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**Eight Years of *Bt* Cotton in Farmer Fields in China:
Is the Reduction of Insecticide Use Sustainable?**

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Abstract

The farmers in China's northern and central provinces began adopting Bt cotton in 1997 and in recent years almost exclusively plant Bt cotton. Adopted largely because traditional means of controlling bollworms by spraying insecticides were largely ineffective, the initial large gains in productivity from adopting Bt cotton, which expresses a toxin that can control bollworms, came mostly from sharply reduced levels of insecticide use. Despite the successes during the first years after adoption, there are uncertainties about the future of Bt cotton. On the one hand, the absence of refuges raises the question about whether or not the gains be sustained in the future. On the other hand, it also is a possibility that as Bt cotton acreage spreads, there may be positive externalities that can increase the gains. The overall goal of this research is to examine whether or not the gains from reduced spraying for bollworms that characterized the initial spread of Bt cotton is being sustained almost one decade after its initial adoption. Based on farm level data collected by the authors in 1999, 2000, 2001 and 2004 in 16 villages in Hebei, Shangdong, Henan, and Anhui provinces, our analyses show that insecticides applied to control bollworms instead of increasing as some expected in fact have declined. While the study's results, which are based on socio-economic data from Bt and non-Bt cotton farmers, are not able to pinpoint the exact mechanism that has allowed Bt to maintain or increase its productivity-enhancing effects, they are consistent with a story that suggests farmers—both those cultivating Bt cotton and non-Bt cotton—have been able to continue to reduce their use of insecticides due to lower populations of bollworm that have fallen as a result of Bt cotton area expansion. Moreover, our results are also consistent with the findings that at least eight years of commercialization, if there is any rise in the inherent resistance of bollworms to the Bt toxin, it still has not induced farmers to increase their use of insecticides to control bollworms. The findings from this study have important implications not only for refuge management policy in agricultural sectors of developing countries that are dominated by small, poor farmers that plant a diversified set of crops, but also for those that are interested in the methodologies that have been used to measure the direct and indirect impacts (or externalities) of insect-resistant GM technologies on crop production decisions.

Key words: *biotechnology, Bt cotton, sustainability, externality, China*

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The development of insect resistant crop varieties has been one of the most successful applications of agricultural biotechnology research to date. Countries that have introduced *Bacillus thuringiensis* (*Bt*) crops have derived significant and multiple benefits, including increased yields, decreased production costs and, especially, a reduction of insecticide applications (Perlak et al. 2001; Traxler et al. 2001; Ismael et al. 2001; Huang et al. 2002a and 2003; Pray et al. 2002; Qaim and Zilberman 2003). According to work inside and outside of China, *Bt* cotton has produced significant economic and social benefits as well as positively contributing to a cleaner production environment (James 2004).

While the rise in productivity of *Bt* cotton is well-documented, one of the major concerns about its success in the long run is the potential vulnerability of *Bt* crops to the adaptation by pests to *Bt* toxin (Bates et al. 2005). It is possible that the spread of *Bt* cotton and other crops will create pressure for the selection of (pre-existing) *Bt* resistant pests which would lead to an increase in their share of the population. If too large of share of the pests developed resistance to the *Bt* toxin, the susceptibility of the pest population to the *Bt* toxin will fall. Such an occurrence would reduce the effectiveness of *Bt* crops in controlling pests and undermine their benefits.

Evidence suggests that a refuge strategy can effectively control resistance in many circumstances, although there is a cost to implementing refuge policy (Shelton

et al. 2000). To implement refuges, farmers are expected to plant part of their crop acreage with a crop that does not use the Bt toxins for pest control. Refuges allow susceptible pests to thrive so they can mate with resistant pests that survive in the Bt cotton fields. Intermixing susceptible pests into the population can reduce selection pressure and extend the efficacy of the insect-resistant varieties. However, since Bt crops are more profitable than non-Bt crops, planting a refuge imposes a cost on the producer.

In contrast, there also are other factors that not only could offset any rise in resistance, but also could enhance the initial effects of Bt cotton. For example, it is possible that there are positive externalities that could be associated with widespread adoption of Bt cotton. If the spread of Bt cotton eliminated a major host of bollworms, the entire pest population could be reduced to a point that it posed less of a threat to Bt cotton and other crops, including non-Bt cotton (Carrière et al. 2003). There could also be learning effects as China's farmers gain more experience in using Bt cotton.

Despite the importance of this issue, there are no empirical studies in China or other developing countries that can provide evidence on the sustainability of the productivity effects of the adoption of Bt cotton after nearly a decade of spread across northern and central China. Specifically, we want to understand after eight years of adoption whether or not the productivity gains associated with Bt cotton in China have deteriorated, stayed the same or been enhanced. At most past knowledge of this issue is anecdotal.

To achieve this goal, the authors analysis these issues by drawing on data that they have been collecting in major cotton producing provinces since the late 1990s. Based on four years of farm-level data—1999, 2000, 2001 and 2004—from 16 villages in Hebei, Shangdong, Henan and Anhui provinces, the frequencies and levels of insecticides applied by farmers to control bollworm and other insects are analyzed. The results demonstrate that there is no evidence of rising insecticide use. In fact, it is found that the amount of insecticide applied to control bollworm has declined over time. The findings suggest that there is a positive externality that is associated with the expansion of Bt cotton area. There also is no evidence that there is any rise in insecticide use that associated with rising resistance.

There also are limitations to the study. Specifically, the nature of our data, which follow households and their cultivation practices in a set of village between 1999 and 2004, limits what can be determined. From socio-economic/production information that is collected from households we can tell the trends of insecticide use and identify determinants. But, we also lack key pieces of evidence will keep us from identifying the exact source of the production decisions of farmers. For example, we do not know how the size of the bollworm population has changed over time or whether or not the genetic make up of the population is evolving. As such, we are only able to infer from relationships that appear in the data provided by farmers on the use of insecticides, the adoption of Bt cotton varieties and the production environment what underlying entomological sources are consistent with the findings.

The rest of the paper is organized as the 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 and a descriptive analysis of insecticide use by farmers in their Bt and non-Bt cotton-producing fields is presented. A multivariate, statistical model and the results of the analysis of whether or not there is any evidence that China's bollworm population is developing resistance to Bt cotton are presented in the fourth section. The last section concludes.

