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THE EMERGENCE OF INSECT RESISTANCE IN BT-CORN: IMPLICATION OF RESISTANCE MANAGEMENT INFORMATION UNDER UNCERTAINTY

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ABSTRACT

The successful management of transgenic technology is likely to depend on the economic behavioral response of farmers to the regulated use of transgenic crops. A well-studied example is the widespread use of Bt-corn, in the United States, and elsewhere, to control the European Corn Borer, a major corn pest. The extensive use of Bt-corn has led to concerns about the emergence of insect resistance. The United States Environment Protection Agency addressed this potential problem by developing an insect resistance management strategy, based, in part, on complex mathematical models using detailed biological assumptions about the population genetics and life history of the European Corn Borer. However, seed companies and others have sometimes used simpler deterministic profit models to justify the economics of Bt-corn to potential growers. Therefore an over reliance, by regulatory agencies, on complex modeling approaches may obscure the likely economic behavioral response of farmers who rely on these less complex models. However, the determinants of adoption are numerous, profit being one of them. We develop a simple model for the spread of resistance based on the logistic growth equation and use it to investigate the effect of uncertainty on farmer decisions to plant Bt-corn and follow EPA management rules. The model results suggest that planting Bt-corn is an optimal strategy under the type of uncertainty assumed in the model and that short-term economic behavior is likely to lead to the Environment Protection Agency management rules not being followed. Our results add weight to existing work on this problem.

Key words: insect resistance, Monte Carlo, Bt-corn, logistic growth, economic

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Nicholas A. Linacre[1] and Colin J. Thompson[2]

1. INTRODUCTION

The development of transgenic corn genetically modified to incorporate various toxin genes from *Bacillus thuringiensis* that act as a chemical defense against insect pests such as the European Corn Borer (ECB), a major corn pest, provides farmers with a new pest management option. However, the extensive use, in the United States, of Bt-corn has led to concerns about the emergence of insect resistance to the Bt toxins in the ECB[3]. The successful management of this transgenic technology is likely to depend on the economic behavioral response of farmers to the regulated use of Bt-corn.

The United States Environment Protection Agency (EPA) and United States Department of Agriculture (USDA) have addressed the potential problem of insect resistance in the ECB by developing an insect resistance management strategy that based on a structured refuge/high dose strategy. The presence of an effective structured refuge, in combination with a high dose expression level of the Bt toxin, has the potential to delay the development of resistance in pests. Refuges are non-Bt host plants that are managed to provide sufficient susceptible adult insects to mate with potential Bt-resistant adult insects to dilute the frequency of resistance genes. Currently EPA requires, in areas planted with Bt-corn, at least 20 percent of the area should be planted with non-Bt, creating refugia for non-resistant insects. High dose refers to the fact that Bt-corn is

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[3] Different mechanisms for the emergence of resistance have been proposed and various technologies are available to deal with the problem (Tabashnik *et al.* 1997).

created to produce levels of Bt toxin in the crop 25 times the toxic concentration needed to kill susceptible larvae. The intent is to kill all ECB larvae with no genes for resistance, plus those with one copy of a resistance gene (Alstad 1997).

This approach is based, in part, on modeling the spread of resistance genes, which requires detailed biological information about the genetics controlling resistance and estimates of fitness parameters of the different genotypes. For example Peck *et al.* (1999), Caprio (2001) and Storer *et al.* (2003) use spatially explicit stochastic simulation models with various assumptions including: insect population age structure, movement of larvae and adults, and development time. Such models have been used to explore the likely economic behavioral responses of farmers to regulation (e.g. Onstad and Guse 1998, 1999). However, the use of complex models is not universal.

Seed companies and others use simpler deterministic profit models to justify the economics of Bt-corn to potential growers. It is therefore possible that an over reliance, by regulatory agencies, on complex mathematical models requiring detailed biological assumptions may obscure the likely economic behavioral response of farmers who rely on less complex models[4]. However, simple deterministic models, used to justify the economics of Bt-corn, ignore effects of uncertainty, which may have important implications for farmer decisions.

Given the widespread availability of Monte Carlo simulation software it is plausible that farmers and their advisors may incorporate uncertainty in their decision-making. Assuming that farmers act to maximize expected profits we investigate the affect of incorporation production uncertainty on farmer decisions to plant Bt-corn and follow EPA management rules. We use a simple dynamical systems model for the spread of

[4] Technology adoption decisions are typically complex; one element of the decision is the expected profit.

insect resistance based on the logistic growth curve (Laxminarayan and Simpson (2000); Linacre and Thompson (2004)).

