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Pesticides, Information, and Pest Management under Uncertainty

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World use of chemical pesticides has been expanding in the last two decades at an unprecedented rate, even though many of them have a negative effect on human health, wildlife, and economic activities. Langham and Edwards were among the first to attempt to measure the extent of such externalities. More refined models have been developed by Hueth and Regev, Taylor and Headley, and Feder and Regev. Because of the externalities inherent in pesticides, it would seem that their use is excessive.

This situation explains the increased efforts to develop technologies which substitute, in part, for pesticides while still reducing infestation levels and pest damage (Hall 1977a, b). An important and related line of action is the dissemination of information regarding old and new technologies. Imperfect information adds perceived uncertainty to the "real" uncertainty regarding various components of the ecosystem. Uncertainty has been hypothesized as a major factor in inducing pesticide use (Norgaard, p. 49). It is thus a matter of importance to investigate the impact of uncertainty on decisions made by risk-averse farmers regarding pesticide use and the way it affects reaction to various changes.

The purpose of this paper is to present such an analysis by introducing random elements in several components of the pest-pesticide-crop system. While adopting several simple features of earlier works on this topic, the model relies on two general hypotheses regarding individual behavior under risk: maximization of expected utility and risk aversion. Within the framework of such a model it is possible to evaluate the impact of improved information regarding old and new technologies as well as the relations between information acquisition, the cost of information, and the effects of pesticide use. In particular, the rationale for a market in pest management information is established.

The first section of this paper presents the pest-pesticide-crop model and farmer behavior. The next two sections analyze model implications given uncertainty regarding the rate of damage and rate of infestation. The following two sections derive, with the effects of two alternative forms of uncertainty with respect to the effectiveness of pesticides.

The Pest-Pesticide-Crop Model

The formulation of the model follows the design of the "decentralized" decision model of Feder and Regev (pp. 79–82). The latter, in turn, relies on earlier works such as Shoemaker (1973 a, b), Talpaz and Borosh, and Hall and Norgaard. In essence, these models are highly simplified descriptions of a complicated system. In the present case, the simplifications are necessary for an analysis of the role of risk in farmers' pest management decisions.

The model focuses on a single farmer within a region containing many similar units. At any given period (the definition of a period is discussed below), there are a number of pests (say \( N \)) present on the farm. Pest cause damage to the crop (or livestock) in an amount related to their number, say \( D(N) \) dollars. It is convenient to specify the damage function as

\[
D(N) = \delta \cdot N,
\]

where \( \delta \) is the damage caused by a single pest (assumed to be independent of the total number of pests).

In general, both \( \delta \) and \( N \) are viewed by the farmer as random variables (with respective means \( \bar{\delta} \) and \( \bar{N} \)), since the number of pests is not known, while the damage per pest is affected by temperature, humidity, differences in plant susceptibility at different periods, arrival of new pest biotypes, and other factors which are not known with certainty.

The farmer can affect \( N \) (or its distribution) within the time period considered by applying pesticides (the volume of which is denoted by \( x \)), thus eliminating a proportion \( k \) of the pest population. In some instances there are other pest-reducing actions which can be adopted, such as fences, screens, and plastic covers. However, these alternative control methods tend to be of a fixed nature, in the sense that once the control has been applied, the essence of the results.

\footnote{As in previous models, only a single crop and a single species of pest is considered. For simplicity, no differences between age groups are assumed. The analysis of a multicropp multispecies case is considerably more complicated, and will not change the essence of the results.}
it is effective for the whole season. The costs of such inputs will be included in a fixed cost element, say \( C_n \), which will be introduced in the profit function. The population of pests in the model implies those pests which are present in spite of the alternative (nonchemical) controls.

The impact of pesticides on pests is reflected through a "kill function" (or dosage response function) which relates the proportion of pest population killed \( (k) \) to the amount of pesticides applied, assuming decreasing returns to scale.

\[ k = k(x); k' > 0; k" < 0; k(0) = 0; k(\infty) = 1. \]

The kill function also may include a random element because pesticide effectiveness depends on such factors as weather, temperature, and wind.

