Tarnishing Silver Bullets: Bt Technology Adoption, Bounded Rationality and the Outbreak of Secondary Pest Infestations in China

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Abstract

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As with other technologies, adoption of Bt seed requires technology specific knowledge. Growing secondary pest populations have slowly eroded the benefits of Bt technology in China. We illustrate the effects of introducing Bt technology among farmers with an imperfect knowledge of secondary pest problems using a simple dynamic model. The stochastic dominance tests based on primary household data from 1999-2001 and 2004 in China provide strong evidence that secondary pests, if unanticipated, could completely erode all benefits from Bt cotton cultivation. Our empirical tests also suggest that planting refuge concurrent with Bt adoption provides for the sustainable development of Bt technology.[*]

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When Monsanto launched Bt cotton in 1996, many expected the crops, designed to resist bollworm infestation, to completely replace existing chemical pesticides. By injecting the *Bacillus Thuringiensis* (Bt) gene into cotton seeds, the resulting cotton would produce toxins lethal to leaf eating bollworms, the primary pest affecting cotton yield. This method of controlling bollworm infestation is by all measures more efficient than traditional chemical spaying which can only perform as well as the application mechanism allows. Because of its touted efficiency, four major cotton growing countries were quick to adopt Bt cotton: the U.S., China, India and Argentina. Effectively 35% of all cotton area is devoted to the cultivation of Bt cotton, ranging from 42.8 million hectares in the U.S. to 3.7 million hectares in China (Huesing and English 2004). While Bt technology is efficient at reducing bollworm infestation, it is not designed to combat other pests that have historically posed less of a threat. The emergence of a secondary pest could prove to be a major problem in countries where GM crops have been widely adopted, particularly in countries where farmers may be undereducated about the performance and use of the technology. Such may be the case in developing nations, exactly those nations where GM crops have been promoted to help solve poverty and undernourishment.

Many studies in the early years of Bt adoption have shown that farmers who grow Bt cotton are able to control bollworm without resorting to pesticide spray, or in the very least with a substantially reduced level of spraying. Such a reduction in pesticide spraying results in huge savings on bollworm pesticide. Before the commercialization of Bt cotton, the Chinese farmers applied an average of 20 pesticide treatments in a season to control bollworm infestations. With the adoption of Bt the average number of treatments has fallen to only 6.6 on average at the early stages of Bt adoption (Huang et. al. 2002). Bt cotton allowed Chinese farmers to reduce their pesticide use by 43.3 kilograms per hectare in 1999, a 71% decrease in pesticide use (Huang 2002). For the years 2000 and 2001, Bt cotton was associated with an average reduction of 35.7 kilograms per hectare of pesticide, or a percentage deduction of 55% (Pray 2003). Similar results have been found in other major cotton growing countries: Indian farmers save 39% of expenditures by planting Bt (Qaim and Zilberman 2003), Argentine farmers save 47% of expenditures (Qaim and deJanvry 2003), Mexican farmers can save 77% (Traxler et al. 2003), and South African farmers can save 58% by planting Bt (Bennett et al. 2004). The ever mounting evidence suggests that, despite the fact that Bt seed can cost two to three times more than conventional seed, savings on pesticide expenditures guarantee a much higher net return for Bt adopters.

Despite this potential to earn higher profits, with the wrong training, farmers without experience with Bt technology can fail to realize the promised profits. Using a household survey from 2004, seven years after the initial commercialization of Bt cotton in China, we show that total pesticide expenditure for Bt cotton farmers in China is nearly equal to that of their conventional counterparts, about $101 per hectare. Bt farmers in 2004 on the average, have to spray pesticide 18.22 times, which are more than 3 times higher compared with 6 times pesticide spray in 1999. Detailed information on pesticide expenditures reveals that, though Bt farmers saved 46% Bollworm pesticide relative to non-Bt farmers, they spend 40% more on pesticides designed to kill an emerging secondary pest. These secondary pests (one example is Mirid) was rarely found in the field prior to the adoption of Bt cotton, presumably kept in check by bollworm populations and regular pesticide spraying. The extra expenditure needed to control secondary pests nearly offsets the savings on primary pesticide frequently cited in the current literature.

The purpose of this paper is to model the value of Bt seeds to boundedly rational farmers. Farmers clearly understand the benefit of using Bt to reduce the use of chemical pesticides to control bollworm. However, farmers may not realize that a secondary pest exists until it has grown to become a significant economic drain to the farm. Additionally, we model the value of clearly understanding the relationship of Bt technology and potential secondary pests. The impact of Bt technology on secondary pests have been ignored by many previous economic studies of the benefits of Bt technology. “Ignoring secondary pests can lead to devastating crop damage that may continue over a considerable period of time. Induced secondary pest infestations, once they arise, may prove difficult to control by chemical means”(Harper and Zilberman 1989).Much like the farmers we model in this paper, economists have generally assumed that secondary pests would be unaffected by Bt adoption despite the multiplicity of research stressing the importance of multi-pest management in agricultural economics. The paper proceeds as follows. In the next section we review much of the existing evidence of secondary pest problems resulting from the (over-)use of Bt technology. We then present a simple dynamic model of pest infestation resulting from adoption of Bt by farmers that are ignorant of secondary pest populations, providing a simple numerical illustration. Our model suggests that farmers that perceive the problems associated with secondary infestations will optimize by using increased refuge. This refuge (suggested in the U.S. to combat bollworm resistance to Bt) allows the maintenance of bollworm population, reducing the ability of secondary pests to multiply. Using household survey data, we present evidence of emerging secondary pest problems in China that appear to overwhelm the benefits of Bt technology, and the potential for refuge to combat the problem.

Bt Technology and Secondary Pests

The emergence of a secondary pest in Bt cotton fields is by no means a random event. Rather, this emergence of secondary pests is a natural result of the use of Bt technology. Chemicals used to control bollworm have a relatively broad spectrum toxicity, unlike the narrowly targeted Bt toxin, and thus should kill many and varied pests. The use of Bt technology thus indirectly creates a safer environment for the growth of non-bollworm pests. “This secondary pest effect has led to the “worldwide elevation of certain species from relatively innocuous to highly destructive levels (Getz and Gutierrez p447). Entomologists suggest it should take five to ten years for such a secondary pest population to proliferate to a level that poses a significant economic threat. Field experiments in China identify the potential damage from secondary pests after several years of Bt use. These reports show that “the density of [the] secondary pest is significantly higher on non-sprayed Bt cotton than sprayed non-Bt cotton due to a reduction in the number of broad-spectrum pesticides. It suggests that the secondary pest have become key insect pests in Bt cotton fields, and their damage to cotton could increase further with the expansion of Bt cotton growing areas if no additional controls are adopted.” (Wu 2002).