The model presented here is simplistic and some of the assumptions, both biological and economic, are almost certainly not universally valid. Allowing for these limitations we use the model to investigate the likely commercial decisions of farmers when borer numbers and crop yields vary. The model results suggest that planting Bt-corn is an optimal strategy under uncertainty and that short-term economic behavior is likely to lead to the EPA management rules not being followed. Our results therefore add weight to existing work on this problem.

2. METHODS

We assume that the emergence of insect resistance in the presence of Bt corn can be modeled by a logistic growth curve. That is the proportion of Bt-resistant borers in the population depends on the resistance spread rate and the initial population of resistant borers. That is, if p_t denotes the proportion of Bt-resistant borers in the population at time t, then p_{t+1} is given by

$$p_{t+1} = p_t + rp_t(1 - p_t) \tag{1}$$

where r is the rate of increase in the proportion of resistant borers in the presence of Bt toxin. The unit time step is assumed to be 1 "year" (or one planting cycle) so that for a given r and initial value p_0, the proportion of Bt-resistant borers in any given year is determined by iterating Equation (1). Having obtained the proportion of resistant borers per plant p_t and assuming that the total number of borers per plant is B_t, it follows that the number of resistant borers per plant in year t is

$$\lambda_t = p_t B_t \tag{2}$$

and the number of non-resistant borers per plant is

$$\lambda_t^{'} = (1 - p_t) B_t \tag{3}$$

If *L* is the yield lost per corn borer per plant and the yield in the absence of borers is M_t. then the yield per hectare from a field of Bt-corn is given by

$$Y_t^{(Bt)} = M_t \left(1 - L\left(\lambda_t + (1-q)\lambda_t^{'}\right)\right) \tag{4}$$

where q is the effective mortality of susceptible borers due to Bt-toxin. And the yield per hectare from a field planted with Bt and non-Bt corn is given by

$$Y_t^{(Mix)} = (1-\alpha) M_t \left(1 - L\left(\lambda_t + (1-q)\lambda_t^{'}\right)\right) + \alpha M (1 - LB_t) \tag{5}$$

where α is the proportion of the area plant with non-Bt-corn. When comparing the different strategies, we consider the profit per hectare in year *t*, given for strategy *i = Bt, Mix*.

$$\Pr_t^{(i)} = Y_t^{(i)} P_t^{(i)} - C_t^{(i)} \tag{6}$$

where the yields $Y_t^{(i)}$ are given in equations (4) and (5), $P_t^{(i)}$ denotes the market price for the corn produced under strategy *i* and $C_t^{(i)}$ denotes the total cost of producing the corn under strategy *i* in year t.

Given prices and costs, we then calculate the net present value for each strategy over a time horizon of *N* years, defined by

$$NPV^i = \sum \Pr_t (1 + y_i)^{-(t+1)} \tag{7}$$

where y_t is the rate of interest used for discounting in year *t*.

In the following we assume that

$$C_t^{(Bt)} = C_t + T_t \tag{8}$$

where C_t is the cost of production in year *t* and T_t is the technology cost of using Bt-corn.

For the mixed strategy, *Mix*, we assume

$$C_t^{(Mix)} = C_t + \alpha T_t \tag{9}$$

i.e. that the production costs are the same as for the pure Bt-corn strategy *Bt* and that the technology costs are in proportion to the use of Bt-corn.

In general we assume that prices satisfy $P_t^{(Bt)} = P_t^{(mix)}$. We further assume that the individual farmer cannot influence the market price for corn or the prices of inputs (i.e. the farmer is a price taker) and that the $P_t^{(i)}$ can be regarded as constants.

In order to demonstrate the impact of the stochastic behavior of the model on the economic value of the two strategies, we take constant values for the various prices and costs in equations (6) – (9).

The model variables and assumptions are listed in Table 1. For additional details and comparisons using deterministic form of this model see Linacre and Thompson (2004).

Table 1--Model parameters values, description and source information.

