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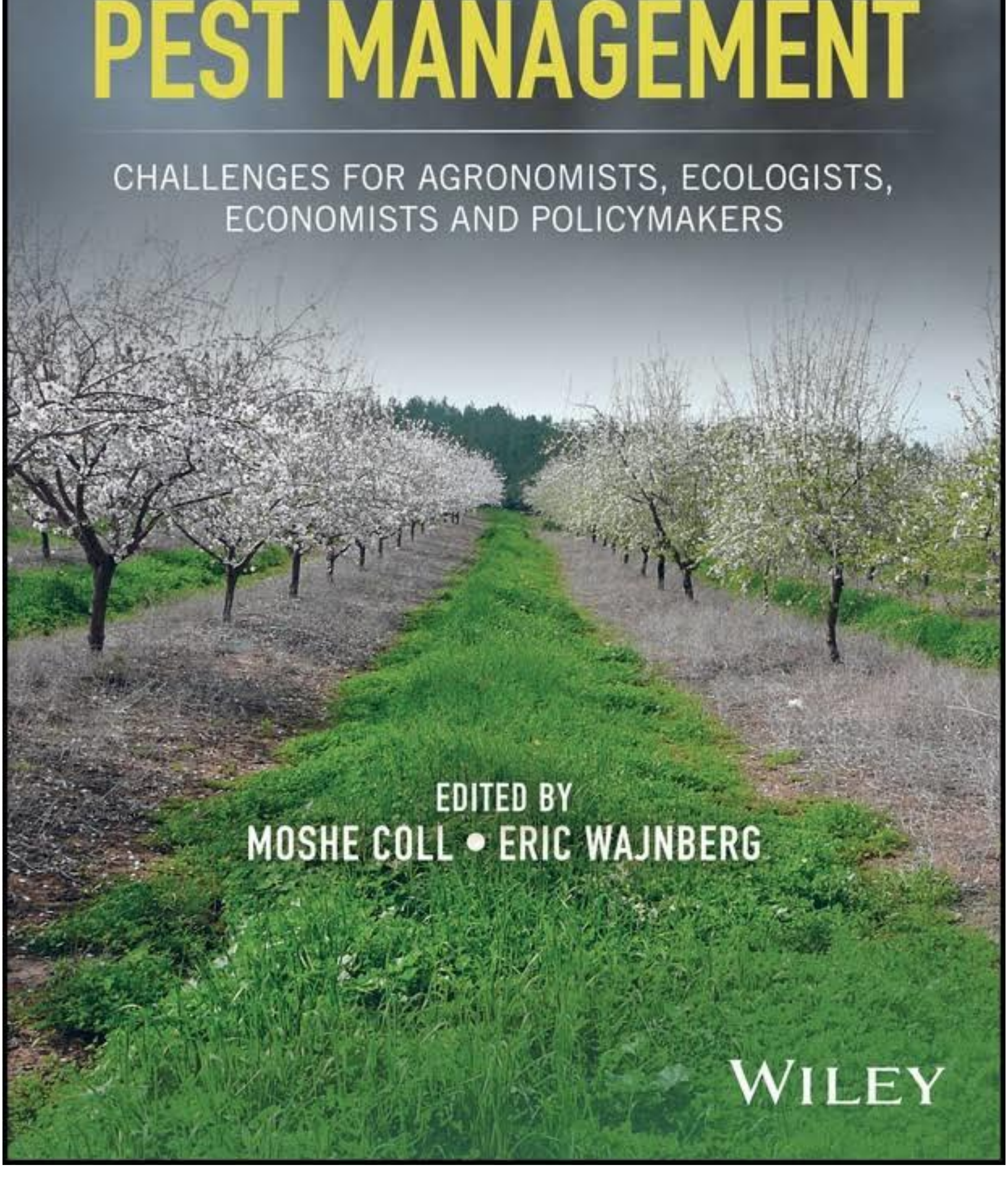

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Chapter 3

The Economics of Alternative Pest Management Strategies: Basic Assessment and Environmental Uncertainties

