A Model of Pesticide Resistance as a Common Property and Exhaustible Resource

By

Silvia Secchi
Department of Economics
Iowa State University
260 Heady Hall
Ames, IA, 50011
Phone: (515) 294-8612
Fax: (515) 294-0221
secchi@iastate.edu
(Primary contact)

Bruce Babcock
Department of Economics
Iowa State University
260 Heady Hall
Ames, IA, 50011
Phone: (515) 294-5764
Fax: (515) 294-6336
babcock@iastate.edu

Keywords: biotechnology, common property resource, European Corn Borer, externalities, pesticide resistance, intertemporal optimization.

Abstract

A dynamic farm production model analyzes the interaction between the externalities caused by pest mobility and the development of pesticide resistance, a nonrenewable resource, in the context of agricultural biotechnologies. The model measures the effect of farmers' myopic behavior and the impact of pest mobility on the path of resistance.

Introduction

The aim of this paper is to analyze the interaction between the externalities caused by pest mobility and the susceptibility to a pesticide, a nonrenewable resource. When different technologies are used in adjacent fields, the natural selection that gives rise to the development of resistance may be countered by the movement of pests from field to field. This movement affects the pest population genetic make-up and may dilute the evolution of resistance. The problem of resistance development had been analyzed by economists since the 1970s (Taylor and Hadley, 1975; Hueth and Regev, 1974; Regev, Gutierrez and Feder, 1976; Regev, Shalit and Gutierrez, 1983). However, the issue is now assuming a new urgency because of the development of biotechnologies for agriculture. Although regulation is still in the process of being established, the Environmental Protection Agency (EPA) is likely to require mandatory resistance management plans for plant-pesticides[1]. Including the issue of mobility in the analysis of resistance development may be extremely important because resistance is essentially a common property resource. The very rationale of the EPA's regulatory effort is based on the possibility that resistance may spread, making the *Bt* used as a spray in organic farming ineffective (EPA, 1998). The level of mobility determines the extent of the externality created and therefore influences the resistance management strategy (Miranowski and Carlson, 1986).

This paper presents a dynamic farm production model that analyzes the interplay between the externalities created by pest mobility and the management of resistance. The toxin studied is *Bacillus Thuringiensis* (*Bt*) plant-pesticides, genetically engineered to

produce toxins that target the European Corn Borer (ECB). The model is developed along the methodological lines of Lazarus and Dixon (1984) and Hurley *et al.* (1997).

Lazarus and Dixon (1984) use a nonlinear programming model to combine both common property resource issues with explicit genetics for the corn rootworm, while Hurley *et al.* (1997) examines the economic value of mechanisms to slow down resistance build-up for *Bt* crops. The model is applied to the case of corn production, with one field planted with the *Bt* crop and the other with a traditional corn hybrid. This scenario is becoming increasingly relevant because of the expansion of the acreage planted with *Bt* plant-pesticides: in the United States, 1.3 million acres were planted to *Bt* corn containing genes from Monsanto alone in 1997, and this figure more than tripled in 1998 (Merritt, 1998). The issues analyzed here are likely to become central to the policy arena, as the industry is developing new genetically modified crops that will be active both against the corn rootworm and the ECB. Because of its limited mobility, the ECB is likely to remain the minimum common denominator in resistance management plans that incorporate stacked genes. The strategy advocated by scientists and implemented by EPA consists of a combination of high-dose and refuge (Alstad and Andow, 1995 and 1996; EPA 1998). The *Bt* crop is engineered to produce a high dose of the toxins throughout the season and throughout the corn plant, so that only the few resistant pests survive. The resistance present in these pests is then diluted when they mate with susceptible pests from the non-*Bt* section of the field, or refuge.

---

[1] For lack of a better term, the EPA term is used here to define this new technology (EPA, 1998).

The model

The model builds on Hurley *et al.* (1997). It is based on pest population dynamics that allows the direct measurement of resistance development following the Hardy-Weinberg principle, with resistance being conferred by a single allele, so that the pest population is composed of homozygote susceptible (SS), heterozygote (RS) and homozygote resistant (RR) individuals. There are three differences with the Hurley *et al.* (1997) model. The first is the introduction of a random element in order to mimic weather conditions. This stochastic shock is assumed to impact the pest population within the field, without altering its genetic make-up. The second difference is that a floor is added to the *Bt* pest population which prevents a collapse in the ECB population in the *Bt* field. Many of the population growth models exhibit such a collapse, a phenomenon which most observers think is unlikely. Third, the model allows for the possibility of non-random mating in the *Bt* field. These last two differences are important from a policy perspective because they more realistically capture the spatial component of the pest population dynamics that, in more stylized models, tends to be at least partially overlooked. The biological rationale for the first feature is to be found in density-dependent mechanisms: reproductive and survival rates tend to be higher for low population densities which prevents a population from being completely wiped out (Royama, 1992). It is worth noting that the floors put on the model are all quite low. With 69,160 corn plants per acre (Onstad and Guse, 1999), the floors correspond to about 100 third instars per acre for the first generation and 400 for the second, densities that produce negligible damage. The representation of mating as non-random is based on

