Efficient Refuge policies for Bt cotton in India

Rohit Singla
(ROHIT.SINGLA@TTU.EDU)

Phillip Johnson
(PHIL.JOHNSON@TTU.EDU)

Sukant Misra
(SUKANT.MISRA@TTU.EDU)

Department of Agricultural and Applied Economics
Texas Tech University, Lubbock, TX

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ABSTRACT

This study examined the efficient refuge policies for Bt cotton for three cotton growing regions in India. This was accomplished by developing a single-pest, dual-toxin biological model simulating bollworm resistance to the Bt toxin and synthetic pyrethroids, followed by formulating profit functions for Bt and non-Bt cotton for a representative producer in each region. Profits received in subsequent periods were considered in the regulatory model in order to choose a refuge constraint (static problem) or a sequence of refuge policies (dynamic problem) for each region that maximize discounted profits received over 15 years, subject to various economic and biological constraints. Dynamic solutions for the regulatory problem were derived for each region using the Bellman equation. Results suggested that South Indian farmers do not need to grow a refuge, but farmers in the North and Central regions do. Results also suggested that planting sprayed refugia might be more profitable than planting unsprayed refugia. Sensitivity analysis revealed that the refuge requirements were sensitive to the initial Bt resistance level, relative proportion of CBWs in natural refuges, and proportions of heterozygous and homozygous fitnesses in all of the three regions. Moreover, static refugia were found more profitable as compared to dynamic refugia in the North and Central regions.

INTRODUCTION

Bt cotton was introduced for commercial cultivation in India in 2002–03, primarily aimed at the cotton bollworm, *Helicoverpa armigera* (Kranthi et al., 2004). All countries including India that have introduced Bt crops have derived significant and multiple benefits, including increased crop yields, reduced costs for pesticide treatments, environmental protection from reduced pesticide use, less fungal contamination and reduced labor (Huesing and English, 2004). Based on trials conducted in Maharashtra state in India, the average increase in yield for Bt over non-Bt varieties was about 45% in 2002 and about 63% in 2003 (Bennett *et. al.*, 2004).

Although the rise in productivity and other benefits of growing Bt cotton are well documented, one of the major concerns about its success in the long run is the potential vulnerability to the adaptation of bollworms to the Bt toxin (Bates et al., 2005). It is likely that a continuous presence of the toxin imposes a strong selection pressure on the target insect pest, eventually resulting in the development of insect resistance to the toxin (Kranthi et al., 2004). If too large a share of the pests developed resistance to the Bt toxin, the susceptibility of the pest population to the Bt toxin will fall. Such an occurrence would reduce the effectiveness of Bt cotton in controlling pests.

Concerns regarding development of bollworm resistance to Bt cotton prompted the Environmental Protection Agency (EPA) to establish legal limits on the proportion of total acres individual producers may plant to Bt cotton, representing the first attempt to regulate the development of insecticide resistance and the first instance of the use of refuge acreage as a policy instrument. The current policy provides cotton producers a choice between a treated-refuge option and an untreated-refuge option: they may plant 80 percent of their total acres under Bt, and 20 percent or five rows, whichever is more, under non-Bt, with conventional insecticides allowed throughout; or plant 95 percent Bt, spray Bt acres as needed with conventional insecticides, with no insecticides allowed on the remaining five percent. Refuges allow susceptible pests to thrive so they can mate with resistant pests that survive in the Bt cotton fields. Intermixing susceptible pests into the population can reduce selection pressure and extend the efficacy of the insect-resistant varieties (Huang et al., 2006).

India has become the largest producer of cotton in the world after the introduction of Bt cotton; however, the increased adoption of Bt cotton poses the possibility of the development of resistance by bollworms. There is no empirical study that provides evidence on sustainability of the productivity effects of Bt cotton in India under a scenario of possible resistance development by pests to the Bt toxin. This is particularly important in the case of India since there is evidence to suggest that Indian farmers do not generally comply with refuge requirements. It could be possible that a natural refuge policy is best for some regions in India or for the entire country, but it is necessary that the efficient refuge policies (in comparison to status quo refuge requirements mandated by EPA) for different cotton growing regions of the country are thoroughly examined.

The specific objectives of this study were:

- To better understand the production relationships for Bt and non-Bt cotton for different cotton growing regions in India.
- To examine static and dynamic refuge policies for different regions in India.

CONCEPTUAL MODEL

The conceptual model consists of three parts: a biological model, which is used to simulate the evolution of resistance in pests to Bt cotton; a cotton production model, which is used to examine the effects of resistance and refuge requirements on the behavior of a representative producer; and a regulatory model, which is used to examine the impacts of refuge policies.

Biological Model

The biological model is an extended version of the Hardy-Weinberg model, which simulates the evolution of resistance of bollworm pests to Bt crops subject to the Hardy-Weinberg model assumptions. The Hardy-Weinberg model assumes that: (a) there are large and equal numbers of diploid males and females that mate randomly; (b) genetic mutation and migration are insignificant relative to selection as determinants of resistance evolution; (c) resistance to each toxin is conferred at one locus by one gene and; (d) the probability a gamete (sperm or egg) contains one allele is independent of its containing one of the other three (linkage equilibrium). Moreover, it is assumed that the pests are selected during the larval stage and there are five non-overlapping generations per calendar year.

For a given pest, let y and Y denote the alleles conferring resistance and susceptibility to Bt cotton at locus one, and let allele frequencies $y_{t,i}$ and $Y_{t,i}$ denote the proportions of the respective alleles in bollworm adults during generation i and growing season t. Under the assumption of independent assortment, the three genotype frequencies are $f(yy) = y_{t,i}^2$, $f(Yy) = 2Y_{t,i}\,y_{t,i}$, $f(YY) = Y_{t,i}^2$. Let $f_{t,\,i+1}$ denote the preceding three-vector of genotype frequencies, let q_t denote the proportion of Bt cotton planted by the representative producer, let c_{i+1} denote the proportion of larvae in cotton at the beginning of generation $i+1$. It is assumed that bollworm larvae, in the following two proportions, are confronted with the following two types of selection environments: selection for Bt resistance, q_tc_{i+1}; and not selected for Bt resistance, $1- q_tc_{i+1}$.

Let S^b denote the three-vector of relative fitnesses (survival and reproductive success rates) for larval genotypes confronted with Bt cotton and S^{ab} denote the three-vector of relative fitnesses for larval genotypes not confronted with Bt cotton. The vectors, S^b and S^{ab}, depict relative fitnesses of the three genotypes discussed before. The average rate of survival and reproductive success for generation $i+1$ larvae is then

$$w_{t,i+1} = q_t c_{i+1} f^{/}_{t,i+1}(S^b) + (1 - q_t c_{i+1}) f^{/}_{t,i+1}(S^{ab}), \tag{1}$$

where / is the transpose operator. The proportion of Bt-resistance alleles contributed to the adult population is

$$n_{t,i+1} = q_t c_{i+1} S^b(1,2) + (1 - q_t c_{i+1}) S^{ab}(1,2), \tag{2}$$

where (1, 2) denotes vector elements 1 and 2, and the first element of $n_{t,i+1}$ is post multiplied by 2, because it corresponds to a homozygous resistant allele pair. The Bt-resistance allele frequencies in bollworm adults are then

$$y_{t,i+1} = f_{t,i+1}(1,2)^{/} n_{t,i+1} / 2w_{t,i+1} . \tag{3}$$

Biological model equations (1) – (3) can be used to simulate the intra-seasonal dynamics of bollworms. Inter-seasonal dynamics could be simulated by setting $y_{t+1,i} = y_{t,6}$, because larvae from the last generation of adults in growing season t survive the winter emerge as adults at the beginning of growing season $t+1$. The initial resistance allele frequency ($y_{t,1}$) is simulated as $[y_{t,i+1}]_{i=0} = y_{t,1}$.

Production Model

The representative producer profit per hectare can be expressed as profit per Bt hectare multiplied by the proportion of Bt hectares planted, plus profit per refuge hectare multiplied by the proportion of refuge hectares planted (Harper & Zilberman, 1989; Hurley *et. al.*, 2001). The profit function in time t is given by

$$\pi_t(.) = q_t * \left[pY_t^b(.) - C^b\right] + (1 - q_t) * [pY_t^{nb}(.) - C^{nb}], \tag{4}$$

where q_t and $(1- q_t)$ are the proportions of area under Bt cotton and refuge (non -Bt cotton), respectively, at time t; $Y_t^b(.)$ and $Y_t^{nb}(.)$ are the yield functions associated with Bt and Non-Bt cotton, respectively, at time t; p is the price of cotton and; C^b and C^{nb} are the production costs associated with Bt and non-Bt cotton, respectively. As the susceptibility nature is open-access, we assume the representative producer chooses the proportion of Bt cotton to plant (q_t) that will maximize year *t's* profit given in equation (4) without considering production possibilities in the future. Profit maximization is subject to: refuge type, $0 \leq q_t \leq r_t \leq 1$, where r_t is the maximum proportion of Bt cotton allowed; the biological model; yield functions $Y_t^b(.)$ and $Y_t^{nb}(.)$; and model parameters.

