# Managing the Risk of European Corn Borer Resistance to Transgenic Corn: An Assessment of Controversial Refuge Recommendations*

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## Abstract

A bioeconomic model is developed to evaluate the tradeoff between the risk of resistance and increased productivity when refuge is planted in conjunction with transgenic pesticidal corn. The model is used to evaluate controversial refuge recommendations when producers are allowed to treat refuge in years of high pest pressure.

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## I. Introduction

The use of Genetically Modified Organisms (GMOs) in agriculture has increased since 1995. In terms of acreage planted, the most successful GMOs are engineered to kill pests by expressing a protein that is found in the soil bacterium *Bacillus thuringiensis* (Bt).[1] The potential for these pesticidal GMOs to increase agricultural productivity is undeniable. Empirical evidence suggests however that the benefits could rapidly dissipate due to the development of resistance (Hama, et. al., 1992; Tabashnik, et. al., 1992; Martinez-Ramirez, et. al., 1995; and Tabashnik, et. al., 1995).

There are two important dimensions to controlling pests with a highly selective pesticidal GMO. First, surviving pests propagate making the pest population renewable (Regev, Shalit, and Gutierrez 1983). Second, resistance is generally considered irreversible so that susceptibility is nonrenewable (Hueth and Regev, 1974; Regev, Gutierrez, and Feder, 1976; Regev, Shalit, and Gutierrez 1983). Since insect pests are mobile, producers will typically fail to account for the external benefits of pest suppression and costs of resistance imposed on their neighbors.

The EPA conditionally registered the first generation of pesticidal GMOs due resistance concerns. The conditional registrations give industry time to develop and implement resistance management plans, while collecting information on the risk of resistance. To manage resistance, a high-dose refuge strategy has been adopted. For a high-dose, the GMO must express enough toxins to kill all but the most resistant pests. For refuge, producers manage part of their acreage without the benefit of the GMO's toxins. Refuge allows susceptible pests to thrive and mate with resistant pests reducing selection pressure and extending the efficacy of the GMO.

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[1] These transgenics operate by producing a crystal-like protein (Cry protein) which is a stomach poison for the insect (Ostlie *et al.*, 1997). So far, more than 60 of these proteins have been identified, but the seven transgenics registered for commercial use in 1998 utilize only four of them, Cry III A, Cry I(A)b, Cry I(A)c and Cry 9 C.

Evidence suggests that a high-dose refuge strategy can effectively slow resistance if there is adequate refuge. How much refuge is adequate remains controversial because of important biological factors that are either random in nature or not precisely known and economic factors that determine a stakeholder group's willingness to accept a greater risk of resistance. The purpose of this paper is to develop a model that provides insight into the debate over refuge recommendations when Bt corn is planted to control the European corn borer (ECB) in the Central and Western US. By exploring key issues of contention within a consistent analytic framework, the model provides useful information to help frame the policy debate. To demonstrate the merits of the model, we explore the current debate over how refuge recommendations should adjust to allow spray treatments on refuge with non-Bt pesticides in years of high ECB pressure.

Originally, different refuge recommendations were offered based on whether or not producers planned to treat refuge using non-Bt pesticides (Ostlie, Hutchison, and Hellmich, 1997). Since the purpose of refuge is to provide enough susceptible ECB to mate with resistant ECB, a producer's pesticide applications on refuge can increase the risk of resistance by reducing the availability of susceptible mates. Due to a higher risk of resistance, more refuge may be necessary. Unfortunately, when planting decisions are made, important information that determines whether a refuge will require treatment is not available. Therefore, having producers commit to a treatment strategy prior to learning ECB pressure poses important practical concerns that have led to the proposal of refuge recommendation that permit spray applications based on treatment thresholds.