The subject of the farmers' planning horizon and the length of the period considered in the model deserves special attention. As argued in Feder and Regev (p. 79), mobile pests can reinfest the farm several times within one crop season regardless of the amount of pesticides applied by the individual farmer. This is so, because with such pests it is the total degree of infestation in the region (on which the single farmer has only negligible control) that essentially determines the number of pests present on the farm once the effect of previous spraying dissipates. Under such circumstances, the farmer has no incentive for considering more than one period at a time, although there will be several periods in a crop season and possibly several applications of pesticides. Such a static decision framework is adopted in the present model. In the case of immobile pests (where a dynamic decision framework may be warranted), the static framework of the present model should be viewed as a simplification necessitated by the complications of analyzing a stochastic dynamic system, and the results should be qualified accordingly.

Aside from pesticides there are additional inputs which are related to pest management, although not all directly affect the number of pests present. Such inputs include the adoption of specific planting patterns, pest resistant varieties of plants, timing, and quantity of water and fertilizer applications. The adoption of such techniques can be viewed as a factor reducing the mean of the distribution of the damage level \( \delta \), while the cost is of a fixed nature and is not related to the amount of information (e.g., consultants charge a per acre rate). All other agricultural inputs are assumed to be applied in an optimal manner, and thus the only control variable in the system at this stage is the amount of pesticides to be applied. If pesticides are to be applied at all.

The contribution to operational profits during the period considered, say II, can be expressed as follows:

\[ II = (II_n - C_n) - \delta N[1 - k(x)] - cx, \]

where \((II_n - C_n)\) denotes profits that would have been realized if no pest were present (i.e., \( N = 0 \)); \( N(1 - k) \) is the number of pests surviving after pesticide application; and \( cx \) is the total cost of pesticide application \( (c \text{ denoting the cost per unit}) \). The distribution of damage levels may change in different periods as the plant develops, but is taken as given for any time period.

Assuming risk aversion on the part of farmers (Norgaard, Hall 1977b), a concave utility function \( U(II) \) is hypothesized, such that

\[ U = U(II); U' > 0; U" < 0. \]

The farmer's objective is the maximization of expected utility by choosing the appropriate level of pesticides, i.e.,

\[ \text{(5) } \max EU \{II_n - C_n - \delta N[1 - k(x)] - cx \}, \]

where \( E \) is the expectations operator.

First order conditions for optimum are given by

\[ \text{(6a) } \frac{\partial E(U)}{\partial x} = E \{ U' (\delta Nk' - c) \} = 0, \]

and the second order condition is satisfied because

\[ \text{(6b) } x \frac{\partial E(U)}{\partial x^2} = 0, \]

\[ \text{(7) } \frac{\partial^2 E(U)}{\partial x^2} = E \{ U" (\delta Nk') + E \{ U" (\delta Nk'') \} < 0. \]

The sign of (7) is verified by the assumptions \( U" < 0, k" < 0. \) The optimal amount of pesticides implied by (6a) and (6b) is "private," not social because the farmer ignores the damage inflicted on wildlife and humans by pesticide drifts and residues and because of the other externalities related to pesticides used.

The model presented above belongs to a general class involving decision making under uncertainty, the mathematical properties of which are analyzed in Feder (1977). Due to space considerations, the mathematical derivations of results will not be developed in the present paper. Rather, all the assertions in the following sections are rigorously verified in Feder (1978), and are available to interested readers upon request to the author.

An additional assumption is adopted at this stage regarding the attitudes towards risk: The Arrow-Pratt measure of absolute risk aversion (given by \(- U"/U\)) is assumed to be nonincreasing. That is, as income increases, aversion to risk is assumed to decline or remain constant, but not to increase. This is a plausible pattern of behavior, as argued by Arrow.