Harper and Zilberman were the first to raise the concept of a “pest-externality” whereby the use of chemical pesticide stimulates the unintended growth of a secondary pest by killing its natural predator. They develop a static model involving a pesticide that only affects a primary pest. The population of the primary pest in turn limits the population of a secondary pest. Harper (1991) further developed the interaction of primary and secondary pests using a dynamic predator-prey model emphasizing the key role of predatory relationships in inter-species modeling. While it is widely acknowledged that optimal pest management requires understanding the interaction between multiple pests (e.g. Getz and Gutierrez, Feder and Regev, Boggess , Harper and Zilberman), unfortunately, the Bt secondary pest effect has been at best underemphasized in the agricultural economic literature, and at worst completely ignored. Most commonly, economists use a single pest management model to explore pest control issues. In the context of Bt technology, this is equivalent to assuming that secondary pest population growth is independent of the use of pesticide or Bt targeting bollworm populations. Of necessity, analyzing the use of Bt using the single pest model produces biased results, overstating the potential benefits to farmers.

Simon (1955, 1959, 1978) popularized the notion of bounded rationality – that individuals fail to optimize due to limits on their ability to understand the consequences of their choices. Bounded rationality has lead to the wide expansion of the field of behavioral economics and the rapid development of heuristic models. Within the context of technology adoption, individuals may lack a full understanding of the technologies that are available. Bt technology has been widely publicized for its singular ability to prevent bollworm. In this case farmers are likely to understand the primary function and performance of Bt technology. However, more detailed understanding may require significant training or education. Schultz (1975) argued that education and training can enable individuals to deal with new and unfamiliar circumstances. But the types of education and training necessary to understand the use of new genetic technology may be exactly the types of resources that are lacking in developing nations. By improperly using new technologies farmers in developing countries may fail to realize the promised profits. In turn, without proper understanding of the technology, farmers may attribute low profits to a failing in the technology, rather than improper use, leading to dis-adoption.

In summary, if agricultural economists have failed to recognize the importance of secondary pests in the adoption of Bt technology, it should not be surprising that many farmers may face the same failures of reason. The presence of such failures underlines the importance of education efforts to accompany the introduction of new technologies in developing countries. Without adequate efforts to educate and train, new technologies may only serve to exacerbate problems associated with poverty and scarcity.

Theoretical Model

We define primary pests as those requiring some type of regular effort or intervention to avoid crop losses. Secondary pests are a species that is of minor or sporadic importance compared to primary pests under conventional cultivation. In our case, bollworm is a primary pest, routinely causing heavy damage to the cotton crop in China. Mirid is a secondary pest, not normally numerous enough to cause any significant loss in yield, although significant outbreaks can sometimes occur due to unusual weather or human interference. We wish to model individual pest control decisions, which depends heavily on the individuals understanding of the dynamic interactions in pest populations. The perceived biological growth rate of primary and secondary pests could be modeled as following:

$$\dot{S}_{1t} = \frac{dS_{1t}}{dt} = F(S_{1t}) - K(P_t, B_t, S_{1t})$$
$$\dot{S}_{2t} = \frac{dS_{2t}}{dt} = \psi\left[H(S_{2t}) - G(P_t, S_{2t})\right]$$

Where $\dot{S}_{1t}$ and $\dot{S}_{2t}$ represent the net growth rate of primary pest and secondary pest populations. S_{1t} and S_{2t} indicate the population of primary and secondary pests at time *t*, $F(\cdot)$ is the growth function of the primary pest, $H(\cdot)$ represents the growth of the secondary pest, P_t is the total amount of pesticides (targeting both pests) sprayed at time *t* while B_t is represents the amount of Bt seeds. The net growth rate of the primary pest will be determined by the population of the pest and the level of Bt toxin and pesticides. Therefore $K(\cdot)$, the killing function for the primary pest, is a concave function of P_t and B_t. Similarly, the killing function of the secondary pest, given by $G(P_t, S_{2t})$ is also a concave function of P_t. However, not every farmer has the knowledge of the potential outbreak of secondary pest in the future, or the effect of primary pesticide on the secondary pest. Therefore, we introduce the variable $\psi \in [0,1]$ to capture the farmer's awareness of the potential outbreak of a secondary pest. Thus, $\psi = 0$ represents a cotton farmer who has no knowledge of the potential for a secondary pest outbreak in the future. Thus, the farmer ignores the potential incidence or seriousness of the secondary pest in the decision of adopting Bt technology. As result, they will not take any extra efforts, such as applying extra pesticides, to reduce the density of secondary pest. For boundedly rational farmers, the secondary pest is unaffected by pesticides used to target the primary pest. Thus its natural initial population is expected to persist no matter what choices are made regarding pesticide and Bt. On the contrary, if a farmer considers the effects of his actions on both primary and secondary pest populations, they may take actions such as spraying extra pesticide to maintain the balance of (or slow the proliferation of) the secondary pest. In the fully informed case, $\psi = 1$, and, as a result, the growth rate of secondary pest population will indicated as $H(S_{2t}) - G(P_t, S_{2t})$ where $G(P_t, S_{2t})$ is the effect of human interference on the secondary pest population.

The optimization problem faced by a cotton-planting farmer is given by:

$$\underset{\{P_t, B_t\}}{Max} \int_0^T e^{-\delta t} [R(S_{1t}, S_{2t}) - uP_t - rB_t$$

Subject to:

$$\dot{S}_{1t} = \frac{dS_{1t}}{dt} = F(S_{1t}) - K(P_t, B_t, S_{1t})$$

$$\dot{S}_{2t} = \frac{dS_{2t}}{dt} = \psi\left[H(S_{2t}) - G(P_t, S_{2t})\right]$$

where function $R(S_{1t}, S_{2t})$ represent the revenue function of a farmer, which is a function of the pest concentrations, δ is the discount rate, u is the price of pesticide and r indicates the price of Bt seed.. Revenue is monotonically decreasing with respect to both arguments, representing pest damage.

The current value Hamiltonian function is :

$$H = R(S_{1t}, S_{2t}) - uP_t - rB_t + \lambda_t [F(S_{1t}) - K(P_t, B_t, S_{1t})] + \phi_t \psi [H(S_{2t}) - G(P_t, S_{2t})]$$

The solution for this system is described by the following necessary and sufficient first order conditions arising from the current value Hamiltonian

$$(1) \qquad 0=\frac{\partial H}{\partial P_t}=-u-\lambda_t\frac{\partial K(P_{t,}B_t,S_{1t})}{\partial P_t}-\psi\phi_t\frac{\partial G(P_{t,}S_{2t})}{\partial P_t},$$

$$(2) \qquad 0=\frac{\partial H}{\partial B_t}=-r-\lambda_t\frac{\partial K(P_{t,}B_t,S_{1t})}{\partial B_t},$$

$$(3) \qquad \dot{\lambda}_t-\delta\lambda_t=-\frac{\partial H}{\partial S_{1t}}=-\frac{\partial R(S_{1t,}S_{2t})}{\partial S_{1t}}-\lambda_t\frac{\partial F(S_{1t})}{\partial S_{1t}}+\lambda_t\frac{\partial K(P_{t,}B_t,S_{1t})}{\partial S_{1t}},$$

$$(4) \qquad \dot{\phi}_t-\delta\phi_t=-\frac{\partial H}{\partial S_{2t}}=-\frac{\partial R(S_{1t,}S_{2t})}{\partial S_{2t}}-\psi\phi_t\left[\frac{\partial H(S_{2t})}{\partial S_{2t}}-\frac{\partial G(P_{t,}S_{2t})}{\partial S_{2t}}\right],$$

$$(5) \qquad \dot{S}_{1t}=\frac{dS_{1t}}{dt}=F(S_{1t})-K(P_t,B_t,S_{1t}),$$

$$(6) \qquad \dot{S}_{2t}=\frac{dS_{2t}}{dt}=\psi\left[H(S_{2t})-G(P_t,S_{2t})\right].$$

We represent co-state variables arising from the Hamiltonian as $\lambda_{t,}\ \phi_t$. We will represent the solution to this dynamic system with the sequence $\left\{B^*{}_t,P^*{}_t\right\}$.