Data and Sample

The data used in this study are a subset of a database established by the Center for Chinese Agricultural Policy (CCAP). This database for the first three years has been used by researchers to assess the efficiency of *Bt* cotton relative to conventional cotton varieties in China (Pray et al. 2001; Pray et al. 2002; Huang et al. 2002a; Huang et al. 2002b; Huang et al. 2002c; Huang et al. 2002d; Huang et al. 2003). The data include four rounds of intensive farm household surveys that focus on *Bt* cotton production. The surveys cover 1999, 2000, 2001 and 2004. In each successive year, the CCAP survey team increased the sample size and coverage as the use of *Bt* cotton spread throughout China. The surveys cover 36 villages in 7 provinces, including Hebei (4 rounds of surveys in 2 villages; 2 rounds in 2 villages), Shandong (4 rounds in 2 villages; 2 rounds in 4 villages), Henan (3 rounds in 4 villages), Anhui (2 rounds in 2 villages; 1 round in 6 villages); Jiangsu (1 round in 8 villages); and Hubei (1 round in 8 villages).

Villages and households that are included in the study were randomly selected. In each village about 25 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, which was provided by the local household registration office. Each farmer was interviewed by trained enumerators from CCAP's survey team for about 2 to 3 hours using standard, recall enumeration techniques that are standard in the economics literature. The information on *Bt* and non-*Bt* cotton production, both inputs and output, is available 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 in the fields of the sample farm households and examine the correlates of the *changes*, the analysis can only draw on sample households that were surveyed in at least 2 periods. Because of this, the analysis does not consider data from the 22 villages that were visited only once (6 villages from Anhui; 8 villages from Jiangsu; 8 villages from Hubei). Hence, the observations from all of the remaining villages in which enumerators visited at least twice (that is, 16 villages from 4 provinces—Hebei; Shandong; Henan and Anhui) are included in this study. Between 1998 and 2004, the four sample provinces accounted for far more than 75 percent of China's total *Bt* cotton area in each year. In total, the sample includes information from 1044 household observations that planted

Bt and non-*Bt* cotton on 1868 plots. Descriptive statistics from the sample households are included in Appendix 1.

Bt Cotton Production and Insecticide Use in China

According to a national survey of Bt cotton adoption conducted by CCAP, the area planted to Bt cotton by China's farmers has spread rapidly since the 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 rapidly adopted the crop, although the speed of adoption has varied by province. For example, the level of adoption had already reached more than 95 percent in Hebei and Shandong by 2001. The rise was slower in Henan and Anhui provinces.

The concern about the need for refuges has arisen recently because of the high rates of adoptions achieved by 2004 (table 1, bottom row).¹ Across China, of the 5.65 million hectares of cotton planted in 2004, nearly 3.7 million hectares were cultivated to Bt cotton. Sixty five percent of China's cotton was being planted to Bt cotton in 2004. In the four study provinces the rates of adoption reached 100 percent in two (Hebei and Shandong) and more than 80 percent in the other two (Henan and Anhui). Although not shown in table 1, the area of Bt cotton has been steadily expanding outside of the study areas—to more southern provinces, such as, Jiangsu and Hubei.

[Insert table 1 here]

The intensity of Bt cotton cultivation

Concerns about high rates of adoptions are reinforced by the levels of adoption by farmers in the 16 sample villages in Hebei, Shandong, Henan and Anhui (table 2, rows 3, 6, 9 and 12). For example, in the study villages by 1998 in Hebei and 2001 in Shandong, all of the villages had achieved 100 percent levels of adoption. The levels of adoption by farmers in the study villages in Henan reached 89 percent by 2004; those in Anhui had reached 97 percent. If the rate of rise of resistance were related to the concentration of Bt cotton as a share of total cotton area, there is clearly reason to be concerned. Certainly it is these high level of Bt cotton adoption rates that worry those that advocate the need for refuges.

[Insert table 2 here]

Scholars that argue against the need for refuges (or that advocate China's "zero refuge policy"), however, can find support for their position in the data from the sample villages (table 2, rows 1, 4, 7, 10). Although rates of Bt cotton adoption are high as a share of 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 area is far from being a monocultured crop. For example, in Hebei between 1997 and 2004 the share of cotton in total cultivated area ranged between 16 and 40 percent. The shares of cotton in total cultivated area in the other sample villages also only ranged between 37 and 54 percent. Hence, unlike the cropping patterns of other nations (e.g., the US and Australia, nations that are known for their large monocultured areas), China's cotton crop is grown along side a diversified set of other crops.

In fact, the cropping patterns of China are such that cotton is being cultivated in the sample villages along side a number of crops that are known to be a host of the bollworm. According to (Wu and Guo 2005), 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 called *refuge crops*.

If only 25 percent of wheat area is counted (since only part of cotton's growing season overlaps with wheat), and if only 75 percent of vegetable area is counted (since about 25 percent of the vegetable crop is planted in hothouses during the time of year when cotton is not being planted), the share of the sample village's total cultivated area that is planted to refuge crops can be calculated and shown to be relatively large (table 2, rows 2, 5, 8, 11). When doing so, it can be seen that refuge crops in villages that cultivate Bt cotton account for a large share of cultivated area. In no province does the share of refuge crop fall below 22 percent (Shandong). In all years in Hebei, Henan and Anhui the share of refuge crops exceeds 28 percent. When looking data for each of the 16 sample villages (not shown), it is found that the share of the refuge crops is never lower than 11.3 percent. On average, the refuge area share was 41.6 percent in 2004. According to the advocates of China's zero refuge policy the existence of the refuge crops, which grow along side China's Bt cotton, is enough to maintain the susceptibility of the bollworm population to the Bt toxin of Bt cotton. While this line of logic appears to be sound, there is no analytical proof. Therefore, the question for the rest of the paper is whether with these high rates of Bt cotton

adoption are enough or whether China needs a cotton refuge requirement in addition to the area planted by the farmers themselves to refuge crops.

It is important to remember that in addition to the negative effects that might be associated with intensive adoption of insect-resistant GM crops, there could be positive externalities. It is possible that as the area of Bt cotton rose, it could have a dampening effect on the growth of the entire bollworm population. If the entire level of population of pests fell enough, farmers may be able to continue to reduce their levels of insecticides past the original point that was enabled by the Bt crop. Such a phenomenon is not without precedent. For example, in the US state of Arizona the population of cotton pests almost disappeared a number of years after the commercialization and comprehensive spread of Bt cotton (Carrière et al. 2003).

