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Managing Pest Resistance in Fragmented Farms: An Analysis of the Risk of Bt Cotton in China and its Zero Refuge Strategy and Beyond

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Summary

The goal of this study is to discuss why China and perhaps other developing countries may not need a refuge policy for Bacillus thuringiensis (Bt) cotton. We describe in detail the different elements that a nation—especially a developing one—should be considering when deciding if a refuge policy is needed. Drawing on a review of scientific data, economic analysis of other cases and a simulation exercise using a bio-economic model that we have produced to examine this question, we show that in the case of Bt cotton in China, the approach of not requiring special cotton refuges is defensible.

Key words**:** biotechnology, Bt cotton, resistance, natural refuge crops, Asia, China

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The development of insect resistant crop varieties has arguably been the most successful application of agricultural biotechnology research to date. Some countries that have introduced Bacillus thuringiensis (Bt) crops have derived significant and multiple benefits, including increased yields and falling production costs from the reduction in insecticide applications of at least 50 percent (James, 2005). Such gains also have been translated into economic, health and environmental benefits for both large and small producers. As a result, even though Bt cotton and Bt maize were grown commercially for the first time in 1996, their combined sown area reached more than 23 million hectares in 2004. Adoption also has spread beyond the borders of developed nations; farmers in China, India, Mexico and South Africa are cultivating large areas of Bt crops (Huang et al., 2002a; Qaim and Zilberman, 2003; Pray, 2001; and Traxler et al., 2001).

While the rise in the 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 the Bt toxin (Bates et al., 2005). It is possible that the large-scale deployment of Bt crops may cause an evolution of pest resistance to the Bt toxin (Tabashnik et al., 1990; Gould et al., 1995). The mechanism for the buildup of resistance is that as Bt crops spread, they create pressure for the selection of (pre-existing) Bt resistant pests because susceptible pests are killed, but resistant ones are not. If too large of a share of a pest population develops resistance to the Bt toxin, the susceptibility of the entire pest population to the Bt toxin will fall. Such an occurrence would reduce the effectiveness of Bt crops for controlling pests and the benefits from Bt crops would fall.

Evidence suggests that a refuge strategy can effectively control resistance in many circumstances, although there is a cost to require farmers to plant refuges. To implement refuges, farmers are expected to plant part of their crop acreage with a crop that does not use the Bt toxin for pest control. Refuges allow susceptible pests to thrive so they can mate with resistant pests that survive in the fields planted to Bt crops, thereby reducing selection pressure and extending the efficacy of the insect-resistant varieties. However, if Bt crops are more profitable than non-Bt crops, planting a refuge imposes a cost on the producer. There also are administrative costs that need to be incurred in order to monitor and enforce the refuge policy.

The United States and other developed countries have the most experience with refuge policies. The United States Environmental Protection Agency (USEPA) adopted a refuge strategy for managing the evolution of Bt resistance in 1996 when Bt crops were first introduced. According to the USEPA, 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 five percent of their land (that is a plot of cotton that is not treated with any conventional pesticide) or a *sprayed* refuge of 20 percent on which the farmer is allowed to spray conventional pesticides to control pests. Following the lead of the United States, other developed countries, such as Canada and Australia, have adopted similar types of refuge policies for Bt crops (Kelly, 2000; Turner, 2000). For example, in the case of Bt cotton, policy makers in Australia currently require cotton farmers to plant 10% of their cotton acreage as non-Bt cotton.

Although most developing countries also have adopted refuge strategies to manage the buildup of resistance in pest populations similar to those in the United States, it is not clear whether these refuge strategies are suitable for them. By the end of 2003, seven developing countries had commercialized Bt cotton: three from Asia (China, India and Indonesia), three from Latin America (Mexico, Argentina and Colombia) and one from Africa (South Africa). In all of these developing countries, except China, agricultural officials require farmers to follow the USEPA's rule of planting at least 20 percent of their cotton as a refuge (Pray, 2001; and Traxler et al., 2001). In contrast, China implicitly has a zero refuge strategy. The refuge policy—or lack thereof, however, does not seem to be based on research conducted in these countries, including China. Are the refuges appropriate? Unfortunately, since there is no quantitative research in developing countries, no one really knows which is correct: the 20 percent rule of the EPA; the 10 percent rule of Australia; or the zero refuge rule of China.

Surprisingly little work has gone into understanding the refuge policy strategies of developing countries, despite the potential importance of these strategies and the increasing use of Bt crops in developing countries. In fact, to the best of our knowledge, all existing quantitative economic studies on refuge management have focused on the strategies in the United States (Hurley et al., 2002; Secchi et al., 2001; Livingston, 2004). In these studies the authors typically examine a single question: in the typical production setting of United States agriculture, what are the implications of various size requirements of set-aside policies, measured as a proportion of the total planted area of a typical farmer. But in most developing countries, even though the nature of the plant-pest interaction may be the same as that in developed countries, the production environment is dramatically different since farms are highly fragmented and a diverse set of crops are grown. As a result, it is likely that a United States-style refuge policy may not be an appropriate choice for developing countries, or even for other developed countries with production settings different from those in the United States.

In almost all respects, China is an appropriate area to examine refuge policies in developing countries. China is leading the developing world in the use of transgenic crops for battling pest infestations. In part due to the introduction and popularization of Monsanto's Bt cotton in 1997 and the extension of the nation's own Bt varieties developed by the Chinese Academy of Agricultural Sciences (CAAS), Bt cotton cultivation has grown quickly. In 2004 Bt cotton sown area in China reached 3.7 million hectares, which comprised more than 40 percent of the total Bt cotton in the world. Moreover, Bt cotton is so popular that cotton-growing households in a number of regions of northern China plant almost exclusively Bt cotton (Huang et al., 2002b). Hence, the size and the concentration of Bt cotton cultivated in China make it an important place to study refuges.

Unlike other Bt-adopting countries in the world, in China there has been a conscious choice to opt for a no refuge policy, despite the fact that there is an active debate on the subject. Some scientists believe that China does not need special non-Bt cotton fields as a refuge because most crops that are grown during the summer/autumn season at the same time as cotton, such as maize, soybean and peanuts, function as natural refuges for the cotton bollworm (CBW)—(Wu et al., 2002, 2004). However, others argue that in cotton-planting areas where cotton is the only host plant of the CBW, selection may be occurring and hence refuge is needed (e.g., Xue, 2002), especially given the past propensity of the CBW to evolve resistance in a relatively rapid manner to other conventional insecticides (e.g., organophosphates and pyrethroids).

The goal of our work is to initiate a discussion about how to design a refuge strategy for developing countries. In simplest terms the paper seeks to meet this goal by discussing why China – at least for the case of Bt cotton – may *not* need a refuge policy in some areas. To do this we describe in detail the different elements that a nation—especially a developing one—should be considering when deciding if a refuge policy is needed. We discuss the nature of the pest population and the process of resistance buildup, adoption trends of Bt cotton, and the cropping patterns that make up the production environment within which Bt cotton is being propagated. Drawing on a review of scientific data, economic analyses of other cases and a simulation exercise using a bio-economic model that we have produced to examine this question, we show that in the case of Bt cotton in China, the approach of not requiring special cotton refuges may be sensible. In other words, China's zero refuge policy appears to be a sound decision. Throughout the paper, we discuss the implications for other developing countries and the implications for other genetically modified crops.

The Nature of the Cotton Bollworm and the Buildup of Resistance

While the increasing use of modern improved varieties has meant the rise of pest infestations and the need to take action to control them in almost all settings (Pingali et al., 1997), cotton producers in China have suffered especially from the intense pest pressures that have plagued cotton growing areas during the previous decades. According to reports of the Ministry of Agriculture's entomological insect and disease prevention teams, during the 1990s cotton yields (even after being sprayed with conventional pesticides) were reduced by 5 to 14 percent due to pest infestations (Table 1, column 1). During the same time period, the team estimated that losses in grain yield only ranged from 2 to 3 percent (column 2). Importantly, in the Yellow River Valley cotton production region (China's largest cotton producing region) the actual cotton yield loss was as high as 29 percent in 1992 (column 3).

As bad as such losses were, the infestation from pests (and the losses that such infestations potentially could have caused) would have been even more severe if farmers had not taken action by using high doses of conventional chemical pesticides. Entomologists estimate that had farmers not sprayed, cotton yield losses nationwide would have ranged from 24 to 50 percent during the 1990s (column 5). Yields would have fallen even more in cotton producing regions in the Yellow River Valley (from 35 to 93 percent—column 6).