The results of our model suggest that current recommendations for untreated refuge are sufficient for refuge sprayed using treatment thresholds in most regions where spray applications are typically rare due to high scouting and application costs and low pesticide efficacy. In regions where spray applications are more frequent due to either higher expected yields or pest damage, higher recommendations are justified. The model suggests that the costs of reducing the risk of resistance increases when the frequency of spray applications increases due to lower agricultural productivity and increased pesticide use. Therefore, economic rational suggests a higher risk of resistance is acceptable in regions where spray treatments are more frequent.

## II. A Conceptual Model

Optimally, as pest susceptibility becomes increasingly scarce and new information resolves unanswered questions, refuge recommendations should evolve. Deriving the optimal exhaustion path ex ante is a daunting task because it requires conditioning on new information. Types of new information include the realization of unpredictable events such as pest pressure; new field data on unknown factors such as resistance levels; and the realization of unforeseen events such as new technologies. Alternatively, imposing a safe minimum refuge based on current information is a more manageable task, though not optimal because its failure to incorporate new information and address the increasing scarcity of pest susceptibility. The difficulty of designing temporally optimal refuge recommendations and the suboptimality of a safe minimum refuge has resulted in the adoption of an adaptive strategy. The adaptive strategy sets a safe minimum refuge recommendation based on current information, but allows for the revision of this recommendation as new information warrants.

Following Hueth and Regev (1974), Taylor and Headley (1975), Regev, Shalit, and Gutierrez (1983), and Roush and Osmond (1996), our model focuses on a simplified production region with a single crop and pest. A closed pest population defines the scope of the region where migration is assumed negligible. While a single crop is planted, there are two varieties.[2] The first, denoted by $i = 0$, is refuge where pest survival rates are normal. The second, denoted by $i = 1$, is a pesticidal GMO where pest survival rates are lower than normal. The expected pest free yield for the $i$th crop is defined as $Y^i$ bushels/acre. The expected production costs for the $i$th crop in season $t$ is $C_t^i$ \$/acre. There are two components to the expected cost of production. The first is a time invariant cost of production exclusive of pesticide spray applications. The second is the time variant cost of spray applications for seasons when pest pressure exceeds the treatment threshold. The expected real price received for the crop is $P$ \$/bushel. The safe minimum proportion of refuge is defined as $1.0 \geq \phi^s \geq 0.0$, while the actual or effective proportion of refuge is defined as $1.0 \geq \phi_t \geq 0.0$. The difference between the safe minimum refuge and the effective refuge depends on Bt corn adoption rates and producer compliance with refuge recommendations.

The model incorporates three important sources of uncertainty. First, pest populations are quite variable due to random environmental and climatic events. Second, the current level of resistance is uncertain. Third, the efficacy of the GMO on susceptible pests is uncertain. Incorporating these sources of uncertainty, the effective proportion of refuge in season $t$, and the level of pest pressure and resistance in season $t + 1$ will be random:

$$\phi_t \sim \phi(N_t, R_t, \phi^s), \text{ and} \tag{1}$$

$$N_{t+1} \sim n(N_t, R_t, \phi^s) \tag{2}$$

$$R_{t+1} \sim r(N_t, R_t, \phi^s) \tag{3}$$

where $N_t$ and $R_t$ are pest pressure and resistance at the beginning of season $t$.

The distribution of the effective refuge in a season, equation (1), depends on the relative

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[2] A refuge crop does not have to be identical to the transgenic crop. However, there is increasing empirical evidence

profitability of the GMO as compared to refuge and compliance with the safe minimum refuge, which are influenced by initial pest pressure, resistance, the efficacy of the GMO, and spray applications.

The distribution of pest pressure at the beginning of a season, equation (2), is conditioned on pest pressure and resistance in the previous season since both influence net pest survival rates directly and indirectly through the effective proportion of refuge. The safe minimum refuge indirectly effects the distribution of pest pressure through the effective proportion of refuge which determines the proportion of the population exposed to the GMO. Spray applications and the uncertain efficacy of the GMO also influence net pest survival rates and the distribution of pest pressure.

