

Incorporating resistance in pesticide management: a dynamic regional approach

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1 Introduction

Pesticide resistance in agricultural systems has been recognised as one of the world's top environmental problems for nearly two decades (UNEP 1979). Occurring in over 500 species of insects (Georghiou 1990), resistance is a genetic phenomenon whereby resistance-conferring genes accumulate in pest populations. Agricultural producers contending with pests that reduce the quality and/or quantity of outputs apply pesticides to increase profits or to decrease income variability. As resistance begins to accumulate, however, these treatments become less effective. Attempting to maintain expected crop yield, producers typically apply additional pesticide applications, yet over time, this practice compounds the problem by increasing environmental selection for resistant traits (Croft and Dunley 1993).

The accumulation of resistance in pest populations imposes substantial economic costs to agricultural production. Resistant pests continue to destroy crops, and the coincidental removal of natural enemies through pesticide treatments exacerbates the problem. A study of California cotton production, for example, reveals resistance costs of approximately \$45 to \$120 per hectare, totalling \$348 million per year (Pimentel et al. 1992). Extrapolating these results to other pesticide-intensive crops, nation-wide costs of resistance in the United States are estimated at \$1.4 billion per year (Pimentel et al. 1992). Despite attempts to deal with this problem, pesticide resistance continues to develop as a biological problem with economic consequences. Devising successful management strategies encompassing property rights and the complexity of biological and economic systems has proven difficult.

This paper proposes a regional model of how pesticide management strategies can incorporate resistance costs. The analysis relies on the assumption that management decisions affect the rate of resistance development, and trade-offs exist between current benefits and future costs of pesticide use. Treating pest susceptibility, or absence of resistance, as a resource,

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a method is derived to determine optimal pesticide use rates.² The temporal dimension of regional resistance accumulation is captured with a multi-period, dynamic optimisation model.

2 The need for regional management

Several factors influence the rate of spread, persistence, and general dynamics of resistance accumulation. These include an organism's: genetic features, such as number, dominance, and fitness of resistant genes; mode and rate of reproduction; and population dynamics and migration characteristics (Georghiou and Taylor 1986). Chemical factors such as pesticide type, frequency of applications, and dosage potency also influence resistance patterns (Green et al. 1990). Together, these natural and anthropogenic variables affect the ability of individual farmers to manage pesticide resistance.

Pest mobility and biological interactions often lead to pesticide resistance spillovers, in which pest resistance in one area is transported to another. This creates situations where individual farmer's actions are rarely isolated from those of others. The more pests are shared across farms, the more resistance-influencing actions will result in externalities affecting the usefulness of pesticides on farms within a common region (Carlson and Wetzstein 1993). The extent of these interactions will increase with higher levels of pest mobility, spatial uniformity, and resistance severity. These characteristics have led researchers to consider maintaining pest susceptibility as an open-access resource, whereby problems typically associated with managing common property resources apply (Clark and Carlson 1990). That is, individual farmer incentives to control pests may lead to levels of pesticide use that increase resistance within a region, and the added costs of resistance to others within the region will not fully factor into the farmer's decision. The unfortunate result of this condition is inefficient levels of resistance accumulation at a cost to all those within the region.

As with most common property resources, regional management is one way to internalise adverse externalities. Whereas individual farmers will tend to overapply pesticides, regional decisions are more likely to equate true marginal benefits and marginal costs (Miranowski and Carlson 1986). Thus, regional pesticide management is likely to result in more efficient control of the economic costs of resistance. Recognising advantages of regional management, various voluntary and compulsory organisational structures have emerged to control pesticide use. These range from community groups, co-operatives, and state and local authorities. The success of

² The method does not, however, address environmental externalities beyond resistance accumulation. While internalising costs associated with effects such as water contamination and harmful effects to fish and wildlife is possible, their consideration is beyond the scope of this paper.

regional initiatives to manage pesticide resistance depends on the effectiveness of these organisations. Studies have shown how regional pesticide management can result in higher individual, producer profits (e.g., Ahouissoussi et al. 1995; Carlson and Suguiyama 1985). Thus, regional management may not only be important for controlling pesticide resistance; such organisations may be more profitable.

Accordingly, the model developed in this paper is intended for implementation at the regional level. For reasons described above, a regional agency is thought to provide the only mechanism for successfully managing pesticide resistance. The technique could be applied to individual producers, but the negative consequences of resistance spillovers would remain. Therefore, regional management is necessary to internalise the negative externality of resistance spillovers, and regions should be determined based on degrees of pest mobility and spatial uniformity. While the specific organisational structure of the regional agency is not specified, the overall goal of maximising profits for all producers within the region is assumed.