Parameter	Value	Description	Source
M	9,500 kg/ha	The expected yield per hectare in the absence of borers	(Monsanto 2000, USDA 2001b)
$P^{(1)}_t$	US$ 0.09/kg	The projected market price of Bt-corn (strategy (1)).	(Monsanto 2000, USDA 2001a)
T_t	US$ 24.70/ha	The technology cost associated with using Bt-corn.	(Onstad and Guse 1999)
I_t	US$ 24.70/ha	The technology cost associated with using Bt insecticide spray.	Assume that approximately the same cost applies for Bt insecticide use as Bt-corn use.
C_t	US$ 800/ha	The cost of production.	(Foreman 2001)
q	0.96	The effective mortality from the use of Bt-corn on the ECB.	(Monsanto 2000)
q'	0.50	The effective mortality from the use of Bt insecticide spray on the ECB.	(Hyde and Martin 2001)
L	0.05	Effective yield lost per ECB	(Monsanto 2000, Hyde and Martin 2001, Monsanto 2001)
B_t	1.19	Number of borers per plant	(Steffey and Gray 1999)
r	Calculated	Resistance growth rate is calculated numerically to give 50% of the population as resistant over 5, 10, and 20 years.	(May and Dodson 1986)
s	0	Rate of decline in resistance	(Onstad and Gould 1998)
y_t	10.00%	The interest rate used for discounting.	N/A
α	0.80	If the proportion of the area planted with Bt-corn is 20% then only 80% of the technology fee is assumed payable	N/A
p_0	0.001	Initial proportion of the population that is resistant.	(Onstad and Gould 1998)

A stochastic version of this model was estimated by Monte Carlo methods and used to incorporate the impact of uncertainty in estimates of resistant borers per plant B_t and the yield in the absence of borers M_t. While B_t and M_t are not the only sources of uncertainty (for example see Moschini and Hennessy 2000) they represent significant sources of biological uncertainty for farmers with B_t representing uncertainty about the level of insect damage and M_t representing uncertainty about the impact of environmental fluctuations on yields.

The stochastic model was used investigate the expected net present value of profits using the following strategies:

(1) plant only Bt-corn;

(2) plant a mixture of Bt and non Bt-corn and do not use insecticide;.

Strategy (1) represents pure Bt-corn farming and strategy (2) represents the EPA recommend strategy for the planting of Bt-corn (Linacre and Thompson 2004).

The stochastic simulation calculated multiple scenarios of the model by repeatedly sampling values from the assumed probability distribution for B_t and M_t. The model prototype was developed in Mathcad 2001i and implemented in C++. Numerical simulation techniques were taken from Numerical Recipes in C (Press *et al*. 1999). One thousand random instances[5], using a 15 year projection period, which was sufficient to estimate the time until the USEPA strategy became profitable. Random values for B_t and M_t were drawn assuming baseline values and that B_t was a normally distributed random variable with mean μ_B = 1.19 kg/ha and σ_B = 0.5 and M_t was a normally distributed random variable with mean μ_M = 9600 kg/ha and σ_M = 500. The Monte Carlo simulation followed methods outlined by Vose (1996) and Nelson (1996). The values for B_t and M_t were combined with other parameter values in the analysis and used to calculate the expected net present value of profits. Additionally the effects of correlations between B_t and M_t were investigated.

For each of the planting strategies the following scenarios where generated:

(1) B_t and M_t are assumed to be independent random variables (ρ = 0.0);

(2) B_t and M_t are assumed to be perfectly positively correlated (ρ = 1.0); and

[5] No changes were found in the model by altering the number of simulations between 1,000 and 10,000.

(3) B_t and M_t are assumed to be perfectly negatively correlated (ρ = -1.0).

The effect of correlations between B_t and M_t was modeled by:

1. independently generating $X \sim N(0,1)$ and $Y \sim N(0,1)$;
2. setting $M_t = \mu_M + \sigma_M \left(\rho X + \sqrt{1-\rho^2}\,Y\right)$; and
3. setting $B_t = \mu_B + \sigma_B X$ (Saucier 2000).