[HELP MORE ON THIS??]

Insecticide use trends in China's cotton fields

As was found in previous work on Bt cotton in China (e.g., Huang et al. 2002a), one of the most important outcomes for farmers that adopt Bt cotton is the sharp reduction of insecticides when compared to non-Bt cotton farmers (table 3). When examining total insecticide use (columns 1 to 4) by focusing insecticide use by farmers within the same villages (e.g., row 4 vs. row 7; row 5 vs. row 8; row 6 vs. row 9), the use by farmers adopting Bt cotton compared to those cultivating conventional cotton is sharply (and significantly in a statistical sense) less in all cases. The same difference between Bt cotton and non-Bt cotton regarding the amount of insecticide used to control for bollworms also is clear (columns 5 to 8).

[Insert table 3 here]

Data across time on total insecticide use for each set of villages (that are examined by looking across each row of table 3) show that the trend in some, although not all, of the sample villages rises in recent years. For example, between 2001 and 2004 total insecticide use on *Bt* cotton rises on the plots of farmers in Hebei-a (from 16.6 to 30.3—row 1) and in the four Henan villages (from 13.3 to 22.5—row 5); the number of spraying (although not quantity of insecticide) drop on non-*Bt* cotton-producing plots in the four Henan villages (from 27.4 to 13.4—row 8). Hence, it may be that the jumps in these figures on total insecticide use are behind some of the concerns that there are rising pressures from secondary insects. While interesting as an issue in and of itself, the trends of insecticide use for the control of secondary pests is not examined here. For most information on the trends of secondary insects, see Huang et al., 2005.² **[please read endnote 2 for accuracy]**

In contrast with total insecticide use, with the exception of the differences between 1999 and 2000, data across time on insecticide use to control for bollworms shows a consistently falling pattern (table 3, columns 5 to 8). For example, the two Hebei sample villages (Hebei-a) and two Shandong sample villages (Shandong-a), villages for which there are data on all years between 2000 and 2004, insecticide use to control for bollworms on *Bt* cotton fields drops from more than 14 kilograms per hectare to less than 4 kilograms per hectare (rows 1 and 3). Insecticide use to control for bollworms on *Bt* cotton fields also falls after 2000 in the four Henan and two Anhui villages (rows 5 and 6). While we can not say for sure, the falling level of

insecticide use to control for bollworms is consistent with the idea that the level of resistance of the bollworm is *not* increasing. It also is consistent with the idea that there is a positive externality (e.g., there is a wholesale fall in the size of the bollworm population) that accompanies the expansion of Bt cotton area (or there is learning). Such a finding, however, may also be due to learning effects of farmers who find that they are able to use increasingly less amounts of insecticides when they adopt the new technologies.

Descriptive data on the level of insecticide use on non-Bt cotton helps isolate part of the effect in several ways. First, when examining the patterns of insecticide use on non-Bt cotton fields there also is not any sign that there is an increase in resistance. The patterns also demonstrate that the effect of Bt cotton may go beyond its impact on bollworms in the Bt cotton fields in the sample villages. Specifically, from table 3 (rows 8 and 9), the level of insecticide used on the non-Bt cotton fields also falls. For example, in the four Henan villages, the use of insecticides for bollworms fell from 36.3 kilograms per hectare in 2000 to 13.4 kilograms per hectare in 2004. Since non-Bt cotton has no way to protect itself against the bollworm, the falling use of insecticide to control for bollworms may be an indication that the total population of bollworms in northern China is falling (which may or may not be the result of widespread adoption of Bt cotton). While not definitive evidence, the source of the fall in pesticide use for controlling bollworms in non-Bt cotton fields would suggest that the externality would be from a factor that affected both Bt and non-Bt

crops (such as a falling pest population) and not a learning effect which would only affect the Bt crop. The patterns in table 3 can visually be seen in figure 1.

[Insert figure 1 here]

Information from the farm household surveys in 2001 and 2004 about the level of infestations of bollworms over the previous three years supports the idea that the levels of infestations are falling over time. Figure 2 summarizes the responses of the sample farmers in four sample provinces. When asked in 2001, farmers stated that between 1999 and 2001 the level of bollworm infestations fell (especially between 2000 and 2001). Similarly, when asked in 2004, farmers stated that between 2002 and 2004 infestation levels also fell. The reported level in the four sample provinces in 2004 was the lowest of any year. Because the trends in figure 2 are merely descriptive in nature, they can not be attributed to the increasing adoption of Bt cotton. However, at the very least it can be surmised that part of the falling levels of insecticide use can be associated with the falling levels of infestations (regardless of the source of the fall in infestations).

[Insert figure 2 here]

Hypothesis, Empirical Model and Multivariate Results

The descriptive analysis in the previous section demonstrates the complex patterns of insecticide use that are observed in the sample villages when comparing observations over time, across villages and between Bt cotton and non-Bt cotton plots. There are, however, several fairly prominent observed facts. Bt cotton adoption has

risen to high levels (as a share of cotton sown area). While this might be cause for concern about the build up of resistance, as noted above, cotton is not monocropped; in all sample villages it is cultivated along side a substantial amount of refuge crops. Perhaps because of this, there is little immediate evidence that resistance is growing over time as shown by the fact that insecticide use to control for bollworms is falling in general. Moreover, and somewhat unexpectedly, the data show that this falling trend is not only true for Bt cotton plots, the level of insecticide used to control for bollworm on non-Bt cotton plots also is falling. The descriptive data are consistent with the argument that the reason for the falling level of insecticide use to control bollworms is that there is a systematic fall in the level of perceived infestation by farmers (which is also observed in the data).

