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Natural refuge crops, buildup of resistance, and zero-refuge strategy for Bt cotton in China

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In the context of genetically modified crops expressing the *Bacillus thuringiensis* (Bt) toxin, a 'refuge' refers to a crop of the same or a related species that is planted nearby to enable growth and reproduction of the target pest without the selection pressure imposed by the Bt toxin. The goal of this study is to discuss the role of natural refuge crops in slowing down the buildup of resistance of cotton bollworm (CBW), and to evaluate China's no-refuge policy for Bt cotton. We describe in detail the different factors that China should consider in relation to the refuge policy. Drawing on a review of scientific data, economic analyses of other cases, and a simulation exercise using a bio-economic model, we show that in the case of Bt cotton in China, the no-refuge policy is defensible.

Bt cotton, resistance, natural refuge crops, China

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To date, there is no field evidence of pests developing resistance to *Bacillus thuringiensis* (Bt) cotton in China. This lack of resistance has been attributed to natural refuge crops. The wide adoption of Bt crops will have placed high selection pressure on cotton bollworm (CBW), and was expected to accelerate the buildup of resistance. However, even after cultivation of Bt crops in China and other countries for more than 10 years, there have been no reports of field-evolved resistance [1,2]. In most countries, there is a requirement to plant non-Bt crops as an insect refuge, and this strategy is thought to have effectively slowed the buildup of resistance. China does not have a mandatory refuge policy for cultivation of Bt cotton; however, natural refuge crops (such as maize, soybean and peanuts) were considered to be functionally similar to the mandatory refuges in other countries where non-Bt cotton is planted to manage the evolution of resistance to Bt cotton [3,4].

Partly encouraged by the role of natural refuge crops in slowing down the buildup of resistance and the lack of field-evolved resistance, the US Environmental Protection Agency (US EPA) is rethinking the requirements for refuges for some regions where highly effective Bt cotton is planted with sufficient natural refuge crops [5]. After extensive analyses and peer reviews of Monsanto's 2006 natural refuge proposal for Bollgard II cotton (a highly effective variety of Bt cotton), the US EPA concluded that the scientific evidence showed that natural refuges would be effective for cultivation of Bollgard II cotton in some areas [6].

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However, in March 2010, Monsanto disclosed a report that pink bollworm had developed resistance to Bt cotton during the 2009 field season [7]. Limited refuge planting was considered to be one of the causes. Even though Monsanto claimed that this was the first report of buildup of resistance in the field, Tabashnik *et al.* [8] noted that resistance to Bt crops in South Africa and the United States had been reported earlier. In China, Liu *et al.* [9] stated that a conservative estimate of the resistance allele frequency was more than 0.10 in 2007, and claimed that their finding was the first report of the resistance allele frequency increasing to such a high level in the field in China. They argued that the lack of a conventional cotton refuge system is one possible reason for the accelerated evolution of resistance. In other words, natural refuge crops might not be able to provide sufficient refuges for CBW to slow down the buildup of resistance.

The goal of our work is to initiate a discussion about whether China needs to rethink its zero-refuge policy. In this paper, we discuss whether natural refuge crops provide sufficient refuge to maintain the susceptibility of the pest populations to Bt cotton under current production systems. Any difference in the biology of the target pests (e.g., the number of generations per season and the number of larvae per generation), the nature of natural refuge crops, or any other biological and economic factors may point to a different optimal refuge strategy. Hence, an empirical study is needed to evaluate whether China's zero-refuge policy is the best policy. To do this, we describe in detail the different factors that China considered when deciding whether or not a refuge policy was required. We discuss the nature of the pest population, the process of the development of resistance, the trends in adopting Bt cotton, and the cropping patterns that make up the Bt cotton production environment. In addition, we review scientific data, summarize economic analyses of other cases, and conduct a simulation exercise using a bio-economic model that we have produced. Together, these analyses suggest that in the case of Bt cotton in China, the lack of mandatory cotton refuges is a sensible policy. In other words, China's zero-refuge policy appears to be a sound decision.

1 The nature of the cotton bollworm and the buildup of resistance

The increasing use of modern improved varieties of cotton has resulted in an increase in pest infestations, and therefore, there is a need for pest control in almost all situations [10]. Cotton producers in China have been particularly hard hit by the intense pest pressures that have plagued cotton growing areas during the previous decades. According to reports from the Ministry of Agriculture's entomological and disease prevention teams, cotton yields during the 1990s were reduced by 5%–14% as a result of pest infestations, even among cotton crops that were sprayed with conventional pesticides (Table 1, column 1). During the same period, losses in grain yield were decreased by an estimated 2%–3% (Table 1, column 2). In the Yellow River Valley cotton production region, China's largest cotton-producing region, the cotton yield loss was as high as 29% in 1992 (Table 1, column 3).

As bad as such losses were, pest infestations and their associated losses would have been even more severe if farmers had not sprayed their crops with high doses of conventional chemical pesticides. Entomologists in China's extension system estimated that had farmers not sprayed, cotton yield losses nationwide would have ranged from 24% to 50% during the 1990s (Table 1, column 5). Yields would have fallen even more in cotton-producing regions in the Yellow River Valley (35%–93%; Table 1, column 6).

These high estimates of actual and potential damage pre-

Table 1 Estimates of pest-related yield losses by National Pest Reporting Stations and Chinese farmers from 1990 to 1997

	Actual loss (%) of grain and cotton[a)]				Potential loss (%) of cotton[b)]				
	China		Yellow River Valley[c)]		Official estimate		Farmers' estimates[d)]		
	Cotton	Grain	Cotton	Grain	China	Yellow River Valley	Mean estimate of losses	Percentage of farmers estimating >50% losses	Percentage of farmers estimating 100% losses
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

a) Actual loss (a better term is 'official estimate of crop production loss') is due to inability of farmers to control pests, i.e., the crop production loss that actually occurred. b) Potential loss is the crop production losses that would have occurred had farmers not sprayed. This figure includes actual production losses and those that would have occurred had farmers not sprayed. c) Values for Yellow River Valley are average values from Hebei and Shandong provinces. d) Values were calculated by the authors from the Center for Chinese Agricultural Policy of the Chinese Academy of Sciences dataset.

dicted by scientists and extension teams are consistent with perceived estimates of the cotton farmers themselves (Table 1, columns 7–9). In a household level survey conducted by the Center for Chinese Agricultural Policy (CCAP) of the Chinese Academy of Sciences (CAS), enumerators asked farmer-respondents about the damage that would have been sustained had they not sprayed for cotton pests. On average, cotton farmers estimated that their yields would have fallen by 56%. More than 60% of farmers believed that cotton yield losses would have exceeded 50%, and 11% of respondents believed that their crops would have been completely destroyed if they had not sprayed (i.e., losses of 100%). While these estimates cannot be considered as scientific, they demonstrate that extension agents and farmers both believe that pest damage would have been severe without active intervention.

