2002

Managing the Risk of European Com Borer Resistance to Bt Corn

Terrance M. Hurley
University of Minnesota - Twin Cities

Silvia Secchi
Iowa State University

Bruce A. Babcock
Iowa State University, babcock@iastate.edu

Richard L. Hellmich
Iowa State University, richard.hellmich@ars.usda.gov

Managing the Risk of European Com Borer Resistance to Bt Corn

Abstract
New pesticidal crops are taking advantage of advances in geneticengineering. For example, corn has been engineered to express Bt proteinsthat are toxic to the European corn borer. These crops are effective pestmanagement tools for United States growers. However, there is concern thatpests will develop resistance to these crops resulting in the increased useof more hazardous pesticides. The purpose of this paper is to develop astochastic dynamic bioeconomic simulation model to help guide regulatorypolicy designed to mitigate the threat of resistance to new pesticidal crops.The model is used to evaluate the insect resistance management guidelinesmandated by the United States Environmental Protection Agency for theuse of Bt corn in the Midwestern United States.

Keywords
European com borer, resistance management, risk management

Disciplines
Agricultural Economics | Entomology | Plant Breeding and Genetics

Comments
This article is from *Environmental and Resource Economics*; 22 (2002); 537-558; doi: 10.1023/A:1019858732103

Environmental and Resource Economics **22:** 537–558, 2002.

Managing the Risk of European Corn Borer Resistance to Bt Corn

TERRANCE M. HURLEY[1], SILVIA SECCHI[2], BRUCE A. BABCOCK[2] and RICHARD L. HELLMICH[2]
[1]*Department of Applied Economics, 1994 Buford Avenue, University of Minnesota, St. Paul, MN 55108-6040, USA (email: thurley@dept.agecon.umn.edu);* [2]*Iowa State University*

Accepted 6 February 2002

Abstract. New pesticidal crops are taking advantage of advances in genetic engineering. For example, corn has been engineered to express Bt proteins that are toxic to the European corn borer. These crops are effective pest management tools for United States growers. However, there is concern that pests will develop resistance to these crops resulting in the increased use of more hazardous pesticides. The purpose of this paper is to develop a stochastic dynamic bioeconomic simulation model to help guide regulatory policy designed to mitigate the threat of resistance to new pesticidal crops. The model is used to evaluate the insect resistance management guidelines mandated by the United States Environmental Protection Agency for the use of Bt corn in the Midwestern United States.

Key words: European corn borer, resistance management, risk management

JEL classification: Q18, Q28, Q38

I. Introduction

Advances in genetic engineering allow genes to be transferred between species. Application of this technology to agriculture include the insertion to a gene from the soil bacterium *Bacillus thuringiensis* (Bt) into corn and other crops. Corn with the Bt gene produces proteins that are toxic when consumed by the European corn borer (ECB) and other lepidopteran insects. Since commercial introduction in 1996, Bt corn has proven to be an effective tool for managing ECB.

The high efficacy of Bt corn has resulted in rapid adoption. In 2000, an estimated 20 percent of United States (US) corn acreage was planted with Bt Corn. Bt corn's high efficacy and rapid adoption raise concerns that ECB will develop resistance. The potential for insect resistance to effective and widely used pesticides is well documented, including resistance to Bt (Bauer 1995; Liu and Tabashnik 1997; McGaughey and Beeman 1998; Perez and Shelton 1997; Tabashnik 1994). Concerns of resistance are heightened because Bt occurs naturally and is believed to pose fewer environmental and human health risks than other pesticides. If resistance diminishes the efficacy of Bt corn, farmers may use more hazardous alternatives.

The US Environmental Protection Agency (EPA) regulates the introduction, use, and registration of plant incorporated protectants – pesticides produced by a plant due to the introduction of new genetic material. Therefore, the EPA is partially responsible for regulating Bt corn. Through this authority and acting in the public's interest, the EPA has worked with industry and academic scientists to develop insect resistance management (IRM) guidelines for Bt corn. The objective of these guidelines is to preserve the efficacy of Bt and reduce the use of more hazardous pesticides, while not overly burdening the regulated community (U.S. EPA 1998a).

The existing economic literature provides rationale for the EPA's promotion of IRM. Since pests damage crops and propagate, the literature argues they are an unwanted renewable resource (Hueth and Regev 1974; Regev et al. 1976; Regev et al. 1983). Pest susceptibility, the converse of resistance, is a valuable nonrenewable resource since susceptible pests can be controlled (Hueth and Regev 1974; Regev et al. 1983). Capturing this value results in resistance and a pest that is harder to control. A mobile pest can be viewed as common property (Clark and Carlson 1990); therefore, farmers have little incentive to voluntary manage resistance.

IRM guidelines for Bt corn are currently based on a high-dose structured refuge strategy. The foundations of this strategy require Bt corn to produce enough toxins to kill all but the most resistant ECB and growers to plant refuge corn in close proximity to Bt corn. Refuge allows susceptible ECB to survive, so they can mate with resistant ECB emerging from Bt corn. If refuge corn is in close proximity to Bt corn, this mating should be random. If there is a high enough dose, sufficient refuge, and random mating, most surviving ECB will be susceptible and so will most offspring.

The EPA did not originally impose mandatory refuge requirements for Bt field corn. However, mandatory requirements were introduced for the 2000-growing season. In the predominant corn growing regions of the US, these requirements obligate Bt corn registrants to ensure farmers plant at least 20 percent refuge with their Bt corn.[1] Treatment with conventional pesticides based on economic thresholds is permitted for controlling ECB on refuge in years of severe infestation.

The mandatory guidelines for the 2000-growing season represent a departure from previous recommendations. Previous recommendations required more refuge when treated with other pesticides because treated refuge produces fewer susceptible ECB and increases the risk of resistance (Ostlie et al. 1997; Mellon and Rissler 1998; U.S. EPA 1998b; ILSI/HESI 1999). Several arguments provide rationale for not differentiating treated and untreated refuge. At planting, farmers do not know whether other pesticide treatments will be economical. In most regions of the US, other pesticide treatments for ECB are uncommon. If refuge is rarely treated, the increased risk of resistance is likely to be small. Therefore, not differentiating treated and untreated refuge benefits farmers by providing greater flexibility without substantially increasing the risk of resistance. However, where other pesticide treatments are common, there is a concern that 20 percent refuge is not enough.

The purpose of this paper is to develop a stochastic dynamic bioeconomic simulation model to compare alternative high-dose refuge strategies based on ECB resistance to Bt corn, conventional pesticide use, and the value of agricultural production to farmers and industry. The model that is developed captures seasonal variation in ECB populations using a density dependent stochastic population model. In addition, field level monitoring data is used to address uncertainty regarding important biological parameters. The model is then used to evaluate the arguments for allowing refuge treatments based on economic thresholds.