Comparing Informed and Unformed Behavior

Equation (1) implies the optimal amount of pesticide is determined at such a point where the marginal cost of primary pesticide, u equal its marginal benefits consisting of $\lambda_t\frac{\partial K(P_{t,}B_t,S_{1t})}{\partial P_t}$, the contribution of primary pesticide to decreasing the population of the primary pest, plus $\psi\phi_t\frac{\partial G}{\partial P_t}$, the "recognized" contribution of the pesticide to decreasing the population of the secondary pest. For a fully informed farmers($\psi=1$), pesticides are used to reduce the population for both primary and secondary pests. Therefore, the marginal benefit of pesticides is equal to the summation of $\lambda_t \dfrac{\partial K(P_{t,}B_t,S_{1t})}{\partial P_t}$ and $\phi_t \dfrac{\partial G}{\partial P_t}$.

However, an uninformed farmer ($\psi = 0$) will not spray pesticide to eliminate secondary pest since they ignore the existence and the potential damage of secondary pest in the decision to spray and/or adopt Bt. To the uninformed farmer, the sole purpose of spraying pesticide is to eliminate the density of the primary pest. Therefore, the optimal amount of primary pesticide is determined where its price u is equal to $\lambda_t \dfrac{\partial K(P_{t,}B_t,S_{1t})}{\partial P_t}$, the contribution of the pesticide to decreasing the population of the primary pest. Clearly, ignoring the secondary pest will lead myopic farmers to mis-calculate the marginal benefits of pesticides and lead them to under spray, leading to larger and larger secondary pest populations.

The linearization of First order condition of equation (1), (2) with regard to choice variables P_t, B_t and the knowledge parameter ψ yields the following system

$$\begin{pmatrix} -\phi_t \dfrac{\partial G(P_{t,}S_{2t})}{\partial P_t} \\ 0 \end{pmatrix} d\psi + \begin{pmatrix} -\lambda_t \dfrac{\partial^2 K(P_{t,}B_t,S_{1t})}{\partial^2 P_t} - \psi\phi_t \dfrac{\partial G^2(P_{t,}S_{2t})}{\partial^2 P_t}, & -\lambda_t \dfrac{\partial^2 K(P_{t,}B_t,S_{1t})}{\partial P_t \partial B_t} \\ -\lambda_t \dfrac{\partial^2 K(P_{t,}B_t,S_{1t})}{\partial B_t \partial P_t} & -\lambda_t \dfrac{\partial^2 K(P_{t,}B_t,S_{1t})}{\partial^2 B_t} \end{pmatrix} \begin{pmatrix} dP_t \\ dB_t \end{pmatrix} = \begin{pmatrix} 0 \\ 0 \end{pmatrix}$$

Solving this linear system yields the comparative statistic result

$$\frac{dB_t}{d\psi} = -\frac{\begin{vmatrix} -\lambda_t \dfrac{\partial^2 K(P_{t,}B_t,S_{1t})}{\partial^2 P_t} - \psi\phi_t \dfrac{\partial G^2(P_{t,}S_{2t})}{\partial^2 P_t} & -\phi_t \dfrac{\partial G(P_{t,}S_{2t})}{\partial P_t} \\ -\lambda_t \dfrac{\partial^2 K(P_{t,}B_t,S_{1t})}{\partial B_t \partial P_t} & 0 \end{vmatrix}}{\begin{vmatrix} -\lambda_t \dfrac{\partial^2 K(P_{t,}B_t,S_{1t})}{\partial^2 P_t} - \psi\phi_t \dfrac{\partial G^2(P_{t,}S_{2t})}{\partial^2 P_t} & -\lambda_t \dfrac{\partial^2 K(P_{t,}B_t,S_{1t})}{\partial P_t \partial B_t} \\ -\lambda_t \dfrac{\partial^2 K(P_{t,}B_t,S_{1t})}{\partial B_t \partial P_t} & -\lambda_t \dfrac{\partial^2 K(P_{t,}B_t,S_{1t})}{\partial^2 B_t} \end{vmatrix}} < 0$$

The value of the numerator, given by $-\lambda_t\phi_t \frac{\partial^2 K(P_{t,}B_t, S_{1t})}{\partial B_t \partial P_t} \frac{\partial G(P_{t,}S_{2t})}{\partial P_t}$, which must be positive if the marginal impact of pesticide on the primary pest is diminished by use of Bt technology, $\frac{\partial^2 K(P_{t,}B_t, S_{1t})}{\partial B_t \partial P_t} < 0$. Hamiltonian co-state coefficients λ_t and ϕ_t are both negative when evaluated at the optimum. Second order conditions require the denominator (the determinant of the Hessian matrix of the Hamiltonian function) to be positive if an interior solution occurs. Therefore, the greater the awareness of the farmer of the impact of pesticide on the secondary pest, the less Bt will be planted. In other words, an informed farmer would use refuge to combat the potential outbreak of the secondary pest. The intuition behind this is that the adoption of Bt cotton will enable cotton-farmers to control the primary pest while using significantly less pesticide. Since chemical pesticide will also kill the secondary pest, large-scale adoption of Bt will induce a serious outbreak of the secondary pest if this secondary pest is not also targeted. By the time the farmer discovers the damage from the secondary pest, cotton planters might need to spray extreme amounts of pesticide to control the problem. This outbreak could result in losses that offset part of, or, if the outbreak is serious enough, all of the returns resulting from adopting Bt technology. Taking this effect into consideration, cotton farmers should plant certain proportion of conventional cotton, using pesticide to prevent the potential outbreak of the secondary pest. This result is similar to the concept of refuge which is currently employed to reduce resistance to Bt by pests.

