribution. Unfortunately, farmers did not apply insecticide to control for bollworms in 625 of the sample's 3576 plots (which are used in regression). Statistically, this was accounted for by using a Tobit estimator to estimate the parameters in equation (2).

3.2 Testable hypotheses

The model, as specified in equation 2, was used to test the following hypotheses that were related to impacts of the adoption and spread of Bt cotton on *Q_bollworm*:

Hypothesis 1: $b=0$. *Bt* cotton did not affect insecticide use to control bollworms in the initial years of adoption (in our case, 1999). We would reject this hypothesis if b would be significantly different from zero.

Hypothesis 2: $c_0=c_1=0$. Rising adoption rates of *Bt* cotton (and other factors) at the village level (captured by the *Year_dummies* and the *Bt*Year_dummies*) did not increase or reduce *Q_bollworm* on either (or both) Bt cotton and non Bt cotton. Specifically, we would reject this hypothesis if both c_0 and c_1 were significantly different from zero.

If $c_0>0$, then there would be rising use of pesticides for the control of bollworms on non-Bt cotton over time (due to some unspecified time varying factors). If $c_0<0$, then there is evidence that the use of pesticides for the control of bollworms on non-Bt cotton over time is falling. One factor that might be behind this fall in pesticide use on non-Bt cotton is a fall in the pest population of bollworms due to the widespread adoption of Bt cotton. Unfortunately, the absence of any entomological assessment of the size of the pest population in each village prevented unambiguous identification of any negative relationship between *Q_bollworm* and Bt adoption, if it is to a *reduced population effect*.

The parameter c_1 (in conjunction with c_0) was used to test whether or not there was any difference between Bt cotton and non-Bt cotton fields in insecticide use associated with Bt adoption. If c_0 is zero and c_1 is positive it would mean that the use of pesticides for controlling bollworms on Bt cotton (and not non-Bt cotton) was higher than in 1999. Such a finding would mean that there was rising resistance. If c_0 is zero and c_1 is negative it would mean that the use of pesticides for controlling bollworms on Bt cotton (and not non-Bt cotton) was lower than in 1999. Such a finding would mean that there was a reduced population effect. When c_0 is zero and c_1 is negative, it also is consistent with a learning effect by farmers who gradually figure out that they need less insecticide as Bt adoption rises over time. If c_0 is negative and c_1 is zero this would mean that the use of pesticides for controlling bollworms fell for both Bt and non-Bt cotton. If this is the case, there would be greater evidence in favor of the reduced bollworm population effect as the learning effect would only occur in Bt cotton plots.

Finally, if c_0 is negative and c_1 is positive (but the magnitude of the absolute value of c_0 is greater than or equal to c_1,) it would also be consistent with a reduced population size effect (as long as the coefficient on Bt was negative and significant). This would mean that the use of pesticide for controlling bollworms in non-Bt was falling and after the initial fall (in 1999 the first year of the study-which is seen from the coefficient for the Bt cotton variable) the use of pesticide for controlling bollworms on Bt cotton was not rising (between 2000 and 2007) after its initial fall in 1999.

One source of the potential negative externality might be rising resistance, although, as indicated above, the absence of genetic data from the bollworm population limits the ability to pinpoint this effect. At most it seems that a positive c_0 is consistent with rising resistance.

Hypothesis 3: $d=0$. If $d=0$, there is no negative (or positive) externality on insecticide use to control bollworms after a village fully adopts Bt cotton (or *Bt_fulladopt*=1). Like the case of Hypothesis 2, if $d>0$, then it would be a finding that would be consistent with a resistance effect. If $d<0$, then it would be a finding that would be consistent with a reduced population effect.

Hypothesis 4a: $e=0$. If $e=0$, then the share of the village's area cultivated with refuge crops (*Refuge_intensity*) is not associated with a negative (or positive) externality in Hebei Province (which is the base province). By contrast, if $e>0$ ($e<0$), *Refuge_intensity* is associated with a less (more) insecticide use in Hebei Province. A negative coefficient would be consistent with an interpretation that if a refuge was too small, the use of pesticides for controlling bollworms might be rising due to an increased resistance effect. By contrast, a positive coefficient would be consistent with an interpretation that as the size of the refuge rises, the population of pests in the village rise (because there are more places for the pests to find refuge) and farmers need to spray more (a cost that may be offset by the fact that a larger refuge reduces the propensity of the bollworm population to build up resistance and leads to higher use of pesticides for controlling bollworms) with one of the two effects, or both.