The distribution of resistance at the beginning of a season, equation (3), depends on net survival rates, which are influenced both directly and indirectly through the effective proportion of refuge by previous resistance. Previous pest pressure and the safe minimum refuge indirectly effect net survival rates and the distribution of resistance through the effective proportion of refuge, which determines the proportion of the population exposed to the GMO. Spray applications and the uncertain efficacy of the GMO also influences net pest survival rates and the distribution of resistance.

The expected yield in season $t$ depends on the level of pest pressure. Let $1.0 \geq D_t^i \geq 0.0$ be the proportion of yield loss on the $i$th variety. $D_t^i$ is randomly distributed depending on pest pressure and resistance at the beginning of the season and the effective proportion of refuge:

$$(4) \qquad D_t^i \sim d^i(N_t, R_t, \phi_t).$$

Pest pressure, resistance, and spray applications influence net survival rates and the distribution of damages both directly and indirectly through the effective proportion of refuge. The safe

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to suggest that refuge is much more effective when it is similar to the transgenic.

minimum refuge effects net survival rates and the distribution of damages indirectly through the effective proportion of refuge.

The expected value of agricultural production in season $t$ is

(5) $$\pi_t = E\left[\phi_t\left\{PY^0\left(1-D_t^0\right)-C_t^0\right\}+\left(1-\phi_t\right)\left\{PY^1\left(1-D_t^1\right)-C_t^1\right\}\right],$$

such that the expected net present value of increased agricultural productivity is

(6) $$\Pi = \sum_{t=0}^{T-1}\delta^t\pi_t$$

where $T$ is the length of the planning horizon and $\delta$ is the discount rate. The value of equation (6) also depends on the initial level of resistance, $R_0$, and the initial pest population, $N_0$. The initial level of resistance is currently uncertain and is assumed to be distributed $R_0 \sim f$.

Two important objectives have guided refuge recommendations, (i) the preservation of pest susceptibility and (ii) the maintenance of agricultural productivity. However, since most current models focus on the biology of resistance management without measuring agricultural productivity, the preservation of pest susceptibility receives more attention. Within the current framework, the effect of refuge on agricultural productivity is explicit providing a more balanced evaluation of refuge recommendations based on both objectives.

Let $\alpha$ represent the probability that resistance remains below the predetermined threshold, $\Omega$. The inherent economic tradeoff between the risk of resistance and the expected value of agricultural productivity can be measured by $\alpha$ and $E(\Pi)$. The efficient tradeoff is constructed by choosing $\phi^s$ to maximize $E(\Pi)$ subject to equations (1) – (4), an initial pest population of $N_0$, $R_0 \sim f$, and $\Pr(R_T \leq \Omega) \geq \alpha$. The lagrangian can be written as

(7) $$L = E(\Pi)+\lambda\left(\Pr\left(R_T \leq \Omega\right)-\alpha\right),$$

while the first-order marginal condition for an interior solution is

$$\begin{aligned}&\sum_{t=0}^{T-1}\delta^{t}E\left[\frac{\partial\phi_t}{\partial\phi^{s}}\left\{\left(PY^{0}\left(1-D_t^{0}\right)-C^{0}\right)-\left(PY^{1}\left(1-D_t^{1}\right)-C^{1}\right)\right\}\right]=\\&\sum_{t=0}^{T-1}\delta^{t}E\left[\phi_t PY^{0}\frac{\partial D_t^{0}}{\partial\phi^{s}}+\left(1-\phi_t\right)PY^{1}\frac{\partial D_t^{1}}{\partial\phi^{s}}\right]+\lambda\frac{\partial\Pr\left(R_T\leq\Omega\right)}{\partial\phi^{s}}\end{aligned}\tag{8}$$

Equation (8) states that the optimal safe minimum refuge balances the short-run private costs to producers of decreased agricultural productivity, the left-hand side of the equals sign, against the long-run private, the first term on the right-hand side of the equals sign, and social benefits of reducing the risk of resistance, the second term on the right-hand side of the equals sign.