The concept of refuge was first introduced by the United States Environmental Protection Agency (EPA) in 2000 for Bt corn growers. At that time, the large scale adoption of Bt corn in US raised concerns that primary pests killed by Bt toxin may soon develop resistance to Bt diminishing the potential pest control benefits. EPA responded to these concerns by obligating Bt growers to plant 20% non-Bt crops as a refuge. The purpose of the refuge is to reserve a population of primary pest not exposed to Bt corn that can mate with potentially resistant moths emerging from nearby Bt corn. The goal is to produce an overwhelming number of susceptible moths for every resistant moth (at least 500:1) and thus slow the proliferation of resistant genes and prolong the efficacy of Bt.

The results from our model suggests an alternate need for refuge from the perspective of potential outbreak of secondary pests due to the decreasing usage of primary pesticide after adopting Bt crops. Non-Bt crops need to be planted concurrently with Bt crops since the chemical pesticide required for non-Bt crops will kill the secondary pest or slow its progress in the future. Though in the short-run, Bt farmers will lose money on refuge, this loss will bring them potentially huge savings on combating the outbreak of secondary pests in the long-run. We examine how big these savings may be in the following section.

Empirical Results

Cotton production plays an important role in the economic development of China. Since 1984, China has become one of the largest cotton producers in the world. On average a total area ranging from 4 to 6 million ha are under cotton cultivation in China, meeting 20% of the annual worldwide demand for cotton. Cotton is produced by millions of small-scale farmers whose incomes constitute a significant part of national agricultural GDP in China. (Wu, 2005) the major challenge facing Chinese cotton planters is combating the bollworm, the primary pest for cotton. Before the commercialization of Bt cotton, Chinese farmers depended heavily on the chemical pesticides to control cotton pests. On the average, Chinese farmers would spray around 30 times each growing season to control pest infestations. The heavy use of pesticide has been greatly diminished since the commercialization of Bt cotton in 1997. Several Bt varieties were approved by the Chinese Biosafety Committee in 1997. The spread of Bt cotton has been rapid. The adoption rate jumped from 1% in 1997 to 65% in 2004. (Huang, et. al 2002)

In China data on the production of cotton are not available from government or industry. Therefore, we conducted a household survey in November 2004, seven years after Bt cotton was initially commercialized in China. This research was jointly conducted by the Center for Chinese Agricultural Policy, Beijing (CCAP) of Chinese Academy of Science (CAS) and Department of Applied Economics & Management at Cornell University. Our research team traveled to 5 provinces: Hebei, Shangdong Henan, Anhui and Hubei, all of which are major cotton-producing areas in China. The sample size of our survey is 481 and each farmer in our sample was interviewed for about two hours in order to collect primary detailed information on cotton production and investment in various inputs and pesticides. The sample was a stratified random sample. We selected the provinces and counties carefully so that we could compare the performances of Bt and conventional cotton. After county selection, we randomly selected the villages and farmers proportionally within the villages. The final sample comes from 20 villages in 10 counties of 5 provinces. CCAP conducted similar surveys in 1999, 2000 and 2001. 283 farmers were interviewed in 1999 while this number increased to 407 in 2000 and 366 in 2001.The unique panel dataset from 1999-2004 enable us to analyze the performance of Bt adoption as well as the optimal amount of pesticide usage in a dynamic setting. A comparison of first degree stochastic dominance tests of farm net revenue between 2004 and 1999-2001 yield a surprising result: In 2004, the net revenue of Bt farmers is significantly lower than non-Bt farmers. This is the opposite of the result found by analyzing household data from the years 1999 to 2001. Figures 1 through 4 present a net revenue first degree stochastic dominance test comparing Bt and Non-Bt farmers using the data from the year 1999, 2000, 2001 and 2004.

Figures 2 through 4 clearly indicate that in the early years of Bt adoption, i.e. 2000 and 2001, the net revenue of Bt clearly dominates the net revenue of Non-Bt growers. Thus Bt farmers earned higher profits than conventional farmers from 2000 to 2001, which supports the results found previously in the literatures. (Pray 2002; Huang 2002, 2003) On average, the net revenue per hectare is $121 more for Bt cotton than conventional cotton (Huang 2003). However, in the year of 2004 (figure 4), the trend reverses. The CDF of net revenue for non-Bt farmers clearly dominates Bt growers in 2004, indicating that Bt farmers earned less money than conventional growers. While the result from 1999 is ambiguous (Bt dominates non-Bt for the low-range income farmers and non-Bt performs better for the comparatively rich farmers), the Chinese cotton market experienced significant reform from a highly government-controlled market to a free market in 1999. Thus, external factors other than Bt adoption may contaminate our stochastic dominance test.

One factor that contributes to the unusual phenomena observed in 2004 is the emergence of a secondary pest. In verbal interviews, a majority of the Bt cotton farmers cited the fact that they must spray 15-20 times more than previously to kill secondary pests, Mirids, which did not require any pesticide in the early years of Bt adoption. Before the introduction of Bt cotton, farmers used chemical pesticides to control the primary pest for cotton. Due to the broad-spectrum of most chemical pesticides, secondary pests such as Mirids were killed as a byproduct of the battle with the primary pest. Adoption of Bt cotton enables farmers to control bollworm without spraying pesticide. Therefore, Bt induces a safer environment for the growth of the secondary pest. It is not easy for Bt farmers to understand the potential outbreak of a secondary pest during the early year's adoption of Bt because they observe little evidence of any secondary pest damage. In particular, it takes 5 to 10 years for the secondary pest to proliferate to a point where it could cause substantial economic damage to cotton producers.

In order to test our hypothesis of emergence of a secondary pest, detailed data on pesticide spraying are required. Fortunately, our survey data in 2001 and 2004 gave us detailed information on pesticide expenditures for each individual pest. The data shows that, though Bt farmers saved money on the primary pesticide, the extra pesticide to combat the outbreak of a secondary pest offset the savings. This apparently unexpected expenditure equalizes the pesticide expenditure between Bt and Non-Bt farmers with an average expenditure for both Bt and Non-Bt adopters around $101/hectar. In figure 5, a first degree stochastic dominance test on secondary pesticide expenditure shows that Bt farmers spend more than Non-Bt farmers over nearly the entire distribution. This indicates that the majority of Bt farmers spend more to combat the secondary pest than

Non-Bt farmers. In 2004, Bt farmers spent an average of $16.01/hectare on secondary pest control compared to $5.7 / hectare for Non-Bt farmers.

Figure 6 clearly shows that the amount of pesticide used to combat secondary pests in 2004 for Bt farmers first order stochastically dominates the amount used in 2001. Thus Bt farmers use more pesticides on secondary pests in 2004 than in 2001. In 2001, Bt farmers applied pesticide an average of 1.6kg/ha in order to kill the secondary pest. This number jumps to 7.61kg/ha in 2004. It reflects the time necessary for secondary pests to proliferate to a point where effort is needed to avoid significant yield loss. The initial low level of effort to control the secondary pest illustrates that farmers misunderstand the changing dynamic population of the secondary pest in the early years of Bt adoption.