Hypothesis 4b: $e+f=0$. If $e+f=0$, then the share of the village's area cultivated with refuge crops (Refuge_intensity) is not associated with a negative (or positive) externality (that might arise if there was a significant resistance effect) in the non-base provinces (Shandong, Henan or Anhui). By contrast, if $e+f>0$ ($e+f<0$), Refuge_intensity is associated with a negative (positive) externality in terms of insecticide use in other provinces.

3.3 Results

The results of the multiple regression estimation of equation (2) demonstrated that the model generally performed well (Table 4). To show this, we examined how well the coefficients of some of the control variables conformed with a priori expectations. For example, the sign of the profitability variable *Price* was as expected. When the price of insecticide rose, insecticide use (*Q_bollworm*) fell. In addition, the sign of the farm size variable was negative. This meant that there was a bit of economy of scale in pesticide use. Ceteris paribus, as the size of the farm rises, the use of pesticide per hectare fell.

When examining how our results clarified the hypotheses, we found a fairly clear and consistent story: while there was little support for the hypotheses that there had been serious negative externalities which were associated with the expansion of Bt cotton sown area, there was evidence that there were positive externalities. Regardless of the choice of estimator (two are used—OLS in columns 1 and 2; Tobit in columns 3 and 4) or specification on the dependent variable (the "volume of insecticide used" in columns 1 and 3; the "cost of insecticide" in columns 2 and 4), the coefficients on the variables of interest used to test the 4 hypotheses were consistent across all of the different models (Table 4). Specifically, regardless of whether or not the dependent variable was specified in physical terms or costs, and regardless of whether or not the model was estimated by OLS or Tobit, the coefficient of the Bt variable was negative and highly significant. According to the strictest interpretation, this coefficient meant that in 1999 (the first year of the study) across all of the sample villages, on average, when farmers used Bt cotton they reduced pesticide use by 54.2 to 55.2 kilograms. The results also suggested that in 1999 farmers also reduced pesticide costs by 1381.9 to 1403.4 yuan. Such findings are consistent with those reported in Huang *et al*. [5,6,12] and Pray *et al*. [7,13]. Hypothesis 1, or the hypothesis that Bt cotton does not reduce insecticide use in the initial year (in 1999), was rejected.

Likewise, the hypothesis that there was no (or that there was a positive) effect of *Year_dummies* on *Q_bollworm* also is rejected (Hypothesis 2). The negative and highly significant signs of the *Year_dummies* suggest that as villages increased the level of Bt cotton adoption over the study period between 1999 and 2007 (and after villages reached full adoption) there were positive externalities (or some positive time varying effect) and *Q_bollworm* fell. Note because we also included a set of interaction terms (Bt*Year_dummies), the negative signs for the Year_dummies meant that over time the amount of pesticide used for bollworms on non-Bt cotton was negative. Hence, this result is consistent with the finding that there is a reduced population effect. In other words, if this interpretation is correct, it means that over the past decade, a time during the rise of Bt cotton, not only did the quantity of pesticide for controlling bollworms on Bt cotton fall (as seen from the previous paragraph), but the amount of pesticide for controlling bollworms on non-Bt cotton also fell because the widespread use of Bt cotton reduced the size of the bollworm population.

Careful interpretation of the coefficients of the Bt*Year_dummy interaction terms also revealed that there was no evidence of a major build-up of resistance by the bollworm to the Bt cotton after 10 years of adoption in China. Although the coefficients were positive and significant, interpreted in conjunction with the coefficient of the Bt cotton variable and the coefficients of the Year_dummies, it is clear that since the initial drop in 1999, the quantity of pesticide use for controlling bollworms in Bt cotton did not increase[3)].

The coefficient of the Full_Adopt variable is consistent with the idea that when the share of Bt cotton area reaches the point that the entire cotton crop in the village is planted with Bt cotton, the bollworm population falls (Hypothesis 3). This fall in pesticide used for controlling bollworms may suggest that a high level adoption of Bt cotton is creating an independent way in which farmers are able to reduce the quantity of insecticides used to control bollworms (Appendix Figure 1).

Because our data lacked direct observations of the evolution of the genetic structure of the bollworm population, the results are interpreted with caution. It is possible that resistance is building up in China's bollworm population. Whenever a population is subject to such stresses (i.e., the Bt toxin from Bt cotton are killing large volumes of the bollworm population), there is nearly a genetic response and

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3) The reduction of pesticide use for controlling bollworms in Bt cotton (compared with non-Bt cotton in 1999) in year t is estimated as the sum of the parameters for the following three dummy variables: Bt, Year_t, and Bt*Year_t. For example, the reduction of pesticide use for controlling bollworms in Bt cotton in 2004 was 54 kg ha^{-1}, which is the sum of –54.2, –40.2 and +40.4.

