REFUGE POLICIES TO MANGE THE RESISTANCE OF PEST POPULATION TO GENETICALLY MODIFIED (GM) CROPS

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EXECUTIVE SUMMARY

The development of Genetically Modified (GM) crop varieties has arguably been the most successful application of agricultural biotechnology research to date. However, the biotechnology is a two-edged sword. Behinds the great success, there are also a lot of concerns about the negative impact of the GM crops. One of the major concerns is the buildup of the resistance in the pest population. Even though refuge policies have been implemented in most of the countries to mange the development of the resistance, all the previous empirical analyses have only focused only on the United States. There is very little empirical work that has focused on other countries, especially developing countries. The overall goal of my study is to analyze, theoretical and empirically, the optimal refuge policy to mange the buildup of the resistance in a developing county. To narrow the scope of the research, I use Bacillus thuringiensis (Bt) cotton in China as a case study.

First, I create a framework for analyzing the optimal refuge policy to mange the buildup of the resistance in the pest population. Specifically, I developed and estimated a single resistance bio-economic model to analyze the optimal control path. The results show that planting non-Bt cotton as refuge is not economic in the short run. In addition, even if planting refuge might be economic in the long run, the refuge can be planted later when the buildup of the resistance becomes a real concern. Then I extend the single resistance bio-economic model developed in the first essay into a double resistance model and empirically analyze the optimal refuge policies in northern China. In this model, we assume that the pest population can develop resistances to both Bt cotton and conventional pesticide. To mimic the real cropping system in the cotton production region in northern China, impact of the natural refuge crops (other host crops of the pest than cotton that are planted adjacent to cotton) on the development of the resistance is considered in the model. The most important finding of my second essay is that I show there is no need for a policy-mandated refuge policy in China. Finally, I extend the static bio-economic model into a dynamic one. I show that even though a dynamic refuge model can provide a smaller production cost than that of the static one, the cost saving is not significant. In fact, compared to the zero refuge policy, the optimal dynamic refuge policy can provided a smaller but not significant production cost. In other words, after considering the transaction costs of the refuge policy, planting non-Bt cotton as refuge is not economic. Another interesting finding is the recover of the susceptibility to conventional pesticide. We find that if 100% Bt cotton is planted without conventional pesticide sprayed, efficiency of the conventional pesticide will recover. Consequently, farmers can use Bt cotton and conventional pesticide, alternatively, to control the pest problem, rather than planting non-Bt cotton annually.

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Chapter 1. Introduction

The development of Genetically Modified (GM) crop varieties has arguably been the most successful application of agricultural biotechnology research to date. Countries that have introduced GM 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 Bacillus thuringiensis (Bt) cotton and Bt maize, the main commercialized varieties of GM crops, were grown commercially for the first time in 1996, their combined sown area reached more than 10 million hectares in 2002. 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., 2002; Qaim and Zilberman, 2003; Pray, 2001; and Traxler et al., 2001).

However, the Bt technology is a two-edged sword. Behinds the great success, there are also a lot of concerns about the negative impact of the Bt crops. 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 and the benefits from Bt crops would fall.

In order to manage the buildup of the resistance in the pest population, following the policies adopted in the United States, many Bt countries (indeed all nations except China) have required farmers to set aside a part of their cotton sown area as a refuge. To implement refuges, farmers are expected to plant part of their crop acreage with non-Bt crop. Refuges allow susceptible pests to Bt toxin 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. In 1996 when Bt crops were first introduced, the United States Environmental Protection Agency (EPA) adopted a refuge strategy for managing the evolution of Bt resistance. According to the EPA, farmers are required to plant minimum percentages of their total cotton acreage with non-Bt varieties. For example, cotton farmers in the southern United States have to leave either a *pure* refuge that equals 5 percent of their land (that is a plot of cotton that is not treated with any conventional pesticide) or a *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, all the other Bt countries except for China have adopted similar types of refuge policies (Kelly, 2000; Turner, 2000).

Although all nations in the developing world require their farmers to have refuges (and, in fact, most of these Bt crop countries require refuges that are almost the same as in the United States), empirical research on these issues has only been conducted in the United States. 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 the developing countries, except China, agricultural officials require farmers to follow the EPA's rule of planting at least 20 percent of their cotton as a refuge (Pray, 2001; and Traxler et al., 2001). However, to the best of my 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 the United States, the production environment is dramatically different since farms are highly fragmented and grow a diverse set of crops. 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 case study 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 in China comprised more than 40 percent of the total Bt cotton in the world, which allows China to become the largest Bt cotton countries 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., 2002). Hence, the size and the concentration of Bt cotton cultivated in China make it an important place to study refuges. And more interestingly, as the only exception, China implicitly has a zero refuge strategy even though the debate of whether China should re-think its zero-refuge policy never stopped. Is the zero-refuge policy appropriate for Bt cotton in China? Or China should follow the United Sates-styled refuge policy?

The overall goal of my dissertation is to analyze, theoretically and empirically, the optimal refuge policy to mange the buildup of the resistance in the pest population in a developing county. Even though we use Bt cotton in China as a case study, similar method can be used in other developing Bt countries. Considering the facts of the rapid spread of Bt crops in the world, especially in the developing countries, and the absence of the empirical studies in these countries, this study is significant.

To achieve the overall goal, my dissertation consists of three essays. The first essay creates a framework for analyzing the optimal refuge policy to manage the buildup of the resistance in the pest population. In the second essay, we developed a dual-toxin model to estimate, empirically, the optimal static refuge policy for Bt cotton in China. In the final essay, I extend the static model to a dynamic model. Together the essays allow us to understand the rules of buildup of resistance in the pest population, to estimate the impact of different factors on the development of the resistance, and to identify the optimal refuge policy for a developing country.

The first essay is methodological in orientation. In this study, I develop a framework that helps the researchers and policy makers to understand the resistance issue and choose the optimal level of control to manage the buildup of resistance. I developed a simple single resistance bio-economic model of the evolution of pest populations and pest resistance to characterize the socially optimal refuge strategy for the management of pest resistance. In this study, I analyze both the circumstances under which a synthesized control strategy is optimal and the circumstances under which an ecological strategy is optimal. In addition, I numerically show for most cases that the optimal path begins with maximum controls, following by a vibrating control, and ending with a constant control which leads to an equilibrium. The policy implication from this study is that the refuge, in general, is not necessarily economic in the short run. I also show that it is possible under certain plausible circumstances that even if refuges are economic to manage resistance in the long run, the establishment of refuge areas might best be delayed until rising resistance becomes an important concern.

In the second essay, I applied the methodology developed in the first essay to analyze the optimal size of refuges in northern China. The debate on whether China needs to maintain or re-think its zero refuge policy focuses on whether the crops that are planted side by side with cotton can supply enough “natural refuge” for the cotton bollworm (CBW), the most important pest in the northern China. To empirically answer this question, I extend the single resistance model developed in the first essay into a “double resistance model”. In this model, we assume that the pest population not only develops resistance (susceptibility) to Bt cotton, it also develops resistance to conventional pesticides. To mimic the real cropping system in northern China, parameters from empirical studies and the impact of natural refuge crops are used to simulate the model. The most important finding of my second essay is that I show that planting policy-mandated refuge is not economic in China, if one takes account of the natural refuges that exist, and compares them with the transaction costs associated with a refuge policy involving millions of small farmers.

In the third essay of my dissertation, I extended the static model in the second essay to a dynamic one. In this essay, I show that even though a dynamic optimal refuge policy can provide a smaller production cost than that of the static one, the cost saving is not significant. In fact, the cost saving of the optimal dynamic refuge policy, from a zero refuge policy, can not even offset the transaction costs of refuge policy. In other words, zero refuge policy is still the best choice in practices. Another interesting finding is the recover of the susceptibility to conventional pesticide. We find that if 100% Bt cotton is planted without conventional pesticide sprayed, efficiency of the conventional pesticide will recover. Consequently, farmers can use Bt cotton and conventional pesticide, alternatively, to control the pest problem, rather than planting non-Bt cotton annually.

Consider the three main elements, separately and combined, this dissertation makes a number of contributions. First of all, the work is policy relevant. By estimating the optimal refuge policy, I provide strong evidence that supports the China's zero refuge policy. The diverse cropping pattern in the Yellow River Valley provides enough natural refuge crops for the cotton bollworm. Hence, a mandatory refuge policy, as those adopted in the United States, is not a appreciate choice for Bt cotton in China. The implication of this finding also includes the refuge policy in other Bt countries. Even though a United States-styled refuge policy is required in almost all the Bt countries, it might not be the appreciate choice for them.

The dissertation also makes a methodological contribution to the relevant literature. In the first essay, we analyzed the optimal path choice of the Bt crops. In contrast to the previous studies on the analysis of the steady states (hence is called "point" analysis), I analyzed the dynamic optimal fraction of the Bt cotton planting over years (hence is called "path" analysis). In addition, I also show, both analytically and numerically, the circumstances under which different optimal refuge policies are chosen. I create a programming framework for studying how to design the optimal refuge policies to mange the buildup of the resistance in the pest population.

In sum, the dissertation contains a balance of new methods and solid empirical work, each essay is policy relevant. The second and the third essays were written based on the empirical data that I collected. And each essay was motivated by and based on some of the many interviews and observations that I made during the time that I spent doing field work.

Chapter 2. Dynamic Optimal Strategy to Mange Resistance to Genetically Modified (GM) crops

2.1 Introduction

The development of genetically modified (GM) crops has been the most successful application of agricultural biotechnology research to date. The main commercialized varieties, *Bacillus thuringiensis* (Bt) transgenic crops, derive their resistance from the insecticide expressed by the gene of the bacterium Bt that is inserted into the DNA of the host crop. Even though cotton and maize engineered with such genes were grown commercially for the first time in 1996, their use has spread very quickly all over the world. The area of both Bt cotton and maize have undergone double-digit growth in every year (James, 2004). In 2004, Bt maize was grown on 11.20 million hectares while Bt cotton was grown on 4.5 million hectares in the world. In addition, James's report predicts that Bt crops as well as other GM crops will be planted on more arable land and in more countries in the future.

The development of biotechnology also has spurred interest in resistance management in recent years. The biotechnologies are also two-edged swords. Even though biotechnology represents the cutting edge of efforts to increase agricultural productivity as well as the improvement of environmental conditions, it also has given rise to a number of concerns. One of the major worries lurking behind this success is the potential vulnerability of GM crops to adaptation by pests. As resistance builds up, the GM crops will lose their efficiency in controlling the pests. In order to control the buildup of resistance in the pest population, an interest in searching for an optimal refuge strategy has arisen (Gould, 1998; Hurley et al., 2001; Livingston et al., 2002; Laxminarayan and Simpson, 2002).

The current literature on the design of a refuge strategy to mange the resistance of the pest population to GM crops roughly can be divided into two types. The main objective of the first type study seeks, above all, to develop an optimal refuge to preserve the pest's susceptibility (henceforth, called biological models). The most typical biological model can be seen in Gould (1998). The other type of study, while also concerned about the buildup of resistance, is more concerned about doing so in a way that maximizes the benefits provided by GM crops to producers (henceforth, called economic models). Among the most notable papers that have dealt with the economic considerations of an optimal refuge strategy to mange Bt crop resistance have been those of Hurley et al. (2001), Livingston et al., (2002), and Laxminarayan and Simpson (2002).

Gould (1998) was one of the first entomologists to examine optimal refuge size using a biological model. In order to preserve the insect population's susceptibility, entomologists try to determine ways to minimize the share of the population of pests that have the resistant genes. The research tried to set this level so that the part of the population that is resistant to a toxin is small enough that it does not become dominant in the population for some set length of time. The overall goal is to try to ensure that the population will not evolve into one that is uncontrollable by the GM toxin. By using a population genetic model, Gould (1998) shows that in order to keep the fraction of the resistant pests below 0.10 within 10 years, the effective non-spray refuge size needs to be larger than the current requirements of 4%.

Hurley and his colleagues (Hurley et al., 1997 and 2001; Secchi et al., 2001) were among the first research team to set up economic models that seeks to establish to estimate an optimal refuge strategy for the management of a pest population's resistance to GM crops. The shortcoming of biological models is that they ignore the economic tradeoffs between the pest control and population management benefits and costs of transgenic varieties. Economists have pointed out that even though the establishment of refuges for pests helps to preserve the pest's susceptibility to the toxins expressed by the GM crops, maintaining susceptibility can be costly. If the cost is too high, it may be that the benefits from the adopting refuge strategy are not substantial enough to offset the costs. Numerically, their studies show that the benefit of maize producer can be maximized with a 10.6% non-Bt maize refuge size which is smaller than the required 20% by the United States Environmental Protection Agency (EPA). Empirical studies by Livingston et al. (2000 and 2002) found a similar set of results for the case of Bt cotton in the United States.

The work of Laxminarayan and Simpson (2000 and 2002) goes one step further than the previous studies that use economic models. Using the analytical model of the evolution of pest populations and pest resistance buildup, Laxminarayan and Simpson characterize the socially optimal refuge strategy for managing pest resistance to GM crops. This chapter in some sense is a response to Hurley et al (2001), who points out that, even with a rather parsimonious model, it is impossible to analytically characterize the optimal path of refuge size because increasing refuge sizes leaves more of the crop unprotected and increases future pest pressure, but it also slows resistance, improving future control on protected crops and decreasing future pest pressure. The second contribution of Laxminarayan and Simpson is that they have extended time limitation from a finite time period to an infinite time. They show both that the establishment of refuge areas might best be delayed until resistance becomes an important concern, and that the use of refuge areas in the long run will not be optimal under some circumstances (i.e. the fitness cost of resistance does not exceed the discount rate). While great interest of the literature, the shortage of

Laxminarayan and Simpson's paper is that it lacks an analysis of the optimal *path* of refuge, which is an important feature of an optimal refuge strategy.

The bio-economic model we use as a foundation for our analysis follows from the epidemiological model in Wilen and Msangi (2002). However, the model we present is not only an application of Wilen and Msangi's model in the case of GM crops, but also a generalization in several directions. The first important generalization is the detailed analysis of the characteristics of the steady states. Wilen and Msangi did solve for the steady states; however, they did not focus on the analytical discussion of the characteristics of the steady states. In this study, we discussed in detail the nature of all the steady states and circumstances under which these steady states will be arrived.

Our second contribution is to generalize the impact of the fitness cost on an optimal refuge strategy. Wilen and Msangi have overcome the shortcoming of the zero fitness cost assumption in Laxminarayan and Brown's model. However, they focus on the differences between zero fitness cost and non-zero fitness cost. We generalized the impact of fitness cost on optimal treatment strategy and numerically showed that a problem with a relatively low fitness cost is more like a non-renewable resource problem, while a problem with a relatively high fitness cost is more like a renewable resource problem. In other words, only when nature is efficient in controlling the pests, is a planting refuge optimal, and vice versa.

The remainder of this chapter is organized as follows. We introduce our model in Section 2. Analysis of our bio-economic model shows that the under different circumstances, the dynamic optimal refuge strategy is also different. For some initial points where pest population and/or the fraction of susceptible pests are high, the dynamic optimal refuge strategy is a combination of the extreme control and a singular control that will drive the whole system into a final equilibrium. For the rest of other initial points, no control is optimal. In Section 3, we developed a discretized form of our bio-economic model to check these theoretical analyses. Results of the numerical simulation of our model are consistent with our theoretical analysis. Section 4 concludes the chapter.

2.2 The Bio-economic Model

The integrated bio-economic model that we use follows the epidemiological model presented by Wilen and Msangi (2002). A similar approach is used in the models presented by Laxminarayan and Simpson (2002), Hurley et al. (2001) and Livingston et al. (2002) in their studies on refuge strategies. The pest population is assumed to be local (that is, both in- and out-migration is ruled out). We also use other standard assumptions implicit in deriving the Hardy-Weinberg principle, such as random mating between resistant and susceptible pests, negligible mutation, non-overlapping pest generations and the sexual reproduction of pests. The model consists of two parts: a biological model which is used to simulate the evolution of pest resistance; and a dynamic regulatory model which is used to examine the impact of refuge policies. Because the regulatory model is easier to describe once the biological model is understood, we begin with the biological model.

2.2.1 Biological Model

The pest population is denoted by D. A number of biological models assume that the pest population grows logistically (see, e.g. Clark 1976). Following the assumption of these studies, we shall assume that the pest population grows logistically with an intrinsic growth rate of g, and a carrying capacity per unit of land normalized to 1. Total land is assumed to be fixed, and is normalized to 1. The total number of new pest organisms hatched (presuming them to be the offspring of egg-bearing insects) in every period is given by gD(1 D). From this gross addition we must subtract to account for mortality among pests.

The pest population is divided among “susceptible” and “resistant” organisms. The former will be assumed to die with a high mortality rate, h, if treated and a zero mortality rate if not. The mortality rate of the resistant organisms is assumed to be r, which is also known as the fitness cost, regardless of whether the pest is treated or not. We assume that a fraction, w, of all pests is susceptible to the toxin, and the remaining fraction 1 w is immune. A refuge strategy calls for planting a fraction, q, of the total land devoted to agriculture in the GM crop. Hence, the fraction 1 – q of agricultural land will be devoted to a non-GM variety. As shown in Appendix 2-1, the dynamic of the pest population and the fraction of the susceptible pests are given by:

$$\frac{dD}{dt} = gD(1-D) - qwhD - (1-w)rD$$

$$\frac{dw}{dt} = (qh - r)w(w-1) \qquad (2\text{-}1)$$

2.2.2 Regulatory Model

The objective economic function is to minimize the discounted sum of treatment costs (cost of planting GM crops) and damage costs as a result of pests. The dynamic model system can be stated as follows:

$$\min_{0 \le q \le 1} \int_0^\infty [\alpha^* D + c^* q]^* e^{-\rho t}\, dt$$

$$\text{s.t.} \quad \frac{dD}{dt} = gD(1 - D) - qwhD - (1-w)rD$$

$$\frac{dw}{dt} = (qh - r)w(w-1) \qquad (2\text{-}2)$$

where α is the average damage cost per unit of pest; c is the average cost associated with GM crop planting; and ρ is the discount rate. The control variable in Equation (2-2) is the fraction of GM crop, q. And the two state variables are the total pest population (D) and the fraction of the susceptible pests (w). The fraction of agricultural land set aside as refuge area in each period (1-q) determines the cost in each period, as well as the effectiveness of the GM crop against pests in the subsequent periods. There is, then an inter-temporal tradeoff between crop losses today and more rapidly eroding toxic effectiveness in the future.

Unfortunately, we find that second-order necessary conditions of a minimum of the Hamiltonian do not hold. The corresponding current value Hamiltonian is:

$$H(.) = \alpha * D + c * q + \lambda[gD(1- D) - wqhD - (1-w)rD] + \mu(qh - r)w(w-1) \qquad (2\text{-}3)$$

As shown in Appendix 2-2, the second order necessary conditions of a minimum do not hold. Correspondingly, we can not analytically solve this system of equations. As a consequence in the following section, we have no choice but to try to solve the system for some equilibria from which the system will not move away as long as it gets there. These fixed points, however, are only local minimums. In this sense, these equilibria are called “potential steady states” (See Appendix 2-3).

2.2.3 Optimal Control Strategies

The Hamiltonian is minimized in each period with an appropriate choice of the optimal fraction of GM crop, q. Since this problem is linear in the control variable, we need to isolate the switching function, which is $\sigma(t) = c - \lambda whD + \mu wh(w-1)$. Here λ and μ are the shadow values of the size of the total pest population and the population that is made up of susceptible pests. In a traditional resource problem (which typically is seeking to maximizing the value of return-based activities), the shadow price of the pest population is negative since the pest population is a “bad” resource. In our study, however, since the objective is to minimize the cost function, and clearly a large pest population will contribute to higher costs, so λ is positive. For a similar reason, μ is negative instead of positive as in a traditional resource problem.