Figure 7 illustrates that farm expenditures on pesticide to combat bollworm for Non-Bt farmers dominates that of the Bt farmer in 2004. In other words, conventional farmers have to spend substantially more to kill the bollworm compared to Bt farmers. It also implies that Bt is an efficient way to control the primary cotton pest. However, Figure 8 indicates the seriousness of the outbreak of the secondary pest. The figure shows that the total expenditures on pesticides (for all pests) for Bt and Non-Bt farmers are statistically identical, with a mean around $101/hector. Though Bt farmers save a lot on primary pesticides, they have to spend more to suppress the outbreak of the secondary pest, leading to total pesticide expenditures between these two groups of farmers that are almost identical. In addition, the price for Bt seeds are 2 to 3 times higher than conventional seed in China. The extra cost of Bt seed must make the net revenue of Bt farmers lower than that of Non-Bt farmers.

A result such as this is inconsistent with unboundedly rational, fully informed, farmers adopting a new technology. Rather, it points to the true underlying difficulties of technology diffusion. Compared with developed countries, such as the US, the Chinese government has no requirement for refuge. Our survey finds that Chinese farmers growing Bt cotton plant no refuge whatsoever, most having no concept of refuge at all. Our theoretical model suggests that, though Bt is more effective for controlling bollworm infestations than chemical pesticides, Bt farmers still need to plant some portion of Non-Bt cotton. The primary pesticide can then be used on the Non-Bt refuge to slow the proliferation of a secondary pest.

The question is thus, “Can Chinese Bt farmers improve income if they begin to plant a refuge?” While answering this question may require significant new research, we propose here a simulation that we feel is compelling, based on dominance tests using our primary data from 2004. The actual pesticide spray in 2004 (W), can be expressed in the following formula:

***W* = Pesticide on Primary pest + Pesticide on Secondary pest**

If Chinese farmers take precautions by planting a portion of their crop as a refuge, and use the primary pesticide on the refuge, they could control the secondary pest before they begin to significantly damage the crop. If the refuge is extensive enough to fully control the secondary pest,[1] the farmer could then eliminate all expenditure on pesticide for the secondary pest in the non-Bt refuge area, replacing this with the added pesticide used to control the primary pest in the refuge area. Therefore, the hypothetical pesticide spray with preventative refuge in 2004 ($\tilde{W}$) can be expressed as

$\tilde{W}$ = **Pesticide on Primary Pest + Additional Pesticide on Refuge**

If planting 20% of refuge, the requirement of the EPA, could successfully prevent the outbreak and the damage of a secondary pest, then the hypothetical pesticide spray on refuge area could be approximated as $20\% \times$ (the average expenditures on pesticides sprayed on Non-Bt cotton area in 2004). "Appropriate refuge proportions, however, are difficult to determine because of uncertainty over the densities of bollworm and (secondary pests) potential in the field" (Livingston 2000) . The requirement of 20% refuge is an arbitrary number chosen by EPA to combat resistance, and it might not be suited for to combat a secondary pest in China. As a more extreme possibility, suppose a 60% refuge is needed to prevent the outbreak of a secondary pest. Then, similarly, $\tilde{W}$ = pesticide on primary pest +60% (average expenditures on pesticide spray for Non-Bt Cotton in 2004). In both cases, we find that employing a refuge (either of 20% or 60%), can increase profits relative to ignoring the secondary pest, if the refuge is effective. Figure 9 shows the hypothetical expenditures of growers using various levels of refuge following the simple formulas above.

A first order stochastic dominance test on total expenditure of pesticides shows the planting of refuge can decrease total pest expenditure relative to ignoring the interaction of secondary pest and Bt toxin. The figure 9 shows that both potential Bt-refuge levels clearly need less pesticide than a non-Bt grower (and thus a Bt grower via figure 8), corresponding to a savings on pesticide and greater profit. The median expenditure on the secondary pest in our simulation is around 60 $/hectare for Bt planters with 20% refuge and 73$ / hectare for those with 60% refuge and around 101 $/hectare for Bt farmers without planting any refuge. Furthermore, figures 10 and 11 present the simulated net revenue of Bt growers employing a 20% refuge and 60% refuge respectively. Both of them have a dominated revenue over non-Bt growers. As shown in figure 4, Bt farmers without any refuge earn less income than Non-Bt farmers in 2004. Thus, Bt farmers with some refuge will earn higher profits compared with Non-Bt farmers so long as sufficient refuge is used to control the secondary pest.

Conclusion

The adoption of Bt cotton had a huge impact on cotton production in the world. Many studies have focused on the potentially positive impact of Bt and the savings on pesticides targeting primary pests. In this paper we illustrate some of the problems in implementing Bt technology that have been ignored to date. Induced emergence of secondary pests present a real and damaging possibility. Our empirical data from China for the year 2004 demonstrated how secondary pests, if unanticipated, could completely erode all benefits from Bt cotton cultivation. In order to help farmers make more informed decision regarding Bt adoption, some effort must be made to educate farmers of the potential for secondary pest infestations, and the need for refuge. Planting refuge concurrent with Bt adoption provides for the sustainable development of Bt technology. The pesticide required to maintain the refuge will reduce the threat of the secondary pest before they proliferate to a damage concentration. The profits lost on the refuge could be compensated by substantial savings on pesticides that otherwise would be used to combat outbreaks of the secondary pest in the future. Such education is particularly necessary in developing countries where Bt technology may be a particularly opaque mechanism. Bt technology has been promoted to solve many of the problems facing the developing world. GM crops show great promise in improving the lives of farmers in developing nations, if they can be taught to implement them in a sustainable fashion. Without the necessary training, GM crops may prove no better than conventional methods.

Footnotes

[1] This should be possible if pests compete for food, or if a predator-prey relationship exists.

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Figure 1. Net revenue (US $/ha) dominance test of Bt and Non-Bt farmers in 1999