In their efforts to control insect infestations between the early 1980s and the mid-1990s, China's cotton farmers used only chemical pesticides, and used increasing quantities of pesticides over this period. According to the State Planning Commission's Cost of Production survey, cotton farmers spent USD30–35 per hm^2 on pesticides in the early 1980s, accounting for 11%–13% of their total material input costs. By 1990, the cost share of pesticides rose to 18%, and by 2000, to 22%. In 1995, the absolute level of pesticide applied to cotton was more than 200% higher in real terms than that in the early 1980s (USD101 vs. USD31–35). Pesticide expenditures were rising so fast during the early 1990s that foreign observers began to express doubt that China could continue to produce cotton profitably [11].

As the level of pesticide use in cotton cultivation rose and the profitability of the crop eroded, there was increasing concern about the other consequences of pesticide use. Huang *et al.* [12] documented that as pesticide use increased, the incidence of morbidity and mortality of farmers due to pesticide overuse also increased sharply. In China, the number of reported hospitalizations connected with pesticide use rose by 116% between 1987 and 1992, and the number of deaths from pesticide-related poisoning (from on-the-job contaminations) rose by 41%. In household surveys conducted by CCAP, more than 33% 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. Workers reported symptoms of nausea, headaches, skin rashes, and eye infections [13,14]. There were also reports in the press and academic journals that high rates of pesticide use were contaminating China's waterways and groundwater resources [15,16]. 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.

While there are many reasons for the increase in pesticide use, particularly in cotton-producing regions, during the 1980s and 1990s in China [12], one of the major reasons is the genetic make-up and population dynamics of CBW. Several different pests infested China's cotton crop at various growth stages during the 1980s and 1990s, but CBW was the most significant. According to Wu and Guo [3,4], CBW affects virtually all of the nation's cotton areas, except for a few counties in the dry western cotton-producing regions. The loss in yields resulting from CBW accounts for 65% of total losses nationwide; however, the severity of the CBW problem differs among the nation's cotton-producing areas. In the Yellow River Valley cotton-producing region, CBW caused up to 78% of the actual yield loss, whereas it resulted in only 12% yield loss in China's western provinces.

While CBW has affected China's cotton crops since modern varieties were introduced in the 1930s, the way in which farmers attempted to control CBW has changed over time [17]. Before 1950, 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 effective chemical pesticides initially improved control of CBW. However, CBW developed resistance to each of the conventional pesticides that was used as the primary tool to control pest infestations [3,4]. For example, in the 1950s and 1960s, farmers regularly used highly toxic organochlorines (OC). While these were initially effective, by the late 1960s, the CBW population had built up resistance, and OCs had become largely ineffective. During the 1970s, farmers began to use organophosphates (OP) and other carbamate chemicals instead of the OCs. As before, the pesticides were initially effective, but became less so as the CBW population quickly built up resistance [18,19]. The story was repeated again with pyrethroid pesticides (PP) in the 1980s. In fact, it took only 10 years for CBW to develop a high level of resistance to PPs in the 1980s [3,4]. Although pest populations in other crops (e.g., rice) during the same time period also developed resistance to chemical pesticides [20], CBW in cotton appears to have developed resistance more rapidly than others.

The propensity of CBW populations to develop resistance to pesticides in the field is supported by the work of entomologists in the laboratory. To gain an evolutionary understanding of the patterns of resistance in CBW, China's entomologists began to monitor the development of resistance early in the 1980s [17]. 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 [21]. Data from laboratory experiments arrived at the same conclusion, suggesting that populations of CBW in China have an ability to rapidly evolve resistance to a wide range of pesticides.

Clearly, the rising levels of pesticide applications and the increasing costs during the early 1990s partly reflect the fact that China's CBW had begun to develop resistance to OCs, OPs, and PPs. Huang *et al.* [12] reported that in the mid-1990s, China's cotton farmers spent more than USD500 million annually on pesticides to control pests, especially CBW. According to household surveys, farmers were spraying for pests, on average, more than 20 times per year by the late 1990s; some were spraying up to 30 times, and about every other day during the periods of peak infestations [12].

2 Bt cotton and refuges

The consequences of the increasing resistance of CBWs to conventional pesticides were real not only for individual farmers, but also for the entire cotton industry in China. In all parts of China, but especially in the Yellow River Valley, production trends deteriorated as the buildup of the resistance to conventional pesticides proceeded. During the late 1970s and in the post-reform period in the early 1980s, the Yellow River Valley became the largest cotton-producing region in China, and its share of national cotton production rose dramatically from 30% to more than 60%. Cotton production in China peaked at over 6 million tons in the late 1980s [11]. After the peak, however, cotton production in the Yellow River Valley steadily declined over the next 10 years. While there are many plausible reasons for this decline, Hsu and Gale [11] argued that one of the most important factors was the increasingly severe CBW infestations, which were occurring as CBW developed 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 accelerated their efforts to produce a new technology to alleviate the problems faced by cotton growers. In 1996, US seed companies commercially released a genetically modified variety of insect-resistant cotton—Bt cotton. Only one year later, in 1997, China's government approved Bt cotton for use in the Yellow River Valley [11]. In that 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 efforts to commercialize and distribute Bt cotton in China were successful, at least initially. Even though the cost of Bt cotton seed was five to six times higher than that of conventional cotton seeds, the savings from the reduced input of pesticides and the revenues from higher yields outweighed the high purchase cost of the seeds [11]. In fact, the private economic benefits from Bt cotton have been well-documented in China and other countries [12,22–26]. According to studies in China, Bt cotton farmers not only reduced their pesticide use by more than 70%, but also obtained higher yields. In addition, the reduction in the use of conventional pesticides meant that Bt cotton also contributed to a cleaner production environment and helped to improve farmer health [13,14,27].

Because of its high profitability and other benefits, Bt cotton became widely adopted in China and many other developing countries. According to a national survey by CCAP, the area planted with Bt cotton by China's farmers spread rapidly after its first release (Figure 1A). Starting from zero in 1996, the area of Bt cotton grew to 3.7 million hm^2 in 2004. Across China, the area in which Bt cotton was grown expanded to approximately two-thirds of the total cotton cultivation area (Figure 1A), and millions of farmers—many of them poor with less than 0.2 hm^2 of cultivated land per capita—cultivated Bt cotton [28]. Moreover, Bt cotton was adopted even more rapidly in the Yellow River Valley. For example, in 2001, Bt cotton accounted for more than 90% of cotton cultivated in Shandong and Hebei provinces, the third and fourth largest cotton-producing provinces in China, respectively (Figure 1B).