Solving equation (8) yields the optimal safe minimum standard given the probability of preserving pest susceptibility below the predetermined threshold, $\phi^{s}(\alpha)$. Substituting back into equation (6) and taking the expectation yields the optimal expected value of agricultural productivity given the probability of preserving pest susceptibility, $E(\Pi(\alpha))$. Important economic tradeoffs will exist when $E(\Pi(\alpha))$ is decreasing in $\alpha$. In this region, an increase in agricultural productivity can only be obtained through an increase in the risk of resistance.

## III. Evaluation of Refuge Recommendations

The conceptual model incorporates the production benefits of a GMO into the current analytical framework used to evaluate refuge recommendations. By incorporating these production benefits, the model allows a more balanced evaluation of refuge recommendations based on the tradeoff between the risk of resistance and expected value of agricultural productivity. Unfortunately, the complex interaction between the irreversible evolution of resistance and a regenerative pest population limit insight based solely on the conceptual model. To gain a better understanding of these complex interactions when Bt corn is planted to control the ECB, Hurley et al (1999) develops a simulation model that imposes additional structure on the conceptual model.

We extend the simulation model developed in Hurley et al (1999) to include the spraying of refuge using treatment thresholds. If the pest population exceeds the treatment threshold, a spray application is simulated. Table 1 summarizes important parametric and distributional assumptions for the benchmark model, which are detailed further in Hurley et al. As a brief overview, the model assumes that resistance is characterized by a single gene trait based on the Hardy-Wienberg model (Hartl, 1980) with random mating. For the Hardy-Weinberg model an ECB can be one of three genetic types, a resistant homozygote, a susceptible homozygote, or a heterozygote. Important parameters for the Hardy-Weinberg model include the survival rates of susceptible and resistant homozygotes and heterozygotes on refuge and Bt corn and the initial frequency of resistance. The distribution of unknown survival rates and the initial frequency of resistance is estimated using Bayesian methods and 1997 ECB survival data from the field. Random pest pressure is captured using a density dependent, log normal distribution estimated from bivoltine (two generation) ECB population counts. Finally, we assume the effective proportion of refuge equals the safe minimum refuge, that the planning horizon is 15 years, and that resistance is defined by $R_T > \Omega = 0.5$ so that the evaluation criteria are comparable to other models currently being used to assess refuge recommendations (ILSI Press, 1999).

Figure 1 illustrates the tradeoff between the risk of resistance and expected agricultural productivity and the probability of spray applications for the benchmark model as the proportion of refuge increases from 0 to 100 percent. The risk of resistance, as defined by $\alpha$, rapidly declines as refuge increases from 0 to about 21 percent. The expected value of production, as defined by $E(\Pi(\alpha))$, initially increase as refuge increases up to about 13 percent, but then steadily declines thereafter. These results support two important conclusions. First, there are private long-run productivity benefits to resistance management that producers may fail to internalize due to the common property nature of the mobile ECB. Second, there is a practical limit to increasing refuge in order to reduce the risk of resistance. Increasing refuge above 23 percent has virtually no effect on the risk of resistance, but reduces the expected value of production. Therefore, with the benchmark model, economically justified refuge recommendations lie somewhere between 13 to 21 percent.

It is also interesting to note that the probability of a spray application initially declines, but then increases as refuge increases. When there is little refuge, resistance develops rapidly and average ECB populations are higher requiring more frequent spray applications. Average ECB populations are also higher and applications more frequent when there is a lot of refuge because fewer ECB are exposed to Bt corn. When there is a significant proportion of Bt corn and sufficient refuge to control resistance, the ECB population is suppressed and fewer spray applications are necessary.