some recent field evidence (Hurley *et al.*, 1999). Resistant insects tend to mate with other resistant ones because the susceptible pests surviving on the refuge are too far away. Therefore, indirectly, the presence of non-random mating suggests that mobility levels are low. The pest population analyzed has two generations per year (bivoltine), as is most prevalent in the Midwest, but the model is easily generalizable to uni-or multi-voltine populations. More generally, this framework is easily applicable to all diploid pests which exhibit some degree of mobility, ranging from insects to weeds and fungi, and to crops which suffer damage from a common pest population[2].

The model is based on two corn fields, one of which--always the same[3]--is planted with *Bt* corn. Following Onstad and Guse (1999) and Mason *et al.* (1996), the damage function of the ECB is linear, but differentiated across generations. The farmer planting the non-*Bt* corn has the choice of applying a non-*Bt* based pesticide. The cost of applying the chemical input is fixed, and the pesticide has a maximum efficacy bound (Mason *et al.,* 1996). For simplicity, the non-*Bt* farmer can apply the pesticide only once, in order to control the first generation of ECB. Since the pest population modeled is in the high range, the farmer will always use the option of spraying. The other farmer will plant *Bt* corn plus a given percentage of refuge, left unsprayed. The baseline case for the refuge size is 20% of the field. This is consistent with current EPA regulation, and with a recent statement endorsed by the National Corn Growers Association and the industry. Following Hurley *et al.* (1997), this proportion of the field is constant throughout the time horizon.

---

[2] For instance, the model could be applied to corn and cotton, which are both ECB hosts.

The yearly profit per acre for the *Bt* farmer is given by:

$$p_y Y[1-(E_{G1}N_{G1}-E_{G2}N_{G2})]- C- P \tag{1}$$

while the non-*Bt* farmer maximizes:

$$p_y Y[1-E_{G1}N_{G1}(\alpha(1-S))-E_{G2}N_{G2}]- C- p_sS \quad \text{s.t. } \alpha \le 0.65 \text{ and } S \in \{0,1\} \tag{2}$$

where[4]:

p_y =$ 2.35, real corn price per bushel at 1992 prices

Y = pest free average yield, 130 bushels per acre

N_{G1} and N_{G2} = number of pests per plant, first and second generation

E_{G1} and E_{G2} = damage per pest per plant, E_{G1} = 0.05 and E_{G2}= 0.024

C = costs of production net of the spraying price, $185 per acre

P = *Bt* premium, $20 per acre

p_s = cost of the spray application, 14$ per acre

S = non-*Bt* spray application

α = maximum efficacy of the non-*Bt* spray, fixed at 65% of the population

Equation (1) incorporates the effects of the population dynamics and the impact of changes in its genetic make-up. Changes in N_{G1} and N_{G2} can be the direct result of changes in the pest population's size or, indirectly, can be due to variations in the genetic frequency of resistant pests. As resistance increases, there is a decrease the effectiveness of the *Bt* toxins, so that a higher number of pests survives and damages the crop. The rate of interest used for the net present value of production is 3%. The time horizon utilized is 10 years, a conservative estimate of the time in which backstop technologies will become

---

[3] This appears to be a non-trivial question when analyzing resistance development. See Peck *et al.* (1999).

available. The mobility of the pest is parameterized by the percentage of pest population moving to the neighboring field and breeding with the local population. Consistently with the field evidence (Dr. David Andow, personal communication), only first generation ECBs are modeled as moving outside the field[5]. This form of effective pest mobility is *de facto* a reduced form embodying two kinds of variables: the first is the pest mobility proper, as determined by biological and environmental factors, and the second is the farm size. The larger the farm, the less likely pests are to create an externality by migrating from one farm to the next, as they tend to live and mate within the perimeter of the farm. The model is programmed in MATLAB.

Results and discussion

In the baseline case of no pest mobility and with 20% refuge[6], as Table 1 shows, the final frequency of homozygote resistant pests is 0.6101, while of course the non-*Bt* field has the same frequency as at time zero.

