Bt Cotton Refuge Policy

Michael J. Livingston
Post-Doctoral Research Associate
Department of Entomology
North Carolina State University

Gerald A. Carlson
Professor
Department of Agricultural and Resource Economics
North Carolina State University

Paul L. Fackler
Associate Professor
Department of Agricultural and Resource Economics
North Carolina State University

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Introduction

Concerns regarding the development of resistance in the bollworm and the budworm to cotton genetically modified to express Bacillus thuringiensis (Bt) toxins prompted the U.S. Environmental Protection Agency (EPA) to establish limits on the proportion of total acres individual producers may plant, representing the first attempt to regulate the development of insecticide resistance and the first instance of the use of refuge as a policy instrument. Appropriate refuge proportions, however, are difficult to determine because of uncertainty over bollworm and budworm genetic resistance potential in the field and uncertainty over the complex relationship between insecticide resistance and insecticide use in the field, particularly considering the fact that cotton producers routinely spray Bt acres with conventional insecticides to manage yield damages associated with numerous insects. The management of resistance can be viewed as an insecticide susceptibility, resource allocation problem (Carlson and Castle), and most economic (e.g., Hueth and Regev; Regev, Shalit, and Gutierrez; Plant, Mangel, and Flynn), entomological (e.g., Taylor and Headley, Georghiou and Taylor 1977a, 1977b), and operations research (e.g., Shoemaker 1973, 1979, 1982) studies have examined the single insect, single insecticide version. Since cotton producers generally use toxin mixtures to manage yield damages associated with more than one insect, and since the use of toxin mixtures may influence the rate of resistance development to toxins used in mixtures (e.g., Georghiou, Curtis, Gould, Mani, Taylor, Caprio) the single insect, single insecticide model may not be well suited for the examination of refuge policies under realistic cotton production settings.

This note examines the influence of genetic resistance potential on treated and untreated refuge policies in an operational, deterministic cotton production system that accounts for producer use of conventional insecticides (Livingston, Carlson, and Fackler 2000a, 2000b). Static refuge policies maximize the present value of average producer profit in the state of Louisiana over five- and 10-year planning horizons, assuming producers plant Bt and non-Bt cotton and use synthetic pyrethroids to manage yield damages associated with bollworm and budworm populations. The policy model incorporates standard, two-locus genetic models of bollworm and budworm, Bt cotton and pyrethroid resistance development (Livingston, Carlson, and Fackler 2000c); relationships between refuge policy, insecticide resistance, insecticide use, and producer profit; and profit maximizing Bt planting behavior and pyrethroid use. The objective of this note is to examine relationships between refuge policies and genetic resistance potential. Since the genetic resistance potential of bollworms and budworms in the field is uncertain it is useful to examine the magnitudes and directions of effects changes in genetic model parameters have on refuge policies. Sensitivity analysis can indicate potential ranges for refuge policies based on available information, as well as which parameters are more important in terms of refuge policy informational requirements and future research on resistance potential. The analysis is particularly important since the EPA is examining the viability of the current refuge policy.

Model

The policy model appears elsewhere and is only briefly summarized in this section (Livingston). There are two types of cotton, Bt and non-Bt. The collective actions of all Louisiana producers are characterized by a representative producer who chooses the proportion of Bt cotton to plant in Louisiana at the beginning of each growing season to maximize average, statewide profit per acre. The model of production is similar to those employed in earlier studies (e.g., Harper and Zilberman). Bales per Bt and non-Bt acre at harvest are given by $y(1-d^b(B_t, A_t))$ and $y(1-d^n(B_t, A_t))$; where y is maximum obtainable yield per acre; d^b and d^n are proportionate damages per Bt and non-Bt acre as functions of B_t, the proportion of Bt acres planted at the beginning of growing season t, and A_t, a four-by-one vector of bollworm and budworm, Bt cotton and pyrethroid resistance levels observed at the beginning of growing season t. Average, statewide profit per acre is then given by

$$\pi(B_t, A_t) \equiv B_t\left[py(1-d^b(B_t, A_t)) - c^b(B_t, A_t)\right] + (1-B_t)\left[py(1-d^n(B_t, A_t)) - c^n(B_t, A_t)\right].$$

Average profit per acre is profit per Bt acre, multiplied by the proportion of *Bt* acres planted, plus profit per non-Bt acre, multiplied by the proportion of non-Bt acres planted. The price received by the representative producer for a bale of cotton at harvest, p, is held constant, as is maximum obtainable yield. Proportionate yield damages, d^b and d^n, and insecticide treatment costs, c^b and c^n, per Bt and non-Bt acre, however, are increasing functions of resistance levels, and profit per Bt and non-Bt acre will differ accordingly. Only costs associated with the use of Bt cotton, pyrethroids, and other conventional insecticides are included in the producer's cost functions. The levels of all other productive inputs are held constant and assumed employed in profit-maximizing proportions independent of insecticide resistance or the proportion of Bt planted in Louisiana.

Refuge policies, R, maximize the present value of average producer profit per acre over a planning horizon that is T years long, solving $\max_R \sum_{t=1}^{T} \rho_t \pi\left(B\left(R, A_t\right), A_t\right)$; subject to the producer's decision rule, $B\left(R, A_t\right) \equiv \max_{B_t} \pi\left(B_t, A_t\right)$, with $0 \leq B_t \leq R,\ t = 1 \ldots T;$ the genetic, resistance development simulation models, $\left[A_{t+1}, S_t\right]' \equiv G\left(B\left(R, A_t\right), A_t, \Theta\right)$; initial resistance levels, A_1; the vector of parameters, Θ, characterizing bollworm and budworm resistance potential in the field; and the constraint $0 \leq R \leq 1$. Since R represents the maximum proportion of Bt acres the representative producer may plant in any given year, 1-R is the minimum, non-Bt refuge proportion.