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The Economics of Alternative Pest Management Strategies: Basic Assessment and Environmental Uncertainties

ABSTRACT

This chapter focuses on the basic economics of choices about pest management at farm and industry levels. In doing so, it first of all examines optimal choices at the farm level assuming that farmers want to maximize their profit. Existing economic threshold models for deciding on pest management at the farm level are then adjusted, for instance, to take account of uncertainties (arising in many cases, from environmental influences) and to allow for the impact of pests not only on crop yields but also on the quality of the produce. In addition, several other factors which influence optimal strategies and choices of pest control techniques at the farm level are explored. These include the size of the cropping area to be treated, the alternative treatment options, and the timing of treatment. Account is taken of the fact that delay in treatment can reduce uncertainty about the economic benefits of pest control (e.g. by reducing uncertainty about the level of pest infestation) but also add to the cost of treatment. Economic issues involved in choosing herbicide resistant crops and Bt modified crops to manage pests are explored. This analysis is followed by a general discussion of additional farm-level economic issues which merit consideration. The basic economic analysis of the industry-wide value of pest control follows, and is extended to take account of the effects of pest control on the quality of the products supplied. In order to round out this introductory overview of the economics of pest management, further relevant industry-wide and community issues (such as the nature of public versus private benefit) are identified (but not analysed in depth) before concluding. The analysis is supported by examples.

1. Introduction

The management of pest populations is an important part of human control of the environment. Overall, it results in increases in the productivity of bio-industries, adds to the quality of their production and increases human welfare. However, some production methods can have negative consequences for human well-being and the environment. In most contemporary economies, decisions about the management of pests (which adversely affect bio-industries) are driven by the desire of the proprietors of production units (e.g. farms) to maximize their profit. Determining pest management strategies to achieve this objective can be very challenging given that the optimal choice usually depends on several uncertain variables. In part, this is due to uncertainty about relevant environmental factors. A further complication is that optimal private profit-maximizing decisions about pest control may not result in socially optimal choices necessitating state intervention in pest control practices.

The purpose of this chapter is to outline the basic economics of choices about pest management focusing initially on decisions at the level of the production unit and then considering economic implications of these choices at the industry level. First, a basic threshold (Smith, 1988) model is introduced. This assumes that a one-off decision is made about whether or not to adopt a given technique to control a pest. The optimal choice is determined initially by assuming certainty (for example, about the density of the pest) and then subsequently by allowing for uncertainty. Various extensions to the basic model are provided. Similar analysis is then undertaken assuming that alternative pest control techniques are available at the farm level. The main focus here is on optimal choice between available alternative techniques. This is followed by an outline of a standard economic method which has been used to evaluate pest control at the industry level and its limitations and extensions are explored

2. Economic Decisions at Farm-Level based on Threshold Models Assuming Use of a Given Technique and Certainty

A simple standard model

A simple economic model, available in the early literature on this subject (Stern, 1966; Headley, 1968), assumes that farmers know or anticipate a particular level of infestation of a crop by a pest and have a specific technique available to them for eliminating the pest. Use of this technique involves a given level of cost per hectare (ha) and the economic benefit achieved by a farmer is the avoidance of the loss in profit which would occur in the absence of use of this technique, that is profit loss avoided by eliminating the pest (Headley, 1972; Carlson, 1970; Auld and Tisdell, 1986; Naranjo et al., 2015). This benefit usually increases with the level of pest infestation avoided by the pest control treatment but may be quite variable (Falkenberg et al., 2012).

Note that in this analysis all values are to be taken as referring to per ha values unless otherwise specified. Let us consider the first basic model for determining the economics of pest control. Where x is the level of infestation of a crop by a pest (that is, the density of the pest per hectare), V is the increase in profit per ha obtained by eliminating it, and C is the cost per ha of doing so, the net benefit per ha of eliminating the pest is

$$G = V(x) - C \tag{1}$$

If this expression is positive, it pays to undertake the pest control; and if this expression is negative it provides a justification for the farmer not to engage in pest control.[1] An example is provided in Figure 1. The curve OAB represents the loss in value of crop production experienced by a farmer as a function of the density of a pest and line EH represents the cost of eliminating the pest. If $x < x_k$, the rational producer will not control the pest but if $x > x_k$ a producer will do so. Consequently, x_k is the threshold value where the management costs equal the benefit derived from that management action (Headley, 1972).