The sign of the switching function determines the choice of the treatment. The switching function is the coefficient of the control, and the Pontryagin optimality conditions state that:

$$\begin{aligned} q &= 0 && \text{if } \sigma(t) > 0 \\ q &= q^* && \text{if } \sigma(t) = 0 \\ q &= 1 && \text{if } \sigma(t) < 0 \end{aligned} \qquad (2\text{-}4)$$

When the switching function is negative, all of the land should be planted with GM crop (or q=1) to minimize the Hamiltonian. And when the switching function is positive, all of the land should be planted to the non-GM crop. When the switching function is zero, however, a so-called singular path is followed. As in Wilen and Msangi (2002), the complete solution to a linear control problem generally involves a "synthesized" control that consists of segments of extreme controls, followed by segments of singular controls.

On the other hand, the choice of treatment also affects the value of the switching function from the setup. For example, if the switching function is negative initially, then a maximum control is used to minimize the Hamiltonian. With the use of the maximum treatment, the total pest population and the fraction of the susceptible pests will decrease. Consequently, both the shadow prices of the total pest population and the susceptible pests will also change. These factors, working together, will change the value of the switching function. And if the sign of the switching function change from negative to positive, then the optimal treatment will change from maximum control (q=1) into minimum control (q=0). In other words, choice of treatment will also change the value of the switching function.

There are three possibilities for the sign of the switching function along the optimal path. First, the sign of the switching function does not change and is always negative before the final equilibrium is arrived at. The second possibility is that the sign of the switching function does not change and is always positive. The third possibility is that the sign of the switching function changes along the optimal path, either from positive to negative or vice versa. Each of these possibilities will be associated with a different optimal control path and a different final equilibrium.

Extreme maximum control will be optimal if the switching function is always negative along the control path. As discussed above, treatment will cause the magnitude of the switching function to change. However, these changes may not lead to a change in the sign of the switching function. If the switching function is always negative, even though it is becoming larger and larger, the optimal choice is always maximum treatment to minimize the Hamiltonian. Consequently, the fraction of the pest population will be driven to zero and the total pest population will return to a high level even though it can not be 1.

Similarly, no control will be optimal if the switching function is always positive along the control path. If the switching function does not change sign before the equilibrium arrives, the second possibility is that the switching function is always positive. According to the optimal decision rule, in order to minimize the Hamiltonian, no control is always optimal. Finally, no control will lead the system back to equilibrium in which both the fraction of the susceptible pests and the total pest population level are at their maximum level.

A synthesized control that consists of segments of extreme control and singular control is optimal if the switching function changes sign along the control path. As discussed above, the sign of the switching function determines the treatment, and the treatment also impacts the magnitude of the switching function. Consequently, along the control path, the switching function may change signs, either from negative to positive or vice versa. Under this situation, the optimal treatment strategy is a combination of extreme control (maximum if the sign of the switching function is negative or/and minimum if the sign of the switching function is positive) and a singular path that will drive the whole system into equilibrium. In Appendix 2-3, we solved for the singular control and proved that the equilibrium led by the singular path is a saddle point.

2.3 Numerical Simulations of the Model

To check these results and perform comparative dynamics experiments, we developed a discretized form of this problem that can be solved with Dynamic Programming methods. We can optimize this problem by using the Bellman Equation, which can be written as:

$$\underset{0 \le q \le 1}{Min} V(D_t) = D_t \alpha + cq + \delta V(D_{t+1})$$

s.t. $$D_{t+1} - D_t = gD_t(1 - D_t) - w_t q_t h D_t - (1 - w_t) r D_t, D_{t=0} = D_0$$

$$w_{t+1} - w_t = (q_t h - r) w_t (w_t - 1), w_{t=0} = w_0 \qquad (2\text{-}5)$$

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 $\delta = 1/(1+\rho)$. The optimal solution of the Bellman equation in each period is equivalent to the optimal solution of the continuous time control problem for the corresponding periods, by Bellman's principle of optimality. We iterate to find a polynomial approximation to the value function $V(D_{t+1})$ and then use it to solve the Bellman equation forward for each period. We employed a Chebychev polynomial approximation algorithm to solve for the value function, which was easily implemented in GAMS. A good discussion of approximation methods is given by Kenneth Judd (Judd, 1998).

Table 2-1 reports the defaults values and resources of the economic and biological parameters that used in the simulation model. The data that form the base for this study are from a dataset collected by the Center for Chinese Agricultural Policy of the Chinese Academy of Sciences in the Yellow River cotton production region. The Yellow River Valley is the largest cotton production region in China and it is also the region where cotton bollworm is most serious. The economic parameters used in this study are based on these empirical data. The biological parameters (i.e. the mortality rates of the pests) come from previous studies and data that were collected by scientists from the Institute of Plant Protection of the Chinese Academy of Agricultural Sciences in their laboratories and during their fieldwork. A detailed discussion about the economic parameters and biological parameters are shown in Chapter 3.

The simulation results demonstrate that the optimal refuge strategy to manage the pest's resistance is made up four distinct phases (Figure 2-1). The solution begins with a phase in which it is optimal to plant the Bt crop on all arable land. Because both the fraction of susceptibility pests and the pest population level are high in the initial period, the marginal cost of control (planting GM crop) is higher than the marginal cost of planting non-GM refuge. Consequently, the optimal refuge size is set to zero at the initial period. In other words, the simulation results demonstrate that planting refuge is not economic until the buildup of resistance in the pest population becomes an important concern. This finding is consistent with previous studies (i.e. Laxminarayan and Simpson, 2002).

The second phase is either full control (100% GM crops) or no control. As discussed in the above, the 100% full control in the first phase will continuously increase the value of the switching function. Consequently, the value of the switching function might become position. In order to minimize the objective function, a no control, or 100% non-GM crops, is optimal. Similarly, no control decreases the value of the switching function, and might allow full control become optimal if the value switching function change signs. In other words, full control and no control will be used according to the value of the switching function in the second phase.

During the third phase, a vibration control is followed when the switching function is zero. After several times of sign switching, either from positive to negative or from negative to positive, the switching function will be zero. Under this situation, the control will follow a singular path. Detailed discussion of single path and the equilibrium driven by the single path is shown in Appendix 2-3. Along the singular path, the switching function stays zero and a non-zero refuge is planted. The vibrating control will lead the whole system into the final equilibrium.

Eventually, the singular path causes the stock of the pest population and the fraction of the susceptible pests to track a moving target optimal stock of effectiveness. In the long run, a balance is achieved in which the pest population of both resistant and susceptible pests is held in a delicate equilibrium by cautious partial treatment of the combined pests. Since the fitness cost is low in this case, the problem is more like a non-renewable resource problem. At the equilibrium, the resource will be almost exhausted, and the pest population finally will return a high level.

In contract, a non-zero refuge is optimal if the fitness cost is high. If the fitness cost is low, the resource (the fraction of susceptible pests in the pest population) is more like a non-renewable resource, and if the fitness cost is high, then the resource is a “real” renewable resource. By changing only the parameter of the fitness cost, we re-simulated the model. The simulation results are shown in Panel B of Figure 2-1. A high fitness cost means that the resistant pest has a high mortality rate, so does the total pest population if non-GM is planted. In other words nature (without GM crops) is more efficient in controlling the pest if the fitness cost is higher. Consequently, the best choice is to use both nature and the GM crop work together to fight against pests at equilibrium. In other words, planting non-zero refuge is economic. As shown in Panel B of Figure 2-1, with a relatively low fraction of the GM crop planting, the system arrived a final equilibrium with a relatively small total pest population and high fraction of the susceptible pests in the total pest population.

The value of the switching function at the initial point determines which treatment strategy is optimal. As discussed above, if the switching function does not change sign along the control path, then extreme control (either full control or no control) will be optimal. To check whether there are indeed initial circumstances under which the extreme control is optimal, we re-simulated the model, changing only the initial values of the state variables, the results are shown in Figure 2-2. Panel A of Figure 2-2 shows the circumstances under which a synthesized control is optimal, while Panel B shows the circumstances under which extreme control (no control in this case) is optimal. As shown in Panel B, for some initial values, it becomes optimal to abandon the interventionist strategy and instead to rely on nature to fight pests. Under this treatment regime, since no control is used, both the pest population and the fraction of the susceptible pests will finally return to their maximums. We also need to point out that, since the switching function does not increase or decrease monotonously, with either the change in the total pest population, or the change in the fraction of the susceptible pests, the initial situations under which an ecological strategy is optimal is more complicated than expected.

2.4 Conclusions

In this study, we theoretically analyze the optimal strategy to mange the buildup of resistance in the pest population. The technical part of this study extends previous theoretical economic analyses of treatment by addressing the optimal path to the equilibrium. In this study, we not only prove, using detailed theoretical analyses of the characteristics of the steady state, but also analytically and numerically show the optimal control path that lead to the final equilibrium. We also study the initial circumstances under which a synthesized interventionist control is optimal and the initial circumstances under which an ecological control is optimal.

We believe that this study has important qualitative implications for economically optimal GM crop planting strategies. Even though this study does not exactly mimic the real production environments of GM crops, results from this study at least provide some useful hint of optimal GM crop planting strategy. As shown in the study, when GM crop is first introduced, both the pest population and the fraction of the susceptible pests are high, the best choice is to plant 100% GM crop. If we believe a new GM variety or conventional pesticide will be developed in a short run, then planting non-GM crop as a refuge might not be needed. In addition, even if a refuge is needed in the long-term, establishment of the refuges can be delayed until the resistance becomes a real concern.

Qualitative implications of the study are not limited in the management of the GM crops. Even though this study deal directly with the management problem of pest’s resistance to GM crops, the analysis method can be used in other similar questions in biological and medicinal fields, such as the antibiotic use in human kind, control the spread of epidemic, etc. In other words, this study contributes to the general resistance management problem.

Appendix 2-1. Solve for Equations of Motion

The essentials of the bio-economic model are captured in the schematic in Figure 2-A1. The pest population is divided among “susceptible” pests (denoted by Ds) and “resistant” pests (denoted by Dr). Since we assume the fraction of the susceptible pests in the total pest population is w, so we have Ds=w*D and Dr=(1-w)*D. Similarly, among the total number of the new pests, there are w*g*D*(1-D) susceptible pests and (1-w)*g*D*(1-D) resistant pests separately. From this gross addition, we must subtract mortality among pests. We continue to assume that the total pest population are distributed evenly in the GM and non-GM crop field, so there are q*D pests in the GM crop field and (1-q)*D pests in the refuge. Since the mortality rate of susceptible and resistance pests are h and r separately, so there are q*w*h*D susceptible and q*(1-w)*r*D resistant pests dieing in the Bt field. Similarly, in the non-GM crop refuge, there are 0 susceptible pests and (1-q)*(1-w)*r*D resistant pests dieing.

We must subtract mortality pests from the intrinsic growth rate for both susceptible pest and resistant pests. Then we have an expression for the evolution of the susceptible pests and resistant pests.

$$\frac{dDs}{dt} = \mathrm{wgD(1 - D) – wqhD} \qquad \text{(2-A1-1)}$$

$$\frac{dDr}{dt} = \mathrm{(1\text{-}w)gD(1\text{-}D) – q(1\text{-}w)rD - (1\text{-}q)(1\text{-}w)rD}$$

$$=\mathrm{(1\text{-}w)gD(1\text{-}D) – (1\text{-}w)rD} \qquad \text{(2-A1-2)}$$

Consequently, the evolution of the total pests is:

$$\frac{dD}{dt} = \frac{dDs}{dt} + \frac{dDr}{dt} = \mathrm{gD(1\text{-}D) – qwhD - (1\text{-}w)rD} \qquad \text{(2-A1-3)}$$

And the evolution of the fraction of the susceptible pests in the total pest population is:

$$\frac{dw}{dt} = \frac{d(\frac{Ds}{D})}{dt} = [(\frac{dDs}{dt}) * \mathrm{D} - \mathrm{Ds}*(\frac{dDr}{dt})] / \mathrm{D}^2$$

$$=\{[\mathrm{wgD(1\text{-}D)} - \mathrm{wqhD}]*\mathrm{D} - \mathrm{wD}*[\mathrm{gD(1\text{-}D)} - \mathrm{wqhD} - \mathrm{(1\text{-}w)rD}]\}/\mathrm{D}^2$$

$$= (- \mathrm{wqh}) - \mathrm{w}[- \mathrm{wqh} - (1\text{-}\mathrm{w})\mathrm{r}]$$

$$= (\mathrm{qh} - \mathrm{r})\mathrm{w}(\mathrm{w}\text{-}1) \qquad \text{(2-A1-4)}$$

Appendix 2-2. Check the Concavity of the Hessian Matrix of Hamiltonian

The sufficient conditions of a minimize Hamiltonian is the Hessian matrix of the Hamiltonian with respect to (q, D, w) must be positive semi-definite. In other words, three types of conditions must be satisfied. First, all the determinants of the three first-order principle minors must be non-negative, or $H_{qq} \geq 0$, $H_{DD} \geq 0$, and $H_{ww} \geq 0$. Secondly, all the determinants of the three second-order principle minors must be non-positive, or

$$\begin{vmatrix} H_{DD} & H_{Dw} \\ H_{Dw} & H_{ww} \end{vmatrix} \leq 0 \qquad \begin{vmatrix} H_{DD} & H_{Dq} \\ H_{Dq} & H_{qq} \end{vmatrix} \leq 0 \qquad \begin{vmatrix} H_{ww} & H_{wq} \\ H_{wq} & H_{qq} \end{vmatrix} \leq 0$$

Finally, the determinant of the third-order principle minors must be non-negative.

$$\begin{vmatrix} H_{DD} & H_{Dw} & H_{Dq} \\ H_{Dw} & H_{ww} & H_{wq} \\ H_{Dq} & H_{wq} & H_{qq} \end{vmatrix} \geq 0$$

In the following, we will check these conditions one by one.

From the Hamiltonian, $H = D*\alpha + c*q + \lambda*dD/dt + u*dw/dt = D\alpha + cq + \lambda[gD(1-D) - wqhD - (1-w)rD] + \mu(qh - r)w(w-1)$, we get:

$H_{DD} = 2g\lambda$

$H_{Dw} = \lambda*[- q*h + r]$

$H_{Dq} = \lambda*[- w*h]$

$H_{ww} = 2\mu*(q*h - r)$

$H_{qw} = -\lambda*h*D + \mu*h*(2w-1)$

$H_{qq} = 0$

As discussed above, the shadow price, λ, is positive in this study. So we have:

$H_{DD} = 2g\lambda \geq 0$, $H_{ww} = 0 \geq 0$, $H_{qq} = 0 \geq 0$.

Secondly, these three second-order principle minors are:

$$\begin{vmatrix} H_{DD} & H_{Dw} \\ H_{Dw} & H_{ww} \end{vmatrix} = \begin{vmatrix} 2g\lambda & 0 \\ 0 & 0 \end{vmatrix} = 0 \le 0$$

$$\begin{vmatrix} H_{DD} & H_{Dq} \\ H_{Dq} & H_{qq} \end{vmatrix} = \begin{vmatrix} 2g\lambda & -\lambda wh \\ -\lambda wh & 0 \end{vmatrix} = -(-\lambda wh)^2 \le 0$$

$$\begin{vmatrix} H_{ww} & H_{wq} \\ H_{wq} & H_{qq} \end{vmatrix} = \begin{vmatrix} 0 & -\lambda hD \\ -\lambda hD & 0 \end{vmatrix} = -(-\lambda hD)^2 \le 0$$

Final, the determinants of the third-order principle minors must be negative, or

$$\begin{vmatrix} H_{DD} & H_{Dw} & H_{Dq} \\ H_{Dw} & H_{ww} & H_{wq} \\ H_{Dq} & H_{wq} & H_{qq} \end{vmatrix} = \begin{vmatrix} 2g\lambda & 0 & -\lambda wh \\ 0 & 0 & -\lambda hD \\ -\lambda wh & -\lambda hD & 0 \end{vmatrix} = -(2g\lambda) * (\lambda hD)^2 \le 0$$

Even though the necessary conditions for the first-order and second-order principle minors are satisfied, the necessary condition for the third-order principle minor does not. Consequently, the second order necessary conditions of the minimum do not hold.

Appendix 2.3 The Optimal Control Path

As discussed in section 2.2 of this chapter, there are three possibilities for the sign of the switching function along the optimal path: always negative, always positive, or sometime positive and sometimes negative. In this appendix, we will discuss these three possibilities, characteristics of the fixed points and the optimal control path for each possibility.

A2.3.1 Case I – Optimal Full Control

If the switching function is always negative, full control, or q=1, will be used to minimize the Hamiltonian. And at the equilibrium, we should have:

$$\frac{dD}{dt} = gD(1 - D) - qwhD - (1-w)rD = gD(1 - D) - whD - (1-w)rD = 0$$

$$\frac{dw}{dt} = (qh - r)w(w-1) = (h - r)w(w-1) = 0$$

$$\sigma(t) = c - \lambda whD + uhw(w-1) < 0 \qquad \text{(2-A3-1)}$$

From $\frac{dw}{dt}$=0, we either have w_1=0 or w_2=1. Plug w=0 into the switching function to get $\sigma(t) = c - \lambda whD + uhw(w-1) = c > 0$, which is contradicted with the negative switching function assumption. Similarly, if we plug w=1 into $\frac{dD}{dt}$=0 to get D_1=0 or $D_2 = \frac{g-h}{g}$. Using the default value of Appendix Table 2-1, we have $D = \frac{g-h}{g} < 0$, which is not a true solution in practice. Plug w=1 and D=0 to the switching function to get $\sigma(t) = c - \lambda whD + uhw(w-1) = c > 0$, which is contradicted with the negative switching function assumption. In other words, the negative switching function and full control can not be an optimal solution.

A2.3.2 Case II – Optimal No Control

If the switching function is always positive, in order to minimize the Hamiltonian, no control is used, or q=0. And at the equilibrium, we should have:

$$\frac{dD}{dt} = gD(1 - D) - qwhD - (1-w)rD = gD(1 - D) - (1-w)rD = 0$$

$$\frac{dw}{dt} = (qh - r)w(w-1) \qquad =(- r)w(w-1) = 0$$

$$\sigma (t) = c - \lambda whD + uhw(w-1) > 0 \qquad (2\text{-A3-2})$$

Solve for the equation system (2-A3-2), we get four steady points. They are:

(D=0, w=0)

(D=0, w=1)

(D=$\frac{g-r}{g}$, w=0) and

(D=1, w=1)

In order to analyze the characteristics of these possible steady points, in the following, I will first discuss the characteristics of these four possible stead states by drawing a phase diagram in a (D, w) plane. Then I will check the analytical results using numerical simulations

$$\frac{dD}{dt} = gD(1 - D) - qwhD - (1-w)rD = gD(1 - D) - (1-w)rD$$

$$\frac{dw}{dt} = (qh - r)w(w-1) \qquad =(- r)w(w-1) \qquad (2\text{-A3-3})$$

First, to solve for the w and D nullclines, we set $\frac{dw}{dt}$=0 and $\frac{dD}{dt}$=0. Solving these two equations yields w=0, w=1, D=0, and D=$\frac{g-r}{g}+\frac{r}{g}w$. These nullclines are plotted in Figure 2-A2, which presents the phase portrait of the dynamic system.

Note that the nullclines divide the phase space into different isosectors. In the following, we will turn to the derivation of the vector field. In other words, we need to figure out the directions of motion for points not on the nullclines. First of all, we take the first derivative of $\frac{dD}{dt}$ with respect to w, and evaluate it at $\frac{dD}{dt}$=0, we get

$$\left.\frac{dD/dt}{dw}\right|_{\frac{dD}{dt}=0} = rD \tag{2-A3-4}$$

So we have $\left.\frac{dD/dt}{dw}\right|_{\frac{dD}{dt}=0}$ >0 when D >0 and $\left.\frac{dD/dt}{dw}\right|_{\frac{dD}{dt}=0}$ <0 when D <0. Sign of $\frac{dD/dt}{dD} = g(1-2D)-(1-w)r$ is positive near (D=0, w=0) and (D=0, w=1). Similarly, $\frac{dw/dt}{dw} = -r(2w-1)$ is positive near (D=0, w=0) and (D=$\frac{g-r}{g}$, w=0), and it is negative near (D=0, w=1) and (D=1,w=1). From these signs, we can determine the direction of motions for points that are not on the nullclines (see Figure 2-A2). In addition, numerical simulation of function 2-A3-3 is consistent with the theoretical analysis above (see Figure 2-A3). In other words, both numerical simulation and analytical discussion show that (D=0, w=0) and (D=0, w=1) are two saddle points, (D=1, w=1) is an asymptotically stable node while (D=$\frac{g-r}{g}$, w=0) is an unstable star node.