Such high estimates of actual and potential damages by scientists and extension teams are consistent with estimates of cotton farmers themselves (Table 1, columns 7 to 9). During a household level survey conducted by the Center for Chinese Agricultural Policy (CCAP) of Chinese Academy of Sciences (CAS) in 2002, enumerators asked farmer-respondents about the damage that would have been sustained had they not sprayed for cotton pests. On average, cotton farmers responded that they believed that their yields would have fallen by 56 percent. More than 60 percent of farmers believed that cotton yield losses would have exceeded 50 percent; 11 percent of the respondents believed that their crops would have been completely destroyed if they had not sprayed (that is, losses would have been 100 percent).

In their battle against insect infestations between the early 1980s and mid-1990s, China's cotton farmers used the only tool that they had access to—chemical pesticides—and they used it in increasing quantities throughout this period. According to the State Planning Commission's Cost of Production survey, cotton farmers spent between US$30 and US$35 per hectare on pesticides in the early 1980s, an amount accounting for 11 to 13 percent of their total material input costs. After the mid-1980s, the quantity of pesticide rose steadily. By 1990 the cost share of pesticides rose to 18 percent; by 2000 the cost share was 22 percent. In 1995 the absolute level of pesticide applied to cotton was 200 percent higher in real terms than in the early 1980s (US$101 vs. US$31-35). Pesticides expenditures were rising so fast during the early 1990s that there was real doubt that China could continue to produce cotton profitably (Hsu and Gale, 2001).

As the level of pesticide use on cotton rose and the crop's profitability eroded, concern also began to emerge about the other consequences of pesticide use. Huang et al. (2002a) document that during the same time that pesticide use rose, the incidence of morbidity and mortality of farmers due to the overuse of pesticides also increased sharply. Between 1987 and 1992 across China the number of reported hospitalizations connected with pesticide use rose by 116 percent (from 32029 to 69290) and the number of deaths from pesticide-related poisoning (from on-the-job contaminations) rose by 41 percent. In household surveys conducted by the Center for Chinese Agricultural Policy, more than 33 percent of households that produced conventional cotton between 1999 and 2001 reported that users (i.e., the member of the household that applied the pesticide) became so sick after applying pesticides in their cotton fields that they had to miss at least one day of work, suffering from symptoms of nausea, headaches, skin rashes and eye infections (Huang et al., 2002b; Hossain et al., 2004). There also are reports in the press and academic journals that high rates of pesticide use were contaminating China's waterways and groundwater resources (Zhang, 1989; Zhu, 1994). Clearly, China's cotton producing sector was facing a crisis of multiple dimensions in the early 1990s—a crisis that affected the economic welfare of farmers, the health of producers and the environment of rural and urban communities.

The Rise of Resistance

While there are many reasons why pesticide use in China, in general, and in cotton producing regions, in particular, rose during the 1980s and 1990s (Huang et al., 2002a), a lot of blame has to be put on the genetic make-up and population dynamics of the cotton bollworm (CBW). Even though there were many pests infesting China's cotton crop at various growth stages during the 1980s and 1990s, the CBW was the most important one. According to Wu and Guo (2005), the CBW affects virtually all of the nation's cotton area except for a few counties in the dry western cotton producing regions. The loss in yields from the CBW also accounts for most of the total loss nationally (65 percent). However, the severity of the CBW problem is experienced unevenly across the nation's production bases. In the Yellow River Valley cotton producing region, the CBW caused up to 78 percent of the actual yield loss. In contrast, yield losses in China's western provinces from the CBW are only 12 percent.

While the CBW has plagued China's cotton farmers since modern varieties were introduced in the 1930s, the nature of the battle against the CBW has shifted over time (Guo, 1998). Before 1950 the CBW was a problem that was mostly faced, albeit not always effectively, by integrated pest management methods and traditional remedies. In the late 1950s the emergence of relatively efficacious chemical pesticides initially aided farmers in controlling the CBW. However, one after another, the CBW developed resistance to each of the conventional pesticides being used as the primary tool in fighting the pest infestations (Wu and Guo, 2005). For example, in the 1950s and 1960s, farmers regularly used highly toxic organochlorines (OC).

Although initially effective, by the end of the 1960s the use of OC had largely become ineffective as the CBW population developed resistance. In place of OC pesticides, during the 1970s farmers began to use organophosphates (OP) and other carbamate chemicals. However, as before, although initially effective, the CBW population quickly built up resistance (Stone, 1988; 1993). The story was repeated again with pyrethroid pesticides (PP) in the 1980s. In fact, it took only 10 years for the CBW to develop a high level of resistance level to PPs during the 1980s (Wu and Guo, 2005). Although pest populations in other crops (e.g., rice) during the same time period have also been documented to have developed resistance to chemical pesticides (Widawsky et al., 1998), the CBW's experience in cotton appears to have developed resistance more rapidly than other cases.

The propensity of the CBW population to develop resistance to pesticides in the field is supported by the work of entomologists in the laboratory. In order to gain an evolutionary understanding of the patterns of the CBW's resistance, China's entomologists began to monitor the development of resistance early in the 1980s (Guo, 1998). In the case of PPs, it took only 15 years for the level of the resistance of CBWs in the field to increase 172 fold (Figure 1). Data from laboratory experiments arrived at the same conclusion, suggesting that populations of the CBW in China have an ability to rapidly build resistance to a wide range of pesticides.

Clearly, the rising levels of pesticide applications and cost during the early 1990s is in part a reflection of the fact that China's CBW had begun to develop resistance to OCs, OPs and PPs. Huang et al (2002a) demonstrate that China's cotton farmers in the mid-1990s spent more than $500 million annually on pesticides to control pests, especially for CBWs. According to household surveys, by the late 1990s farmers were spraying for pests, on average, more than 20 times per year

(Huang et al., 2002a); some were spraying up to 30 times, about every other day during the periods of peak infestations (Wu and Guo, 2005). During our interviews in cotton producing regions during this time, one farmer reported to us, only half-jokingly, that the CBW population was so resistant to chemical pesticides that the reason that farmers sprayed so frequently was that they were trying to drown the pests rather than hoping to kill them with the toxicity of the chemical.

Bt Cotton and Refuges

The consequences of the increasing resistance of CBWs to conventional pesticides were real not only to individual farmers, but to the entire cotton industry in China. In all parts of China, but especially in the Yellow River Valley, production trends, after rising dramatically during the post reform period at the early 1980s, deteriorated as the buildup of the resistance to conventional pesticides proceeded. During the late 1970s and early 1980s the Yellow River Valley became the largest cotton producing region in China. During this time the national share of production in the Yellow River Valley rose dramatically from 30 percent to over 60 percent. Cotton production in China peaked at over 6 million tons in the late 1980s (Hsu and Gale, 2001). However, after the peak cotton production in the Yellow River Valley steadily declined for the next ten years. While certainly there are many plausible reasons, Hsu and Gale (2001) argue that one of the most important ones was the increasingly severe CBW infestations, which were occurring as the CBW was developing resistance to the remaining conventional pesticides.

Facing the rising economic pressures created by declining cotton production in the late 1980s and early 1990s, officials in China’s agricultural R&D sector began to accelerate their efforts to produce a new technology that held a promise of alleviating problems facing the cotton sector. In 1996, for the first time, U.S. seed companies sold commercially a genetically modified variety of insect-resistant cotton—Bt cotton. In 1997, only one year later, China's government approved Bt cotton for use in the Yellow River Valley (Huang et al., 2002a). During the same year, two companies—one a joint venture between Monsanto, Delta-Pineland and the Hebei Provincial Seed Company; the other a domestic company based in the Chinese Academy of Agricultural Sciences—began to sell Bt cotton seeds to farmers.

The results of the initial efforts to commercialize Bt cotton in China were nothing less than remarkable—on many margins. Even though the cost of Bt cotton seed was five to six times higher than that of the seeds for conventional cotton, the savings enjoyed by the farmers and the revenues from higher yields far exceeded the differences in seed cost (Huang et al., 2002b). In fact, the private economic benefits produced by Bt cotton have been well-documented in China as well as other Bt cotton countries (Pray et al., 2001; Huang et al. 2002a; Huang et al., 2004; Qaim and Zilberman, 2003 ; Traxler et al., 2001; Gouse et al., 2004). According to the studies in China, Bt cotton farmers not only reduced their pesticide use by more than 70 percent, they also had higher yields. In addition, due to the reduction in use of conventional pesticides, Bt cotton also contributed to a cleaner production environment and helped to improve farmer health (Hossain et al., 2004; Pray et al., 2002; Huang et al., 2002b).