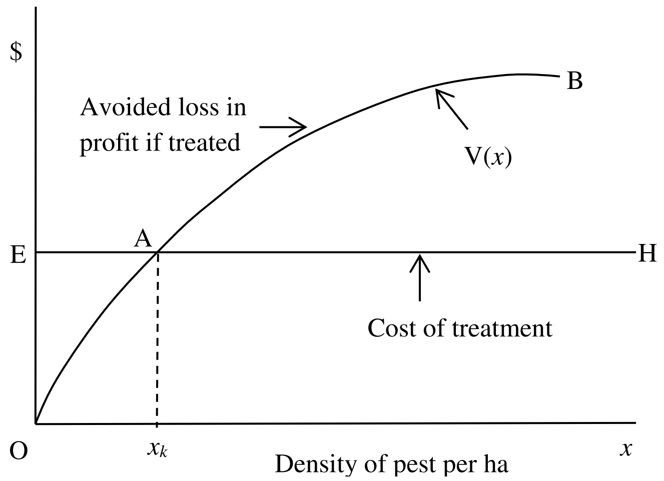

Figure 1: A typical representation of the threshold economic model for deciding whether or not it is economic to control a pest.

It is sometimes assumed that the reduction in the yield of the crop due to the presence of pest times the price per unit of the output of the crop represents the extra economic benefit the farmer will obtain by eliminating the pest.[2] This is actually the extra revenue, R, generated by controlling the pest. Therefore, where $f(x)$ represents the extra yield obtained by making sure the pest is eliminated and p is the price per unit of the output of the crop.

$$R(x) = pf(x) \tag{2}$$

Usually, p is assumed to be a constant, probably on the assumption that individual farmers are unable to influence the price they receive for their products. However, this assumes that increased yield does not involve any increase in production costs such as extra harvesting costs.

The possibility that it does should be allowed for. Therefore, if $\lambda(x)$ represents the extra cost of processing the higher yield, the economic value of the extra yield if a level of pest infestation of x is avoided, is

$$V(x) = pf(x) - \lambda(x) \tag{3}$$

Also this basic economic model of pest control can be extended further to allow for additional possibilities.

Extensions of the basic model

First, the presence of pest in many cases not only affects the yield of a crop but also the quality of the produce (e.g. weed seeds contaminating harvested grain). Poorer quality produce will fetch a lower price, and if its quality is too poor, it may be unsaleable. So for some products p is likely to be a function of x. Therefore, for greater generality, Equation (2) can be re-expressed as:

$$R(x) = p(x)\, f(x) \tag{4}$$

where, as a rule, $dp/dx < o$, that is the price per unit received for produce falls with the level of pest infestation. Note that it is still appropriate to assume that an individual farmer is unable to influence the price received for his/her produce of a given quality. The type of relationship shown in Figure 2 by relationship may be common. For produce unaffected by a pest, a price of OH is received but the price falls with greater pest infestation. For damages occurring to the produce when the density of a pest is $x \geq x_m$, the output from the crop is unsaleable. In some cases, however, it may be possible to sort pest-affected produce from the unaffected. This will add to costs and reduce effective yields. This case is not analysed here.