S_t is a four-by-one vector of insecticide survival rates of bollworm and budworm larvae facing Bt cotton and non-Bt cotton. In the case of treated refuge policy, larvae face Bt and pyrethroids on Bt acres and pyrethroids on non-Bt acres. In the case of untreated refuge policy, larvae face Bt and pyrethroids on Bt acres and no insecticides on non-Bt acres. Larval survival rates depend on cotton and refuge policy types. Likewise, yield damages and management costs depend on cotton and refuge policy types. Larval survival rates, therefore, are used to link the refuge policy, the Bt cotton planting decision, and insecticide resistance to producer profit through the genetic models and the damage and cost functions. See Livingston for a complete discussion of the methods and data used to estimate the parameters of the genetic, resistance development simulation models and the damage and cost functions.

Costs and benefits of refuge policies are measured in terms of cotton producer profitability over finite planning horizons. All other policy costs and benefits are ignored. In particular, the long run profitability of the market supplier of Bt cotton is ignored. The costs of firm compliance and technology registration are ignored, including barriers to entry facing potential competitors that may be exacerbated by policy compliance. Costs associated with deriving, initiating, maintaining, and enforcing the policy are ignored. Costs associated with Bt and pyrethroid resistance in cotton insects that infest other transgenic Bt crops, fruit and vegetable crops in which producers rely on foliar Bt insecticides, and crops in which producers use pyrethroids are ignored. The future availability of alternative pest management technologies is also ignored. Cotton producer profitability provides a tractable measure of the costs and benefits associated with resistance management. Producer profits do not capture all costs and benefits; however, the measure certainly captures some of the costs and benefits of resistance management.

An interior solution to the resistance management problem equates the present value of average producer profits per acre to the present value of average resistance costs per acre over the planning horizon. Ceteris paribus, refuge increases (decreases) when a parametric shift increases (decreases) the present value of average resistance costs per acre relative to the present value of average profits per acre. Bollworm and budworm susceptibility to Bt is a resource that is mined more rapidly when higher proportions are planted. As is the case with any resource, the efficient rate of exploitation decreases with the length of the planning horizon; accordingly, refuges increase with the length of the planning horizon. Likewise, refuges increase with parameters that increase the present value of average resistance costs relative to the present value of average profits.

Unit output price and insecticide treatment costs per acre are held constant for the Louisiana production region, which is on average responsible for only seven percent of total U.S. cotton production (U. S. Department of Agriculture 1998). Louisiana acre-weighted averages are used to specify unit costs per acre. The Bt technology fee is $32.00 per acre, and the costs of Bt and non-Bt seed per acre are ignored due to a low discrepancy between the two (Hubbell et al. 2000). The cost of one pyrethroid application is $7.81 per acre, and is the cost of treating by air, weighted by the proportion of acres treated by air, plus the cost of ground treatment, weighted by the proportion of acres treated using ground sprayers in Louisiana for the 1998 crop year (Bagwell 1999). The cost of one conventional insecticide application is $15.00 per acre, which is a conservative estimate of the average unit cost of available insecticides used to manage bollworm and budworm populations.

Output price is $305.67 per 480-pound bale, which is the average price received by U.S. producers over the 1987 to 1997 crop years (U. S. Department of Agriculture 1998). Data on pounds per harvested acre, total acres harvested, and total acres planted are used to estimate maximum obtainable pest-free bales of cotton per planted acre (U. S. Department of Agriculture 1998). Pounds per harvested acre are deflated by the ratio of harvested to planted acres for the years 1987 to 1998 to obtain observations on pounds per planted acre. Pounds per planted acre are inflated by five percent to adjust yields roughly for yield damages associated with the bollworm – budworm complex. Average, seasonal bollworm – budworm complex yield damages for the state of Louisiana over this period are 3.4 percent, with a high of 7.5 percent and a low of 1.7 percent. The five-percent weighting factor provides a conservative estimate of the maximum obtainable yield. The mean of this series, 1.5014, is pest-free bales per planted acre, which is assumed the same on Bt and non-Bt acres. Treated and untreated refuge policies are derived to maximize the present value of average profit per acre received by the representative producer over five- and 10-year planning horizons. Profits received in future periods are converted into present value equivalents using an annual, three-percent interest rate and an appropriate discount rate schedule.

Results

The genetic simulation models used to predict bollworm and budworm, Bt and pyrethroid resistance development are specified using vectors of parameters that characterize bollworm and budworm genetic resistance potential in the field. Since Bt became commercially available in 1996 sufficient field data on resistance measures are unavailable, thus parameters that characterize bollworm and budworm, Bt resistance potential in the field are specified exogenously based on available information. Field data on pyrethroid resistance measures for both species, however, are available and are used to estimate parameters that characterize bollworm and budworm, pyrethroid resistance potential in the field. The specified and estimated parameters are provided in Tables 1 and 2. Livingston provides a complete discussion of the data, estimation procedures, and information sources.