The next step is to model yield functions for Bt and Non-Bt cotton, i.e. $Y_t^b(.)$ and $Y_t^{nb}(.)$. The observed yield of cotton, *Y*, can be specified as a function of both standard inputs (X_t) and damage control measures (Z_t):

$$Y_t = f(X_t)G(Z_t), \qquad (5)$$

where X_t is the vector of conventional inputs, farm-specific factors, location and time-specific factors, and other climate and natural disaster factors (Lichtenberg and Zilberman, 1986). The term $f(X_t)$ is the pest-free yield or potential yield. $G(Z_t)$ is a damage abatement function of the level of control agents such as pesticides used by farmers. The Bt cotton variety dummy variable could be included in both $f(X_t)$ and $G(Z_t)$ to separate out yields of Bt and non-Bt cotton. The abatement function possesses the properties of a cumulative probability distribution function that is defined over the interval of [0, 1]. If we assume a Cobb-Douglas production function, $f(X_t)$, and further assume that the damage abatement function $G(Z_t)$ follows an exponential specification, equation (5) can be written as

$$Y_t = aX_t^{\alpha}[1 - \exp(-cZ_t)], \qquad (6)$$

where *a, α*, and *c* are parameters of the yield function and the variable Z_t represents pesticide use. Z_t is endogenous in this case, which means it has indirect impact on yield by abating the damage rather than having direct impact like fertilizers and irrigation. To account for endogeneity, instrument variables, which are correlated with pesticide use but not yield, can be used as independent variables to estimate pesticide use in the first stage of a 2SLS (Two Stage Least Squares) regression. The predicted value of Z_t must be used in the estimation of the abatement function in equation (6) in the second stage. The model in equation (6) could be estimated for Bt and non-Bt cotton separately, by switching the value of the Bt dummy, to find $Y_t^b(.)$ and $Y_t^{nb}(.)$ in equation (4) (Huang et al., 2002; Qaim, 2003; Qaim *et. al.* 2003; Qaim and Zilberman, 2003).

<u>*Regulatory model*</u>

The representative producer's profit per hectare was formulated in equation (4), where we assumed that the representative producer choose q_t to maximize year *t's* profit without considering future production possibilities. Profits received in subsequent periods are considered in the regulatory model in order to choose a refuge constraint (static problem) or a sequence of refuge policies (dynamic problem) that maximize discounted profits received during *T* years. The regulatory model is

$$max_{r_t} \sum_{t=1}^{T} \rho^{t-1}\, \pi(q_t;\ y_{t,1}), \qquad (7)$$

subject to: refuge type $0 \leq r_t \leq 1$; initial resistance allele frequency at the beginning of the growing season, given by the state transition equation, $y_{t+1,1} = f(y_{t,1},\ q_t)$; biological model equations (1) – (3); profit model equation (4); yield model equations $Y_t^b(.)$ and $Y_t^{nb}(.)$; a discount rate ρ; and other economic and biological parameters. Dynamic solutions to regulatory problems can be found by using the Bellman equation as shown below

$$v_t(y_{t,1}) = \max_{r_t} \pi(q_t; y_{t,1}) + \rho v_{t+1}(y_{t+1,1}), \qquad (8)$$

where v_t maps resistance allele frequencies observed at the beginning of the growing season into the maximum of discounted profits received during the current and remaining growing seasons.

METHODS

Based on the conceptualized single resistance biological model, and the dual-pest, dual-toxin biological model developed by Livingston *et. al.*, 2004; a single-pest, dual-toxin model was developed to simulate the resistance evolution in the cotton bollworm (CBW) population to Bt cotton and synthetic pyrethroids insecticides in India under the Hardy-Weinberg assumptions.

For a given CBW, let x and X denote the alleles that confer susceptibility and resistance to pyrethroids at locus one, respectively; let y and Y denote the alleles that confer susceptibility and resistance to Bt cotton at locus two, and let $x_{t,i}$, $X_{t,i}$, $y_{t,i}$, and $Y_{t,i}$ denote allele frequencies for generation *i* adults during growing season t. It is assumed that the CBWs are selected during the larval stage and there are five non-overlapping generations, per calendar year. Under the assumption of independent assortment/linkage equilibrium, there are four gametes and nine genotypes. The four gamete frequencies are $g_{t,i}^1 = x_{t,i}y_{t,i}$, $g_{t,i}^2 = x_{t,i}Y_{t,i}$, $g_{t,i}^3 = X_{t,i}y_{t,i}$, and $g_{t,i}^4 = X_{t,i}Y_{t,i}$. The nine genotypes, their frequencies (as function of gamete frequencies), and their relative fitnesses[1] under different selection environments (S^b, S^p, S^{ab} and S^{ap}) are tabulated in *Appendix 1*. Let $f_{t,i+1}$ denote the preceding nine-vector of genotype frequencies, let q_t denote the proportion of Bt cotton planted by the representative producer, let c_{i+1} denote the proportion of bollworm larvae in cotton and let s_{i+1} denote the proportion of larvae in cotton sprayed with pyrethroids. It is assumed that bollworm larvae, in the following proportions, are confronted with the following selection environments: selection for Bt resistance, $q_tc_{i+1}(1- s_{i+1})$; selection for Bt and pyrethroid resistance, $q_tc_{i+1}s_{i+1}$; selection for pyrethroid resistance, $(1-q_t)c_{i+1}s_{i+1}$; and not selected, $r_{t,i+1} = 1 - c_{i+1}(b_t + s_{i+1} + b_ts_{i+1})$, which is the remainder. The average rate of survival and reproductive success for generation $i+1$ larvae is then

$$w_{t,i+1} = r_{t,i+1}f_{t,i+1}^{/}(S^{ab}.* S^{ap}) + b_tc_{i+1} f_{t,i+1}^{/}(S^b.* S^{ap}) + b_tc_{i+1}s_{i+1} f_{i,t+1}^{/}S^{bp} + (1 - b_t)c_{i+1}s_{i+1}f_{i,t+1}^{/}(S^p.* S^{ab}), \tag{9}$$

where $^{/}$ denotes the transpose operator, and .* denotes element-by-element multiplication. The proportion of pyrethroid resistance alleles contributed to the adult population is

$$m_{t,i+1} = r_{t,i+1}\left(S^{ab}(1:6).* S^{ap}(1:6)\right) + b_tc_{i+1}\left(S^b(1:6).* S^{ap}(1:6)\right) + b_tc_{i+1}s_{i+1}S^{bp}(1:6) + (1 - b_t)c_{i+1}s_{i+1}\left(S^p(1:6).* S^{ab}(1:6)\right), \tag{10}$$

where (1:6) denotes vector elements one through six, with the first three elements of $m_{t,i+1}$ post-multiplied by two, as they have pair of resistant alleles; and the proportion of Bt resistance alleles contributed to the adult population is

$$n_{t,i+1} = r_{t,i+1}\left(S^{ab}(\theta).* S^{ap}(\theta)\right) + b_tc_{i+1}\left(S^b(\theta).* S^{ap}(\theta)\right) + b_tc_{i+1}s_{i+1}S^{bp}(\theta) + (1 - b_t)c_{i+1}s_{i+1}\left(S^p(\theta).* S^{ab}(\theta)\right), \tag{11}$$

[1] Fitnesses are defined as survival and reproductive success rates of pests.

where (θ) denotes vector elements 1, 2, 4, 5, 7, and 8, with elements 1, 4, and 7 of $n_{t,i+1}$ post-multiplied by two, as they have pair of resistant alleles. Pyrethroid and Bt resistance allele frequencies in the adult population are then

$$x_{t,i+1} = f_{t,i+1}(1:6)'m_{t,i+1}/2w_{t,i+1} \quad (12)$$

$$y_{t,i+1} = f_{t,i+1}(\theta)'n_{t,i+1}/2w_{t,i+1} \,. \quad (13)$$

Equations (9) – (13) simulate the intra-seasonal dynamics of resistance evolution by CBWs to Bt toxin and pyrethroids, in three cotton growing regions in India (to be elaborated in the next section). The inter-seasonal dynamics is simulated by setting $x_{t+1,1} = x_{t,6}$ and $y_{t+1,1} = y_{t,6}$, because bollworm larvae from the last (fifth) generation of adults in growing season t survive the winter and emerge as adults at the beginning of growing season next year i.e. $t+1$.

Instead of simulating pest population, larval survival rates of pests in Bt ($w_{j,t}^{b}$) and non-Bt ($w_{j,t}^{nb}$) cotton are mapped in each of the three cotton growing regions in India, into annual pyrethroids and yield losses equations estimated by Livingston *et. al.* (2004) on almost similar pest i.e. *Helicoverpa zea* in Louisiana. Average survival rates for CBW in Bt and non-Bt cotton in the j^{th} cotton growing region in India are calculated as

$$w_{j,t}^{b} = \sum_{i=2}^{5} e_i c_{j,i} f_{j,t,i}^{'} \times \left[S^b(1-s_i) + \left(S^b.* S^p\right)s_i\right]/4 \quad (14)$$

$$w_{j,t}^{nb} = \sum_{i=2}^{5} e_i c_{j,i} f_{j,t,i}^{'} \times \left[\left(S^{ab}.* S^{ap}\right)(1-s_i) + S^p s_i\right]/4, \quad (15)$$

$0 \le e_i \le 1$ denote environmental fitness parameters, with value less than 1 indicating an environmental obstruction to survival independent of resistance, and equal to 1 indicating no environmental obstruction to resistance. S^b, S^p, S^{ab} and S^{ap} are the relative fitnesses; s_i is the proportion of CBWs larvae in cotton sprayed with pyrethroids; $c_{j,i}$ is the proportion of CBW larvae in cotton in the j^{th} region; $f_{j,t,i}^{'}$ is the nine-vector of genotype frequencies in the j^{th} region. Environmental fitnesses, relative fitnesses and proportion of sprayed CBWs larvae are taken as similar in three cotton growing regions.

