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Examination of Regional-level Efficient Refuge Requirements for Bt Cotton in India

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Refuge requirements for Bt cotton varieties were examined for three cotton-growing regions in India, considering resistance evolution in cotton bollworm (*Helicoverpa armigera*) to Bt toxin and pyrethroid pesticides. Biological, yield, and regulatory models were used. Results indicated that the optimal refuge requirements varied significantly across cotton-growing regions. The North and Central regions require higher refuge compared to the South region. Results suggest that sprayed refuge is more profitable than unsprayed refuge. Refuge requirements were found to be sensitive to relative proportion of pests in natural refuge and initial Bt resistance levels in all three regions.

***Key words*:** Bt technology, cotton bollworm, India, natural refuge, resistance, structured refuge.

Introduction

Bt cotton varieties are transgenic varieties that produce a toxin (*Bacillus thuringiensis*) that kills bollworm pests, which are responsible for most of the damage to cotton crops worldwide. Countries that have introduced Bt cotton varieties have derived significant and multiple benefits, including increased yields, reduced costs for pesticide treatments, environmental benefits from reduced pesticide use, less fungal contamination, and reduced labor requirements (Bennett, Ismael, Kambhampati, & Morse, 2004; Bennett, Kambhampati, Morse, & Ismael, 2006; Huang, Hu, Fan, Pray, & Rozelle, 2002; Huesing & English, 2004; Purcell & Perlak, 2004; Qaim, Cap, & de Janvry, 2003). A major concern regarding the long term use of Bt varieties is their potential vulnerability to the adaptation of bollworms to the Bt toxin (Bates, Zhao, Roush, & Shelton, 2005). A continuous presence of the Bt toxin will impose strong selection pressure on bollworm, eventually resulting in the development of insect resistance to the toxin. If a large share of the pest population develops resistance, the susceptibility to the Bt toxin will decline, thus reducing the effectiveness of Bt cotton in controlling pests; this will result in declines in yields and increases in insect control costs.

Concerns regarding development of bollworm resistance in Bt cotton prompted the US Environmental Protection Agency (EPA) to establish limits on the proportion of total cotton area that individual producers may plant to Bt cotton. This represents the first attempt to regulate the development of insecticide resistance and the first instance of the use of refuge as a policy instrument. Although the EPA has approved a ‘no refuge’[1] requirement policy for many cotton-growing regions in the United States, India still follows the very first refuge policy mandated by the EPA. The current policy in India provides cotton producers a choice between a sprayed refuge option and an unsprayed refuge option (the sprayed option is more popular, however). With the sprayed refuge option, producers may plant 80% of their total cotton area to Bt varieties and 20%—or five rows, whichever is greater—to non-Bt varieties, with conventional insecticide use allowed throughout (Government of India, Ministry of Environment & Forests, 2002). With the non-sprayed option, producers may plant 95% of their cotton area to Bt varieties and spray that area as needed with conventional insecticides; however, no insecticides may be used on the 5% of the non-Bt varieties planted in the refuge. For these insect resistance management (IRM) plans to be effective, farmers must implement refuge requirements both in terms of area and configuration (Alexander, 2007; Hyde, Martin, Preckel, Dobbins, & Edwards, 2000). The refuge strategy is widely acclaimed as the best IRM option in effectively controlling resistance in many circumstances despite the costs involved in its implementation (Shelton, Tang, Roush, Metz, & Earle, 2000). 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., 2010).

1. *The US EPA has announced zero structured refuge requirements for stacked Bt cotton (Bollgard II) varieties in the United States (US EPA, 2008). On the other hand, Indian regulators did not make any change in refuge requirements for stacked varieties.*

Since the introduction of Bt cotton in 2002/2003, India has become the second-largest producer of cotton in the world (after China). The area under Bt cotton in India increased to 9.4 million hectares in the 2010/2011 crop season, representing 85.5% of the total cotton area (Indiastat.com, n.d.). The area planted to Bt has increased beyond the refuge threshold of 80% because Indian farmers generally do not comply with mandated refuge requirements. In 2002, out of 15 fields inspected by the Genetic Engineering Approval Committee in India, only 50% of the farmers were compliant with refuge requirements (Government of India, Ministry of Environment & Forests, 2002).

Non-compliance with refuge requirements in India may be due to the lack of regulatory restrictions imposed by the Indian government and the inability of the commercial seed industry to enforce restrictions. It is also contended that Indian farmers do not grow a refuge either because they are unaware of refuge requirements or their land holdings are too small to implement refuge requirements in a cost-effective manner. Moreover, the relevance of refuge compliance is often dismissed because the Indian farming system is multi-cropped, which presumably provides a natural refuge. Regardless of the reason, after eight years of Bt cotton plantings in India, there has been no reported finding of Bt-resistant cotton bollworm[2] (CBW hereafter). While it is possible that the widespread adoption of Bt cotton has permanently eliminated a major host of CBW (Carrière et al., 2003), it seems more plausible that with increased adoption of Bt cotton, the area under structured refuge and natural refuge has gone down.[3] This could potentially increase the rate of resistance development in CBW populations, making refuge compliance necessary to maintain the productivity effects of Bt cotton.