Treated and untreated refuge policies are derived for various specifications of the genetic model parameters in order to examine relationships between refuge policies and genetic resistance potential. Treated refuge policies allow producers to apply conventional insecticides on Bt and non-Bt acres; untreated refuge policies allow producers to apply conventional insecticides only on Bt acres. Refuge policies and profit-maximizing Bt cotton planting proportions are computed using a simple grid search constrained to the finite set {0.00,0.01,0.02…0.98,0.99,1.00}, subject to estimates of initial Bt and pyrethroid resistance levels in Louisiana at the beginning of the year 1999 growing season.

Treated Refuge Policies

Figures 1 and 2 present treated refuge policies for different specifications of the degree of recessiveness of the inherited Bt resistance trait in both species for the five- and 10-year planning horizons, beginning with the 1999 Louisiana crop year. Recessiveness values are taken from the set {0.00,0.25,0.50,0.75,1.00} for bollworms and from the set {0.50,0.75,0.90, 0.99,1.00} for budworms. Unless otherwise stated, genetic model parameters are set at the values provided in Tables 1 and 2, some of which are different from those specified earlier (Livingston; Livingston, Carlson, and Fackler, 2000c).

Treated refuge policies are highly dependent on specifications of the degree of recessiveness of the inherited Bt resistance trait in both species. Generally, treated refuge policies decrease with the level of recessiveness of the inherited Bt resistance trait, because resistance develops less rapidly in both species for any given statewide proportion of Bt planted.[1] When bollworm recessiveness is 0.50 or 0.75, however, refuge policies decrease when budworm recessiveness is reduced from 0.75 to 0.50. When budworm recessiveness is 0.50 and the bollworm inherits Bt resistance as a completely dominant, or as an intermediately dominant trait, Bt resistance levels at the beginning of the year 1999 growing season are very high, and the treated refuge proportion declines so that a higher proportion of Bt can be planted in the first growing season. Bt is not planted

[1] Recall recessiveness parameters are constrained to the unit interval, [0,1]. Values close to 0 indicate dominant resistance inheritance, and values close to 1 indicate recessive resistance inheritance.

Table 1. Estimated and specified genetic model parameters for the budworm.

Cypermethrin Resistance Parameters

Dependent Variable Average, annual budworm survival vs. 10 μg/vial cypermethrin

Observations 12

Parameter	Estimate	St. Error	P-Value	95% C.I.
Fitness cost	0.51068	0.10370	0.00116	[0.272,0.750]
Recessiveness	0.83059	0.24933	0.01036	[0.256,1.406]
Larval Mortality[g]	0.85510	0.06898	0.00000	[0.696,1.014]
Initial Frequency	0.00614	0.04018	0.88236	[-0.09,0.099]
Regression Statistics	SSE 0.03414	TSS 0.19357	R^2 0.82364	s^2 0.00428

Bt Cotton Resistance Parameters

Parameter	Value	Source(s)
Fitness cost	0.0000	a
Recessiveness	0.8000	b
Larval Mortality	0.9500	c
Initial Frequency	0.0015	d
Generations per season	3	e
Generations per year	5	e
Winter survival	0.0350	f

Sources and Notes: (a) Gould and Anderson, 1991. (b) Van Duyn, 2000. (c) Hardee et al., 1997; Lambert et al., 1998. (d) Gould et al., 1997. (e) Ralph Bagwell, 1999; Steve Micinski, 1999. (f) Stadelbacher and Pfrimmer, 1972; Stadelbacher and Martin, 1980.

Table 2. Estimated and specified genetic model parameters for the bollworm.
Cypermethrin Resistance Parameters

Dependent Variable Average, annual bollworm survival vs. 5 µg/vial cypermethrin

Observations 12

Parameter	Estimate	St. Error	P-Value	95% C.I.
Fitness Cost	0.56973	1.25121	0.66097	[-2.316,3.455]
Recessiveness	0.98343	1.28416	0.46578	[-1.978,3.945]
Larval Mortality[f]	0.94943	0.00878	0.00000	[0.929,0.970]
Initial Frequency	0.00037	0.10718	0.99731	[-0.247,0.248]
Regression statistics	SSE 0.00461	TSS 0.02287	R^2 0.79828	s^2 0.00058

Bt Cotton Resistance Parameters

Parameter	Value	Source(s)
Fitness Cost	0.0000	a
Recessiveness	0.5000	b
Larval Mortality	0.6000	c
Initial Frequency	0.0135	
Generations per season	2	d
Generations per year	5	d
Winter survival	0.0350	e

Sources and Notes: (a) Gould and Anderson, 1991. (b) Fred Gould recommended the interval [0.25,0.75]. (c) Hardee et al., 1997. (d) Ralph Bagwell and Steve Micinski, 1999. (e) Stadelbacher and Pfrimmer, 1972; Stadelbacher and Martin, 1980.