The average annual survival rates used to simulate annual synthetic pyrethroids sprays, spray costs and yield losses on Bt and non-Bt cotton in each cotton growing region are

$$w_{j,t}^{b} = \min\,(w_{j,t}^{b}, \varepsilon_j) \quad (16)$$
$$w_{j,t}^{n} = \min\,(w_{j,t}^{n}, \varepsilon_j), \quad (17)$$

where ε_j is the value of average survival that maximizes the pyrethroid use in the j^{th} region. Pyrethroids use was set at the maximum level in each region when average survival rates $\geq \varepsilon_j$, because producer use of synthetic pyrethroid alterative is not simulated in the base model. Because the base model does not incorporate this behavior, spray costs and yield losses may be overestimated during the periods in which producers would have otherwise switched to alternative insecticide spray, leading to an upward bias on refuge requirements estimation. For this reason, refuge requirements without pyrethroid resistance evolution in the base model are also estimated. Using the base model with and without pyrethroid resistance evolution, upper and lower bounds on refuge sizes were estimated.

Cotton Production Functions

To estimate the cotton yield functions in India, the cotton producing area is segregated into three regions in order to account for heterogenous growing conditions (Chaudhary, 2005). The three regions are comprised of North, Central, and South India. The map of the selected cotton growing regions is shown in *Appendix 2*. Cotton yield in the j^{th} region can be specified as follows:

$$Y_{j,t} = f(Y_{j,t-1},\ q_{j,t},\ Irri_{j,t}, FU_{j,t}, RF_{j,t}, t), \quad (18)$$

where $Y_{j,t}$ represents cotton yield in the j^{th} region at time *t*; $Y_{j,t-1}$ is lagged cotton yield in the j^{th} region; $q_{j,t}$ is the proportion of refuge a farmer is growing in the j^{th} region at time *t*; $Irri_{j,t}$ is the area under irrigation for the j^{th} region at time *t*: $RF_{j,t}$ is rainfall in the j^{th} region at time *t* ; $FU_{j,t}$ is the fertilizer use in the j^{th} region at time *t*; and *t* is the time trend. The yield model in equation (18) was estimated to obtain yield values (at means) for Bt cotton and non-Bt cotton (Y_j^b and Y_j^{nb}), separately. The next step was to calculate the bollworm-free yields of cotton in j^{th} region. For simplicity we assume that the bollworm-free yields for Bt and non-Bt are the same. The bollworm-free yield for j^{th} region is calculated as:

$$Y_j^{PF} = \frac{1}{1-\emptyset_j} Y_j^{nb}, \tag{19}$$

where, Y_j^{PF} is the bollworm-free yield of cotton in the j^{th} region; $\emptyset_j$ is the proportionate damage caused by bollworms in the j^{th} region; and Y_j^{nb} is the yield value (at means) for non-Bt cotton in the j^{th} region.

The yield functions for Bt and non-Bt cotton for j^{th} region after incorporating the damage function for cotton in the United States (see *Appendix 3*) are:

$$Y_{j,t}^{b}\left(w_{j,t}^{b}\right) = Y_j^{PF} * [1 - \varphi\{\gamma + \delta * E(P_t/w_{j,t}^{b})\}], \tag{20}$$

$$Y_{j,t}^{nb}\left(w_{j,t}^{nb}\right) = Y_j^{PF} * \left[1 - \varphi\{\gamma + \delta * E(P_t/w_{j,t}^{nb})\}\right], \tag{21}$$

where, $E(P_t/w_{j,t}^{b}) = \left(\alpha w_{j,t}^{b} - \beta (w_{j,t}^{b})^2\right)$, and $E(P_t/w_{j,t}^{nb}) = \left(\alpha w_{j,t}^{nb} - \beta (w_{j,t}^{nb})^2\right)$ are the simulated pyrethroid uses on Bt and non-Bt cotton, respectively, in the j^{th} region. The term $\varphi\{.\}$ is the damage function, defined on the interval [0, 1], and uses the standard normal cumulative distribution function to map simulated pyrethroid use into proportionate yield losses per hectare (Lichtenberg and Zilberman, 1986; Livingston *et. al.*, 2004); and α, β, γ and δ are the parameters of the damage function estimated for CBW in the U.S. (See *Appendix 3*); $w_{j,t}^{b}$ and $w_{j,t}^{nb}$ are survival rates of bollworms on Bt and non-Bt cotton, respectively, in j^{th} region (see equations 14 and 15).

The cost function for the j^{th} region is formulated as the sum of fixed costs and variable costs. All costs but pyrethroid spray costs are assumed as fixed. The cost functions for Bt and non-Bt cotton for the j^{th} region are:

$$C_{j,t}^{b}(w_{j,t}^{b}) = C_j^{Fb} + C^V * E(P_t/w_{j,t}^{b}), \text{ and} \tag{22}$$

$$C_{j,t}^{nb}(w_{j,t}^{nb}) = C_j^{Fnb} + C^V * E(P_t/w_{j,t}^{nb}), \tag{23}$$

where C_j^{Fb} and C_j^{Fnb} are fixed costs associated with Bt and non-Bt cotton, respectively, in j^{th} region (where C_j^{Fb} includes technology cost of Bt cotton); and C^V is cost of single pyrethroid spray (including labor cost of spraying) which is multiplying with pyrethroid use, a function of survival rates of pests. The yield and cost models developed for Bt cotton and non-Bt cotton ($Y_{j,t}^{b}$, $Y_{j,t}^{nb}$, $C_{j,t}^{b}$, $C_{j,t}^{nb}$) are plugged into the profit function conceptualized. Therefore, the profit function for a representative producer in the j^{th} region is:

$$\pi_{j,t} = q_{j,t} * \left[p_j Y_{j,t}^{b}\left(w_{j,t}^{b}\right) - C_{j,t}^{b}\left(w_{j,t}^{b}\right)\right] + (1 - q_{j,t}) * \left[p_j Y_{j,t}^{nb}\left(w_{j,t}^{nb}\right) - C_{j,t}^{nb}\left(w_{j,t}^{nb}\right)\right], \quad (24)$$

where p_j is the price of cotton in j^{th} region. It is assumed that the representative producer in the j^{th} region chooses the proportion of Bt cotton to plant ($q_{j,t}$) to maximize year *t's* profit given in equation (24) without considering production possibilities in the future. Profit maximization is subject to: refuge type, $0 \leq q_{j,t} \leq r_{j,t} \leq 1$, where $r_{j,t}$ is the maximum proportion of Bt cotton allowed in j^{th} region; initial resistance allele frequencies, $x_{t,1}^{j}$ and $y_{t,1}^{j}$; biological model equations (9) – (18); yield models $Y_{j,t}^{b}$ and $Y_{j,t}^{nb}$; cost model equations $C_{j,t}^{b}$ and $C_{j,t}^{nb}$; and economic and biological parameters.

Static/Dynamic Regulatory Models

The objective of the regulatory model is to select an optimal refuge size in the j^{th} region that maximizes the discounted average profits per hectare over T years, subject to the dynamics of CBW resistance (Qiao, 2006; Livingston *et. al.*, 2004). Profits received in subsequent periods are considered in the regulatory model in order to choose a refuge constraint (static problem) or a sequence of refuge policies (dynamic problem) that maximize discounted profits received over T years in the j^{th} region. The regulatory model is given by

$$\max_{r_{j,t}} \sum_{t=1}^{T} \rho^{t-1} \pi\left(q_{j,t}; \alpha_t^j\right), \quad (25)$$

subject to: refuge type $0 \leq r_{j,t} \leq 1$ in the j^{th} region; initial resistance allele frequency, $\alpha_t^j = [x_{t,1}^{j}, y_{t,1}^{j}]$ in the j^{th} region; biological model equations (9) – (18); profit model equation (24); yield model equations $Y_{j,t}^{b}$ and $Y_{j,t}^{nb}$; cost equations $C_{j,t}^{b}$ and $C_{j,t}^{nb}$; a discount rate ρ; and other parameters. Dynamic solutions to the regulatory problem for j^{th} region can be found by using the Bellman equation

$$v_t\left(a_t^j \right) = \max_{r_{j,t}} \pi\left(q_{j,t}; a_t^j\right) + \rho v_{t+1}\left(a_{t+1}^j\right), \tag{26}$$

A dynamic solution to the regulatory problems is a sequence of policy functions which map resistance allele frequencies observed at the beginning of growing seasons.

DATA

Economic data/parameters: The time series data on area, production and yield for cotton at the state level was obtained from indiastat.com and agcoop.nic.in. The time series data on percentage area under Bt cotton, rainfall, cotton area irrigated and fertilizer use were obtained from Indiastat.com and its associated sites at the state level. The district (similar to 'county' in the U.S.) level data on area under different bollworm host crops, i.e., pigeon pea, sunflower, tomatoes, Okra and chilies were obtained from associated sites of Indiastat.com at the state level.

The data on different economic parameters that are assumed as being the same across all three cotton growing regions were obtained from different sources, described in Table 1 as follows:

Table 1. Economic parameter values in India.