A2.3.3 Case III – Synthesized Optimal Control

As discussed above, when a synthesized optimal control is optimal, a singular control will also lead the whole system into an equilibrium. We will derive the singular path and analyze the characteristics of the equilibria driven by the singular path in this case. In our model, the singular path results in two equilibria. Both theoretical analysis and numerical simulation show that one of the potential steady states is an unstable star node, while the other is a saddle point. Detailed discussion is shown in the following. In the following, I will first solve for the single path. Then I will turn to analyzing the characteristics of the equilibria driven by the singular path, numerically and analytically.

Solving for the singular path involves investigating conditions that must hold when the switching function is identically zero for some finite interval. If the switching function, σ (t), is zero, then its derivative must also be zero. Differentiating the switching function gives us:

$$\frac{d\sigma}{dt} = -\lambda whD\left[\frac{d\lambda/dt}{\lambda} + \frac{dw/dt}{w} + \frac{dD/dt}{D}\right] +$$

$$\mu hw(w-1)\left[\frac{d\mu/dt}{\mu} + \frac{dw/dt}{w}\right] + \mu hw^2\frac{dw/dt}{w} \qquad \text{(2-A3-5)}$$

We also know from the Pontryagin conditions that the adjoint variables must satisfy:

$$\rho\lambda - \frac{d\lambda}{dt} = \frac{dH}{dD} = \alpha + \lambda[g(1 - 2*D) - wqh - (1-w)r] \qquad \text{(2-A3-6)}$$

and $$\rho\mu - \frac{d\mu}{dt} = \frac{dH}{dw} = -\lambda[qhD - rD] + \mu(qh - r)(2w-1) \qquad \text{(2-A3-7)}$$

From (2-A3-6) and (2-A3-7), it can be shown that:

$$\frac{d\lambda/dt}{\lambda} + \frac{dD/dt}{D} = \rho - \frac{\alpha}{\lambda} + gD \qquad \text{(2-A3-8)}$$

$$\frac{d\mu/dt}{\mu} + \frac{dw/dt}{w} = \rho - \left(w - \frac{\lambda D}{\mu}\right)*(qh - r) \qquad \text{(2-A3-9)}$$

Substituting (2-A3-8), (2-A3-9), $\frac{dw}{dt}$, and $\frac{dD}{dt}$ into the expression for the rate of change of the switching function (2-A3-5), we have:

$$\frac{d\sigma}{dt} = -\lambda whD*\left[\frac{d\lambda/dt}{\lambda} + \frac{dD/dt}{D}\right] + \left[\frac{dw/dt}{w}\right]*(\mu hw^2 - \lambda whD)$$

$$+ \mu hw(w-1)[\frac{d\mu/dt}{\mu} + \frac{dw/dt}{w}]$$

$$= - \lambda whD * [\rho - \frac{\alpha}{\lambda} + \frac{gD}{K}] + [\frac{dw/dt}{w}]*(\mu hw^2 - \lambda whD) +$$

$$+ \mu hw(w-1)[\rho - (\frac{\lambda D}{\mu} + w)*(qh-r)] \qquad (2\text{-A3-10})$$

Expanding this gives us:

$$\frac{d\sigma}{dt} = - \rho[\lambda whD - \mu hw(w-1)] + whD\alpha - \lambda whD*gD \qquad (2\text{-A3-11})$$

With the switching function, it can be shown that the terms inside the first bracket in (2-A3-11) equals to c. So, the equation (2-A3-5) becomes

$$\frac{d\sigma}{dt} = - \rho c + whD\alpha - \lambda whD*\frac{gD}{K} = 0 \qquad (2\text{-A3-12})$$

Since the switching function is zero along the singular interval, its first derivative also must be zero and hence the above equation (2-A3-12) must hold. For the same reason, it second derivative of the switching function also must be zero, or

$$\frac{d(d\sigma/dt)}{dt} = whD\alpha [\frac{dw/dt}{w} + \frac{dD/dt}{D}]$$

$$- \lambda whD*\frac{gD}{K} [\frac{d\lambda/dt}{\lambda} + \frac{dw/dt}{w} + 2*\frac{dD/dt}{D}] \qquad (2\text{-A3-13})$$

Substituting $\frac{d\lambda/dt}{\lambda} + \frac{dD/dt}{D} = \rho - \frac{\alpha}{\lambda} + gD$, and the two co-state equations into Equation (2-A3-13), and collecting terms, we get:

$$\frac{d(d\sigma/dt)}{dt} = whD(\alpha - \lambda gD)*(\frac{dw/dt}{w} + \frac{dD/dt}{D}) - \lambda whD*gD*(\rho - \frac{\alpha}{\lambda} + gD) \qquad (2\text{-A3-14})$$

Since Equation (2-A3-14) equals zero, dividing whD on both sides and inserting the state equation for $\frac{dw/dt}{w}$ and $\frac{dD/dt}{D}$ yields:

$$\frac{\rho c}{whD}*[(qh - r)(w-1) + g(1- D) – wqh – (1-w)r + \rho + gD] - \alpha\rho = 0 \qquad (2\text{-A3-15})$$

Or $$q^{\text{singular control}} = \frac{\rho + g}{h} - \frac{\alpha w D}{c} \qquad (2\text{-A3-16})$$

This equation must be satisfied along the singular path. In the following, I turn to analyzing the characteristics of the equilibria driven by the singular path. I will first solve for the possible steady states.

As discussed above, if the equilibrium is driven by a singular path, then, at the equilibrium, these following conditions must hold:

$$\frac{dD}{dt} = gD(1 - D) – qwhD - (1-w)rD = 0$$

$$\frac{dw}{dt} = (qh – r)w(w-1) = 0$$

$$\sigma(t) = c - \lambda whD + \mu hw(w-1) = 0 \qquad (2\text{-A3-17})$$

We also need to note that since the second order necessary conditions of a minimum do not hold (see Appendix 2-A2), solutions of function system (2-A3-17) are not “real” steady states. We call these solutions, in this sense, “potential steady states”.

From the Pontryagin conditions of the Hamiltonian, we know that the adjoint variables must satisfy: $\rho\lambda - \frac{d\lambda}{dt} = \frac{dH}{dD} = \alpha + \lambda[g(1\text{-}2D) – wqh – (1\text{-}w)r]$. At the steady state, $\frac{d\lambda}{dt} = 0$, and $\frac{dD}{dt} = 0$. Therefore, we have $\rho\lambda = \alpha + \lambda[g(1\text{-}2D) – wqh – (1\text{-}w)r] = \alpha + \lambda[\frac{dD}{dt} - gD] = \alpha - \lambda gD$. Solving this equation, we get $\lambda = \frac{\alpha}{\rho + gD}$.

Similarly, another Pontryagin condition that the adjoint variables must satisfy is that ρμ - $\frac{d\mu}{dt} = \frac{dH}{dw}$ = λ[– qhD + rD] + μ(qh -r) (2w-1)= (qh -r)*[μ(2w-1) - λD].

Solving this question, we get $u = \frac{(qh-r)\lambda D}{w(qh-r)-\rho} = \frac{(qh-r)D*\frac{\alpha}{\rho+gD}}{w(qh-r)-\rho}$.

Plugging λ and μ into the switching function, we have σ (t) = c-whD*$\frac{\alpha}{\rho+gD}$+ hw(w-1)* $\frac{(qh-r)D*\frac{\alpha}{\rho+gD}}{w(qh-r)-\rho}$ =0. Now, the origional function system (2-A3-17) becomes,

$$\frac{dD}{dt} = gD(1 - D) - qwhD - (1-w)rD \qquad =0$$

$$\frac{dw}{dt} = (qh - r)w(w-1) \qquad =0$$

$$\sigma(t) = c-whD*\frac{\alpha}{\rho+gD} + hw(w-1)*\frac{(qh-r)D*\frac{\alpha}{\rho+gD}}{w(qh-r)-\rho} = 0 \qquad (2\text{-A3-18})$$

From $\frac{dw}{dt}$ = (qh – r)w(w-1) =0, we can get three solution: w=0, w=1, and q=$\frac{r}{h}$.

First of all, if we plug q=$\frac{r}{h}$ into $\frac{dD}{dt}$=0, we get two solutions: D_1 =0 and $D_2 = \frac{g-r}{g}$. Next, plugging q = $\frac{r}{h}$ and D=0 into the switching function, we get σ (t) = c-whD*$\frac{\alpha}{\rho+gD}$+ hw(w-1)* $\frac{(qh-r)D*\frac{\alpha}{\rho+gD}}{w(qh-r)-\rho}$ =c $\neq 0$. In other words, (q = $\frac{r}{h}$, D=0) can not be a steady state. However, if we plug another solution q = $\frac{r}{h}$ and D=$\frac{g-r}{g}$ into the switching function, we get w = $\frac{cg(\rho+g-r)}{ha(g-r)}$, which is a possible solution. So the first potential steady state is (q= $\frac{r}{h}$, D=$\frac{g-r}{g}$, and w =$\frac{cg(\rho+g-r)}{ha(g-r)}$).

Secondly, if we plug w=0 into $\frac{dD}{dt}$=0, we get $D_1 =$ 0 and $D_2 = \frac{g-r}{g}$. However, if we plug in w=0 into the switching function, we get σ (t) = c - λwhD + uhw(w-1) = c $\neq 0$, no matter what D is. In other words, w=0 can not be a possible steady state.

Finally, if we plug w=1 into $\frac{dD}{dt}$=0, we get two solutions: $D_1 =$ 0 and $D_2 = \frac{g-qh}{g}$. Then, we plug w=1 and D=0 into the switching function to get σ (t) = c - whD*$\frac{\alpha}{\rho+gD}$+ hw(w-1)* $\frac{(qh-r)D*\frac{\alpha}{\rho+gD}}{w(qh-r)-\rho}$ =c $\neq 0$. So w=1 and D=0 can not be a possible steady state. However, if we plug w=1 and D=$\frac{g-qh}{g}$ into the switching function, we get σ (t) = c - whD*$\frac{\alpha}{\rho+gD}$+ hw(w-1)* $\frac{(qh-r)D*\frac{\alpha}{\rho+gD}}{w(qh-r)-\rho}$ = c – h*$\frac{g-qh}{g}$*$\frac{\alpha}{\rho+g-qh}$. Solving this equation by setting σ (t) =0 yields $q=\frac{h\alpha g-cg(\rho+g)}{h^2\alpha-cgh}$. Finally if we plug this solution back into D=$\frac{g-qh}{g}$, we get $D=\frac{c\rho}{h\alpha-cg}$. So the second possible steady state is ($q=\frac{h\alpha g-cg(\rho+g)}{h^2\alpha-cgh}$, $D=\frac{c\rho}{h\alpha-cg}$, and w=1). Let us call these two possible stead states as points PSS1 and PSS2 respectively (Figure 2-A4). In the following, I will first discuss the characteristics of these possible stead states both analytically. Then I will check the analytical results using numerical simulations.

In order to analytically discuss the characteristics of these two possible steady points, I will draw a phase diagram in a (D, w) plane. If we plug the singular path (2-

A3-16), or $q^{\text{singular control}} = \frac{\rho + g}{h}$ - $\frac{\alpha w D}{c}$, into the equation of motion $\frac{dD}{dt}$ = gD(1 - D) – qwhD - (1-w)rD , and $\frac{dw}{dt}$ = (qh – r)w(w-1), we get:

$$\frac{dD}{dt} = gD(1-D) - (\rho + g - \frac{\alpha h}{c} wD)wD - (1-w)rD$$

$$\frac{dw}{dt} = (\rho + g - r - \frac{\alpha h}{c} wD)w(w-1) \qquad \text{(2-A3-19)}$$

The phase diagram is determined by the equation system (2-A3-19).

First of all, to solve for the w and D nullclines, we set $\frac{dw}{dt} = (\rho + g - r - \frac{\alpha h}{c} wD)w(w-1) = 0$, and $\frac{dD}{dt} = gD(1-D) - (\rho + g - \frac{\alpha h}{c} wD)wD - (1-w)rD = 0$.

Solving these two equations yields w=0, w=1, and w=$\frac{c*(\rho + g - r)}{\alpha h D}$; D=0, and D=$\frac{g - (\rho + g)w - (1-w)r}{g - \frac{\alpha h w^2}{c}}$. These nullclines are plotted in Figure 2-A4, which presents the phase portrait of the dynamic system.

Note that the nullclines divide the phase space into different isosectors. In the following, we will turn to the derivation of the vector field. In other words, we need to figure out the directions of motion for points not on the nullclines. First of all, we take the first derivative of $\frac{dD}{dt}$ with respect to w, and evaluate it at $\frac{dD}{dt}$=0, we get

$$\left.\frac{dD/dt}{dw}\right|_{\frac{dD}{dt}=0} = -(\rho + g)D - \frac{\alpha h}{c} 2wD^2 + rD = D*[-(\rho + g)D - \frac{\alpha h}{c} 2wD + r] \qquad \text{(2-A3-20)}$$

The sign of $\left.\frac{dD/dt}{dw}\right|_{\frac{dD}{dt}=0}$ depends on the magnitude of w and D. Using the default value from Table 1, we can determine its sign numerically at the two steady states. If we plug the values of these two potential steady states (PSS1 and PSS2), the sign of

$\left.\frac{dD/dt}{dw}\right|_{\frac{dD}{dt}=0}$ is positive at the first potential steady state (PSS1), with a high pest population and a relatively low fraction of susceptible pests, and its sign is negative at the second potential steady state (PSS2), with a small pest population and a maximum fraction of susceptible pests.

Similarly, by taking the first derivative of $\frac{dw}{dt}$ with respect to D and estimating it at $\frac{dw}{dt}$=0, we have:

$$\left.\frac{dw/dt}{dD}\right|_{\frac{dw}{dt}=0} = -\frac{\alpha h}{c} w^* w^* (w-1) \qquad \text{(2-A3-21)}$$

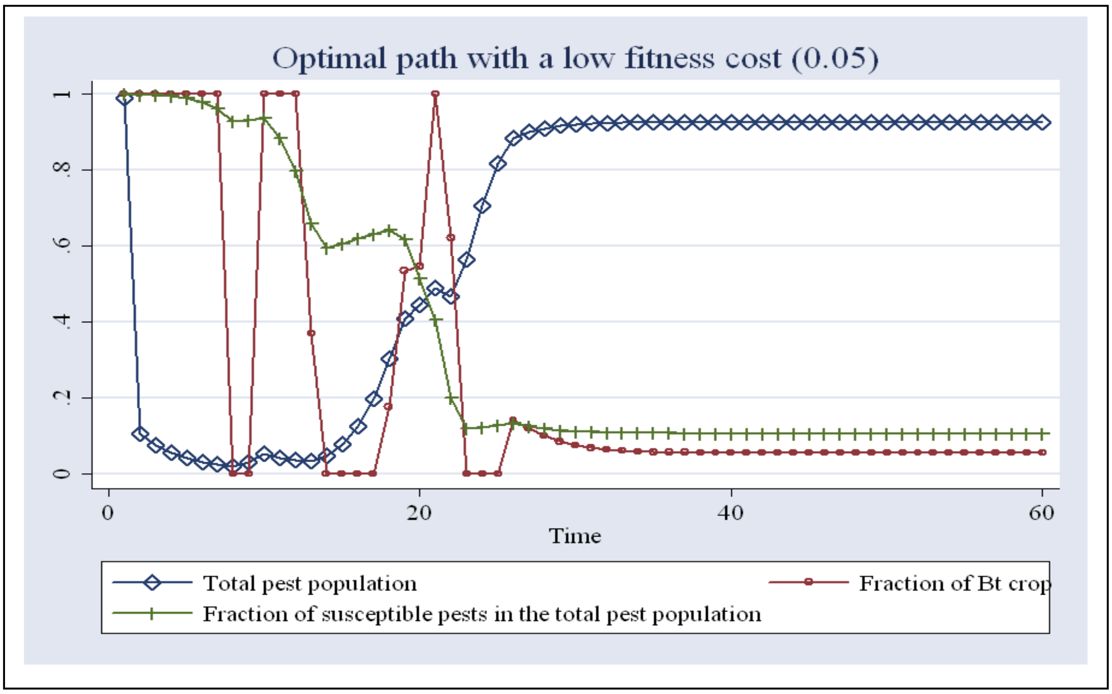
It is easy to see that $\left.\frac{dw/dt}{dD}\right|_{\frac{dw}{dt}=0}$ will be positive as long as w is less than 1, and it is negative when w is greater than 1. In other words, its sign will be positive near the first potential steady state, and it will be negative near the second potential steady state.

From the signs of $\left.\frac{dw/dt}{dD}\right|_{\frac{dw}{dt}=0}$ and $\left.\frac{dD/dt}{dw}\right|_{\frac{dD}{dt}=0}$, we can determine the direction of motions for points that are not on the nullclines (See Figure 2-A4). In addition, numerical simulation of function 2-A3-5 is consistent with the theoretical analysis above (Figure 2-A5). Figure 2-A5 shows that the equilibrium driven by the singular path is a saddle point.

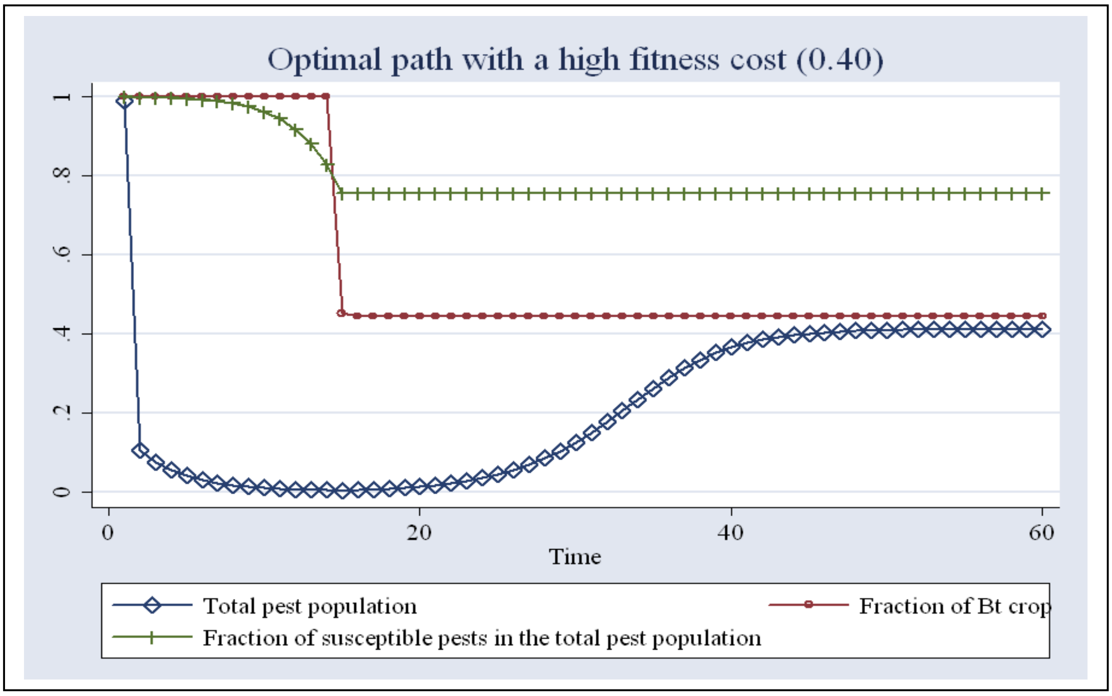
Table 2-1: Parameters, sources and range for Bt-resistance and economic parameters explored in the sensitivity analysis

Parameter	Default	Source
Average yield loss due to pest	\$1030/ha	Calculated based on data collected by IPP[a]
Average Bt cotton planting cost	\$143/ha	Calculated based on data collected by CCAP[b]
Discount rate	0.036	0.1 (Livingston et al., 2002); 0.04 (Hurley et al., 2001)
Initial fraction of resistant pests	0.001	No data
Mortality rate of susceptible pest in Bt field	0.90	0.85-0.95 (Wu et al., 2000); 0.75((Livingston et al., 2002); Storer et al. (2003); 0.95(Caprio, 2000)
Intrinsic growth rate	0.68	Author's Calculation

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).