There is no empirical evidence on sustainability of the productivity effects of Bt cotton in India under a scenario of development of possible resistance by CBW pests to the Bt toxin. A study by Kranthi and Kranthi (2004) does, however, provide some evidence on sustainability of Bt cotton under Indian farming conditions. They developed a biological model to simulate the development of potential resistance by CBW to the Bt toxin. However, their study approaches the problem only from a biological perspective and does not take into account the economics of planting refuge. Moreover, their study does not model CBW resistance to the Bt toxin in the presence of pesticide use. Hurley, Babcock, and Hellmich (2001) were the first to develop a bio-economic model to examine profit-maximizing refuge requirements for Bt corn in the United States under the scenario of a target pest (European pod borer) that was subjected to Bt toxin and pesticides simultaneously. Livingston, Carlson, and Fackler (2004) extended the Hurley et al. (2001) study by developing a dual-pest, dual-toxin regulatory model to examine non-Bt cotton (refuge) planting requirements designed to manage Bt resistance evolution in the mid-south region of the United States; this location is where two major insect pests of cotton—the cotton bollworm and tobacco budworm—were subjected to Bt toxin and pesticides treatments. Qiao, Huang, Rozelle, and Wilen (2010) developed static regulatory models to examine optimal refuge in northern China. Their findings supported a natural refuge policy for Bt cotton in China as they found that planting structured (policy mandated) refuges was not economical. They also found evidence of faster evolution of CBW susceptibility to conventional pesticides due to more Bt cotton being planted without conventional pesticide applications. Livingston et al. (2004) and Livingston, Storer, Van Duyn, and Kennedy (2007) reported similar findings.

This study represents a first attempt at examining sustainability of the productivity effects of Bt cotton under Indian farming conditions with potential development of resistance by CBW to the Bt toxin.[4] A natural refuge policy, as in China, may be the best policy for India since both countries have similar cropping patterns. However, efficient refuge policies (compared to status-quo refuge requirements mandated by the EPA) for different cotton-growing regions in India should be thoroughly examined. Our study focuses on examining static refuge policies for Bt cotton in India. The objec-

2. *The CBW in question is 'Helicoverpa armigera', and Bt cotton was primarily introduced in India to control this pest. It was responsible for causing most of the damage to the cotton crop in India, and a majority of pesticides failed to control this pest. Only one paper (Tabashnik, Van Rensburg, & Carrière, 2009) discussed some 'ambiguous evidences' of Helicoverpa armigera resistance in India, but it is not confirmed yet.*
3. *Total area under cotton is increasing in India after the introduction of Bt cotton, as it is not only replacing structured refuge (non-Bt cotton), but is also replacing area under natural refuges (other bollworm host crops) grown along with Bt cotton. This is because returns from Bt cotton are comparatively higher than alternative crops.*
4. *We considered a single Bt toxin representing Cry1c (Bollgard I) and Cry1b (Stacked Bollgard II) genes. Stacked Bollgard II is considered only an improvement over Bollgard I.*

tive of this study is to formulate regional production models to examine the effects of resistance by CBW at the individual cotton-producer level and to formulate regional regulatory models to examine the impacts of refuge requirements for the three major cotton-producing regions in India. The importance of this study that sets it apart from previous studies is the examination of separate refuge requirements for three cotton-growing regions (North, Central, and South) of India that considers the heterogeneity in agro-climatic conditions across regions.

Methods

The methods and procedures that are used to evaluate refuge requirements consist of (1) a single-pest, dual-toxin biological model, (2) cotton yield and profit equations for each production region in India, and (3) a static regulatory model. The biological model estimates the development of resistance in the CBW population to the Bt toxin and pyrethroid insecticides, which is then mapped into insect damage functions for Bt and non-Bt cotton utilized in this study. The cotton yield models are based on projected yields with no insect infestation and the estimated insect damage functions for Bt and non-Bt cotton. Profit equations for Bt and non-Bt cotton are expressed as functions of estimated yields and production costs. The regulatory model evaluates optimal refuge size and type to maximize discounted profits over time.