Economic Parameters	***Default Value***	***Source***
Annual Interest rate	7.75%	HDFC Bank, India
Pyrethroid treatment cost (C^V)	$7.82/ha	Pesticides Retailers
Alternative Insecticide cost	$21.63/ha	Pesticides Retailers
Bt technology Fee	$13.34/ha	Pesticides Retailers
Exchange Rate	$0.0211/Rupee	XE.com

The data on various economic parameters that were assumed as different across all three cotton growing regions were obtained from different sources, presented in Table 2:

Table 2. Economic parameter values in three cotton growing regions in India

Economic parameters	North	Central	South	Sources
Cotton Lint price, p_j ($/Kg)	1.25	1.13	1.24	Indiastat.com
Fixed Costs Bt, C_j^{Fb} ($/ha) Sprayed	282.13	286.60	293.62	Indiastat.com; CICR, Nagpur; Bennett *et al.*, 2004; Orphal, 2005
Fixed Costs Non-Bt, C_j^{Fnb} ($/ha) Sprayed	287.43	278.72	285.74	Indiastat.com; CICR, Nagpur; Bennett *et al.*, 2004; Orphal, 2005
Costs Unsprayed, C_j^{Un} ($/ha)	292.73	270.84	277.86	Indiastat.com; CICR, Nagpur; Bennett *et al.*, 2004; Orphal, 2005
Percentage damage bollworms, $\emptyset_j$	50%	60%	60%	Sundaram *et. al.* (1999), Yang (2003)

<u>Biological parameters:</u> The data on different biological parameters are described in Table 3 as follows:

Table 3. Biological parameter values in three cotton growing regions in India

Parameter	***Pyrethroids***	***Source***	***Bt***	***Source***
Initial Resistance allele frequency	0.5	Ru et al., 2002; Wu, 2004	0.00075 (North) 0.0015 (Central) 0.0013 (South)	Kranthi et al., 2006
Treated fitness homozygote	0.5862 (RR^p)	Kranthi *et.al.*, 2002	0.95 (RR^{Bt})	Kranthi et al., 2006
Treated fitness heterozygote	0.1324 (RS^p)	Livingston *et. al.*, 2004	0.46 (RS^{Bt})	Kranthi et al., 2006
Treated fitness susceptible	0.0042 (SS^p)	Kranthi et.al. 2002	0.25 (SS^{Bt})	Livingston et al., 2004
Untreated fitness homozygote	1 (RR^{ap})	(No data)	0.95 (RR^{aBt})	(No data)
Untreated fitness heterozygote	1 (RS^{ap})	(No data)	0.9625 (RS^{aBt})	(No data)
Untreated fitness susceptible	1 (SS^{ap})	(No data)	1 (SS^{aBt})	(No data)

The initial resistance allele frequencies for Bt cotton were reported differently across each cotton growing region in India. The initial resistance allele frequency of CBW to Bt toxin in the Northern region is much less compared to the South and Central regions because Bt cotton was introduced three years later in the North as compared to South and Central India. The other biological parameters were assumed to be the same across the three cotton growing regions. The parameters of untreated fitnesses for homozygote resistant, heterozygote resistant and susceptible CBWs were assumed to approach one for both the Bt and pyrethroid. This implies that if CBWs not treated with either of the toxins, the survival will be nearly 100%. All the biological parameters were subjected to sensitivity analysis based on various published estimates and some arbitrary ranges around parameter values.

Other parameters: It was assumed that there are five generations (1st, 2nd, 3rd, 4th and 5th) of CBWs in each cotton growing region in India. The parameter values of proportions of CBWs in cotton ($c_{j,i}$), proportions of CBWs in cotton sprayed (s_i) and environmental fitness factors (e_i) of CBWs for each generation are tabulated in Table 4.

Table 4. Other parameter values.

Generation/Month, i	*North*	*Central*	*South*	*Sources*
		Proportion of bollworms in Cotton ($c_{j,i}$)		
1st	0.01	0.01	0.01	Ravi *et. al.*, (2005), Indiastat.com
2nd	0.8758	0.4841	0.4441	-do-
3rd	0.9112	0.8795	0.4112	-do-
4th	0.8975	0.7277	0.5872	-do-
5th	0.8033	0.2049	0.6114	-do-
		Proportion of bollworm in cotton sprayed (s_i)		
1st	-	-	-	Author's guess
2nd	-	-	-	-do-
3rd	0.80	0.80	-	-do-
4th	0.50	0.50	0.80	-do-
5th	-	-	0.50	-do-
		Environmental fitness factor of bollworms(e_i)		
1st	0.4732	0.4732	0.4732	Livingston *et. al.*, (2004)
2nd	0.4104	0.4104	0.4104	-do-
3rd	-	-	-	-do-
4th	-	-	-	-do-
5th	-	-	-	-do-

RESULTS

The results of the stepwise regression used to estimate yield functions for the three regions are presented in Table 5. The proportion of area under Bt cotton ($q_{j,t}$) was included in the yield model of each cotton growing region to separate out yields of Bt and non-Bt cotton. This proportion was found to be statistically significant in explaining yields in Central and South India because of the higher yield potential of Bt cotton as compared to non-Bt cotton. The proportion of area under Bt cotton was not statistically significant for North India due to lack of a sufficient number of observations for Bt cotton because of its late adoption.

Lagged yield ($y_{j,t-1}$) was included in the cotton yield model for the North region and was found to be statistically significant and different from zero, suggesting that the yield realized in the previous year influences the current cotton yield in that region. In Central India, fertilizer use, irrigation and their interaction were all found to be statistically significant. This means that proper integration of irrigation levels and fertilizer is essential to obtaining the optimum cotton yield. The coefficient of fertilizer-irrigation interaction ($\boldsymbol{FU_{j,t} * Irri_{j,t}}$) is positive, which implies that an additional unit of fertilizer causes an increase in cotton yield for areas in Central India that have more access to irrigation. In South India, the coefficient of time trend (t) was found to be positive and statistically significant and different from zero in determining cotton yield. A possible explanation for this is improvement in agricultural technology over time.

The coefficients of determination (R^2) for the North, Central, and South regions were 0.54, 0.89, and 0.86, respectively. A value of $R^2 = 0.89$ in South India implies that 89% of the variation in cotton yield in that region is explained by explanatory variables, i.e. time trend and proportion of area under Bt technology ($\boldsymbol{q_{j,t}}$). The R^2 value in North India is much less as compared to the corresponding values in Central and South India. A low value of R^2 in the North region may be due to erratic monsoon rainfall and high weather variability, which are not being captured by the model (Chaudhary, 2005).

Table 5. Regression estimates of regional cotton yield models in India

Independent Variables	*North*	*Central*	*South*
Intercept	144.05 (90.01)	2212.54 (1059.31)*	268.99 (19.87)***
$q_{j,t}$	249.67 (246.69)	243.05 (64.42)***	204.55 (55.82)**
$Y_{j,t-1}$	0.62 (0.24)**	-	-
$FU_{j,t}$	-	-6.52 (3.11)*	-
$Irri_{j,t}$	-	-11439 (5986.81)*	-
$FU_{j,t} * Irri_{j,t}$	-	38.37 (17.25)**	-
t	-	-	9.27 (2.21)***
R^2	0.54	0.89	0.86
DW Statistic	1.80	1.92	2.02
Number of observations	18	18	18

The estimated regression coefficients of the regional yield models were utilized to calculate regional yield values (at means of explanatory variables), which were further used to calculate regional pest-free yields, as shown in Table 6. The regional pest-free yields were utilized in the revised yield functions for Bt and non-Bt cotton, which included the damage function for CBWs in the U.S. The revised yield models and cost models for Bt and non-Bt cotton in each region were used to formulate the regional cotton profit function for a representative producer. The regional profit function was maximized, subject to various biological and economic constraints. The regional regulatory models were used in order to find the optimal static refuges that maximize the present value of average profits per hectare in each region under a 15-year planning horizon, subject to the dynamics of CBW resistance. Regional optimal refuges were examined for sprayed and unsprayed options, with and without pyrethroid resistance evolution in the base model.

Table 6. Regional pest-free yield estimations for cotton in India

Particulars	*North*	*Central*	*South*
Yield of Non-Bt Cotton (at means), y_j^{nb}, Kg/Ha	381.01	325.62	357.07
Yield of Bt Cotton (at means), y_j^{b}, Kg/Ha	630.68	568.67	561.62
Proportionate damage by bollworms in non-Bt cotton, $\emptyset_j$	0.50	0.60	0.60
Bollworm-free yield, $y_j^{PF} = \frac{1}{1-\emptyset_j} y_j^{nb}$	762.03	814.05	892.66

Regional static optimal solutions and annualized producer returns under the sprayed refuge option with pyrethroid resistance considered are presented in Table 7. Optimal refuge solutions are reported for the one-through fifteen-year planning horizons starting in 2008. Resistance allele frequencies at the beginning of 2008 in each region were based on the biological model of CBW resistance, base parameters, and proportion of total cotton acreage planted to Bt cotton. Regulated planting decisions and refugia were obtained using a grid search over the finite set ranging from 0.00 to 1.00 at interval of 0.01, for static solutions.

For the most common scenario i.e. sprayed refuges with pyrethroid resistance considered, static refugia were 0% in each region for one- through four-year horizons as shown in Table 7. Beginning with the fifth-year, static refugia increased with time in North India. In Central India, static refugia were 0% for the first eight years, and increased with time after that. For the one- through fifteen-year planning horizon static refugia increased from 0% to 19% and 42% in Central and North India, respectively. In South India, the static refugia were 0% for all fifteen years. The major reasons behind the different regional refuge policies were; different initial Bt resistance allele frequencies, and the difference in proportion of natural refuge across regions.

Table 7. Profit maximizing static sprayed refugia for the three cotton growing regions in India, with pyrethroid resistance considered.