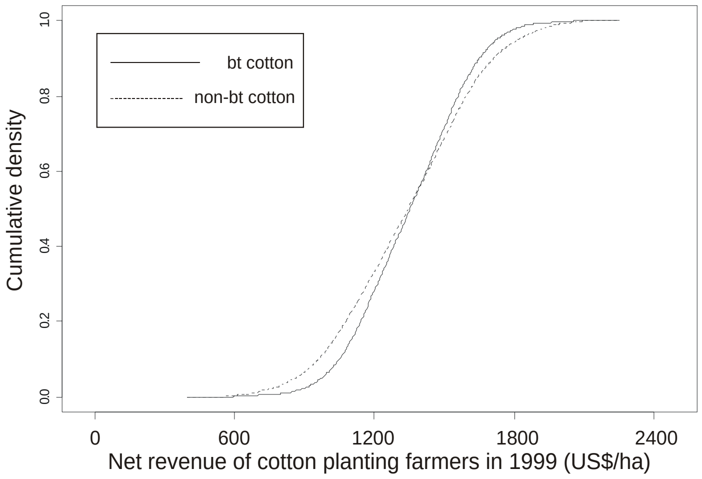

Figure 2. Net revenue (US $/ha) dominance test of Bt and Non-Bt farmers in 2000

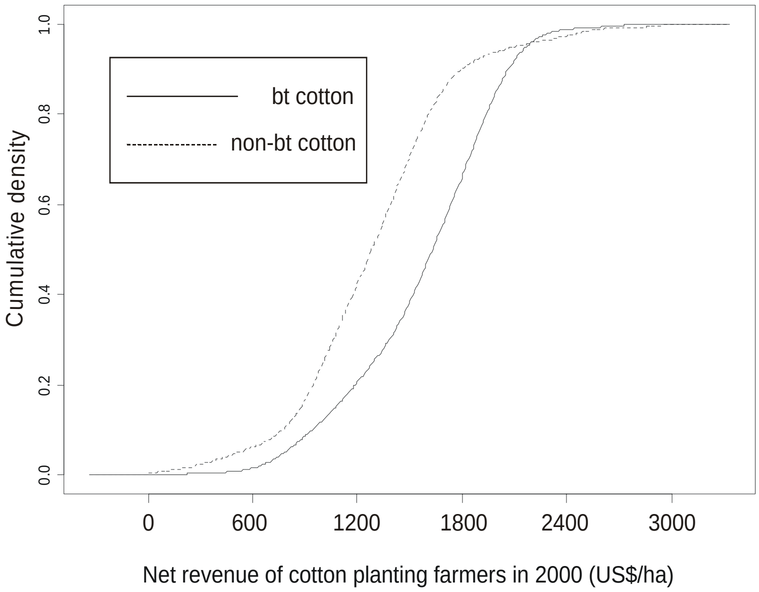

Figure 3. Net revenue (US$/ha) dominance test of Bt and Non-Bt farmers in 2001

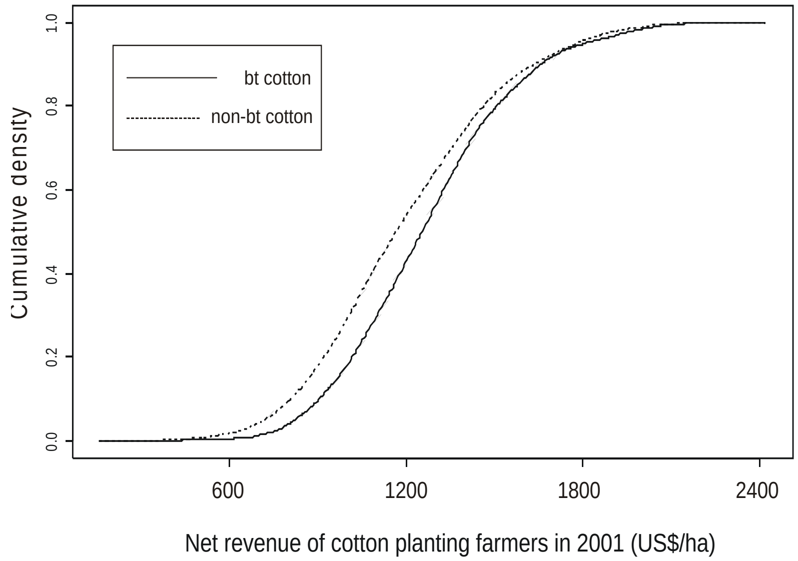

Figure 4. Net revenue (US$ /ha) dominance test of Bt and Non-Bt farmers in 2004

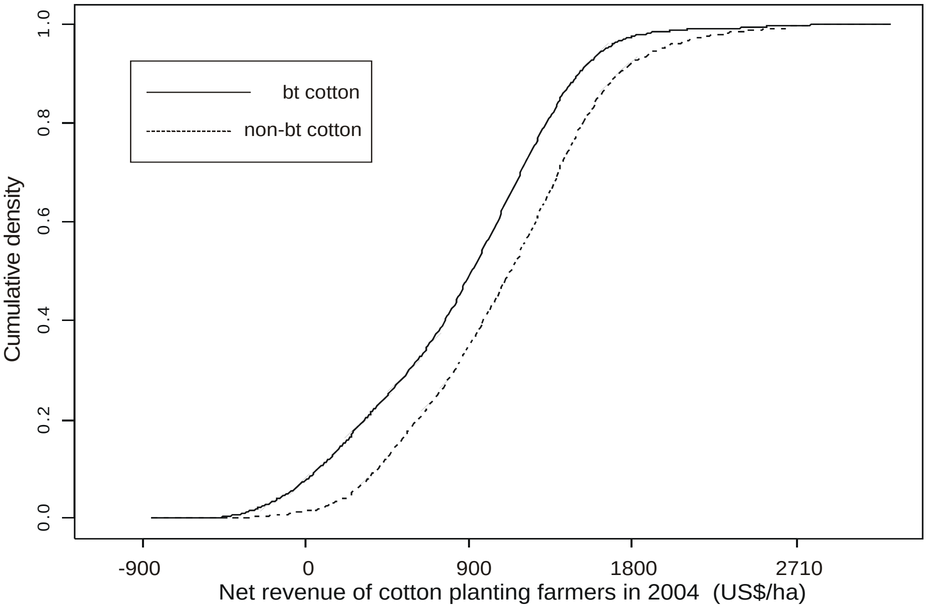

Figure 5. First Order Stochastic Dominance Test of Pesticide expenditure (US $/ha) on the Secondary Pest between Bt and Non-Bt farmers in 2004

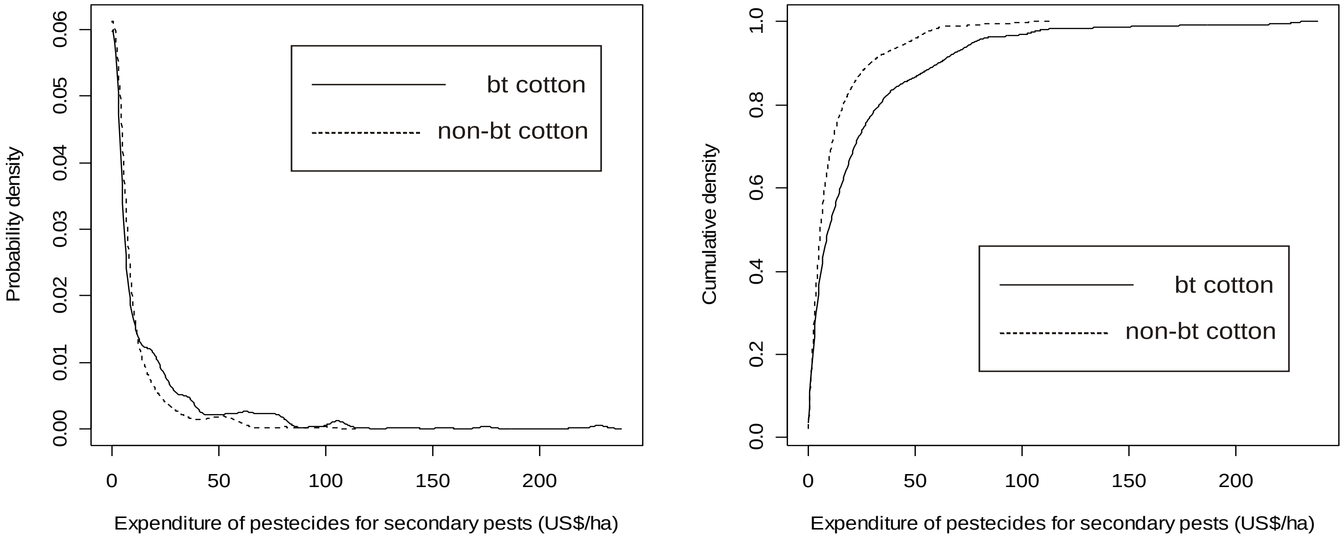

Figure 6. First Order Stochastic Dominance Test of Amount of Pesticides (kg/hectare) used on Secondary Pests for Bt Farmers in years 2001 and 2004