Because of its high profitability, as well as the other benefits, Bt cotton spread rapidly in China (as it did in many developing countries). According to a national survey of Bt cotton adoption conducted by the Center for Chinese Agricultural Policy (CCAP), the area planted to Bt cotton by China's farmers spread rapidly following its initial commercialization (Figure 2, Panel A). From zero in 1996, the area of Bt cotton grew to 3.7 million hectares in 2004. By 2005, millions of farmers—many of them poor with less than 0.2 hectares of cultivated land per capita—were cultivating Bt cotton (Huang et al., 2006). Across China, of the 5.65 million hectares of cotton planted in 2004, Bt cotton had expanded to account for about two thirds of all the cotton area (Figure 2, panel B). Moreover, the growth was even faster in the Yellow River Valley. For example, by 2001 Bt cotton adoption reached more than 90 percent in Shandong and Hebei provinces, the third and fourth largest cotton producing provinces in China (Figure 2, panel C).

Potential Dangers Behinds the Success

While the rise in productivity of Bt cotton is well-documented and certainly is the driving force behind the remarkable expansion of the crop, the history of cotton in China (reviewed above) suggests that there is a reason to be concerned about its sustainability. Given the propensity of the CBW to develop resistance to conventional pesticides, one of the major concerns about its success in the long run (in China and the rest of the world) is the potential vulnerability of Bt crops to the adaptation by the major pest populations to the Bt toxin expressed by the crop (Bates et al., 2005). In a similar manner to what happened with conventional pesticides, it is possible that the large-scale use of Bt crops may cause the evolution of pests resistant to Bt toxin (Tabashnik et al, 2003). If too large a share of the pests develop resistance to the Bt toxin, there will be a reduction in the effectiveness of Bt crops in controlling pests and the benefits of Bt cotton will be undermined.

Via the same mechanisms by which the CBW rapidly developed resistance to conventional pesticides, scientists have experimentally demonstrated how the CBW may react the same way in response to the use of Bt cotton. For example, Tabashnika et al. (2003) show that certain sub-populations of a cultured pest population have survived on the material of Bt cotton in laboratories and greenhouse tests (meaning that they developed resistance). Wu et al. (2004) demonstrates that the resistance level can be 106 fold higher after the CBW has been selected by treatment with the Bt toxin over 44 generations (Figure 3). Based on these kinds of laboratory experiments, some entomologists have predicted that after Bt cotton has spread across a large enough cotton production area and is produced intensely (that is, without being mixed in with refuge of conventional cotton varieties), the effective service life of Bt cotton may only persist for several years (Gould, 1998). According to Gould (1998), the implications of such predictions are that China should begin a system of refuges.

The refuge system, in fact, has been adopted—either explicitly or implicitly—by almost all countries that have introduced Bt cotton (Shelton et al., 2000). Following the lead of the United EPA, which requires producers to allocate a share of their land to a non-Bt crop, all Bt cotton-producing in the developed world—e.g., Australia—have policies that require producers to plant refuges. Although there is no research basis for adopting such policies in developing countries, a number of countries—India, Indonesia and South Africa—have also followed the example of the U.S. and required that farmers put 20 percent of their cotton area into non-Bt cotton. While refuges allow susceptible pests to thrive so they can mate with resistant pests that survive in the Bt cotton fields and extend the efficacy of the insect-resistant varieties, planting a refuge imposes a cost on the producer which equals the foregone profit advantages of the technology.

In contrast to polices in developed and other developing countries, China implicitly has a zero refuge strategy. This policy is not without controversy as some scientists (e.g., Gould, 1998) and environmentalists (Xue, 2002) argue that refuges should be planted. Their arguments are based on the past propensities of the CBW to develop resistance to conventional pesticides and the laboratory tests that demonstrate that CBW can also develop resistance to the Bt toxin. Proponents of refuges thus believe that resistance to Bt cotton will build up in the near future absent any adoption of refuge policies.

Despite the potential and anticipated risks from Bt resistance that are central to argument in favor of refuge policy, there has been no field evidence to show that the buildup of the resistance to the Bt toxin in China has begun. In fact, there is no field evidence to show the buildup of resistance to Bt toxin in any other Bt-producing countries of the world. Thus even though the pest has survived on Bt plants in laboratories and in greenhouses during scientific tests, resistance to Bt crops in field applications has not been documented to date (Tabashnika et al., 2003).[1]

Cropping Systems in the Yellow River Valley: Natural Refuges?

The absence of evidence on the buildup of resistance in the field from both the United States and China raises a puzzle. In the United States it is argued that the cotton pest population has maintained its susceptibility to Bt cotton because of its refuge policy. While this is perhaps true, it does not explain why the evidence from China, which does not have a refuge policy, also demonstrates that the cotton pest populations have not shown signs of building up resistance. In this section of the paper we explore one possible explanation.

The main theory explaining the absence of field buildup of resistance in China has been put forth by Wu et al. (2002), namely that there are natural refuge crops in the cotton-growing regions of the Yellow River Valley that serve to maintain the susceptibility of the pests to Bt toxin. In the United States (and many other Bt cotton-growing nations), cotton tends to be grown in vast tracts of single mono-cropped cultivars. In contrast, in China the cropping patterns are much more diverse, so that cotton is typically grown within a mosaic of small patches, where neighboring crops can act as a de facto refuge for CBW populations. Because of this, even when farmers in China plant all of their cotton sown area to Bt cotton (which might lead to the build up of resistance in a mono-cultured cotton cropping system), in China the CBW will typically also reproduce in areas planted to non-cotton crops. The subpopulations from the natural refuge crops are sufficiently large and mix with the subpopulations that survive the Bt fields with sufficient frequency that the build up of resistance can be avoided without an explicit refuge policy.

While such an explanation has been generally accepted by many agricultural scientists in China in recent years, in fact, the empirical basis on which the theory is based is mostly anecdotal. In order to get a clearer understanding of the nature of China's cropping system, and the way that these natural refuge crops may be acting as a substitute for explicit cotton refuges, in the rest of this section we will discuss the characteristics of the main cropping systems in the Yellow River Valley's cotton producing regions. This builds a picture based on a broad sampling of the main cotton producing areas in the regions of China enabling us to see what the production environment of the typical Bt cotton farmer looks like. We also summarize the regression results of a new study by Huang et al. (2006) that shows econometrically the effectiveness of natural refuge crops.

Natural Refuge Crops in China

In order to understand the cropping patterns in the Yellow River Valley, we use two sources of data. The first source of data is from a two-stage, village-level survey that we conducted in 2004. During the first stage we used a comprehensive list of counties and information on the intensity of each county's cotton production to create a sampling frame (database, Chinese Academy of Sciences). From the list of counties, we randomly chose four using a stratified choice strategy. From the top five counties (the places where we are most likely find the buildup of resistance), we chose two counties. From counties numbered 6 to 20, we chose one county. From the rest of the list we chose one more county. In total, after the selection process, we ended up with four counties—the 2nd, 3rd, 18th and 107th largest cotton producing counties in Yellow River Basin. Two of the counties are in Henan province; one in Shandong province; and one in Hebei province. The three provinces are not only the most important production provinces in the Yellow River Valley, but also are in the 2nd, 3rd and 4th largest cotton producing provinces in China.[2]

After the selection of the sample counties, we moved to the second stage of the sample selection procedure. In each county we first obtained a list of townships and the intensity of cotton production in each township. The list was then divided into two groups—one group with the most intensive cotton production; and the other group with less intensive cotton production. From each of these two stratified lists, we then randomly chose one township, a total of two townships per county—one with higher intensity and one with lower intensity. After choosing the townships, we then had the township mayors in charge of agriculture convene a meeting with all of the village leaders in each township. Village leaders provided information on the intensity of cotton planting, cropping patterns and other relevant information. After the interviews (in the township office), we randomly selected a subset of villages to visit to ground-truth the survey data (which, in general, appear to be fairly accurate).

Consistent with the assumptions of the agricultural scientists, the results of our survey show that cropping patterns in China's Yellow River Valley are diverse. Even in the second and third most intensive cotton-producing counties in the Yellow River Valley, in about half of the villages the largest contiguous area of cotton is less than

100 hectares (Table 2). Table 2 also shows that once one moves out of the most intensive cotton-producing counties, the cropping patterns are even more fragmented. For example, in the 18th largest cotton-producing county, more than 60 percent of cotton is planted in plots that are less (often much less) than 1 hectare. There are no areas of contiguous cotton production greater than 50 hectares. In the 107th most intensive cotton-producing county, 93 percent of the cotton is grown on plots that are less than 1 hectare. A collection of pictures showing different views of cotton in different cropping environments is shown in Appendix Figure 1.

We also draw on an alternative set of data (from a survey carried out by the Center for Chinese Agricultural Policy of Chinese Academy of Sciences—henceforth called the *CCAP data*) to show the nature of the cotton production environment from another perspective.[3] In doing so, we find additional support for the natural refuge cropping hypothesis (Table 3, rows 1, 4 and 7). Although rates of Bt cotton adoption are high as a share of total cotton area (above 80%), in all of the CCAP study villages (even though the villages are in the heart of one of China's main cotton producing regions), cotton is far from a mono-cultured 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 of the other sample provinces also only ranged between 37 and 54 percent. Hence, unlike the cropping patterns of other nations (e.g., the U.S. and Australia, nations that are known for their large mono-cultured areas), China's cotton crop is grown along side along a diversified set of other crops.