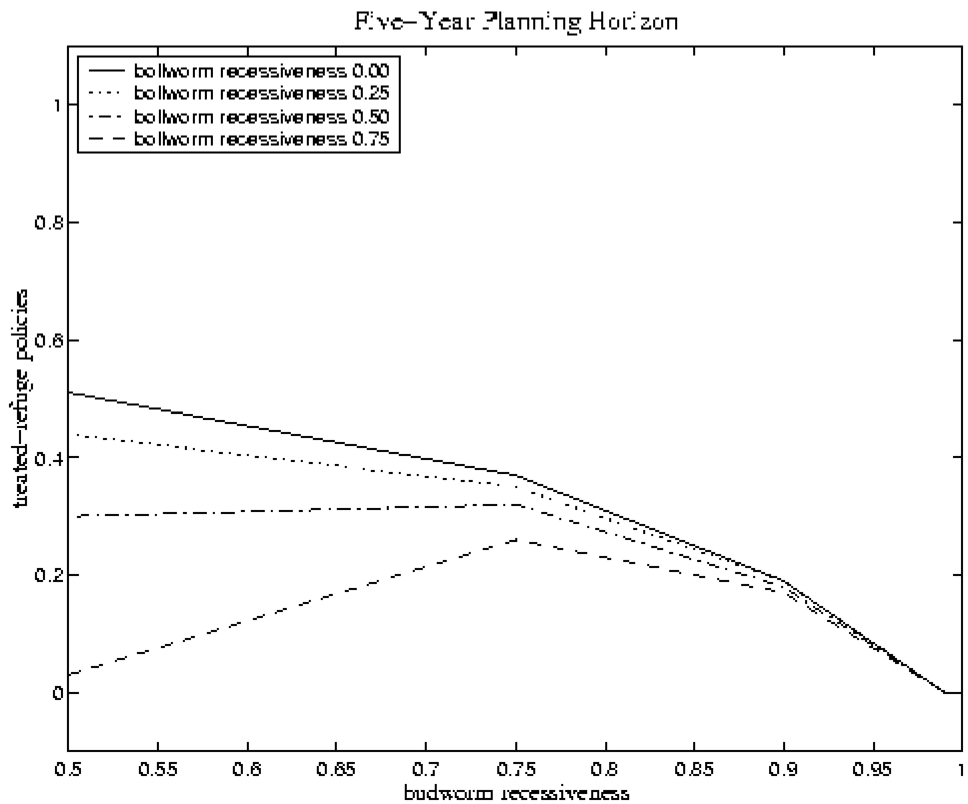

Figure 1 Treated refuge policies for the five-year planning horizon for various bollworm and budworm, Bt recessiveness specifications. All other parameters are set at the values specified in Tables 1 and 2.

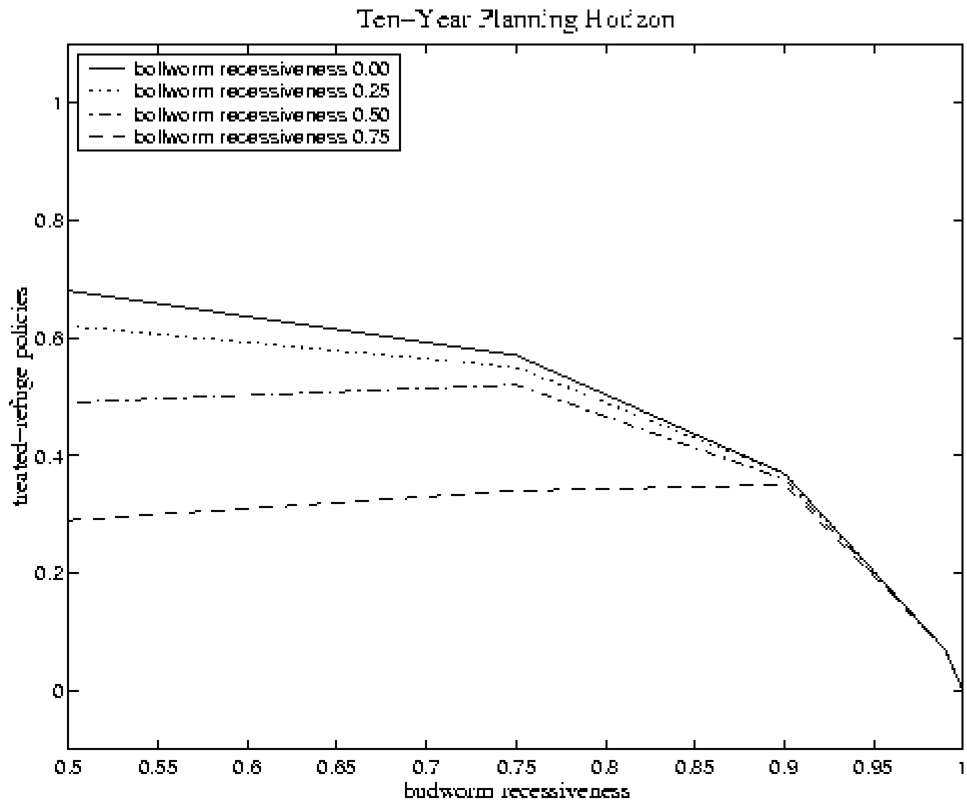

Figure 2 Treated refuge policies for the 10-year planning horizon for various bollworm and budworm, Bt recessiveness specifications. All other parameters are set at the values specified in Tables 1 and 2.

for the remainder of the five- or 10-year horizons in either case due to high levels of resistance arising from producer exploitation of the low treated refuge policy in the first growing season. Treated refuge policies increase with the length of the planning horizon, since Bt cotton must be maintained as an effective management tool for relatively longer. Note that after 0.90 budworm recessiveness, treated refuge policies decline dramatically independent of the level of bollworm recessiveness. Note also that the rate of decline of treated refuge policies over the [0.90,1.00] budworm recessiveness interval increases with the length of the planning horizon.