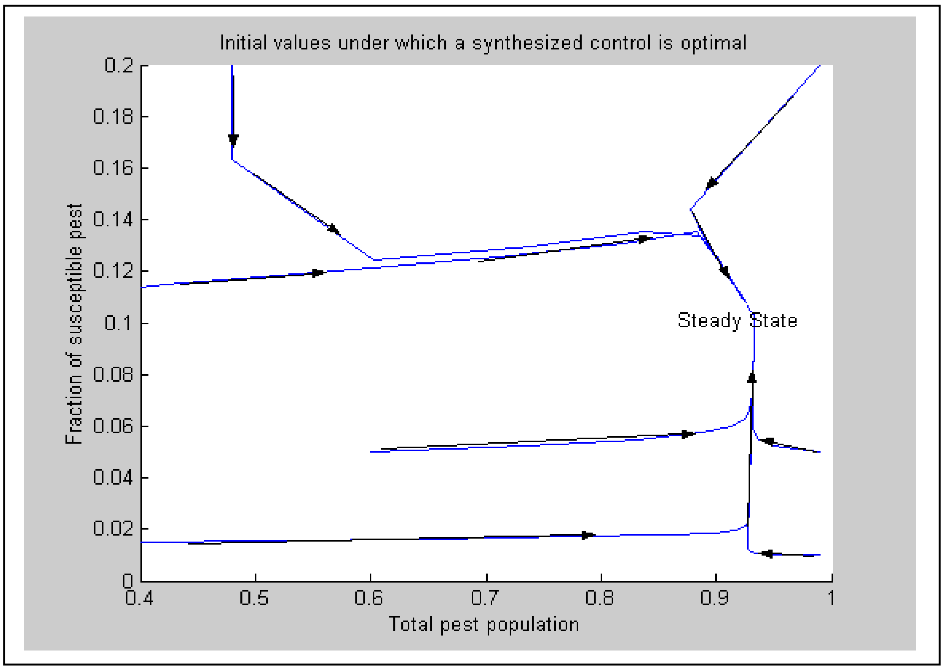


Panel A

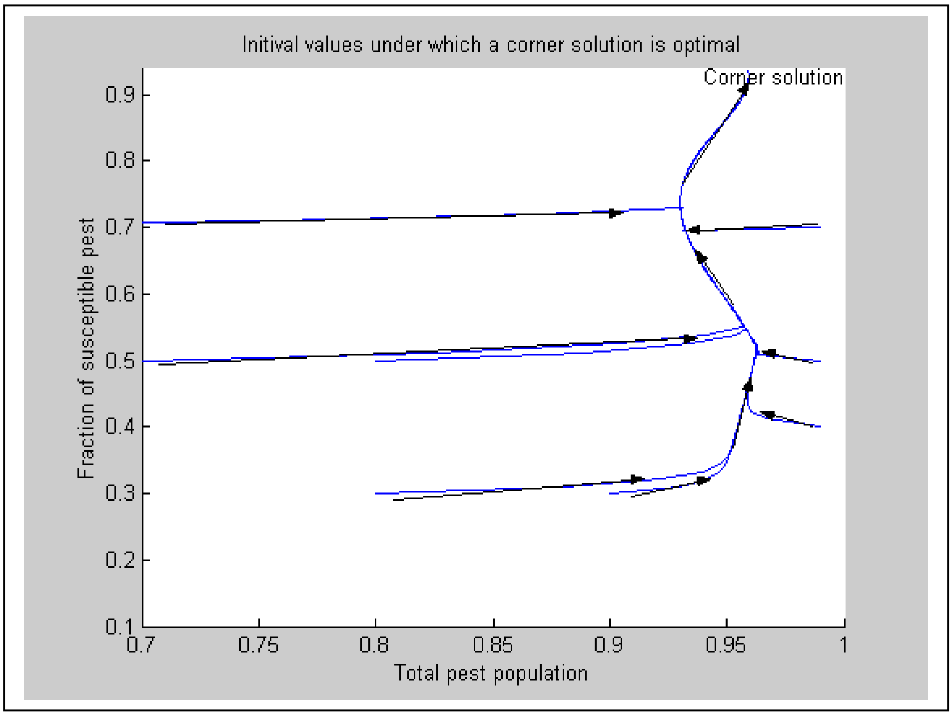


Panel B

Figure 2-1. Simulation results of the bio-economic model

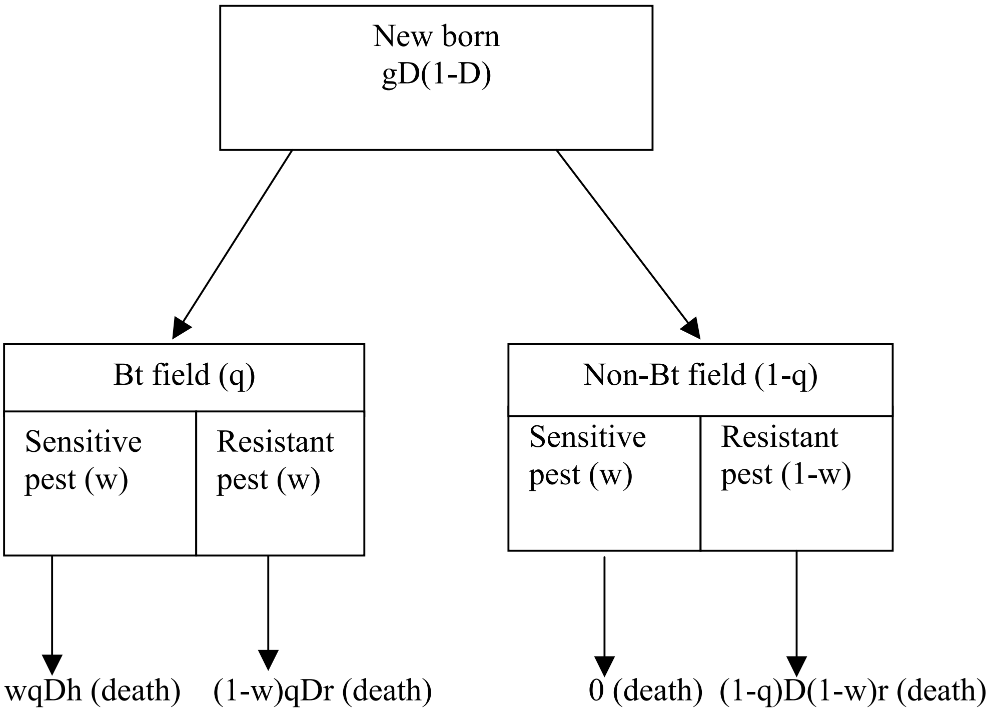


Panel A



Panel B

Figure 2-2. Initial values and optimal control path



D: total pest population
g: an intrinsic growth rate
w: the proportion of susceptible pests in the population
q: fraction of Bt land
h: death rate of susceptible pests in Bt field
r: death rate of resistant pests in either Bt or non-Bt field

Figure 2-A1. Schematic of the biological model with refuge

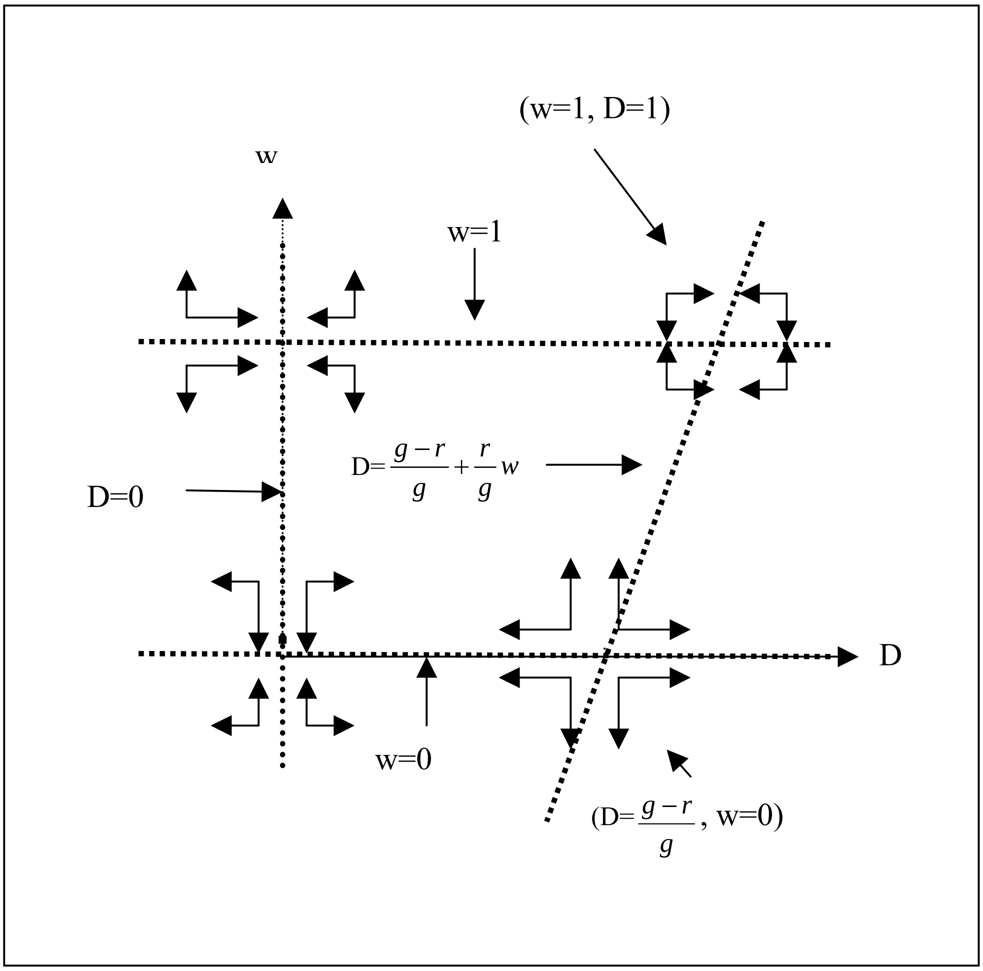


Figure 2-A2. Phase diagram to show the characteristics of the four fixed points led by the no control strategy: (D=0, w=0) and (D=0, w=1) are two saddle points, (D=1, w=1) is an asymptotically stable node while (D=$\frac{g-r}{g}$, w=0) is an unstable star node.

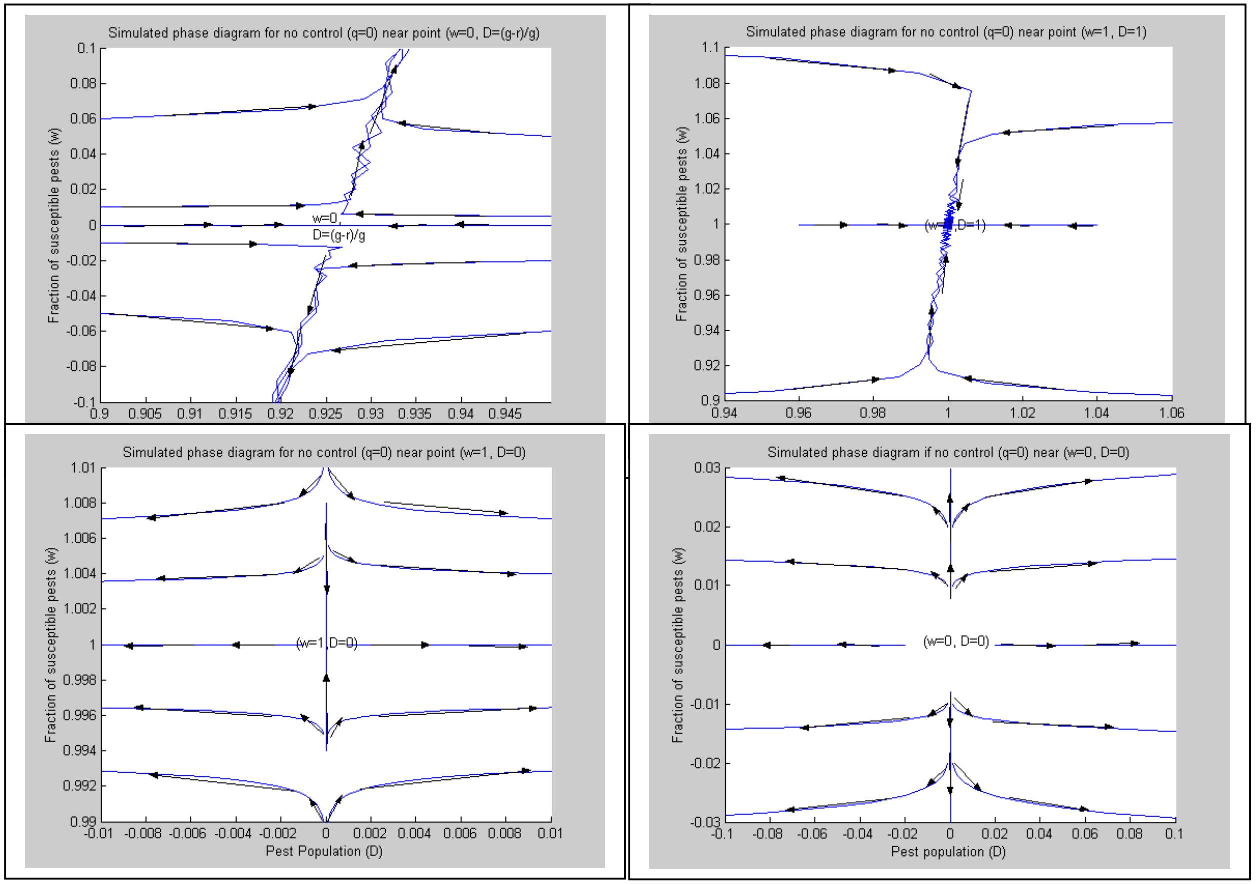


Figure 2-A3. Numerical analysis of the characteristics of the four fixed points led by the no control strategy: (D=0, w=0) and (D=0, w=1) are two saddle points, (D=1, w=1) is an asymptotically stable node while (D=$\frac{g-r}{g}$, w=0) is an unstable star node.

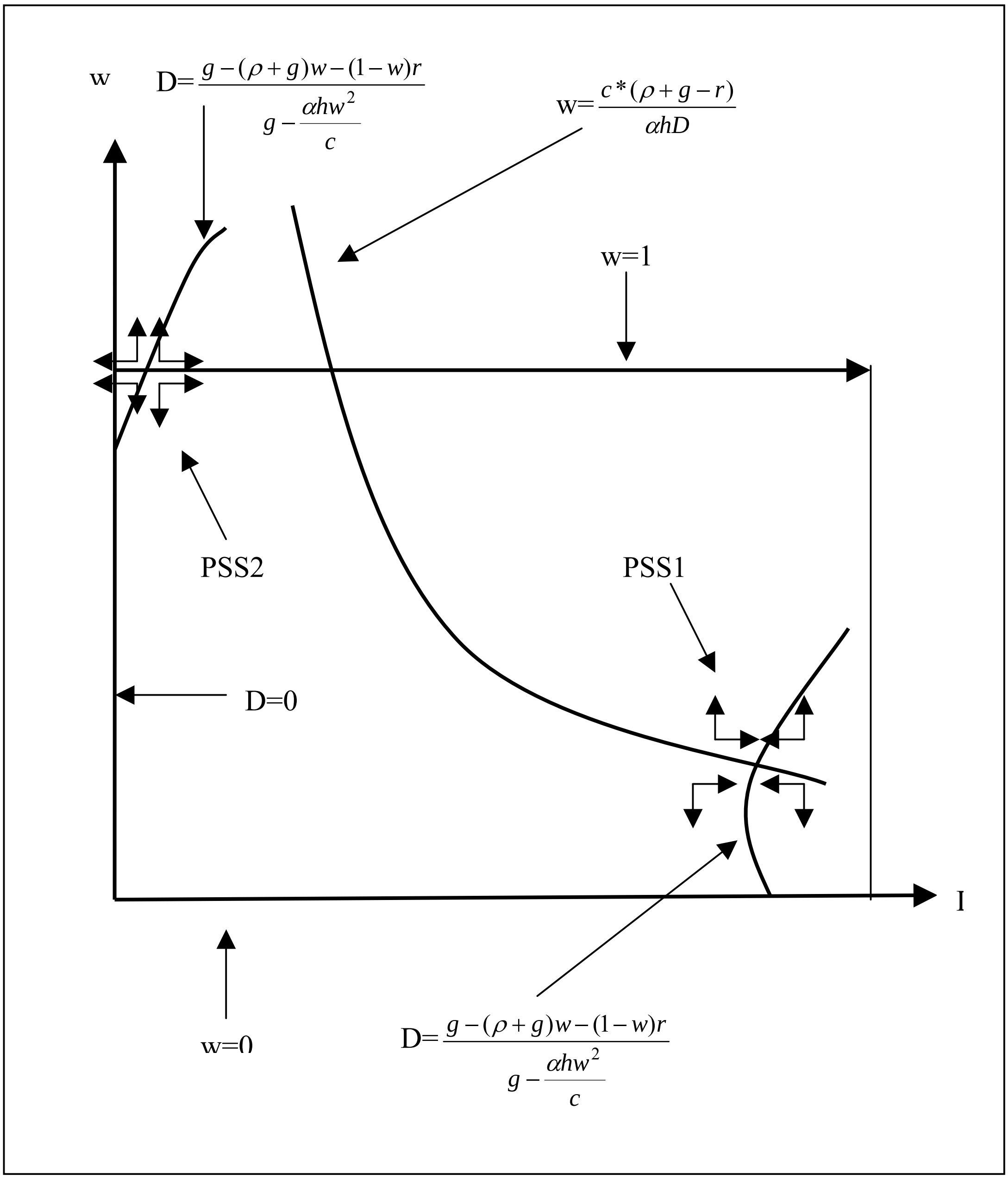


Figure 2-A4. Phase diagram to show the characteristics of the two fixed points led by the singular path: ($D=\frac{c\rho}{h\alpha-cg}$**, w=1) is a unstable star node, (D=**$\frac{g-r}{g}$**, w =**$\frac{cg(\rho+g-r)}{ha(g-r)}$**) is a saddle point.**

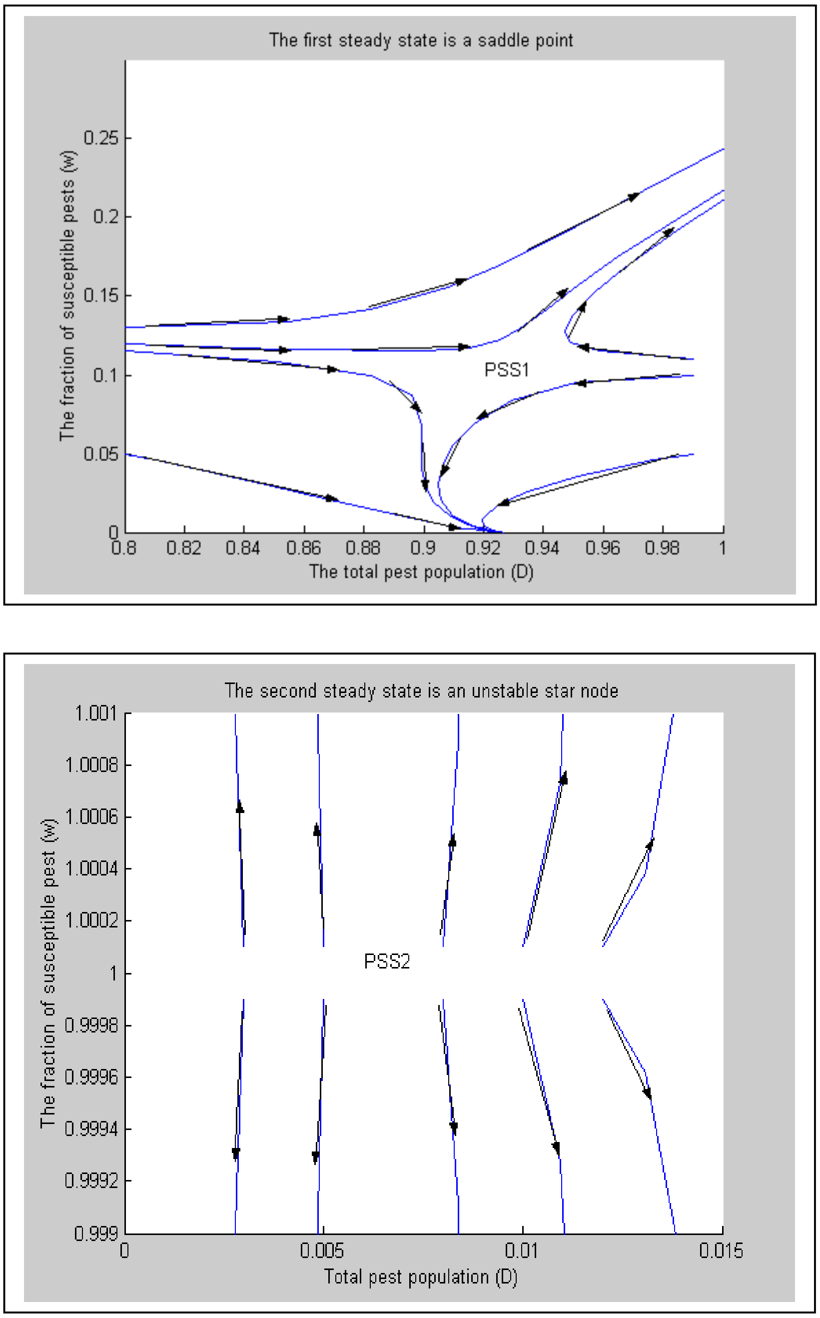


Figure 2-A5. Numerical analysis of the characteristics of the two fixed points led by the singular path: ($D=\frac{c\rho}{h\alpha-cg}$, w=1) is a unstable star node, (D=$\frac{g-r}{g}$, w $=\frac{cg(\rho+g-r)}{ha(g-r)}$) is a saddle point.

