European Review of Agricultural Economics Vol **36 (2)** (2009) pp. 253–279
doi:10.1093/erae/jbp014
Advance Access Publication 6 July 2009

Dynamically optimal strategies for managing the joint resistance of pests to Bt toxin and conventional pesticides in a developing country

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Received November 2007; final version received May 2009*

Abstract

In this study we discuss why planting non-*Bacillus thuringiensis* (non-Bt) cotton as a refuge crop in China (and other developing countries) may not be economically optimal. To show this, we develop a bioeconomic model to run simulations that will help find the optimal strategies for managing the joint resistance of pests to the Bt toxin and conventional pesticides. We show that the approach of not requiring non-Bt cotton as a refuge is defensible given initial conditions and parameters calibrated to China's cotton production environment. Of special importance is the existence of natural refuge crops. The nature of transaction costs associated with implementing a refuge policy is also considered.

Keywords: biotechnology, Bt cotton, resistance, natural refuge crops, China

JEL classification: C15, Q16, Q28

*Review coordinated by Paolo Sckokai.

1. Introduction

Bacillus thuringiensis (Bt) crops have spread quickly throughout the world, especially in the developing countries, because of significant and multiple benefits including increased yield and lower production costs due to reduced insecticide applications. China is leading the developing world in the use of Bt crops for battling pest infestation (Huang *et al.*, 2002b). China was an early adopter of Bt cotton, in response to the serious infestation of cotton bollworm[1] in the early 1990s. Bt cotton proved so popular that cotton-growing households in northern China were planting Bt cotton almost exclusively just a few years after it was introduced in 1997 (Huang *et al.*, 2003). In 2004 the area of Bt cotton sown in China reached 3.7 million ha, making China the leading adopter of Bt cotton technology. In 2006, 6.3 million farmers, or more than 60 per cent of the number of farmers who planted GM crops in the world, planted Bt cotton in China (James, 2006).

Although there are great benefits to planting Bt cotton, biotechnologies like Bt cotton appear to be two-edged swords. On the one hand, insect-resistant crop varieties have proven successful productivity-enhancing agricultural biotechnologies. On the other hand, there have been continual worries about the potential vulnerability of Bt crops to resistance adaptation by pests. An early strategy proposed to control the build up of resistance in the pest population was the use of contiguous non-Bt refuges, where non-Bt crops are planted to preserve populations of Bt-susceptible insects (Gould, 1998; Tabashnik *et al.*, 2003; Bates *et al.*, 2005). Following the initial lead of the United States, developing and developed countries alike adopted refuge policies that promote the planting of non-Bt crops in conjunction with the use of Bt technology (Kelly, 2000; Turner, 2000; Pray *et al.*, 2001; Traxler *et al.*, 2001).

China is one of the only exceptions in the world to require refuges, although this may be changing. Since its initial adoption, officials have not promoted nor required Bt cotton farmers to plant refuges of non-Bt cotton as a precondition for using Bt technology. Almost all existing quantitative economic studies have focused on refuge strategies in US cropping systems (Gould, 1998; Hurley *et al.*, 2002, 2006; Livingston *et al.*, 2004, 2007), and hence it is not clear whether findings pertinent to such systems are appropriate for every country. Some scientists believe that China does not need special non-Bt cotton refuges because most crops that are grown in conjunction with cotton in China, such as maize, soybean and peanuts, can function as natural refuges for cotton bollworm *Helicoverpa armigera* (Wu *et al.*, 2002, 2005). It is also not clear whether the United States will continue to require refuges in the future. In fact, the United States Environmental Protection Agency is rethinking the requirements for refuges for some regions where dual toxin Bt cotton is planted with sufficient natural refuge crops (NRC) (Banerjee and Martin, 2008).

1 In China, as well as in Australia, the cotton bollworm is *Helicoverpa armigera*, which is a similar species to the cotton bollworm in the United States (*Helicoverpa zea*).

Even if refuges were a way of reducing the build up of resistance to the Bt toxin, the large number of small householders makes enforcing any refuge strategy in a developing country like China a challenging activity. In previous studies on refuge policies in large-scale, extensive US agricultural systems, it is implicitly assumed that the monitoring and implementation costs associated with refuge policies are negligible. Although these assumptions may be reasonable in extensive systems with small numbers of farms, they may not be appropriate in developing countries. In developing countries like China, the farming sector is composed of millions of small-holder households on highly fragmented farms. Each household often grows a diverse set of crops. As a result, it is likely that implementing the US-style refuge strategy (i.e. all farmers who plant Bt cotton are required to plant non-Bt cotton as refuge) would require a large enforcement effort, making these kinds of refuge strategies unfeasible unless farmers have strong individual incentives to implement refuges based on self-interest. This is unlikely, since the build up of resistance to Bt technology is a collective bad (as compared with the more common public good) that is unlikely to be accounted for by individuals.

The goal of this study was to empirically examine whether China needs to re-think its zero-refuge policy for managing the resistance of the pests to Bt cotton. To do this, in the next section we develop a dynamic bioeconomic model to estimate the optimal refuge strategy for Bt cotton. In this model, both resistance of the pest to Bt toxin and resistance to conventional pesticides are considered. Data sources and parameters are discussed in the third section. Biological and economic parameters, which are based on either empirical data or previous studies, are used to mimic different facets of north China's actual production environment, such as the nature of the region's cropping patterns (with a focus especially on the existence of NRC). In the fourth section, simulation results of the model 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. Finally, we discuss the implications of this study.

2. The model

The integrated bioeconomic model we use follows the epidemiological model presented by Wilen and Msangi (2002). A similar approach has been used in the models presented by Laxminarayan and Simpson (2002), Hurley *et al.* (2002) and Livingston *et al.* (2004) in their studies on refuge strategies. We build our bioeconomic model in two steps. First, we set up a biological model to simulate the dynamics of the pest population size and the evolution of the build up of resistance over time. Second, we build a regulatory model to examine which refuge strategy is economically optimal.

2.1. Biological model

In biological models of pests, extended Hardy–Weinberg models are routinely used to simulate the evolution of resistance to Bt toxin, with demonstrated empirical success (Hurley *et al.*, 2002; Livingston *et al.*, 2004). The pest population is assumed to be local and both in- and out-migration is ruled out.[2] We use a two-locus four-allele model to simulate resistance evolution to both Bt toxin and conventional pesticide under the following assumptions: (a) there are large and equal numbers of diploid females and males that mate randomly; (b) genetic mutation in resistance evolution can be ignored; (c) resistance to each toxin is conferred at one locus by one gene; (d) the probability that a gamete (sperm or egg) contains one allele is independent of its containing one of the other three; and (e) there are four non-overlapping generations of pests per calendar year and pests have different host plants during each generation.

Following previous studies (Clark, 1976), we assume that the pest population (denoted by D) grows logistically at an intrinsic growth rate of g. The carrying capacity of the total number of pests per unit of cotton land is normalised to 1. If this is so, the total number of newborn cotton bollworms in every generation is given by $gD(1-D)$. From this gross addition to the population, we must subtract mortality among pests to get the net addition to the size of the total pest population in time step.

For a given pest, let x and X denote the alleles that confer resistance and susceptibility to Bt toxin at locus one, respectively. Similarly, let y and Y denote the alleles that confer resistance and susceptibility to a conventional pesticide at locus two. Under these assumptions, we can identify nine types of pests with different genotypes. These genotypes are *XXYY*, *XXYy*, *XXyy*, *XxYY*, *XxYy*, *Xxyy*, *xxYY*, *xxYy* and *xxyy* (see Appendix 1 for details). We use allele frequency w to denote the proportion of the alleles that are susceptible to Bt toxin; we also use allele frequency v to denote the proportion of the alleles that are susceptible to conventional pesticides. Given this, the fractions of these nine types of pests with different genotypes in the total pest population (denoted by f_l) are: w^2v^2, $2w^2v(1-v)$, $w^2(1-v)^2$, $2w(1-w)v^2$, $4w(1-w)v(1-v)$, $2w(1-w)(1-v)^2$, $(1-w)^2v^2$, $2(1-w)^2v(1-v)$ and $(1-w)^2(1-v)^2$.