Table 1 – Simulation results with zero mobility and random mating, at 20% refuge[7]

	Final frequencies			Average yield per acre	Net Present Value of Production per acre
	RR Homozygote resistant	RS Heterozygote	SS Homozygote susceptible		
Bt field	0.610100	0.342000	0.0479	129.987	882.81
Non-*Bt* field	0.000001	0.001998	0.9980	123.084	792.98

---

[4] For the specific values see Mason *et al.* (1996), Onstad and Guse (1999) and Hurley *et al.* (1997)

[5] The reason for this appears to be that second generation pests have less of an incentive to leave their corn field, since the corn is at a later development stage and provides a better habitat.

[6] With population floors, in terms of pests per plant, at G1= 0.0015 and G2= 0.0060.

[7] The population floors used are relatively high, and they cause very high resistance levels to occur. Reducing the floors by a factor of five, for instance, dramatically decreases resistance without a strong impact on profits. The table below illustrates the effect at 20% refuge, with random mating:

	RR	RS	SS
G1=0.0015, G2=0.0060	0.6101	0.3420	0.0479
G1=0.0003, G2=0.0024	0.2325	0.4994	0.2681

The high resistance frequency, however, allows a much clearer illustration of the impact of mobility and it is therefore maintained.

The technology is obviously beneficial to the farmer, since it increases the net present value of production by almost 90 dollars per acre.

The presence of non-random mating does not substantially alter the yield and profit for the *Bt* crop, because the pest population remains small. However, its genetic make-up is affected. The higher the proportion of population mating within its own genetic group, the higher the incidence of resistance will be. For instance, if the proportion of non-random mating population is 50%, the final frequency of resistant homozygotes is 0.7178, as opposed to 0.6101 in the case of random mating. This relationship is partially reversed if mating is totally non-random (the final frequency of resistant homozygotes is 0.501), because in this case the susceptible pests in the refuge will mate among themselves, thus preserving a higher level of susceptibility.

Table 2 illustrates how changing the refuge size in the absence of mobility affects the frequency of resistance. There is a very clear trade-off between resistance and refuge. However, the profit levels are not significantly affected, because the population levels within the time horizon considered are still too low to cause significant damage to the crop.

Table 2 – Simulation results with zero mobility and random mating varying refuge sizes

Refuge size	Final frequencies		
	RR Homozygote resistant	RS Heterozygote	SS Homozygote susceptible
10%	0.6389	0.3208	0.0403
20%	0.6101	0.3420	0.0479
30%	0.3691	0.4769	0.1540
35%	0.2182	0.4978	0.2840
40%	0.1002	0.4327	0.4671
50%	0.0904	0.4206	0.4890

The introduction of very small levels of pest mobility has substantial effects on the population's genetic make-up. Table 3 shows how 1% pest mobility is enough to dramatically decrease the final frequency of resistance in the *Bt* field without substantially diminishing profits. The rationale for this result is that the *Bt* plant–pesticide is extremely effective, so that the pest pressure in the *Bt* field is very low compared to that in the non-*Bt* field. Very low levels of mobility are enough to allow the migration towards the *Bt* field of a high enough number of susceptible pests to substantially alter its genetic composition. The reverse flow, on the other hand, is too small in absolute terms to produce a significant increase in the number of resistant pests in the non-*Bt* field.

Table 3 – Simulation results with 1% mobility and random mating, at 20% refuge[8]

	Final frequencies			Average yield per acre	Net Present Value of Production per acre
	RR Homozygote resistant	RS Heterozygote	SS Homozygote susceptible		
Bt field	0.0419	0.3257	0.6324	129.970	882.39
Non-*Bt* field	0.0023	0.09124	0.9065	123.115	793.56

Here, the presence of non-random mating does not significantly increase the frequency of homozygote resistant pests but it does considerably decrease that of heterozygotes. For instance, if the proportion of non-random mating population is 50%, the final frequency of heterozygotes is 0.1229 , vs. 0.3257 in random mating. This is due to the fact that, as the pest populations in the refuge and in the *Bt*-planted portion of the field mix less and less, there is less of a chance for the SS from the refuge to mate with the RR pest surviving on the *Bt* corn. On the other hand, since the absolute numbers

---

[8] Note that frequencies, in this table and the following ones, may not exactly add up to one due to rounding.

remain very small in the *Bt* field, there is little or no effect on the genetic make-up of the non-*Bt* field. Table 4 shows how increasing the refuge size reduces resistance. Because of the relative small frequencies due to the mobility, however, the marginal benefits are substantially lower than those represented in Table 1. Again, the absolute numbers of ECBs in the *Bt* field remain very small, so they do not influence the non-*Bt* field.