3 The limitation of threshold models

Considering genetic and life history information on agricultural pests has become increasingly important to integrated pest management (IPM) strategies, which seek to farm more ecologically. An integral part of the IPM paradigm is the use of threshold decision models, which link pesticide use with actual pest numbers (Peck and Ellner 1997). In effect, crops are not treated with pesticides until insect populations reach damaging levels. The threshold decision framework is a widely used tool by agricultural producers for reducing pesticide loading in agroecosystems, yet incorporating resistance costs is limited by the static approach inherent to these models.

Threshold models are useful when producers must make decisions about whether or not to apply pesticide treatments. Assuming producers attempt to maximise profits when managing pests, threshold models are a single period application of the marginal principle. The decision relies on whether the marginal value of crop saved equals the marginal cost of treatment, and this condition occurs at some critical pest density, above which treatment is advisable. Thus, the problem is to determine the critical pest density. When managing pesticide use at the regional level, the problem is expanded to determining the critical pest density within the entire region.

Modifying an analysis presented by Carlson and Wetzstein (1993), a basic regional threshold model without treatment can be written as:

$$\pi = p(y - mN) - c \quad (1)$$

where π is regional profits, p is crop price, which is assumed to be constant for all producers in the region, y is expected yield in the region with no pest damage, m is damage in physical units of lost yield per pest unit,

N is the spatial density of pests within the region, and c is regional production costs.

This model follows the general rationale that profits are equal to total revenues (py) minus the costs of production (c) and the costs of pest damage (pmN). An expansion of (1) to include pesticide treatment can then be written as:

$$\pi = p[y - m(1 - b)N] - c - \tilde{c} \quad (2)$$

where b is the percent reduction in pest numbers, and \tilde{c} is the regional cost of pesticide treatment. Now, subtracting (1) from (2) yields a condition where only the marginal benefits and costs of the pesticide treatment are considered. Since the decision is only whether to apply a single treatment, the marginal cost is \tilde{c} , and the marginal benefit is equal to the marginal value of crop saved, or $pmbN$. The critical pest density (N^*) can then be determined by equating marginal benefits and marginal costs and solving for N^* , which yields:

$$N^* = \frac{\tilde{c}}{pmb} \quad (3)$$

Thus, marginal benefits exceed marginal costs at pest densities greater than N^* , at which point pesticide treatment begins to be profitable. At pest densities below N^* , treatment would not be advisable.

Threshold models of this type are useful for determining the appropriateness of pesticide treatments, but more detail is frequently necessary to capture actual biological and economic dynamics (Smith et al. 1987). Resistance build-up, for example, is one factor regional managers will not adequately consider if only threshold principles are used to determine pesticide use. A recent study by Peck and Ellner (1997) found that using regional economic thresholds can influence the rate of resistance build-up, but their paper did not mention how consideration of resistance within a threshold decision framework is limited. The static character of threshold models only enables existing levels of resistance to be incorporated. This would translate into adjusting the parameter b in (2). While such an approach does consider reduced susceptibility a cost of production, there is failure to recognise how resistance build-up is a dynamic function of previous pesticide applications, and current decisions influence future conditions. Therefore, fully incorporating resistance costs requires use of a dynamic optimisation model.

4 Dynamic optimisation with resistance costs

Dynamic optimisation models, unlike threshold models, enable consideration of an objective over several sequential periods. Attention is given to the fact that foregone benefits in current periods may result in greater benefits over several periods. In particular, recognition is possible of the way pesti-

cide management decisions affect the rate of resistance development, and trade-offs exist between current benefits and future costs, where current benefits are a reduction in pests and future costs are increased pest resistance.

The threshold model in (2) provides a foundation for developing a dynamic optimisation model that incorporates resistance costs over time. To focus on the relationship between resistance and pesticides, all factors of production, except the frequency of pesticide applications, are assumed to be constant. Crop price is also assumed to remain constant between periods. Three periods are used as the time horizon to demonstrate the model's features while maintaining simplicity of presentation. The model can be written as:

$$\begin{aligned} \text{Period 0: } \pi_0 &= p[y(A_0) - mNR] - c - \tilde{c}(A_0) \\ \text{Period 1: } \pi_1 &= p[y(A_1) - mNR(A_0)] - c - \tilde{c}(A_1) \\ \text{Period 2: } \pi_2 &= p[y(A_2) - mNR(A_0, A_1)] - c - \tilde{c}(A_2) \end{aligned} \quad (4)$$

where π_t is regional profits in period t ; A_t is regional frequency of pesticide applications in period t ; p is crop price; $y(A_t)$ is regional yield as a function of A_t ; m is damage in physical units of lost yield per pest unit; N is spatial density of pests within the region; R is the proportion of resistant pests, which may be given in period 0 and is a function of (A_0) and (A_0, A_1) in periods 1 and 2, respectively; c is regional production costs without treatment; and $\tilde{c}(A_t)$ is regional cost of pesticide treatment as a function of A_t .