Chapter 3. Managing Pest Resistance in Fragmented Farms: An Analysis of the Risk of Bt Cotton in China and its Zero Refuge Strategy and Beyond

3.1 Introduction

The development of insect resistant crop varieties has arguably been the most successful application of agricultural biotechnology research to date. 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 10 million hectares in 2002. 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., 2002; 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 requiring 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 (EPA) adopted a refuge strategy for managing the evolution of Bt resistance in 1996 when Bt crops were first introduced. According to the EPA, farmers are required to plant minimum percentages of their total cotton acreage with non-Bt varieties. For example, cotton farmers in the southern United States have to leave either a *pure* refuge that equals 5 percent of their land (that is a plot of cotton that is not treated with any conventional pesticide) or a *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 require cotton farmers to plant Bt cotton on a maximum of 30% of their cotton acreage.

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 the developing countries, except China, agricultural officials require farmers to follow the EPA'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 70 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 U.S. 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 grow a diverse set of crops. 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 U.S.

In almost all respects, China is an appropriate case study 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 in China 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., 2002). 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, also 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 (e.g., Xue, 2002) and hence refuges may be needed, 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 chapter 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 chapter, we discuss the implications for other developing countries and the implications for other genetically modified crops.

3.2 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 3-1, 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 3-1, 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 input costs (Table 3-2, row 1 and row 2). After the mid-1980s, the quantity of pesticide rose steadily. By 1990 the cost share of pesticides rose to 18 percent (row 4); by 2000 the cost share was 22 percent (row 4). In 1995 the absolute level of pesticide applied to cotton was 200 percent higher than in the early 1980s (US$101 vs. US$31-35, see Table 3-2). 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. (2000) 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 per year) 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 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., 2002; Pray 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.

3.2.1 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., 2002), a lot of blame has to be put on the genetic make-up and population dynamics of the 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). Their studies show that 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 3-1). 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 (2002) demonstrate that China's cotton farmers in the mid-1990s spent more than $500 million annually on pesticides to control pests—and most of the pests were 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., 2002); some were spraying up to 30 times, about every other day during the periods of peak infestations. 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.

3.2.2 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, 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., 2002). 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., 2002). 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. 2002; 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., 2002).

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 3-2, 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., 2002). Across China, of the 5.65 million hectares of cotton planted in 2004, Bt cotton had expanded to account for nearly 70 percent of all the cotton area (Figure 3-2, 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 second and third largest cotton producing provinces in China (Figure 3-2, panel C).

3.2.3 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 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 3-3). 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]

3.3 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. We explore one explanation in this section.

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

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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).

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 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.

3.3.1 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 build up 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. In total, after the selection process, we ended up with four counties – the 2nd, 3rd, 18th and 107th largest cotton producing counties in China. 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

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[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.

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 3-3). Table 3-3 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 3-1.

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 3-4, 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 villages 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

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[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.

for their large mono-cultured areas), China's cotton crop is grown 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 other minor crops. In the rest of the chapter, 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 in the same time of cotton production season can be calculated and shown to be relatively large (Table 3-4, rows 2, 5 and 8). When doing so, it can be seen that refuge crops in villages that cultivate Bt cotton account for a large share of cultivated area. In no province does the share of refuge 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).

3.3.2 Multivariate Findings

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[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.

While this line of logic appears to be sound as a coarse scale argument, it would be desirable to draw on other evidence about mechanisms and processes as 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.

3.4 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 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 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 pesticide use. 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 also have built a simulation model to try to understand the long run cost and benefits of establishing refuges (or not).

The integrated bio-economic model we use follows the model presented 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. (2001) 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 author 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 a paper that creates a 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 reliable data or 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., 2002) and other journals (Huang et al., 2002; Hossain et al., 2004). The initial values of these biological and economic parameters are shown in Appendix Table 3-2.

3.4.1 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 3-4). In other words, the simulation results show that the optimal policy choice is to allow farmers to plant whatever variety of cotton they want 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 consequent 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 U.S. 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 even though it also helps to keep a relatively high pest population (Figure 3-5). 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 no conventional cotton is planted as a refuge, the average cost—damage cost caused by the CBW and treatment costs—is US $ 176.71 (Table 3-5, 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 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 also shown in Table 3-5 (second row). The simulation 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. As shown in Table 3-5, 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 (row 2).

3.4.2 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 3-3 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 3-3). Considering the high monitoring cost and other costs associated with a non-zero refuge policy (see chapter 4), a zero refuge policy is better in practice.

3.5 Conclusions

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 chapter 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 are 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 economic.

The economic efficiency case against reserves in China would be even stronger if implementation costs and health 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 reserves 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 reserve system, a prospect that would be even more expensive.

Appendix 3-1. 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., 2001; 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 3-1. The biological dynamics of the pest populations are shown in the following functional system (Appendix Function 3-A1) 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 Chapter 4. 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:

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

s.t.

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

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

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

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

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

$$MR_t^{geno} = f^{geno} * \sum^{j=sbt,bt,snbt,nbt} (lf_j * m_j^{geno}) \qquad \text{(3-A1)}$$

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 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 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 the others un-defined denotations are shown in the Appendix Table 3-1.

Table 3-1. 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

[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 3-2. Per hectare pesticide costs in cotton production in China, 1980-1995

Year	Per hectare pesticide cost (US$/ha)	Share (%) of pesticide cost in total material costs of crop production
1980	31.0	13.1
1985	35.2	11.5
1990	45.9	18.1
1995	100.5	21.7

Note: Rural retail price index of pesticides was used to deflate the current value. The per hectare pesticide cost is the in 1995 prices. The exchange rate is 1US$ = 8.3 RMB.
Source: State Economic Planning Commission.

Table 3-3. The distribution of cotton plots in selected Yellow River Valley cotton production region in China, 2004

		Proportion of cotton area				Accumulated cotton share in Yellow River valley
County [a]	Rank in term of fraction of cotton	Greater than 100 ha	Greater than 50, but less than 100ha	Greater than 1, but less than 50ha	Less than 1 ha	
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

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[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 3-4. 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 3-5. 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

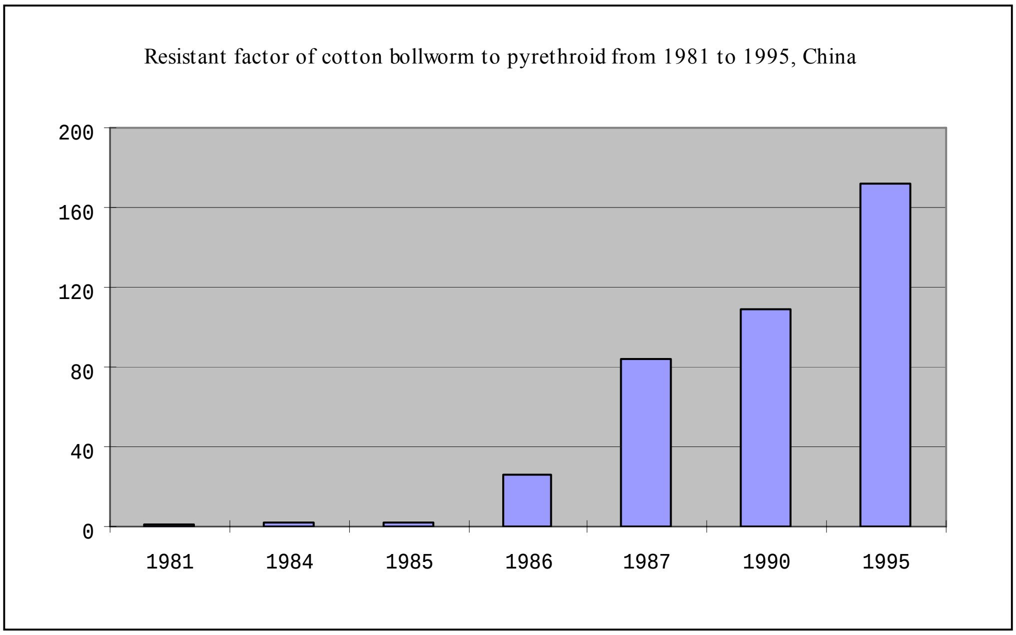
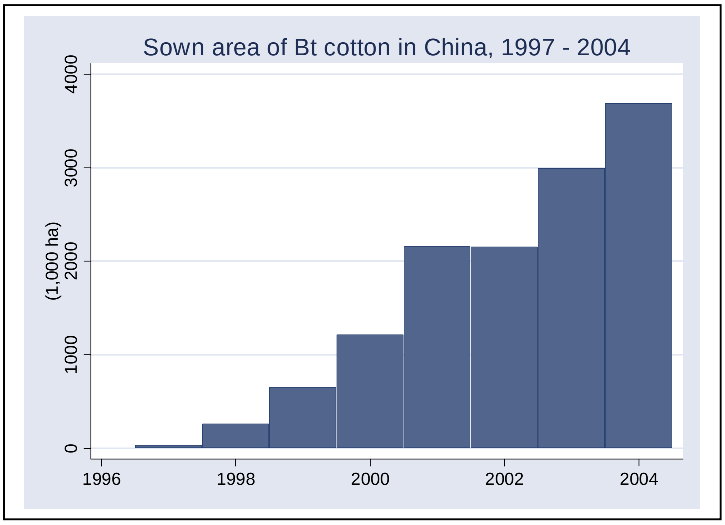
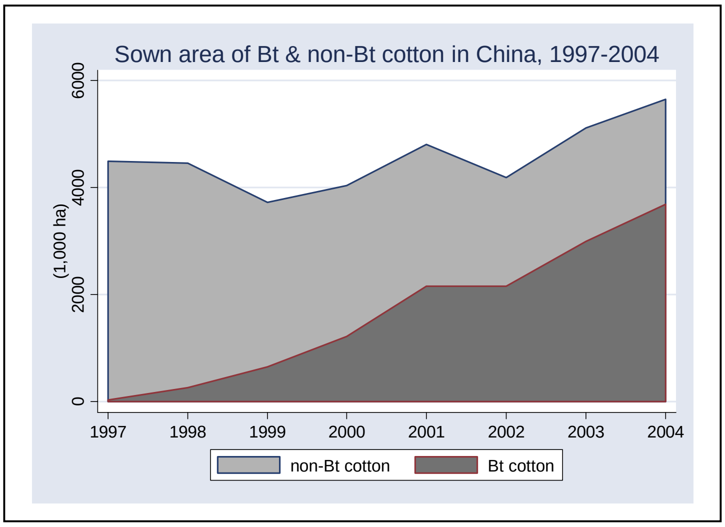


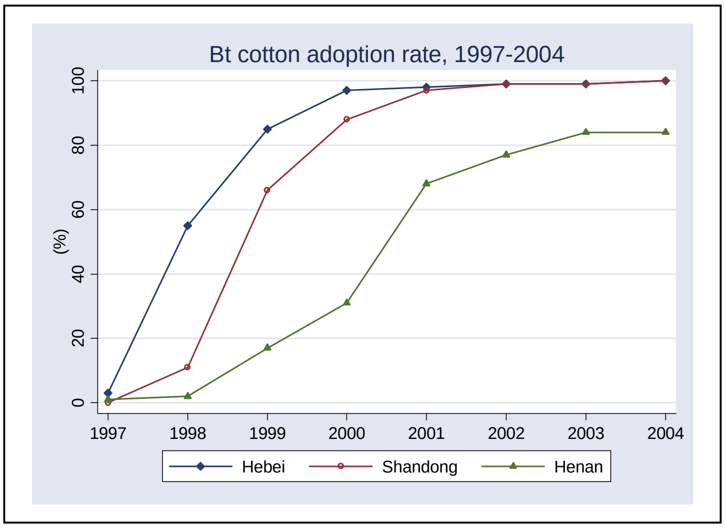
Figure 3-1. Development of the CBW to the pyrethroid deltamethrin in the filed and to the Bt toxin in the laboratory



Panel A



Panel B



Panel C

Figure 3-2. Spread of Bt cotton in China and Bt cotton adoption rate in Yellow River valley, 1997-2004

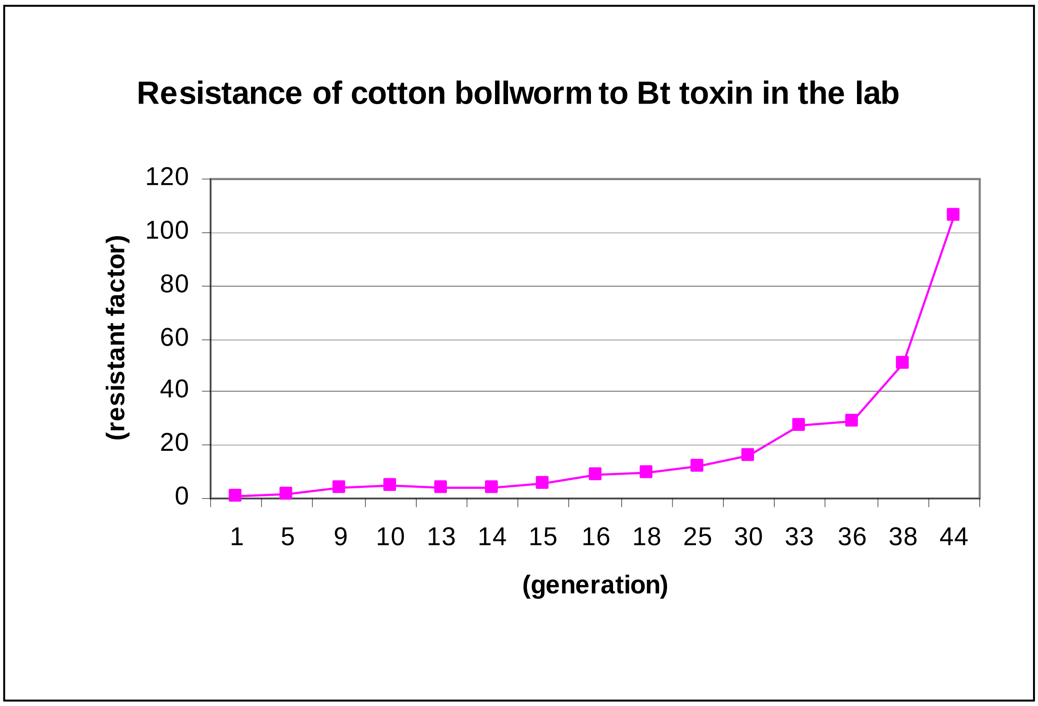


Figure 3-3. Development of the CBW to the Bt toxin in the laboratory

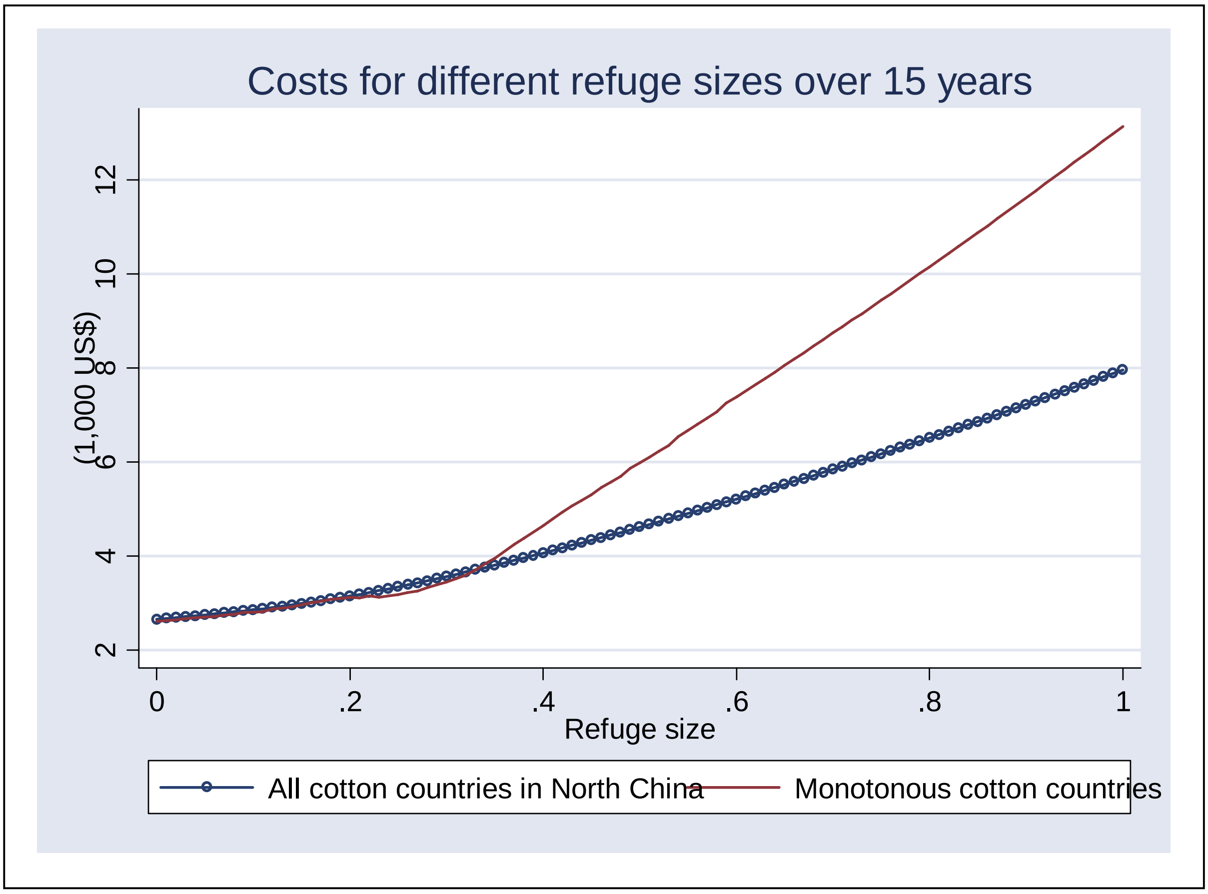


Figure 3-4. Costs for different refuge sizes over 15 years

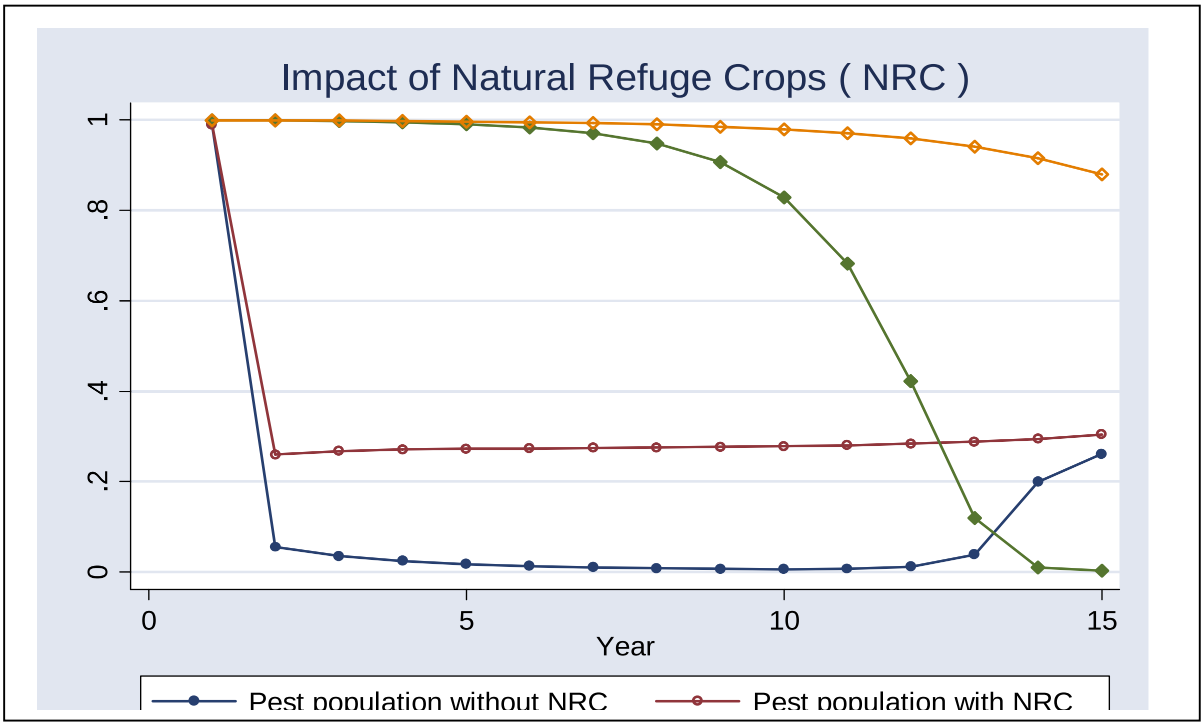


Figure 3-5. Impact of Natural Refuge Crops (NRC) on pest population and the buildup of the pest's resistance to Bt toxin