In fact, the cropping patterns of China are such that cotton is being cultivated in the sample villages alongside 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 many other minor crops, weeds and even fruit trees. In the rest of the paper, these crops planted side by side with cotton in the summer/autumn seasons will be referred to as *natural refuge crops*.

If only 25 percent of wheat area is counted (since the CBW only feeds on wheat during their first generation), then the share of a sample village's total cultivated area that is planted to refuge crops during the same time of cotton production season can be calculated and shown to be relatively large (Table 3, rows 2, 5 and 8). When doing so, it can be seen that natural refuge crops in villages that cultivate Bt cotton account for a large share of cultivated area. In no province does the share of refuge crops fall below 22 percent (Shandong).[4] In all years in Hebei and Henan provinces, the share of refuge crops exceeds 40 percent. When looking at data for each of the 16 sample villages (not shown), it is found that the share of the refuge crops is never lower than 18 percent. On average, the refuge area share was 45 percent. 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 populations to the Bt toxin of Bt cotton (far more than the 20 percent required by the US EPA, for example).

Multivariate Findings

While this line of logic appears to be sound on a coarse scale argument, it would be desirable to have other evidence about mechanisms and processes on a finer scale. In a recent paper by Huang et al. (2006), the authors seek evidence from a multivariate model that explains the level of pesticide used to kill the CBW. Based on the expectation that farmers should need additional levels of pesticides to control the CBW as the CBW populations begin to build up resistance to the Bt toxin, their main finding is that farmers in villages with higher levels of natural refuges (ranging from 17 percent to more than 90 percent) do not use greater quantities of pesticide for controlling the CBW (which would support the hypothesis that refuges are already sufficiently large to keep resistance from building up). In the Huang et al. (2006) analysis, after holding constant the proportion of the cotton sown area in the village that is planted to Bt cotton (and whether or not the village was 100 percent Bt cotton), the authors found no evidence that the quantity of pesticides used to control for the CBW was any higher in villages with higher or lower natural cropping refuges. They also found that the quantity of pesticide used for controlling the CBW on conventional cotton did not rise with the share of cotton area planted to Bt cotton. In other words, their work provides evidence from the field that—at least through the eighth year of commercialization of Bt cotton—there is no evidence that the CBW is building up resistance to the Bt toxin. Hence, this evidence also is supportive of the zero refuge policy.

Bio-economic Model Simulation Analysis

While the information from the laboratory and the field are supportive of China's zero refuge policy, there are shortcomings of such efforts. Most conspicuously, the laboratory work is experiment-based and does not seek to assess the economic costs and benefits of the different refuge policies. The field-based quantitative work, while also persuasive, is only based on eight years of field experience. It is possible that the resistance problem will show up after more than eight years. In fact, Gould (1998) argues that the nature of the buildup of resistance is so explosive it is dangerous to only rely on field monitoring. According to this line of thinking, it is not surprising to find no evidence of the buildup of resistance during the early phases of Bt crops planting. Gould argues that by the time resistance is detected in the field, it may be too late since the shift from nearly zero resistance share in the population to high shares of resistant insects is rapid and irreversible. As a further test, in addition to our field-based empirical work, we have built a bio-economic simulation model to try to understand the long run costs and benefits of establishing refuges (or not).

The integrated bio-economic model that we use follows the model developed by Wilen and Msangi (2002). The approach, in fact, is the similar to those used in the models developed by Laxminarayan and Simpson (2002), Hurley et al. (2002) and Livingston et al. (2004) in their studies on refuge strategies. The bio-economic model includes two parts: a biological model, which is used to simulate the evolution of resistance and the pest population, and a regulation model which is used to examine the impacts of refuge policies. A detailed discussion of the model is in Appendix 1.

Two types of parameters are used in the model: biological parameters and economic parameters. Most of the biological parameters, such as the efficiency of the Bt toxin in killing the CBW and the carrying capacities of the different natural refuge crops, are based on parameters that have been published or at least have been calculated by the authors using the experimental data from the Institute of Plant Protection (IPP), Chinese Academy of Agricultural Sciences (CAAS). In other words, almost all of the coefficients in the bio-economic model are science-based. The only exception is the *fitness cost* parameters of the CBWs that develop resistance. While having only one parameter that is not based on firm science may seem to be trivial, in fact, the fitness cost parameter plays a key role in the analysis. This parameter measures the difference of the mortality rates of susceptible pests and resistant pests in non-Bt cotton fields. In our model the fitness cost of the resistant CBW parameter is based on the parameter used by Livingston et al. (2004) in his bio-economic model of refuges in the U.S. Before using this parameter, we spent many days with Chinese entomologists trying to understand the appropriateness of this parameter to model the CBW. Because such a parameter is not available from either laboratory or field studies in China or other countries, it is admittedly only our best guess. Because of the uncertainty, in the analysis we do use sensitivity analysis to understand how this assumed parameters affects the results.

The economic parameters likewise are based almost completely on data that have been used elsewhere and on previously published results. For example, the treatment costs associated with Bt cotton and the treatment costs associated with conventional pesticides, two key economic parameters, come from the CCAP data. These data have been used in analyses that are published in *Science* (Huang et al., 2002b) and other journals (Huang et al., 2002a; Hossain et al., 2004). The initial values of these biological and economic parameters are shown in Appendix Table 1.

The Results of the Simulation: Does China Need Refuges?

Supporting the work in laboratories and field work-based scientific and economic empirical work (Huang et al., 2006), the simulation results of our model provide evidence that policy-mandated refuges are not needed in China. When we simulate the total costs of cotton production, including the damage cost caused by the CBW and the treatment costs under different refuge scenarios, we find that costs monotonically increase as the refuge size increases (Figure 4). In other words, the simulation results show that the optimal policy choice is to allow farmers to plant 100% Bt cotton on their cotton field without requiring them to maintain a non-Bt cotton refuge. While consistent with much of the work in China, such a result is in stark contrast to work done on refuges of Bt cotton in the United States (Livingston et al., 2004) and on the need for refuges in other Bt crops (Hurely et al., 2002).

The key to understanding the simulation results is to understand the impact of the natural refuge crops in the cotton-producing environment in China and the costs of planting a non-Bt cotton refuge. Planting non-Bt cotton as a refuge can be a double-edged sword. On the one hand, a non-Bt cotton refuge will slow down the buildup of the resistance and maintain the effectiveness (and profitability) of Bt cotton for a longer time. On the other hand, given a certain size of pest population, planting non-Bt cotton will either require the farmer to spray high level of conventional pesticides (on a sprayed refuge, which has been shown to be expensive) or prevent the farmer from spraying (on a pure refuge) with a concomitant high level of yield damage.

In general, the best policy is the one that justifies the costs of foregoing current profits from a refuge by generating a high enough future payoff from the maintenance of susceptibility. If the “right” share of land is set aside as a refuge, costs in the short run are offset by higher returns in the longer run. However, if the refuge size is larger than necessary, the foregone revenues will not be earned back in the future (or could be dominated by the earning streams from a strategy that used a smaller refuge or relies on natural refuge crops and does not require farmers to plant any non-Bt cotton as a refuge).

The differences between our results for China and those from other studies calibrated to the United States agriculture, come from the important role played by the presence of natural refuge crops. Like a non-Bt cotton refuge, natural refuge crops provide refuge for the CBW and help to slow down the buildup of the resistance (Figure 5). As long as non-cotton crops in a small-scale multi-cropping patchwork system can provide a large enough natural refuge to slow down the development of resistance, policy-mandated refuges are not needed. In such a setting, if non-Bt cotton refuges are mandated when not needed, the costs associated with the non-Bt refuge in the early years (higher pesticide costs and/or yield damage) will not be offset by later gains (since the non-Bt refuge does not extend the life of Bt cotton—at all or enough to matter).

The simulation results from our model clearly support the zero refuge policy as the most economically efficient policy. For example, the simulation results show that if conventional cotton is *not* planted as a refuge, the average cost—damage cost caused by the CBW and treatment costs—is US $ 176.71 (Table 4, first row) per hectare per year. If a 20 percent sprayed refuge is planted, as required in the United States, then the average cost will increase to US $ 209.67 per hectare per year. In other words, if China's government followed the US-style refuge requirements without considering the actual production environment of the CBW in the Yellow River Valley, cotton farmers would had to incur, at least, additional expenses of US $ 32.96 (or 18.65 percent more) per hectare per year. The benefits of the no-refuge policy, it should be noted, do not consider the additional costs that would be incurred by the government to implement and monitor a refuge policy. They also leave out the potentially significant health benefits that are associated with reduced use of conventional pesticide.