Unlike threshold model (2), this model considers expected yield (y) and costs of pesticide treatment (\tilde{c}) as functions of pesticide use rate. The proportion of resistant pests (R) replaces $(1-b)$ in (2) and becomes a function of pesticide use rates in previous periods. As demonstrated in (4), the operational assumption is that reducing pesticide use rates is the only way to reduce pesticide resistance.

Given the generalised model in (4), biological and economic theory provide insights as to the functional relationships between pesticide use rate and y , \tilde{c} , and R . Signs of the first and second derivatives may be inferred in the following way. As pesticide use rate increases, the crop yield will increase at a decreasing rate (Comins 1986); $y'(A_t) > 0$ and $y''(A_t) < 0$. Assuming previous capital investments for pesticide applications, the cost of treatments per period will increase with the number of treatments at a constant rate, since there will only be material and application costs; $\tilde{c}'(A_t) > 0$ and $\tilde{c}''(A_t) = 0$. Increases in prior cumulative pesticide use (A_2) will lead

to increases in resistance at an increasing rate (Comins 1977); $R'(A_2) > 0$ and $R''(A_2) > 0$. Thus, some common functional forms are assumed for the purposes of further analysis:

$$\begin{aligned} \text{Period 0: } \pi_0 &= p[\ln A_0 - mN\gamma] - c - \alpha A_0 \\ \text{Period 1: } \pi_1 &= p[\ln A_1 - mN\gamma e^{A_0}] - c - \alpha A_1 \\ \text{Period 2: } \pi_2 &= p[\ln A_2 - mN\gamma e^{A_0 + A_1}] - c - \alpha A_2. \end{aligned} \quad (5)$$

Specifically, $y_t = \ln A_t$; $c_t = \alpha A_t$, where α is some constant greater than 0; and $R_t = \gamma e^{A_2}$, where $\gamma \in (0,1)$ is a constant representing the initial proportion of resistant pests.

Given the specified functional forms in (5), the regional management objective is to maximise profits over time by selecting the appropriate number of pesticide applications per period (A_t). Profit is the present value sum of net revenues in current and future periods; therefore, returns in periods 1 and 2 must be converted to present values. The formal objective function can be written as:

$$\text{Max } \pi = \pi_0 + \lambda_1 \pi_1 + \lambda_2 \pi_2 \quad (6)$$

where $\lambda_t = 1/(1+r)^t$, and r is the discount rate. Solving this maximisation problem with a recursive solution procedure ensures the optimal choice of A_t in current periods is consistent with optimal choices in previous and future periods (Bellman 1957). That is, determining optimal pesticide use rates in reverse chronological order captures interaction between periods.

The first step is to maximise period 2 with respect to pesticide use in period 2. This gives the optimal level of pesticide use in period 2, the final period. Next, the objective is to maximise period 1 with respect to pesticide use in period 1. This, however, includes the solution to the first step and yields optimal levels of pesticide use in period 1 for period 1 and period 2. Finally, period 0 is maximised with respect to optimal pesticide use in period 0, but this time, the maximisation includes periods 1 and 2 as well. Thus, the overall solution is the choice of optimal pesticide use over all periods.

The optimal conditions derived from the recursive solution procedure can be written as:

$$\begin{aligned} \text{Period 0: } \frac{p}{A_0} &= \alpha + pmN\gamma(\lambda_1 e^{A_0} + \lambda_2 e^{A_0 + A_1}) \\ \text{Period 1: } \frac{p}{A_1} &= \alpha + \lambda_2 pmN\gamma e^{A_0 + A_1} \\ \text{Period 2: } \frac{p}{A_2} &= \alpha \end{aligned} \quad (7)$$

where α is the cost per pesticide treatment. These conditions for each period identify the point where marginal benefits of pesticide use (p/A_t) equal marginal costs, including the costs of future resistance. The marginal cost in period 2 is simply the marginal cost of the pesticide application (α), since no future periods are within the model's scope. Periods 0 and 1, however, include the additional discounted marginal costs of future resistance, which is $pmN\gamma(\lambda_1 e^{A_0} + \lambda_2 e^{A_0+A_1})$ and $\lambda_2 pmNe^{A_0+A_1}$, respectively. Whereas period 1 only includes resistance costs for period 2, period 0 includes resistance costs for periods 1 and 2. Thus, the optimal levels of pesticide use for each period (A_t^*) can be expressed as an implicit function of parameters: $A_0^*(p, \alpha, r, m, N, \gamma, A_1)$, $A_1^*(p, \alpha, r, m, N, \gamma, A_0)$ and $A_2^*(p, \alpha)$.