One of the keys to the modelling of our problem is that the mortality rate of the pests varies with both the genotypes and the treatments. To simplify, the total sown land of cotton is normalised to 1. The two treatments, Bt toxin and the conventional pesticide, divide the total arable land into four land fractions (denoted by lf): Bt cotton field (with the fraction of q) with conventional pesticide spray (with a fraction A), Bt cotton field without conventional

2 In reality, moths can move freely across relatively large areas that extend beyond the boundaries of each decision-maker's spatial purview. We ignore this because it would be difficult to combine both the intertemporal dynamics that we are interested in (that is, the intertemporal dynamics in the bioeconomic model) and more realistic spatial characteristics of the actual landscape. We acknowledge that in some applications the spatial dynamics could be interesting and could produce insights about refuge policy questions. However, as has been discussed by Wilen (2007), incorporating realistic spatial–dynamic processes calls for a much more complex entomological model as well as a landscape model with multiple decision-makers.

pesticide spray (with the fraction $1 - A$), non-Bt cotton field (with the fraction of $1 - q$) with the conventional pesticide spray (with the fraction B), non-Bt cotton field without conventional pesticide spray (with a fraction $1 - B$) and natural refuge crop field which is assumed to be non-Bt and without conventional pesticide spray. The mortality rates of different genotypes (denoted by m_l) on land with different treatments are shown in Table 1. The sub-total mortality rate of each genotype, MR, is the fraction of the genotype in the total pest population (f_l) multiplied by the sum of the mortalities on different lands (m_l) multiplied by the share of the land type (or the land fraction – lf), or

$$MR_{t,l} = f_l \sum_j lf_j m_{j,l} \quad j = \text{sbt, bt, snbt, nbt} \tag{1}$$

In addition, the *total* mortality rate of the pest population is the sum of the sub-total mortality rate of different genotypes, or $\sum_{l=1}^{l=9} MR_{t,l}$. With these definitions, the dynamics of the susceptibility to Bt toxin ($\mathrm{d}w/\mathrm{d}t$), the susceptibility to conventional pesticide ($\mathrm{d}v/\mathrm{d}t$), and the total pest population ($\mathrm{d}D/\mathrm{d}t$) can be written as (see Appendix 1 for details)[3]:

$$\begin{aligned}
\frac{\mathrm{d}w}{\mathrm{d}t} &= (1-w)\left(w^2 gD(1-D) - \sum_{l=1}^{l=3} MR_l\right) + (0.5-w) \\
&\quad \times \left(2w(1-w)gD(1-D) - \sum_{l=4}^{l=6} MR_l\right) \\
&\quad - w\left((1-w)^2 gD(1-D) - \sum_{l=7}^{l=9} MR_l\right) \\
\frac{\mathrm{d}v}{\mathrm{d}t} &= (1-v)\left(v^2 gD(1-D) - \sum_{l=1,4,7} MR_l\right) + (0.5-v) \\
&\quad \times \left(2v(1-v)gD(1-D) - \sum_{l=2,5,8} MR_l\right) \\
&\quad - v\left((1-v)^2 gD(1-D) - \sum_{l=3,6,9} MR_l\right) \\
\frac{\mathrm{d}D}{\mathrm{d}t} &= gD(1-D) - D\sum_{l=1}^{l=9} MR_l
\end{aligned} \tag{2}$$

3 Each of the nine possible genotypes is numbered consecutively. See Appendix 1 for details.

Table 1. Nine pests with different genotypes, their fractions in the total pest population and mortality rates in different fields

Genotype (p^l)	Fraction (f^l)	Mortality rates in different fields (m^l)			
		Sprayed Bt field (m^l_{sbt})	Non-sprayed Bt field (m^l_{bt})	Sprayed non-Bt field (m^l_{snbt})	Non-sprayed non-Bt field (m^l_{nbt})
XXYY	w^2v^2	$h_{bt} + h_{cp} - h_{bt}h_{cp}$	h_{bt}	h_{cp}	0
XXYy	$2w^2v(1 - v)$	$h_{bt} + h_{cp}d_{cp} + r_{cp}(1 - d_{cp}) - h_{bt}[h_{cp}d_{cp} + r_{cp}(1 - d_{cp})]$	$h_{bt} + r_{cp}(1 - d_{cp}) - h_{bt}r_{cp}(1 - d_{cp})$	$h_{cp}d_{cp} + r_{cp}(1 - d_{cp})$	$r_{cp}(1 - d_{cp})$
XXyy	$w^2(1 - v)^2$	$h_{bt} + r_{cp} - h_{bt}r_{cp}$	$h_{bt} + r_{cp} - h_{bt}r_{cp}$	r_{cp}	r_{cp}
XxYY	$2w(1 - w)v^2$	$h_{bt}d_{bt} + r_{bt}(1 - d_{bt}) + h_{cp} - h_{cp}[h_{bt}d_{bt} + r_{bt}(1 - d_{bt})]$	$h_{bt}d_{bt} + r_{bt}(1 - d_{bt})$	$r_{bt}(1 - d_{bt}) + h_{cp}h_{cp}r_{bt}(1 - d_{bt})$	$r_{bt}(1 - d_{bt})$
XxYy	$4w(1 - w)v(1 - v)$	$h_{bt}d_{bt} + r_{bt}(1 - d_{bt}) + h_{cp}d_{cp} + r_{cp}(1 - d_{cp}) - [h_{bt}d_{bt} + r_{bt}(1 - d_{bt})][h_{cp}d_{cp} + r_{cp}(1 - d_{cp})]$	$h_{bt}d_{bt} + r_{bt}(1 - d_{bt}) + r_{cp}(1 - d_{cp}) - [h_{bt}d_{bt} + r_{bt}(1 - d_{bt})]$ $r_{cp}(1 - d_{cp})$	$r_{bt}(1 - d_{bt}) + h_{cp}d_{cp} + r_{cp}(1 - d_{cp})$ $r_{bt}(1 - d_{bt})[h_{cp}d_{cp} + r_{cp}(1 - d_{cp})]$	$r_{bt}(1 - d_{bt}) + r_{cp}(1 - d_{cp}) - r_{bt}(1 - d_{bt})r_{cp}(1 - d_{cp})$
Xxyy	$2w(1 - w)(1 - v)^2$	$h_{bt}d_{bt} + r_{bt}(1 - d_{bt}) + r_{cp} - r_{cp}[h_{bt}d_{bt} + r_{bt}(1 - d_{bt})]$	$h_{bt}d_{bt} + r_{bt}(1 - d_{bt}) + r_{cp} - r_{cp}[h_{bt}d_{bt} + r_{bt}(1 - d_{bt})]$	$r_{bt}(1 - d_{bt}) + r_{cp} - r_{cp}r_{bt}(1 - d_{bt})$	$r_{bt}(1 - d_{bt}) + r_{cp} - r_{cp}r_{bt}(1 - d_{bt})$
xxYY	$(1 - w)^2v^2$	$r_{bt} + h_{cp} - r_{bt}h_{cp}$	r_{bt}	r_{bt}	$r_{bt} + h_{cp} - r_{bt}h_{cp}$
xxYy	$2(1 - w)^2v(1 - v)$	$r_{bt} + (h_{cp})d_{cp} + r_{cp}(1 - d_{cp}) - r_{bt}[h_{cp}d_{cp} + r_{cp}(1 - d_{cp})]$	$r_{bt} + r_{cp}(1 - d_{cp}) - r_{bt}r_{cp}(1 - d_{cp})$	$r_{bt} + h_{cp}d_{cp} + r_{cp}(1 - d_{cp}) - r_{bt}[h_{cp}d_{cp} + r_{cp}(1 - d_{cp})]$	$r_{bt} + r_{cp}(1 - d_{cp}) - r_{bt}r_{cp}(1 - d_{cp})$
xxyy	$(1 - w)^2(1 - v)^2$	$r_{bt} + r_{cp} - r_{bt}r_{cp}$	$r_{bt} + r_{cp} - r_{bt}r_{cp}$	$r_{bt} + r_{cp} - r_{bt}r_{cp}$	$r_{bt} + r_{cp} - r_{bt}r_{cp}$

Note: x and X are alleles that confer resistance and susceptibility to Bt cotton at locus one, respectively; y and Y are 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; h_{bt} is the mortality rate of the homozygote susceptible pests to Bt toxin in Bt cotton field; r_{bt} is the mortality rate of the homozygote resistant pests to Bt toxin; d_{bt} is the dominance of x allele in the heterozygosity pests with Xx alleles; h_{cp} is the mortality rate of the homozygote susceptible pests to conventional pesticides if sprayed; r_{cp} is the mortality rate of the homozygote resistant pests to conventional pesticides; d_{cp} is the dominance of y allele in the heterozygosity pests with Yy alleles.