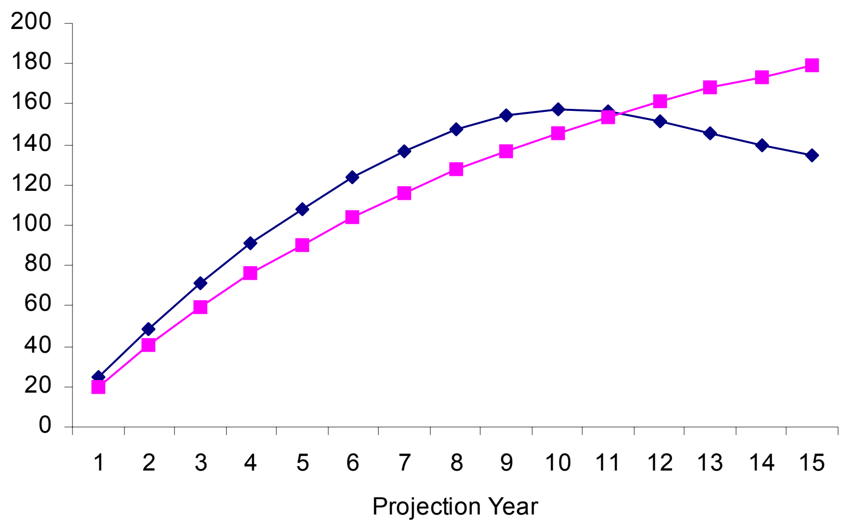
Giving $M_t \sim N(\mu_M, \sigma_M^2)$, $B_t \sim N(\mu_B, \sigma_B^2)$ and $corr(M_t, B_t) = \rho$.

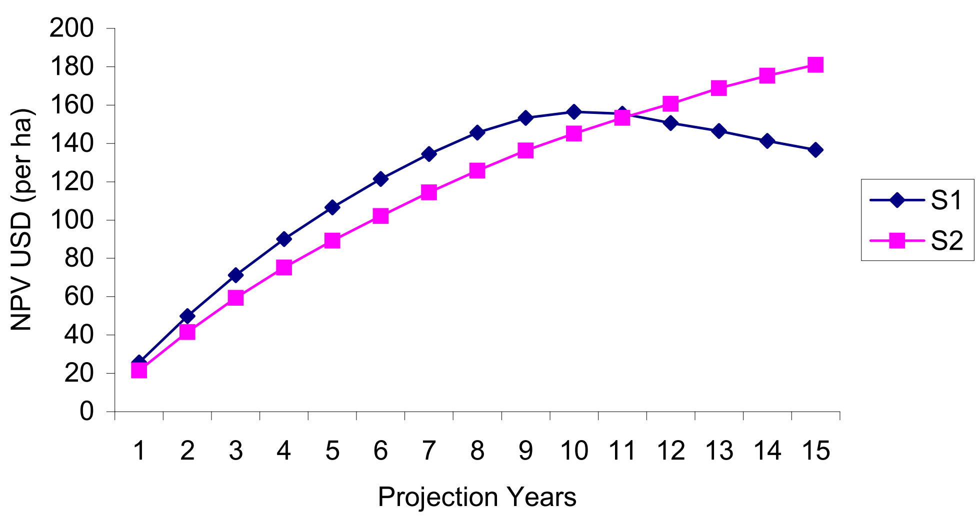
Other parameter values such as the resistance growth rate were assumed constant However, in reality this would be expected to vary stochastically. Variation of r is not considered because the focus of this paper is on the impact of production uncertainty on farmer behavior when simple decision models are used.

3. RESULTS

Figure 1 presents results from the simulation of the net present value of profits from different planting strategies. The curve S1 represents planting of a pure stand of Bt corn, while the curve S2 represents the US EPA recommended strategy of planting a mixed stand of (80%) Bt and (20%) non-Bt corn. For each of the planting strategies (S1 and S2) numerical results are presented for perfect positive (ρ = +1.0) and negative (ρ = -1.0) correlation between borer numbers and crop yields and the uncorrelated (ρ = 0.0). As a decision indicator the net present value of profits (NPV) was insensitive to random effects and correlations between borer numbers and crop yields (Figure 1).

Figure 1--S1 represents strategy 1, planting only Bt corn and S2 represents strategy 2, planting a mixture of Bt and non-Bt corn. The expected net present value of profit per hectare with $\rho = +1.0$, $\rho = 0.0$, $\rho = -1.0$ comparing planting strategies 1 (S1) and 2 (S2). At year 11 the profit becomes negative because the population of European corn borers becomes resistant and continued expenditure on the technology fee results in losses.