Appendix Table 3-1. Nine genotype pests, their fractions in the total pest population, and mortality rate in different fields

		Mortality rate in different fields (m^{geno})			
Genotype (p^{geno})	Fraction (f^{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 Table 3-2. 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 (1999?)
Natural growth rate	0.68	Calculated by the author using field date

[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 3-3. 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 Figure 3-1. A Sample of cotton cropping pattern in China

Chapter 4. Dynamic Optimal Strategy to Mange the Pest Resistance to Bt Cotton in China?

4.1 Introduction

We use a regulatory model with resistance evolution to both *Bacillus thuringiensis* (Bt) cotton and a conventional insecticide to answer whether China needs to re-think its zero-refuge policy to manage the buildup of the resistance in the pest population. Our analysis suggests that the refuge policy that is adopted in all the other Bt countries is not appropriate for China. At one hand, the diverse cropping pattern in the cotton production region provides enough “natural refuge” for the cotton bollworm, the most important pest in the cotton field in China. At the other hand, fragmented land system and the millions of cotton farmers are associated with high monitoring cost and implementation costs of refuge policy. Consequently, planting non-Bt cotton as refuge is not economic. In addition, we find that the pest’s susceptibility to conventional pesticides will recover if 100% Bt cotton is continuously planted. Consequently, farmers can use Bt cotton and conventional pesticide, alternatively, to control the pest problem in a long run.

The cotton bollworm, *Helicoverpa zea*, is the most damaging insect pest of cotton in China, especially in the Yellow River Valley cotton production region which is the largest one in China. Because cotton bollworm is highly mobile (Guo, 1998) and there is no direct pecuniary cost for killing it, regional susceptibility to insecticides is open-access resource. Profit maximizers may not account for the full cost of using insecticides and may therefore use too much relative to the social optimum, leading potentially to an inefficient rate of resistance evolution (Livingston et al., 2004). Resistance evolution in both pests to organochlorines, organophosphates, carbamates, and pyrethroids rendered these compounds ineffective in varying degrees by the 1990s, the time at which Bt cotton became available. Bt cotton expressing toxic proteins from the common soil bacterium Bacillus thuringiensis (Bt) is extremely toxic to the cotton bollworm, and became commercially available in 1997 in North China. However, due to the significant economic benefit, Bt cotton has been planted in more than two thirds of all the cotton fields in 2004 (Huang et al., 2004). And the fast spread of Bt cotton also allows China to become the largest Bt cotton country in the world (James, 2004).

However, Bt cotton is a two-edged sword. There are also a few worries behind the great success. One of the worries is the buildup of resistance in the pest population to Bt toxin. Buildup of the resistance will decrease the efficiency of the Bt cotton in the short run, and make it useless in the long run. In order to manage buildup of the resistance, a refuge policy is first adopted in the United States (Livinston et al., 2004). Following the refuge required in the United States, a similar refuge policy is adopted in almost all the other Bt crop countries, except for China. However, the debate on whether China needs to re-think its zero refuge policy has never been stopped. Some environmentalists argue that a refuge policy, similar as that in the United States, should be adopted in China (Xue, 2002). On the other hand, some entomologists believes that the “natural refuge crops” (which are planted immediately adjacent to cotton) can efficiently slow down the buildup of the resistance. Hence, planting non-Bt cotton as refuge is not economic in China.

Surprisingly little work has gone into understanding the refuge policy strategies in all the Bt countries except for the United States. Even though almost all of other Bt countries adopted refuge policies similar to that of the United States, their refuge policies do not seem to be based on empirical research conducted in these countries. In fact, to the best of our knowledge, all the previous empirical studies have focused on the United States (Hurley et al., 2001 and 2002; Secchi et al., 2001; Livingston et al., 2004). However, as Livingston et al. (2004) pointed out that any difference of nature of the pest or nature of the production system would yield different refuge policy. Considering the difference that among these Bt countries, we have reasons to believe that different refuge policies should be adopted in different countries.

In addition, even if mandatory refuge policy is theoretically optimal in some developed countries, it might not be noneconomic after considering the high monitoring cost and implementation costs associated with refuge policy in some developing countries. In addition to having different crop system and different pests, the large number of farmers makes implementing any refuge strategy in a developing country a challenging, if not impossible, activity. In all the previous studies on refuge policy, it is assumed by all researchers that the implementation cost of the refuge policy is trivial and can be ignored. Although this assumption may be reasonable in developed countries considering the production environment (there are fewer farmers and each farmer has larger tracts of land), it is not appropriate in developing countries. In developing countries, like China, millions of households make up the farming sector. Moreover, in most developing countries, farms are highly fragmented and grow a diverse set of crops. As a result, it is likely that implementing the refuge strategies like those in the United States that would require a huge enforcement cost, should farmers be unwilling to do it on their own, and could make these kinds of refuge strategies infeasible if farmers in developing countries have an incentive to not implement the refuge.

The primary objective of this study is to determine whether China needs to re-think its zero refuge policy. We focus on the Yellow River Valley cotton production region because adoption of Bt cotton has been significant in this area and because cotton bollworm is most serious in this region. Contrast to the refuge requirements in all the other Bt cotton countries, I developed a simple single resistance model and demonstrated that planting refuge might not be economic in Chapter 2. In Chapter 3, I estimated a more realistic dual-toxin static model and show that China's zero refuge policy is indeed the optimal choice. However, in this empirical study, the refuge size is defined as a constant number over time. By allowing the refuge size varies annually, we might be able to get a better solution. This study will fill this niche. In this chapter, I will extend the static model into a dynamic model. By simulating the model, I will assess the potential efficiency gains of optimal dynamic from zero refuge policy. And finally, we will answer whether China need to plant a mandatory refuge.

The rest of this chapter is organized as follows. In the second part, we will develop a dynamic bio-economic model that will be used to simulate the optimal dynamic refuge size over finite time horizon. The biological and economics parameters that will be used in the model are discussed in the third part. In the fourth parts, we will discuss the simulation results. Our simulation results show that non-Bt cotton refuge is not economic in China after considering the impact of natural refuge crops. We concluded the chapter in the last part.

4.1 The Model

The integrated bio-economic model we use follows the epidemiological model presented by Wilen and Msangi (2002). The similar approach has been found in the models presented by Laxminarayan and Simpson (2002), Hurley et al. (2001) and

Livingston et al. (2002) in their studies on refuge strategies. The pest population is assumed to be local and both in- and out-migration is ruled out. Other standard assumptions implicit in deriving the Hardy-Weinberg principle, such as random mating between resistant and susceptible pests, negligible mutation, non-overlapping pest generations and sexual reproduction of pests, are all assumed to be held. The model consists of two parts: a biological model which is used to simulate the evolution of pest resistance and pest population; and a dynamic regulatory model which is used to examine the impact of refuge policies. Because the regulatory model is easier to describe once the biological model is understood, we begin with the biological model.

4.2.1 Biological 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., 2001; Livingston et al., 2004). We use a two-locus four-allele model to simulate resistance evolution to both Bt cotton and conventional pesticides under the following assumptions: (a) there are large and equal numbers of diploid females and makes 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. Wheat is the only host plant for the cotton bollworm (CBW) at the first generation. Cotton, soybean, peanuts, and other crops, fruit trees and even weeds are the host plants for the CBW at the second and third generations. At the fourth generation, maize becomes another important host plant. For the simplicity and data availability, I will only consider wheat, soybean, peanut and maize as the "natural refuge crops". In this sense, this study underestimate the impact of natural refuge crops on the buildup of resistance in the pest population.

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 into 1. Then the total number of new born 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 resistance and susceptibility to Bt toxin at locus one, respectively; let y and Y denote the alleles that confer resistance and susceptibility to conventional pesticide at locus two. Under these assumptions, there will be nine types of pests with different genotypes. These genotypes are XXYY, XXYy, XXyy, XxYY, XxYy, XXyy, xxYY, xxYy, and xxyy. Allele frequency w denotes the proportion of the susceptible alleles to Bt toxin. Similarly, allele frequencies v denote the proportions of the susceptible alleles to conventional pesticide in adults. Then the fractions of these nine genotypes in the total pest population (denoted by f^{geno}) are: w^2*v^2, $2*w^2*v*(1-v)$, $w^2*(1-v)^2$, $2*w*(1-w)*v^2$, $4*w*(1-w)*v*(1-v)$, $2*w*(1-w)*(1-v)^2$, $(1-w)^2*v^2$, $2*(1-w)^2*v*(1-v)$, $(1-w)^2*(1-v)^2$.

The mortality rate varies with both the genotypes and the treatments. For simplification reason, the sown land of cotton is normalized into 1. The sown land of natural refuge crops is denoted by NRC. The two treatments, Bt and conventional pesticide, divided the total areable land into four types (denoted by lf): Bt field (with the faction of q) with conventional pesticides spray (with the possibility of "A"), Bt field without conventional pesticides spray (with the possibility of 1- A), non-Bt field (with the faction of 1-q) with conventional pesticides spray (with the possibility of B), non-Bt field without conventional pesticides spray(with a possibility of 1- B) and natural refuge crops field. The mortalities of different genotypes (denoted by m^{geno}) at land with different treatments are shown in Table 1. The sub-total mortality rate of each genotype, MR, is the sum of the mortality rate at different land type multiply the possibility of the land type, or

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

And the total mortality rate of the pest population is the sum of the sub-total mortality rate of different genotypes, or $\sum_{geno=1}^{geno=9} MR_t^{geno}$. The dynamic of the total pest population, susceptibility to Bt toxin, and the susceptibility to conventional pesticides are shown in Appendix 4-1.

4.2.2 Regulatory Model

The objective of regulatory model is to minimize the discounted sum of planting costs. Two types of cost are included at each calendar year. The first type of cost is damage cost caused by the pest, which is assumed to have a linear relationship with the total pest population in the cotton field. In this study, we assume that the damage caused by the cotton bollworm of natural refuge crops is ignorable. In other words, only the damage in the cotton field is calculated. We also assume that farmers will not spray in those natural refuge crops fields. 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 a series of optimal refuge sizes, subjected to the dynamic of the pest population and the buildup of the resistance to both Bt toxin and conventional pesticide, which are simulated in the biological model. Following Wilen and Msangi (2002), I developed a discretized form of this problem that can be solved with empirical statistics software. We can optimize this problem by using the Bellman Equation, which can be written as:

$$\underset{0\le q_t \le 1}{Min}_{t=1}^{t=T} \; V(D_t) = DCTN_t * \alpha + cbt * q_t + ccp * [q_t * dbt_t + (1-q_t) * dnbt_t] + \delta V(D_{t+1})$$

s.t.

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

$$\begin{aligned} w_{t+1} - w_t &= (1-w_t)*(w_t^2 * g * D_t * (1-D_t) - \sum_{geno=1}^{geno=3} MR_t^{geno}) + (0.5-w_t)*(2*w_t*(1-w_t)*g*D_t*(1-D_t) - \sum_{geno=4}^{geno=6} MR_t^{geno}) \\ &+ (w_t)*((1-w_t)^2 * g * D_t * (1-D_t) - \sum_{geno=7}^{geno=9} MR_t^{geno}), w_{t=0} = w_0 \end{aligned}$$

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

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

$$DCTN_t = D_{g,t+1} - \frac{nrc}{1+nrc} * (D_t + g * D_t * (1-D_t) - D_t * \sum_{geno=1}^{geno=9} (f^{geno} * m^{geno})) \tag{4-1}$$

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 $\delta = 1/(1+\rho)$. D_t is the total pest population at time t; $DCTN_t$ is the total pest population in cotton field at time t; α is the average damage cost caused by unit of pest; cbt is the average cost associated with Bt cotton planting; ccp is the unit price of conventional pesticides spray; and 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.

4.3 Data Sources and Parameters

4.3.1 Dataset

The data that used in this study come from three main sources – a household-level survey undertaken by the Center for Chinese Agricultural Policy (CCAP) of the Chinese Academy of Sciences (CAS) during 1999-2001, a village-level survey undertaken by the author in 2004, and lab and field experiments undertaken by Institute of Plant Protection (IPP) of Chinese Academy of Agricultural Sciences (CAAS) during 1994-2003. The first two dataset are used to estimate the economic parameters while the third dataset is necessary for the biological parameters.

The first dataset was collected by the Center for Chinese Agricultural Policy (CCAP) of the Chinese Academy of Sciences (CAS). Since 1999, CCAP has collected household level data for three years and has data on more than 1000 households mainly in Yellow River Valley cotton production region (Hebei, Henan, Shandong provinces). In the household-survey, enumerators collected a wide range of information both on the Bt cotton production activities and non-Bt cotton production activities, as well as the other household-specific characteristics. Detailed description of these data can be found in several previous studies (Pray et al., 2001; Huang, et al. 2001, 2002).

The second set of primary data has been collected by the author in the summer 2004 in Hebei, Henan and Shandong provinces. The village-level dataset contains information of the spatial patterns of cropping, especially the distribution and density of cotton, in four different counties in the Yellow River Valley cotton production region. Enforcement and monitoring costs associated with refuge policy is also intensively surveyed in the 114 sample villages.

The third set of primary data was put together after extensive interactions with scientists from the Institute of Plant Protection (IPP) of the Chinese Academy of Agricultural Science (CAAS) in their laboratories and field. The IPP has collected information about the pests' resistance to commonly used insecticides (such as phoxim, lambda-cyhalothrin, and endosulfan) since 1994 when the resistance of cotton bollworms to conventional pesticides became a real concern. After the introduction of Bt cotton in 1997, IPP also began to monitor the resistance revolution of cotton bollworm to Bt gene.

4.3.2 Parameters

Appropriate refuge requirements depends on both the genetic and biological parameters used to simulate resistance evolution of different pests and economic parameters used to estimate the costs and benefits of managing resistance with refugia. Most of the parameters used in this study come from the pervious studies, author's estimation based on the available data, and private communication with entomologists in China. Table 4-2 presents the benchmark configuration for all parameters.

4.3.2.1 Biological Parameters

The levels of all biological parameters used to simulate resistance evolution and average larval survival rates are either from the previous studies or calculated based on the available dataset. We based Bt-resistance parameters on available laboratory studies, because sufficient field data on Bt resistance were unavailable. Fortunately, we have sufficient field data to estimate the relevant biological parameters about conventional pesticide. The other remaining parameters, such as intrinsic growth rate of the pest population, are calculated using the data collected by IPP.

The survival rates of susceptible homozygotes and heterozygotes is very uncertain since Bt varieties are new and until recently, have not been available for widespread production. The previous studies show that the in the Yellow River Valley, Bt cotton can control about 80-95% pests on average (Wu et al., 2000). Based on these studies in China and those empirical studies in the United States (Livingston et al., 2004; Gould et al., 1997; Burd et al., 2001; Storer et al., 2003; Caprio, 2000), we assume that the mortality rate of the susceptible pests is 0.90 in this study. As assumed in Livingston et al (2004), we also assume that mortality rate of resistant pests, or the fitness cost, is 0.05. According to my personal discussion with Dr. Wu Kongming, the chief entomologists in China, we assume that the dominant level of susceptible gene in the heterozygote pests is 0.75. Similarly, we define the mortality rate of pests with double susceptible gene to conventional pesticide, pests with double resistant gene to conventional pesticide, the dominant level of susceptible gene to conventional pesticide in the heterozygote as 0.90, 0.05 and 0.75.

Previous studies found the frequencies of resistant alleles to Bt toxins in the cotton bollworm to be of the order of magnitude of one in a thousand in China (Li et al., 2003; Ru et al., 2002) as well as in the United States (Gould et al., 1995; Onstad and Gould, 1997; Livingston et al., 2002). Subsequently, Onstad and Gould (1997) use this value in their studies of Bt resistance in the Europe corn bollworm while Livingston et al (2004) use this same value in their studies of Bt resistance in the pests in the cotton field. We also adopt an initial frequency of resistant alleles of one in a thousand. The fraction of the susceptible gene is calculated using the dataset collected by IPP. As a result, the simulation results show that the fraction of the susceptible gene at the initial year is 0.60. According authors communication with local farmers, this number is consistent with efficiency of the conventional pesticide in recent years.

The natural growth rate of the pest population is estimated using the historical data. I assume that CBW population (denoted by D) grows logistically with an intrinsic growth rate of g, and a carrying capacity of K per unit of land (K is normalized into 1). Historical data collected from 1998 to 2002 by the entomologists of Institute of Plant Protection, Chinese Academy of Agricultural Sciences, are used to estimate the intrinsic growth rate. The estimation results show the intrinsic growth rate is 0.68 per generation.