While the rise in productivity of Bt cotton is well-documented and certainly contributed to the expansion of the crop, the history of cotton in China suggests that there is reason to be concerned about its sustainability. Given the propensity of CBW to develop resistance to conventional pesticides, one of the major concerns about the long-term success of Bt cotton is its potential vulnerability to adaptation by the major pest populations to the toxin it expresses [29]. Similar to the case of conventional pesticides, it is possible that the large-scale use of Bt crops may accelerate the evolution of pests' resistance to Bt toxin 1. If too large a

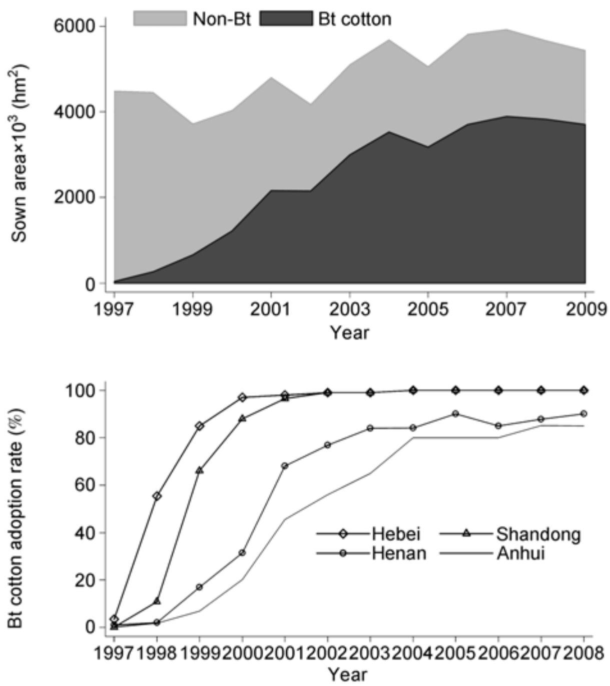

Figure 1 Adoption of Bt cotton in China. A, Sown area of Bt and non-Bt cotton in China from 1997 to 2009. B, Bt cotton adoption rate from 1997 to 2008.

proportion of pests develop resistance to the Bt toxin, the effectiveness of Bt crops to control pests will decrease, and the benefits of Bt cotton will be undermined.

Experimental evidence from laboratory studies showed that CBW rapidly developed resistance to conventional pesticides. Using similar methods, scientists have experimentally demonstrated that CBW may react in the same way to Bt cotton. For example, Tabashnik *et al.* [1] showed that certain sub-populations of a cultured pest population were able to survive on Bt cotton in laboratories and greenhouse tests (i.e., these populations had developed resistance). Wu *et al.* [21] demonstrated that the resistance level was 106-fold higher after CBW had been selected by treatment with the Bt toxin over 44 generations. On the basis of such laboratory experiments, some entomologists have predicted that when Bt cotton is planted across a sufficiently large production area and is intensively cultivated (i.e., without conventional cotton refuge crops), its effective service life may only persist for a few years [30]. According to Gould, the implications of such predictions are that China should begin a system of refuges.

In fact, the refuge system has been adopted—either explicitly or implicitly—by almost all countries that have introduced Bt cotton [31]. The US EPA requires producers to allocate a share of their land to a non-Bt crop. Following their lead, all Bt cotton producing countries in the developed world (e.g., Australia) have policies that require producers to plant refuges. Although there is no apparent research basis for adopting such policies in developing countries, a number of countries—India, Indonesia, and South Africa—followed the example of the United States and required farmers to plant non-Bt cotton as a refuge. Refuges allow susceptible pests to survive so they can mate with resistant pests that survive in the Bt cotton fields and extend the efficacy of the insect-resistant varieties. However, planting a refuge imposes a cost on the producer which can equal the profit advantages of the technology.

Unlike other Bt-cotton-producing countries, China implicitly has a natural refuge (or zero non-Bt cotton refuge) policy. This policy has two components: China's natural refuge crops, i.e., its diverse cropping system, provide a large amount of susceptible pests; and biosafety regulation of Bt cotton is implemented in a way that helps to reduce the rate of CBW survival on Bt cotton [3,4]. This policy is not without controversy, as some scientists [30] and environmentalists [32] have argued that refuges should be planted. Their arguments are based on the fact that CBW has shown a propensity to develop resistance to conventional pesticides in the recent past, and on laboratory tests that demonstrate that CBW can develop resistance to the Bt toxin. Thus, proponents of refuges believe that resistance to Bt cotton will build up in the near future if China does not adopt a refuge policy.

Despite the potential and anticipated risks from Bt resistance that are central to arguments in favor of the refuge policy, there has been no field evidence of a buildup in Bt toxin resistance in China to date. In fact, there has been no field evidence of Bt toxin resistance in any of the countries cultivating Bt crops. Thus, even though the pest has survived on Bt plants in laboratories and greenhouses during scientific tests, there is no evidence that this has occurred in the field [1][1)].

3 Cropping systems in the Yellow River Valley: natural refuges?

To date, there has been no evidence of a buildup of resistance of CBW in the field either in the United States or China. In the United States, it is argued that the cotton pest population has maintained its susceptibility to Bt cotton because of the refuge policy. While this is perhaps true, it does not explain why resistance has not developed in China, which does not have a refuge policy. In this section, we explore one possible explanation.

As proposed by Wu *et al.* [33], the main theory explaining the absence of field buildup of resistance is that natural refuge crops in the cotton growing regions of the Yellow River Valley maintain the susceptibility of the pests to Bt toxin. In the United States and many other Bt cotton growing nations, cotton is generally grown in vast tracts of single mono-cropped cultivars. In China, the cropping patterns are much more diverse, so that cotton is typically grown within a mosaic of small patches, where neighboring crops act as a de facto refuge for CBW populations. Thus, even when farmers in China plant Bt cotton in 100% of their cotton cultivation area (which might lead to the buildup of resistance in a mono-cultured cotton cropping system), in China CBW will also reproduce in neighboring areas planted with 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 buildup of resistance can be avoided without an explicit refuge policy.