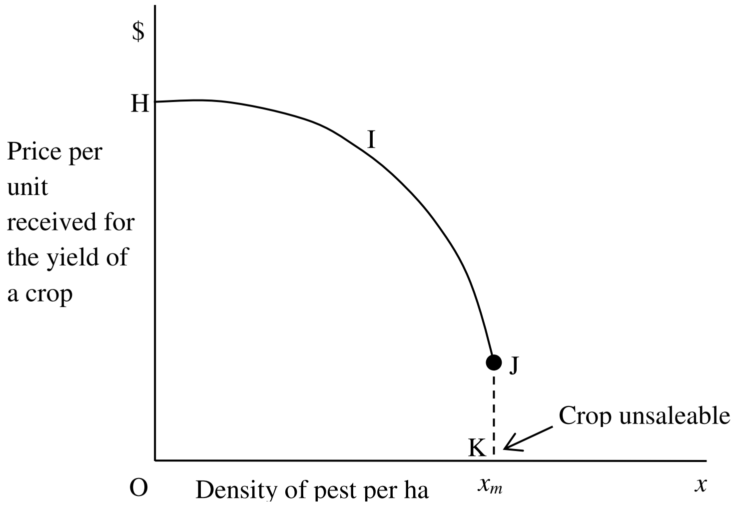

Figure 2: Illustration of the relationship for the price received per unit yield of some crops as a function of the level of pest infestation.

Note that because of the adverse quality impacts of a pest, it is possible for V(x) to increase at an increasing rate rather than at a decreasing rate as is often assumed.

A second aspect is that the pest treatment may not be fully effective in eliminating the pest, perhaps due to the timing of the application or environmental factors (Myers et al., 2005; Carlson et al., 2011). This can easily be allowed for in this threshold-type of analysis. Let x_r represent the density of the pest prior to treatment and x_t represent its density after treatment. Then, the net economic gain from treatment is:

$$G = V(x_r) - V(x_t) - C \qquad (5)$$

If this expression is positive, it pays to treat the pest but not if it is negative.

A third possibility is that the cost of controlling a pest may not be independent of its density. For example, costs can rise as density increases, for example labour costs increase as density increases when the management option is weeding by hand or cut and painting[3] woody weeds. This can result in a 'double threshold'. It may not pay to control the pest if it is present at a low density, nor if it occurs at a high density. An example is shown in Figure 3. In the case illustrated, it does not pay to control the pest if its density is less than x_1 or greater than x_2.

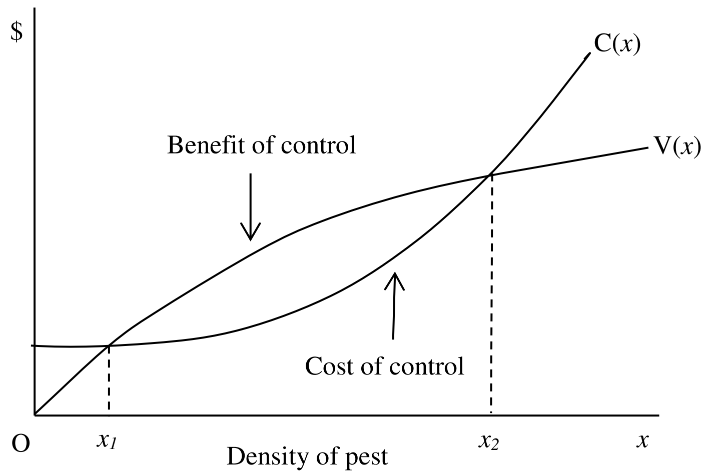

Figure 3: Illustration of a case in which two pest-control thresholds exist

A fourth important aspect of the economics of pest control is that the cost per hectare of pest control often depends on the size of the cropping area which needs to be treated to control the pest. While this is not true for all methods of control, it is true for many. This aspect will be covered when the economics of alternative techniques for controlling pests is discussed below.

If a number of alternative techniques (methods) are available to control a pest then the one adopted should be the least cost one for the level of pest-infestation experienced. Therefore, in Figure 3, C(x) should correspond to the lower envelope of the cost curve corresponding to all the available techniques (methods) for controlling the pest. Another possible response to the increased prevalence of a pest is for a farmer to change the type of produce being produced so it is less attractive to the pest. For example, due to increased numbers of feral pigs (Tisdell, 1982, Ch. 2, especially p.3) and wild dogs, some graziers in Australia have switched from running sheep to grazing cattle because this has become the most profitable alternative. Cattle are unlikely to be attacked by these pests.