Biological Model

A single-pest,[5] dual-toxin biological model was developed to simulate the evolution of resistance within the CBW population to the Bt toxin and synthetic pyrethroid insecticides, taking into account parameters such as the proportion of Bt cotton planted, relative proportion of CBW larvae in cotton in comparison to those in natural refuge, proportion of CBW larvae sprayed with pesticides, initial resistance levels, and fitness parameters of CBW treated/untreated with Bt toxin and pyrethroid insecticides. Fitness parameters represent survival and reproductive success rates of pests. The model was based on the dual-pest, dual-toxin model set forth in Livingston et al. (2004) and is an extended version of the Hardy-Weinberg model (Kowles, 2001). The biological model was used to estimate survival rates for CBW larvae in cotton in the presence of the Bt toxin or sprayed with pyrethroid insecticides. The survival rates of CBW on Bt and non-Bt for each region were the principal input into the insect damage functions utilized in the cotton production model. Parameters used in the biological model are presented in Tables 1 and 2, and for detailed discussion of the biological model readers are referred to Singla (2010).

Cotton Production Model

The production functions estimated for Bt and non-Bt cotton in India were considered to be non-linear in parameters because the major input (pesticide use) differs fundamentally from other inputs (e.g., fertilizers, irrigation). This is because pesticides abate insect damage rather than directly increasing output (Huang et al., 2002; Lichtenberg & Zilberman, 1986; Qaim, 2003). Thus, the per-hectare production models for Bt and non-Bt cotton for the j^{th} region are specified as

$$Y_{j,t}^{b}(w_{j,t}^{b}) = Y_{j}^{PF} * [1 - \varphi\{\gamma + \delta * P_{j,t}^{b}(w_{j,t}^{b})\}] \text{ and} \tag{1}$$

$$Y_{j,t}^{nb}(w_{j,t}^{nb}) = Y_{j}^{PF} * [1 - \varphi\{\gamma + \delta * P_{j,t}^{nb}(w_{j,t}^{nb})\}], \tag{2}$$

where $P_{j,t}^{b}(w_{j,t}^{b}) = [\alpha w_{j,t}^{b} - \beta(w_{j,t}^{b})^2]$ and $P_{j,t}^{nb}(w_{j,t}^{nb}) = [\alpha w_{j,t}^{nb} - \beta(w_{j,t}^{nb})^2]$ are the simulated pesticide[6] use on Bt and non-Bt cotton, respectively, expressed as function of corresponding survival rates of CBW on Bt and non-Bt cotton ($w_{j,t}^{b}$ and $w_{j,t}^{nb}$, in the j^{th} region at time t. The term φ is the damage function, defined on the interval [0, 1], and uses the standard normal cumulative distribution function to map simulated pesticide use into proportionate yield losses per hectare. α, β, γ, and δ are the parameters of the pesticide use and damage function equations. Y_{j}^{PF} is the bollworm-free yield for the j^{th} region,[7] which is calculated as

$$Y_{j}^{PF} = [1/(1 - \phi_j)]\, Y_{j}^{nb}, \tag{3}$$

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5. *There are two additional types of bollworms (spotted and pink bollworms) found along with CBW (Helicoverpa armigera) in India. This study, however, considers only the CBW because it was responsible for most of the damage to cotton in India. Bt cotton was introduced in India mainly to control this pest.*

6. *Bollworm-free yield (Y_j^{PF}) was assumed as the same for Bt and non-Bt cotton.*

7. *Helicoverpa armigera and Helicoverpa zea are extremely closely related species (Laster & Hardee, 1995; Li, Berenbaum, & Schuler, 2001).*

where ϕ_j is the proportionate damage caused by CBW in the j^{th} region, and Y_j^{nb} is the average yield for non-Bt cotton in the j^{th} region. Because of the lack of data to estimate parameters of the cotton damage function for CBW (*Helicoverpa armigera*) in India, the parameters estimated by Livingston et al. (2004) for a similar[8] pest (*Helicoverpa zea*) in the United States were used as proxies (see Appendix 1). The parameters were subjected to sensitivity analysis, however.

The cost function for the j^{th} region was formulated as the sum of fixed costs and variable costs. All costs with the exception of pesticide spray costs were assumed to be fixed. The per-hectare cost equations for Bt and non-Bt cotton for the j^{th} region are specified as

$$C_{j,t}^{b}\,(w_{j,t}^{b}) = C_j^{Fb} + C^V * P_{j,t}^{b}(w_{j,t}^{b}) \text{ and} \tag{4}$$

$$C_{j,t}^{nb}\,(w_{j,t}^{nb}) = C_j^{Fnb} + C^V * P_{j,t}^{nb}(w_{j,t}^{nb}), \tag{5}$$

where C_j^{Fb} and C_j^{Fnb} are fixed costs associated with Bt and non-Bt cotton, respectively, in j^{th} region (C_j^{Fb} includes technology costs of Bt cotton), and C^V is the cost of a single pyrethroid spray application (including labor cost). The per-hectare profits[9] for a representative producer in the j^{th} region producing Bt and a non-Bt cotton refuge is specified as:

$$\pi_{j,t} = q_{j,t} * [p_j\, Y_{j,t}^{b}\,(w_{j,t}^{b}) - C_{j,t}^{b}\,(w_{j,t}^{b})] + (1 - q_{j,t}) * [p_j Y_{j,t}^{nb}\,(w_{j,t}^{nb}) - C_{j,t}^{nb}\,(w_{j,t}^{nb})], \tag{6}$$

where p_j is the price of cotton in j^{th} region. It is assumed that a representative producer in the j^{th} region chooses the proportion of Bt cotton to plant ($q_{j,t}$) to maximize year t's profit as given in Equation 6 without considering production possibilities in the future. Profit maximization is subjected 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 the j^{th} region; yield models $Y_{j,t}^{b}$ and $Y_{j,t}^{nb}$; cost model equations $C_{j,t}^{b}$ and $C_{j,t}^{nb}$; economic and biological parameters; and the biological model simulating the inter- and intra-seasonal dynamics of CBW resistance to Bt toxin and pesticides in the j^{th} region.

Static Regulatory Models

Current policies call for a static refuge, which is a required proportion of total cotton plantings to non-Bt varieties that remains the same each year. The size of the required refuge may differ depending on the resistance characteristics of the pest population, presence of natural refuge, and the length of the time horizon chosen. A desire to maintain effectiveness of a toxin, whether Bt or pyrethroid, may require a different level of refuge over different time horizons. It is expected that to maintain effectiveness over a longer time horizon, the proportion of area devoted to refuge would be higher.

The regulatory model selected the 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. The regulatory model is specified as

$$max_{r_{j,t}} \sum_{t=1}^{T} \rho^{t-1}\, \pi\,(q_{j,t}\,;\, x_{t,1}^{j}\,,\, y_{t,1}^{j}\,), \tag{7}$$

subject to refuge type $0 \leq r_{j,t} \leq 1$ in the j^{th} region; initial resistance levels of CBW to pesticides and Bt toxin, given as $x_{t,1}^{j}$ and $y_{t,1}^{j}$, respectively, which are simulated by the biological model; profit Equation 6; 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.

Data/Parameters

Economic Data/Parameters

Economic parameters used in modeling refuge requirements and the source of the data are presented in Table 1. The values of economic parameters such as pyrethroid treatment costs, alternative insecticide costs, Bt technology fee, unsprayed refuge yield, and currency exchange rates were assumed to be the same across all cotton growing regions. Average non-Bt cotton yields for the regions were obtained from regression estimates of regional cotton yields estimated by Singla (2010).

Biological Parameters

Parameters used in the biological model are presented in Table 2. The initial resistance allele frequencies (repre-

8. *The model is similar to the ones applied by Harper and Zilberman (1989) and Hurley et al. (2001).*
9. *Areas under cotton and natural refuges were calculated only for the districts having relatively higher area under cotton.*

Table 1. Economic parameters for three cotton-growing regions in India.

Economic parameters	North	Central	South	Source
Cotton lint price, p_j ($/kg)	1.25	1.13	1.24	Indiastat.com (n.d.)
Fixed costs Bt sprayed, C_j^{Fb} ($/ha)	282.13	286.60	293.62	Indiastat.com (n.d.); Central Institute for Cotton Research (CICR, n.d.); Bennett et al. (2004); Orphal (2001)
Fixed costs non-Bt sprayed, C_j^{Fb} ($/ha)	287.43	278.72	285.74	Indiastat.com (n.d.); CICR (n.d.); Bennett et al. (2004); Orphal (2001)
Costs unsprayed, C_j^{Un} ($/ha)	292.73	270.84	277.86	Indiastat.com (n.d.); CICR (n.d.); Bennett et al. (2004); Orphal (2001)
Percentage damage CBW, $Ø_j$	50%	60%	60%	Sundaram, Basu, Krishna Iyer, Narayanan, and Rajendran (1999)
Average non-Bt cotton yield, Y_j^{nb} (kg/ha)	382.01	325.62	357.07	Singla (2010)
Average non-Bt unsprayed refuge yield (kg/ha)	286.24	286.24	286.24	Indiastat.com (n.d.); CICR (n.d.); Bennett et al. (2004); Orphal (2001)
Annual interest rate	7.75%	7.75%	7.75%	HDFC Bank, India
Pyrethroid treatment cost (C^V) ($/ha)	7.82	7.82	7.82	Pesticides retailers
Alternative insecticide cost ($/ha)	21.63	21.63	21.63	Pesticides retailers
Bt technology fee ($/ha)	13.34	13.34	13.34	Pesticides retailers
Exchange rate ($/Rupee)	0.0211	0.0211	0.0211	XE.com

Table 2. Biological parameters for three cotton-growing regions in India.