While this explanation has been generally accepted by many agricultural scientists in China in recent years, it is largely based on anecdotal evidence, rather than scientific evidence. To better understand the nature of China's cropping system and the ways in which these natural refuges can substitute for explicit cotton refuges, in the rest of this sec-

1) Based on the published results of monitoring studies 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, no incidences of field-evolved resistance to Bt crops have been detected to date (Tabashnik *et al.* [1]; Gao *et al.* [17]; Wu *et al.* [33]).

tion we will discuss the characteristics of the main cropping systems in the Yellow River Valley's cotton-producing regions. This will paint a picture of the main cotton-producing region in China, enabling us to see what the production environment of the typical Bt cotton farmer looks like.

We used two sources of data to understand the cropping patterns in the Yellow River Valley. 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 chose four using the following stratified choice strategy: the counties were ranked order of their likelihood of buildup of Bt resistance. Then, we selected two counties from among the top five ranked counties, one from those ranked between 6 and 20, and one from the remaining counties on the list. Using this selection process we selected four counties—the 2nd, 3rd, 18th, and 107th largest cotton-producing counties in the Yellow River Basin. Two of the counties are in Henan Province, one is in Shandong Province, and one is in Hebei Province; these provinces are not only the most important production provinces in the Yellow River Valley, but also the 2nd, 3rd, and 4th largest cotton-producing provinces, respectively, in China[1)].

After the selection of the sample counties, we implemented the second stage of the sample selection procedure. In each county, we obtained a list of townships and their rate of cotton production. The towns on the list were then classified as intensive cotton producers or less intensive cotton producers. From each of these two stratified lists, we randomly chose one township, giving a total of two townships per county—one with higher intensity and one with lower intensity production. After choosing the townships, we then had the township mayors in charge of agriculture convene a meeting with all of the village leaders in that township. Village leaders provided information on the intensity of cotton planting, cropping patterns, and other relevant information. After interviews in the township office, we randomly selected a subset of villages to visit to verify the survey data. In general, the survey data was found to be accurate.

Consistent with the assumptions of the agricultural scientists, the results of our survey confirm the diversity of cropping patterns in China's Yellow River Valley. 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 hm^2 (Table 2). The cropping patterns are even more fragmented outside most intensive cotton producing counties (Table 2). For example, in the 18th largest cotton-producing county, more than 60% of cotton is planted in plots that are less (and often much less) than 1 hm^2. There are no areas of contiguous cotton production greater than 50 hm^2. In the 107th most intensive cotton-producing county, 93% of the cotton is grown on plots that are less than 1 hm^2.

To show the nature of the cotton production environment from another perspective, we also draw on an alternative dataset from a survey carried out by the CCAP of the Chinese Academy of Sciences[2)]. In doing so, we find additional support for the natural refuge cropping hypothesis (Table 3). Although there is a very high rate of Bt cotton adoption as a proportion of the total cotton cultivation area, cotton is far from a monocultured crop in all of the surveyed villages, even though these villages are in the heart of one of China's main cotton-producing regions. For example, in the Yellow River Valley, cotton cultivation accounted for between 37% and 52% of the total cultivated area between 1997 and 2007. For comparison, cotton cultivation accounted for only 35%–42% of the total cultivation in the Yangtze River Valley. Hence, unlike the cropping patterns of other nations (e.g., the United States and Australia, which are known for their large mono-cultured areas), China's cotton crop is grown alongside a diversified set of other crops.

Table 2 Distribution of cotton plots in selected Yellow River Valley cotton production regions in China in 2004[a)]

County	Rank in terms of cotton production	Proportion of cotton area				Cumulative cotton proportion in Yellow River Valley
		Greater than 100 hm^2	Greater than 50, but less than 100 hm^2	Greater than 1, but less than 50 hm^2	Less than 1 hm^2	
Xiajin	2nd	0.55	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) Values represent the cotton area in each category (e.g., greater than 100 hm^2) divided by the total cotton area.

1) Xinjiang Uyghur Autonomous Region is the largest cotton production region in China. However, because of the hot and dry climate, the cotton bollworm is not a serious problem in Xinjiang.

2) The surveys cover 1999, 2000, 2001, and 2004 and were carried out in three provinces: Hebei, Shandong, and Henan. Villages and households included in the study were randomly selected. In each village, approximately 25–30 farm households were randomly selected from a comprehensive list (provided by the local household registration office) of all farming households in the village. Each farmer was interviewed by trained enumerators from CCAP's survey team for approximately 2–3 h using recall enumeration techniques that are standard in the economics literature.

Table 3 Bt cotton, refuge crops and the role of cotton in Northern China's cropping patterns from 1997 to 2007[a)]

	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007
					Yellow River Valley						
Cotton area share (%)	37	41	43	49	50	49	48	52	42	42	44
Refuge crops share (%)	89	72	52	40	38	38	39	39	45	46	46
Bt cotton adoption (%)	32	57	81	91	93	94	95	96	98	98	98
					Yangtze River Valley						
Cotton area share (%)	35	35	38	39	41	41	42	40	42	42	–
Refuge crops share (%)	100	97	92	72	50	50	46	46	42	42	–
Bt cotton adoption (%)	0	19	27	50	85	85	92	98	99	99	–

a) Cotton area share is the proportion of the cotton area of the total crop cultivation area. Refuge crops include wheat, maize, soybeans, rapeseed, vegetables, and other minor crops. Refuge crops share is the proportion of refuge crops (with 25% of the wheat area and 75% of the vegetable area) of the total cultivated area. Bt cotton adoption is the proportion of Bt cotton of the total area planted with cotton. Yellow River Valley stretches through Hebei, Shandong, and Henan provinces; Yangtze River Valley is in Anhui Province.

In fact, the cropping patterns of China are such that cotton is being cultivated alongside a number of crops that are CBW hosts. According to Wu and Guo [3,4], CBW not only infests cotton during the growing season in northern China, but also lives and breeds in fields of wheat, maize, soybeans, rapeseed (or canola), vegetables, and many other minor crops, weeds, and even fruit trees. Hereafter, we refer to these crops planted alongside cotton in summer/autumn as natural refuge crops.

As shown in Table 3, the proportion of a sample village's total cultivated area planted with natural refuge crops during the cotton production season was relatively large (Table 3, rows 2 and 5). In villages that cultivate Bt cotton, natural refuge crops account for large proportion (on average, 45%) of the total cultivated area in both the Yellow River Valley and the Yangtze River Valley. This proportion is far larger than the 20% refuge required by the US EPA. According to the advocates of China's zero-refuge policy, these refuge crops that grow alongside China's Bt cotton are sufficient to maintain the susceptibility of the CBW populations to the Bt toxin of Bt cotton.