Although the above results were run for the "average" cotton-producing area in northern China, the results also hold for the most intensive cotton-producing counties. We re-simulated the model by assuming that cotton is mono-cultured in larger tracts in some counties. The simulation results are shown in Table 4 and Figure 4. Table 4 shows that non-Bt cotton refuges also are inefficient even in counties where natural refuge crops, such as maize, soybean and peanuts, are not planted immediately adjacent to cotton. For example, as shown in Table 4, if a 20 percent sprayed refuge is enforced in these counties, average cost will increase from the optimal level, US $173.86 per hectare per year when non-Bt cotton refuge is zero, to US $207.49 per hectare per year (Table 4, row 2).

Sensitivity Analysis

In order to test whether our results are sensitive to the assumed values of the parameters, we use sensitivity analysis to understand the robustness of the findings. For example, we estimated optimal refuge size for different time horizons (a 10 year horizon; a 15 year horizon; a 20 year horizon). We also used different assumptions about the natural refuge cropping patterns. The maximum threshold value for conventional pesticide use and the fitness cost parameter were also varied. During each sensitivity analysis run, only one parameter was adjusted. Importantly, the results are mostly consistent with our findings that policy-mandated refuges are not economic for Bt cotton in China. Appendix Table 2 only shows the simulation results for two sets of sensitivity analysis runs—those based on the different time horizons and different assumptions about natural refuge crops. For a 20 year plan, even though the optimal refuge size is not zero, compared to zero refuge policy, the extra benefit provided by the optimal refuge policy is relatively small (the third and sixth rows of Appendix Table 2). Considering the high monitoring cost and other costs associated with a non-zero refuge policy, a zero refuge policy is better in practice (Qiao, 2006).

Conclusion

China is unique among the nations of world that have made the decision to adopt 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. Although the policies were initially made without evidence from the field of farmers, this paper suggests that the policy is correct. Because of the diversified nature of China's farming systems in the cotton producing areas in northern China, there is sufficient area of refuge crops to act as hosts 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, which currently require farmers to plant refuges. Although individually tailored analyses should be conducted, it may be found that planting non-Bt cotton as refuges is uneconomic and that the expense of implementing refuges (both from the government's and individuals farmer's point of view) may be avoided.

Although China's no Bt cotton refuge policy may be justified for the case of cotton in northern China, we do not mean to imply that that refuge policies are unnecessary in all developing countries under all circumstances. China's cotton economy in northern China just happens, at this stage of the evolution of Chinese agriculture, to be part of a highly diversified set of cropping systems, all mostly conducted on mixed small-scale plots. In countries or regions with different farming systems, a no refuge policy could lead to a more rapid build up of resistance in the pest population. In particular, in countries in which cotton is grown in large mono-cropped areas that are not next to natural refuge crops, refuges may be economic. For a similar reason, if Bt rice is commercialized in China, planting non-Bt rice as refuge may be needed.

The economic efficiency of no refuge would be even clear if implementation costs and monitoring cost were considered. During our field work, we actually asked the village leaders in a number of Bt cotton-producing communities a set of hypothetical questions about whether they could enforce a policy-mandated sprayed or pure refuge. Village leaders by and large said three things that are relevant for the discussion. First, they said they could enforce it. However, second, they said it would require a lot of time and effort, especially if they caught a villager ignoring the mandate. Typically, village leader respondents said that farmers would not voluntarily adopt refuges and would ask for considerable compensation if asked to do it. Finally, and most telling, many village leaders said that they themselves had no incentive to turn in farmers that they caught cheating. In other words, the very individuals who would be the ones to enforce such policies seem inclined to turn their heads the other way. This would imply in China that perhaps a set of professional enforcement teams would need to be used to monitor and enforce a reguge system, a prospect that would be even more expensive.

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Appendix 1. The bio-economical model

In the biological model, extended Hardy-Weinberg models are routinely used to simulate the evolution of resistance to Bt crops, with demonstrated empirical success (Hurley et al., 2002; Livingston et al., 2002). We use a two-locus four-allele model to simulate resistance evolution to Bt cotton and conventional pesticides under the following assumptions: (a) there are large and equal numbers of diploid females that mate randomly; (b) genetic mutation and migration are insignificant relative to selection as determinants of resistance evolution; (c) resistance to each toxin is conferred at one locus by one gene; (d) the probability a gamete (sperm or egg) contains one allele is independent of its containing one of the other three (linkage equilibrium); and (e) there are four non-overlapping generations per calendar year, and they have different host plants at each generation.

The diverse cropping pattern that exists in the Yellow River Valley is mimicked in order to estimate the impact of natural refuge crops on refuge policy. The setting is a large area in which cotton is planted side by side with other host crops of cotton bollworm, such as corn, soybean, peanuts etc. The CBW population is assumed to be local and both in- and out-migration is ruled out. After normalizing the cotton land to 1, we assume that the land size of natural refuge crops is denoted by nrc. The two treatments, Bt and conventional pesticide, divide the land into four types (denoted by lf): a Bt field (with a faction of q) using conventional pesticides (with a possibility dbt), a Bt field without conventional pesticides (with a possibility 1-dbt), a non-Bt field (with a faction of 1-q) with conventional pesticides (with a possibility dnbt), a non-Bt field without conventional pesticides (with a possibility 1-dbt) and a natural refuge crops field.

Following previous studies (see, e.g., Clark, 1976), we assume that CBW population (denoted by D) grows logistically with an intrinsic growth rate of g. The carrying capacity of total number of pests per unit of land is normalized to 1. Then the total number of newborn CBWs in every period is given by g*D*(1- D). From this gross addition, we must subtract mortality among pests. For a given pest, let x and X denote the alleles that confer susceptibility and resistance to Bt toxin at locus one, respectively; let y and Y denote the alleles that confer susceptibility and resistance to conventional pesticides at locus two. Allele frequencies w_t and v_t denote the proportions of the respective susceptible alleles to Bt toxin and conventional pesticides in adults at generation t. Under these assumptions, the nine types of pests with different genotypes (denote by p^{geno}), their fractions in the total pest population (denote by f^{geno}), and their mortality rates (denote by m^{geno}) are shown in Appendix Table 3. The biological dynamics of the pest populations are shown in the following functional system (Appendix Function 1) as constraints of the regulatory function.

The objective of regulatory model is to minimize the discounted sum of damage and treatment costs. Two types of costs occur at each calendar year. The first type of cost is the damage cost caused by the pest, which is assumed to have a linear relationship with the total pest population. The second type of cost is the treatment cost, or the cost associated with Bt cotton planting and/or conventional pesticides spray. Similarly, both of these treatment costs are assumed to have linear relationships with the fraction of land treated. These costs are discounted and summed up over a fixed time horizon. A social planner minimizes the total cost by choosing an optimal refuge size, subject to the dynamics of the pest population and the buildup of the resistance, which are simulated in the biological model. The theoretical analysis of a similar model is discussed in Qiao et al (2006). Following Wilen and Msangi

(2002), we developed a discretized form of this problem that can be solved with empirical numerical optimization software. We can optimize this problem by using the Bellman Equation, which can be written as:

$$\underset{0 \le q_t \le 1}{Min}_{t=1}^{t=T} \ V(D_t) = D_t * \mathrm{a} + c * q_t + cc * [q_t * dbt_t + (1 - q_t) * dnbt_t] + \mathrm{d} V(D_{t+1})$$

s.t.

$$D_{t+1} - D_t = g * D_t * (1 - D_t) - \sum_{geno=1}^{geno=9} MR_t^{geno}, D_{t=0} = D_0$$

$$w_{t+1} - w_t = (1 - w_t) * (w_t^2 * g * D_t * (1 - D_t) - \sum_{geno=1}^{geno=3} MR_t^{geno}) + (0.5 - w_t) * (2 * w_t * (1 - w_t) * g * D_t * (1 - D_t) - \sum_{geno=4}^{geno=6} MR_t^{geno})$$

$$+ (w_t) * ((1 - w_t)^2 * g * D_t * (1 - D_t) - \sum_{geno=7}^{geno=9} MR_t^{geno}), w_{t=0} = w_0$$

$$v_{t+1} - v_t = (1 - v_t) * (v_t^2 * g * D_t * (1 - D_t) - \sum^{geno=1,4,7} MR_t^{geno}) + (0.5 - v_t) * (2 * v_t * (1 - v_t) * g * D_t * (1 - D_t) - \sum^{geno=2,5,8} MR_t^{geno})$$

$$+ (v_t) * ((1 - v_t)^2 * g * D_t * (1 - D_t) - \sum^{geno=3,6,9} MR_t^{geno}), v_{t=0} = v_0$$

$$MR_t^{geno} = f^{geno} * \sum^{j=sbt,bt,snbt,nbt} (lf_j * m_j^{geno}) \tag{A-1}$$

where the function $V(D_{t+1})$ gives the carry-over cost from one period (t) to the next (t+1) of the residual pest population level, which we also seek to minimize and discount with the factor $\mathrm{d} = 1/(1+ \mathrm{r})$. D_t is the total pest population at time t; α is the average damage cost caused by unit of pest; c is the average cost associated with Bt cotton planting; cc is the unit price of conventional pesticides spray; dbt_t and $dnbt_t$ are the dummy variables for conventional pesticides spray in Bt and non-Bt fields respectively; and • is the discount rate; MR^{geno} is the mortality rate of pests with different genotypes; lf_j is fraction of j^{th} type of land. All the others un-defined denotations are shown in the Appendix Table 3.