The results of the analysis support arguments for allowing treated refuge in regions with a low historic frequency of conventional pesticide use. Allowing growers to treat refuge in these regions can increase the value of production with a negligible increase or even a decrease in the risk of resistance. However, conventional pesticide use will be higher. Whether the 20 percent refuge requirement is enough with treated refuge in regions with a high historical frequency of conventional pesticide use depends on the primary objectives of IRM policy. If the primary objective is to reduce conventional pesticide use or increase agricultural production, then higher refuge requirements are not warranted. However, if reducing the risk of resistance is of primary concern, then more refuge is warranted. Finally, we find that increased agricultural production and reduced conventional pesticide use are usually complementary benefits. Therefore, refuge requirements that result in greater agricultural productivity tend to also reduce conventional pesticide use. Refuge requirements resulting in a lower risk of resistance tend to increase conventional pesticide use and decrease agricultural productivity.

II. The Model

Two approaches to modeling resistance management are found in the literature. In the economics literature, Hueth and Regev (1974), Taylor and Headley (1975), Regev et al. (1983), and Gorddard et al. (1995) develop dynamic models to evaluate the optimal use conventional pesticides with increasing resistance. These models are deterministic and account for important biological factors with varying degrees of detail. The objective of the analysis is to characterize the time path for pesticide use that maximizes the value of agricultural production. While these models do not explicitly address the high-dose structured refuge strategy, they do offer insight into how managing resistance can enhance the value of production in the long run. They also show that the optimal amount of pesticide varies as resistance emerges.

Alstad and Andow (1995), Roush (1996), Ellner (1998, 2001), Gould (1998), Onstad and Gould (1998a, b), and Peck, Gould, and Ellner (1999) provide a sample of the second type of models found in the entomology literature. These biological simulation models vary in spatial and temporal detail. Some models use a single habitat, others a network of habitat patches. Some models use a daily time step, others a generational time step. Most are deterministic, but some have stochastic elements. All are designed to evaluate the potential and limitations of a high-dose refuge strategy and focus on describing how fast resistance evolves. The models have identified key biological factors that influence the evolution of resistance.

The model we develop extends Hurley et al. (1997), which is founded more in the tradition of the entomology literature and less in the tradition of the economic literature. The purpose of the model is to broaden the set of objectives used to evaluate how much refuge should be planted to include the risk of resistance, value of agricultural production, and conventional pesticide use. We assume that refuge is structured so that pest mating is random and dispersal is uniform. This assumption matches the aims of current EPA policy and it is commonly used in the entomology literature (for example, Onstad and Gould (1998b), and Roush). Though, it has not been rigorously tested. We also assume Bt corn produces a high dose throughout the growing season. With these assumptions it is reasonable to limit the scope of the model to a single habitat with a generational time step. In addition, the model includes a density dependent random pest population, parametric uncertainty, and conventional pesticide applications based on economic thresholds, which allow the evaluation of arguments for treated refuge.

Consier a simplified production region with a single crop and pest. The region is divided between two varieties. The first, denoted by $i = 0$, is conventional and serves as refuge. The second, denoted by $i = 1$, is a Bt variety that is toxic when consumed by susceptible pests. Let $1.0 \geq \phi \geq 0.0$ be the proportion of refuge acreage planted in each season. This value is held constant from one season to the next to facilitate exposition and comparisons with previous recommendations. However, the model can be generalized to specify the proportion of refuge as both time and state dependent. The pest reproduces with G generations per season where g denotes the generation in season t. Let $1.0 \geq t^i_{tg} \geq 0.0$ be the proportion of crop i that receives a conventional pesticide application in season t and generation g. The model allows for conventional pesticide treatments on Bt acreage and refuge acreage because if Bt fails due to resistance, farmers may turn to conventional pesticides for supplemental control.

The number of pests emerging to damage crops and reproduce is $n_{tg} \geq 0.0$. Pest populations are variable over time due to random environmental events such as storms, though not independent from the past due to reproduction. To capture this random interdependence,

$$n_{tg} \sim \begin{cases} N_g(n^S_{tg-1}), & \text{for } g > 1 \\ N_g(n^S_{t-1G}), & \text{for } g = 1 \end{cases} \tag{1}$$

where n^S_{tg} is the number of pests that escape control and survive to damage crops and reproduce and $N_g(\cdot)$ is a conditional distribution function. Equation (1) states that the pest population is a random variable that is conditionally distributed based on the number of surviving pests in the previous generation.

The Hardy-Weinberg model characterizes resistance, which is assumed to be conferred by a single allele that is not sex linked.[2] There are two types of alleles: resistant and susceptible. The proportion of resistant alleles is $1.0 \geq r_{tg} \geq 0$. Each pest has two alleles, one contributed by its mother and one by its father, and can be one of three genotypes: a resistant homozygote – with two resistant alleles; a heterozygote – with one resistant allele; or a susceptible homozygote – with no resistant alleles. The Hardy-Weinberg model implies the proportion of each genotype is

$$\eta_{tg} = [r_{tg}^2, 2r_{tg}(1 - r_{tg}), (1 - r_{tg})^2] \tag{2}$$

where the vector elements correspond to resistant homozygotes, heterozygotes, and susceptible homozygotes.

The Hardy-Weinberg model assumes no selection pressure – survival rates are the same for all genotypes. Bt crops impose selection pressure on pests with at least one susceptible allele. Let σ_g^i be a 1×3 vector of genotypic survival rates for pests on crop i in generation g with elements corresponding to resistant homozygotes, heterozygotes, and susceptible homozygotes. The survival rate of all genotypes treated with a conventional spray application is σ_g^ι. The vector of genotypic survival rates for each crop, season, and generation is $\rho_{tg}^i = \sigma_g^i + \iota_{tg}^i(\sigma_g^i \sigma_g^\iota - \sigma_g^i)$, which implies the number of pests surviving to damage crop i and reproduce is $n_{tg}^{S\,i} = \rho_{tg}^i \cdot \eta_{tg}^i n_{tg}$. The vector of genotypic survival rates for the region is $\rho_{tg} = \rho_{tg}^1 + \phi_t(\rho_{tg}^0 - \rho_{tg}^1)$, which implies the number of pests surviving to reproduce is $n_{tg}^S = \rho_{tg} \cdot \eta_{tg} n_{tg}$. Since each surviving pest contributes two alleles, resistant homozygotes contribute two resistant alleles, heterozygotes contribute one resistant allele, and susceptible homozygotes contribute no resistant alleles, the proportion of resistant alleles in the subsequent genreation is

$$r_{tg} = \begin{cases} \dfrac{\rho_{tg-1} M \eta_{tg-1}}{\rho_{tg-1} \cdot \eta_{tg-1}}, & \text{for } g > 1 \\ \dfrac{\rho_{t-1G} M \eta_{t-1G}}{\rho_{t-1G} \cdot \eta_{t-1G}}, & \text{for } g = 1 \end{cases} \tag{3}$$

where M is the 3×3 diagonal matrix [1.0, 0.5, 0.0].