Whether the appropriate recommendation is 13 percent, 21 percent, or somewhere in between depends on the willingness to accept a greater risk of resistance in exchange for increased productivity and lower pesticide use. With 100 percent refuge, the expected annualized value of production is $110.80 an acre, while the risk of resistance is 0.0 and the probability of a spray application is 0.15. With 13 percent refuge, the expected value of production is $119.76 an acre, while the risk of resistance is 0.16 and the probability of a spray application is about 0.03. Therefore, Bt corn has the potential to increase the value of production by almost $10 an acre, while decreasing the probability of an annual pesticide application by 80 percent. With 21 percent refuge the risk of resistance is less about 1 percent, while the expected value of production is about $119.49 an acre and the probability of a spray application is 0.04. Therefore, if 21 percent refuge is planted instead of 13 percent, the risk of resistance falls by 94 percent. However, the value of production declines by almost 3 percent, while the probability that an acre of land receives an annual spray treatment increases by about 2.3 percent. In elasticity terms, for an increase in refuge from 13 to 21, a 1.0 percent decrease in the risk of resistance results in a 0.03 percent decrease in productivity (Production Elasticity) and a 0.02 percent increase in percentage of acreage treated annually (Spray Elasticity).

Figure 2 illustrates the sensitivity of these results to the probability of a spray application with 100 percent refuge by proportionally decreasing the treatment thresholds. As the probability of a spray application increases from 0.0 to 1.0, the percentage of refuge required to maintain the risk of resistance below 1.0 percent (Low Risk Refuge) increases from just over 20 percent to just under 40 percent. The proportion of refuge that maximizes the value of production (High Risk Refuge) declines slightly from 13 to 10 percent. In absolute terms, the Production Elasticity increases from 0.03 to 0.36, while the Spray Elasticity increases from 0.02 to 0.28. These results indicate that when spray applications are required more often the cost of reducing the risk of resistance increases in terms of both lost agricultural productivity and increased pesticide use.

## IV. Conclusions

Genetically Modified Organisms (GMOs) such as Bt corn offer producers a new and powerful pest management tool. However, experience has taught us that with any highly selective pest management program, pest resistance can be a problem. In a proactive effort to reduce the risk of resistance to Bt corn, the EPA offered conditional registrations that require industry to develop and implement resistance management plans. The plans that have been developed utilize a high-dose refuge strategy: Bt corn is engineered to express a high enough level of toxin to kill all but the most resistant pests and producers are asked to plant a proportion of their acreage to refuge, so that more susceptible pests survive to mate with resistant pests thereby reducing selection. How much refuge producers should plant is a contentious issue.

Ostlie et al (1997) recommend 20 to 30 percent untreated and 40 percent treated refuge. Figure 2 suggests that a 20 to 30 percent untreated recommendation provides a lower risk of resistance than the 40 percent treated recommendation. However, the increased costs of reducing the risk of resistance with more frequent treatments, provides economic justification for this apparent decrease in the demand for risk reduction. Alternatively, 20 percent refuge with spraying at treatment thresholds was recently proposed by members of industry and the National Corn Growers Association. In our benchmark model, this proposal also provides a low risk of resistance at relatively little cost in terms of lost productivity and increased pesticide use, but only if treatment thresholds result in infrequent spray applications, which is the case across much of the Midwest.

Our model demonstrates the inherent economic tradeoff between the risk of resistance and agricultural productivity and how refuge recommendations can adapt to allow refuge treatments using thresholds. Another important tradeoff demonstrated by our model is between the risk of resistance and pesticide use. GMOs have the potential to reduce the use of more toxic synthetic pesticides. In general, increased agricultural productivity is synonymous with lower pest pressure and lower pest pressure reduces the incentives for producers to apply pesticides. Therefore, increased productivity and decreased pesticide use will tend to be complementary benefits that decrease as refuge is increased to lower the risk of resistance. As the frequency of pesticide applications increase, the cost of reducing the risk of resistance in terms of both agricultural productivity and pesticide use also increases. Therefore in regions, where pesticide treatments are more necessary, a greater risk of resistance is economically justified.