Because the descriptive analysis is inconclusive, and due to the fact that conceptually it is possible (indeed probable) that other factors might affect insecticide use to control for bollworm (in addition to the level of adoption of Bt cotton), multiple regression analysis is needed. To implement a test that can isolate the effect of Bt cotton adoption (and other factors—e.g., the level of refuge; the intensity of adoption; etc.) on insecticide use to control for bollworm, a general pesticide use model at the farm level is used as a starting point for the analysis (Pingali et al. 1994; Huang et al. 2002b; Huang et al. 2003; Qaim and Zilberman 2003). **[are these all correct citations??? Someone criticized us once on our citation for a pesiticide use ... or maybe yield model ... just be sure]** In our analysis, however, four modifications are made to the basic “determinants of

insecticide use” framework, however, four modifications are made: a.) the model is estimated for the level of insecticide used to control for bollworms (that is, the left hand side dependent variable is volume of insecticide used to control for bollworms, not total insecticide use); b.) on the right hand side of the equation, a measure is used to indicate whether the farmer’s plot cultivated Bt or non-Bt since there should be a difference given the fact that Bt cotton naturally expresses a toxin that can partially control bollworms and non-Bt cotton does not; c.) a measure is used of the share of total cultivated area that is planted to refuge crops; and d.) a measure of the intensity of Bt cotton adoption at the village level is included. We include the measures of refuges and intensity in order to understand if there are any positive or negative externalities that are associated with the production environment our sample of China’s cotton growing villages.

The conceptual model can be specified as:

$$(1) \text{ Insecticide use to control for bollworms (plot level)} = f(\text{Bt cotton (plot level); Refuge crop intensity (village level); Bt cotton adoption level (village level); Others factors})$$

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); *Refuge intensity* is the share of total sown area planted to wheat (times 0.25) and other crops (e.g., maize, soybeans, non-Bt cotton, rapeseed and vegetables) that are planted the same time as the Bt cotton; Bt cotton adoption at the village level is a matrix that includes two variables, one, the share of total cotton area cultivated to Bt cotton at the village level ($Bt_intensity$), and two, an indicator variable that is one if the village has completely

adopted Bt cotton and zero if there is still some share that is cultivated in non-Bt (*Bt_fulladopt*).

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

$$(2) \quad Q_bollworm_{ijt} = a + bBt_{ijt} + (c_0 + c_1 Bt_{ijt}) Bt_intensity_{vt} + d Bt_fulladopt_{vt} + e Refuge_intensity_{vt} + g Hybrid_{ijt} + h Price_{it} + k YldLoss_{it} + l Farmsize_{it} + m Age_{it} + p Edu_{it} + q Training_{it} + r County\ dummies + u_{ijt}$$

where i , j , v and t 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).

In order to explain the net effect of *Bt*, *Bt_intensity*, *Bt_fulladopt* and *Refuge_intensity* on *Q-bollworm*, other factors that influence insecticide use on the plots of farmers need to be controlled for. In this analysis, eight other variables (or sets of variables) are included. In particular, we include *Hybrid* cotton variety dummy variable with value one if the variety is a hybrid and zero if otherwise. In addition, three profitability variables of insecticide use are included. The first is the price of pesticides (*Price*—measured as yuan per kilogram). The second is the farmer's perception of the severity of the farm's pest infestation problem (*YldLoss*—measured as the % of the crop that the farmer believes would have been lost if the crop were not sprayed). The third is the size of the household's total area of cultivated land (or *FarmSize*). The human capital of the farmer is included and is measured as the

household head's *Age*, Education (*Edu*) and *Training* (measured as a dummy variable, in which one equals the case in which the household has attended at some time in the past a course focused on training in insect management; and zero otherwise). *County dummies* are also included to control location-specific impacts (including weather). The symbols *a, b, c, d, e, g, h, k, l, m, p, q,* and *r* are parameters to be estimated.

Equation (2) can be estimated by Ordinary Least Squares (OLS) if it is assumed the error term, u_{ijt} , follows a normal distribution. Unfortunately, of the sample's 1868 plots which are used in regression, in 494 of them farmers did not apply insecticides to control for bollworms. Statistically, this can be accounted for by using a Tobit estimator to estimate the parameters in equation (2).

Testable hypotheses

The model as specified in equation can be used to test the following hypotheses that are related to impacts of the adoption and spread of Bt cotton on

Q_bollworm:

Hypothesis 1: $b = 0$. *Bt* cotton does not affect insecticide used to control for 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 at the village level (*Bt_intensity*) does not increase or reduce *Q_bollworm*. 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 a negative externality association with rising levels of *Bt_intensity*. One source of the negative externality could be rising resistance, although, as indicated above, the absence on genetic data from the bollworm population limits the ability to pinpoint this effect. At most we can say that a positive c_0 is consistent with rising resistance. If $c_0 < 0$, then the evidence is not consistent with emerging bollworm resistance (henceforth, *resistance effect*); instead, the negative sign would be evidence of a positive externality associated with rising *Bt_intensity*. Likewise, the absence of an entomological

assessment of the size of the pest population in each village keeps us from identifying if the negative relationship between $Q_{bollworm}$ and $Bt_intensity$ is due to the *reduced population effect*. In fact, when c_0 is negative, it also is consistent with a learning effect by farmers who gradually figure out that they need less insecticide as $Bt_intensity$ rises. The parameter c_1 can be used to test whether or not there is difference in either the negative or positive externality that is associated with different levels of $Bt_intensity$. If c_0 is negative and c_1 is zero (or there is no statistical difference in the effect of $Bt_intensity$ on insecticide use), there would be greater evidence in favor of the reduced population effect since the learning effect would only occur on Bt cotton plots.

[make sure you read hypothesis 2 carefully ... if you think the hypotheses are too long, we could put part of them into a couple of endnotes]

Hypothesis 3: $d = 0$. If $d = 0$, there is no negative externality on insecticide use even when 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 4: $e = 0$. If $e = 0$, then the level of the share of the village's area cultivated with refuge crops ($Refuge_intensity$) is not associated with a negative externality (that might arise if there was a significant resistance effect). Otherwise, if $e > 0$, $Refuge_intensity$ is associated with a negative externality in terms of insecticide use.

Results

The results of the multiple regression estimation of equation (2) demonstrates that the model performs well generally and that while there is little support for the hypotheses that there have been serious negative externalities (at least so far) that are associated with the expansion of Bt cotton sown area, there is evidence that there are positive externalities (table 4). One way to evaluate the performance of the model is by examining how well the coefficients on some of the control variables conform with a priori expectations. In fact, the signs on two of the profitability variables (*Price* and

YldLoss) are as expected. When the price of insecticide rises, insecticide use (*Q_bollworm*) falls; and, when there is a high expected loss due to high levels of expected infestation, insecticide use rises. Likewise, the results also show that *Q_bollworm* falls with *Farmsize* and the experience of household head (*Age*).