2.2. Regulatory model

The regulatory model is used to determine economically optimal refuge strategies. In this model, we assume a social planner is minimising the total discounted cost subject to the dynamics of the pest population over time. Two types of costs are included during each calendar year. The first type of cost is the damage costs caused by the pest. Damage costs are assumed to have a linear relationship with the total pest population in the cotton field. Even though cotton bollworms can also damage NRC, the damage costs are relatively small and farmers usually do not spray pesticide in these fields (Guo *et al.*, 2004; Ding and Zhang, 1994). Hence in this study, we ignore the damage costs in these natural refuge crop fields and assume farmers do not spray for bollworms in these fields. The second type of cost is the treatment cost, or the costs associated with Bt cotton planting and/or conventional pesticide sprays of cotton. These treatment costs are assumed to be proportional to the fraction of land treated. Total costs are calculated as the sum of the discounted damage costs and treatment costs. The social planner minimises total costs by choosing a series of optimal refuge sizes, subject to the dynamics of the size of the pest population and the build up of the resistance to both Bt toxin and the conventional pesticide, both simulated with the biological model.

Following Wilen and Msangi (2002), we develop a discretised form of this problem that can be solved with empirical numerical optimisation software. We can optimise this problem by using the Bellman equation, which can be written as:

$$\underset{\substack{0\le q_k\le 1\\ 0\le A_k\le 1\\ 0\le B_k\le 1}}{\text{Min}}\; V_k(D_k) = n_k\alpha + c_{\text{bt}}q_k + c_{\text{cp}}[q_kA_k + (1-q_k)B_k] + \delta V_{k+1}(D_{k+1})$$

s.t.

$$D_{t+1} - D_t = gD_t(1-D_t) - \sum_{l=1}^{l=9} MR_{t,l}, \quad D_{t=0} = D_0$$

$$\begin{aligned} w_{t+1} - w_t = (1-w_t)\left(w_t^2 gD_t(1-D_t) - \sum_{l=1}^{l=3} MR_{t,l}\right) + (0.5-w_t) \\ \times\left(2w_t(1-w_t)gD_t(1-D_t) - \sum_{l=4}^{l=6} MR_{t,l}\right) \\ + w_t\left((1-w_t)^2 gD_t(1-D_t) - \sum_{l=7}^{l=9} MR_{t,l}\right), \quad w_{t=0} = w_0 \end{aligned}$$

$$v_{t+1} - v_t = (1-v_t)\left(v_t^2 gD_t(1-D_t) - \sum_{l=1,4,7} MR_{t,l}\right) + (0.5-v_t)$$

$$
\begin{aligned}
&\times\left(2v_t(1-v_t)gD_t(1-D_t)-\sum_{l=2,5,8} MR_{t,l}\right)\\
&\quad+v_t\left((1-v_t)^2 gD_t(1-D_t)-\sum_{l=3,6,9} MR_{t,l}\right),\qquad v_{t=0}=v_0\\
&\mathrm{DCTN}_t=D_{t+1}-\frac{\mathrm{NRC}_t}{1+\mathrm{NRC}_t}\left(D_t+gD_t(1-D_t)-D_t\sum_{l=1}^{l=9} f_l m_l\right)\\
&n_k=\sum_{t=2+4(k-1)}^{t=4+4(k-1)}\frac{\mathrm{DCTN}_t}{3}
\end{aligned}
\tag{3}
$$

where the function $V(D_{k+1})$ gives the carry-over cost from one year k to the next year $k+1$ which we also seek to minimise and discount (ρ is the discount rate) with the factor; t denotes the generation time; α is the average damage cost caused by a unit of the pest population; c_{bt} is the unit cost associated with Bt cotton planting; c_{cp} is the unit cost of conventional pesticides spray; n_k is the total pest population in the cotton field portion of the farming system during year k; DCTN_t is the total pest population in the cotton field portion of the farming system belonging to generation t; NRC_t is the coefficient of the NRC faced by generation t, which is defined as $\mathrm{NRC}_t=\left(\sum_{i=1} Q_{t,i}P_i/\sum_{i=1} Q_{t,i}P_i+P_c\right)$ where i is the ith natural refuge crop, $Q_{t,i}$ is the relative pest density of the ith crop at generation t. P_i is the crop proportion of the ith crop while P_c is the crop proportion of cotton. As assumed above, the cotton bollworm passes through (reproduces and dies and reproduces again) four generations per year. Bollworms feed on cotton only during the second, third and fourth generations. Hence, we assume $n_k=\sum_{t=2+4(k-1)}^{t=4+4(k-1)}(\mathrm{DCTN}_t/3)$. In addition, we assume that both the proportions of Bt cotton fields sprayed with conventional pesticides, and the proportions of non-Bt cotton fields sprayed with conventional pesticides are constant during the second, third and fourth generations.

3. Data and parameters

3.1. Data set

The data for this study come from three sources: household-level field surveys undertaken during 1999–2003 in China, a village-level field survey undertaken in 2004 and lab and field experiments undertaken during 1999–2003. The first two data sets are used to estimate the economic parameters. The third data set is used to estimate the biological parameters. Table 2 presents the benchmark configuration for all parameters used in this study.

The first data set was collected by the Center for Chinese Agricultural Policy (CCAP) of the Chinese Academy of Sciences (CAS). In 1999,

Table 2. Default values of biological and economic parameters and their sources

	Default value	Source
Economic parameters		
Unit damage cost caused by the cotton bollworm	$1,030/ha	Calculated based on data collected by IPP
Bt cotton planting cost	$143/ha	Calculated based on data collected by CCAP
Conventional pesticide spray cost	$ 252/ha	Calculated based on data collected by CCAP
Discount rate	0.036	The People's Bank of China (2006)
Biological parameters		
Initial resistant (to Bt toxin) gene frequency	0.001	Livingston *et al.* (2004) and Gould (1998)
Initial resistant (to conventional pesticide) gene frequency	0.60	Ru *et al.* (2002) and Li *et al.* (2004)
Mortality rate of susceptible pest to Bt toxin in Bt field	0.90	Livingston *et al.* (2004), Storer *et al.* (2003), Wu (2002) and Caprio (1998)
Mortality rate of susceptible pest to conventional pesticides if spray	0.90	Authors' assumption
Fitness cost of resistant pests to Bt toxin	0.05	Livingston *et al.* (2002, 2004) and Wu (personal communication)
Fitness cost of resistant pests to conventional pesticides	0.05	Authors' assumption
Dominance of susceptible gene (to Bt toxin) in heterozygote	0.75	Wu (personal communication)
Dominance of susceptible gene (to conventional pesticide) in heterozygote	0.75	Authors' assumption
Natural growth rate	0.68	Calculated using CCAP's data set

IPP, Institute of Plant Protection of the Chinese Academy of Agricultural Science; CCAP, Center for Chinese Agricultural Policy of the Chinese Academy of Sciences.