When budworm recessiveness is approximately complete, Bt resistance is managed efficiently with relatively small treated refuges. Budworm susceptibility to Bt is conserved completely, but bollworm susceptibility is exhausted completely over the [0.90,1.00] budworm recessiveness interval for each planning horizon. In terms of producer profitability, it is efficient to conserve budworm susceptibility but exhaust bollworm susceptibility over this interval for the five- and 10-year horizons. As a result, treated refuge policies decline with budworm recessiveness irrespective of the level of bollworm dominance.

Figures 3 and 4 display the relationship between treated refuge policies and the level of bollworm Bt mortality. Treated refuge policies are derived for the same set of recessiveness values when bollworm Bt mortality is set at 80%. As expected, treated refuge policies increase with the level of bollworm Bt mortality because Bt resistance develops sooner the higher the mortality rate for any given statewide proportion of Bt planted. Under the base case parameters in Tables 1 and 2, treated refuge policies are

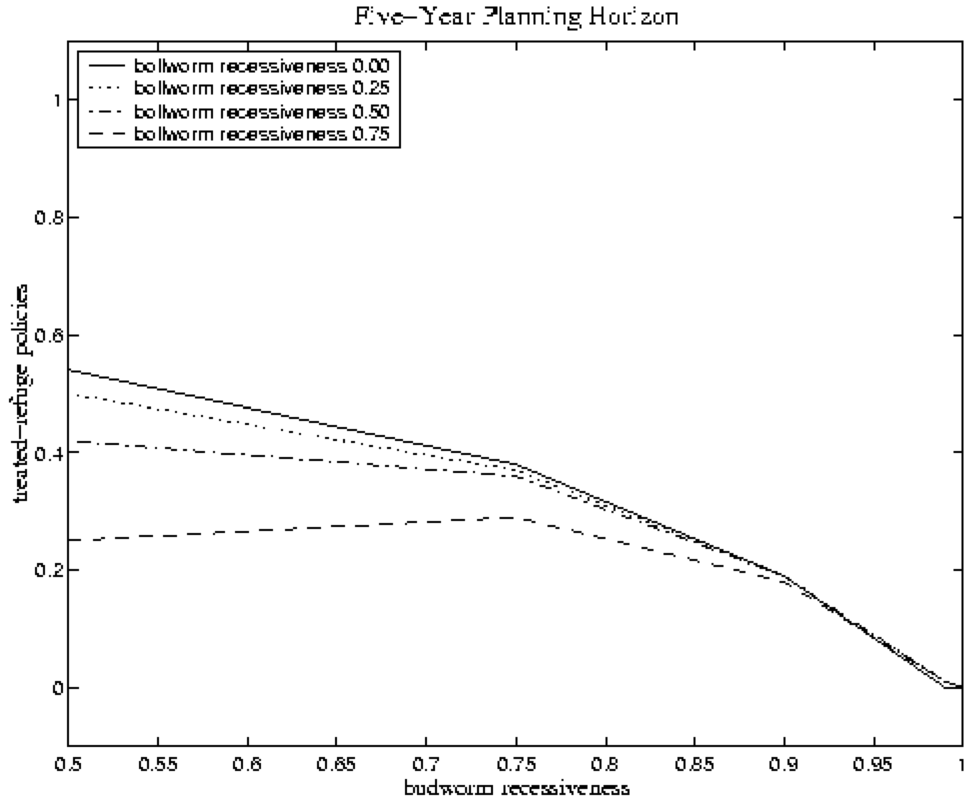

Figure 3 Treated refuge policies for the five-year planning horizon for various bollworm and budworm, Bt recessiveness specifications. Bollworm and budworm Bt mortality are set at 80% and 95%, respectively. All other parameters are set at the values specified in Tables 1 and 2.