[Insert table 4 here]

More importantly, regardless of the choice of estimator (two are used—OLS in columns 1 and 2; Tobit in columns 3 and 4) or specification of 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 that can be used to test the four hypotheses are consistent across all of the different models (table 4). Specifically, regardless of whether the dependent variable is specified in physical terms or cost, and regardless of whether the model is estimated by OLS or Tobit, the coefficient on the *Bt* variable is negative and highly significant. During the four years of study period across all of the sample villages, on average, when farmers use *Bt* cotton they reduce pesticide use by 32.61 to 36.81 kilograms and they reduce pesticide costs by 644.54 to 725.94 yuan. The results are consistent with those reported in Huang et al. (2002a; 2002b; 2003) and Pray et al. (2001; 2002). In short, the hypothesis that *Bt* cotton does not reduce insecticide use in the initial year (in 1999) is rejected.

Likewise, the hypothesis that there is no (or that there is a positive) effect of *Bt_Intensity* or *Bt_fulladopt* on *Q_bollworm* also is rejected. The negative and highly significant signs on the *Bt_Intensity* and *Bt_fulladopt* variables suggest that as villages

increase the level of Bt cotton adoption (and when they reach full adoption) there are positive externalities and $Q_{bollworm}$ falls. Hence, this result is consistent with the finding that there is no major build up of resistance by the bollworm to the Bt cotton after 8 years of adoption in China. The finding, in fact, goes further, suggesting that there is a positive externality as a sizeable share of the farmers in the village adopts Bt cotton.

While we can not isolate the precise mechanism, the results are consistent with the idea that as the share of Bt cotton area rises, the bollworm population falls, creating an independent way in which farmers are able to reduce the quantity of insecticides used to control for bollworms. Of course, by itself, there is no way to distinguish between the reduce population effect or if farmers are just learning about the effectiveness of Bt cotton as $Bt_intensity$ rises. The insignificant sign on the c_1 coefficient (which is the coefficient associated with the variable created by interacting Bt and $Bt_intensity$) means that it is more likely that the externality is associated with the population reducing effect and is not due to learning since the positive externality is enjoyed by farmers on both Bt and non-Bt cotton plots. Such a finding also provides an explanation of why it is that non-Bt cotton farmers have been able to reduce their insecticide use to control for bollworm during the sample period. It also is another benefit that should be counted when assessing the overall effect of the adoption of Bt cotton. In other words, many of the benefits that have been associated with the adoption of Bt cotton for users of Bt cotton (higher production, lower costs and

improved health) may also be true for non-Bt cotton producers because Bt cotton adoption has been effective in reducing China's overall population of bollworms.

Because our data lack direct observation on the evolution of the genetic structure of the bollworm population, the results should be interpreted with caution. In fact, it is possible (actually quite likely) that resistance is building up in China's bollworm population. Whenever a population is subject to such stresses, there is almost always a genetic response and 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 eight years of commercialization, the population's genetic structure has not evolved enough 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, the insignificant sign on *Refuge_intensity* may be interpreted as additional support for the rejecting the resistance effect (with the proper caveats noted). Specifically, the insignificant coefficient can be interpreted as evidence that China's "no refuge policy" at least so far has been sufficient to keep any negative externality from appearing. In other words, a lesson from our findings in that to this point in China's adoption history *Q_bollworm* is not affected if the shares of the village's total cultivated area planted to refuge crops are similar to the patterns found in the sample villages.

Conclusions

China is unique among the nations of world that have made the decision to extend GM crops. Unlike all other nations—both develop and developing—that have commercialized Bt cotton, China’s agricultural officials do not require their farmers to set aside a refuge as a way to maintain the susceptibility of the bollworm population to the Bt toxin that is expressed by the Bt cotton plant. Instead, China allows farmers to devote 100 percent of their cotton area to Bt cotton. The argument of those that support such a decision is that because of the diversified nature of China’s farming systems in the cotton producing areas in northern China, there are sufficient levels of refuge crops that act as a host for the bollworm population so that additional cotton refuges are not required. Such a finding is important to other developing countries, such as India and South Africa, that decided to require farmers to plant refuges. It could be that such refuges are unneeded and the expense of implementing them (both from the government’s and individuals farmer’s point of view) may be avoided, which would lead to even greater productivity gains.

China’s agricultural leaders acted differently from leaders of other countries in their decision not to require Bt cotton refuges and did so without evidence from the fields of farmers. The significance of this paper is that we provide such evidence from farm level surveys that span four provinces, 16 villages and 6 years that China’s “no 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—but has not yet reached a point at which it is strong enough to affect the efficacy of the Bt cotton

plant, our analysis discovered other powerful positive externalities that are associated with the expansion of Bt cotton. Above all, the analysis shows *both* the direct effect (associated with hypothesis one, which is consistent with the findings previously reported in the literature) *and* the indirect effects of Bt cotton adoption. The results of the study are consistent with a story that suggests Bt cotton's spread has reduced the population of bollworms enough that farmers of both Bt cotton and non-Bt cotton can reduce their reliance on chemical pesticides for controlling bollworms. When assessing the costs and benefits of technologies, to our knowledge such an effect has never been reported in the developing world.

It is important to remember when thinking about implications for the rest of the developing, however, that the effect of *Bt_intensity* on insecticide use 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, so much research is needed before the lessons from China would ever be ready to be applied to other developing countries. Therefore, it is possible that there are farming systems in other developing countries in which small farmers grow cotton as part of a mixed cropping pattern (which includes alternative hosts for bollworms) in which a cotton refuge policy is not necessary. However, this does not mean that refuge policies are never needed in developing countries. China's cotton economy in northern China perhaps just happens to be part of a highly diversified set of cropping patterns. In countries or regions in which this characteristic does not exist, it is possible that implementing a no refuge policy could lead to a more rapid build up

of resistance in the pest population. For example, while a no refuge policy may be appropriate for northern China's cotton growing area, it may not be appropriate if China were to allow commercialization of Bt cotton in Xinjiang province, a western province in which there are vast areas of monocropped cotton. Likewise, if China were to commercialize Bt rice it is possible that in many parts of southern China in which rice is almost the only crop in many counties and prefectures some kind of refuge policy would be beneficial in the long run. Such decisions may be important as there is now increasing pressure to commercialize Bt cotton in Xinjiang and Bt rice is in the final stages of testing before being commercialized.