Parameter	Pyrethroids	Source	Bt	Source
Initial resistance allele frequency	0.5	Ru, Zhao, and Rui (2002); Wu, Mu, Liang, and Guo (2004)	0.00075 (North) 0.0015 (Central) 0.0013 (South)	Kranthi and Kranthi (2004)
Treated fitness homozygote	0.5862 (RR^p)	Kranthi, Kranthi, Siddhabhatti, and Dhepe (2004)	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. (2004)	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)

senting the resistance levels) for Bt cotton were specified for each cotton-growing region in India. All other biological parameters were assumed to be the same across the three cotton-growing regions. The parameters of untreated fitnesses for resistant and susceptible CBW were assumed to be at the higher end (0.95 to 1.0) for both the Bt and synthetic pyrethroid insecticides, which imply that the survival rate of CBW not treated with either of the toxins will be nearly 100%.

Other Parameters

Proportions of CBW in cotton ($c_{j,i}$), proportions of CBW in sprayed cotton (s_i), and environmental fitness factors (e_i) of CBW for each generation are given in Table 3. It was assumed that there are five generations (1st, 2nd, 3rd, 4th, and 5th) of CBW in each cotton-growing region in India (Oztemiz, Karacaoglu, & Yarpuzlu, 2009). As sowing time of cotton differs across the three regions, the five generations correspond to May, June, July, August, and September in North India; July, August, September, October, and November in Central India; and September, October, November, December,

Table 3. Other parameters for three cotton-growing regions in India.

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

and January in South India. The proportions of CBW in cotton relative to those in natural host plants were calculated based on data from trials conducted in Central and South India by Ravi et al. (2005) and Indiastat.com (n.d.). The trials were conducted to find relative densities of CBW in cotton and other natural refuges such as pigeon pea, sunflower, chili peppers, and tomatoes during different months of the season. To find the proportions of CBW in cotton (for the five generations/months) in Central and South India, district-wide area under cotton and natural refuge for the states in Central and South India were used to calculate the relative proportion of CBW in different crops in these two regions. Only districts having a relatively higher area under cotton crop were selected to reasonably assume that the cotton and natural refuges are randomly distributed within those districts. The area under cotton and different natural refuges of CBW, along with average farm size in the regions, is presented in Appendix 2. Since data were unavailable for relative densities of CBW on different host plants in North India, the relative densities in Central India were used to calculate proportions of CBW in cotton in North India since the latter is relatively closer to the cotton-growing regions in Central India than to those in South India. As expected, the relative densities of bollworms on cotton are higher in North India than in the central and southern regions due to the presence of less acreage under natural refuge crops.

Finally, the sensitivity analysis was performed for important parameters in the model.

Results

Regional static optimal solutions and annualized producer returns under the sprayed/unsprayed refuge options with and without[10] consideration of pesticide resistance are presented in Tables 4 and 5. As defined earlier, static refuge is the required proportion of total cotton plantings to non-Bt varieties that remains the same each year of a time horizon to maintain the initial CBW resistance level. Optimal refuge solutions are reported for up to a 15-year time horizon beginning in 2008. Resistance levels at the start of 2008 in each region were based on the biological model of CBW resistance using baseline parameters and the proportion of total cotton area planted to Bt cotton. Static optimal refuge requirements were obtained using a grid search over the finite set ranging from 0.00 to 1.00 at intervals of 0.01.

For the most common scenario—sprayed[11] refuge with pyrethroid resistance—static refuge was 0% in each region for up to a 4-year time horizon as shown in Table 4. Beginning with a 5-year time horizon, static refuge increased over time in North India to 42% for a 15-year time horizon. In Central India, static refuge was 0% up to an 8-year time horizon and increased to 19% for a 15-year time horizon. In South India, the static refuge was 0% for all 1- to 15-year time horizons. The different initial Bt resistance allele frequencies and differences in the proportion of natural refuge in each region were both major reasons for the different regional refuge percentages.

The scenario of sprayed refuge without pyrethroid resistance is also given in Table 4. The static refuge was 0% for up to a 5-year time horizon for all regions. After five years, static refuge increased to 35% in the North region and 8% in the Central region for a 15-year time

10. *Optimal refuges were examined for both with and without pyrethroid-resistance scenarios because a pyrethroid alternative is not simulated in the base model. Exclusion of a pyrethroid alternative in the base model could overestimate the spray costs and yield losses, and hence, the refuge requirements. See Singla (2010) and Livingston et al. (2004) for more details.*

11. *Under sprayed refuges, producers may plant 80% of their total cotton area to Bt varieties and 20% to non-Bt varieties, with conventional insecticide use allowed throughout.*

Table 4. Profit-maximizing, static sprayed refuge for the three cotton-growing regions in India, with and without pyrethroid resistance considered.