Table 4 – Simulation results with 1% mobility and random mating varying refuge sizes

Refuge size	Final frequencies		
	RR Homozygote resistant	RS Heterozygote	SS Homozygote susceptible
10%	0.0922	0.4229	0.4850
20%	0.0419	0.3257	0.6324
30%	0.0278	0.2781	0.6941
35%	0.0180	0.2324	0.7496
40%	0.0138	0.2072	0.7791

Table 5 – Simulation results with 5% mobility and random mating, at 20% refuge

	Final frequencies			Average yield per acre	Net Present Value of Production per acre
	RR Homozygote resistant	RS Heterozygote	SS Homozygote susceptible		
Bt field	0.0009	0.0579	0.9412	129.909	881.08
Non-*Bt* field	0.0000	0.0015	0.9985	123.224	795.79

If the level of mobility is increased to 5% of the pest population, Table 5 shows that resistance, with a 20% refuge size, becomes virtually irrelevant without substantially altering yields and profits.

The effects of non-random mating on the genetic composition of the pest population, at this level of mobility, are very small. The flux of susceptible pests from the non-*Bt* field is the dominating factor in the population dynamics. Similarly, increasing (or decreasing) refuge size has little effect on absolute population sizes and produces very little benefits in terms of reduced resistance. For instance, increasing the

refuge to 30% decreases the RR frequency from 0.0009 to 0.0003 and the RS frequency from 0.0579 to 0.0311.

Table 6 – Simulation results with 0.5% mobility and random mating varying refuge sizes (model with no floors)

Refuge size	Final frequencies in the Bt field		
	RR Homozygote resistant	RS Heterozygote	SS Homozygote susceptible
0%	0.3231	0.4906	0.1863
5%	0.0000	0.0036	0.9964
10%	0.0000	0.0024	0.9976
20%	0.0000	0.0013	0.9987

Since this is the first paper to introduce a population floor, simulations were also conducted using the basic Hurley *et al.* (1997) model. The main restriction that model imposes is that the pest population may collapse and not be able to recover. The introduction of mobility is enough to guarantee that this will not happen: local populations recover from very low numbers because they are not completely isolated from each other. Table 6 shows that with only 0.5% of the populations migrating between the two fields, the population in the *Bt* field will not collapse and that, if mating is random, 5% refuge is enough to virtually eliminate problems of resistance. If the mating is not random, 10% refuge is enough to guarantee no resistance build-up.

Table 7 – Simulation results with 5% mobility and random mating, at 20% refuge (model with no floors)

	Final frequencies			Average Yield per acre	Net Present Value of Production per acre
	RR Homozygote resistant	RS Heterozygote	SS Homozygote susceptible		
Bt field	0.0000	0.0000	1.0000	129.909	881.22
Non-*Bt* field	0.0000	0.0000	1.0000	123.227	795.79

Assuming higher levels of pest mobility strengthens these results. Table 7 illustrates what happens at 5% mobility. In all these cases again, the absolute pest

numbers remain very small in the *Bt* field, so there is little or no effect on the genetic make-up of the non-*Bt* field. Further increases of mobility will eventually enlarge the pest population size in the *Bt* field so that the *Bt* technology becomes ineffective. However, entomological field data strongly indicate that mobility levels are not high (Dr. Rick Hellmich, personal communication). Simulations were conducted for up to 15% mobility, assuming random mating, and the absolute numbers remain very small in the *Bt* field, while there is little or no effect on the genetic make-up of either field.   The most important consequence of the results above is that, in the time horizon considered, the returns for both farmers are fairly robust to changes in the parameters considered, and the *Bt* technology appears to remain productive for the whole time.

Conclusions

The zero mobility scenario analyzed is indicative of what would happen in case of a 100% market penetration in a region concentrating on corn production. In such a case, there would be no secondary hosts for the ECBs, and mobility would become irrelevant, since all farmers would be growing the same identical crop, thereby offsetting each other's externalities. However, for incomplete market penetration, and within the time horizon considered, the results discussed above indicate that mobility may be important in preserving susceptibility, and even more substantially, that the externality created by mobility is economically significant in only one direction, since the pest population in the non-*Bt* field is not seriously affected. The extent of the externality depends critically on the mobility parameter. Clearly, more field-level entomological studies are needed to determine realistic values of the mobility parameter for the various cropping regions of

the US. This model is simply a first attempt at characterizing possible magnitudes of the economic effects of pest migration.