4 Bio-economic model simulation analysis

While the data from laboratory and field studies support China's zero-refuge policy, there are certain shortcomings that should be considered. Most conspicuously, the laboratory work is experiment-based and does not consider the economic costs and benefits of the various refuge policies. Quantitative field-based studies are also persuasive, but they are based on only a few years of field experience, and it is possible that it will take longer for problems to become evident. In fact, Gould [30] argued that the nature of resistance buildup is so explosive that it is dangerous to rely only on field monitoring. According to this line of thinking, it is not surprising that there has been no evidence of a buildup of resistance during the early phases of Bt crop cultivation. Gould argued that by the time resistance is detected in the field, it may be too late. The shift from nearly zero resistance to a high proportion of resistant insects is rapid and irreversible. Therefore, to add to the data obtained from our field-based empirical work, we constructed a bio-economic simulation model to better understand the long-term costs and benefits of establishing (or not establishing) refuges.

Our integrated bio-economic model follows that developed by Wilen and Msangi [34]. The approach, in fact, is similar to those used in the models developed by Laxminarayan and Simpson [35], Secchi *et al.* [36], and Livingston *et al.* [37] in their studies on refuge strategies. The bio-economic model comprises two parts: a biological model, which is used to simulate the evolution of resistance and the pest population, and a regulation model, which estimates the impacts of refuge policies. A detailed discussion of the model is given in Appendix and in Qiao [38].

Two types of parameters—biological and empirical—are used in the model. Most of the biological parameters, such as the efficiency of the Bt toxin in killing CBW and the carrying capacities of the different natural refuge crops, are based on parameters that have been published or have been calculated by the authors using experimental data from the Institute of Plant Protection (IPP), Chinese Academy of Agricultural Sciences. 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 CBWs that develop resistance. While it may seem to be trivial to have only one parameter that is not based on firm science, in fact, the fitness cost parameter plays a key role in the analysis. This parameter measures the difference between the mortality rates of susceptible 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.* [37] in his bio-economic model of refuges in the United States. This parameter is not available from either laboratory or field studies in China or elsewhere, and therefore, there is a degree of uncertainty associated with it. For this reason, we included a sensitivity analysis to understand how this assumed parameter affects the results.

Like the scientific parameters, almost all of the economic parameters are based on data that have been used elsewhere and on previously published results. For example, the treatment costs associated with Bt cotton and with conventional pesticides, two key economic parameters, come from CCAP data. These data have been used in analyses that are published in *Science* [13] and other journals [12,14]. The initial values of these biological and economic parameters are shown in Appendix Table 1.

4.1 Simulation results: does China need refuges?

Supporting the findings from laboratories and field work-based scientific and economic empirical work [28], the simulation results of our model provide evidence that policy-mandated refuges are not required in China. When we simulate the total costs of cotton production, including the cost of CBW damage and the treatment costs under different refuge scenarios, we find that costs monotonically increase as the refuge size increases (Figure 2). In other words, the results of the simulation show that the best policy is to allow farmers to plant 100% Bt cotton in their cultivation area without requiring a non-Bt cotton refuge. This result is consistent with much of the work carried out in China, but it is in stark contrast to work done on refuges of Bt cotton in the United States [37] and other Bt crops [39].

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 one hand, a non-Bt cotton refuge will slow the buildup of 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 require the farmer to either spray with conventional pesticides (which are expensive) or to not spray, and suffer high levels of crop damage.

In general, the best policy is the one that justifies the costs of foregoing current profits from a refuge by generating higher future paybacks from maintaining susceptibility. If the right proportion of land is allocated to refuges, the costs in the short term are offset by higher returns in the long term. However, if the refuge size is larger than necessary, the expense will not be earned back in the future.

The differences between our results for China and those from other studies based on agriculture in the United States arise from the important roles played by natural refuge crops. Like a non-Bt cotton refuge, natural refuge crops provide a refuge for CBW and help to slow the buildup of resistance (Figure 3). As long as non-cotton crops in a small-scale multi-cropping patchwork system provide a large sufficient natural refuge to slow the development of resistance, policy-mandated refuges are not required. Therefore, if non-Bt cotton refuges become mandatory when this is not necessary, the costs incurred in establishing and maintaining 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 CBW and treatment costs—is USD176.71 (Table 4, row 1) per hm^2 per year. If a refuge equivalent to 20% of the Bt cotton area is planted and sprayed, as required in the United States, then the average cost will increase to USD209.67 per hm^2 per year. In other words, if China's government followed the US-style refuge requirements without considering the cotton production environment in the Yellow River Valley, cotton farmers would incur additional expenses of at least USD32.96 (or 18.65% more) per hm^2 per year. It should be noted that the benefits of the zero-refuge policy do not take into account the additional costs that would be incurred by the government to implement and monitor a refuge policy. They also do not consider the potentially significant health benefits that are associated with reduced use of conventional pesticides.

Although the above results were obtained by analyzing an "average" cotton-producing area in northern China, they hold true for the most intensive cotton-producing counties. We re-simulated the model by assuming that cotton is

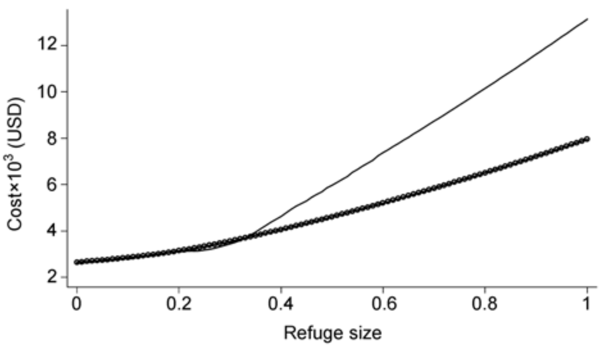

Figure 2 Costs for different refuge sizes over 15 years. —○—, All cotton counties in North China; ——, mono-cropping cotton counties in North China.

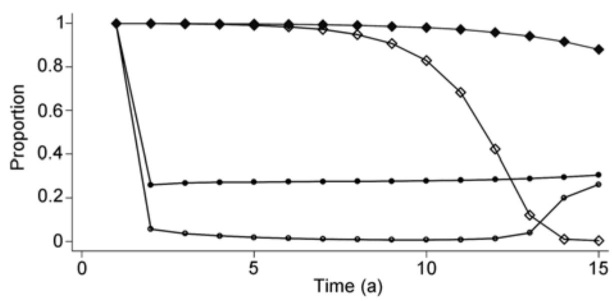

Figure 3 Impact of Natural Refuge Crops (NRC) on pest population and buildup of pest resistance to Bt toxin. —○—, Total pest population without NRC; —●—, total pest population with NRC; —◇—, susceptibility of the pest to Bt toxin without NRC; —◆—, susceptibility of the pest to Bt toxin with NRC.