The optimality of China's current no refuge policy for Bt cotton in northern China's cotton growing area also may affect the nation's decisions to commercialize other GM crops. For example, scientists are now experimenting with Bt maize. While the extension of Bt maize could have positive benefits for maize farmers, the widespread adoption of the crop would reduce the refuge crop areas for Bt cotton. If this would lead to a rise in the resistance of the bollworm to the Bt toxin, this could have negative consequences for both maize and cotton farmers. Hence, future R&D and commercialization decisions need to account for these secondary effects, which, as this paper shows, in some cases can be important.

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Table 1. Bt cotton adoption in China and sample provinces, 1997 to 2004.

Year	Cotton area (000 ha)		Bt cotton adoption rate (%)					Share of 4 provinces' 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	5650	3688	65	100	100	84	80	77

Note: Data source is based on CCAP's annual survey of Bt cotton adoption in each cotton production province.

Table 2. Bt cotton, refuge crops and the role of cotton in Northern China's cropping patterns, 1997 to 2004.

	1997	1998	1999	2000	2001	2002	2003	2004
Hebei								
Cotton area share %	16	20	25	36	30	39	39	40
Refuge crops share %	84	72	66	56	61	54	54	54
Bt cotton adoption %	77	100	100	100	100	100	100	100
Shandong								
Cotton area share %	37	42	45	49	46	54	53	53
Refuge crops share %	84	58	45	38	26	22	23	23
Bt cotton adoption %	31	74	91	97	100	100	100	100
Henan								
Cotton area share %	46	47	47	44	46	47	42	38
Refuge crops share %	100	94	91	60	41	44	49	51
Bt cotton adoption %	0	8	13	59	80	81	84	89
Anhui								
Cotton area share %	43	42	52	53	51	43	42	43
Refuge crops share %	100	100	100	97	58	45	32	28
Bt cotton adoption %	0	0	0	4	66	75	94	97

Notes: Cotton area share is the share of cotton area in total cultivated area. Refuge crops include wheat, maize, soybeans, rapeseed, vegetables, and other minor crops. Refuge crops share is the share of refuge crops (with 25% of wheat area; and 75 percent of vegetable area) in total cultivated area. Bt cotton adoption is the share of Bt cotton in total cotton area.

Data source is from authors' survey.

Table 3. Insecticide Use to Control for Bollworms (in kilograms per hectare) in the Sample Villages in China on Bt Cotton and Non-Bt Cotton Plots, 1999 to 2004

	Total insecticide use				Insecticide use for bollworm			
	1999	2000	2001	2004	1999	2000	2001	2004
Bt cotton								
Hebei-a (2 villages)	5.7	22.4	16.6	30.3	2.0	14.7	9.8	2.9
Hebei-b (2)	5.7	5.9	-	-	2.1	3.0	-	-
Shandong-a (2)	17.3	22.5	18.7	10.6	8.5	14.5	8.2	3.2
Shandong-b (4)	14.1	25.7	-	-	7.4	16.2	-	-
Henan (4)	-	19.2	13.3	22.5	-	12.0	3.8	3.8
Anhui (2)	-	-	44.7	29.4	-	-	18.7	5.8
Non Bt cotton								
Shandong-b (4)	64.1	-	-	-	53.2	-	-	-
Henan (4)	-	48.5	36.2	36.2	-	36.3	27.4	13.4
Anhui (2)	-	-	94.7	40.7	-	-	69.9	6.1

Note: Hebei-a (2) refers to 2 villages in Xinji county; Hebei-b (2) refers to 2 villages in Shenzhou county; Shandong-a (2) refers to 2 villages in Liangshan county; Shandong-b (4) refers to 4 villages in Xiajin and Lingxian counties; Henan (4) refers to 4 villages in Taikan and Fugou counties; Anhui (2) refers to 2 villages in Dongzi and Wangjiang counties.

Table 4. Ordinary Least Squares and Tobit Estimates of Insecticide Use for Controlling Bollworm in Bt and Non-Bt Cotton Production in China.

	Dependent variable: Insecticide to control for bollworm			
	OLS estimation		Tobit estimation	
	Quantity (kg/ha)	Cost (RMB/ha)	Quantity (kg/ha)	Cost (RMB/ha)
Intercept	45.15 (6.29)***	904.16 (5.90)***	49.67 (4.59)***	960.09 (4.42)***
Bt cotton dummy (<i>b</i>)	-32.61 (6.02)***	-644.54 (6.28)***	-36.81 (7.57)***	-725.94 (7.44)***
Bt_intensity (<i>c₀</i>)	-0.13 (2.01)**	-2.36 (1.75)*	-0.13 (1.96)*	-2.40 (1.86)*
Bt_intensity x Bt cotton dummy (<i>c₁</i>)	0.06 (0.82)	0.60 (0.42)	0.06 (0.93)	0.51 (0.42)
Bt_fulladopt (<i>d</i>)	-4.30 (3.74)***	-75.94 (3.60)***	-3.76 (2.21)**	-66.28 (1.94)*
Refuge_intensity (<i>e</i>)	0.07 (1.54)	0.98 (1.07)	0.11 (1.39)	1.74 (1.13)
Hybrid variety dummy	-0.88 (0.66)	0.88 (0.03)	-2.64 (1.60)	-32.35 (0.98)
Insecticide price	-0.11 (6.81)***	-0.83 (3.48)***	-0.31 (8.09)***	-3.27 (4.85)***
Farmer's yield perception loss	0.04 (2.40)**	0.55 (1.40)	0.07 (2.37)**	1.04 (1.91)*
Land per household	-3.60 (3.74)***	-78.71 (3.96)***	-6.27 (4.06)***	-121.54 (3.96)***
Household head age	-0.06 (1.26)	-0.65 (0.71)	-0.13 (2.24)**	-1.81 (1.57)
Household head education	0.42 (3.32)***	8.57 (3.43)***	0.48 (2.68)***	9.48 (2.63)***
Training dummy	-0.94 (1.44)	-14.57 (1.14)	-1.29 (1.07)	-20.33 (0.84)
8 county dummies	Included but not reported			
R-squared	0.37	0.38		

Note: *, ** and *** denotes statistically significant at 10%, 5% and 1% levels, respectively. The figures in parentheses are t-ratios. Total number of observation in each regression is 1868.