The final biological parameter to specify is the natural refuge crops coefficient (NRC). Even though cotton bollworm can feed on almost many crops, fruit tress and even many weeds, we focus on the most important four crops: wheat, maize, soybean and peanut. At the first generation, cotton bollworm only feed on wheat in the spring. They can feed on cotton, soybean, peanuts and other crops at the second and third generations. At the fourth generation, maize becomes one of the most important host plants for cotton bollworm. The magnitude of the NRC depends on two factors: the relative carrying capacity and the relative area of of natural refuge crops. The carrying capacity of one crop is defined as the pest density when the pest density in cotton is normalized into 1. As Table 4-3 shows, the carrying capacity of soybean and peanuts are 12% and 29 for the second; 29% and 26% for the third; and 73% and 62% for the fourth generation. No cotton bollworm will feed on maize at the second and third generation, but the pest density in maize field is 132% of those in cotton field at the fourth generation. Another factor is the relative crop proportions. Maize is the most popular crop in term of planting area in Yellow River Valley. In all the 374 counties in Shandong, Henan and Hebei provinces, maize area is 2.81 times of cotton area. Areas of soybean and peanuts are 0.63 and 0.53 times of cotton (First column). After defining the relative carrying capacity and crop proportion of these crops, we define

NRC as NRC = $\sum_{i=1} K_i*P_i / (\sum_{i=1} K_i*P_i + P_c)$ where i is the ith natural refuge crops, K_i is the carrying capacity of the ith crops; P_i is the crop proportion of the ith crops. P_c is the crop proportion of cotton. The NRC is 0.18, 0.26 and 3.70 for the second, third and fourth generations (last row, Table 4-3).

4.3.2.2 Economic Parameters

Most of the economic parameters come from the CCAP dataset. Objective cost function includes three parts: yield loss caused by pest population, extra planting cost of Bt, and the expenditures on conventional pesticide. Other costs associated with deriving, initiating, maintaining and enforcing the policy is excluded in the model even though we will discuss it in the later. The damage costs caused by the cottonw bollworm without any treatments is $1030 per ha. The cost of conventional pesticides spray for cotton bollworm controlling was $252 per ha, including both expenditures on pesticides and labor cost of pesticides spray. Control cost associated with Bt cotton planting is $143 per ha, which includes the Bt cotton seed cost, expenditures on pesticides for other pests except for CBW, and related labor cost. All other inputs cost, except for seed and expenditures on conventional pesticides for cotton bollworm controlling, between Bt and non-Bt are assumed to be same.

Costs were discounted using a 3.6% annual interest rate over 15 years for a finite optimal refuge strategy. Interest rate and time horizon are two important parameters in optimal refuge strategy choice. The 3.6% interest rate is the new long-term (> 5 years) deposit rate in China. Similar discount rate is used Livingston et al. (2002) and Secchi et al. (2001). In this study, year 2000 is defined as the initial year when 90% of the cotton in the Yellow River Valley cotton production region is Bt cotton. Similar as in the previous empirical studies (Livingston et al., 2004; Secchi et al., 2001) in the United States, a 15 year planning horizon is used in this study.

4.4 Simulation Results of the Bio-economic Model

Annualized costs under static solutions (static refugia) and under dynamic solutions (dynamic refugia) to our regulatory problem are reported in Table 4-4 for the 10-year, 15-year, and 20-year time horizons. The 15-year planning horizon is considered as the basic scenario while the 10-year and 20-year horizons are simulated to test the robustness of the model and show the impact of time horizon on refuge policy strategy. Optimal dynamic and static solutions were found using a standard solver of GAMS.

For the 10-year and 15-year horizons, both dynamic and static refugia show that planting non-Bt cotton as refuge is not economic (Table 4-4, the first two rows). Table 4-4 shows that the refuge size for both optimal dynamic and static refuge policy is always zero for both the 10-year and 15-year time horizons. In other words, planting non-Bt cotton as refuge is not economic if the planning horizon is 15 years or less. As shown in Panel A of Figure 4-1, the optimal dynamic refuge policy shows that the fraction of the Bt cotton is always 100% for the 15-year planning horizon. In other words, planting non-Bt cotton as refuge is not economic. The evolution of the susceptibilities of the pest to Bt toxin for 15-year planning horizon is shown in Panel B of Figure 4-1. From Panel B of Figure 4-1, we can see that even though the 100% Bt cotton planting causes the decrease of the susceptibility of the pest population to Bt toxin. However, the decline is not significant, given a high initial value of the susceptibility and a converted S shape of decreasing (slow in the beginning and the end, but fast in the middle).

The key to understand the simulation results is to understand the impact of the natural refuge crops on the buildup of the resistance in the pest population. If natural refuge crops are not available and the 100% Bt cotton is continuously planted, the susceptibility of the pest will decline quickly. Ten years later, the susceptibility is almost ignorable even though the initial level of the susceptibility is high (Pane C of Figure 4-1). Planting non-Bt cotton as refuge allows susceptible pests to thrive so that they can mate with resistant pests that survive in the Bt fields, thereby reducing selection pressure and extending the efficacy of the insect-resistant varieties. Natural refuge crops that are planted immediately adjacent with the cotton can act in the same way. By providing refuges for susceptible pests, these natural refuge crops also help to slow down the buildup of the resistance and maintain the effectiveness of the Bt cotton. Consequently planting non-Bt cotton as refuge is not economic. As shown in the Panel C of Figure 4-1, because of the natural refuge crops, the susceptibility of the pest population to Bt toxin is still relatively high after 100% is continuously planted for 15 years.

Compared to the optimal static refuge policy, the optimal dynamic refuge policy will provide a lower production cost. As planning horizon gets longer, continuously planting 100% Bt cotton is no longer optimal for both static and dynamic refuge policy. As shown in Table 4-4 (third row), for the 20-year planning horizon, the optimal static refuge size is 5% (with conventional pesticide spray). Compared to the annual cost of the optimal static refuge policy, US $ 175.38 per hectare, annual cost of the optimal dynamic one is smaller (Table 4-4, third row). However, the US $ 1.02 (or 0.58%) per hectare cost difference between the optimal static and the optimal dynamic refuge policy is not significant. This finding is consistent with previous studies (Livingston et al., 2004; Hurley et al., 2001).

In addition, the cost difference between the zero refuge policy and the optimal dynamic refuge policy is also relatively small. For the 10-year and 15-year planning horizons, the dynamic optimal refuge strategies show that refuge size does not vary from the 100% Bt cotton over time. For the 20-year planning horizon, even though the annual cost of the optimal dynamic strategy is US $ 174.37 per hectare while the annual cost of the zero refuge strategy is US $ 176.83 per hectare, the US $ 2.46 per hectare cost difference (or 1.39% more) might be relatively small (Table 4-5).

Whether the dynamic optimal refuge policy is preferred in practices also depends on the transaction costs associated with the implementation and monitoring of refuge policy. If the extra benefit of the optimal dynamic refuge can not offset the transaction costs associated with the implementation and monitoring of refuge policy which are excluded in our bio-economic model, it does not pay to implement it. In other words, in order to answer whether optimal dynamic refuge policy is a better choice than the zero refuge policy for the 20-year planning horizon, we also need to investigate the transaction cost of the refuge policy.

The implementation and monitoring costs associated with the refuge policy are high because of the land fragmentation in China. As in other rural areas, there are millions of small farmers in the cotton production region. To effectively mange these millions of small households, China sets up a special policy management system in rural areas. In this system, village is the basic official government unit, which is constituted by several production teams. Before the land reform at the end of the 1970s and early of the 1980s, the production team is the basic production unit for couples of hundreds people in the team. After the implementation of the household responsibility system, even though all the lands and collective assets are allocated to individual farmers, most of the policies, such as land reallocation and adjustment, tax collection et al, are still based on the production team.

A field survey by the author in the summer 2004 shows the transaction cost is high if similar refuge policy as in the United States is implemented in China. In order to monitor farmers, at least one person is needed for each production team. Statistics shows that the total monitoring cost will be US $ 6.97 per hectare per years. On the other hand, the simulation results show that the extra benefit obtained from zero refuge to optimal dynamic refuge strategy is only US $ 2.46 per hectare per years (3rd row of Table 4-5). It is clear that the extra benefit can not even offset the extra monitoring cost, let alone other costs.

The second important finding is the recovery of the susceptibility in the pest population to conventional pesticide as the continuously planting of the 100% Bt cotton. As assumed, the susceptibility of the pest population to conventional pesticide is a renewable resource. In other words, if conventional pesticide is not used, resistant pests will die with a faster speed than that of the susceptible pests because of the fitness cost. Consequently, fraction of the susceptible pests in the total pest population will increase. As a result, the conventional pesticide will become efficient again many years later. Panel B of Figure 4-1 shows that the 100% Bt cotton for 15 years causes the increase of the susceptibility to conventional pesticides in the pest population. This trend becomes clearer in the 20-year planning horizon. Panel B of the Figure 4-2 shows that the continuously planting of the Bt cotton allows the susceptibility to conventional pesticide finally surpass the susceptibility to Bt toxin. In other words, conventional pesticide becomes more efficient than the Bt cotton in controlling the pests. Hence, as shown in the Panel A of Figure 4-2, the dynamic optimal strategy requires to use the conventional pesticide for the 20-year planning horizon.

This finding provided alternative method to manage the pest’s resistance. As shown in Panel B (Figure 4-1 and Figure 4-2), efficiency of the convention pesticide will recover if 100% Bt cotton is planted without spray. In the similar way, we can also expect that efficiency of the Bt cotton will recover if 100% non-Bt cotton is continuously planted. Hence, in order to manage the buildup of the resistance in the pest population, instead of planting a fraction of land as refuge annually, farmers might use either Bt cotton or conventional pesticide, alternatively, to control the pest. The non-Bt cotton provided refuge for pests which are susceptible to Bt toxin. Similarly, the 100% Bt cotton without conventional pesticide spray provided refuge for pests which are susceptible to conventional pesticide. The optimal dynamic strategy, as shown in Panel A of the Figure 4-3, for the 100-year planning horizon is consistent with our expectations. As shown in the Panel B of the Figure 4-3, if 100% Bt cotton without conventional pesticide spray is planted, susceptibility to conventional pesticide will recover. Similarly, the susceptibility to Bt toxin will recover if non-Bt cotton is planted.

4.5 Conclusions

This article presents a dual – toxin regulatory model and use it to estimate Bt cotton refuge sizes that minimize the production cost. The analysis yields several important conceptual and policy findings. First, we show that planting refuge is not economic for Bt cotton in China for at least two reasons. First, the diverse cropping pattern in the cotton production region allows cotton bollworm find enough refuges on natural refuge crops, so that the buildup of the resistance will be slow down. Secondly, the monitoring and implementation cost is high because of the diverse cropping system and fragmented land management. The transaction cost will offset the extra benefit of the refuge policy. Consequently, China does not need to re-think its zero refuge policy.

Another important finding is the recover of the pest's susceptibility. As discussed in the above, the susceptibility of the pest is a renewable resource. Hence, the 100% Bt cotton without conventional pesticide will allow the recovery of the susceptibility to conventional pesticide. Consequently, if 100% Bt cotton without conventional pesticide is planted for a few years, the convention pesticide will become efficient again in controlling the pests. Similarly, the susceptibility of the pest to Bt cotton will also recover if Bt cotton is not planted. Consequently, instead of planting a fraction of land as refuge annually, the dynamic optimal refuge policy shows that farmers can use Bt cotton and conventional pesticide alternatively to control the pests.

The simulation results have important policy implications. First of all, it empirically answered whether China need to re-think its zero refuge policy. Even though the United States- styled refuge policy is adopted by most of the Bt crop countries, we show that planting non-Bt cotton as refuge is not economic in China.

Secondly, it shed light on the policy of the management of other Bt crops in China. Currently, Chinese government is facing the pressure to commercialize Bt corn and Bt rice. Commercialization of the Bt corn will let the cotton bollworm lose the most important natural refuge crop (non-Bt corn). Accordingly, China might need to re-think its zero-refuge policy. Cropping system in rice field is much different from that in the cotton field. In South China, rice is monotonously planted. In other words, the pest in rice field almost can not find enough natural refuge crops nearby. Consequently if Bt rice is commercialized, a mandatory refuge might needed.

Finally, this study also provided an example to mange the buildup of the resistance in the pest population for other Bt country countries, especially for developing countries. As discussed above, even though all the other Bt countries also adopted the similar refuge policy as did in the United States, none of their requirement is based on the quantitatively analysis. However, due to the diverse cropping pattern and difficulty in implementing and monitoring the refuge policy, it seems that the refuge policy of the United States might not be appreciate at last for most of the developing countries. This study provided an example.

Appendix 4-1 Dynamic of the Total Pest Population, Susceptibility to Bt Toxin and Susceptibility to Conventional Pesticides.

As discussed above, the susceptibility (X) and resistant (x) alleles to Bt toxin at locus one, and the susceptibility (Y) and resistant (y) alleles to conventional pesticide at locus two divided the total pest population into nine different genotypes of pests. These nine types of pests are: (1). XXYY is the pest population with double susceptible genes to Bt toxin, and double susceptible genes to conventional pesticide; (2). XXYy is the pest population with double susceptible genes to Bt toxin, one susceptible and one resistant gene to conventional pesticide; (3). XXyy is the pest population with double susceptible genes to Bt toxin, and double resistant genes to conventional pesticide; (4). XxYY is the pest population with one susceptible and one resistant genes to Bt toxin, and double susceptible genes to conventional pesticide; (5). XxYy is the pest population with one resistant and one susceptible genes to Bt toxin, and one susceptible and one resistant genes to conventional pesticide; (6). Xxyy is the pest population with one susceptible and one resistant genes to Bt toxin, and double resistant genes to conventional pesticide; (7). xxYY is the pest population with two resistant genes to Bt toxin, and double susceptible genes to conventional pesticide; (8). xxYy is the pest population with two resistant genes to Bt toxin, and one susceptible and one resistant genes to conventional pesticide; (9). xxyy is the pest population with two resistant genes to Bt toxin, and double resistant genes to conventional pesticide. These nine types of pests are denoted as geno=1, 2, …9.

And if we use allele frequencies w and v denote the proportions of the respective susceptible alleles to Bt toxin and conventional pesticides in adults, the fractions of the pest population of XXYY, XXYy, XXyy, XxYY, XxYy, Xxyy, xxYY,

xxYy, xxyy are: w^2*v^2, $2*w^2*v*(1-v)$, $w^2*(1-v)^2$, $2*w*(1-w)*v^2$, $4*w*(1-w)*v*(1-v)$, $2*w*(1-w)*(1-v)^2$, $(1-w)^2*v^2$, $2*(1-w)^2*v*(1-v)$, $(1-w)^2*(1-v)^2$. The dynamic of the pest population of XXYY equal the new born minus the death. If we define the death as MR^{XXYY}, we can get that:

$$\frac{dXXYY}{dt} = w^2 * v^2 * g * D * (1-D) - MR^{XXYY}$$

Similarly, the dynamic of the pest population of XXYy, XXyy, XxYY, XxYy, Xxyy, xxYY, xxYy, xxyy are:

$$\frac{dXXYy}{dt} = 2 * w^2 * v * (1-v) * g * D * (1-D) - MR^{XXYy}$$

$$\frac{dXXyy}{dt} = w^2 * (1-v)^2 * g * D * (1-D) - MR^{XXyy}$$

$$\frac{dXxYY}{dt} = 2 * w * (1-w) * v^2 * g * D * (1-D) - MR^{XxYY}$$

$$\frac{dXxYy}{dt} = 4 * w * (1-w) * v * (1-v) * g * D * (1-D) - MR^{XxYy}$$

$$\frac{dXxyy}{dt} = 2 * w * (1-w) * (1-v)^2 * g * D * (1-D) - MR^{Xxyy}$$

$$\frac{dxxYY}{dt} = (1-w)^2 * v^2 * g * D * (1-D) - MR^{xxYY}$$

$$\frac{dxxYy}{dt} = 2 * (1-w)^2 * v * (1-v) * g * D * (1-D) - MR^{xxYy}$$

$$\frac{dxxyy}{dt} = (1-w)^2 * (1-v)^2 * g * D * (1-D) - MR^{xxyy} \qquad (4\text{-A-}1)$$

The dynamic of the pest population is straight forward:

$$\begin{aligned}\frac{dD}{dt} &= \frac{dXXYY}{dt} + \frac{dXXYy}{dt} + \frac{dXXyy}{dt} + \frac{dXxYY}{dt} + \frac{dXxYy}{dt} + \frac{dXxyy}{dt} + \frac{dxxYY}{dt} + \frac{dxxYy}{dt} + \frac{dxxyy}{dt}) \\ &= g * D * (1-D) - D * (MR^{XXYY} + MR^{XXYy} + MR^{XXyy} + MR^{XxYY} + MR^{XxYy} + MR^{Xxyy} + MR^{xxYY} + MR^{xxYy} + MR^{xxyy}) \\ &= g * D * (1-D) - D * \sum_{geno=1}^{9} MR^{geno} \end{aligned} \qquad (4\text{-A-}2)$$

The dynamic of the susceptibility of the pest population to Bt toxin, $\frac{dw}{dt}$, is

$$
\begin{aligned}
\frac{dw}{dt} &= \frac{d(\frac{wD}{D})}{dt} = \frac{d\,\frac{(w^2*v^2+w^2*v(1-v)+w^2*(1-v)^2+0.5*(2*w*(1-w)*v^2+4*w*(1-w)*v(1-v)+2*w*(1-w)*(1-v)^2)D}{D}}{dt} \\
&= \frac{(d(\frac{XXYY}{dt})+d(\frac{XXYy}{dt})+d(\frac{XXyy}{dt})+0.5*(d(\frac{XxYY}{dt})+d(\frac{XxYy}{dt})+d(\frac{Xxyy}{dt}))*D}{D^2} - \frac{\frac{dD}{dt}*(w*D)}{D^2} \\
&= \frac{\frac{dXXYY}{dt}+\frac{dXXYy}{dt}+\frac{dXXyy}{dt}+0.5*(\frac{dXxYY}{dt}+\frac{dXxYy}{dt}+\frac{dXxyy}{dt})}{D} - \frac{w*(\frac{dXXYY}{dt}+\frac{dXXYy}{dt}+\frac{dXXyy}{dt}+\frac{dXxYY}{dt}+\frac{dXxYy}{dt}+\frac{dXxyy}{dt}+\frac{dxxYY}{dt}+\frac{dxxYy}{dt}+\frac{dxxyy}{dt})}{D} \\
&= \frac{1}{D}*((1-w)*(\frac{dXXYY}{dt}+\frac{dXXYy}{dt}+\frac{dXXyy}{dt})+(0.5-w)*(\frac{dXxYY}{dt}+\frac{dXxYy}{dt}+\frac{dXxyy}{dt})-w*(\frac{dxxYY}{dt}+\frac{dxxYy}{dt}+\frac{dxxyy}{dt})) \\
&= (1-w)*(w^2*g*D*(1-D)-MR^{XXYY}-MR^{XXYy}-MR^{XXyy})+(0.5-w)*(2*w*(1-w)*g*D*(1-D)-MR^{XxYY}-MR^{XxYy}-MR^{Xxyy}) \\
&\quad -w*((1-w)^2*g*D*(1-D)-MR^{xxYY}-MR^{xxYy}-MR^{xxyy}) \\
&= (1-w)*(w^2*g*D*(1-D)-\sum^{geno=1,2,3}MR^{geno})+(0.5-w)*(2*w*(1-w)*g*D*(1-D)-\sum^{geno=4,5,6}MR^{geno})-w*((1-w)^2*g*D*(1-D)-\sum^{geno=7,8,9}MR^{geno})
\end{aligned}
\tag{4-A-3}
$$

Similarly, the dynamic of the susceptibility of the pest population to conventional pesticide, $\frac{dv}{dt}$, is

$$
\frac{dv}{dt} = (1-v)*(v^2*g*D*(1-D)-\sum^{geno=1,4,7}MR^{geno})+(0.5-v)*(2*v*(1-v)*g*D*(1-D)-\sum^{geno=2,5,8}MR^{geno})-v*((1-v)^2*g*D*(1-D)-\sum^{geno=3,6,9}MR^{geno})
\tag{4-A-4}
$$

Then the dynamic of the total pest population, susceptibility to Bt toxin and susceptibility to conventional pesticide is:

$$
\begin{aligned}
\frac{dD}{dt} &= g*D*(1-D)-D*\sum_{geno=1}^{9}MR^{geno} \\
\frac{dw}{dt} &= (1-w)*(w^2*g*D*(1-D)-\sum^{geno=1,2,3}MR^{geno})+(0.5-w)*(2*w*(1-w)*g*D*(1-D)-\sum^{geno=4,5,6}MR^{geno})-w*((1-w)^2*g*D*(1-D)-\sum^{geno=7,8,9}MR^{geno}) \\
\frac{dv}{dt} &= (1-v)*(v^2*g*D*(1-D)-\sum^{geno=1,4,7}MR^{geno})+(0.5-v)*(2*v*(1-v)*g*D*(1-D)-\sum^{geno=2,5,8}MR^{geno})-v*((1-v)^2*g*D*(1-D)-\sum^{geno=3,6,9}MR^{geno})
\end{aligned}
\tag{4-A-5}
$$