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

	Cost of 0% refuge (USD per hm^2 per year)	Cost of 20% refuge (USD per hm^2 per year)	Cost saving from 0% refuge to 20% sprayed refuge	
			Absolute value (USD per hm^2 per year)	Percentage (%)
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

mono-cultured in larger tracts in some counties (Table 4, Figure 3). As shown in Table 4, 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, if it becomes mandatory to plant and spray a 20% refuge in these counties, the average cost will increase from the optimal level, USD173.86 per hm^2 per year (for a zero non-Bt cotton refuge), to USD207.49 per hm^2 per year (Table 4, row 2).

4.2 Sensitivity analysis

To test whether our results are sensitive to the assumed values of the parameters, we used sensitivity analysis to test the robustness of the findings. For example, we estimated the optimal refuge size for different time horizons (10, 15, and 20-year horizons), and used different assumptions about natural refuge cropping patterns. The maximum threshold value for conventional pesticide use and the fitness cost parameter were also varied. Only one parameter was adjusted for each sensitivity analysis run. Importantly, the results are largely consistent with our findings that policy-mandated refuges are not economic for Bt cotton in China. Appendix Table 2 shows the simulation results for two sets of sensitivity analysis runs; those based on the different time horizons, and those with different assumptions about natural refuge crops. For the 20-year plan the optimal refuge size was not zero, but compared with the zero-refuge policy, the extra benefit provided by the optimal refuge policy is relatively small (Appendix Table 2, rows 3 and 6). Considering the high monitoring costs and other costs associated with a non-zero refuge policy, a zero-refuge policy is better in practice [38].

5 Conclusion

China is unique among countries that have decided to cultivate GM crops. Unlike all other nations—both developed and developing—that have commercialized Bt cotton, China's agricultural officials do not require their farmers to set aside a refuge to maintain the susceptibility of CBW to the Bt toxin expressed by the Bt cotton plant. Instead, China allows farmers to plant 100% of their cultivation area with Bt cotton. Although this policy was initially made without field evidence, the data in this paper suggest that the policy is correct. Because of the diversified nature of China's farming systems in cotton-producing areas, there is sufficient area of refuge crops to act as hosts for the CBW populations so that additional cotton refuges are not required. Under these circumstances, planting non-Bt cotton as a refuge is uneconomic, and the expense of implementing refuges (both from the government's and individual farmer's point of view) may be avoided.

Although China's zero-refuge policy for Bt cotton may be justified for cotton production in northern China at present, we do not suggest that refuge policies are always unnecessary under all circumstances. In the case of Bt cotton, the highly diversified cropping system provides the CBW population enough natural refuge to maintain its susceptibility to Bt cotton. Any changes in the cropping system could alter the situation, and new policy strategies may become more appropriate. A good example is Bt maize; since non-Bt maize is the most important natural refuge crop for CBW in both Yellow River and Yangtze River basins, the resistance of CBW to Bt cotton may evolve faster if Bt maize is commercialized [39]. Another example is Bt rice. If Bt rice is commercialized, the planting of non-Bt rice as a refuge may be required because there may be insufficient natural refuge crops for the target pest of Bt rice. Under these circumstances, China may need to reconsider its zero-refuge policy.

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1 Tabashnik B E, Carrière Y, Dennehy T J, *et al.* Insect resistance to transgenic Bt crops: lessons from the laboratory and field. J Econ Entomol, 2003, 96: 1031–1038
2 Heckel D G, Gahan L J, Baxter S W, *et al.* The diversity of Bt resistance genes in species of Lepidoptera. J Invertebr Pathol, 2007, 95: 192–197
3 Gao Y, Wu K, Gould F. Frequency of Bt resistance alleles in *H. armigera* during 2006–2008 in northern China. Environ Entomol, 2009, 38: 1336–1342
4 Wu K M, Guo Y Y. Evolution of cotton pest management practice in China. Annu Rev Entomol, 2005, 50: 31–52
5 Banerjee S, Martin S. An estimation of producer returns from Bt cotton with varying refuge sizes. Crop Prot, 2008, 27: 1003–1008
6 United States Environmental Protection Agency. Pesticide news story: EPA approves natural refuge for insect resistance management in Bollgard II cotton. June 4, 2007. http://www.epa.gov/oppfead1/cb/