CCAP began its first round of Bt cotton field surveys in the Yellow River Valley, which is the largest cotton producing region in China. This region was also the first region where Bt cotton was released. After 1999, CCAP not only repeated the field survey in the Yellow River Valley, but it also conducted the same survey in the Yangtze River Valley, the nation's second largest cotton producing region. During these household surveys, enumerators collected a wide range of information on Bt cotton and non-Bt cotton producing activities as well as information on other household-specific characteristics. Details of this data set can be found in several previous studies (Pray *et al.*, 2001; Huang *et al.*, 2002a, 2003).

The second data set was collected by the authors in the Yellow River Valley during the summer of 2004. The first objective of this field survey was to understand the diversity of cropping patterns in China's main cotton producing regions. The second objective was to estimate the enforcement and monitoring costs associated with a refuge policy, if China's officials were to require them. This field survey was conducted in 114 villages in four counties in the Yellow River Valley. The share of the sown area that was planted to cotton was more than 50 per cent in two of the four sample counties; it was less than 50 per cent in the other two counties. In each county, one township with a high proportion of cotton and one township with a low proportion of cotton were randomly chosen. All the village leaders in these two townships were interviewed. The village-level data set contains information on the spatial patterns of cropping, especially the distribution and planting areas of cotton and all the NRC for cotton bollworms. Village leaders were also asked to estimate the enforcement and monitoring costs associated with a hypothetical refuge monitoring policy. To our knowledge, this is the first data gathered anywhere in any system on the monitoring and enforcement costs of implementing a refuge for Bt cotton.[4]

The third data set was collected by the scientists of the Institute of Plant Protection (IPP) of the Chinese Academy of Agricultural Science (CAAS) in both their laboratories and fields. The IPP began to systematically collect detailed information about the build up of resistance in pest populations to commonly used insecticides beginning in 1994. This was shortly after huge yield losses began to occur in the Yellow River Valley due to outbreaks of cotton bollworm that could not be effectively controlled by spraying conventional pesticides. After the introduction of Bt cotton in 1997, IPP also began to monitor the evolution of the resistance of the cotton bollworm to Bt toxin. This data set not only includes the information about the build up of resistance in the pest population in the lab when all the environmental conditions were controlled for, but also information about the build up of resistance in the field. Other related information, such as yield loss due to pests and pest density in cotton fields as well as in different natural refuge crop fields, was also collected.

3.2. Biological parameters

The levels of all biological parameters used to simulate resistance evolution and average larval survival rates were either based on previous studies or calculated using the data sets described above. We based Bt-resistance parameters on available laboratory studies, because sufficient field data on Bt-resistance were unavailable. Even though Bt cotton has been commercialised for about 10 years, there is no field evidence of the build up of resistance (Fox, 2003; Tabashnik *et al.*, 2003) and hence we had to rely on laboratory data. Fortunately, we had sufficient field data to estimate the relevant biological parameters of the build up of the resistance to the conventional pesticide.

4 Details on the survey design are provided in Appendix 2.

The other remaining parameters, such as the intrinsic growth rate of the pest population, were calculated using the data set collected by IPP.

The survival rates of susceptible homozygotes and heterozygotes were based on previous studies. Earlier work demonstrated that Bt cotton could control about 80–95 per cent pests on average in the Yellow River Valley (Wu, 2002; Li *et al.*, 2004). Based on these studies (from China) and empirical studies in the United States (Caprio, 1998; Burd *et al.*, 2001; Storer *et al.*, 2003; Livingston *et al.*, 2004), we assume that the mortality rate of pests with double susceptible genes to Bt toxin is 0.90 in Bt cotton fields. As assumed in Livingston *et al.* (2004, 2002), we also assume that the mortality rate of pests with double resistant genes to Bt toxin, the so-called 'fitness cost', is 0.05. Following interviews with Dr Wu Kongming, the chief entomologist in China, we make the assumption that the dominant level of susceptible genes in the heterozygote pests is 0.75. In other words, a pest with a susceptible gene and a resistant gene is 75 per cent like a pest with double susceptible genes, and 25 per cent like a pest with double resistant genes. Similarly, we assume the mortality rates of pests with double susceptible genes to the conventional pesticide, the mortality rate of pests with the double-resistant genes (or the fitness cost) to the conventional pesticide, and the dominant level of susceptible gene to the conventional pesticide in the heterozygote are 0.90, 0.05 and 0.75, respectively.

Previous studies also found the frequency of resistance alleles to Bt toxin in the cotton bollworm to be of the order of magnitude of one in a thousand in China (Ru *et al.*, 2002; Li *et al.*, 2004) as well as in the United States (Gould, 1995; Onstad and Gould, 1998; Livingston *et al.*, 2004). As a result, this value has been widely used in many empirical studies, such as Onstad and Gould (1998), Livingston *et al.* (2004, 2002), etc. In this study, we also assume an initial frequency of resistant alleles of one in a thousand.

Fortunately, we had enough field data to estimate the fraction of susceptible genes to the conventional pesticide. Using a model similar to equation (1), and using data collected by the Institute of Plant Protection of the Chinese Academy of Agricultural Sciences during the time period 1991 to 2002, we estimated the fraction of the genes in the bollworm population that were susceptible to conventional pesticides. According to equation (2), changes in the susceptible genes alleles (dependent variable) are a function of the level of susceptible genes, mortality rate of susceptible pests, mortality rate of resistant pests, etc. Using data collected by IPP, we estimated the coefficients using ordinary least squares (OLS) regression in a manner similar to that of Livingston *et al.* (2002).

The estimation shows that the fraction of the susceptible genes was 0.60 after Bt cotton had been widely planted in Yellow River Valley in 2000. Although it is difficult to verify precisely, these numbers are consistent with the situation that is observed in the field where farmers claim that the mortality rates of pests that are found in their fields after spraying are about this level.

Similarly, using data that the IPP has collected over time, we estimated the intrinsic growth rate per generation (available from the authors upon request).

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

	Planting area when cotton area is normalised to 1	Relative pest density when pest density in cotton field is normalised to 1		
		Second generation	Third generation	Fourth 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_t^a		0.18	0.26	3.70

Source: Author's survey.
[a]NRC_t is the NRC coefficient, see Section 3 for its definition, calculation and explanation.

According to equation (2), the change of the pest population (our dependent variable) is a function of level of the pest population and the population's mortality rate. Because we have all of these data over time, we can estimate the intrinsic growth rate by OLS regression.

The magnitude of the NRC coefficient is determined by the relative pest density and the relative area of NRC. Even though many crops, fruit trees and weeds are the host plants for cotton bollworm, for simplicity (and for reasons related to the availability of data), we focus on the most important four NRC: wheat, maize, soybeans and peanuts. These four crops are not only the main crops in Yellow River Valley, but also the crops with relatively high pest densities. During the first generation, cotton bollworms only feed on wheat in the spring. In the second, third and fourth generations, bollworms can feed on cotton, soybeans, peanuts and other crops. During the fourth generation, maize becomes one of the most important host plants. Pest density and planting area of NRC and cotton are shown in Table 3. As in Table 3, the NRC coefficient is 0.18, 0.26 and 3.70 for the second, third and fourth generations (last row).

3.3. Economic parameters

Most of the economic parameters in the model were calculated using information from CCAP's household-level data set. The cost parameter in the objective function includes three parts: yield loss caused by the pests, costs associated with Bt cotton planting and expenditures on conventional pesticide sprays. Transaction costs associated with implementing and enforcing the policy are excluded in the model, although we discuss them later. The damage cost caused by the cotton bollworm is USD 1,030 per ha if no conventional pesticides are sprayed in the non-Bt cotton field. The cost of conventional pesticides spray for cotton bollworm control, including both expenditures on pesticides and related labour costs, is USD 252 per ha.