Equations (1)–(3) and the initial conditions $n_{01} = N_0$ and $r_{01} = R_0$ describe a dynamic stochastic system, which is controlled by the proportion of refuge and conventional pesticide use. To evaluate and compare the perforance of this system under alternative control strategies, we focus on measures of the risk of resistance, conventional pesticide use, and the value of production over a fixed time period. The probability that the proportion of resistant alleles exceeds 0.5 within T years measures the risk of resistance:

$$\Theta = \Pr(r_{1T} \geq 0.5) \tag{4}$$

where the probability is defined over the random distribution of pests for $t = 0, \ldots, T$ and $g = 1, \ldots, G$. The expected number of conventional pesticide applications per acre measures pesticide use:

$$\Gamma = E_n \left[\sum_{t=0}^{T-1} \sum_{g=1}^{G} \frac{\phi_t \iota_{tg}^0 + (1 - \phi_t)\iota_{tg}^1}{T} \right] \tag{5}$$

where E_n is the expectation operator defined over the random distribution of pests for $t = 0, \ldots, T$ and $g, \ldots, G$. The expected annualized net present value of production to farmers and industry measures the value of production:

$$\Pi = E_n \left[\frac{\sum_{t=0}^{T-1} \delta^t \pi_t}{\sum_{t=0}^{T-1} \delta^t} \right] \tag{6}$$

where π_t is the annual value of production to farmers and industry in season t, $\delta = 1/(1 + r)$ is the rate at which the future production is discounted, and r is the real rate of interest. The annual value of production to farmers and industry is

$$\begin{aligned} \pi_t = {} & \phi \left\{ P_t^0 Y_t^0 \left[1 - D(n_{t1}^{S^0}, \ldots n_{tG}^{S^0}) - FC_t^0 - \sum_{g=1}^{G} \iota_{tg}^0 VC_{tg}^0 \right] \right\} + \\ & (1 - \phi) \left\{ P_t^1 Y_t^1 \left[1 - D(n_{t1}^{S^1}, \ldots, n_{tG}^{S^1}) - FC_t^1 - \sum_{g=1}^{G} \iota_{tg}^1 VC_{tg}^1 \right] \right\} \end{aligned} \tag{7}$$

where Y_t^i bushels/acre and P_t^i \$/bushel are the pest free yield and crop price, FC_t^i \$/acre is the production cost for items such as seed (excluding industry rents from the sale of Bt seed corn), fertilizer, and labor that are exclusive of the cost of a conventional pesticide application; VC_{tg}^i \$/acre is the cost of a conventional pesticide application; and $D_t^i(n_{t1}^{S\,i}, \ldots, n_{tG}^{S\,i})$ is the proportion of pest free yield lost to pests throughout the season. Equation (7) represents the average net return to farmers plus the proportion of the technology fee collected by industry that represents rents paid by farmers to industry for the right to plant the Bt variety.

Equations (4)–(6) are conditional on the values assigned to the number of generations of pest per season, genotypic survival rates, survival rates for conventional spray applications, number of time periods, prices, pest free yields, production costs, discount rate, initial pest population, and initial proportion of resistance. While reasonable values are readily available for many of these parameters, others are uncertain. The typical method for addressing this uncertainty is to test the sensitivity of the results to reasonable variations in parameter values. However, if suitable data is available, this uncertainty can be captured explicitly using the estimated distributions for the parameters, such that equations (4)–(6) can be rewritten as

$$\Theta = E[\Pr(r_{1T} \geq 0.5)], \tag{4'}$$

$$\Gamma = E\left[E_n\left[\sum_{t=0}^{T-1}\sum_{g=1}^{G}\frac{\phi_t\iota_{tg}^0 + (1-\phi_t)\iota_{tg}^1}{T}\right]\right], and \tag{5'}$$

$$\Pi = E\left[E_n\left[\frac{\sum_{t=0}^{T-1}\delta^t\pi_t}{\sum_{t=0}^{T-1}\delta^t}\right]\right] \tag{6'}$$

where $E[\cdot]$ is the expectation operator defined over the estimated distribution of uncertain parameters. Combined with equations (1)–(3) and (7), equations (4′)–(6′) allow for the comparison of alternative refuge requirements based on the tradeoffs between measures of the expected risk of resistance, pesticide use, and value of production.

III. Model Implementation

Implementing the model described in equations (1)–(3), (7), and (4′)–(6′) requires estimates of the conditional distribution of ECB; values or distributions for the exogenous parameters; the proportion of refuge; and ι_{tg}^i $\forall\, i \in [1, 2], t \in [1, \ldots, T]$, and $g \in [1, \ldots, G]$. We focus on distributions and parameter values that are characteristic of the Midwestern US when Bt corn is planted to control the ECB.

DISTRIBUTION OF ECB

ECB populations in the Midwestern US are typically bivoltine (two generations per season). Capturing the variability in these bivoltine populations and intergenerational dependencies requires longitudinal data for both first and second generation ECB under conditions without control. Recent surveys of ECB pressure focus on quantifying ECB tunneling and moth flights. Tunneling data does not allow for generational distinctions and moth flight data is difficult to calibrate to the field level. An older survey conducted between 1960 and 1969 measured first and second generation larval populations (ECB/plant) at six sites across the Midwest (see Calvin 1996). Since Mitchell et al. (2000) suggests that state average second-generation ECB populations for Illinois, Minnesota, and Wisconsin were stabile between 1960 and 1990, we use the 1960s survey to estimate the conditional distributions.

Assuming ECB populations are log-normally distributed with parameters μ_g and σ_g, the Midwestern data were pooled and maximum likelihood techniques used for estimation.[3] To capture intergeneration dependencies, we assume $\mu_1 = \beta_{01} + \beta_{11}n^S_{t-1\,2} + \beta_{21}{n^S_{t-1\,2}}^2$, $\mu_2 = \beta_{02} + \beta_{12}n^S_{t1} + \beta_{22}{n^S_{t1}}^2$ and $\sigma_g = \beta_{4g}$ for $g = 1, 2$. This specification allows the mean and variance to vary based on pests surviving in the previous generation, while the coefficient of variation remains constant. When the coefficient estimates are positive for the linear terms and negative for quadratic terms, the form of μ_g implies that factors such as food scarcity naturally limit ECB populations.

Table I reports the maximum likelihood coefficient estimates, the maximized value of the log-likelihood function, and the test for restriction $\beta_{11} = \beta_{21} = \beta_{12} = \beta_{22} = 0$ which is indicative of intergeneration independence. The log-likelihood ratio test is statistically significant, which suggests intergeneration dependencies are important. As anticipated, the linear terms are positive and quadratic terms are negative. We initialize the model with the average number of first generation of ECB per plant, 0.12.

PEST SURVIVAL RATES ON BT CORN AND RESISTANCE

Genotypic survival rates on Bt corn relative to refuge are uncertain due to the lack of a confirmed case of ECB resistance. Though, Venette et al. (2000) demonstrate how field level monitoring data provides useful information on survival rates. Their method uses information on larvae, L, found in a sample of size N from untreated refuge and larvae, S, found in a sample of size M from an adjacent Bt field to calculate the mean and variance of the survival rate for ECB on Bt corn relative to refuge. While the method they propose focuses on sampling ears of sweet corn, it is more generally applicable to any consistent sampling protocol applied to adjacent fields of refuge and Bt corn.