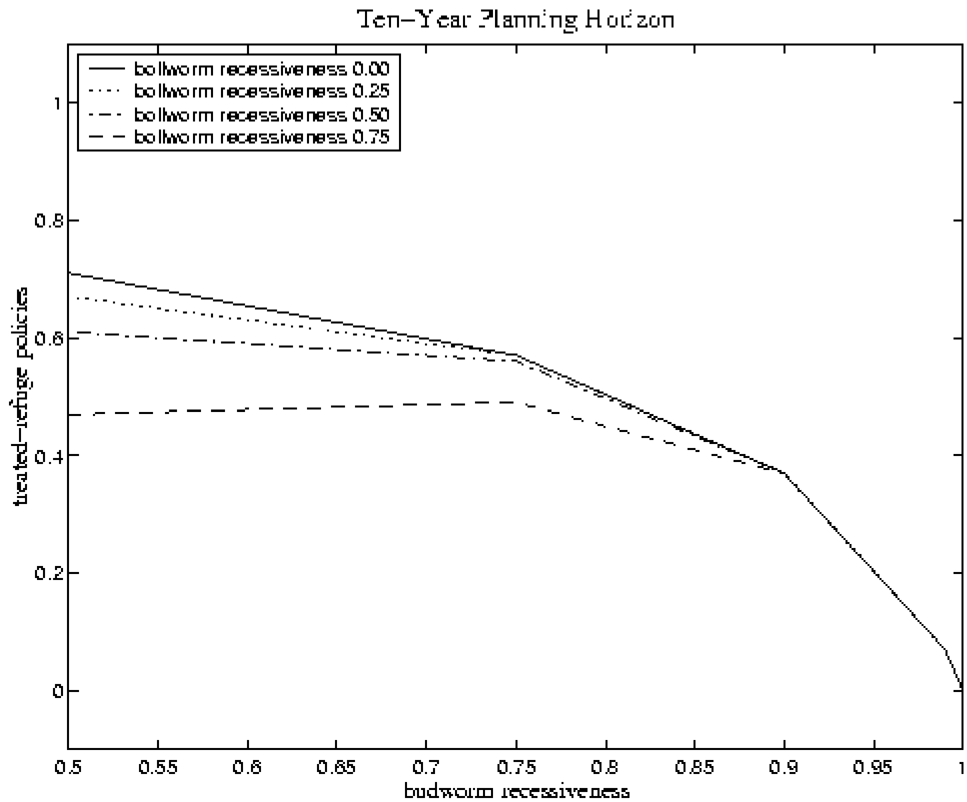

Figure 4 Treated refuge policies for the 10-year planning horizon for various bollworm and budworm, Bt recessiveness specifications. Bollworm and budworm Bt mortality are set at 80% and 95%, respectively. All other parameters are set at the values specified in Tables 1 and 2.

relatively invariant with respect to increases in budworm mortality above 95%. Treated refuge policies still decline over the [0.90,1.00] budworm recessiveness interval, irrespective of the level of bollworm recessiveness, and the rate of decline increases with the length of the planning horizon. The same is true when bollworm and budworm, Bt mortality is set at 80 and 99%, respectively. If budworm recessiveness is between 0.90 and 1.00, present value maximizing treated refuge policies do not depend appreciably on the level of bollworm recessiveness. If, however, budworm recessiveness is less than 0.90, treated refuge policies depend on bollworm recessiveness.

Untreated Refuge Policy

Untreated refuge policies are sensitive to Bt recessiveness, however, the magnitude of the dependence is minimal relative to the treated refuge case. This is because the estimated fitness cost of pyrethroid resistance is high for both species (Livingston; Livingston, Carlson, and Fackler 2000b). As a result, susceptibility to pyrethroids is actually regenerated in both species under untreated refuge scenarios. This in turn leads to toxin mixture effects that reduce the rate of Bt resistance in both species (Livingston). It is, therefore, not surprising that minimum non-Bt refuge policies are not very sensitive to changes in Bt recessiveness. Notice also that untreated refuge policies do not vary significantly with the length of the planning horizon when fitness costs are this high.

Figures 5 and 6 present untreated refuge policies for various combinations of the fitness cost parameters. Recessiveness is set at 0.50 and 0.80, and Bt mortality is set at 0.80 and 0.99 for the bollworm and budworm, respectively. As shown, untreated refuge

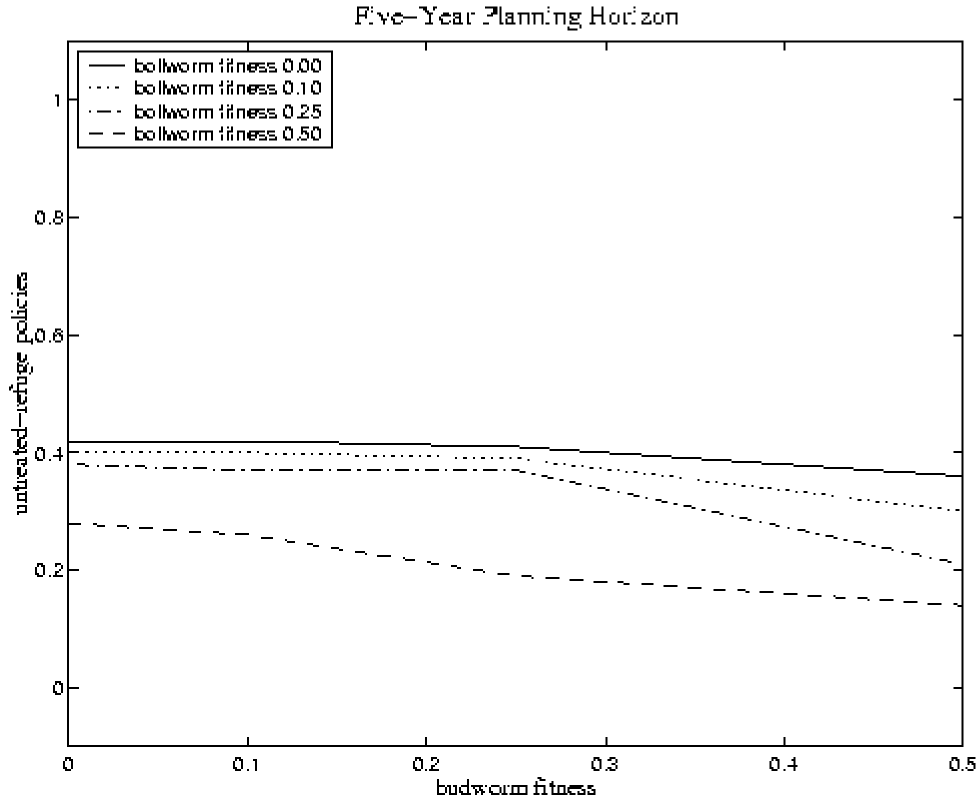

Figure 5 Untreated refuge policies for the five-year horizon for various fitness costs, 0.50 and 0.80 recessiveness, and 80% and 99% Bt mortality for the bollworm and the budworm, respectively. All other parameters are set at the values specified in Tables 1 and 2.