Note that the standard economic threshold model does not allow for variability in the level of pest density in a field. However, the model can be adjusted to allow for this (Auld and Tisdell, 1988). Observe also that these single economic threshold models do not take account of the dynamics of pest reproduction on farm, and the possible immigration of the pest from elsewhere. Tisdell (1982, pp. 361-378) specifically discusses both these issues in relation to the Headley's (1972) threshold models. Yokomizo et al. (2009) take some account of relevant population reproduction issues.

Basic economic threshold models also do not take account of the management of multiple pests and the impact of controls on economically beneficial organisms. In addition, some pest control techniques (although effective in controlling a pest) may have some negative effect on crop/produce yields and its quality and on the price received for the output.

Implications of the above basic models summarised

Despite these limitations, several inferences can be drawn from the above basic models. These are as follows. If other things are held constant and if $V'(x) > 0$ throughout, pest control is more likely to be profitable:

1. The higher is the price per unit obtained for the yield of a crop;
2. The larger is the amount of yield saved as a result of treatment;
3. The lower is the cost of control;

4. The larger is the reduction in the price of the product avoided as a result of pest control; and
5. The larger is the level of pest infestation avoided as a result of pest control.

3. Economic Decisions at Farm-Level Based on Threshold Models Assuming a Given Technique and Uncertainty

Most variables of relevance for decisions about whether or not to undertake pest control are subject to uncertainty. These variables include the effectiveness of the control (the kill rate), the price of the product, and the increase in yield attributable to the treatment of the pest. Both the kill rate and the increase in yield can be expected to be influenced by environmental factors. Furthermore, in many situations, the decision about whether or not to institute a pest control measure is made before the density of the pest is known. This applies particularly to the common practice of prophylactic applications of fungicides for disease management in vineyards and orchards, before the disease is present and/or symptoms are present. In these circumstances, optimal decisions at farm-level will depend on attitudes of farmers to risk-bearing. Nevertheless, in most cases, we can narrow optimal choices down to a restricted set, no matter what is the attitude of a farmer to risk-bearing. Let us consider the consequences of uncertainty for decisions about whether or not to control a pest for two different types of situations. In the first case, it is assumed that the benefit of controlling the pest is uncertain. In the second case, it is supposed that the (anticipated) level of pest infestation is uncertain. Bear in mind that both uncertainties can occur together.

The benefit function for pest control is uncertain

In Figure 4, the benefit function is uncertain.[4] It is believed that it may be as low as shown by the relationship OCD, $V_1(x)$, or as high as OAB, $V_2(x)$, and that it may assume any value in between. Consequently, in these circumstances (given the goal of profit maximization), it will always be rational for a farmer to undertake pest treatment of $x > x_2$ and not to do so if $x < x_1$. For values of x in the range $x_1 < x < x_2$, the choice of whether or not to undertake pest control depends on attitudes to risk-bearing.