The paper does not address the issue of the value of *Bt*, in the spray form, for organic farmers. The EPA is basing its resistance management policy on the grounds that *Bt* is used in spray form in organic and Integrated Pest Management (IPM) crop systems and that finding organically acceptable, low impact backstop technologies for *Bt* sprays may require very long time horizons (EPA, 1998). In order to properly evaluate the costs of resistance, an explicit economic evaluation of the *Bt* technology in the spray form is needed, since the results discussed above indicate that, within the time frame relevant to the *Bt* plant-pesticides, the build-up of resistance is not likely to substantially decrease the effectiveness of the technology, particularly if market penetration is less than 100%.

The model highlights the importance of regional considerations in resistance management policy, as the most important crops and pests will be differentiated by region. It also indicates that there may be substantial benefits from local coordination schemes such as pest management groups, even though more explicit spatial modeling would be needed in order to better quantify them. This is particularly important in terms of policy because the use of refuges poses compliance problems, since the farmers may not perceive the intertemporal relation between planting refuge and controlling resistance development (and rightly so, according to the results of the model, since the development of resistance does not significantly affect their returns). Moreover, refuge sizes and locations may be hard to monitor, and the costs of planting refuge may be substantial for the farmer.

References

Alstad D.N. and D.A. Andow, 1995, Managing the Evolution of Insect Resistance to Transgenic Plants, *Science*, Vol.268, pp. 1984-1896.

Alstad D.N. and D.A. Andow, 1996, Evolution of Insect Resistance to *Bacillus Thuringiensis*-Transformed Plants, *Science*, Vol.273, p. 1413.

Environmental Protection Agency, 1998, *The Environmental Protection Agency's White Paper on Bt Plant-pesticide Resistance Management*, Environmental Protection Agency, Washington D.C.

Hueth D. and U. Regev, 1974, Optimal Agricultural Pest Management with Increasing Pest resistance, *American Journal of Agricultural Economics*, Vol. 56, pp. 543-551.

Hurley T.M., B.A. Babcock and R.L. Hellmich, 1997, Biotechnology and Pest resistance: An Economic Assessment of Refuges, Center for Agricultural and Rural Development, Working Paper 1997 WP 183, Iowa State University, Ames, IA.

Hurley T.M., S. Secchi, B.A. Babcock and R.L. Hellmich, 1999, Managing the Risk of European Corn Borer Resistance to Transgenic Corn: An Assessment of Refuge Recommendations, Center for Agricultural and Rural Development, Staff Report 99-SR88, Iowa State University, Ames, IA.

Lazarus W.F. and B.L. Dixon, 1984, Agricultural Pests as Common Property: Control of the Corn Rootworm, *American Journal of Agricultural Economics*, Vol. 66, pp.456-465.

Mason C.E., M.E. Rice, D.D. Calvin, J.W. Van Duyn, W.B. Showers, W.D. Hutchinson, J.F. Witkowski, R.A. Higgins, D.A. Onstad, and G.P. Dively, 1996, *European Corn Borer Ecology and Management*, North Central Regional Extension, Publication No.327, Iowa State University, Ames, IA.

Merritt C.R., 1998, The Commercialization of Transgenic Crops: The *Bt* Experience, In: British Crop Protection Council, *Biotechnology in Crop Protection: Facts and Fallacies*, Symposium Proceedings No.71, Farnham, Surrey, England.

Miranowski, J.A. and G.A. Carlson, 1986, Economic Issues in Public and Private Approaches to Preserving Pest Susceptibility, in Committee on Strategies for the Management of Pesticide Resistant Pest Populations, *Pesticide Resistance: Strategies and Tactics for Management*, National Academy Press, Washington D.C.

Onstad D. W. and C. A. Guse, 1999, Economic analysis of Transgenic maize and Nontransgenic Refuges for managing European corn Borer (Lepidoptera: Pyralidae), mimeo, Center for Economic Entomology, Illinois Natural History Survey, Champaign, IL.

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

Regev U., A.P. Gutierrez and G. Feder, 1976, Pests as a Common Property Resource: A Case Study of Alfalfa Weevil Control, *American Journal of Agricultural Economics*, Vol. 58, pp.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,* Vol. 10, pp.86-100.

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

Taylor C. R. and J.C. Hadley, 1975, Insecticide Resistance and the Evaluation of Control Strategies for an Insect Population, *The Canadian Entomologist*, Vol. 107, pp. 237-242.