As discussed above, MR is the total mortality rate of different genotype. For example, MR^{XXYY} is the mortality rate of the pest population with XXYY genotype. According to function (4-1), the mortality rates of different genotypes are:

$$
MR^{XXYY} = w^2*v^2*D*(q*A*(hbt+hcp-hbt*hcp)+q*(1-A)*hbt+(1-q)*B*hcp)
$$

$$
\begin{aligned}
MR^{XXYy} &= 2*w^2*v*(1-v)*D*(q*A*(hbt+hcp*dcp+rcp*(1-dcp)-hbt*(hcp*dcp+rcp*(1-dcp))) \\
&+q*(1-A)*(hbt+rcp*(1-dcp)-hbt*rcp*(1-dcp)) \\
&+(1-q)*B*(hcp*dcp+rcp*(1-dcp))+((1-q)*(1-B)+nrc)*rcp*(1-dcp))
\end{aligned}
$$

$$
MR^{XXYy} = w^2*(1-v)^2*D*(q*(hbt+rcp-hbt*rcp)+((1-q)+nrc)*rcp)
$$

$$
\begin{aligned}
MR^{XxYY} &= 2*w*(1-w)*v^2*D*(q*A*(hbt*dbt+rbt*(1-dbt)+hcp-hcp*(hbt*dbt+rbt*(1-dbt))) \\
&+q*(1-A)*(hbt*dbt+rbt*(1-dbt)+rcp*(hbt*dbt+rbt*(1-dbt))) \\
&+(1-q)*B*(rbt*(1-dbt)+hcp-hcp*rbt*(1-dbt))+((1-q)*(1-B)+nrc)*rbt*(1-dbt))
\end{aligned}
$$

$$\begin{aligned}
MR^{XxYy} &= 4*w*(1-w)*v*(1-v)*D*(q*A*(hbt*dbt+rbt*(1-dbt)+hcp*dcp+rcp*(1-dcp) \\
&-(hbt*dbt+rbt*(1-dbt))*(hcp*dcp+rcp*(1-dcp))) \\
&+q*(1-A)*(hbt*dbt+rbt*(1-dbt)+rcp*(1-dcp)-rcp*(1-dcp)*(hbt*dbt+rbt*(1-dbt))) \\
&+(1-q)*B*(rbt*(1-dbt)+hcp*dcp+rcp*(1-dcp)-rbt*(1-dbt)*(hcp*dcp+rcp*(1-dcp))) \\
&+((1-q)*(1-B)+nrc)*(rbt*(1-dbt)+rcp*(1-dcp)-rbt*(1-dbt)*rcp*(1-dcp)))
\end{aligned}$$

$$\begin{aligned}
MR^{Xxyy} &= 2*w*(1-w)*(1-v)^2*D*(q*(hbt*dbt+rbt*(1-dbt)+rcp-rcp*(hbt*dbt+rbt*(1-dbt))) \\
&+(1-q+nrc)*(rbt*(1-dbt)+rcp-rcp*rbt*(1-dbt))
\end{aligned}$$

$$MR^{xxYY} = (1-w)^2*v^2*D*((q*A+(1-q)*B)*(rbt+hcp-rbt*hcp)+(q*(1-A)+(1-q)*(1-B)+nrc)*rbt)$$

$$\begin{aligned}
MR^{xxYy} &= 2*(1-w)^2*v*(1-v)*D*((q*A+(1-q)*B)*(rbt+hcp*dcp+rcp*(1-dcp)-rbt*(hcp*dcp+rcp*(1-dcp))) \\
&+(q*(1-A)+(1-q)*(1-B)+nrc)*(rbt+rcp*(1-dcp)-rbt*rcp*(1-dcp)))
\end{aligned}$$

$$MR^{xxyy} = (1-w)^2*(1-v)^2*D*(rbt+rcp-rbt*rcp) \qquad \text{(4-A-6)}$$

Where 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.

Table 4-1. 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})			
		Spread Bt field (m_{sbt}^{geno})	Non-sprayed Bt field (m_{bt}^{geno})	Spread non-Bt field (m_{snbt}^{geno})	Non-sprayed non-Bt field (m_{nbt}^{geno})
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 resistance and susceptibility to Bt cotton at locus one, respectively; and y and Y are the alleles that confer resistance and susceptibility 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.

Table 4-2: 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	0.60	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 (1999?)
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).

Table 4-3. Crop structure and carrying capacity of different crops in Yellow River Valley cotton production region, China.

	Planting area when cotton area is normalized into 1.	Carrying capacity of different crops at different generations of the CBW		
		2nd generation	3rd generation	4th generation
Cotton	1.00	1.00	1.00	1.00
Maize	2.31	0.00	0.00	1.32
Soybean	0.53	0.12	0.29	0.73
Peanut	0.40	0.29	0.26	0.62
NRC[a]		0.18	0.26	3.70

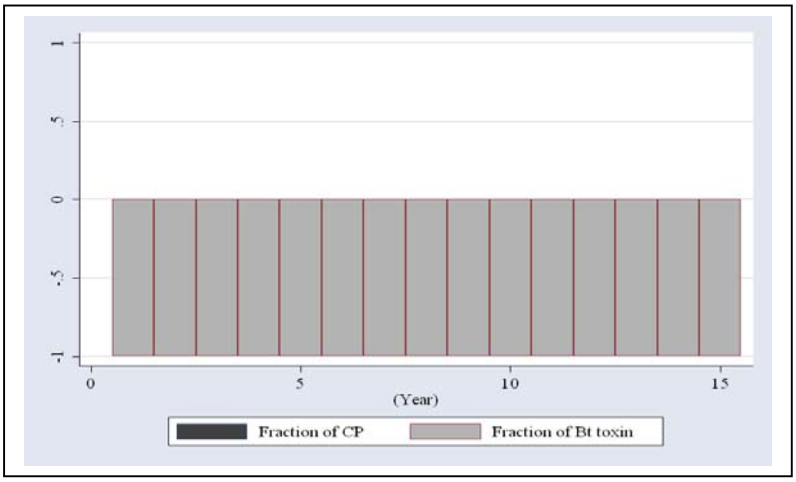
[a] NRC is the natural refuge crops coefficient, see 4.3.2.1 for its definition, calculation and explanation.

Table 4-4. Compare the cost of optimal static refuge policy and optimal dynamic refuge policy

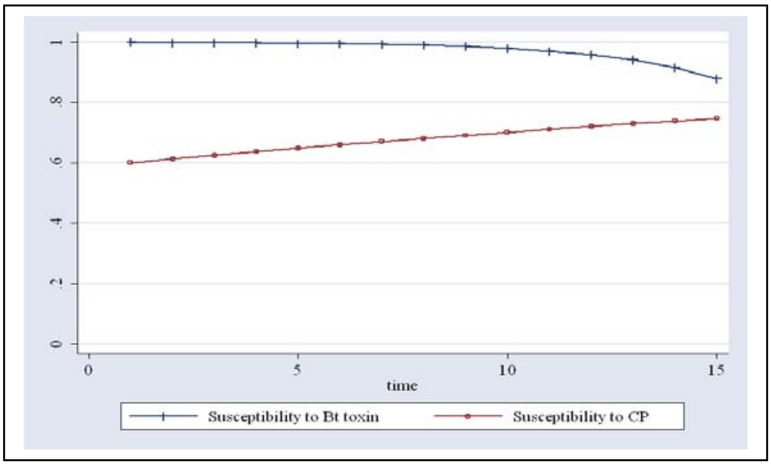
	Optimal static refuge policy		Optimal dynamic refuge policy	Cost saving from optimal static refuge policy to optimal dynamic refuge policy	
	Refuge size (%)	Average cost (US$ per ha per year)	Average cost (US$ per ha per year)	In absolute value (US$ per ha per year)	In percentage (%)
10- year-plan	0	189.59	189.59	0.00	0.00
15- year-plan	0	176.71	176.71	0.00	0.00
20- year-plan	5	175.38	174.37	1.02	0.58

Table 4-5. Compare the cost of zero refuge policy and optimal dynamic refuge policy

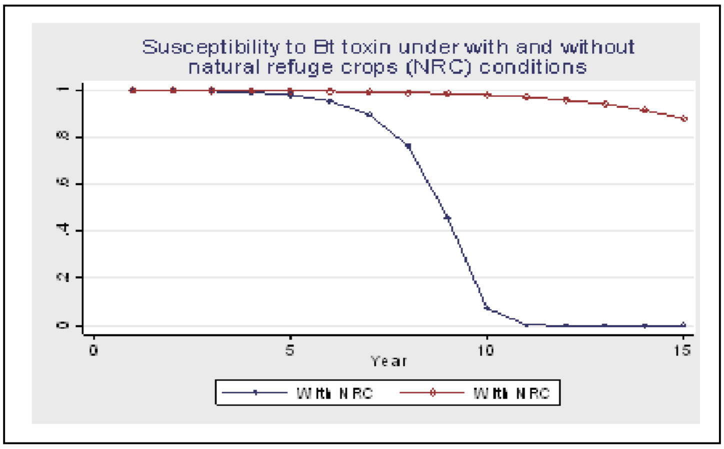
	Optimal static refuge policy	Optimal dynamic policy	Cost saving from zero refuge policy to optimal dynamic refuge strategy	
	Average cost (US$ per ha per year)	Average cost (US$ per ha per year)	In absolute value (US$ per ha per year)	In percentage (%)
10- year-plan	189.59	189.59	0.00	0.00
15- year-plan	176.71	176.71	0.00	0.00
20- year-plan	176.83	174.37	2.46	1.39



Panel A

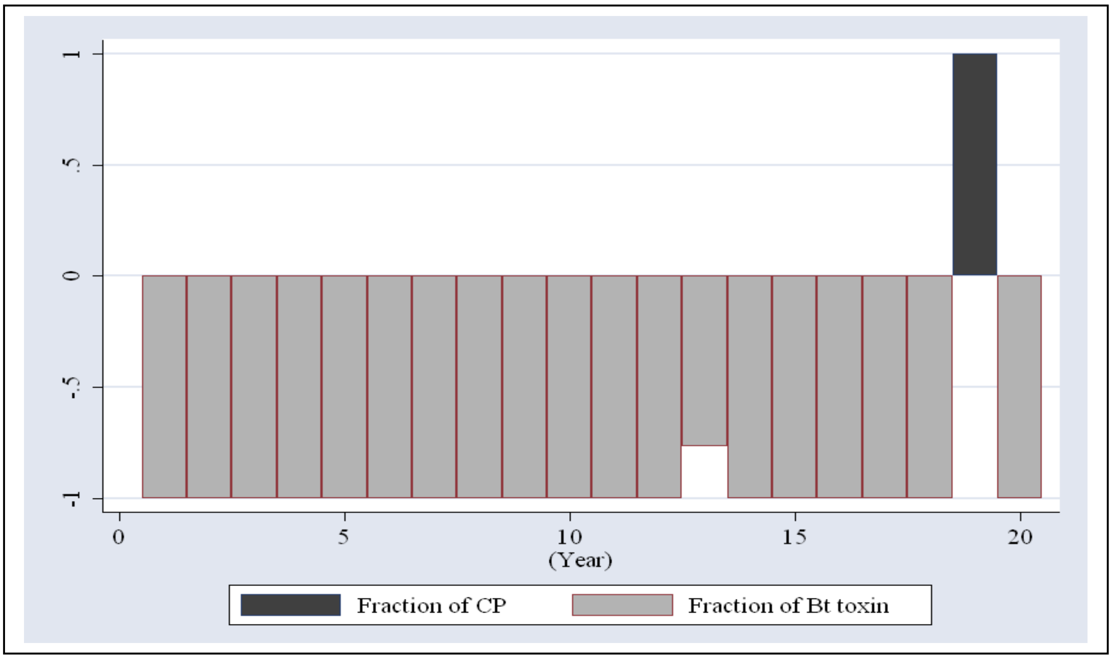


Panel B

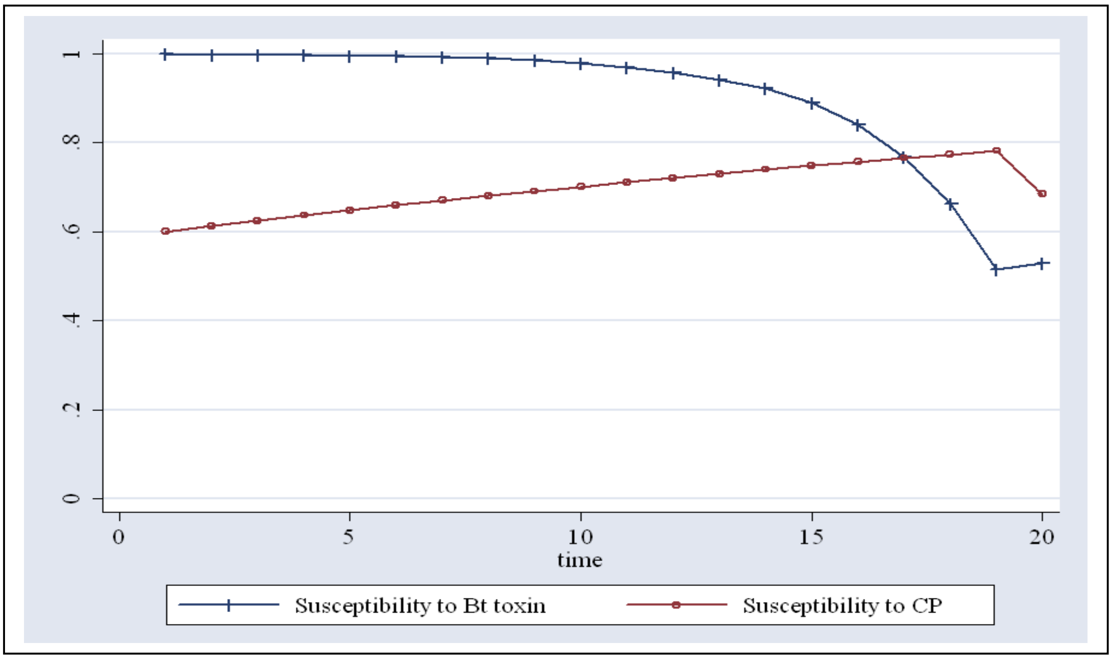


Panel C

Figure 4-1. Dynamic optimal control (fraction of land planted with Bt cotton and fraction of land spread with conventional pesticides (CP) in Panel A) and pest's susceptibilities (to both Bt toxin and conventional pesticides (CP) in Panel B) for a 15-year plan in North China.

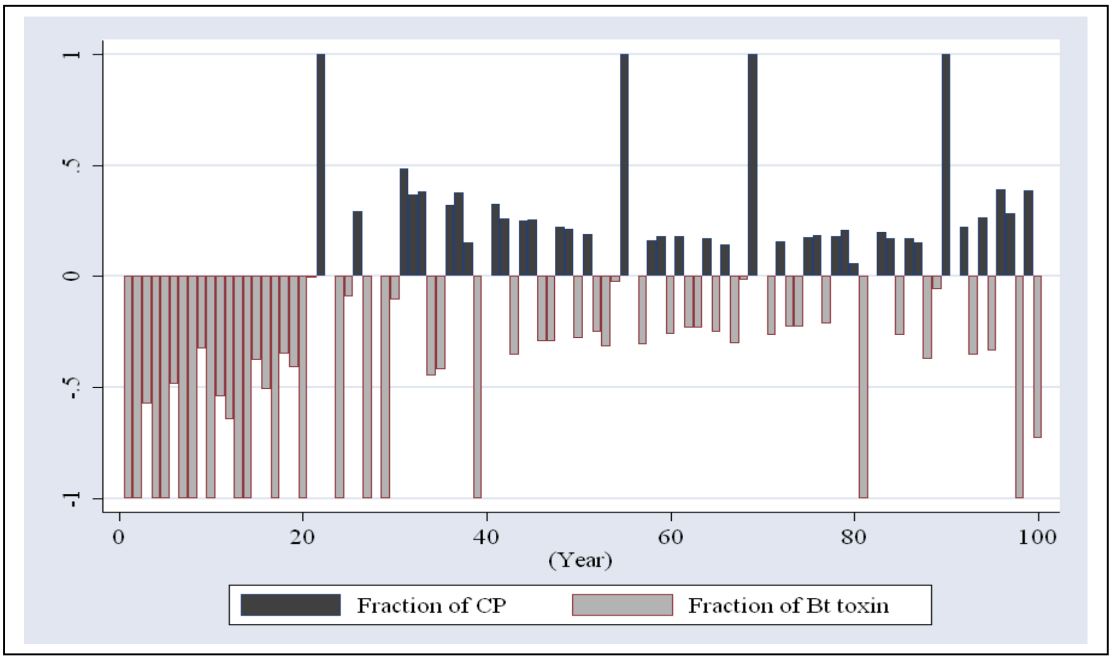


Panel A

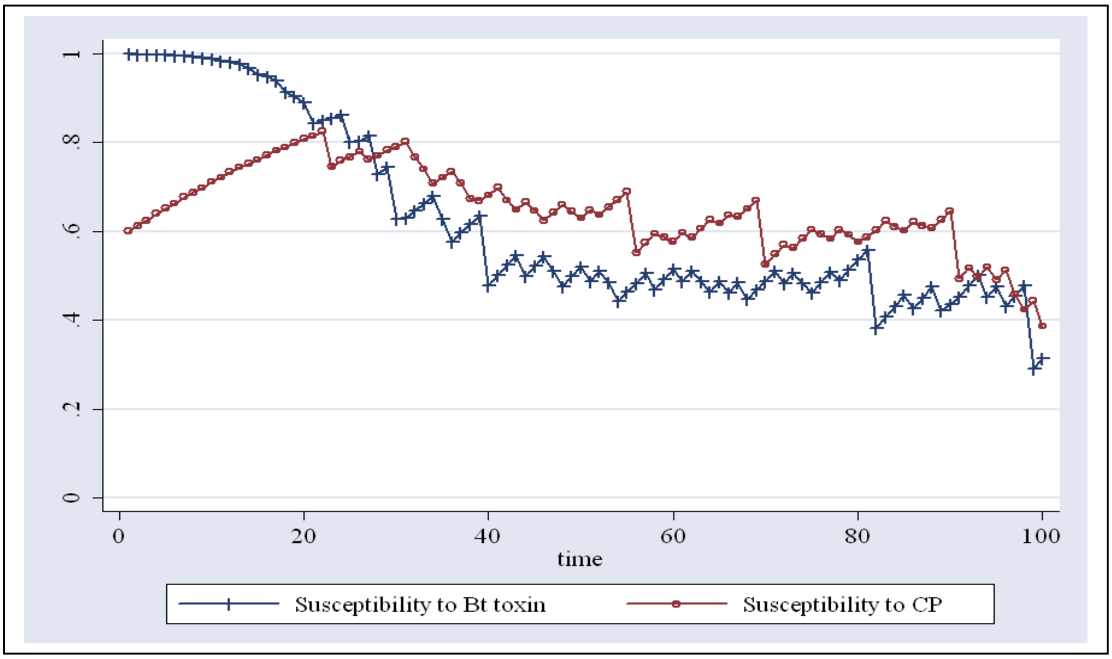


Panel B

Figure 4-2. Dynamic optimal control (fraction of land planted with Bt cotton and fraction of land spread with conventional pesticides (CP) in Panel A) and pest's susceptibilities (to both Bt toxin and conventional pesticides (CP) in Panel B) for a 20-year plan in North China.



Panel A



Panel B

Figure 4-3. Dynamic optimal control (fraction of land planted with Bt cotton and fraction of land spread with conventional pesticides (CP) in Panel A) and pest's susceptibilities (to both Bt toxin and conventional pesticides (CP) in Panel B) for a 100-year plan in North China.

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