Table 1: Summary of (A) parameter values and (B) distributions.

A

| Parameter Name | Benchmark Value/ Other Values |
|---|---|
| *Biological Parameters* | |
| Generations of Pests Per Cropping Season | 2 |
| Resistant Homozygote Survival Rate | 1.0 |
| Susceptible Homozygote Survival Rate on Refuge | 1.0 |
| Susceptible Homozygote Survival Rate on Bt Corn | 0.0 |
| Heterozygotes Survival Rate on Refuge | 1.0 |
| Spray Application Survival Rate for First Generation | 0.27 |
| Spray Application Survival Rate for Second Generation | 0.33 |
| Initial Pest Population (Pests/Plant) | 0.23 |
| Resistance Threshold ($\Omega$) | 0.50 |
| *Economic Parameters* | |
| Planning Horizon (Years) | 15 |
| Interest Rate | 0.04 |
| Price of Corn ($/Bushel) | $2.35 |
| Pest Free Yield for Bt Corn and Refuge (Bushels/Acre) | 130 |
| Production Cost for Bt Corn and Refuge ($/Acre) | $185.00 |
| Spray Application Cost ($/Acre) | $15.00 |
| Constant Marginal Yield Loss for First Generation (Pests/Plant) | 0.055 |
| Constant Marginal Yield Loss for Second Generation (Pests/Plant) | 0.028 |
| Treatment Threshold for First Generation (Pests/Plant) | 0.89 |
| Treatment Threshold for Second Generation (Pests/Plant) | 1.75 |

B

| Parameter | Mean | Standard Deviation | 95th Percentile | Correlation |
|---|---|---|---|---|
| Initial Frequency of Resistant Alleles | $3.2\times10^{-4}$ | $4.4\times10^{-4}$ | $1.3\times10^{-3}$ | -0.49 |
| Heterozygote Survival on Bt Corn | 0.020 | 0.025 | 0.078 | |
| Annual Pest Population with 100 Percent Refuge and No Spray Applications (Pest/Plant) | 1.10 | 0.50 | 2.01 | |

# References

*An Evaluation of Insect Resistance Management in Bt Field Corn: A Science Based Framework for Risk Assessment and Risk Management* (1999). ILSI Press, Washington D.C.

Andow, D. A. and D. N. Alstad (1998). The $F_2$ Screen for Rare Resistance Alleles. *Journal of Economic Entomology*. 91:572-578.

Calvin, Dennis D. (1996). Economic Benefits of Transgenic Corn Hybrids for European Corn Borer Management in the United States. *Public Interest Document Supporting the Registration and Exemption from the Requirement of a Tolerance for the Plant Pesticide Bacillus thuringiensis subsp kurstaki Insect Control Protein as Expressed in Corn (Zea mays L.)* (Kent A. Croon).

Gould, Fred (1998). Sustainability of Transgenic Insecticidal Cultivars: Integrating Pest Genetics and Econology. *Annual Review of Entomology* 43:701-26.

Hama, Hiroshi, Ken Suzuki, and Hiroshi Tanaka (1992). Inheritance and Stability of Resistance to *Bacillus thuringiensis* Formulations of the Diamondback Moth, Plutella xylostella (Linnaeus) (Lepidoptera: Yponomeutidae). *Applied Entomology and Zoology* 27(3):355-362.

Hartl, Daniel L. (1988). *A Primer of Population Genetics: Second Edition*. Sinauer and Associates, Inc. Sunderland, MA.

Hueth D. and U. Regev (1974). Optimal Agricultural Pest Management with Increasing Pest Resistance. *American Journal of Agricultural Economics* 56 (3, August):543-552.

Hurley, Terrance, Babcock Babcock, and Richard Hellmich (October 1997). Biotechnology and Pest Resistance: An Economic Assessment of Refuges. CARD Working Paper 97-WP 183.