Table 4 Ordinary Least Squares and Tobit estimates of insecticide use for controlling bollworm in Bt and non-Bt cotton production in China[a)]

	Dependent variable: Insecticide to control bollworms			
	OLS estimation		Tobit estimation	
	Quantity (kg ha^{-1})	Cost (RMB ha^{-1})	Quantity (kg ha^{-1})	Cost (RMB ha^{-1})
Bt	–54.2	–1381.9	–55.2	–1403.4
	(6.62)***	(7.81)***	(20.92)***	(25.10)***
Year_2000	–18.0	–614.6	–15.4	–565.6
	(2.11)**	(3.33)***	(5.00)***	(8.66)***
Year_2001	–13.1	–564.0	–11.3	–530.1
	(1.50)	(3.03)***	(3.58)***	(7.95)***
Year_2004	–40.2	–1070.9	–39.4	–1056.8
	(4.77)***	(5.87)***	(11.09)***	(14.06)***
Year_2006	–37.7	-953.9	–36.1	–921.9
	(4.33)***	(4.97)***	(8.21)***	(9.91)***
Year_2007	–47.9	-1180.6	–46.8	–1158.0
	(5.64)***	(6.47)***	(8.00)***	(9.34)***
Bt*Year_2000	29.1	866.1	28.6	857.8
	(3.38)***	(4.67)***	(9.23)***	(13.06)***
Bt*Year_2001	15.5	646.4	12.5	581.5
	(1.77)*	(3.47)***	(4.08)***	(8.94)***
Bt*Year_2004	40.4	1107.9	35.7	1009.9
	(4.80)***	(6.08)***	(10.25)***	(13.70)***
Bt*Year_2006	44.5	1141.9	44.8	1151.2
	(5.11)***	(5.95)***	(10.34)***	(12.55)***
Bt*Year_2007	53.7	1346.9	54.6	1364.8
	(6.33)***	(7.40)***	(9.44)***	(11.15)***
Bt_Full_adopt	–5.4	–102.9	–5.2	–100.5
	(4.03)***	(4.27)***	(4.78)***	(4.40)***
Refuge_intensity	45.2	993.1	53.6	1167.0
	(9.74)***	(9.26)***	(8.17)***	(8.41)***
Refuge intensity*HN	–42.4	–956.0	–51.6	–1154.0
	(7.57)***	(7.37)***	(6.81)***	(7.20)***
Refuge intensity*SD	–36.1	–846.8	–40.4	–946.2
	(3.88)***	(4.58)***	(4.51)***	(5.00)***
Refuge intensity*AH	–39.5	–745.0	–41.9	–741.0
	(3.14)***	(3.09)***	(3.62)***	(3.03)***
Insecticide_price	–0.2	1.4	–0.2	1.1
	(9.42)***	(1.45)	(11.89)***	(2.96)***
Farm size	–2.8	–51.8	–3.6	–66.4
	(2.69)***	(2.21)**	(3.53)***	(3.09)***
524 household dummies	Included but not reported			
Intercept	65.5	1391.7	67.8	1414.6
	(6.34)***	(6.39)***	(7.58)***	(7.46)***
Observations	3576	3576	3576	3576
R-squared	0.62	0.61		
x^2 test				
Refuge+HN_refuge=0	0.49	0.17	0.23	0.02
Refuge+SD_refuge=0	1.37	1.16	5.67**	3.52*
Refuge+AH_refuge=0	0.24	1.35	1.57	4.56**

a) *, ** and *** denote statistically significant respectively at 10%, 5% and 1% levels. The figures in parentheses are t-ratios.

a tendency to evolve resistance (as susceptible members of the population systematically die and produce fewer offspring and those with greater resistance survive). At the most our findings suggest that after nine years of commercialization (1999 to 2007), the population's genetic structure has not evolved enough (at least yet) to induce farmers to spray more. Alternatively, it could be that there already is emerging resistance but that the reduced population effect is great enough to offset it.

Finally, signs of the coefficients of the *Refuge_intensity* variables (and interaction terms—*e* and *f*) need to be separately interpreted for Hebei province (Hypothesis 4a) and for the other provinces (Hypothesis 4b). When adding the two coefficients together (*e*+*f*), the combined coefficients in the case of Shandong, Henan and Anhui are all insignificant from zero. Specifically, the insignificant set of coefficients may be interpreted as evidence that is consistent with the fact that China's "natural refuge policy", at least so far, has been sufficient to keep any negative externality from appearing.