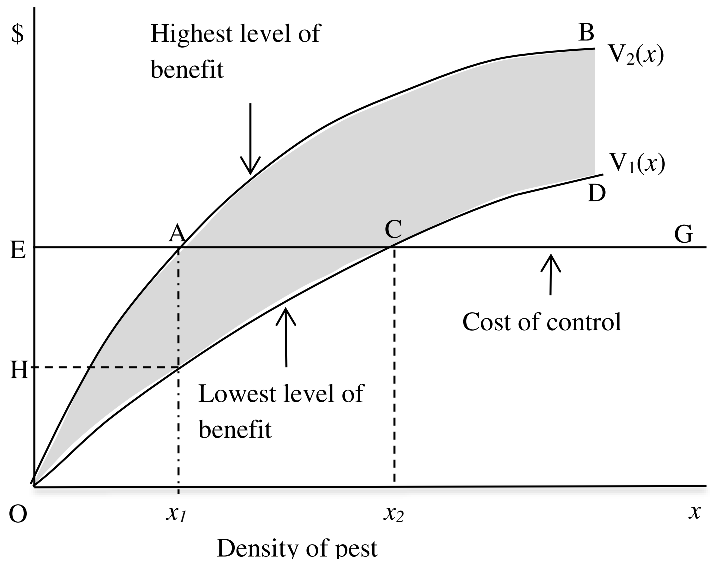

Figure 4: A case in which the benefit function of pest control is uncertain

Consider some different cases. If the farmers' prime objective is to minimize risk, then he or she may adopt the minimax loss rule. This rule requires that the maximum possible loss be minimized. In the case illustrated, the maximum possible loss occurs when the benefit function is $V_1(x)$ and the extent of this loss is at its highest level when $x = x_1$ (it is then equivalent to the distance EH) and tapers off as x approaches x_2. In these circumstances, the adoption of this risk-adverse strategy reduces the willingness of farmers to control the pest. Therefore, it is not always the case that a high preference for income security favours the control of a pest. At the other end of the spectrum, farmers who like to gamble may adopt a maximax strategy, that is, a strategy which maximizes their profit in the most favourable circumstances. They will assume (in the case shown in Figure 4) that the benefit function for control of the pest is $V_2(x)$. Therefore, if the range of possible levels of pest infestation is $x_1 \leq x \leq x_2$, they will control the pest.

In some cases, the farmer may weigh the likelihood of different benefit functions occurring by their subjective probabilities and maximize expected net benefit of pest control on that basis. Depending on the distribution of probabilities, this will result in a value of x between x_1 and x_2 becoming the critical value for determining whether or not to undertake pest control. If the probabilities are skewed towards $V_2(x)$, control will occur at a lower pest density than if they are skewed towards $V_1(x)$. Most farmers operate within this framework of uncertainty. Moreover the case illustrated in Figure 4 represents one year or growing season. If the current year's control impacts on future pest levels, the threshold density x_1 may be significantly lower if one is considering longer term benefits. This particularly applies to annual weeds in annual crops such as wheat. In practice, threshold levels for weed density are very low (e.g. Trezzi et al., 2015).

The level of pest infestation is uncertain

Another important case is that in which the density of the pest is uncertain at the time pest control is undertaken. This is so for pre-emergence pest controls, and is effectively the case for use of Bt modified plants. It is, however, common in many situations. It can, for example, be difficult to predict from the density of their eggs the subsequent levels of infestation by caterpillars of lepidoptera species. (Paula-Moraes et al., 2013).[5] Risk-aversion strongly favours the adoption of pest control in these cases. Some of the effects on the decision of whether or not to control a pest can be illustrated by Figure 5 if there is uncertainty about the level of pest infestation.

In Figure 5, the same basic assumptions are made as those relating to Figure 1. However, the economic benefit function (disregarding control costs) of eliminating a pest are in this illustration, assumed to be incremental at an increasing rate, that is, it is supposed $V''(x) > 0$. Nevertheless, depending on circumstances, $V''(x)$ may be positive, negative or zero. The likelihood is high that $V''(x)$ is positive if the price received for a pest damaged product falls rapidly with the extent of its damage by the pest.

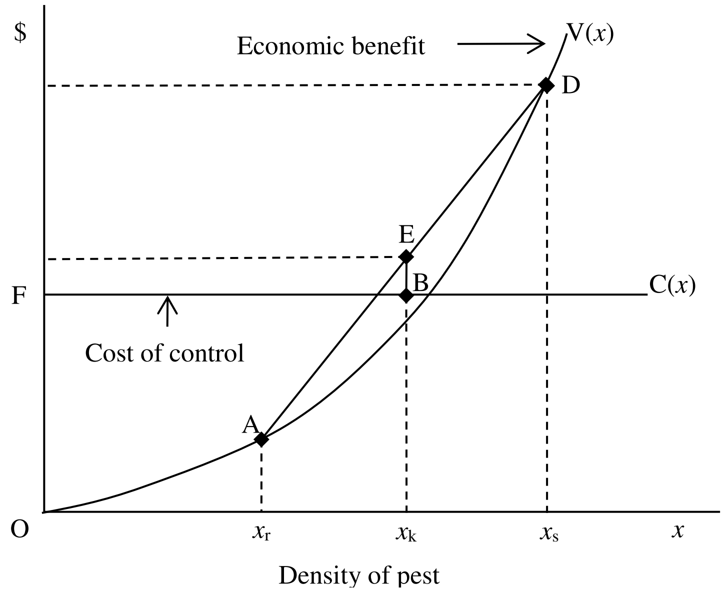

Figure 5: Diagram to illustrate influences on decisions to undertake pest control if there is uncertainty about the level of a pest infestation when pest control is undertaken