Table 1. Estimates of pest-related yield losses by National Pest Reporting Stations and farmers in China, 1990-1997

	Actual loss (%) of grain and cotton [a]				Potential loss (%) of cotton [b]				
	China		Yellow River Valley [c]		Official estimation		Farmers' estimation [d]		
	Cotton	Grain	Cotton	Grain	China	Yellow River Valley	Mean of their estimation	Percentage whose estimation is greater than 50%	Percentage of farmers whose estimate is 100%
1990	5	3	8	4	24	35			
1992	14	2	29	3	45	93			
1994	12	2	9	3	50	53			
1996	6	2	10	3	33	53			
1997	6	2	9	3	35	62			
2002							56	62	11

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[a] Actual loss (a better term is 'official estimate of crop production loss') is due to inability of pest control effect by farmers, which is the crop production loss that happened in practice.

[b] Potential loss is the crop production loss that would happen if farmers did not control the pests. It includes the actual crop production loss happened in the practice and the production crop loss that would happen if farmers had not spray.

[c] All the numbers of Yellow River valley is the average of Hebei and Shandong provinces.

[d] All the numbers are calculated by the authors using the CCAP's dataset .

Table 2. The distribution of cotton plots in selected Yellow River Valley cotton production region in China, 2004

County [a]	Rank in term of fraction of cotton	Proportion of cotton area: Greater than 100 ha	Greater than 50, but less than 100ha	Greater than 1, but less than 50ha	Less than 1 ha	Accumulated cotton share in Yellow River valley
Xiajin	2nd	0.55 [c]	0.33	0.13	0.00	0.04
Weixian	3rd	0.54	0.36	0.10	0.00	0.06
Taikang	18th	0	0.10	0.30	0.60	0.25
Yanjin	107th	0	0	0.07	0.93	0.79

[a] Weixian is the second, Xiajin is the third, Taikaing is the 18th, and the Yanjin is the 107th largest cotton production counties among the 315 counties in Henan, Shandong, and Hebei provinces. In addition, Henan, Shandong, and Hebei is the second, third and fourth largest cotton production provinces (Xinjiang is the largest cotton production provinces) in China.

[b] The large cotton villages are those in which there are at least one cotton plot is more than 100 ha.

[c] The value is the proportion of the cotton area of one special category (such as “Greater than 100 ha”) divided by the total cotton area.

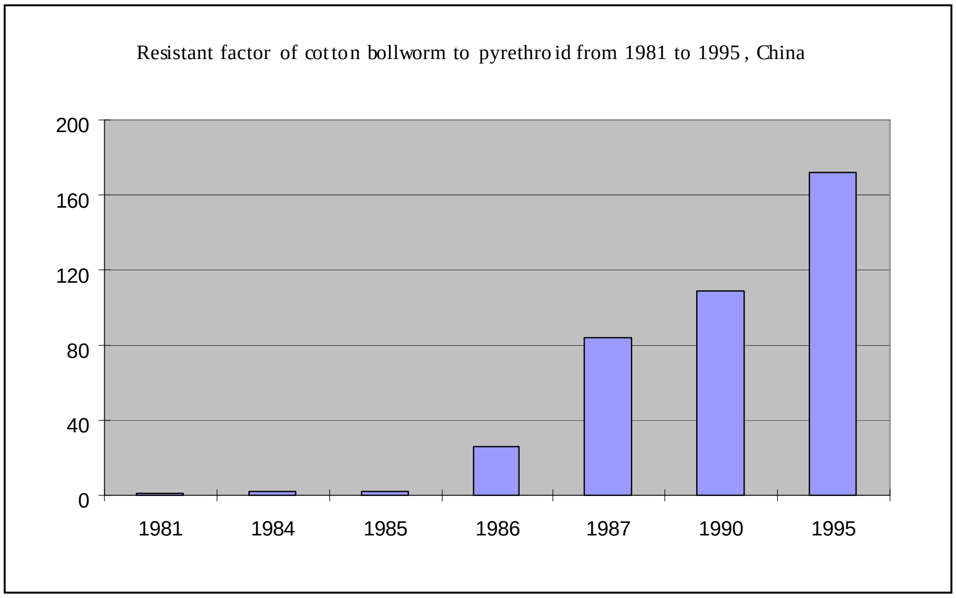
Table 3. Bt cotton, refuge crops and the role of cotton in Northern China's cropping patterns, 1997 to 2004

	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	48	47	45	46	48	43	39
Refuge crops share %	100	94	91	60	41	44	49	51
Bt cotton adoption %	0	8	13	59	80	81	84	89

Notes: Cotton area share is the share of cotton area in total crop sown 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) in total cultivated area. Bt cotton adoption is the share of Bt cotton in total cotton area. Date source: Authors' survey.

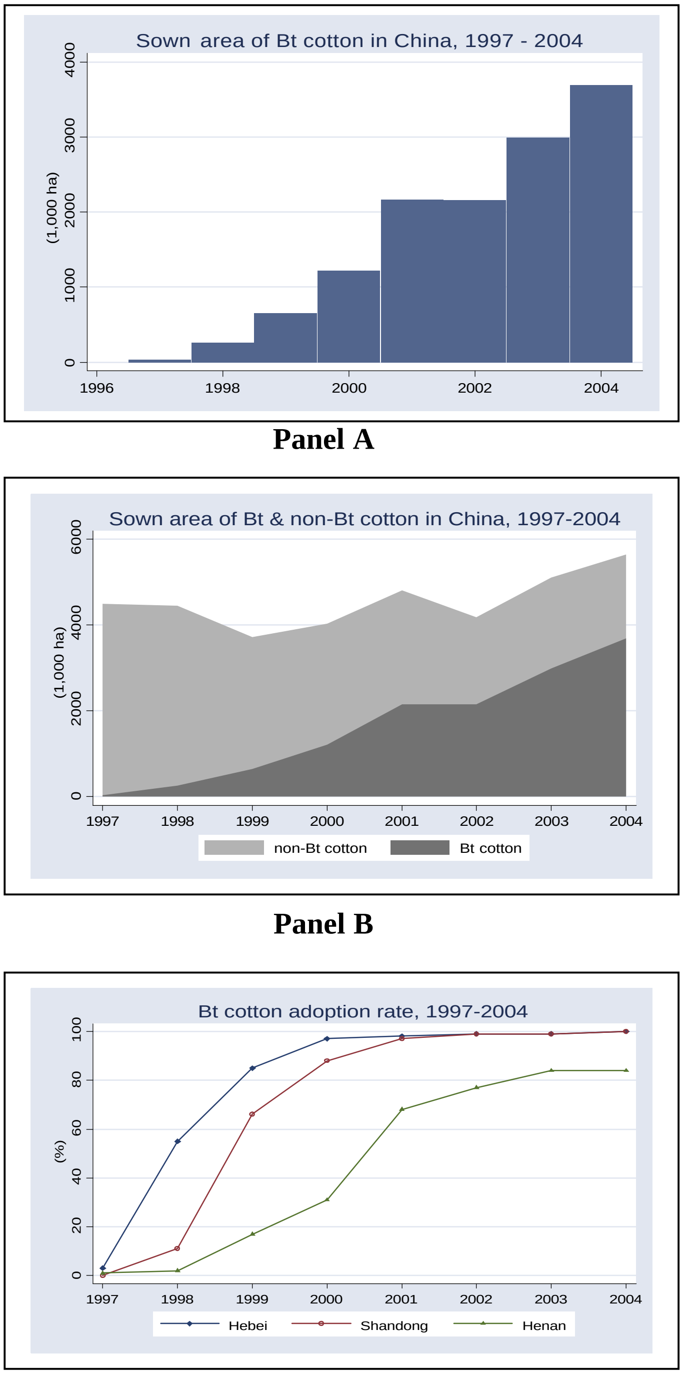
Table 4. Costs and cost increases from 0% non-Bt cotton refuge to 20% non-Bt cotton refuge in China