Time (Years)	North		Central		South	
	Static Sprayed Refugia	**APV[1]**	**Static Sprayed Refugia**	**APV**	**Static Sprayed Refugia**	**APV**
1	0%	602.69 (0.59%)[2]	0%	583.11 (0.71%)	0%	759.00 (0.66%)
2	0%	602.37 (0.54%)	0%	583.09 (0.71%)	0%	758.99 (0.66%)
3	0%	602.20 (0.54%)	0%	583.07 (0.71%)	0%	758.98 (0.66%)
4	0%	601.78 (0.48%)	0%	583.05 (0.71%)	0%	758.96 (0.65%)
5	4%	600.68 (0.31%)	0%	583.01 (0.70%)	0%	758.95 (0.65%)
6	10%	599.45 (0.13%)	0%	582.88 (0.68%)	0%	758.86 (0.65%)
7	17%	598.50 (0.03%)	0%	582.68 (0.65%)	0%	758.79 (0.65%)
8	23%	597.75 (0.02%)	0%	582.32 (0.59%)	0%	758.73 (0.65%)
9	24%	597.07 (0.07%)	1%	581.70 (0.49%)	0%	758.67 (0.64%)
10	29%	596.49 (0.11%)	4%	580.92 (0.36%)	0%	758.57 (0.63%)
11	33%	595.98 (0.13%)	8%	580.22 (0.25%)	0%	758.47 (0.62%)
12	34%	595.57 (0.15%)	11%	579.54 (0.15%)	0%	758.33 (0.61%)
13	37%	595.20 (0.16%)	14%	579.02 (0.08%)	0%	758.11 (0.58%)
14	40%	594.85 (0.17%)	16%	578.53 (0.03%)	0%	757.79 (0.54%)
15	42%	594.56 (0.18%)	19%	578.06 (0.00%)	0%	757.32 (0.48%)

1. APV is the annualized present value of return OR annualized profits per hectare
2. Percent difference between annualized profits per hectare under optimal and current sprayed refuge options are in ( )

When pyrethroid resistance was not considered in the base model, the static refugia were 0% for the first five-year horizon as shown in Table 8. Afterwards, static refugia increased to 35% in the North and 8% in the Central region, for the fifteen-year horizon. Static refugia remained 0% in South India for one- through fifteen-year planning horizon, with and without pyrethroid resistance considered in the base model. The reason behind less refuge requirements under the scenario without pyrethroid resistance compared to the scenario with pyrethroid resistance is the lower Bt-resistance allele frequencies in CBWs in the former scenario; because the toxin-mixture impact on Bt-resistance evolution is more effective.

Table 8. Profit maximizing static sprayed refugia for the three cotton growing regions in India, without pyrethroid resistance considered.

Time (Years)	North		Central		South	
	Static Sprayed Refugia	**APV[1]**	**Static Sprayed Refugia**	**APV**	**Static Sprayed Refugia**	**APV**
1	0%	613.16 (0.93%)[2]	0%	590.66 (0.87%)	0%	767.46 (0.79%)
2	0%	613.15 (0.92%)	0%	590.65 (0.87%)	0%	767.46 (0.79%)
3	0%	613.11 (0.92%)	0%	590.65 (0.87%)	0%	767.46 (0.79%)
4	0%	612.90 (0.89%)	0%	590.64 (0.86%)	0%	767.46 (0.79%)
5	0%	612.33 (0.79%)	0%	590.63 (0.86%)	0%	767.46 (0.79%)
6	3%	610.72 (0.54%)	0%	590.61 (0.86%)	0%	767.45 (0.79%)
7	10%	609.10 (0.29%)	0%	590.53 (0.85%)	0%	767.45 (0.79%)
8	13%	607.76 (0.11%)	0%	590.45 (0.83%)	0%	767.45 (0.79%)
9	20%	606.55 (0%)	0%	590.31 (0.81%)	0%	767.44 (0.79%)
10	22%	605.60 (0.02%)	0%	590.08 (0.77%)	0%	767.43 (0.79%)
11	26%	604.70 (0.07%)	0%	589.69 (0.71%)	0%	767.43 (0.79%)
12	29%	603.91 (0.11%)	1%	589.04 (0.60%)	0%	767.39 (0.78%)
13	31%	603.23 (0.14%)	3%	588.32 (0.48%)	0%	767.36 (0.78%)
14	34%	602.61 (0.16%)	7%	587.67 (0.38%)	0%	767.32 (0.78%)
15	35%	602.06 (0.17%)	8%	587.01 (0.28%)	0%	767.28 (0.77%)

1. APV is the annualized present value of return OR annualized profits per hectare
2. Percent difference between annualized profits per hectare under optimal and current sprayed refuge options are in ( )

Annualized present values (APV) or annualized returns were slightly higher than those received under current refuge options in all of the three cotton growing regions with and without pyrethroid resistance considered. The current refuge option in this case are the sprayed refuge option mandated by

Environmental Protection Agency (EPA) under which farmers are required to grow 20% of their total cotton acreage under non-Bt cotton which could be sprayed.

For unsprayed refuge, with and without pyrethroid resistance, static refugia were 0% in each region, for the one- through fifteen-year horizons as shown in Tables 9 and 10. The reason behind the 0% refuge policy is that the susceptible pests to Bt and pyrethroids in unsprayed cotton will mate with resistant pests to both toxins in Bt cotton, resulting in declining resistant allele frequencies of CBWs to Bt and pesticides. Moreover, there is considerable difference between potential yields of Bt and unsprayed non-Bt cotton. APV were significantly higher than those received under current refuge options in all of the three cotton growing regions with and without pyrethroid resistance consideration. The current refuge options in this case are the unsprayed refuge options mandated by the EPA under which farmers are required to grow 5% of their total cotton acreage under non-Bt cotton without spraying. A reduction in unsprayed refugia from 5% to 0%, improved estimated annualized returns by 4.41%, 4.25%, and 4.60% in North, Central, and South India, respectively, with pyrethroid resistance for the fifteen-year planning horizon. When pyrethroid resistance was not considered, the estimated returns were improved by 4.24%, 4.23%, and 4.70% for North, Central, and South India, respectively, as compared to the current refuge option of 5%. A comparison of sprayed and unsprayed refuge policies suggests that sprayed refugia have higher estimated returns as compared to unsprayed refugia.

With pyrethroid resistance consideration, resistance evolution by CBWs to the Bt-toxin was faster in unsprayed refugia as compared to sprayed refugia in case of North and Central India (Figures 1 and 2). A possible reason for this could be the movement of Bt resistant CBWs from Bt cotton to unsprayed refuge, which increases the frequency of Bt resistant alleles in overall CBWs population. In South India, the resistance evolved almost at the same rate in sprayed and unsprayed refugia because of the 0% refuge policies under both the scenarios. Without pyrethroid resistance consideration, Bt resistance evolved faster in unsprayed refugia as compared to sprayed refugia in the case of North and Central India (Figures 3 and 4). In South India, the resistance evolved at the same rate in sprayed and unsprayed refugia because of the 0% efficient refuge policies under both the scenarios. Moreover, Bt resistance evolved faster without pyrethroid resistance as compared to the scenario with pyrethroid resistance because of higher refuge requirements in the later. As has been already discussed, high refuge requirements slow down the resistance evolution.

Table 9. Profit maximizing static unsprayed refugia for the three cotton growing regions in India, with pyrethroid resistance considered.

Time (Years)	North		Central		South	
	Static Unsprayed Refugia	APV[1]	Static Unsprayed Refugia	APV	Static Unsprayed Refugia	APV
1	0%	602.69 (4.67%)[2]	0%	583.11 (4.77%)	0%	759.00 (4.70%)
2	0%	602.37 (4.62%)	0%	583.09 (4.77%)	0%	758.99 (4.70%)
3	0%	602.20 (4.62%)	0%	583.07 (4.76%)	0%	758.98 (4.70%)
4	0%	601.78 (4.59%)	0%	583.05 (4.76%)	0%	758.96 (4.70%)
5	0%	600.05 (4.41%)	0%	583.01 (4.76%)	0%	758.95 (4.70%)
6	0%	596.88 (4.21%)	0%	582.88 (4.75%)	0%	758.86 (4.70%)
7	0%	594.64 (4.26%)	0%	582.68 (4.73%)	0%	758.79 (4.70%)
8	0%	592.97 (4.30%)	0%	582.32 (4.70%)	0%	758.73 (4.70%)
9	0%	591.68 (4.32%)	0%	581.62 (4.62%)	0%	758.67 (4.70%)
10	0%	590.66 (4.35%)	0%	580.34 (4.49%)	0%	758.57 (4.70%)
11	0%	580.83 (4.36%)	0%	578.39 (4.30%)	0%	758.46 (4.69%)
12	0%	589.14 (4.38%)	0%	576.41 (4.21%)	0%	758.32 (4.68%)
13	0%	588.57 (4.39%)	0%	574.75 (4.21%)	0%	758.10 (4.66%)
14	0%	588.08 (4.40%)	0%	573.35 (4.23%)	0%	757.77 (4.64%)
15	0%	587.67 (4.41%)	0%	572.15 (4.25%)	0%	757.29 (4.60%)

1. APV is the annualized present value of return OR annualized profits per hectare
2. Percent difference between annualized profits per hectare under optimal and current sprayed refuge options are in ( )

Table 10. Profit maximizing static unsprayed refugia for the three cotton growing regions in India, without pyrethroid resistance considered.