We extend the method proposed by Venette, Hutchison, and Andow to integrate sampling from different sites assuming the sites have the same survival rates and frequency of resistance. Let P be the survival rate of ECB on Bt corn relative to refuge in the season and generation sampled. If the samples are taken in season t and generation g, $P = \rho^1_{tg} \cdot \eta_{tg} / \rho^0_{tg} \cdot \eta_{tg}$ for $\iota^0_{tg} = \iota^1_{tg} = 0$. Suppose K sites are sampled such that L_k, S_k, N_k and M_k for $k = 1, \ldots, K$ are the number of larvae found in the samples and the number of samples drawn from adjacent refuge and Bt fields at site k. Assuming that the refuge and Bt samples represent independent draws from Poisson distributions with mean $z_k > 0.0$ and $Pz_k > 0.0$, Bayes rule implies

$$\Pr(P, z|L, S, N, M) \propto \Pr(P, z) \prod_{k=1}^{K} \frac{e^{-N_k z_k}(N_k z_k)^{L_k}}{L_k!} \frac{e^{-M_k P z_k}(M_k P z_k)^{S_k}}{S_k!} \tag{8}$$

where z, L, S, N and M are vectors containing the elements of z_k, L_k, S_k, N_k, and M_k for $k = 1, \ldots, K$ and $\Pr(P, z)$ represents prior beliefs about the distribution of

Table I. Parameter estimates for ECB population models.

Coefficient	Model 1	Model 2
First generation		
Constant	-3.52^a	-2.50^a
	(0.31)	(0.19)
Previous surviving population	1.81^b	
	(0.72)	
Previous surviving population^2	−0.39	
	(0.27)	
Standard deviation	0.96^a	1.17^a
	(0.14)	(0.20)
Second generation		
Constant	-1.59^a	-0.66^a
	(0.30)	(0.21)
Previous surviving population	9.47^b	
	(4.481)	
Previous surviving population^3	−11.31	
	(10.9)	
Standard deviation	11.1^a	1.28^a
	(0.13)	(0.13)
Maximized log-likelihood	5.99	−10.01
$\chi^2(4)$	32.00^a	
Observations	92	92

Notes: Standard errors are in parentheses, [a]denotes a one-percent level of significance, [b]denotes a five-percent level of significance, and [c]denotes a ten-percent level of significance.

P and z. Let $\Pr(P, z) = \Pr(P)\Pi_{k=1}^{K} Pr(z_k)$ and $\Pr(z_k)$ be an improper prior for $k = 1, \ldots, K$. After intergrating over z_k for $k = 1, \ldots, K$, equation (9) can be rewritten as

$$\Pr(P|L, S, N, M) \propto \Pr(P) \prod_{k=1}^{K} \frac{P^{S_k}}{(N_k + M_k P)^{L_k+S_k+1}}. \quad (9)$$

Equation (9) is an improper distribution for the relative survival of ECB on Bt corn and provides information on the distribution of σ_g^0, σ_g^1, and r_{tg}. To use this distribution, priors for σ_g^0, σ_g^1, and r_{tg} and sampling data for L, S, N, and M are needed. Following the analysis reported in ILSI/HESI (1999), we assume $\Pr(\sigma_1^0 = \sigma_2^0 = [1.0, 1.0, 1.0], \sigma_1^1 = \sigma_2^1 = [1.0, \sigma_{RS}, 0.0], r_{tg} = R_0) = \Pr(R_0, \sigma_{RS})$. These assumptions imply that all ECB have normal survival rates on refuge, resistant homozygotes have normal survival rates on Bt corn, and susceptible homozygotes do not survive on Bt corn. It also implies that the heterozygote survival rate on Bt corn is uncertain, as is the frequency of resistant alleles. As with Hurley et al. (1999), we choose $\Pr(R_0, \sigma_{RS})$ to be uniformly distributed such that $\Pr(R_0 < 4.38 \times 10^{-3}) = 0.95$ and $0.1 \geq 0.0$.

Sampling data is taken from two sources. Monsanto Company provided data collected by university and industry collaborators from 8 Midwestern states and 104 different sampling sites. Drs. Robert Venette and William Hutchison from the University of Minnesota provided data collected from 4 sites in Minnesota. The data that are used were collected in 1997. While 1998 and 1999 data are available, aggregation across sites is hard to justify because increased resistance may have already developed in regions with higher Bt corn adoption rates. Since 1997 represents the first year that Bt corn was extensively planted, most samples of second-generation larve could have been exposed to the selection pressures of Bt for less than one generation prior to sampling.

A total of 8,814 larvae were found in 6,670 samples taken from refuge fields. A total of 36 larvae were found in 8,640 samples taken from Bt fields. Assuming that all larvae that were found in Bt fields possessed a resistant allele, the estimated average frequency of resistant alleles from equation (9) is 4.4×10^{-3}. This estimates is fourfold higher than estimates for the tobacco budworm reported in Gould et al. (1997) and exceeds the 95 percent confidence interval estimated for Midwestern ECB using the F_2 screen developed by Andow and Alstad (1998).[4] Alternatively, if we assume none of the 36 larvae possessed a resistant allele because resistance was not confirmed and there are other reasonable explanations for their presence on Bt corn, the estimated frequency of resistant alleles from equation (9) is 1.1×10^{-3}. The 95th percentile for this estimate is 3.6×10^{-3}.

The relatively small decline in the estimate of the frequency of resistant alleles when we go from assuming 36 to 0 survivors on Bt corn is at first puzzling. The reason is our choice of priors and the relatively small sample of insects taken from Bt corn. With a large enough sample, priors have a negligible impact on the estimated distribution. Even though 8,640 samples were taken from Bt corn, this sample is still relatively small given the low expected frequency of resistance. Therefore, the prior is likely to be more influential. The prior we use captures the belief that there are resistant insects. But, observing 36 larvae on Bt corn in a sample of 8,640 is substantially higher than anticipated. Therefore, the weight of the prior reduces the estimate of the resistant allele frequency. Alternatively observing 0 larvae supports the conclusion that there are no resistant alleles, which is lower than anticipated. In this instance, the weight of the prior increases the estimate.

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

A

Parameter	Benchmark value/ other values
Biological parameters	
Generations of pests per cropping season	2
Survival rate of ECB on refuge corn for all genotypes	1.0
Survival rate of ECB on Bt corn for resistant homozygote	1.0
Survival rate of ECB on Bt corn for susceptible homozygote	0.0
Survival rate for conventional pesticide applications 1st generation	0.20
Survival rate for conventional pesticide application 2nd generation	0.33
Initial pest population (pests/plant)	0.12
Economic parameters	
Planning horizon (years)	15
Interest rate	0.04
Price of corn per bushel	$2.35
Pest free yield for Bt corn and refuge (bushels/acre)	130
Production cost for Bt and refuge corn ($/acre)	$185.00
Constant marginal yield loss for first generation (pests/plant)	0.055
Constant marginal yield loss for second generation (pests/plant)	0.028

B

Parameter	Mean	Standard deviation	95th percentile	Correlation
Initial Frequency of Resistant Alleles	1.1×10^{-3}	1.1×10^{-3}	3.6×10^{-3}	−0.49
Heterozygote Survival on Bt Corn	0.027	0.026	0.083	

Since the later estimate is more consistent with Gould et al. (1997) and other recent estimates, we assume none of the 36 larvae found on Bt corn were resistant. Table II summaries the distribution of the initial frequency of resistance and heterozygote survival rate used in the analysis.