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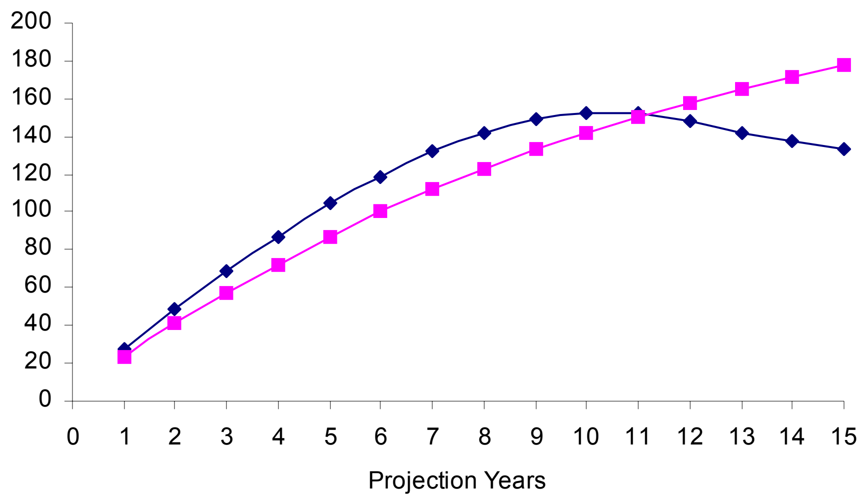

The results suggests that short-term crop management decisions based on NPV will favor a pure strategy of planting Bt-corn over the US EPA mixed strategy.

4. DISCUSSION

The effects of correlation are potentially significant as it might be argued that farmers would profit more by planting pure Bt-corn stands when the total number of borers per plant, B_t, is perfectly positively correlated with yield in the absence of borers, M_t. Conversely it could be argued that planting pure stands of Bt-corn when B_t and M_t are perfectly negatively correlated might be a less profitable strategy. The results suggest that irrespective of the correlation effects planting pure stands of Bt-corn is the optimal strategy over the first 11 years.

The model is restricted in a number of important areas. Firstly the model does not allow for the possibility of adoption and dis-adoption. Extensions of the model could be developed to allow for varying rates of adoption and dis-adoption. The model is also limited by the assumptions about the nature of the uncertainty: the distribution, mean, and variance. To obtain exact numerical results the actual distributions and parameter estimates are required. However, the key issue is the impact uncertainty may play in farmer decisions on planting Bt-corn and this impact may be assessed without recourse to knowledge about the exact distributional forms associated with the sources of production uncertainty considered here. Another potentially problematic assumption is that r, the resistance growth rate, is treated as constant in the analysis, which is done because the focus on the paper is on how correlations between variation in environmental factors and borer numbers may affect farmer decisions. If stochasticity in the environment causes variations in the emergence of insect resistance then this assumption may not be valid.

Finally another important and implicit assumption made in model is that the spatial nature of the environment is a taken into account through the resistance growth rate parameter r. This implies that r is related to the area planted with Bt-corn. An explicit spatial analysis like those of Peck *et al.* (1999), Caprio (2001), and Storer *et al.* (2003) is possible by using our model to describe the emergence of insect resistance in the subpopulations of a meta population model (Tilman 1997), with resistance emerging in the subpopulations occurring on Bt-corn habitat patches. However, detailed understanding of insect dispersal behavior between patches is required for this approach.

Such data is likely to be lacking for some of the species we may be interested in. We therefore believe that the spatially explicit approaches taken by Peck *et al.* (1999), Caprio (2001), and Storer *et al.* (2003) are likely to be beyond the scope of the average analyst or farmer. However, it is plausible where companies offer estimates of the technology lifetime that analysts may be prepared to put upper and lower bounds on the time to resistance based on these estimates (i.e. estimates of r).

However, given the model limitations we still found that the model provided insights into why non-compliance rates with the 80/20 planting rule might occur[6]. Also, given the widespread use by investment analysts and accountants of net present value for making investment decisions and easy access to Monte Carlo software it is plausible that farmers and their advisors may incorporate uncertain information in their decision-making using models similar to the one illustrated here. It is therefore possible that an over reliance, by regulatory agencies, on complex mathematical models requiring detailed biological assumptions may obscure the likely economic behavioral response of farmers who rely on less complex models.

[6] Some studies have examined compliance with the voluntary guidelines which suggests non-compliance rates as high as 20%. For example see Jaffee, G. "Planting Trouble: Are Farmers Squandering Bt Corn Technology? An Analysis of USDA Data showing Significant Noncompliance with EPA's Refuge Requirements." Washington, D.C.: Center for Science in the Public Interest, 2003.

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