Time (Years)	North		Central		South	
	Static Unsprayed Refugia	APV[1]	Static Unsprayed Refugia	APV	Static Unsprayed Refugia	APV
1	0%	613.16 (4.68%)[2]	0%	590.66 (4.77%)	0%	767.46 (4.71%)
2	0%	613.15 (4.68%)	0%	590.65 (4.77%)	0%	767.46 (4.71%)
3	0%	613.11 (4.68%)	0%	590.65 (4.77%)	0%	767.46 (4.71%)
4	0%	612.90 (4.65%)	0%	590.64 (4.77%)	0%	767.46 (4.71%)
5	0%	612.33 (4.58%)	0%	590.63 (4.77%)	0%	767.46 (4.71%)
6	0%	610.36 (4.35%)	0%	590.61 (4.77%)	0%	767.45 (4.71%)
7	0%	606.72 (4.02%)	0%	590.53 (4.76%)	0%	767.45 (4.71%)
8	0%	603.90 (4.05%)	0%	590.45 (4.76%)	0%	767.45 (4.71%)
9	0%	601.72 (4.10%)	0%	590.31 (4.74%)	0%	767.44 (4.71%)
10	0%	600.00 (4.13%)	0%	590.08 (4.72%)	0%	767.43 (4.71%)
11	0%	598.60 (4.16%)	0%	589.69 (4.68%)	0%	767.43 (4.71%)
12	0%	597.45 (4.19%)	0%	589.00 (4.60%)	0%	767.39 (4.70%)
13	0%	596.48 (4.21%)	0%	587.89 (4.47%)	0%	767.36 (4.70%)
14	0%	595.66 (4.23%)	0%	586.44 (4.32%)	0%	767.32 (4.70%)
15	0%	594.96 (4.24%)	0%	584.95 (4.23%)	0%	767.28 (4.70%)

1. APV is the annualized present value of return OR annualized profits per hectare
2. Percent difference between annualized profits per hectare under optimal and current sprayed refuge options are in ( )

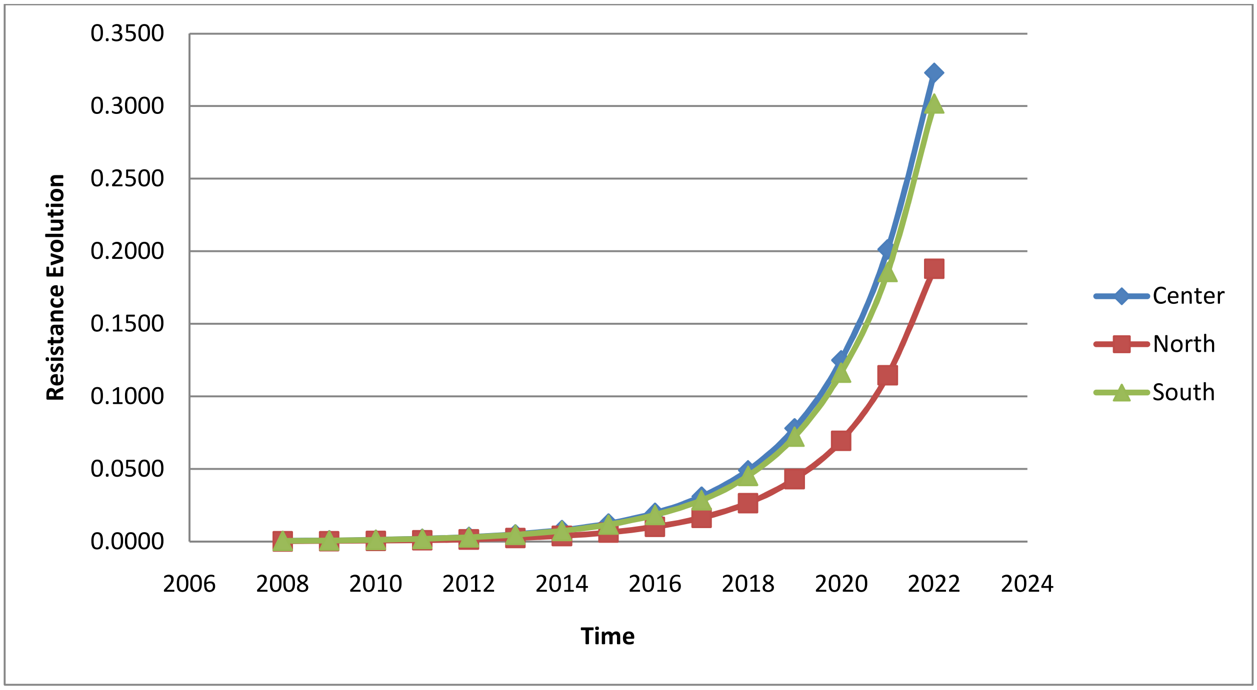

Figure 1. Resistance evolution to Bt toxin under static sprayed refuge option with pyrethroid resistance considered

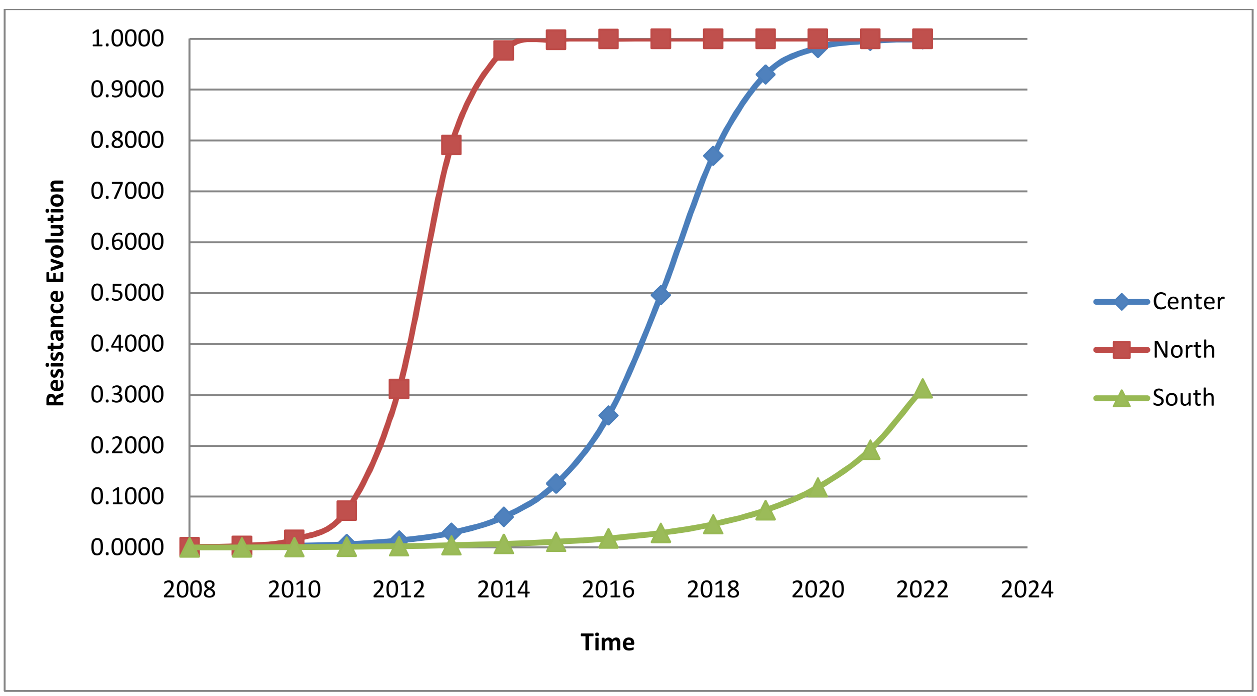

Figure 2. Resistance evolution to Bt toxin under static unsprayed refuge option with pyrethroid resistance considered

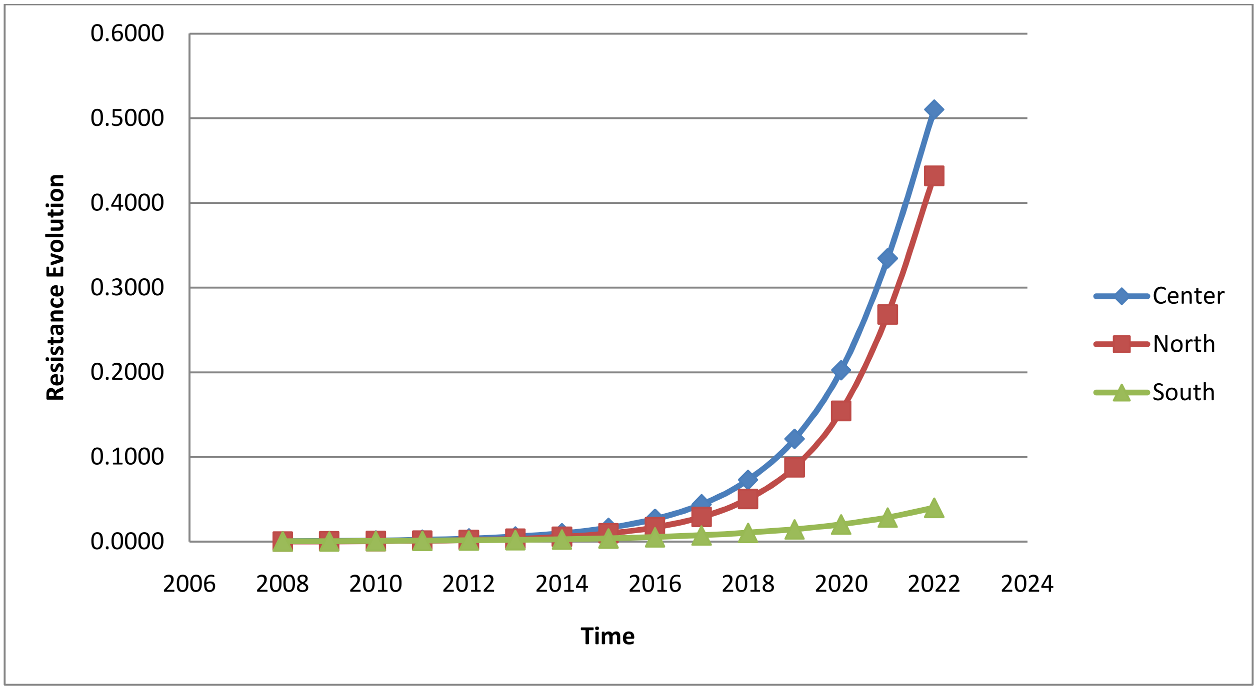

Figure 3. Resistance evolution to Bt toxin under static sprayed refuge option without pyrethroid resistance considered