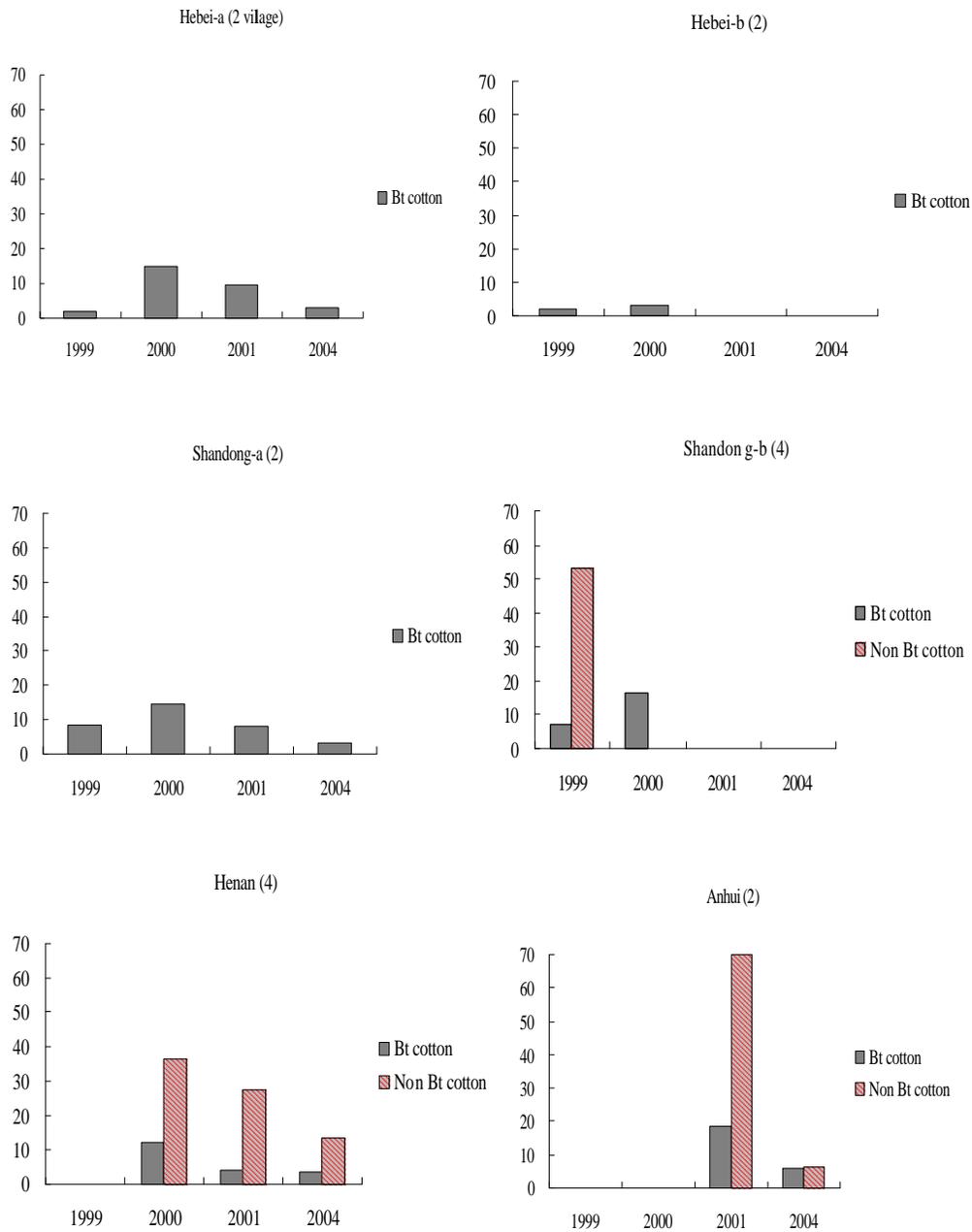


Figure 1. Insecticide use to control for bollworms on Bt cotton and Non-Bt cotton plots (kilograms per hectare) in sample provinces in China, 1999 to 2004.

Note: Data source is from authors' survey.

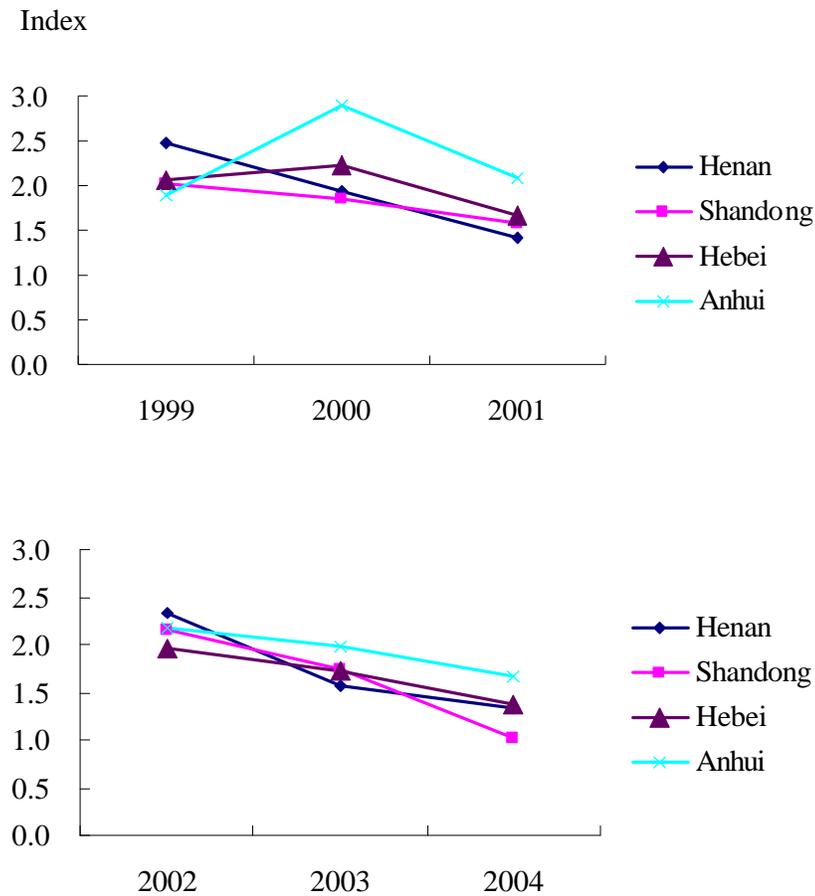


Figure 2. Degree of bollworm infestation as perceived by farmers in sample villages in China, 1999 to 2004.