COSTS, REVENUES, AND PEST DAMAGE

Point estimates were used for information on costs, revenues, and pest damages because reasonable estimates are readily available. A summary of the benchmark assumptions is reported in Table II. US Department of Agriculture National Agricultural Statistics Service (NASS) and Economic Research Service (ERS) data provide reasonable estimates for the real price, pest free yield, and production cost of refuge corn, which are held constant over time. The real price of corn, \$2.35, is the monthly average from 1991 to 1996 deflated to 1992.[5] The average Iowa yield from 1991 to 1996 was about 123 bushels per acre. Assuming an average annual ECB yield loss of 6.4 percent (Calvin 1996) implies a pest free yield of 130 bushels per acre. Excluding returns to management, the average production cost, \$185, comes from 1995 ERS corn budgets deflated to 1992 prices and is assumed to include scouting costs. The cost of a conventional pesticide treatment, \$14 an acre, is taken from Mason et al. (1996).

The pest-free yield for Bt corn is assumed to be the same as refuge for the benchmark simulation because we have no evidence to suggest that Bt yields are lower in the absence of ECB. Most of the increased cost of Bt seed is sunken research and development. While farmers may pay a technology fee, only part of this fee reflects an increase an marginal cost of growing Bt corn. The remainder represents rents paid to industry by farmers in order to use Bt corn. The percentage of the technology fee that represents an increase in the marginal production cost is proprietary information, but likely to be small because no special handling is required once the Bt gene has been introduced into the plant. Therefore, we presume the entire technology fee represents industry rents and that any difference in the marginal cost is negligible.

Damage estimates for the ECB vary depending on a variety of environmental and management factors. For instance, damages will be higher when corn is stressed and in early or late-planted corn. Depending on a plant's stage of development, estimates indicate a marginal yield loss ranging from 2 to 6 percent pests/plant (Mason et al. 1996). Since our interest is in evaluating the average season damage of the ECB over a production region, we assume $D_t^i(n_{t1}^{S\,i}, n_{t2}^{S\,i}) = \text{Min}\{d_1 n_{t1}^{S\,i} + d_2 n_{t2}^{S\,i}, 1.0\}$ where $d_1 = 0.055$ and $d_2 = 0.028$ based on Mason et al.

A time frame of reference and discount rate are also needed in order to compare alternative IRM requirements. The time frame used for the analysis is 15 years, which is based on recommendations made by the scientific advisory panel convened by the EPA in 1998 (US EPA 1998b) and the value used in ILSI-HESI. A real interest rate of four percent is used for discounting the value of production.

SPRAY APPLICATIONS

Originally, separate refuge recommendations were based on whether refuge was treated with conventional pesticides. Recently, the EPA mandated a single recommendation that allows treated refuge using economic thresholds. The method for calculating the economic thresholds is not specified. To incorporate economic thresholds into the model, we use the methodology offered by Mason et al. (1996), which implies $\iota_{tg}^i = \begin{cases} 1.0, & \text{for } n_{tg} > \frac{VC_{tg}^i}{P_t^i Y_t^i d_g \sigma_g^i \eta_{tg}(1-\sigma_g^i)} \\ 0.0, & \text{for } n_{tg} \leq \frac{VC_{tg}^i}{P_i^i Y_t^i d_g \sigma_g^i \eta_{tg}(1-\sigma_g^i)} \end{cases}$. The method is based on a cost benefit analysis that compares the value of improved ECB control to the cost of the pesticide treatment. The calculation does not factor in risk or population dynamics. However, the calculation is practical and a common starting point for many farmers. Typical ECB survival rates for conventional pesticide applications are 0.20 for the first generation and 0.33 for the second generation (Mason et al. 1996).

IV. Results

The economic and environmental tradeoffs of increasing refuge to reduce the risk of resistance are evaluated by comparing the risk of resistance, pesticide use, and the value of production as refuge increases from 0 to 100 percent. To calculate these tradeoffs, Monte Carlo integration is used to evaluate equations (4′)–(6′) for the benchmark parameters assumptions. First, we characterize the economic and environmental tradeoffs when refuge treatments are made using economic thresholds. We then compare treated versus untreated refuge. Finally, we explore the sensitivity of the results for treated refuge to factors that increase the frequency of conventional pesticide applications.

TRADEOFFS FOR TREATED REFUGE

Figure 1 presents the benchmark simulation results. The value of production increases from $112.57 to $119.43 as refuge increases from 0 to 19 percent and then falls to $110.76 as refuge increases to 100 percent. Conventional pesticide use falls from 0.082 to 0.0047 applications per acre as refuge increases from 0 to 22 percent, but then increases to 0.10 applications per acre as refuge increases to 100 percent. As refuge increases from 0 to almost 40 percent, the risk of resistance falls from 1.0 to 0.0.

These results illustrate how managing resistance can increase production and reduce conventional pesticide use in the long run. With the full adoption of Bt corn and no refuge, the value of production increases by 1.6 percent, while conventional pesticide use declines by 20 percent. However, with 19 percent refuge, the value of production increases by 7.8 percent, while conventional pesticide use falls by 90 percent. Therefore, over 15 years, there is only a modest increase in the value of production and decrease in conventional pesticide use when no refuge is planted. When no refuge is planted, both farmers and the environment lose substantial benefits from Bt corn in the long run due the rapid evolution of resistance. By planting refuge, the evolution of resistance is slower, which extends the efficacy of Bt corn and provides better ECB control in the long run with fewer conventional pesticides.

The results also suggest that the long run cost of obtaining reductions in the risk of resistance is relatively small. With 19 percent refuge, there is more than a 1 in 5 chance of resistance developing within 15 years. When there is 27 percent refuge, there is only a 1 in 20 chance. By increasing refuge from 19 to 27 percent,

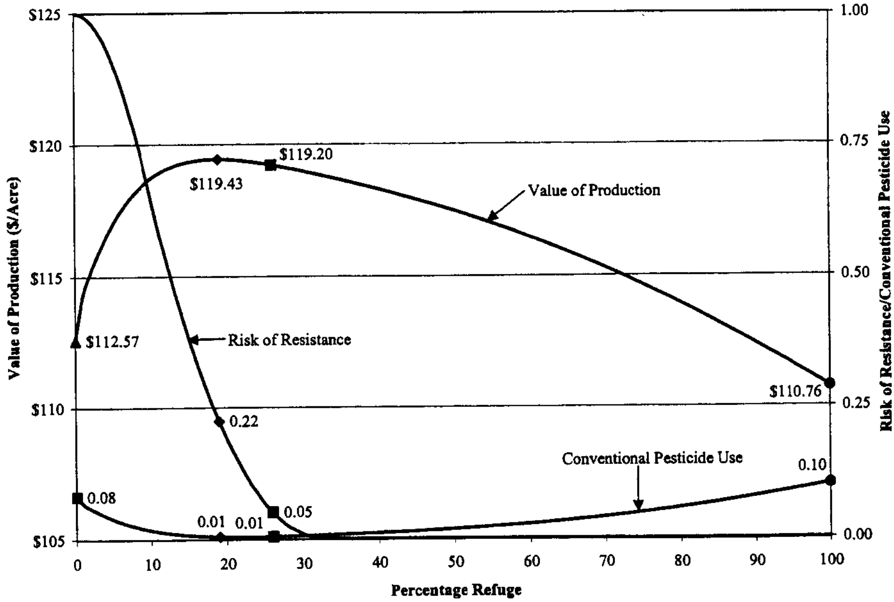

Figure 1. Benchmark tradeoffs between agricultural production, conventional pesticide use, and risk of resistance.

conventional pesticide use is virtually unaffected, while the value of production falls by less than 0.2 percent. The value of production decreases negligibly because of the density dependence of ECB populations. This density dependence allows Bt corn to suppress ECB populations over time provided resistance does not develop too fast. With lower average populations, the cost of planting refuge is reduced along with the need for conventional pesticides. However, if not enough Bt corn is planted, ECB suppression is weak, which raises the cost of planting refuge and the need for conventional pesticides. Therefore, the value of production decreases at an increasing rate as refuge increases above 19 percent.