	Cost of 0% refuge	Cost of 20% refuge	Cost saving from 0% refuge to 20% sprayed refuge	
			In absolute value	In percentage
	(US$ per ha per year)	(US$ per ha per year)	(US$ per ha per year)	(%)
For all cotton counties in Yellow River Valley	176.71	209.67	32.96	18.65
For the most intensive cotton-producing counties	173.86	207.49	33.63	19.34



Source: Wu Kongming, Institute of Plant Protection, Chinese Academy of Agricultural Sciences, 2004

Figure 1. Development of the CBW to the pyrethroid deltamethrin in the field



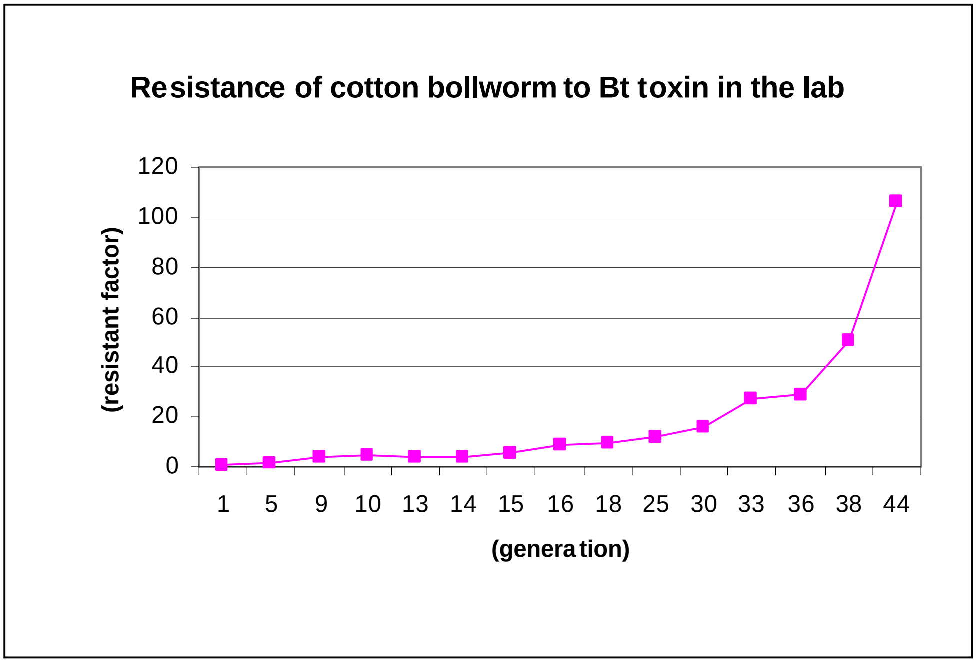
Panel A

Panel B

Panel C

Source: Center for Chinese Agricultural Policy, Chinese Academy of Agricultural Sciences (CCAP) dataset

Figure 2. Spread of Bt cotton in China and Bt cotton adoption rate in Yellow River valley, 1997-2004



Source: Kongming Wu, Institute of Plant Protection, Chinese Academy of Agricultural Sciences, 2004

Figure 3. Development of the CBW to the Bt toxin in the laboratory

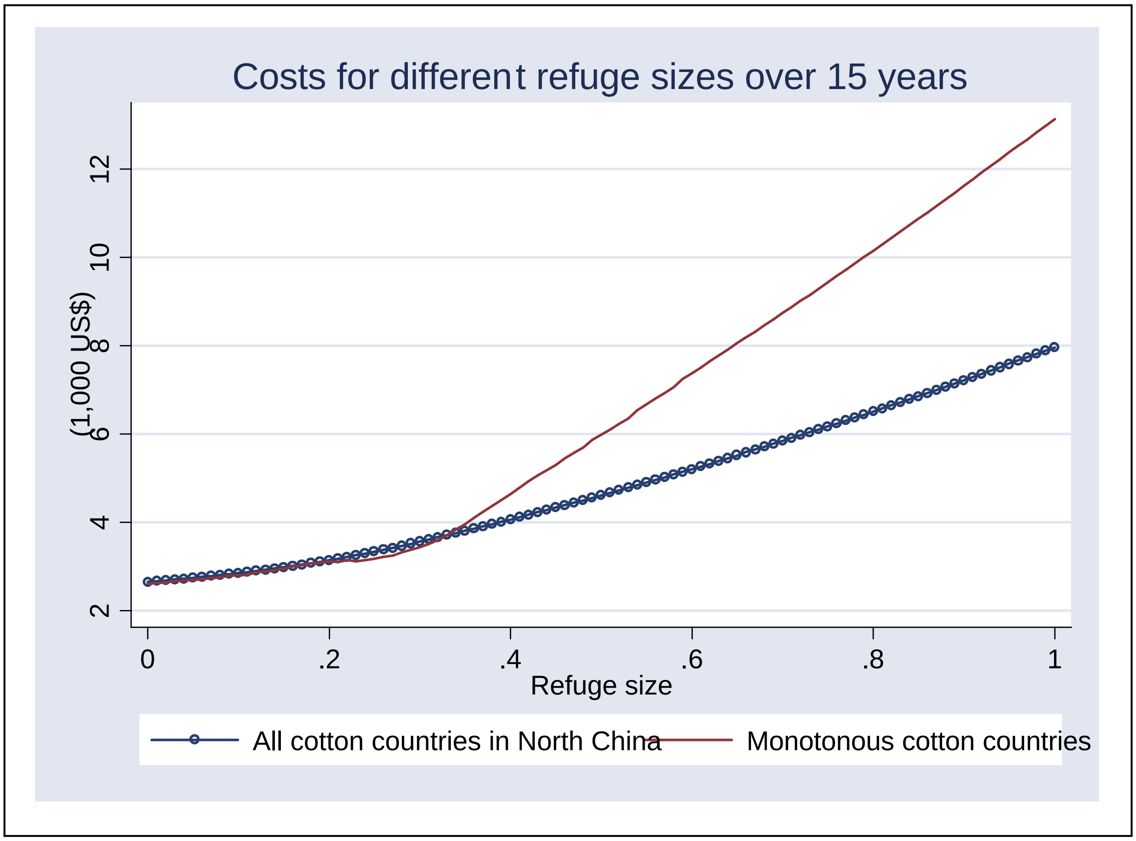


Figure 4. Costs for different refuge sizes over 15 years

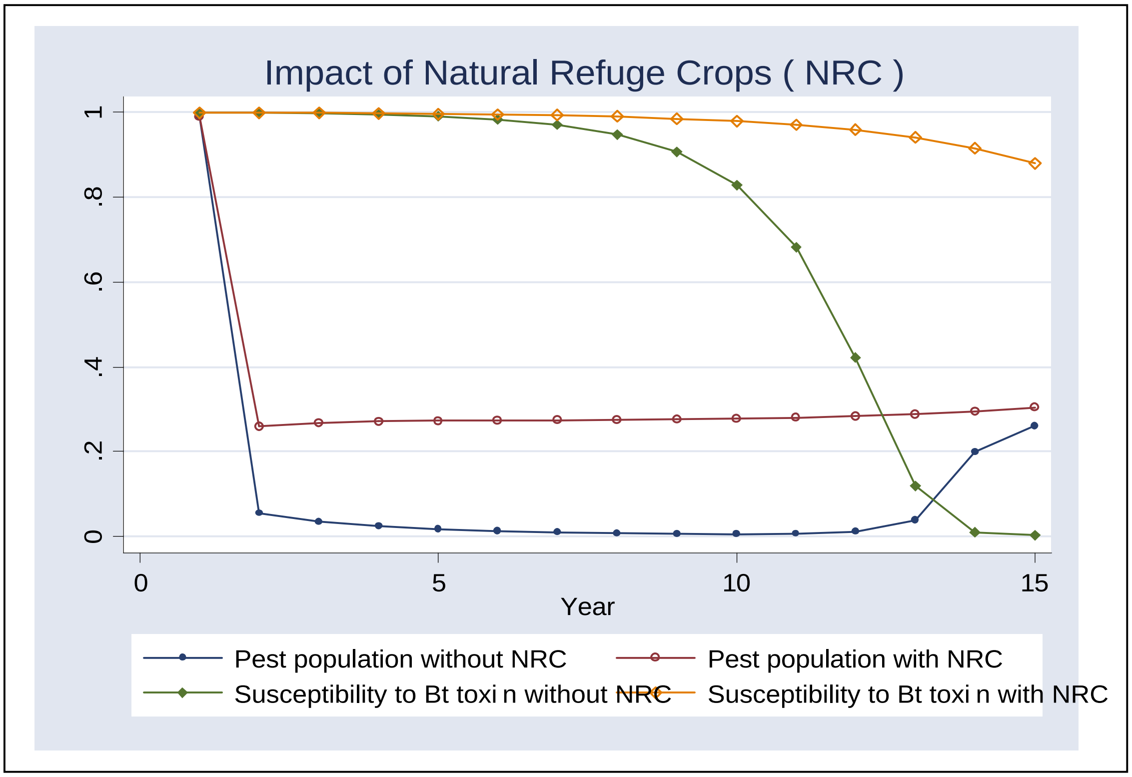


Figure 5. Impact of Natural Refuge Crops (NRC) on pest population and the buildup of the pest's resistance to Bt toxin