	Sprayed refuge With pyrethroid resistance						Sprayed refuge Without pyrethroid resistance					
	North		Central		South		North		Central		South	
Time (years)	Static refuge	APV[a] ($/ha)	Static refuge	APV ($/ha)	Static refuge	APV ($/ha)	Static refuge	APV ($/ha)	Static refuge	APV ($/ha)	Static refuge	APV ($/ha)
1	0%	602.69	0%	583.11	0%	759.00	0%	613.16	0%	590.66	0%	767.46
2	0%	602.37	0%	583.09	0%	758.99	0%	613.15	0%	590.65	0%	767.46
3	0%	602.20	0%	583.07	0%	758.98	0%	613.11	0%	590.65	0%	767.46
4	0%	601.78	0%	583.05	0%	758.96	0%	612.90	0%	590.64	0%	767.46
5	4%	600.68	0%	583.01	0%	758.95	0%	612.33	0%	590.63	0%	767.46
6	10%	599.45	0%	582.88	0%	758.86	3%	610.72	0%	590.61	0%	767.45
7	17%	598.50	0%	582.68	0%	758.79	10%	609.10	0%	590.53	0%	767.45
8	23%	597.75	0%	582.32	0%	758.73	13%	607.76	0%	590.45	0%	767.45
9	24%	597.07	1%	581.70	0%	758.67	20%	606.55	0%	590.31	0%	767.44
10	29%	596.49	4%	580.92	0%	758.57	22%	605.60	0%	590.08	0%	767.43
11	33%	595.98	8%	580.22	0%	758.47	26%	604.70	0%	589.69	0%	767.43
12	34%	595.57	11%	579.54	0%	758.33	29%	603.91	1%	589.04	0%	767.39
13	37%	595.20	14%	579.02	0%	758.11	31%	603.20	3%	588.32	0%	767.36
14	40%	594.85	16%	578.53	0%	757.79	34%	602.61	7%	587.67	0%	767.32
15	42%	594.56	19%	578.06	0%	757.32	35%	602.06	8%	587.01	0%	767.28

[a] APV is the annualized present value of return or annualized profits per hectare.

horizon. Static refuge remained 0% in South India for all 1- to 15-year time horizons. Lower refuge requirements without pyrethroid resistance than those with pyrethroid resistance are due to the lower Bt resistance allele frequencies in CBW without pyrethroid resistance because the toxin mixture impact on Bt resistance evolution is more effective.

Annualized present values of returns per hectare (APV) were slightly higher than those received under current refuge options in all cotton-growing regions with and without consideration of pyrethroid resistance. As mentioned earlier, the current refuge option in India requires farmers to grow 20% of their total cotton area under non-Bt cotton, which may be sprayed with insecticides.

For unsprayed[12] refuge with and without pyrethroid resistance, static refuges were 0% for all years of the time horizon in each region, as shown in Table 5. The reason behind the 0% refuge is that susceptible pests to Bt and pyrethroid insecticides in unsprayed cotton mate with resistant pests to both toxins in Bt cotton, resulting in declining resistant-allele frequencies of CBW to Bt and pyrethroids. Moreover, there is a considerable difference between potential yields of Bt and unsprayed non-Bt cotton. APVs were significantly higher than those received under current refuge options in all of the three cotton-growing regions in India with and without pyrethroid resistance consideration. The current refuge options in this case are the unsprayed refuge options, under which Indian farmers are required to grow 5% of their total cotton area under non-Bt cotton without spraying insecticides. A reduction in unsprayed refuge from 5% to 0% with pyrethroid resistance improved estimated annualized returns by 4.41%, 4.25%, and 4.60% in North, Central, and South India, respectively, for the 15-year time horizon. When pyrethroid resistance was not considered, the estimated returns 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 refuge areas have higher estimated returns than unsprayed refuge.

It is widely thought that, as in China, India may not need structured refuges because of small, highly fragmented farms and different host crops for CBW that are

12. *Under unsprayed refuges, producers may plant 95% of their cotton area to Bt varieties, and spray Bt varieties as needed with conventional insecticides; however, no insecticides may be used on the 5% of non-Bt varieties planted in the refuge.*

Table 5. Profit-maximizing, static unsprayed refuge for the three cotton-growing regions in India, with and without pyrethroid resistance considered.