It is also important to note the complementary relationships between the value of production, conventional pesticide use, and the risk of resistance. increasing refuge between 0 and 19 percent produces the complementary results of increasing the value of production and decreasing pesticide use and the risk of resistance. Increasing refuge between 19 and 22 percent decreases pesticide use and the risk of resistance, but also decreases the value of production. Increasing refuge above 22 percent decreases the risk of resistance, but also decreases the value of production and increases pesticide use. Therefore, increases in the value of production and decreases in pesticide use tend to be complementary benefits that are usually obtained through an increase in the risk of resistance.

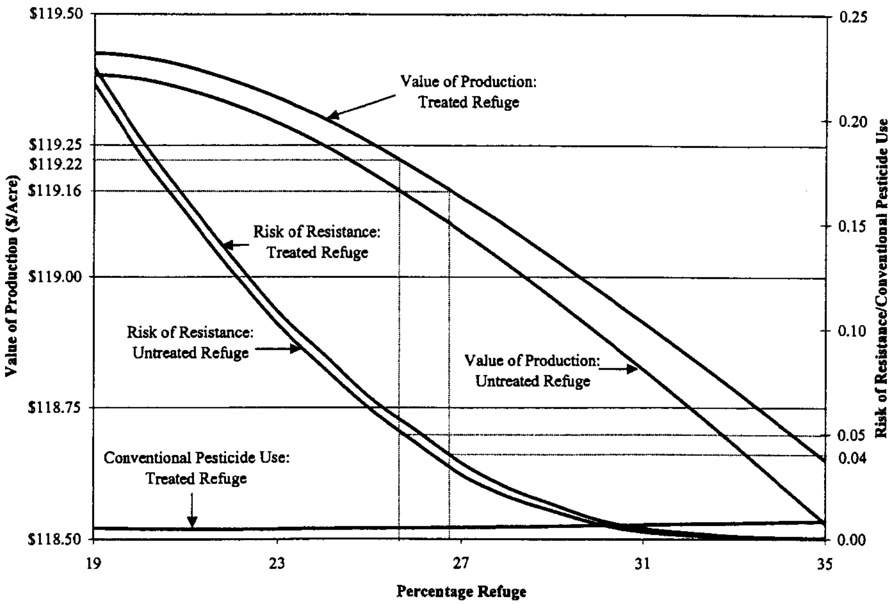

Figure 2. Value of production, conventional pesticide use, and risk of resistance with and without refuge treatments based on economic thresholds.

TREATED VERSUS UNTREATED REFUGE

Figure 2 illustrates the effect of allowing conventional pesticide treatments on refuge based on economic thresholds. In Figure 2, the value of production and risk of resistance are compared for treated and untreated refuge as refuge increases from 19 to 35 percent. At 19 percent refuge, the value of production is maximized for both treated and untreated refuge. As refuge approaches 35 percent, the risk of resistance approaches 0 for treated and untreated refuge. Conventional pesticide use is also shown for when refuge is treated using economic thresholds.

Allowing conventional pesticide treatments using economic thresholds has a number of notable impacts. As suspected, allowing refuge treatments increases the risk of resistance and conventional pesticide use, though modestly. It also increases the value of production, but again rather modestly. The value of production is less sensitive to increasing refuge when refuge treatments are allowed because farmers have more flexibility and can use conventional pesticide applications to enhance control on refuge in years of severe ECB infestations.

The implications of these results are that allowing refuge treatments decreases the cost of resistance management to farmers and industry, while increasing the cost to the environment in terms of increased conventional pesticide use. Without refuge treatments, 25.7 percent refuge is required to reduce the risk of resistance to 1 in 20. With 25.7 percent refuge, the value of production is $119.16 without treatments. This same value of production could be achieved by increasing refuge to 26.9 percent and allowing growers to treat using economic thresholds.

With 26.9 percent treated refuge, the risk of resistance becomes 1 in 25. Therefore, allowing refuge treatments provides the opportunity to either increase the value of production, reduce the risk of resistance, or both. Again, these benefits are not free because allowing refuge treatments increases conventional pesticide use.

MODEL SENSITIVITY

It is important to keep in mind that the results reported in Figures 1 and 2 depend on a variety of assumptions. While we find that the qualitative results of the model are robust to changes in parameter values, more specific results, such as the proportion of refuge that maximizes the value of production, are more sensitive. Therefore, the qualitative results are more important to remember than specific numbers.

The benchmark simulations imply that an acre of land would have received a conventional spray application in 1 out of every 10 years prior to the introduction of Bt corn. This is a result that is consistent with grower surveys on pesticide use in the Midwestern US. In these regions, allowing refuge treatments has little impact on the risk of resistance and value of production because conventional pesticide applications are likely to be even less frequent with the widespread adoption of Bt corn. Treatments will be less frequent because ECB populations are likely to be lower on average due the efficacy of Bt corn.

Allowing refuge treatments will have a greater impact in regions where the frequency of conventional pesticide treatments has been historically high. Two categories of factors can result in more frequent pesticide treatments. On the revenue side, if pest free yield is higher, damages more severe, ECB infestations more frequent and severe, or the survival rates for conventional pesticides are lower, economic thresholds will be lower and treatments more frequent. On the cost side, lower pesticide and application costs reduce economic thresholds resulting in more frequent conventional treatments. We now explore the sensitivity of our results for treated refuge to both revenue and cost factors. For revenue factors, we increase the pest free yield from 0 to 100 percent. For cost factors, we reduced the cost of a conventional pesticide treatment from 0 to 90 percent.

Table III and IV report the sensitivity of the simulation results to increases in crop revenues and decreases in conventional pesticide treatment costs. The first column reports the average frequency of conventional pesticide treatments when no Bt corn is planted. This frequency of treatment is a measure of the historic frequency of treatment prior to the introduction of Bt corn and increases with increasing crop revenues and decreasing conventional treatment costs.

The second column reports the percentage of refuge that maximizes the value of production without regard for resistance or conventional pesticide use. The third column reports the percentage increase in the proportion of refuge that maximizes the value of production, while constraining the risk of resistance to less than 1 in 20.

Table III. Sensitivity of simulation results to an increase in crop revenues.