Given the relationships illustrated in Figure 5, first note that if all the possible densities of the pest are less than x_r (the boundary between control and non-control of the pest being optimal), it does not rationally pay to control the pest. Similarly, if the set of possible densities of the pest all exceed x_k, it is always rational to undertake pest control irrespective of attitudes of the pest manager to taking risks and the distribution of probable values of x. These are strong results. They hold for all possible forms of V(x) for which V(x) is less than C(x) for $x < x_k$, and for which V(x) exceeds C(x) for $x > x_k$. However, the optimal decision about whether or not to control a pest is sensitive to attitudes to risk-taking (and some other factors) and the density of the pest when $x_r \leq x \leq x_s$.

In these circumstances, a highly risk-averse approach to decision making will result in a decision to control the pest. For example, if the minimax loss approach is adopted, it results in the pest manager deciding to undertake pest control. This decision prevents the largest possible reduction in profit, V(x_s), occurring.

For a decision-maker with the objective of minimizing the expected reduction in profit by deciding whether or not to engage in pest control, the situation is more complicated. In this case, the optimal decision is sensitive to the nature of the probability distribution of x and to the sign and size of the second derivative of V(x). As the range of uncertain values of x increases (and if the expected value of x remains constant), this tends to increase the likelihood, that pest control minimizes the expected loss in profit, if $V''(x) > 0$. The opposite is the case if $V''(x) < 0$. A simple illustration of this is provided in Figure 5. If the value of x is certain and equal to x_k, there is no net benefit to be had by engaging in pest control because V(x) = C(x). However, assuming that x_r and x_s are equidistant from x_k and that each has a probability of 0.5, the expected net benefit from controlling the pest is equal to the distance EB. It pays to control the pest in this case. The further apart are x_r and x_s the greater is the net benefit to be obtained by controlling the pest. The opposite relationship occur if $V''(x) < 0$.

Taking another example, suppose that

$$V(x) = ax \pm bx^2 \tag{6}$$

Then, if E[V] represents the expected value of V(x),

$$E[V] = aE[x] \pm bE[x]^2 \pm bV(x) \quad (7)$$

In this expression, var x represents the variance of x and is a measure of the extent of uncertainty about its value. Hence, given E[x], the loss in profit if pest control is not undertaken, will increase with the size of b and the value of var x if b is positive. Consequently, with E[x] constant, the likelihood that pest control is optimal rises. If b is negative, the opposite relationship occurs. In some cases, a quadratic function is a close approximation to V(x). Note that only the branches of parabolas in the positive quadrant of Cartesian space are relevant. In all these cases, given that $V(x) > 0$ for all x, E[V] increases with E[x], var x constant. Consequently, it is also true that as the expected level of pest infestation rises, (other things being held constant) and if the aim of the decision-maker is to maximize his or her expected profit, the likelihood of pest control being optimal increases.

In general, when the economic penalties imposed by a pest infestation tend to escalate rapidly with that level of infestation, increased uncertainty about the level of infestation increases the likelihood that pest control is a farmer's superior economic choice compared to no control. Research on the likelihood of pest outbreaks (Guillemin et al., 2013; Izquierdo et al., 2013) will reduce the level of uncertainty. Increased information about the magnitude of pest outbreaks not only improves the profit-maximizing decisions of farmers (because they are less likely to undertake pest control when they know that the level of pest infestation will be lower than they would have otherwise thought possible) but it also has social benefits if pest controls have negative environmental spillovers or health risks.[6] Furthermore, the most economic control of some pests requires the collective gathering of information and in some instances, collective action for instance, by state bodies, for example, in the case of highly mobile pests, such as locusts.