Implications of the Pest-Pesticide Model: Uncertainty in the Rate of Damage

It will be convenient to conduct the analysis by considering one random element at a time. We thus
start by assuming that the rate of damage per pest ($\delta$) is random, while all other variables and parameters (including $N$) are nonrandom. It is noted that in this framework riskiness increases with $N$ and decreases with $x$, i.e., pesticides reduce risk.

One result which is intuitively expected can be derived from equations (6a, 6b); that is, the level of pesticides application ($x$) increases with higher infestation levels ($N$). With higher pest numbers, the marginal benefit of pesticides increases while the marginal cost $c$ is constant, thus inducing higher volume of pesticide use.

Because the relation between $x$ and $N$ is monotonic, and because at $N = 0$ obviously $x = 0$, there must exist some level of $N$, say $N^*$, at which the farmer is indifferent between applying pesticides and not applying pesticides at all. At pest levels below $N^*$ pesticides are not applied. The critical pest level $N^*$ (defined by $c \{U[N^*k'xN^* - c] = 0\}$ is referred to as the “economic threshold population” and has been discussed extensively in the literature on pest management. We note that the economic threshold population is defined for a given distribution of $\delta$, for a given cost of pesticides application, and for a given fixed cost $C_f$.

It can be shown that a reduction in the average rate of damage ($\delta$) and an increase in the cost per unit of pesticide ($c$) will increase the level of the economic threshold ($N^*$) because such changes induce lower levels of pesticide use when $N$ is low. As for the fixed cost ($C_f$), it has no effect on $N^*$ when absolute risk aversion is constant (because in that case the relation between pesticide use and infestation level is unchanged). However, with decreasing absolute risk aversion (which implies more risk aversion at low levels of profit), an increase in the fixed cost will reduce expected levels of profit and thus induce higher pesticide use for any given level of infestation, so as to reduce risk. Because this is true for all $N$, it follows that the level of $N$ at which there is indifference between no pesticides and one unit of pesticides ($N^*$) is lower with higher fixed costs. Lower threshold levels imply more frequent use of pesticides because pesticides will be applied at infestation levels which would not initiate response otherwise and thus are not desirable from a social welfare point of view.

It should be noted that while the impact of an increase in pesticide costs on pesticide dosage may be ambiguous at high levels of infestation, it has an unambiguous negative effect on the frequency of application (through the increased economic threshold). At high levels of $N$, risk and risk aversion are high if absolute risk aversion is decreasing. In that case, an increase in pesticide cost ($c$) increases further risk aversion and the incentive to reduce pesticide use may be checked by a tendency to increase use so as to reduce risk at the margin. With constant absolute risk aversion, this ambiguity does not appear.

An increase in the mean of $\delta$ will induce a higher level of pesticide application. This is intuitively expected because, as the expected damage per pest increases, there is an incentive to further reduce the number of pests on the farm by applying more pesticides. This result, together with the impact of changes in $\delta$ on frequency of use, underscores the importance of policies for dissemination of technologies such as resistant plant varieties and other cultivation methods which reduce pest damage.

Because a reduction in $\delta$ increases expected utility, farmers will agree to pay some fixed cost (as long as their expected utility is not reduced) for the acquisition of information and technology leading to a given reduction in $\delta$. In fact, under such circumstances one would expect a commercial market to emerge where agents sell information leading to reduction in $\delta$ and also information leading to reduced uncertainty. Indeed, such a market is already functioning and growing fast where the agents are consultants not related to pesticide producers (Hall 1977a,b). These consultants charge a fixed rate per acre for their services. Such a cost is accommodated in the present model as a component in the fixed cost $C_f$, because it is not related to the level of pesticide use.

The result of acquiring information of this type is to reduce pesticide use and frequency of applications, even though the information is costly. This prediction is confirmed by the results in Hall (1977a), who concludes on the basis of a survey among cotton and citrus growers that pesticide use dropped 33%–66% for farmers using pest management consultants.