Hurley, Terrance, Silvia Secchi, Bruce Babcock, and Richard Hellmich (1999). Managing the Risk of European Corn Borer Resistance to Transgenic Corn: An Assessment of Refuge Recommendations. CARD Staff Report 99-SR 88.

Lee Peter M. (1997). *Bayesian statistics: An Introduction*. Wiley, New York.

Martinez-Ramirez, Amparo C., Baltasar Escriche, M. Dolores Real, Francisco J. Silva, and Juan Ferre (1995). Inheritance of Resistant *Bacillus thuringiensis* Toxin in a Field Population of Diamondback Moth (Plutella xylostella). *Pesticide Science* 43:115-120.

Mason, Charles E., Marlin E. Rice, Dennis D. Calvin, John W. Van Duyn, William B. Showers, William D. Hutchison, John F. Witkowski, Randall A. Higgins, David W. Onstad, and Galen P. Dively (1996). *European Corn Borer Ecology and Management*. North Central Regional Extension. Publication No. 327. Iowa State University, Ames IA.

Onstad, David W. and Fred Gould (1998a). Do Dynamics of Crop Maturation and Herbivorous Insect Life Cycle Influence the Risk of Adaptation to Toxins in Transgenic Host Plants? *Environmental Entomology* 27: 515-522.

Onstad, David W. and Fred Gould (1998b). Modeling the Dynamics of Adaptation to Transgenic Maize by European Corn Borer (Lepidoptera: Pyralidae). *Journal of Economic Entomology* 91:585-593.

Ostlie, K. R., W. D. Hutchison, and R. L. Hellmich (1997). Bt Corn and the European Corn Borer. NCR publication 602. University of Minnesota, St. Paul, MN.

Peferoen M. (1997). Insect Control with Transgenic Plants Expressing Bt Crystal Proteins. *Advances in Insect Control: The Role of Transgenics* (eds. Carozzi and Koziel). Taylor & Francis, Bristol PA. p. 35.

Regev, Uri, Andrew P. Gutierrez, and Gershon Feder (1976). Pests as a Common Property Resource: A Case Study of Alfalfa Weevil Control. *American Journal of Agricultural Economics* May:186-197.

Regev, Uri, Haim Shalit, and A. P. Gutierrez (1983). On the Optimal Allocation of Pesticides with Increasing Resistance: The Case of the Alfalfa Weevil. *Journal of Environmental Economics and Management* 10:86-100.

Royama T. (1992). *Analytical Population Dynamics*, Chapman & Hall, London.

Roush, Rick and Glen Osmond (1996). Managing Resistance to Transgenic Crops. *Advances in Insect Control: The Role of Transgenic Plants* N. Carozzi and M. Koziel, eds.). Taylor and Francis, London. pp. 271-294.

*Scientific Justification for 10/20 Refuge Plan for Single-Gene, High Dose Bt Corn Events, Region: Central and Western U.S., Key pest target: European Corn Borer, Other primary pests: Southwestern corn borer (Kansas, Texas panhandle)* (1998). Communication from Monsanto Company, St. Louis MO.

Tabashnik, Bruce E., James M Scwartz, Naomi Finson, and Marshall W. Johnson (1992). Inheritance of Resistance to *Bacillus thuringiensis* in Diamondback Moth (Lepidoptera: Plutellidae). *Journal of Economic Entomology* 85(4):1046-1055.

Tabashnik, Bruce E., James M Scwartz, Naomi Finson, Marshall W. Johnson, and David G. Heckel (1995). Prolonged Selection Affects Stability to *Bacillus thuringiensis* in Diamondback Moth (Lepidoptera: Plutellidae). *Journal of Economic Entomology* 88(2, April):219-224.

Figure 1. Tradeoff between the risk of resistance and the expected annualized value of production in the benchmark model with spray applications using treatment thresholds.