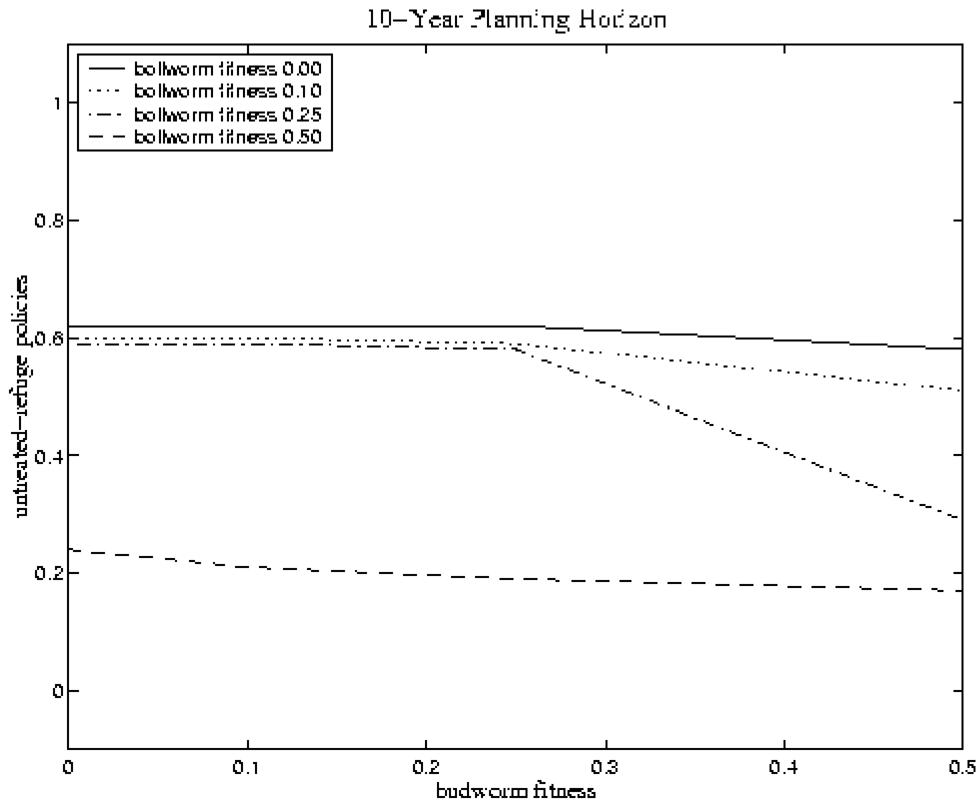

Figure 6 Untreated refuge policies for the 10-year horizon for various fitness costs, 0.50 and 0.80 recessiveness, and 80% and 99% Bt mortality for the bollworm and the budworm, respectively. All other parameters are set at the values specified in Tables 1 and 2.

policies decrease with bollworm and budworm fitness costs. When fitness cost increases, relatively small untreated refuges lead to pyrethroid susceptibility regeneration and to toxin mixture effects that reduce the rate of Bt resistance development. The effect is more pronounced in the bollworm since mortality is relatively higher in the bollworm, magnifying the impact of refuge on resistance development with changes in fitness cost. Note also that the effect of fitness on untreated refuge policies increases with the length of the time horizon.

The influence of fitness on untreated refuge policies depends on bollworm pyrethroid recessiveness. At high fitness costs, levels of recessiveness at or below the estimated value have no effect on pyrethroid resistance; that is the base case value is effectively dominant. To illustrate the influence of bollworm pyrethroid recessiveness on fitness cost effects, figures 7 and 8 present untreated refuge policies for various fitness costs when bollworm pyrethroid recessiveness is complete. When bollworm pyrethroid recessiveness is complete, bollworm fitness cost no longer influences untreated refuge policies. Over the five-year horizon, untreated refuge policies still decline with budworm fitness cost. Over the 10-year horizon untreated refuge policies decline with budworm fitness cost, but then increase with fitness cost levels over 0.25. Remarkably, untreated refuge policies actually decline with the length of the planning horizon. When the bollworm inherits pyrethroid resistance as a completely recessive genetic trait, pyrethroid resistance develops very slowly in the bollworm, independent of the cost of fitness. As a result, a significant pyrethroid toxin mixture effect is present which reduces the rate of Bt resistance development for any constant proportion of Bt cotton planted in the state of