**The Impact of Risk**

It has been argued (Norgaard, p. 99) that a major motivation for pesticide applications is the provision of some “insurance” against damage, that is, the existence of uncertainty in the pest-pesticide system is by itself a factor leading to a higher and a more frequent use of chemicals. These intuitive impressions are verified by the present model. It can be shown that an increase in the degree of uncertainty regarding the damage per pest will cause an increase in the volume of pesticide application for any given level of $N$ and $c$, even though the mean value of $\delta$ remains unchanged. By increasing $x$, the farmers reduce the level of risk at the margin (which was increased due to the change in the distribution of $\delta$). This result is contrary to the standard result for the firm under production uncertainty, where an increase in uncertainty will cause a decline in production and a decrease in input use (Batra, p. 58). The explanation for this result is that in the present case the input (pesticides) reduces risk, while in standard models of the firm the inputs increase the risk.

The discussion is demonstrated in figure 1. Panel (a) describes two alternative distributions of the
damage per pest. Both distributions have an identical mean (\(\delta\)), but distribution \(d_2\) is more dispersed and implies a higher degree of risk relative to distribution \(d_1\) (Feder 1977, Rothschild and Stiglitz). Panel (b) presents the relationships between optimal pesticide level and the degree of infestation corresponding to two densities. The response function \(x(d_2)\) that corresponds to the more risky density function \(d_2\) lies to the left of \(x(d_1)\), implying higher pesticide applications for any infestation level above the economic threshold population \(N^*\).

In particular, the economic threshold population corresponding to \(d_2\) is lower than the threshold level under \(d_1\) (\(N^* < N^*\)). This verifies that with a higher level of uncertainty there will be a more frequent use of pesticides. Obviously, a response function corresponding to a situation of full certainty will lie to the right of \(x(d_1)\).

While part of the uncertainty regarding \(\delta\) is real (i.e., it is a result of genuine random factors), there is a portion which is perceived in the sense that it exists in the farmer's mind because of insufficient access to available information. Some of the variability of \(\delta\) can be reduced by the same technologies that reduce the mean of \(\delta\). However, even technologies that do not change the average rate of damage are beneficial for the farmer if they can reduce the degree of uncertainty. The provision of information having such an effect is obviously a matter of importance for social welfare because it will reduce pesticide use which currently may be excessive due to the disparity between private and social costs.

Furthermore, as reductions in the degree of uncertainty increase farmer's expected utility, farmers can be charged a fixed cost for such information. This would also explain the emergence of commercial markets for information leading to reduction in the degree of uncertainty (as well as the reduction in \(\delta\)). That such information is indeed being sold is evident from the findings in Hall (1977a, b), who reports a significant reduction in yield and profit variability for farmers using consultants. For a given reduction in the uncertainty, a farmer will pay a fixed cost, the upper limit of which is the level that retains his expected utility unchanged (relative to a situation with the original degree of uncertainty).

**Uncertainty Regarding the Degree of Infestation \((N)\)**

So far the analysis assumed that \(N\) was nonrandom. It is technically easy to replicate the preceding analysis assuming that \(N\) is random while \(\delta\) is fixed, because mathematically \(\delta\) and \(N\) perform the same role in the objective function. In this section, because \(N\) is random, the concept of economic threshold population \((N^*)\) needs to be replaced by the economic threshold mean population (to be denoted by \(\bar{N}\)). The latter concept refers to a distribution with a mean at such a level that leaves the farmer indifferent between applying some pesticides or not applying any (for a given level of \(\delta\) and costs per unit).

The uncertainty regarding \(N\) is due essentially to the inability of farmers to count the number of pests present at the beginning of the period. Through sampling, farmers generate a subjective distribution of \(N\), but the distribution is probably affected by prior beliefs and experiences. More efficient estimation techniques will reduce the degree of risk (without changing the mean). This will reduce the volume and frequency of pesticide use. Cultivation techniques that support a higher population of natural enemies of the pest and allow them to operate more efficiently will reduce the mean of \(N (\bar{N})\).
Similarly, the use of screens and special cultivation techniques may reduce pest accessibility to the crops (or livestock), which implies a reduction in \( N \) and thus a reduction in pesticide use.