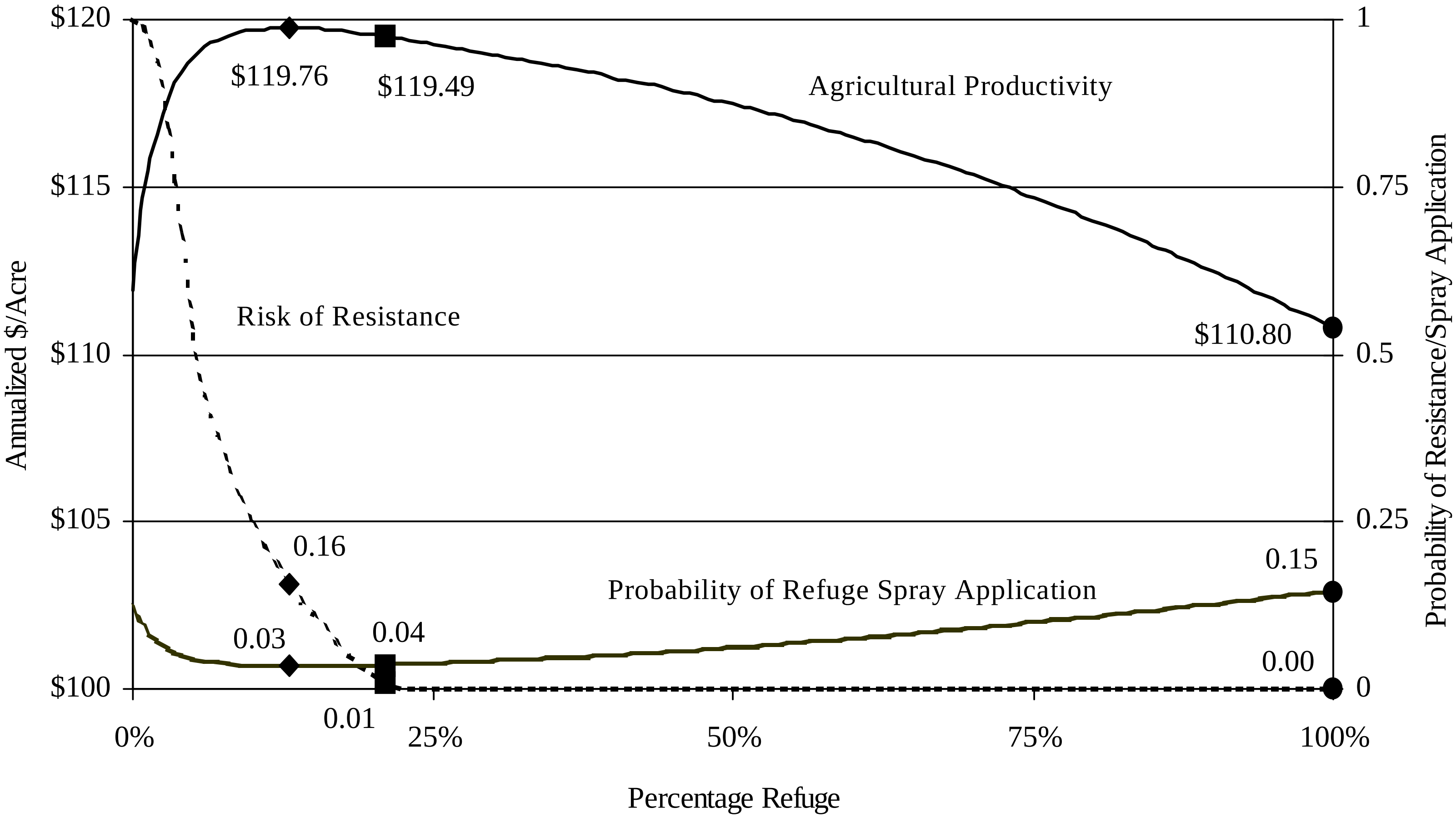

Figure 2. Sensitivity analysis for spray application thresholds.