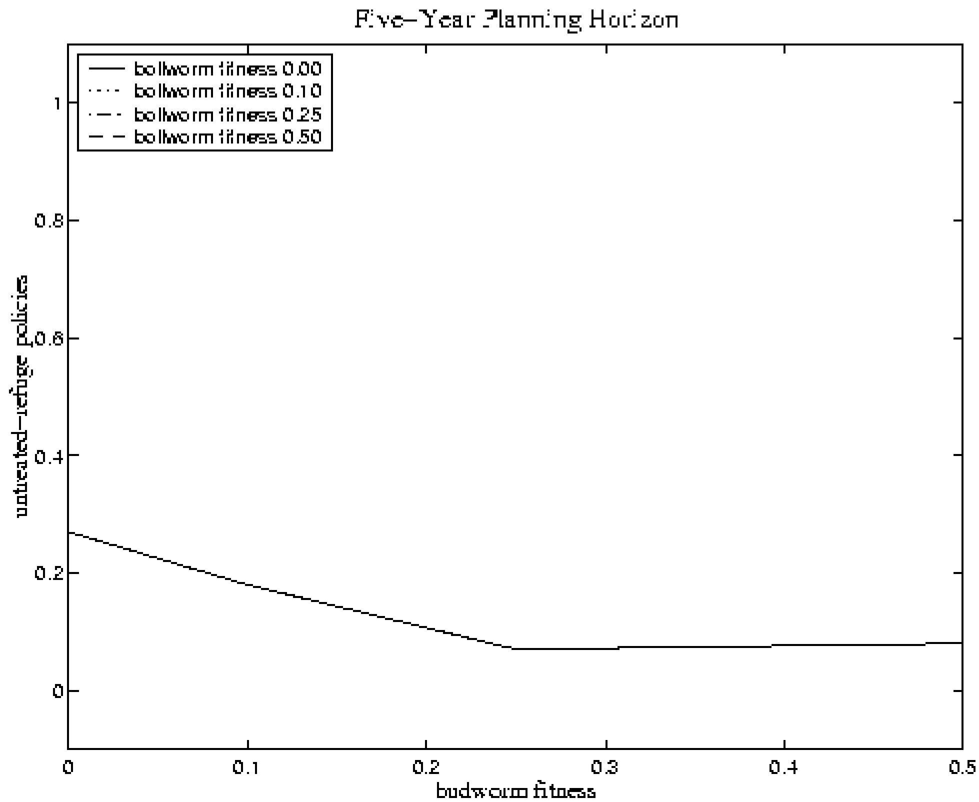

Figure 7 Untreated refuge policies for the five-year horizon for various fitness costs, 0.50 and 0.80 recessiveness, 80% and 99% Bt mortality for bollworms and budworms, respectively, and 1.00 bollworm pyrethroid recessiveness. All other parameters are set at the values specified in Tables 1 and 2.

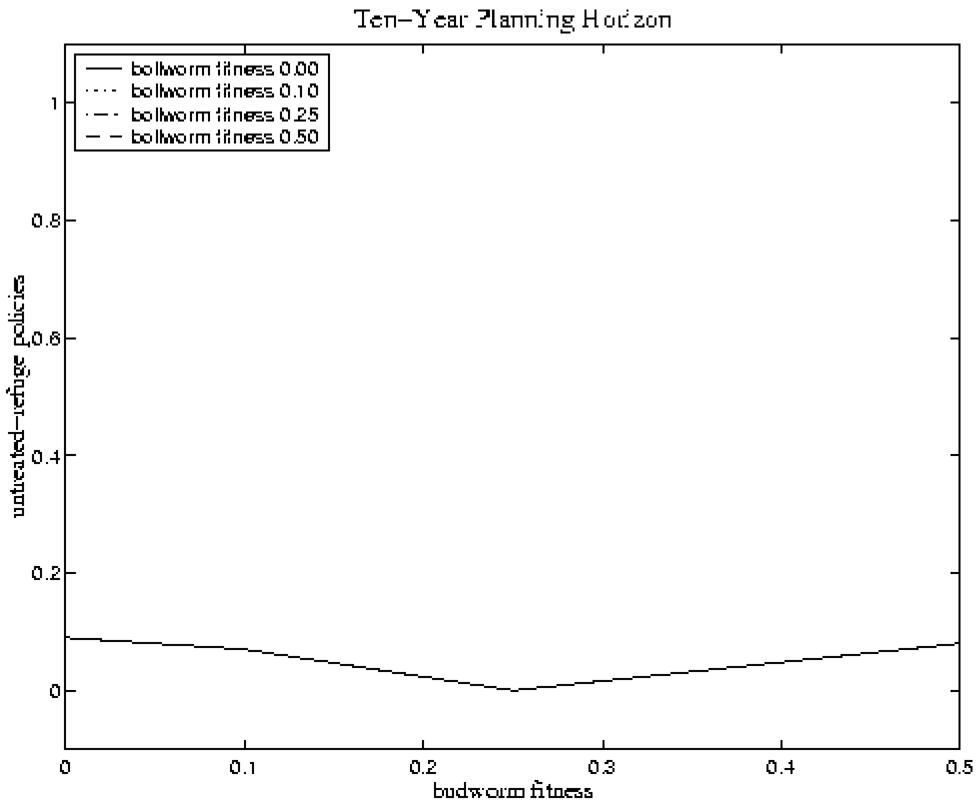

Figure 8 Untreated refuge policies for the 10-year horizon for various fitness costs, 0.50 and 0.80 recessiveness, 80% and 99% Bt mortality for bollworms and budworms, respectively, and 1.00 bollworm pyrethroid recessiveness. All other parameters are set at the values specified in Tables 1 and 2.

Louisiana. This in turn reduces untreated refuge policies. The toxin mixture effect on long run, discounted producer profit increases with the length of the planning horizon, reducing the need to conserve Bt susceptibility even more.

Summary Remarks

This note demonstrates the dependence of treated and untreated refuge policies on genetic simulation model parameters and on the length of the planning horizon. Policy makers are urged to obtain as accurate a picture as possible regarding the potential the bollworm and the budworm possess for developing resistance to Bt cotton, as well as conventional insecticides that are currently being used with Bt cotton, or those that may be used with Bt cotton in the future. An accurate representation of the complex dynamics associated with potential cross-effects on resistance and producer response must play a role in refuge policy design, since cotton producers will continue to use conventional insecticides when planting Bt cotton. The length of the planning horizon and the arrival and availability schedule for alternative bollworm and budworm management technologies are of critical importance and should also be given due consideration.

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