Costs associated with Bt cotton planting are USD 143 per ha, which include Bt cotton seed cost, expenditures on conventional pesticides for other pests besides cotton bollworm and disease and related labour costs. All other inputs costs (for example, expenditures on fertiliser and irrigation) are assumed to be the same whether the farmer planted Bt cotton or non-Bt cotton.

The real discount rate and the length of the time horizon are two important parameters in our study of the optimal refuge strategy. The long-term (longer than 5 years) deposit rate, 3.6 per cent per year, is used in this study as a proxy for the discount rate. A similar discount rate was used by Livingston *et al.* (2004) and Hurley *et al.* (2006). We define the year 2000 as the initial year when the proportion of Bt cotton was more than 90 per cent in the Yellow River Valley. Following other empirical studies (Livingston *et al.*, 2004; Hurley *et al.*, 2006), we use a 15-year planning horizon in our model's benchmark and alternative scenarios.

4. Results

Annualised costs under static and dynamic solutions to our bioeconomic model are reported in Table 4. The model was simulated under two assumptions: a constant refuge size (the solution we refer to as the *static solution*) and optimally varying refuge sizes (the solution we call the *dynamic solution*) over the time horizon. The 15-year planning horizon was considered as the benchmark scenario, while 10- and 20-year planning horizons were also simulated to test the robustness of the model and the impact of the time horizon on refuge policy strategy. We used a standard solver for General Algebraic Modeling System to compute both the optimal dynamic and static solutions.

For the 10- and 15-year planning horizons, both the dynamic and static solutions show that planting non-Bt cotton as refuge crops is not economically optimal (Table 4, the first two rows). As shown in Table 4, always planting

Table 4. Comparison of the cost of optimal static and dynamically refuge policies

	Optimal static refuge policy		Optimal dynamic refuge policy; Average cost ($ per ha per year)	Cost saving from optimal dynamic refuge policy vs. optimal static refuge policy	
	Refuge size (%)	Average cost ($ per ha per year)		In absolute value ($ per ha per year)	In percentage (%)
10-year planning horizon	0	189.59	189.59	0.00	0.00
15-year planning horizon	0	176.71	176.71	0.00	0.00
20-year planning horizon	5	175.38	174.37	1.01	0.58

100 per cent Bt cotton minimises the average annual cost of cotton production. In other words, planting non-Bt cotton as refuge is not economic for a short-term plan (15 or 10 years). Optimal dynamic controls of Bt cotton and conventional pesticide for a 15-year planning horizon are shown in Figure 1A. As shown in the figure, the optimal choice is to plant 100 per cent Bt cotton without conventional pesticide sprays for 15 years.

The key to understanding the simulation results is to understand the impact of the NRC on the build up of the resistance. Having non-Bt cotton as a refuge allows Bt-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. NRC function in the same way. By providing refuges for susceptible pests, these NRC help to slow the build up of resistance and maintain the effectiveness of the Bt cotton. Hence, as shown in Figure 1B, the fraction of susceptible pests to the Bt toxin is still relatively high even after 100 per cent Bt cotton is continuously planted for 15 years. However, if NRC are not available and 100 per cent Bt cotton is continuously planted, the susceptibility of the pest to Bt toxin declines quickly. As shown in Figure 1C, under these assumptions, the proportion of Bt-susceptible pests is driven to virtually zero at the 15th year.

Compared with those of the optimal static refuge strategy, the production costs of the optimal dynamic refuge strategy are lower, as would be expected. As the time horizon gets longer, continuously planting 100 per cent Bt cotton is no longer optimal for either a static or a dynamic refuge policy. As shown in Figure 1B, the susceptibility of the pest to Bt toxin decreases as 100 per cent Bt cotton is continuously planted. We can expect that the susceptibility will be driven to a low level so that Bt toxin at some point becomes inefficient. Under these circumstances, farmers finally have to totally or partly give up their strategy of planning 100 per cent Bt cotton. In other words, planting non-Bt cotton as a refuge is needed to maintain susceptibility. As shown in Table 4 (third row), for the 20-year planning horizon, the optimal static refuge size is 5 per cent. The average annual cost of the optimal static refuge policy (USD 175.38 per ha) is larger than that of the optimal dynamic one (USD 174.37 per ha). However, the USD 1.01 per ha (or 0.58 per cent) cost difference between the optimal static refuge policy and the optimal dynamic refuge policy is not significant economically. This finding is consistent with previous studies (Hurley *et al.*, 2002; Livingston *et al.*, 2004).

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 dynamically optimal refuge strategies are zero-refuge policies. For the 20-year planning horizon, the annual cost of the optimal dynamic strategy is USD 174.37 per ha while the annual cost of the zero-refuge strategy is USD 176.83 per ha. The cost difference of USD 2.46 per ha between these two refuge policies is also relatively small (Table 5).

In practice, whether the dynamically optimal refuge policy should be preferred in the real world would also be affected by the implementation and

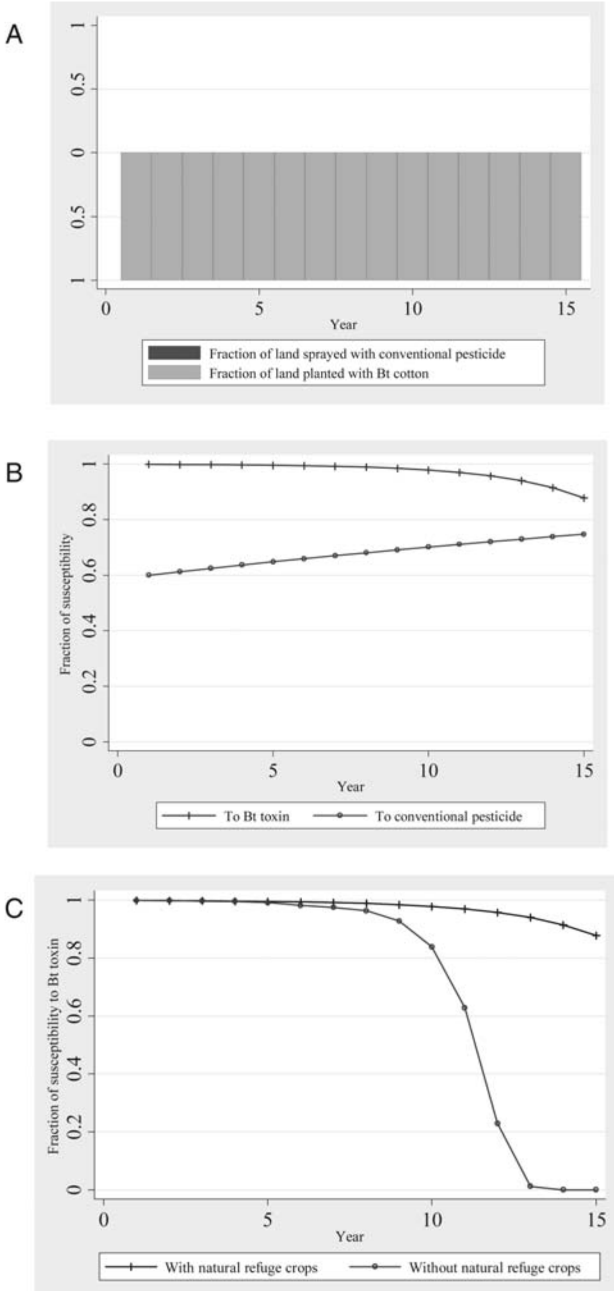

Figure 1. Dynamically optimal control and pest susceptibilities to both Bt toxin and conventional pesticide for a 15-year planning horizon. (A) Dynamically optimal control. (B) Pest susceptibilities to both Bt toxin and conventional pesticide. (C) Pest susceptibilities to Bt toxin under scenarios with and without NRC.