Average annual frequency of conventional pesticide treatments without Bt corn	Percentage of refuge that maximizes the value of production	Percentage increase in refuge required to reduce the risk of resistance to 1 in 20	Elasticity of the value of production with respect to the risk of resistance	Elasticity of conventional pesticide use with respect to the risk of resistance
0.10	18.9	38.0	2.4×10^{-3}	0.017
0.12	18.8	39.2	2.1×10^{-3}	0.025
0.14	18.9	39.2	1.9×10^{-3}	0.053
0.15	18.9	39.8	1.7×10^{-3}	0.073
0.17	18.8	41.0	1.6×10^{-3}	0.076
0.20	18.8	42.7	1.5×10^{-3}	0.105
0.22	18.8	43.5	1.4×10^{-3}	0.135

Table IV. Sensitivity of simulation results to a decrease in the cost of conventional pesticide treatments.

Average annual frequency of conventional pesticide treatments without Bt corn	Percentage of refuge that maximizes the value of production	Percentage increase in refuge required to reduce the risk of resistance to 1 in 20	Elasticity of the value of production with respect to the risk of resistance	Elasticity of conventional pesticide use with respect to the risk of resistance
0.10	18.9	38.0	2.4×10^{-3}	0.017
0.12	18.9	39.0	2.4×10^{-3}	0.030
0.15	18.9	39.8	2.4×10^{-3}	0.060
0.18	18.8	41.8	2.5×10^{-3}	0.091
0.22	18.9	43.1	2.5×10^{-3}	0.139
0.29	18.9	47.0	2.6×10^{-3}	0.171
0.40	19.2	54.3	2.8×10^{-3}	0.232
0.53	21.5	53.2	2.7×10^{-3}	0.295
0.69	22.3	61.4	2.8×10^{-3}	0.317
0.97	24.5	69.3	2.9×10^{-3}	0.347

The fourth column reports the elasticity of the value of production with respect to the risk of resistance for increasing refuge to reduce the risk of resistance to less than 1 in 20. This elasticity is the percentage decrease in the value of production divided by the percentage decrease in the risk of resistance and is a measure of the cost of reducing the risk of resistance in terms of the value of production.

The fifth column reports the elasticity of conventional pesticide use as refuge increases to reduce the risk of resistance to less than 1 in 20. This elasticity is the percentage increase in the conventional pesticide use divided by the percentage decrease in the risk of resistance and measures the cost of reducing the risk of resistance in terms of increased pesticide use.

The percentage of refuge that maximizes the value of production is relatively insensitive to higher crop revenues or lower application costs that result in more frequent conventional pesticide treatments. This is not the case for the percentage of refuge that reduces the risk of resistance to less than 1 in 20. As the frequency of conventional pesticide treatment increases, the size of refuge needed to reduce the risk of resistance to less than 1 in 20 also increases substantially.

The elasticity of the value of production is small and relatively insensitive to increases in treatment frequency due to either revenue or cost factors. This result suggests that the cost of increasing refuge to reduce the risk of resistance in terms of the value of production is small. It is also interesting to note that if treatments are more frequent due to higher revenues, then the relative cost of increasing refuge to lower the risk of resistance is lower. Alternatively, if treatments are more frequent due to lower treatment cost, then the relative cost of increasing refuge to lower the risk of resistance is higher.

The elasticity of conventional pesticide use is larger and increases as revenues rise or treatment costs fall. Therefore, the cost of reducing the risk of resistance in terms of conventional pesticide use is higher than the cost of reduced agricultural production. The cost will also be higher in regions where the historic frequency of treatments is higher.

V. Conclusion

Bt corn offers farmers a new tool for controlling the European corn borer (ECB), a significant agricultural pest in the Midwestern United States (US). Unfortunately, the high efficacy and widespread adoption of Bt corn could result in the rapid development of ECB resistance to Bt. If ECB resistance to Bt develops, growers will lose a valuable new technology and may turn to more hazardous pesticides.

The US Environmental Protection Agency (EPA) is concerned about resistance and would like to preserve Bt corn as a reduced risk pesticide. Industry and academic scientists have developed a high-dose refuge strategy to combat ECB resistance to Bt corn. The foundations of this strategy are for Bt corn to express enough toxins to kill all but the most resistant ECB and for growers to plant a proportion of their acreage to refuge corn where Bt is not used for control. Refuge slows the evolution of resistance and serves to preserve the efficacy of Bt corn.

Recently, the EPA mandated that farmers in the Midwestern US plant at least 20 percent refuge corn with their Bt corn. This 20 percent requirement allows farmers to treat refuge with conventional pesticides in years of severe ECB infestation using economic thresholds. This mandate represents a departure from previous recommendations, which required farmers to plant more refuge when it was treated with conventional pesticides. Therefore, concerns have emerged regarding whether 20 percent refuge is enough when conventional pesticide treatments are allowed using economic thresholds.

We develop a stochastic dynamic bioeconomic simulation model to evaluate the effect of refuge treatments with economic thresholds on agricultural productivity, conventional pesticide use, and the risk of resistance. We find that treated refuge will not substantially increase the risk of ECB resistance to Bt corn throughout most of the Midwestern US, but does increase the value of production to farmers and industry and the use of conventional pesticides. The reason for this result is that conventional pesticide treatments for the ECB have been historically low due to high application costs and poor efficacy. With the widespread adoption of Bt corn, average ECB populations are likely to fall and refuge treatments will be even more unlikely. Infrequent refuge treatments have little impact on the risk of resistance.

Whether treated refuge should be allowed in regions with historically high frequencies of pesticide use depends on the primary objectives of the policy. Refuge treatments should not be allowed without higher refuge requirements if the primary goal is to limit the risk of resistance. However, if the primary goal is to reduce conventional pesticide use or improve agricultural production, then allowing treatments using economic thresholds with current refuge requirements should be sufficient.

The model we develop provides a framework for comparing alternative resistance management strategies based on a range of different policy objectives provided the assumptions of structured refuge, random mating, and uniform dispersal are not too unreasonable. An important weakness the model shares with many others is a failure to account for factors that influence farmer adoption of Bt corn and compliance with insect resistance management requirements.

With 80 percent of corn acreage not planted Bt corn, there is a substantial amount of "unstructured" refuge available to help slow the evolution of resistance. There has been reluctance to include "unstructured" refuge in the evaluation of refuge requirements because mating is less likely to be random and dispersal is less likely to be uniform. However, Gould (1986), Peck et al. (1999), and Caprio (2001) suggest that even with nonrandom mating and heterogeneous dispersal, a moderate amount of unstructured refuge can substantially reduce the risk of resistance. Particularly, if pest suppression occurs more in Bt, than in "unstructured" refuge corn. The intuition behind the result is that the larger more suspectable pest population in "unstructured" refuge will flood the smaller more resistant population in Bt corn when there is enough movement between the two types of habitat. Therefore, including "unstructured" refuge into the model by making it more spatially explicit would be a useful extension.

Currently, more research is also needed to understand farmer adoption and compliance behavior. Once a better understanding is obtained, the model can specify the proportion of refuge actually planted as a function of adoption and compliance incentives. Models that more explicitly consider adoption and compliance behavior will provide more reliable estimates the economic and environmental tradeoffs of using refuge to manage ECB resistance to Bt corn. Of course, this modeling extension would benefit from considering the pricing behavior of Bt corn registrants, which is also an important determinant of adoption and compliance.