Appendix Table 1. Default value of biological and economic parameters and their sources

	Default value	Source
Economic parameters		
Unit damage cost caused by the CBW	\$1030/ha	Calculated based on data collected by IPP[a]
Bt cotton planting cost	\$143/ha	Calculated based on data collected by CCAP[b]
Conventional pesticide spray cost	\$252/ha	Calculated based on data collected by CCAP[b]
Discount rate	0.036	The People's Bank of China
Biological parameters		
Initial resistant (to Bt toxin) gene frequency	0.001	Gould, 1998; Livingston et al., 2002
Initial resistant (to conventional pesticide) gene frequency	0.50	Ru et al., 2002; Wu, 2000
Mortality rate of susceptible pest to Bt toxin in Bt field	0.90	Wu et al., 2000; Livingston et al., 2002; Storer et al. 2003; Mike Caprio, 2000
Mortality rate of susceptible pest to conventional pesticides if spray	0.90	No data
Fitness cost of resistant pests to Bt toxin	0.05	Livingston et al., 2002
Fitness cost of resistant pests to conventional pesticides	0.05	No data
Dominance of susceptible gene (to Bt toxin) in heterozygote	0.75	Private discussion with Wu
Dominance of susceptible gene (to conventional pesticide) in heterozygote	0.75	No data
The threshold value for spray	0.28	Guo (1998)
Natural growth rate	0.68	Calculated by the author using field date

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[a] IPP is the Institute of Plant Protection of the Chinese Academy of Agricultural Science.

[b] CCAP is the Center for Chinese Agricultural Policy (CCAP) of the Chinese Academy of Sciences (CAS).

Appendix Table 2. Sensitive analysis of the static model

	Optimal static refuge policy		Zero refuge policy	Cost saving from zero refuge strategy to optimal refuge strategy	
	Refuge size (%)	Average cost (US$ per ha per year)	Average cost (US$ per ha per year)	In absolute value (US$ per ha per year)	In percentage (%)
Scenario 1					
For all cotton counties in Yellow River Valley					
10 - year-plan	0	189.59	189.59	0.00	0.00
15 - year-plan	0	176.71	176.71	0.00	0.00
20 - year-plan	4	178.25	178.70	0.45	0.25
Scenario 2					
For the most intensive cotton-producing counties					
10 - year-plan	0	143.23	143.23	0.00	0.00
15 - year-plan	0	173.86	173.86	0.00	0.00
20 - year-plan	17	287.17	290.59	3.42	1.19

Appendix Table 3. Nine genotype pests, their fractions in the total pest population, and mortality rate in different fields

Genotype (p^{geno})	Fraction (f^{geno})	Mortality rate in different fields (m^{geno})			
		Sprayed Bt field ($lf_{sbt} = \frac{q*dbt}{1+nrc_k}$)	Non-sprayed Bt field ($lf_{bt} = \frac{q*(1-dbt)}{1+nrc_k}$)	Spread non-Bt field ($lf_{snbt} = \frac{(1-q)*dnbt}{1+nrc_k}$)	Non-sprayed non-Bt field ($lf_{nbt} = \frac{(1-q)*(1-dnbt)+nrc_k}{1+nrc_k}$)
xxyy	w^2*v^2	hbt+hcp-h*hcp	hbt	hcp	0
xxyY	$2w^2*v(1-v)$	hbt+hcp*dcp+rcp*(1-dcp)-hbt*[hcp*dcp+rcp*(1-dcp)]	hbt +rcp*(1-dcp)-hbt*rcp*(1-dcp)	hcp*dcp+rcp*(1-dcp)	rcp*(1-dcp)
xxYY	$w^2*(1-v)^2$	hbt+rcp-hbt*rcp	hbt+rcp-hbt*rcp	rcp	rcp
xXyy	$2w(1-w)*v^2$	hbt*dbt+rbt*(1-dbt) +hcp-hcp*[hbt*dbt+rbt*(1-dbt)]	hbt*dbt+rbt*(1-dbt)	rbt*(1-dbt) +hcp - hcp* rbt*(1-dbt)	rbt*(1-dbt)
xXyY	4w(1-w)*v(1-v)	hbt*dbt+rbt*(1-dbt) + hcp*dcp+rcp*(1-dcp) – [hbt*dbt+rbt*(1-dbt)]*[hcp*dcp+rcp*(1-dcp)]	hbt*dbt+rbt*(1-dbt) + rcp*(1-dcp) – [hbt*dbt+rbt*(1-dbt)]* rcp*(1-dcp)	rbt*(1-dbt) + hcp*dcp +rcp*(1-dcp) – rbt*(1-dbt)* [hcp*dcp+rcp*(1-dcp)]	rbt*(1-dbt) + rcp*(1-dcp) –rbt*(1-dbt)*rcp*(1-dcp)
xXYY	$2w(1-w)*(1-v)^2$	hbt*dbt+rbt*(1-dbt) +rcp-rcp*[hbt*dbt+rbt*(1-dbt)]	hbt*dbt+rbt*(1-dbt) +rcp-rcp*[hbt*dbt+rbt*(1-dbt)]	rbt*(1-dbt) + rcp-rcp*rbt*(1-dbt)	rbt*(1-dbt) +rcp -rcp*rbt*(1-dbt)
XXyy	$(1-w)^2*v^2$	rbt+hcp-rbt*hcp	rbt	rbt	rbt+hcp-rbt*hcp
XXyY	$2(1-w)^2*v(1-v)$	rbt+hcp*dcp+rcp*(1-dcp)-rbt*[hcp*dcp+rcp*(1-dcp)]	rbt+ rcp*(1-dcp) - rbt*rcp*(1-dcp)	rbt+hcp*dcp+rcp*(1-dcp)-rbt*[hcp*dcp+rcp*(1-dcp)]	rbt+ rcp*(1-dcp) - rbt*rcp*(1-dcp)
XXYY	$(1-w)^2*(1-v)^2$	rbt+rcp-rbt*rcp	rbt+rcp-rbt*rcp	rbt+rcp-rbt*rcp	rbt+rcp-rbt*rcp

Note: x and X are the alleles that confer susceptibility and resistance to Bt cotton at locus one, respectively; and y and Y are the alleles that confer susceptibility and resistance to conventional pesticides at locus two. w is the fraction of the susceptible gene frequency to the Bt toxin, and v is the fraction of the susceptible gene frequency to the conventional pesticide. hbt is the mortality rate of those homozygote susceptible pests to Bt toxin in Bt cotton field; rbt is the mortality rate of those homzygote resistant pests to Bt toxin; dbt is the dominance of x allele in the heterozygosity pests xX. hcp is the mortality rate of those homozygote susceptible pests to conventional pesticides if sprayed; rcp is the mortality rate of those homzygote resistant pests to conventional pesticides; dcp is the dominance of y allele in the heterozygosity pests yY.
k denotes the generation; subscript sbt, bt, snbt, nbt denote sprayed Bt cotton field, non-sprayed Bt cotton field, sprayed non-Bt cotton field, non-sprayed non-Bt cotton field and other natural refuge crops fields, repectively.

Appendix Figure 1. Samples of cotton cropping pattern in China

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1 Based on the published results of monitoring efforts in the United States and China, which account for the vast majority of Bt crops grown worldwide, at least seven resistant strains of three species of pests have survived on Bt crops in lab and greenhouse tests. However, there has yet to be any resistance to Bt crops that has been detected in the field (Tabashnika et al., 2003; Wu et al., 2002).

2 Xinjiang Province in western China, is the largest cotton production province in China. However, because of the hot and dry climate, the cotton bollworm is not a serious problem in Xinjiang.

3 The surveys cover 1999, 2000, 2001 and 2004 and were carried out in three provinces—Hebei, Shandong and Henan. Villages and households that are included in the study were randomly selected. In each village about 25 to 30 farm households were randomly 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 numerators from CCAP's survey team for about 2 to 3 hours using recall enumeration techniques that are standard in the economics literature.

4 These numbers from the CCAP data are also consistent with our own data collection effort in the four cotton-producing counties. According to our data, the crop areas of maize, soybeans and peanuts are about 3 times of the cotton area in the Yellow River Valley cotton production region.