Note: Because the data are from two rounds of surveys (in 2001 and 2004), during each round, enumerators asked farmers about their perception of the nature of the infestation for the current year and over the previous two years. The index created from the data was based on the question: Was it very serious (3); was it normal (2); was it “light” (1). Because the comparisons were made with the current year, comparison between that data from the 2001 survey and the 2004 survey should be made with caution.

Data source is from a authors’ survey in 2001 and 2004.

Appendix Table 1. Mean and Standard Deviations of Key Variables Used in the Model.

	Mean	Std. Dev.
Household-/plot-level variables		
Insecticide to control bollworm: Quantity (kg/ha)	12.3	21.1
Insecticide to control bollworm: Cost (RMB/ha)	251.6	424.0
Bt cotton dummy (1=yes)	0.9	0.4
Insecticide price (yuan/ha)	26.5	19.7
Land per household (hectares)	0.8	0.4
Household head age (years)	44.9	9.3
Household education (years)	6.3	3.2
Attended technical training? (1=yes; 0=no)	0.3	0.4
Hybrid variety dummy (1=yes; 0=no)	0.1	0.4
Farmer's perception of yield loss due to bollworms (%)	84.7	19.2
Village-level variables		
Bt_intensity (% of cotton area in villages adopting Bt)	88.4	20.7
Bt_intensity (% of sown area planted to refuge crops)	47.0	18.2
Bt cotton dummy x Bt_intensity	79.0	35.3
Bt cotton dummy x dummy for villages with full adoption more than 1 year (Bt_fulladopt)	0.5	0.5
County level dummies:		
Taikang	0.1	0.4
Fugou	0.1	0.3
Liangshan	0.2	0.4
Xiajin	0.1	0.3
Xinji	0.2	0.4
Shenzhou	0.1	0.2
Dongzi	0.1	0.2
Wangjiang	0.0	0.2

Note: Data source is from a authors' survey.

Endnotes

¹ The United States and other developed countries have the most experience with refuge policies. The United States Environmental Protection Agency (EPA) adopted a refuge strategy for managing the evolution of Bt resistance in 1996 when Bt crops were first introduced (EPA 1998). According to the EPA, farmers are required to plant minimum percentages of their total cotton acreage with non-Bt varieties. For example, cotton farmers in the southern United States have to leave either a “pure” refuge that equals 5 percent of their land (that is a plot of cotton that is not treated with any conventional pesticide) or a “partial” refuge of 20 percent on which the farmer is allowed to spray conventional pesticides to control pests. Following the process of setting a refuge policy that is being used in the United States, other developed countries, such as Canada and Australia, have adopted similar types of refuge policies for Bt crops (Fitt 1996). Most developing countries that have adopted Bt cotton—India, Indonesia and South Africa—have simply followed the example of the US and required that farmers put 20 percent of their cotton area into Bt cotton without studying whether this is any way needed or if it is an optimal size.

In contrast, China implicitly has a zero refuge strategy. While officials in China do not require farmers to plant refuges, this does not mean that there has not been a debate. Some scientists in China believe that since crops, such as, maize, wheat, rice and peanuts, serve as alternative hosts of the bollworm, China’s cotton producing region already has sufficiently large natural refuges (Wu et al. 2002, 2004), and they point out the difficulty of trying to enforce a Bt cotton refuge policy on millions of small farmers (Wu and Guo 2005). Currently Bt maize is not grown in China. There are also some environmentalists in China that believe that the bollworm may evolve resistance to the Bt toxin (Xue 2002). In some counties in northern China, surveys have determined that there are farmers that nearly exclusively grow cotton (Huang et al. 2003; Pray et al. 2002). Scientists base their concern on the fact that China’s bollworm populations resistant to organophosphate and pyrethroid insecticides quickly evolved even though farmers sprayed other host crops with much lower doses of chemical pesticides (than cotton). It is argued 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.

² In Huang et al., 2005, in fact, it is shown that most of the rise in secondary insects (specifically about 80% of the rise) appears to be due to weather and other time specific conditions. A survey of farmers in 2005 showed that the use of insecticides for the control of secondary insects fell significantly. Even if part of the rise in 2004 of secondary pest were associated with the expansion of Bt cotton, it is so small that the value of the pesticides used to control the secondary pests are only 3% of the measured value of the benefits of adoption Bt cotton (including the drop in the value of the pesticides needed to control bollworms and the value of the rise of yields).

Table 11.1 Impacts of Bt cotton on insecticide use and yield of Bt cotton compared to conventional cotton in several countries worldwide. Average insecticide use (kg/ha). Number of sprays. (2006) indicate a 44% reduction in insecticide applications on Bt cotton in Arizona in a system where pink bollworm (*P. gossypiella*) is the major target. Most recently Brookes and Barfoot (2006) have applied the protocols developed by Gianessi et al. China is the world's largest cotton producer with 7.5 million small holder farmers now growing 3.5 million hectares of Bt cotton (66% of the total crop) spread across three major ecological regions: the Yangtze River Region, the Yellow River Region, and the Northwestern Region (Wu, 2007). The Bt cotton farmers of the Makhathini Flats, in northern KwaZulu Natal, South Africa, had become a centrepiece of the GM industry's global promotion of GM crops as a solution to poverty and hunger. Why? Alternative methods for reducing pesticide use in cotton are not promoted even though it has proven to be very successful. [6] Bt cotton is just a distraction that maintains the pesticide industry and lures countries of the South into accepting GM. For it is clear that Bt cotton is also a Trojan Horse. None of the farmers interviewed kept any record of purchases, yields, amounts of insecticides sprayed. It can be safely assumed that hardly any small-scale farmer in the study area keep farming or financial records. China is the largest cotton producer in the world (21). It is also one of the largest pesticide consumers worldwide. For instance, China used 4.4 times more pesticides (in tons of active ingredients) than the United States in 2012 (22). The effects of insecticide use on both human health and ecological systems need to be mitigated. Different agricultural, land use, conservation, and climate adaptation policy measures may address different drivers of pest severity and insecticide use (32). Land use diversity had no significant effect on the severity of cotton bollworm (Table 1). The proportion of cotton area that was genetically resistant to bollworm had a significant negative impact on bollworm severity, indicating that this pest control strategy was effective.