Such changes increase farmers' expected utility; and, as indicated in the earlier discussion, they may be beneficial for society as a whole. For the same reasons as in the case of random \( \delta \), a commercial market for information leading to these changes in the distribution of \( N \) is functioning (obviously the same economic agents engage in selling such information). As in the earlier analysis, the net result of information acquisition is a reduction in the frequency and quantity of pesticide use, even though a fixed charge per acre is paid for such information.

Uncertainty Regarding the Effectiveness of Pesticides

The preceding analysis assumes that the farmer has perfect knowledge of the relation between pesticide and pest mortality (i.e., the kill function \( k(x) \) was treated as nonrandom). However, real and perceived uncertainty may in fact prevail with respect to this element of the system. For instance, the number of pests exposed at a particular point in time is random. Changing wind, humidity, and temperature conditions may influence the effectiveness of pesticides. Lack of information adds a subjective element of uncertainty, and thus it will be proper to investigate the impact of randomness in the kill function, assuming \( \delta \) and \( N \) to be nonrandom for simplicity.

A major problem in the analysis of this subject arises because there is no obvious way of specifying the element of risk in \( k(x) \). In general, two possible situations may prevail: (a) the variation in pest response to the pesticide declines for higher dosages of pesticide; and (b) the variation increases with higher dosages. These two situations are demonstrated in figure 2, under panels a and b, respectively. In reality there are probably pesticides of both types. The first type is characterized by long durability of effect and is highly toxic, while the second is of short residue and/or low toxicity. Parathion and DDT are examples of type a, while Malathion and Pyrethroids belong to the second group (Gutierrez).

A specification that reflects situation (a) implies that the degree of variability declines as the average rate of pest survival declines. One possible way of approximating such a relation is

\[
1 - k(x) = \epsilon [1 - h(x)],
\]

where \( \epsilon \) is random with mean \( \bar{\epsilon} \) and \( h(x) \) has properties similar to those of \( k(x) \), as specified in equation (2). The term \( [1 - k(x)] \) is the actual (random) survival rate of pests for any given \( x \). The term \( [1 - h(x)] \) may be viewed as the theoretical survival rate under ideal (laboratory) conditions. The random factor \( \epsilon \) reflects various environmental and biological factors as well as subjective uncertainty.

Adopting specification (8), the model remains technically the same as in the previous sections except that \( \epsilon \) replaces \( \delta \) or \( N \) as the random variable. The results of the earlier analysis then apply directly: the volume of pesticide application in a given period increases with the degree of uncertainty regarding pesticide effectiveness because there is an incentive to move into the range of higher \( x \) values where the degree of variability of pesticide impact is reduced. This implies also that the threshold level of \( N \) is reduced with higher \( \epsilon \) variability, yielding a more frequent use of pesticides. A reduction in \( \epsilon \) which reflects a more potent pesticide, will reduce pesticide use. However, even with a more effective pesticide, a smaller quantity is needed to maintain a given level of average kill. Intuition may be somewhat misleading in this case since it would seem that with higher effectiveness and unchanged price more will be demanded of the pesticide.

The increased effectiveness of the pesticide may be achieved either by obtaining information as to the proper way of its application, or by buying an improved variety of the chemical. In the first case, an analysis analogous to that of previous sections demonstrates that the farmers will agree to pay the fixed cost \( (C_e) \) required to obtain and apply the new knowledge, and that whatever the fixed cost is the use of pesticide will decline. In the case of improved material, farmers are willing to pay a higher variable cost \( (c) \) for the better chemical as long as their expected utility is not reduced. It can be shown, however, that even if they pay the maximal price for improved chemicals (i.e., a price such that their expected utility remains unchanged), the overall amount of pesticides used will be lower. It is thus to the benefit of society to promote the development of pesticides and methods of application that perform more effectively under field conditions (even though they are not more effective in the laboratory) provided they do not cause higher environmental damage. Reduction of the uncertainty in pesticide effectiveness is another worthy social goal.