5 Advantages and limitations of the model

The marginal conditions derived from the model demonstrate how regional resistance costs can be incorporated in pesticide use decisions. The standard economic solution of setting marginal benefits equal to marginal costs is maintained. The model's dynamic character, however, enables the marginal costs of each period to include the discounted marginal cost of resistance in subsequent periods. Thus, the cost of future resistance affects the marginal conditions from which pesticide use is derived. This approach moves beyond the static limitations of threshold decision models. While only three periods are used for demonstrative purposes, the time horizon could readily be extended.

Advantages are associated with the model's ability to incorporate actual biological conditions. Management regions could be determined based on the degree of spatial pest interactions or relative isolation. This approach would be best equipped to internalise externalities associated with individual management. The dynamic optimisation could also incorporate genetic information that may be known prior to pesticide applications. The nature of resistant genotypes and initial gene frequencies affect the rate of resistance development. Improvements in genetic technology and the high probability of specific pesticides having been used elsewhere make such preliminary information increasingly available. While the model is capable of incorporating this information, there is no such requirement. Information about initial levels of resistance could be captured in R of (4), or alternatively, $(1-b)$ from (2) could be used as an approximation. A two-period Lagrangian model presented by Regev et al. (1983) to consider resistance build-up does not provide this option. They assumed all prior information would remain unknown.

The specified relationship between resistance build-up and pesticide use provides another advantage. No general functional relationship exists for all

management situations, yet a reasonable starting point is that resistant genes exist at low equilibrium frequencies determined by the natural processes of pre-treatment mutation and adverse selection. Preferential selection for these genes begins once treatment regimes are initiated. Pesticide efficacy will continue until resistant genes begin spreading more and more rapidly through the population, at which point control measures fail (Comins 1986). Attempting to match these observed genetic dynamics, an exponential relationship between pesticide use and resistance build-up is specified. This contrasts other studies that may have oversimplified the genetic dynamics by specifying a linear functional relationship (Regev et al. 1983).

Specifying the exponential function is an improvement for generalised scenarios, but there is even more potential to develop the relationship between pesticides and resistance for particular pest situations. May and Dobson (1986), for example, have developed more detailed models for the timing of resistance development. Moreover, Comins (1977) predicted specific resistance dynamics for the sugarcane froghopper using a deterministic density dependent Mendelian model. Similar analyses conducted for other pest situations would be useful to include in pesticide management models. This information, however, may be difficult to obtain, and functions such as the exponential increase the model's generality, which is not trivial since the simplicity of models is important to pesticide managers when considering the relative usefulness of decision tools (Musser et al. 1986).

Failure to consider alternative IPM strategies or technological advancements is a limitation of the regional model presented here. The assumption is that only one technique is used to manage pests, and decreasing the frequency of pesticide applications is the only way to reduce resistance. While this assumption characterises the majority of large-scale agricultural producers, alternative IPM strategies frequently involve a diversity of techniques to control pests, which are not captured by this analysis. Alternating years of treatments and rotating through different pesticides are examples. The problem is that such techniques are under-utilised. Changes in weather patterns, new developments in pesticides, or biotechnologies may also threaten the efficiency of following the program outlined by the model. Current foregone profits to compensate future resistant costs may be lost if resistance levels are altered by climatic conditions or new developments emerge. Selecting appropriate time horizons for application of the model, however, could begin to incorporate factors such as assessments about the probability of new developments.

There must also be recognition that the optimal conditions derived in this model do not incorporate all social costs of pesticide use. The total costs resulting from environmental externalities associated with pesticides have been estimated in the United States at \$8 billion annually (Pimentel et al. 1992). These include human health effects, contaminated products, fish and

wildlife poisonings, and destruction of beneficial predators and parasites. Incorporating resistance is one step in the process of internalising adverse externalities of pesticide use, but research and policies designed to include these other social costs should be a priority as well.

In sum, pesticide resistance is an important factor in determining appropriate pest control strategies. Pest susceptibility is a valuable biological resource that imposes substantial economic costs when diminished. Regional management is an important means to controlling resistance build-up. The use of threshold decision models in IPM strategies is an effective way to reduce pesticide loading in agroecosystems; however, the decision framework is limited in its ability to incorporate resistance. Fully considering resistance in regional management strategies requires the use of a dynamic optimisation model. Building on the threshold approach, the model presented in this paper provides a conceptual approach as to how resistance can be incorporated in regional pesticide management. The analysis expands upon other techniques by attempting to integrate the complicated dimensions of property rights and biological and economic dynamics.

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