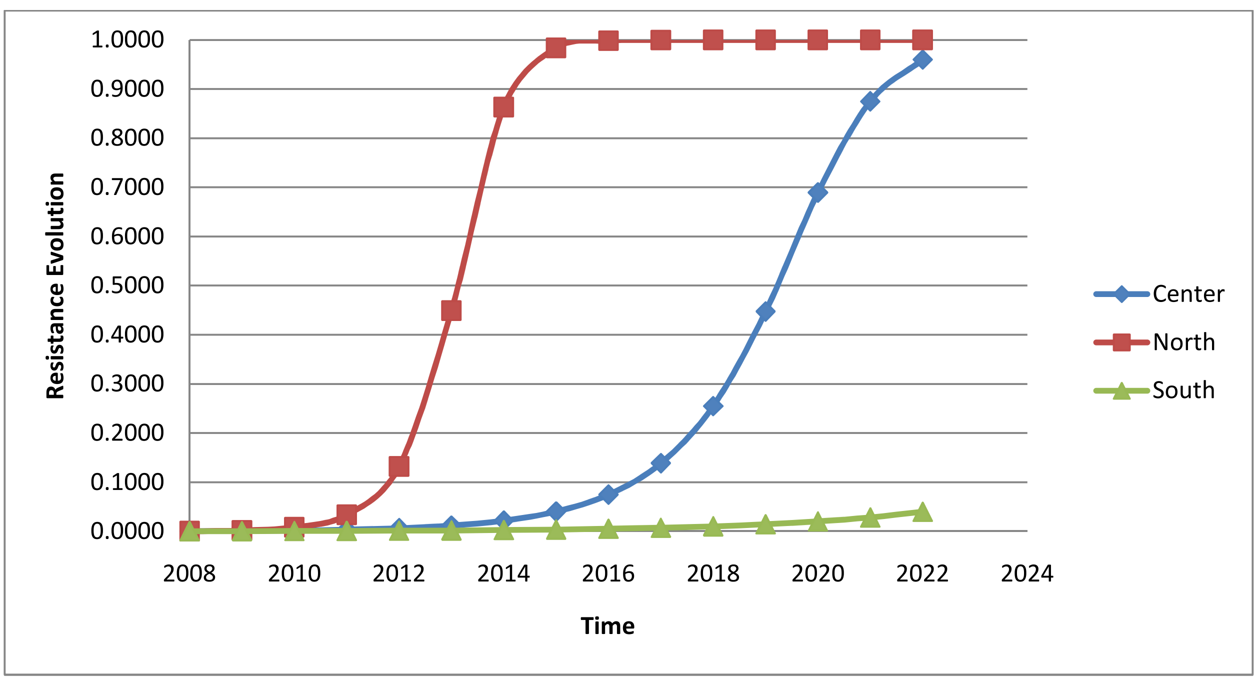

Figure 4. Resistance evolution to Bt toxin under static unsprayed refuge option without pyrethroid resistance considered

It is widely thought that as in China, India may not need structured refuges since both countries have small highly fragmented farms and different host crops for CBWs that are cultivated alongside cotton, providing natural refuges for the cotton crop (Qiao, 2006; Ravi *et. al.*, 2005). Results of this study, however, support this hypothesis only for South India. In Central and North India, there is need of structured refuges, according to current study. On the other hand, in the U.S., the optimal structured refugia found were 16% under the 11-year horizon (Livingston *et. al.*, 2004). In India, it was 33%, 8%, and 0% for North, Central, and South regions, respectively, under the 11-year horizon. The reason for the high requirement of structured refuges in the U.S. and North India might be the prevalence of mono-cropped cropping patterns in these regions. In Central and South India, however, the cropping pattern was mostly multi-cropped.

Dynamic refuge policies were examined using a standard, recursive dynamic programming algorithm. Basically, unique two-vector value combinations were approximated using eleven nodes for Bt and pyrethroid resistance allele frequencies. The period-T value function was found by maximizing the representative producer profit per hectare at each two-vector value with respect to the refuge constraint. Bellman equation was used to compute the period-(T-1) value function, approximating the period-T value function using cubic splines. Likewise, the solution algorithm proceeded recursively until the period-1 value function was obtained. Subsequent period value functions and refuge policy functions were approximated, because it was necessary to be able to evaluate these functions at non-nodal resistance allele frequencies.

The regional sprayed and unsprayed dynamic refugia, along with the corresponding annual present value in US$ per hectare are presented in Tables 11 and 12. The results suggested that there would be higher dynamic sprayed refuge requirements in North India followed by Central and South India. In Central India, the dynamic refugia would not be required for the first ten years, but would require a heavy refuge for last three years. In South India, the dynamic analysis did not require a refuge policy under either sprayed or unsprayed options; except, only a 1% dynamic refugia requirement for the

Table 11. Regional dynamic sprayed refuge policies in India

Time (Years)	North		Central		South	
	Dynamic Sprayed Refuge	APV[1]	Dynamic Sprayed Refuge	APV	Dynamic Sprayed Refuge	APV
1	0%	602.41	0%	583.23	0%	758.76
2	0%	602.38	0%	583.21	0%	758.74
3	41%	602.26	0%	583.18	0%	758.72
4	0%	601.86	0%	583.15	0%	758.71
5	31%	600.44	0%	583.10	0%	758.69
6	62%	596.65	0%	583.00	0%	758.66
7	0%	595.27	0%	582.84	0%	758.63
8	0%	594.25	0%	582.54	0%	758.60
9	80%	593.59	0%	582.00	0%	758.55
10	100%	590.51	0%	580.84	0%	758.49
11	100%	592.86	2%	579.09	0%	758.41
12	98%	588.92	0%	577.32	0%	758.29
13	99%	583.76	71%	576.00	0%	758.12
14	98%	587.79	91%	575.14	0%	757.88
15	97%	581.99	98%	574.58	1%	757.46

1. APV is the annualized present value of return OR annualized profits per hectare

Table 12. Regional dynamic unsprayed refuge policies in India

Time (Years)	North		Central		South	
	Dynamic Unsprayed Refuge	APV[1]	Dynamic Unsprayed Refuge	APV	Dynamic Unsprayed Refuge	APV
1	0%	602.41	0%	583.23	0%	758.76
2	1%	602.38	0%	583.21	0%	758.74
3	38%	602.26	0%	583.18	0%	758.72
4	0%	601.86	0%	583.15	0%	758.71
5	17%	600.44	0%	583.10	0%	758.69
6	25%	597.31	0%	583.00	0%	758.66
7	0%	595.06	0%	582.84	0%	758.63
8	0%	593.38	0%	582.54	0%	758.60
9	0%	592.09	0%	582.00	0%	758.55
10	0%	591.06	0%	581.03	0%	758.49
11	0%	590.22	0%	579.44	0%	758.41
12	0%	589.52	0%	577.56	0%	758.29
13	0%	587.80	0%	575.86	0%	758.12
14	0%	567.42	0%	574.42	0%	757.88
15	0%	554.18	0%	573.19	0%	757.51

1. APV is the annualized present value of return OR annualized profits per hectare

15th year in the sprayed option. Under the unsprayed option, dynamic refugia were not recommended in Central and South India for the 15 years. In Central India, there were some dynamic refuge requirements at the beginning of the time horizon, but no refuge requirements after the 6th year. High refuge requirements in the North region are likely due to a higher proportion of CBWs on cotton crop throughout the season as compared to Central and South India. The North region cropping pattern is mostly mono-cropped, where a significant acreage is under cotton, thus making the existence of CBWs on cotton more probable.

The estimated returns were almost the same under sprayed and unsprayed refuges for Central and South India because of no refuge requirements in the two regions. In North India, estimated returns were significantly higher under the sprayed option as compared to the unsprayed option. A comparison of the static and dynamic refuge requirements reveals no difference between estimated returns for South India because of the zero percent refuge policy throughout the 15-year time horizon. In North and Central India, static refugia were more profitable as compared to dynamic refugia under sprayed option. Dynamic refugia were comparatively more profitable under unsprayed option. The difference in profits, however, is so small that it is questionable whether enforcement of dynamic refuge policies by the government would be cost effective.