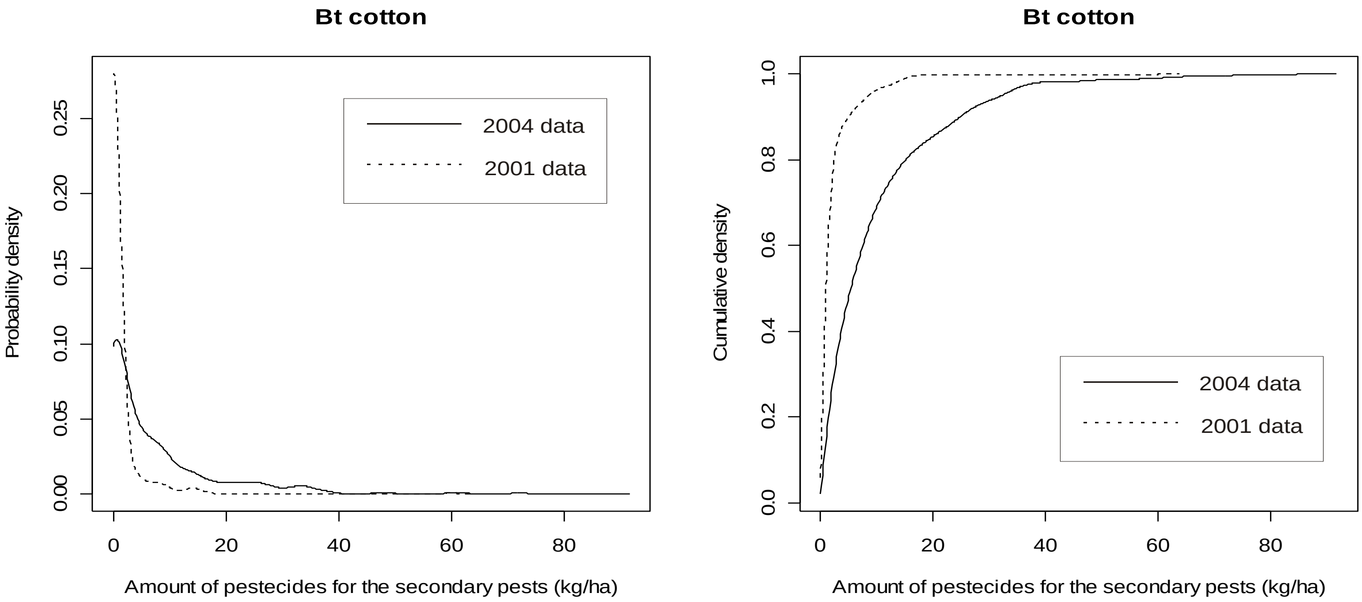

Figure 7. Pesticide Expenditure (US $/hectare) on Primary Pest Bollworm for Bt and Non-Bt in 2004

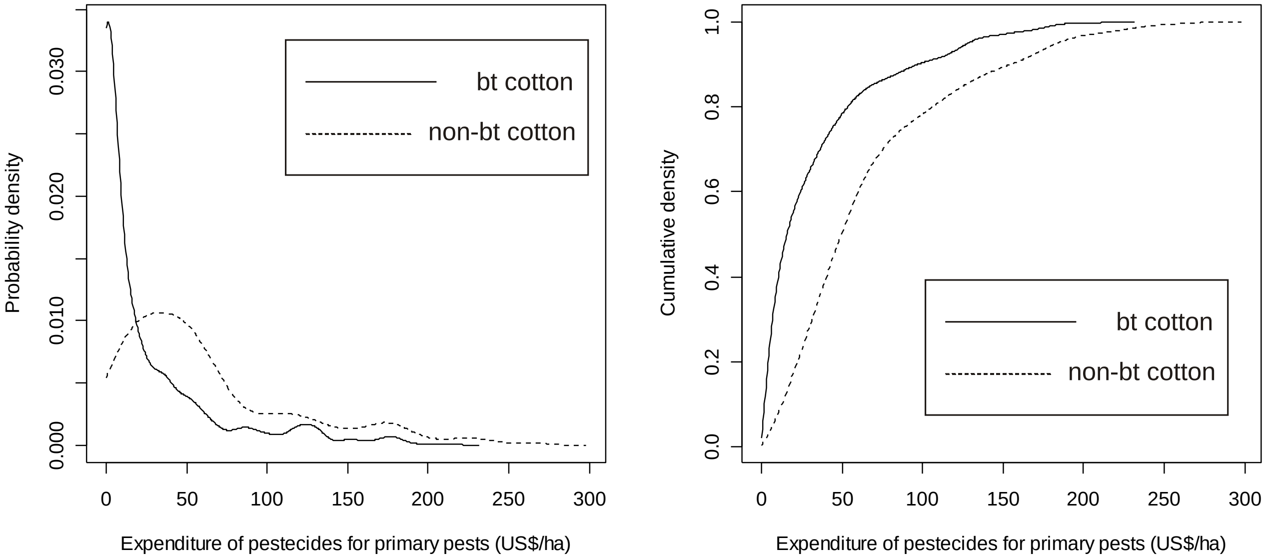

Figure 8. Pesticide expenditure (US$/hectare) between Bt and Non-Bt Farmers in 2004