	Unsprayed refuge With pyrethroid resistance						Unsprayed refuge Without pyrethroid resistance					
	North		Central		South		North		Central		South	
Time (years)	Static refuge	APV [a] ($/ha)	Static refuge	APV ($/ha)	Static refuge	APV ($/ha)	Static refuge	APV ($/ha)	Static refuge	APV ($/ha)	Static refuge	APV ($/ha)
1	0%	602.69	0%	583.11	0%	759.00	0%	613.16	0%	590.66	0%	767.46
2	0%	602.37	0%	583.09	0%	758.99	0%	613.15	0%	590.65	0%	767.46
3	0%	602.20	0%	583.07	0%	758.98	0%	613.11	0%	590.65	0%	767.46
4	0%	601.78	0%	583.05	0%	758.96	0%	612.90	0%	590.64	0%	767.46
5	0%	600.05	0%	583.01	0%	758.95	0%	612.33	0%	590.63	0%	767.46
6	0%	596.88	0%	582.88	0%	758.86	0%	610.36	0%	590.61	0%	767.45
7	0%	594.64	0%	582.68	0%	758.79	0%	606.72	0%	590.53	0%	767.45
8	0%	592.97	0%	582.32	0%	758.73	0%	603.90	0%	590.45	0%	767.45
9	0%	591.68	0%	581.62	0%	758.67	0%	601.72	0%	590.31	0%	767.44
10	0%	590.66	0%	580.34	0%	758.57	0%	600.00	0%	590.08	0%	767.43
11	0%	580.83	0%	578.39	0%	758.46	0%	598.60	0%	589.69	0%	767.43
12	0%	589.14	0%	576.41	0%	758.32	0%	597.45	0%	589.00	0%	767.39
13	0%	588.57	0%	574.75	0%	758.10	0%	596.48	0%	587.89	0%	767.36
14	0%	588.08	0%	573.35	0%	757.77	0%	595.66	0%	586.44	0%	767.32
15	0%	587.67	0%	572.15	0%	757.29	0%	594.96	0%	584.95	0%	767.28

[a] *APV is the annualized present value of return or annualized profits per hectare.*

cultivated alongside cotton, providing natural refuges for the cotton crop (Qiao et al., 2010; Ravi et al., 2005). Results of this study, however, support this hypothesis only for South India. In the United States, the optimal structured refuge was found to be 16% for an 11-year time horizon (Livingston et al., 2004). In India, however, optimal structured refuges appear to be 33%, 8%, and 0% for the North, Central, and South regions, respectively, for an 11-year time horizon. The reason for the higher structured refuges requirement in the United States and North India might be the prevalence of monocropped cropping patterns in these regions. In Central and South India, cropping patterns are mostly multicropped.

Sensitivity Analysis

Static refuges for a 5-year time horizon were estimated by using different levels of biological and economic parameters for the three cotton-growing regions. The sensitivity of the percentage of static refuge was analyzed for changes in the initial Bt resistance levels, relative proportion of CBW in cotton, untreated fitness parameters (i.e., fitness costs), and damage function parameters. As the relative fitness parameters (homozygous resistant, heterozygous resistant, and susceptible) are highly covariant, we fixed the relative fitness of heterozygotes and susceptible, and varied only relative fitness of homozygotes. The sensitivity analyses were also conducted to check responsiveness of refuge requirements to changes in the proportion of resistant pests (both homozygous and heterozygous)[13] and environmental fitness factors.

Under the scenario of static sprayed refuge with pyrethroid resistance, refuge requirements increased with an increase in initial Bt resistance levels in the North, Central, and South regions. In North India, the refuge requirement increased from 4% to 20% and 38% when the initial Bt resistance allele frequency increased from 0.00075 to 0.01 and 0.05, respectively. In Central India, 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

13. *A homozygous resistant pest has a pair of resistant alleles, whereas a heterozygous pest has one resistant and one susceptible allele.*

refuge requirement from 0% to 2% and 32%, respectively. The possible reasons for different rates of increase in refuge requirements in the three regions could be a difference in Bt cotton area and a difference in relative proportion of CBW at the regional level.

Static sprayed refuge increased from 0% to 20% as the proportion of CBW in cotton increased from 0.82 (i.e., 82% of CBW are in cotton) to 1.0. Similar results were observed in South India where static refuge increased from 0% to 70% as the proportion of CBW in cotton increased from 0.75 to 1.0. Static refuge requirements increased at a faster rate in the case of Central India, increasing to 100% when the proportion of CBW in cotton increased to 0.93. It should be noted that the increase in static refuge was experienced only after the proportion of CBW in cotton exceeded 0.75, indicating that higher proportions of CBW in cotton corresponds to lower proportions of CBW in natural refuge crops. Therefore, there would be a higher probability of exposure of CBW in cotton to the Bt toxin, which eventually results in a higher rate of mating within Bt-resistant pests, making evolution of resistance and growth in refuge requirements occur sooner. If there was a higher proportion of CBW in natural refuge, the resistance evolution to Bt toxin would be slower because the CBW 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 a fewer number of Bt-resistant pests on Bt cotton, which eventually results in relatively more susceptible pests in the population, as well as a lower level of Bt resistance and a lesser need of refuges over time.