Table 5. Comparison of the cost of the dynamically optimal refuge policies with the no refuge policy

	Static zero-refuge policy; Average annual cost ($ per ha per year)	Optimal dynamic refuge policy; Average annual cost ($ per ha per year)	Cost saving from the dynamically optimal policy vs. the zero-refuge policy	
			In absolute value ($ per ha per year)	In percentage (%)
10-year planning horizon	189.59	189.59	0.00	0.00
15-year planning horizon	176.71	176.71	0.00	0.00
20-year planning horizon	176.83	174.37	2.46	1.39

monitoring costs associated with such a refuge policy. As discussed above, the costs of implementing a non-zero-refuge policy and monitoring farmers are ignored in our model. However, we would need to consider these costs if the government were trying to decide whether or not a refuge policy should be used. If the extra benefit of the optimally dynamic refuge cannot offset these transaction costs, it would not pay to implement the policy. Hence, in order to answer whether the optimal dynamic refuge policy is better than the zero-refuge policy for the 20-year planning horizon, we also need to investigate the transaction costs.

The implementation and monitoring costs associated with any refuge policy are likely to be high because of the land fragmentation and the existence of millions of small householders in China. To effectively manage these millions of small households, China has set up a special governance system in rural areas. Under this system, a village leadership council acts as the government's representative at the grassroots level. The village actually is also formed of several subunits called production teams (or small groups – *xiaozu*). Each production team has about one hundred people. Before decollectivisation at the end of the 1970s, the production team acted as the basic production unit. After the implementation of the household responsibility system, even though all the lands were allocated to individual farmers, most of the policies that dealt with land, such as land reallocation and tax collection, were still based on the production team. According to the authors' field survey in Yellow River Valley, monitoring costs would at least be USD 6.97 per ha per year for a US-styled refuge policy (see Appendix 2 for details about how this number was estimated). In comparison, as shown in our bioeconomic model, the extra benefit obtained by using a dynamically optimal refuge strategy (compared with a zero-refuge policy) is only USD 2.46 per ha per year (third row of Table 5). It is clear that the extra benefit could not even offset the extra monitoring costs.

The second important finding from the simulation results of our bioeconomic model concerns the recovery of susceptibility to conventional pesticides when a no spray strategy is implemented. As with the susceptibility of the pest population to Bt toxin, the susceptibility of the pest population to conventional pesticides is also a valuable renewable resource. In other words, if no conventional pesticides are used, resistant pests will die at a higher rate than susceptible pests because of the fitness cost assumption. Consequently, the fraction of the susceptible pests (to conventional pesticides) in the total pest population increases. And, while conventional pesticides could not control the cotton bollworm in the mid-1990s, at some point in the future, according to our results, conventional pesticides will once again become an efficient form of pest control. Figure 1B shows that continuously planting 100 per cent Bt cotton without conventional pesticide spray for 15 years causes a decrease of the susceptibility to Bt toxin and an increase in the susceptibility to conventional pesticides. This trend becomes even clearer in the 20-year planning horizon scenario. As shown in Figure 2B, continuously planting 100 per cent Bt cotton without conventional pesticide sprays allows the susceptibility to conventional pesticides to finally surpass the susceptibility to Bt toxin. Hence over time as 100 per cent Bt cropping is implemented, conventional pesticide become increasingly effective in controlling the cotton bollworms. Ultimately (as shown in Figure 2A), the dynamically optimal strategy requires some use of the conventional pesticide in later stages of the planning horizon.

This finding suggests the possibility in the future of using alternating instruments to control the total pest population while also managing pest resistance build up to both tools. As shown in Figures 1B and 2B, the effectiveness of conventional pesticides recovers as 100 per cent Bt cotton is planted without conventional pesticide spray. In a similar way, it is expected that the effectiveness of Bt cotton recovers if no Bt cotton acreage is planted. Hence, in order to manage the build up of the resistance in the pest population, instead of planting a constant fraction of land as a refuge annually, farmers might alternate the use of Bt cotton and conventional pesticides to control the pest. In this case, non-Bt cotton provides a refuge for pests that are susceptible to Bt toxin. Similarly, the cotton fields without conventional pesticide spray provide a refuge for pests that are susceptible to conventional pesticides. The optimal dynamic strategy for the 100-year planning horizon is consistent with our expectations (Figure 3).

4.1. Sensitivity analysis for fitness cost and discount rate

We also carried out additional sensitivity analyses using different levels of fitness cost parameters, and different levels of discount rates. The levels of the key parameters in the benchmark scenario are fitness cost = 0.05 and discount rate = 0.036. Using these key parameters as the focus of our sensitivity

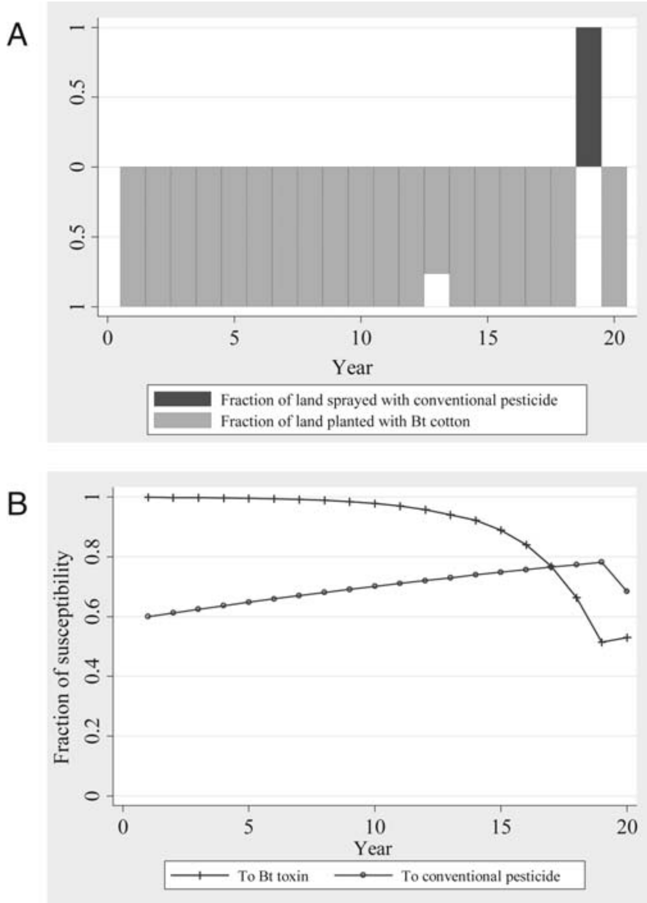

Figure 2. Dynamically optimal control and pest susceptibilities to both Bt toxin and conventional pesticide for a 20-year planning horizon. (A) Dynamically optimal control. (B) Pest susceptibilities to both Bt toxin and conventional pesticide.

analysis, in total, we ran four scenarios. In Scenario 1, we re-ran the model by allowing the level of the fitness cost to vary in a relatively narrow range near the base level (from 0.045 to 0.50 (base level) and 0.055). Then, we increased the range by allowing the level of the fitness cost to vary in Scenario 2 (from 0.01 to 0.05 and 0.10). Similarly, the range of the discount rate in Scenario 3 is relatively narrow (0.018 to 0.036 (base level) and 0.072). In Scenario 4 we increased the range (0.010 to 0.036 and 0.100). As is typical in sensitivity analyses, only one parameter was adjusted per model run. The actual simulation results in graphic/tabular form are available from the authors upon request.