csb_page/updates/2007/bollgard-cotton.htm
7 Bagla P. Hardy cotton-munching pests are latest blow to GM crops. Science, 2010, 19: 1439
8 Tabashnik B E, Van Rensburg J B J, Carrière Y. Field-evolved insect resistance to Bt crops: definition, theory, and data, J Econ Entomol, 2009, 102: 2011–2025
9 Liu F Y, Xu Z P, Chang J H, *et al.* Resistance allele frequency to Bt cotton in field populations of *Helicoverpa armigera* (Lepidoptera: Noctuidae) in China. J Econ Entomol, 2008, 101: 933–943
10 Pingali P L, Hossain M, Gerpacio R V. Asian Rice Bowls: The Returning Crisis? Oxon: CAB International for the International Rice Research Institute, 1997
11 Hsu H, Gale F. Regional shifts in China's cotton production and use. In: Cotton and Wool Situation and Outlook. Washington DC: Economic Research Service, USDA, 2001
12 Huang J K, Hu R F, Rozelle S D, *et al.* Small holders, transgenic varieties, and production efficiency: the case of cotton farmers in China. Aust J Agr Resour Ec, 2002, 46: 367–387
13 Huang J K, Rozelle S D, Pray C E, *et al.* Plant biotechnology in China. Science, 2002, 295: 674–677
14 Hossain F, Pray C E, Lu Y M, *et al.* Genetically modified cotton and farmers' health in China. Int J Environ Health Res, 2004, 10: 296–303
15 Zhang Y S, Xu F. The primary research on remain of BHC in the soil of rice field in Zhujiang Delta. Agro-Environmental Protection (in Chinese), 1989, 1: 4–9
16 Xiong W L, Chen Y B. Review of effect of pesticide leaching into groundwater. Southwest China Journal of Agricultural Sciences (in Chinese), 2003, S1: 43–48
17 Guo Y Y. Research on Cotton Bollworm. Beijing: China Agricultural Press, 1998
18 Stone B. Agricultural technology in China. China Quarterly, 1988, 116: 767–822
19 Stone B. Basic agricultural technology under reform. In: Yuch Y Y, Ash R F, eds. Economic Trends in Chinese Agriculture: The Impact of Post-Mao Reforms. Oxford: Clarendon Press, 1993
20 Widawsky D, Rozelle S D, Jin S Q, *et al.* Pesticide productivity, host-plant resistance and productivity in China. Agricultural Economics, 1998, 19: 203–217
21 Wu K M, Wu W, Liang G M, *et al.* Regional reversion of insecticide resistance in *Helicoverpa armigera* (Lepidoptera: Noctuidae) is associated with the use of Bt cotton in northern China. Pest Manage Science, 2004, 61: 491–498
22 Gouse M, Pray C E, Schimmelpfennig D. The distribution of benefits from Bt cotton adoption in South Africa. AgBioForum, 2004, 7: 187–194
23 Huang J K, Hu R F, van Meijl H, *et al.* Biotechnology boosts to crop productivity in China: trade and welfare implications. Journal of Development Economics, 2004, 75: 27–54
24 Pray C E, Ma D M, Huang J K, *et al.* Impact of Bt cotton in China. World Development, 2001, 29: 813–825
25 Qaim M, Zilberman D. Yield effects of genetically modified crops in developing countries. Science, 2003, 299: 900–902
26 Traxler G, Godoy-Avila S, Falck-Zepeda J, *et al.* Transgenic cotton in Mexico: economic and environmental impacts (unpublished report). Auburn, AL: Department of Agricultural Economics, Auburn University, 2001
27 Pray C E, Huang J K, Rozelle S D. Five years of Bt cotton production in China: the benefits continue. The Plant Journal, 2002, 31: 423–430
28 Huang J K, Hai L, Hu R F, *et al.* Eight years of Bt cotton in farmer fields in China: has the bollworm population developed resistance? Working paper, Center for Chinese Agricultural Policy of Chinese Academy of Sciences. Beijing, China, 2006
29 Bates S L, Zhao J, Roush R T, *et al.* Insect resistance management in GM crops: past, present and future. Nature Biotechnology, 2005, 23: 57–62
30 Gould F. Sustainability of transgenic insecticidal cultivars: integrating pest genetics and ecology. Annu Rev Entomol, 1998, 43: 701–722
31 Shelton A M, Tang J D, Roush R T, *et al.* Field tests on managing resistance to Bt-engineered plants. Nature Biotechnology, 2000, 18: 339–342
32 Xue D Y. The report in the studies on the impact of transgenic Bt cotton on environment. International Biosafety Newsletter (suppl.), 2002
33 Wu K M, Guo Y Y, Gao S S. Evaluation of the natural refuge function for *Helicoverpa armigera* (Lepidoptera: Noctuidae) within *Bacillus thuringiensis* transgenic cotton growing areas in North China. J Econ Entomol, 2002, 95: 832–837
34 Wilen J E, Msangi S. Dynamics of antibiotic use: ecological versus interventionist strategies to manage resistance to antibiotics. In: Laxminarayan R, ed. Battling Resistance to Antibiotics and Pesticides: An Economic Approach. Washington DC: Resource for the Future, 2002, 18–41
35 Laxminarayan R, Simpson R D. Refuge strategy for managing pest resistance in transgenic agricultural. Environment and Resource Economics, 2002, 22: 521–536
36 Secchi S, Hurley T M, Hellmich R L. Managing European corn borer resistance to Bt corn with dynamic refuges. The 5th ICABR International Conference, Ravello, Italy, 2001
37 Livingston M J, Carlson G A, Fackler P L. Managing resistance evolution in two pests to two toxins with refugia. American Journal of Agricultural Economics, 2004, 86: 1–13
38 Qiao F B. Refuge Policies to Manage the Resistance of Pest Population to Genetically Modified (GM) Crops. Dissertation. Davis (CA): University of California, 2006
39 Wu K. Monitoring and management strategy for *Helicoverpa armigera* resistance to Bt cotton in China. Journal of Invertebrate Pathology, 2007, 95: 220–223
40 Hurley T M, Secchi S, Babcock B A, *et al.* Managing the risk of European corn borer resistance to Bt corn. Environmental and Resource Economics, 2002, 22: 537–558
41 Livingston M, Carlson G, Fackler P. Use of mathematical models to estimate characteristics of pkethroid resistance in tobacco budworm and bollworm (Lepidoptera: Noctuidae) field populations. J Econ Entomol, 2002, 95: 1008–17
42 Clark C W. Mathematical Bioeconomics: the Optimal Management of Renewable Resources. New York: John Wiley & Sons, 1976
43 Ru L, Zhao J, Rui C. A simulation model for adaptation of cotton bollworm to transgenic Bt cotton in Northern China. Acta Entomologica Sinica (in Chinese), 2002, 45: 153–159
44 Li G, Wu K, Gould F, *et al.* Frequency of Bt resistance genes in *Helicoverpa armigera* populations from the Yellow River cotton-farming region of China. Entomologia Experimentalis et Applicata, 2004, 112: 135–143
45 Caprio M. Evaluating resistance management strategies for multiple toxins in the presence of external refuge. J Econ Entomol,1998, 91: 1021–1031
46 Storer N, Peck S, Gould F, *et al.* Spatial processes in the evolution of resistance in *Helicoverpa zea* (Lepidoptera: Noctuidae) to Bt transgenic maize and cotton in a mixed agroecosystem: a biology-rich stochastic simulation model. J Econ Entomol, 2003, 96: 156–172

Appendix The bio-economical model

In the biological model, we used extended Hardy-Weinberg models to simulate the evolution of resistance to Bt crops with demonstrated empirical success [40,41]. We use a two-locus four-allele model to simulate evolution of resistance 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 of a gamete (sperm or egg) containing one allele is independent of it containing one of the other three (linkage equilibrium); (e) there are four non-overlapping generations per calendar year, and CBW have different host plants at each generation.

The diverse cropping pattern that exists in the Yellow River Valley is mimicked to estimate the impact of natural refuge crops on refuge policy. The setting is a large area in which cotton is planted alongside other host crops of CBW, such as corn, soybean, and peanuts. 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 fraction 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 fraction 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 (e.g., Clark [42]), we assume that the 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 newly hatched CBWs in every period is given by $g\times D\times(1-D)$. 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, respectively. 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 (denoted p^{geno}), their proportion of the total pest population (denoted f^{geno}), and their mortality rates (denoted 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 the regulatory model is to minimize the discounted sum of damage and treatment costs. Two types of costs are incurred during each calendar year. The first is the damage cost caused by the pest, which is assumed to have a linear relationship with the total pest population. The second is the treatment cost, or the cost associated with Bt cotton planting and/or spraying with conventional pesticides. 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 resistance that are simulated in the biological model.