While pest management consultants’ work probably involves such effects, it is not obvious to what extent a chemical’s salesman will provide information to this end. Reduction of \( \epsilon \) through the sale of more potent pesticides may be consistent with the agent’s aims, because a higher price for the better material is possible, and the agent’s revenue may still increase. However, since it is not common for salesmen to charge for advice, it is not likely that they will provide information reducing the variabil-

2 The pesticide is more potent in the sense that under field conditions it is more effective than before (e.g., because it is less sensitive to humidity levels). The performance under ideal laboratory conditions (reflected by \( h(x) \), is not changed when \( \epsilon \) is changed.
ity in ε. Neither will they be enthusiastic about reducing the means of δ, N, or their degree of variation.

The preceding analysis assumed a specification consistent with situation (a) of figure 2. An approximation for situation (b) is given by

\[ k(x) = \varepsilon h(x), \]

where \( h(x) \), as before, is the kill rate under ideal conditions, and \( \varepsilon \) is random with mean \( \bar{\varepsilon} \). It can be shown that specification (9) implies higher variability of the kill rate with higher levels of \( x \), consistent with panel (b) of figure 2. With specification (9) some of the results of the model are contrary to those of the earlier analysis. For instance, an increase in uncertainty regarding pesticide effectiveness (while \( \bar{\varepsilon} \) remains constant) will cause a decline in the amount of pesticide applied and will reduce the frequency of applications by increasing the threshold level of \( N \). The difference in impact (relative to the earlier analysis) is a result of the fact that under specification (9) pesticides are not a risk-reducing input, but rather with higher \( x \) levels the distribution of utility becomes more dispersed. An increase in uncertainty regarding \( \varepsilon \) induces the farmer to retreat into lower levels of \( x \), such that risk is reduced.

It is this variety of pesticides for which chemical salesmen have an incentive to provide farmers with information leading to reduced perceived uncertainty regarding effectiveness of the pesticide. Similarly, because with this type of pesticide an increase in the mean of \( \varepsilon (\bar{\varepsilon}) \) will induce a higher and more frequent pesticide use, salesmen have an incentive to promote pesticide varieties and application technologies that increase pesticide effectiveness in the field, while such was not the case with the alternative specification of \( k(x) \), unless an appropriately higher cost could be charged for more potent pesticides.

Because farmer's expected utility is increased by reduced uncertainty and higher \( \bar{\varepsilon} \), a higher fixed or variable cost related to these changes will be acceptable (up to the point where expected utility remains the same as in the initial situation). Consultants therefore will be inducing higher pesticide use when providing information on this type of chemical. However, as evidence suggests that with consultants the use of pesticides decreases, it must be concluded that in most cases the effect of pesticide-substituting information provided by consultants (regarding \( \delta \) and \( N \)) outweighs the effect of information regarding pesticides of specification (9).

Results regarding changes in fixed costs in the present version of the model are contrary to those of the earlier sections, while for a change in variable costs (c) it is possible to conclude \( \frac{\partial x}{\partial c} < 0 \) whether or not absolute risk aversion is constant. However, only under constant absolute risk aversion one can show that pesticide use increases with higher \( \delta \) and \( N \) levels, while with decreasing absolute risk aversion the sign is inconclusive. This follows from the fact that with higher levels of \( \delta \) and \( N \), the marginal benefit of spraying increases, but, on the other hand, such circumstances induce higher risk aversion and therefore reluctance to increase \( x \) (thereby increasing risk). The economic threshold level of \( N \) can be shown to be negatively related to the level of \( \delta \).

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