In brief, the simulation results show that optimal dynamic control strategies do not vary with the magnitude of fitness cost (in both Scenarios 1 and 2). Under different scenarios, the dynamics of fraction of land planted with

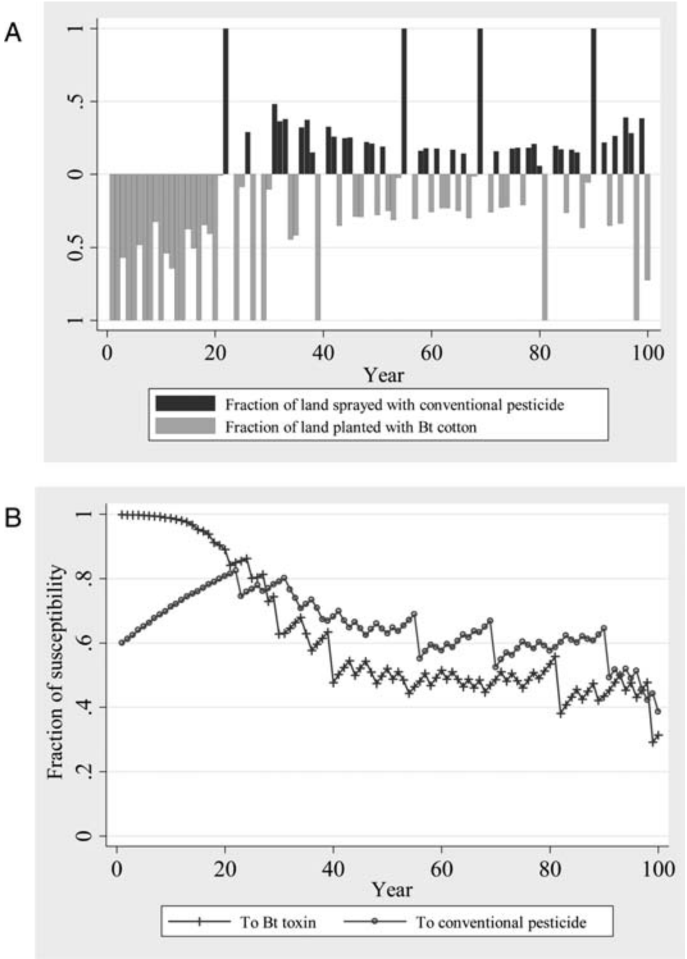

Figure 3. Dynamically optimal control and pest susceptibilities to both Bt toxin and conventional pesticide for a 100-year planning horizon. (A) Dynamically optimal control. (B) Pest susceptibilities to both Bt toxin and conventional pesticide.

Bt cotton and the dynamics of fraction of land sprayed with conventional pesticide, the two control variables, are the same as in the base model. At the same time, the changes in the state variables (the pest population, the frequency of the susceptible genes to the Bt toxin and the frequency of susceptible gene to pesticide) from the base model are minimal, and they move consistently across the span of the sensitivity analysis. Indeed, while the exact levels of the state variables change, the patterns of the results do not change.

Similarly, optimal dynamic control strategies were also insensitive to changes in the discount rate. In fact, the dynamics of both the control and state variables are virtually identical under different scenarios. Since both the control and state variables did not vary under different scenarios, changing the magnitude of the discount rate affects only the magnitude of the minimised present value of total cost. As expected, a high discount rate lowers the present value of the total cost.

In addition, we also run a scenario in which the fitness cost approached zero. We cannot make it zero, since it would change the entire structure of the problem. However, we can set it equal to a very small number and do so in the scenario analysis (Scenario 5) by setting the fitness cost equal to 0.00001.

In fact, most entomologists would not support the concept of a zero fitness cost scenario analysis. Most believe that susceptibility to Bt cotton is a renewable resource. For example, Wu, a well-known entomologist in the Chinese Academy of Agricultural Sciences, implicitly believes that fitness cost is important (Wu *et al.*, 2005). In addition, almost all economists working in this area (for example Livingston *et al.*, 2002, 2004) include the concept of fitness cost in their models.

In carrying out the scenario, we find that the simulation results demonstrate that the optimal dynamic control strategy did not vary with the magnitude of fitness cost. When the fitness cost is set near zero, the fraction of the land planted with Bt cotton and the fraction of land sprayed with conventional pesticide follow the same dynamic path as the benchmark scenario. In other words, the two control variables are the same as in the base model. At the same time, the changes in the levels of the state variables (pest population; resistance to conventional pesticide; resistance to the Bt toxin) from the base model are also minimal.

5. Conclusions

This paper presents a dual-toxin regulatory model and uses it to numerically compute optimal refuge sizes that minimise the damage cost caused by the pest and treatment costs associated with Bt toxin and conventional pesticides. The analysis yields several important findings. First, we show, given our initial conditions and parameters calibrated to China's cotton production environment, that planting non-Bt cotton as refuge is likely not economically optimal for Bt cotton in China for at least two reasons. First, the diverse cropping patterns within which cotton is planted over the landscape allow cotton bollworms to find enough natural refuge, so that the build up of resistance is slowed. Secondly, the transaction costs necessary to support an extensive refuge policy, such as that of the United States, cannot be offset by the small extra benefit that are gained by implementing a dynamically optimal refuge policy. For both of these reasons, the analysis suggests that China does not need to re-think its zero-refuge policy.

Another important finding concerns strategies to maintain susceptibility in the pest population. Susceptibility to either Bt toxin or conventional pesticides can be thought of as a renewable resource. Repeated use of conventional pesticides reduces subsequent susceptibility; avoiding spraying allows the recovery of the susceptibility to conventional pesticide. Symmetrically, the susceptibility to Bt toxin recovers if Bt cotton is not planted. Consequently, instead of planting a fraction of land as refuge annually, the dynamically optimal refuge policy shows that farmers might alternate the use of Bt cotton and conventional pesticides to control the pests while managing both kinds of resistance.

The simulation results have important policy implications in practice. First of all, they provide an empirical answer to whether China needs to re-think its zero-refuge policy for Bt cotton. In this study, we illuminate reasons why a US-style refuge policy is not economically optimal in China. The analysis of this study shows that under existing agricultural practices involving fragmented small scale farms, NRC can efficiently slow and control the build up of resistance and planting non-Bt cotton as refuge is not economically optimal except very marginally in an extremely long-term plan.

Secondly, our results shed light on the issues of other Bt crops in China. Currently, China's government is facing pressure to commercialise both Bt corn and Bt rice. However, there may be additional costs to the commercialisation of these crops that were not incurred when Bt cotton was commercialised. The commercialisation of Bt corn will cause the cotton bollworm to lose its most important natural refuge crop (non-Bt corn). If this occurs, China might need to re-think its zero-refuge policy for cotton.

With respect to rice, cropping systems in rice fields are much different from those in cotton fields. In South China, rice at the village level is often planted as a mono-cropped system. As a result, pests in rice fields may be less likely to find enough natural refuges nearby. So if Bt rice is commercialised, a mandatory refuge might be economically optimal. The lessons from all of these examples is that optimal management of resistance in farm pests must account for a range of economic and farming practice conventions, in addition to factors directly describing entomological characteristics of the pests themselves.

One potential shortcoming of our modelling approach is that we have assumed that the moth population dynamics are local and that net in- and out-migration to each decision-makers' plot is negligible. This is a reasonable assumption to make as a first-order approximation, particularly if the main interest is in resistance build up and dynamically optimal decisions. Future work might be aimed at understanding a much more complex landscape with multiple decision-makers making decisions on their own individual plots, but with pests diffusing across the landscape in some way. This is a much more difficult problem since it is not only dynamic, but also spatially dynamic. As has been discussed by Wilen (2007), spatially dynamic processes are best depicted with partial differential equations rather than our more tractable ordinary differential equation descriptions of pest dynamics. These kinds of problems are at the forefront of bioeconomic modelling, and there are only a handful of examples that have been attempted thus far. We thus acknowledge the limitations of an approach that ignores some important features that an explicitly spatial approach would capture, but we believe that important insights are nevertheless gleaned by starting with a more simple and tractable approach.

Acknowledgements

The authors are grateful to the staff members of the Center for Chinese Agricultural Policy of the Chinese Academy of Sciences who worked so hard in collecting data. We also would like to thank Kongming Wu, director of the Institute of Plant Protection, Chinese Academy of Agricultural Sciences; Ruifa Hu, research fellow, Center for Chinese Agricultural Policy, Chinese Academy of Sciences; and Siwa Msangi, Environment and Production Technology Division, International Food Policy Research Institute for their comments. We thank Editor Paolo Sckokai and the three anonymous referees for their careful reading and useful comments/suggestions. Additionally, the authors acknowledge the financial support of the Economy and Environment Program for Southeast Asia (EEPSEA), International Development Research Center (103783-001) and National Science Foundation of China (70873137 and 70333001).