Acknowledgement

The authors acknowledge the helpful comments of an anonymous reviewer and participants at the Biotechnology, Environmental Policy, and Agriculture workshop on the Management of the Impacts of Biotechnologies sponsored by the European Science Foundation and the UK Department of International Development and hosted by the International Plant Genetic Resources Institute.

Names are necessary to report factually on available data; however, the USDA, Iowa State University, and the University of Minnesota do not guarantee or warrant the standard of a product, and the use of names implies no approval of the product to the exclusion of others that may be suitable.

Notes

1. There is a separate 50 percent requirement for Bt corn in areas of the US where cotton is predominantly grown due to the potential interactions between Bt corn and Bt cotton.
2. The Hardy-Weinberg model lies at the foundation of population genetics due to its remarkable ability to predict gene frequencies and heritability. The principle is an extension of Mendelian inheritance and is used extensively by population biologist to describe the inheritance of genetic traits such as resistance. Examples exploring ECB resistance to Bt corn are Gould; Onstad and Gould (a, b) and Roush. The fundamental assumptions of the model are (i) a diploid pest, (ii) sexual reproduction, (iii) non-overlapping generations, (iv) random mating, (v) large populations, (vi) negligible migration, (vii) negligible mutation, and (vii) no selection pressure (Hartl 1988).
3. A gamma distribution was also explored, but the predicted population did not fit as well.
4. Personal communication: Dr. D.A. Andow, University of Minnesota.
5. Depending on the rate of adoption of Bt corn, there could be supply-side price effects that are not treated and depend on refuge size.

References

Alstad, D.N. and D.A. Andow (1995), 'Managing the Evolution of Resistance to Transgenic Plants', *Science* **268**, 1894–1896.

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

Bauer, L.S. (1995), 'Resistance: A Threat to Insecticidal Crystal Proteins of *Bacillus Thuringiensis*', *Florida Entomologist* **78**(3), 414–443.

Calvin, D.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).

Caprio, M.A. (1998), 'Evaluating Resistance Management Strategies for Multiple-Toxins in the Presence of External Refuges', *Journal of Economic Entomology* **91**(5), 1021–1031.

Caprio, M.A. (2001), 'Source-Sink Dynamics Between Transgenic and Non-Trangenic Habitats and Their Role in the Evolution of Resistance', *Journal of Economic Entomology* **94**(3), 698–705.

Clark, J.S. and G.A. Carlson (1990), 'Testing for Common Versus Private Property: The Case of Pesticide Resistance', *Journal of Environmental Economics and Management* **19**, 45–60.

Gorddard, R.J., D.J. Pannel and G. Hertzler (1995), 'An Optimal Control Model for Integrated Weed Management Under Herbicide Resistance', *Australian Journal of Agricultural Economics* **39**(1), 71–87.

Gould, F. (1986), 'Simulation Models for Predicting Durability of Insect-Resistant Germ Plasm: Hessian Fly (Diptera: Cecidomyiidae)-Resistant Winter Wheat', *Environmental Entomology* **15**, 11–23.

Gould, F. (1998), 'Sustainability of Transgenic Insecticidal Cultivars: Integrating Pest Genetics and Ecology', *Annual Review of Entomology* **43**, 701–726.

Gould, F., A. Anderson, A. Jones, D. Sumerford, D.G. Heckel, J. Lopez, S. Micinski and R. Leonard (1997), 'Initial Frequency of Alleles for *Bacillus thuringiensis* Toxins in Field Populations of *Heliothis virescens*', *Proceedings of the National Academy of Science USA* **94**, 3519–3523.

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

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

Hurley, T.M., B.A. Babcock and R.L. Hellmich (October 1997). *Biotechnology and Pest Resistance: An Economic Assessment of Refuges*. Center for Agricultural and Rural Development, Ames IA. Working Paper 97-WP 183.

Hurley, T.M., S. Seechi, B.A. Babcock and R.L. Hellmich (1999), *Managing the Risk of European Corn Borer Resistance to Transgenic Corn: An Assessment of Refuge Recommendations*. CARD Staff Report 99-SR 88.

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

Liu, Y.B. and B.E. Tabashnik (1997), 'Experimental Evidence That Refuges Delay Insect Adaptation to *Bacillus thuringiensis*', *Proc. R. Soc. Lond. B* **264**, 605–610.

Mason, C.E., M.E., Rice, D.D. Calvin, J.W. Van Duyn, W.B. Showers, W.D. Hutchison, J.F. Sitkowski, R.A. Higgins, D.W. Onstad and G.P. Dively (1996), *European corn Borer Ecology and Managemnet*. North Central Regional Extension. Publication No. 327. Ames IA: Iowa State University.

McGaughey, W.H. and R.W. Beeman (1988), 'Resistance to *Bacillus thuringiensis* in Colonies of Indian Meal Moth and Almond Moth (Lepidoptera: Pyralidae)', *Journal of Economic Entomology* **81**, 28–33.

Mellon, M. and J. Rissler (1998), *Now or Never: Serious New Plans to Save a Natural Pest Control.* Cambridge, MA: Union of Concerned Scientists.

Mitchell, P.D., T.M. Hurley and R.L. Hellmich (2000), *Economic Evaluation of Bt Corn Refuge Insurance*. Working Paper 00-WP 243. Ames IA: Center for Agricultural and Rural Development.

Onstad, D.W. and F. 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, D.W. and F. 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. St. Paul, MN: University of Minnesota.

Peck, S.L., F. Gould and S.P. Ellner (1999), 'Spread of Resistance in Spatially Extended Regions of Transgenic Cotton: Implications for Management of *Helliothis virescens* (Lepidoptera: Noctuidae)', *Journal of Economic Entomology* **92**(1), 1–16.

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

Regev, U., H. 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.

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

Tabashnik, B.E. (1994), 'Evolution of resistance to *Bacillus thuringiensis*', *Annual Review of Entomology* **39**, 47–79.

Taylor, C.R. and J.C. Headley (March 1975), 'Insecticide Resistance and the Evaluation of Control Strategies for an Insect Population', *The Canadian Entomologist* **107**, 237–242.

U.S. Environmental Protection Agency (1998a), The Environmental Protection Agency's White Paper on *Bt* Plant-Pesticide Resistance Management. Biopesticides and Pollution Prevention Division, Office of Pesticide Programs, Office of the Assistance Administrator for Prevention, Pesticides and Toxic Substances, U.S. Environmental Protection Agency, 401 M Street, SW, Washington, DC 20460.

U.S. Environmental Protection Agency (1998b), FIFRA Scientific Advisory Panel, Subpanel on *Bacillus thuringiensis* (Bt) Plant-Pesticide and Resistance Management, February 9–10, 1998 (Docket Number: OPP 00231).

Venette, R.C., W.D. Hutchison and D.A. Andow (2000), 'Early Detection of Insect Resistance to *Bacillus Thuringiensis* in Transgenic Crops: Practical and Statistical Considerations for a Field-Based Method', *Journal of Economic Entomology* **93**(4), 1055–1064.