Sensitivity Analysis

Static refugia for a five-year horizon were estimated by using different levels of biological and economic parameters for the three cotton growing regions. Static refugia increased with an increase in initial Bt resistance allele frequencies in North, Central, and South regions. In the North India, the initial resistance allele frequency was 0.00075 at the beginning of the planning horizon. The refuge requirement increased to 20% and 38% when the initial resistance allele frequency increased to 0.01 and 0.05, respectively. Similarly, with an increase in initial Bt resistance allele frequency from 0.0015 to 0.07 and 0.3 the refuge requirement increased from 0% to 9% and 49%, respectively. A similar relationship between initial Bt resistance allele frequency and refuge requirements was found in South India, where an increase in the initial Bt resistance allele frequency from 0.0013 to 0.12 and 0.25 increased the refuge requirement from 0% to 2% and 32%, respectively. Overall, the increase in static refugia was higher with an increase in initial Bt resistance allele frequency in the North followed by Central and South India. The possible reasons for these results could be the difference in regional acreage under Bt cotton over time, and the difference in monthly proportion of bollworms on cotton among the three cotton growing regions.

Static sprayed refugia increased from 0 to 20% as the proportion of CBWs in cotton increased from 0.82 to 1.0. A similar trend was noticed in South India where static refugia increased from 0 to 70% as the proportion of CBWs in cotton increased from 0.75 to 1.0. Static refuge requirements increased at a faster rate in the case of Central India. It increased to 100% when the proportion of CBWs in cotton increased to 0.93 (i.e., 93% of CBWs are in cotton). It was, however, noted that the increase in static refugia was experienced only after the proportion of CBWs in cotton exceeded 0.75, indicating that higher proportions of CBWs in cotton corresponds to lower proportions of CBWs in natural refuge crops such as sunflower, pigeon pea, tomatoes, okra and chilies. Therefore, there would be a higher probability of exposure of CBWs in cotton to Bt toxin, which eventually results in higher rate of mating within Bt resistant pests, making evolution of resistance and growth in refuge requirements faster. If there was a higher proportion of CBWs in natural refuge, the resistance evolution to Bt toxin would be slower because the CBWs present on natural refuge would not be selected for the Bt toxin. A higher number of Bt susceptible pests from natural refuge would mate with lesser number of Bt resistant pests on Bt cotton, which eventually results in relatively more susceptible pests in the population, and a lower level of Bt resistance and a lesser need of refuges over time.

The refuge requirements were found sensitive to change in the proportion of homozygous and heterozygous resistant pests in North, Central, and South India. Static refugia increased considerably with an increase in environmental fitness factors of May and June in North India. Also, static refugia varied between 4% and 11% with a 95% confidence interval of damage function parameters in North India.

CONCLUSIONS

Based on the available data and parameter values, this study concludes that farmers in North and Central India would need to grow structured refuge but South Indian farmers would not need to grow refuge. It was widely thought that India may not need structured refuges as in the case of China since both countries have small, highly fragmented farms and different host crops of CBWs that are cultivated alongside cotton, thus providing natural refuges. Our results, however, supports this belief only in the case of South India based on the available information.

In terms of the type of refuge to use, results suggest that planting sprayed refugia might be more profitable than planting unsprayed refugia, although this depends on harvested yield per unsprayed refuge hectare. The yield value we used in our analysis was calculated by using information based on published studies; therefore, more data are needed to draw a final conclusion.

Moreover, it was concluded on the basis of sensitivity analysis that refuge requirements were sensitive to initial Bt resistance level, relative proportion of CBWs in natural refuges and proportions of heterozygous and homozygous fitnesses in all of the three regions In India. Also, refuge requirements were found to be sensitive to values of environmental fitnesses and damage function parameters in the case of North India.

If we compare static and dynamic refuge policies, we found that static refugia were more profitable as compared to dynamic refugia under sprayed options. Dynamic refugia were comparatively more profitable under unsprayed option. The difference in profits, however, was so small that it is questionable whether enforcement of dynamic refuge policies by the government would be cost effective.

Limitations

This study is a first attempt to find the efficient refuge policies for Bt cotton in India, and has some limitations. The major limitation is the lack of data required to estimate damage function in three cotton growing regions. It would have been better if data regarding yield losses, pesticide use, and field population of CBWs would have been available. Another limitation is the lack of pyrethroid fitness parameter values of CBWs. Only laboratory data calculating LD_{50} and LC_{50} were available. Moreover, data on environmental fitnesses and proportion of CBWs sprayed in any of the cotton growing region were not available. The parameters of CBWs in the U.S. were used as proxies when parameter values for CBWs in India were unavailable. Also, most of the parameters values are assumed same for the three regions because of unavailability of data. Only two parameters i.e. initial Bt resistance allele frequency and monthly proportion of CBWs on cotton were differentiating the regions.

Moreover, this study calculated refuge policies on the basis of single pest i.e. CBW, *Helicoverpa armigera*. There are two more bollworms i.e. spotted and pink bollworms found on the cotton crop along with CBW in India. Although CBW is responsible for most of the damage to cotton crop in India, the information on the other two bollworms could be useful in re-examining optimal refugia.

Although, this study has some limitations but it provides encouragement to explore the topic further. Cotton farmers in the three regions in India can be surveyed to get data on various inputs, yields and perception of yield losses. Data regarding bollworms dynamics can be collected by visiting randomly selected cotton farms in three regions. This information would likely help in designing better refuge policies for cotton in India.

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Appendix 1

Genotypes, frequencies of genotypes in the progeny of generation *i* adults during growing season *t*, and genotype rates of surviving and reproducing successfully under Bt, pyrethroid, and no selection pressure

Genotypes	Frequencies ($f_{t,i+1}$)	Bt Fitnesses (s^b)	Pyrethroid Fitnesses (s^p)	No Bt Fitnesses (s^{ab})	No Pyrethroid Fitnesses (s^{ap})
xy/xy	${g^1_{t,i}}^2$	RR^{Bt}	RR^p	RR^{aBt}	RR^{ap}
xy/xY	$2\ g^1_{t,i}\ g^2_{t,i}$	RS^{Bt}	RR^p	RS^{aBt}	RR^{ap}
xY/xY	${g^2_{t,i}}^2$	SS^{Bt}	RR^p	SS^{aBt}	RR^{ap}
xy/Xy	$2\ g^1_{t,i}\ g^3_{t,i}$	RR^{Bt}	RS^p	RR^{aBt}	RS^{ap}
xy/XY–xY/Xy	$2(g^1_{t,i}\ g^4_{t,i} + g^2_{t,i}\ g^3_{t,i})$	RS^{Bt}	RS^p	RS^{aBt}	RS^{ap}
xY/XY	$2\ g^2_{t,i}\ g^4_{t,i}$	SS^{Bt}	RS^p	SS^{aBt}	RS^{ap}
Xy/Xy	${g^3_{t,i}}^2$	RR^{Bt}	SS^p	RR^{aBt}	SS^{ap}
Xy/XY	$2\ g^3_{t,i}\ g^4_{t,i}$	RS^{Bt}	SS^p	RS^{aBt}	SS^{ap}
XY/XY	${g^4_{t,i}}^2$	SS^{Bt}	SS^p	SS^{aBt}	SS^{ap}

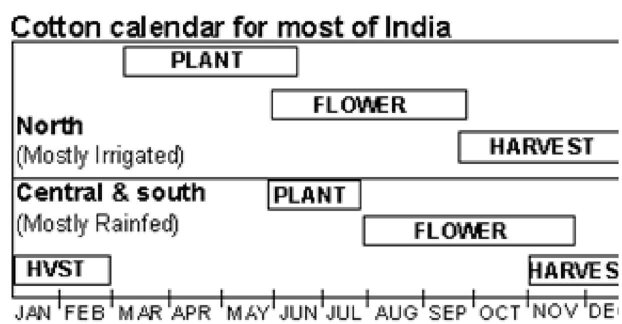
Appendix 2

Regional classification of study area based on geography

NORTH: Punjab, Haryana and Rajasthan

CENTRAL: Gujarat, Maharashtra, Madhya Pradesh

SOUTH: Tamilnadu, Andhra Pradesh, Karnataka



Appendix 3

Damage function for cotton in the U.S.

Livingston *et. al.* (2004) estimated a simple quadratic relationship between annual pyrethroid use and average annual survival rates of budworms and bollworms as follows

$$E[P_t/w_t^{nb}] = \alpha w_t^{nb} + \beta(w_t^{nb})^2 \qquad \text{(A.3.1)}$$

where P_t denotes annual statewide pyrethroid sprays used to control the budworm-bollworm complex during 1987-1995 in Louisiana; and w_t^{nb} denotes average annual survival rates for budworms and bollworms in the Louisiana bioassays. Furthermore, Livingston estimated a nonlinear relationship between yield loss and pyrethroid use as follows

$$E[\varphi^{-1}(d_t) \,/\, \widehat{P_t}] = \gamma + \delta.(\widehat{P_t}) \qquad \text{(A.3.2)}$$

where d_t denotes annual proportionate yield losses attributed to the budworm-bollworm complex during 1987-1995 in Louisiana; and $\widehat{P_t}$ are the predicted values from insecticide-use equation A.3.1. The least squares and two-stage least squares estimates for equations A.3.1 and A.3.2 are as follows

Parameters	***Value***	***95% Confidence Interval***
α (alpha)	35.03 (5.34)***	[22.39, 47.67]
β (beta)	-63.06 (21.38)**	[-113.61, -12.52]
δ (delta)	-2.39 (0.30)***	[-3.11, -1.67]
γ (gamma)	0.14 (0.07)*	[-0.03, 0.31]

Taking into account some possible variation in parameters of the damage function for CBW in India, a sensitivity analysis of the parameters of damage function for CBW in U.S. was performed within 95% confidence intervals of the parameters values.