Static sprayed refuges were insensitive to fitness cost parameters for Bt and pyrethroids in central and south India; however, the static refuges decreased from 4% (baseline) to 0% in North India, with a decrease in untreated homozygous fitness parameter for Bt from 0.95 to 0.8. Also, the refuge requirements decreased to 1% in North India with a decrease in untreated homozygous fitness parameter for pyrethroids from 1.0 to 0.66. Intuitively, a lower value of untreated fitness corresponds to a lower pest survival rate, which leads to a lower refuge requirement. Apart from this, sensitivity of sprayed refuges to damage function parameters (α, β, γ, and δ) was checked by varying these parameters within 95% of their confidence intervals, which are shown in Appendix 1. The refuge requirements were not sensitive to damage function parameters, except in North India where it reduces from 4% to 0% for a 5-year time horizon.

The refuge requirements were found to be sensitive to changes in the proportion of resistant pests and environmental fitness factors. The refuge requirements increased with an increase in the proportion of resistant pests in all the three cotton-growing regions in India. Static refuge increased considerably with the environmental fitness factors of May and June in North India only. Refuge requirement varied from 2% to 24% with a change in environmental fitness from 0.25 to 1 in North India.

Conclusions

The examinations and comparison of the regional-level, profit-maximizing refuge requirements for Bt cotton in India found that the refuge requirements varied significantly across the three cotton-growing regions. Based on the available data and parameter values, the results indicated that farmers in North and Central India would need to grow larger areas under structured refuge than farmers in South India in order to earn higher profits per hectare than current refuge policies in India. The findings suggest that costs of refuges can be reduced by having regional flexibility rather than having a ‘one-size-fits-all’ approach. It has been suggested that India may not need structured refuges due to the small, highly fragmented farms and natural refuges provided by different host crops of CBW that are cultivated alongside cotton. However, results of this study support this belief only in the case of South India.

Refuge requirements were found to be very sensitive to the initial Bt resistance level, relative proportion of CBW in natural refuges, and proportions of heterozygous and homozygous resistant pests in all the three cotton-growing regions in India. Static refuges were sensitive to fitness cost and damage function parameters in North India only.

This study also contributes to the development of an analytical framework to examine efficient refuge requirements for Bt cotton in India by taking into consideration the heterogeneity in agro-climatic conditions across regions. Also, the new insect-resistant genetically modified crops (e.g., Bt maize) are expected to be released in India in the near future; the framework developed by this study would provide a foundation to determine the profit-maximizing refuge requirements for those crops.

The model in this study, however, did not consider reported resistance of pink bollworm to Bt cotton in India. The resistance of pink bollworm to the Bt toxin has been recently seen, but it has been reported only in some cotton-growing areas of in Central India (Dhurua & Gujar, 2011; Tabashnik & Carrière, 2010). The resistance of this pest to the Bt toxin is likely to push the refuge requirements up for the central cotton-growing regions in India. The actual refuge requirements, however, depend on the efficacy of pesticides in controlling the pink bollworm. Future studies can include this pest in the model to re-examine refuge requirements.

Another limitation of this study was the lack of regional data on yield losses, pesticide use, and field populations of CBW, which were required to estimate damage functions in the three cotton-growing regions in India. Field-level data collection on these variables would likely improve future policy discussions on refuge requirements in India.

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Appendix 1

Damage Function for Cotton in the United States

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

$$E\,(P_t \,/\, w_t^{nb}) = \alpha w_t^{nb} + \beta\,(w_t^{nb})^2, \tag{A1}$$

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

$$E\,[\varphi^{-1}\,(d_t) \,/\, \widehat{P}_t\,] = \gamma + \delta.\,(\widehat{P}_t)\,, \tag{A2}$$

where d_t denotes annual proportionate yield losses attributed to the budworm-bollworm complex from 1987 to 1995 in Louisiana, and $\widehat{P}_t$ are the predicted values from insecticide use. The least squares and two-stage least squares estimates for Equations A1 and A2 are reported in Table A1.

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 the United States was performed within 95% confidence intervals of the parameters values.

Table A1. Least squares and two-stage least squares estimates for Equations A1 and A2.

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]

Appendix 2

Table A2. Area under natural refuges/cotton (thousand hectares) and average farm size in the three regions.

Particulars	North	Central ('000 ha)	South
Pigeon pea	32.00	757.60	122.24
Sunflower	-	81.00	554.88
Tomato	1.65	-	30.93
Okra	5.40	-	3.36
Pearl millet	4.00	-	-
Peas	15.31	-	-
Total area under natural refuges	58.46	838.60	711.41
Area under cotton	1462.72	2928.30	725.46
Average farm size (hectares)	4.38	2.73	1.26

Source: Indiastat.com (n.d.)