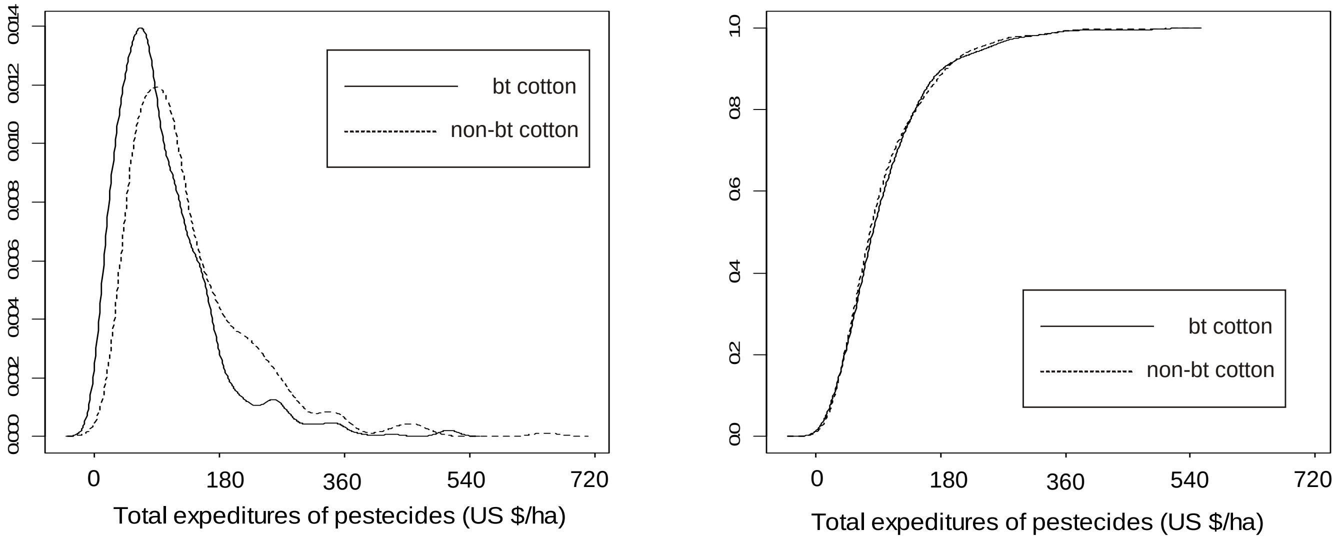

Figure 9: dominance test on total Pesticide expenditure (US $/hectare) between Bt growers with refuge and Non-Bt farmers in 2004

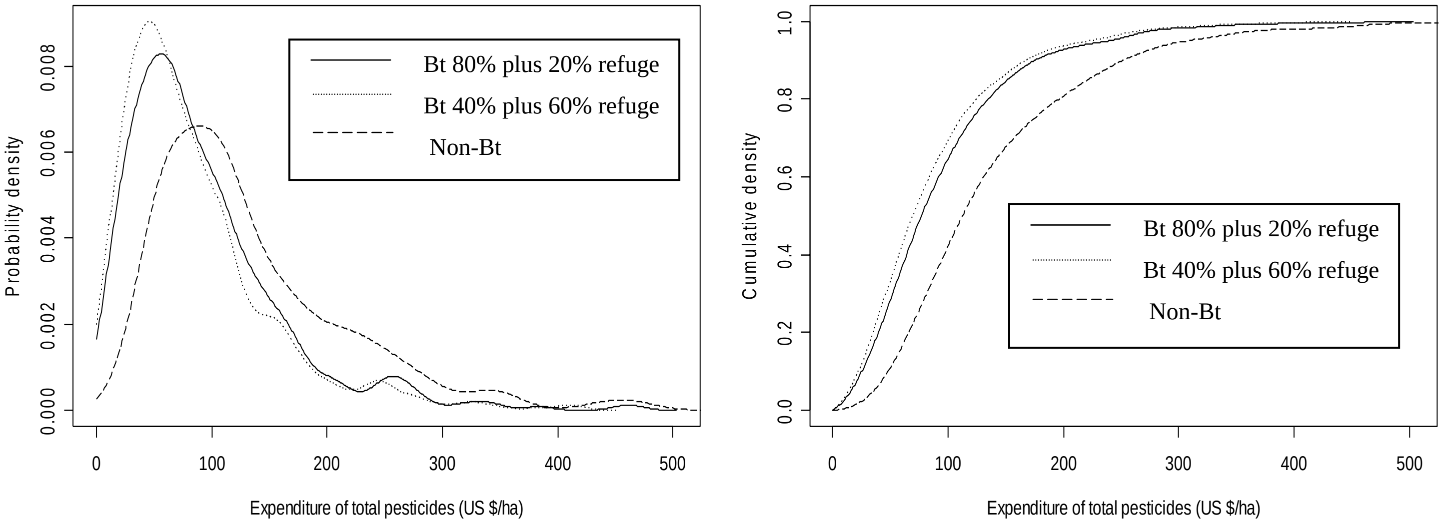

Figure 10:Net revenue comparison of Bt growers with 20% refuge and Non-Bt farmers in 2004

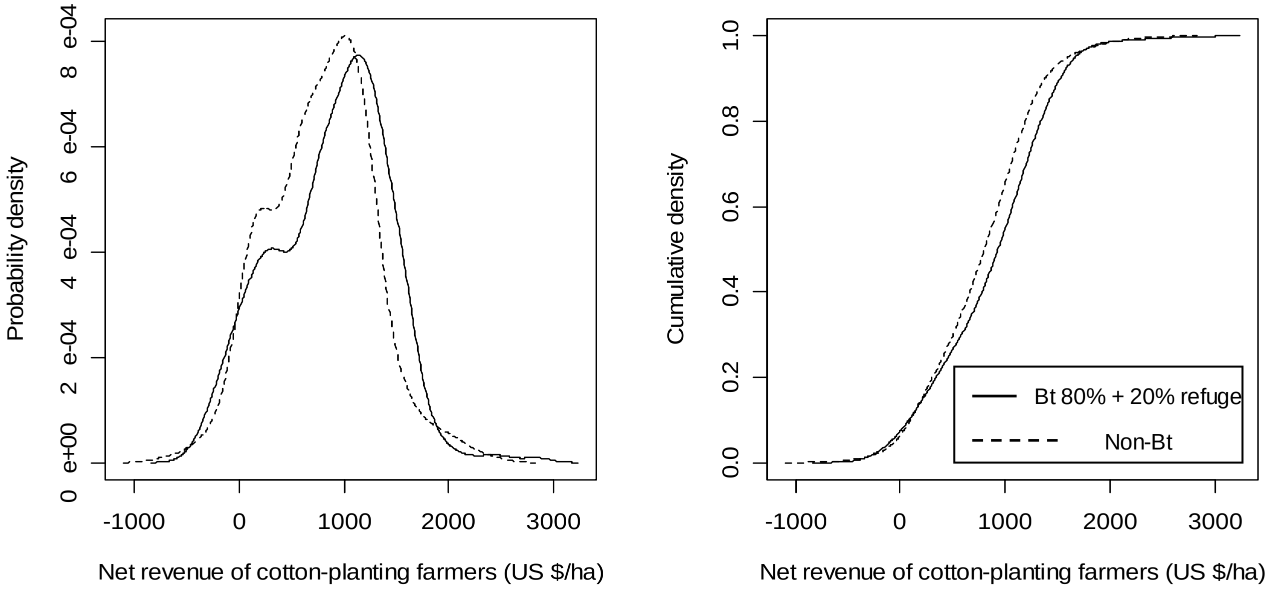

Figure 11:Net revenue CDF dominance comparison between Bt growers with 60% refuge and Non-Bt farmers in 2004