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Appendix 1: Dynamics of the size of the pest population, susceptibility to Bt toxin and susceptibility to conventional pesticide

The susceptible (X) and resistant (x) alleles to Bt toxin at locus one and the susceptible (Y) and resistant (y) alleles to conventional pesticide at locus two divide the whole pest population into nine types of pests with different genotypes. These nine types of pests are:

1. pests with *XXYY* genotype (denoted as $l = 1$)
2. pests with *XXYy* genotype ($l = 2$)
3. pests with *XXyy* genotype ($l = 3$)
4. pests with *XxYY* genotype ($l = 4$)
5. pests with *XxYy* genotype ($l = 5$)
6. pests with *Xxyy* genotype ($l = 6$)
7. pests with *xxYY* genotype ($l = 7$)
8. pests with *xxYy* genotype ($l = 8$)
9. pests with *xxyy* genotype ($l = 9$).

The characteristics of each genotype are straightforward: pests with *XXYY* genotype are the pests with double susceptible alleles to Bt toxin and double susceptible alleles to conventional pesticides; pests with *XXYy* genotype are the pests with double susceptible alleles to Bt toxin, one susceptible allele and one resistant allele to conventional pesticides, and so on.

Since the proportion of susceptible alleles to Bt toxin is w while the proportion of the susceptible alleles to conventional pesticide is v, the fractions of the pests with *XXYY, XXYy, XXyy, XxYY, XxYy, Xxyy, xxYY, xxYy, xxyy* genotypes are w^2v^2, $2w^2v(1 - v)$, $w^2(1 - v)^2$, $2w(1 - w)v^2$, $4w(1 - w)v(1 - v)$,

$2w(1-w)(1-v)^2$, $(1-w)^2v^2$, $2(1-w)^2v(1-v)$, and $(1-w)^2(1-v)^2$, respectively. The dynamic of the pests with different genotype equal the new born minus the death. For example, by defining the mortality rate of pests with *XXYY* genotype as MR_{XXYY}, we get the dynamic of the pests with *XXYY* genotype: $(\mathrm{d}XXYY/\mathrm{d}t) = w^2v^2gD(1-D) - (D)MR_{XXYY}$. Hence, the dynamics of the size of the total pest population is straightforward:

$$\begin{aligned}\frac{\mathrm{d}D}{\mathrm{d}t} &= \frac{\mathrm{d}XXYY}{\mathrm{d}t} + \frac{\mathrm{d}XXYy}{\mathrm{d}t} + \frac{\mathrm{d}XXyy}{\mathrm{d}t} + \frac{\mathrm{d}XxYY}{\mathrm{d}t} \\ &\quad + \frac{\mathrm{d}XxYy}{\mathrm{d}t} + \frac{\mathrm{d}Xxyy}{\mathrm{d}t} + \frac{\mathrm{d}xxYY}{\mathrm{d}t} + \frac{\mathrm{d}xxYy}{\mathrm{d}t} + \frac{\mathrm{d}xxyy}{\mathrm{d}t} \\ &= gD(1-D) - D(MR_{XXYY} + MR_{XXYy} \\ &\quad + MR_{XXyy} + MR_{XxYY} + MR_{XxYy} + MR_{Xxyy} \\ &\quad + MR_{xxYY} + MR_{xxYy} + MR_{xxyy})\end{aligned} \tag{A1}$$

The dynamics of the susceptible alleles of the pest population to Bt toxin, (d*w*/d*t*), is

$$\begin{aligned}\frac{\mathrm{d}w}{\mathrm{d}t} &= \frac{\mathrm{d}(wD/D)}{\mathrm{d}t} \\ &= \frac{\begin{array}{c}(\mathrm{d}(XXYY)/\mathrm{d}t + \mathrm{d}(XXYy)/\mathrm{d}t + \mathrm{d}(XXyy)/\mathrm{d}t + 0.5 \\ (\mathrm{d}(XxYY)/\mathrm{d}t + \mathrm{d}(XxYy)/\mathrm{d}t + \mathrm{d}(Xxyy)/\mathrm{d}t))D\end{array}}{D^2} \\ &\quad - \frac{(\mathrm{d}D/\mathrm{d}t)(wD)}{D^2} \\ &= (1-w)\left(w^2g(1-D) - \sum_{l=1}^{l=3} MR_l\right) + (0.5-w) \\ &\quad \left(2w(1-w)g(1-D) - \sum_{l=4}^{l=6} MR_l\right) \\ &\quad - w\left((1-w)^2 g(1-D) - \sum_{l=7}^{l=9} MR_l\right)\end{aligned} \tag{A2}$$

Similarly, we can get the dynamics of the susceptibility of the pest population to conventional pesticides, (d*v*/d*t*). In summary, the dynamics of the size of the total pest population, susceptible alleles to Bt toxin and susceptible alleles to conventional pesticide are:

$$
\begin{aligned}
\frac{\mathrm{d}D}{\mathrm{d}t} &= gD(1-D) - D\sum_{l=1}^{l=9} MR_l \\
\frac{\mathrm{d}w}{\mathrm{d}t} &= (1-w)\left(w^2\, g(1-D) - \sum_{l=1}^{l=3} MR_l\right) + (0.5-w) \\
&\quad \times \left(2w(1-w)g(1-D) - \sum_{l=3}^{l=6} MR_l\right) \\
&\quad - w\left((1-w)^2\, g(1-D) - \sum_{l=7}^{l=9} MR_l\right) \\
\frac{\mathrm{d}v}{\mathrm{d}t} &= (1-v)\left(v^2\, g(1-D) - \sum_{l=1,4,7} MR_l\right) + (0.5-v) \\
&\quad \times \left(2v(1-v)g(1-D) - \sum_{l=2,5,8} MR_l\right) \\
&\quad - v\left((1-v)^2\, g(1-D) - \sum_{l=3,6,9} MR_l\right)
\end{aligned}
\tag{A3}
$$

Appendix 2: Monitoring cost associated with a US-style refuge policy

To understand the monitoring and enforcement cost associated with a US-style refuge policy, we conducted a field survey in Yellow River Valley cotton production region, one of the three main cotton production regions in China. The field survey was a two-stage, village-level survey that was carried out 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. From the list of counties, we randomly chose four counties using a stratified selection strategy. From the top five counties (the places where we are most likely to find the build up of resistance – because the intensity is the greatest), we chose two counties. From counties ranking 6 to 20 (in cotton production intensity), we chose one county. From the rest of the list we chose one more county. In total, after the selection process, we ended up with four counties – the 2nd, 3rd, 18th and 107th largest cotton producing counties in Yellow River Basin. Two of the counties are in Henan province, one in Shandong province and one in Hebei province. The three provinces are not only the most important production provinces in the Yellow River Valley, but are also the 2nd, 3rd and 4th largest cotton producing provinces in China.

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, with a total of two townships per county – one with higher intensity and one with lower intensity.

After choosing the townships, we then proceeded to collect the data that we needed to estimate the cost of monitoring a US-style refuge. In each township we asked the township vice mayor (the one in charge of agriculture) to convene a meeting with the leaders from all of the township's villages. Each village leader provided information on variables for elements such as the total area under cultivation in the village; the intensity of cotton planting; the village's cropping patterns; etc. We also asked the village leader to provide information (based on his/her subjective opinions) that could help us to estimate how much it would cost to monitor a US-style refuge policy in their village. Specifically, we asked each village leader if each of the farmers who planted Bt cotton needed to plant non-Bt cotton as refuge, and if he/she was in charge of the monitoring task in the village, how much compensation would be appropriate for him/her to perform the task effectively.

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