However, in the case of Hebei Province, the coefficient of the base Refuge_intensity variable is positive and significant. This means that when there are more refuge crops planted in a village, the use of pesticides for bollworms rises. While at first this may seem counterintuitive, according to interviews with investigators and farmers in the field, there is a logical explanation. When cotton-which is mostly Bt cotton-is planted in close proximity to many other refuge crops, there is higher pest pressure. Because none of the refuge crops are expressing Bt, the population of bollworms is apt to grow (they are breeding in the non-Bt refuges). In Hebei province this increased pest pressure seems to have been enough to make cotton farmers spray more pesticides for controlling bollworms. This is exactly what a refuge is supposed to be doing, which is producing relatively more of the pests from refuges (which are not being selected for increased resistance to the Bt toxin) so that they breed with the populations of bollworms that have been in the Bt cotton fields and have been subject to selection pressure for the Bt toxin.

4 Conclusions

China's agricultural leaders acted differently from their counterparts in other nations in their decision not to require Bt cotton refuges or to encourage the introduction of the double Bt gene constructs that are used elsewhere. The significance of this paper is that we provide evidence from farm level surveys that China's "natural refuge policy" appears to be justified, at least so far. Although it is possible that the resistance of the bollworm population to the Bt toxins is building up, at least through the late 2000s resistance had not yet reached the point where it was strong enough to affect the efficacy of the Bt cotton plant. This finding is also consistent with recent studies by Wu *et al*. [25] and Gao *et al*. [26].

Our analysis also provides evidence of positive externalities associated with the expansion of Bt cotton. It appears that pesticide use is being reduced but not only the direct effect of Bt (associated with Hypothesis 1, which is consistent with the findings previously reported in the literature) which is what farmers paid for when they bought Bt cotton seed, but also by the effects of Bt cotton adoption (Hypothesis 2) on bollworm populations. The results of the study are consistent with the notion that suggests Bt cotton's spread has reduced the population of bollworms enough that farmers of both Bt cotton and non-Bt cotton are able to reduce their reliance on chemical pesticides for controlling bollworms. This is consistent with the work of Wu *et al*. [11] who directly measured bollworm populations and found that they are declining. When assessing the costs and benefits of technologies, this additional component needs to be attributed to the adoption of Bt cotton.

When thinking about the implications of these results for other developing countries, it is also essential to remember that the effect of *Bt_intensity* on insecticide use for controlling bollworms is likely to be highly environment-specific. Pest population dynamics depend on many factors, such as climate, topography, general cropping systems and the nature of the pest population itself. Therefore much research is needed before the lessons from China might be applied to other developing countries.

The authors wish to express their sincere gratitude to the staff of the Center for Chinese Agricultural Policy who worked so hard in collecting data. We would also like to thank Ellie Osir, Robert Tripp, Derek Byerlee, Wally Falcon, Fred Gould, Keijiro Otsuka, Per Pinstrup-Andersen, Prabhu Pingali, Qiao FangBin and Wu KongMing for their comments. This work was supported by the National Natural Science Foundation of China (*Grant No. 70333001*)*, the GMO Program of the Ministry of Agriculture* (*Grant No. 2009ZX08015-002*)*, the International Development Research Center* (*Grant No. 105562-001*)*, the Knowledge Innovative Program of the Chinese Academy of Sciences* (*Grant Nos. KSCX-YW-09 and KSCX2-YW-N-039*)*, the Rockefeller Foundation, Cornell University, and Oxfam for various years of the surveys from 1999 to 2007.*

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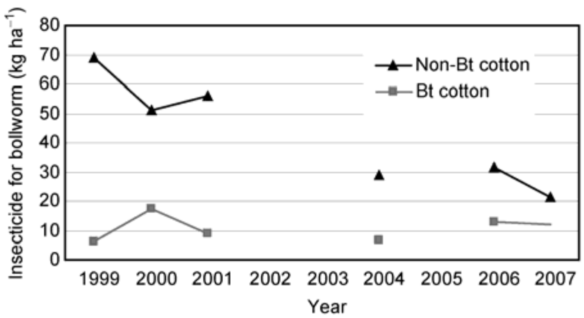
Appendix Table1 Characteristics of sample households in 1999–2007[a)]

	Mean	Standard deviation
Farm size (ha)	0.73	0.38
Total crop cultivation area (ha)	1.19	0.68
Cotton area (ha)	0.53	0.30
Bt-cotton area (ha)	0.47	0.32
Education of household head (years)	7.3	2.8
Age of household head (years)	46.4	9.3

a) Source: authors' survey in 1999–2007.



Appendix Figure 1 Simulated trends of insecticide used for controlling bollworms in Bt and non-Bt fields, 1999-2007. The numbers are estimated from the parameters c_0 and c_1 in equation 2 and reported in column 1 of Table 4.