Following Wilen and Msangi [34], we developed a discretized form of this problem that can be solved with empirical numerical optimization software. We can optimize this problem using the Bellman Equation, as follows:

$$\underset{0\leqslant q_t\leqslant 1}{Min_{t=1}^{t=T}}\, V(D_t) = D_t\times\alpha + c\times q_t + cc\times[q_t\times dbt_t + (1-q_t)\times dnbt_t] + \delta V(D_{t+1})$$

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

$$\begin{aligned} w_{t+1}-w_t = {} & (1-w_t)\times(w_t^2\times g\times D_t\times(1-D_t) - \sum_{geno=1}^{geno=3} MR_t^{geno}) \\ & + (0.5-w_t)\times(2\times w_t\times(1-w_t)\times g\times D_t\times(1-D_t) \\ & - \sum_{geno=4}^{geno=6} MR_t^{geno}) + (w_t)\times((1-w_t)^2\times g\times D_t\times(1-D_t) \\ & - \sum_{geno=7}^{geno=9} MR_t^{geno}), \end{aligned}$$

$$w_{t=0}=w_0$$

$$\begin{aligned} v_{t+1}-v_t = {} & (1-v_t)\times(v_t^2\times g\times D_t\times(1-D_t) - \sum^{geno=1,4,7} MR_t^{geno}) \\ & + (0.5-v_t)\times(2\times v_t\times(1-v_t)\times g\times D_t\times(1-D_t) \\ & - \sum^{geno=2,5,8} MR_t^{geno}) + (v_t)\times((1-v_t)^2\times g\times D_t\times(1-D_t) \\ & - \sum^{geno=3,6,9} MR_t^{geno}),\ v_{t=0}=v_0 \end{aligned}$$

$$MR_t^{geno} = f^{geno}\times \sum^{j=sbt,bt,snbt,nbt} (lf_j\times m_j^{geno})$$

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 $\delta=1/(1+\rho)$. D_t is the total pest population at time *t*; α is the average damage cost per unit of pest; *c* is the average cost associated with Bt cotton planting; *cc* is the unit price of spraying with conventional pesticides; dbt_t and $dnbt_t$ are the dummy variables for conventional pesticides spray in Bt and non-Bt fields, respectively; ρ 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 other un-defined denotations are shown in Appendix Table 3.

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

	Default value	Source
Economic parameters		
Unit damage cost caused by CBW	USD1030/hm^2	Calculated from data collected by IPP[a)]
Bt cotton planting cost	USD143/hm^2	Calculated from data collected by CCAP[b)]
Conventional pesticide spray cost	USD252/ hm^2	Calculated from data collected by CCAP[b)]
Discount rate	0.036	The People's Bank of China
Biological parameters		
Initial resistance (to Bt toxin) gene frequency	0.001	Gould [30]; Livingston *et al.* [41]
Initial resistance (to conventional pesticide) gene frequency	0.50	Ru *et al.* [43]; Li *et al.* [44]
Mortality rate of susceptible pest to Bt toxin in Bt field	0.90	Livingston *et al.* [41]; Wu *et al.* [33]; Caprio [45]; Storer *et al.* [46]
Mortality rate of susceptible pest to conventional pesticides if sprayed	0.90	No data
Fitness cost of resistant pests to Bt toxin	0.05	Livingston *et al.* [41]
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 Dr. Wu KongMing
Dominance of susceptible gene (to conventional pesticide) in heterozygote	0.75	No data
The threshold value for spray	0.28	Guo [17]
Natural growth rate	0.68	Calculated by the author using field date

a) IPP: Institute of Plant Protection of the Chinese Academy of Agricultural Science. b) CCAP: Center for Chinese Agricultural Policy of the Chinese Academy of Sciences.

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 (USD per hm^2 per year)	Average cost (USD per hm^2 per year)	Absolute value (USD per hm^2 per year)	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 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 rates in different fields[a)]

		Mortality rate in different fields (m^{geno})			
Genotype (p^{geno})	Fraction (f^{geno})	Sprayed Bt field $\left(lf_{sbt}=\frac{q\times dbt}{1+nrc_k}\right)$	Non-sprayed Bt field $\left(lf_{bt}=\frac{q\times(1-dbt)}{1+nrc_k}\right)$	Spread non-Bt field $\left(lf_{snbt}=\frac{(1-q)\times dnbt}{1+nrc_k}\right)$	Non-sprayed non-Bt field $\left(lf_{nbt}=\frac{(1-q)\times(1-dnbt)+nrc_k}{1+nrc_k}\right)$
xxyy	$w^2\times v^2$	*hbt*+*hcp*−*h*×*hcp*	*hbt*	*hcp*	0
xxyY	2$w^2\times v(1-v)$	*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	$w^2\times(1-v)^2$	*hbt*+*rcp*−*hbt*×*rcp*	*hbt*+*rcp*−*hbt*×*rcp*	*rcp*	*rcp*
xXyy	2$w(1-w)\times v^2$	*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	4$w(1-w)\times v(1-v)$	*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	2$w(1-w)\times(1-v)^2$	*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	$(1-w)^2\times v^2$	*rbt*+*hcp*−*rbt*×*hcp*	*rbt*	*rbt*	*rbt*+*hcp*−*rbt*×*hcp*
XXyY	2$(1-w)^2\times v(1-v)$	*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	$(1-w)^2\times(1-v)^2$	*rbt*+*rcp*−*rbt*×*rcp*	*rbt*+*rcp*−*rbt*×*rcp*	*rbt*+*rcp*−*rbt*×*rcp*	*rbt*+*rcp*−*rbt*×*rcp*

a) x and X are alleles that confer susceptibility and resistance, respectively, to Bt cotton at locus one; y and Y are alleles that confer susceptibility and resistance, respectively, 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 homozygote pests susceptible to Bt toxin in Bt cotton field; *rbt* is mortality rate of homozygote pests resistant to Bt toxin; *dbt* is dominance of x allele in heterozygous pests xX. *hcp* is mortality rate of homozygote pests susceptible to conventional pesticides if sprayed; *rcp* is mortality rate of homozygous resistant pests to conventional pesticides; *dcp* is dominance of y allele in heterozygous pests yY. *k* denotes the generation; subscripts sbt, bt, snbt, and 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, respectively.