4. Choice of Alternative Pest Control Techniques at Farm Level Assuming Certainty

Methods of controlling pests can be classified in several different ways. For example, this can be done according to:

- The means used to kill a pest or limit its population e.g. destruction of the pest by hand, machinery, chemical pesticide use, biologically based controls;
- In relevant cases, the method used to distribute pesticides; and
- According to the effectiveness of the method adopted for controlling the pest.

Consider situations in which the optimal choice of a method for distributing a pesticide, for example, spraying it on a crop, varies with the size of the area to be treated. This analysis enables the modelling considered in Section 2 to be extended.

Cost minimization

Assume that a pesticide is to be sprayed onto a crop, and suppose that no matter what method is used to spray a pesticide that it is equally effective in controlling a pest. The least cost per ha method of spraying the crop should be chosen in order to maximize the profitability of pest control. For example, the lowest cost per hectare of spraying a small area maybe by hand, but if a large area is to be treated, the least cost method per ha, may be by the use of a tractor or if the area is quite large, by a plane or a drone.

The following indicates (for a simple case) how this matter can be analysed. Suppose that two techniques, I and II are available for spraying a pesticide and that in each case, the cost per hectare of spraying it declines with the size of the area to be sprayed. Using technique II to spray a small area results in greater cost per ha than using technique I but the position is reversed when a larger area needs to be sprayed. This relationship may exist because using technique II results in higher overhead costs (fixed costs) than does using technique I but lower variable costs.

Figure 6 illustrates this choice problem. Let function $C_1(z)$ represent the cost per hectare of use of the pesticide if technique I is adopted. The variable z indicates the size of the area to be treated. For example, the relationship $C_1(z)$ might be as shown by KLM in Figure 6. Similarly let $C_2(z)$ represent the cost per ha of controlling a pest when technique II is used. This is represented in Figure 6 by curve HLJ.

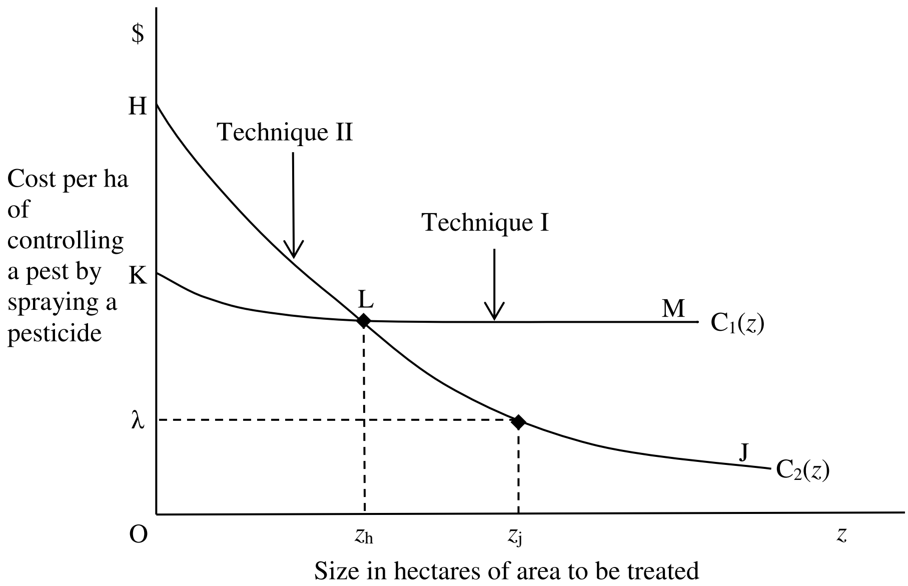

Figure 6: A case in which the optimal method of applying a pesticide depends on size of the area to be treated.

In the case illustrated in Figure 6, the costs per ha of controlling a pest are minimized when $z < z_h$ by adopting technique I and if $z > z_h$, by adopting technique II. The lower boundaries of the cost curves shown (that is, their envelope), KLJ, designate the least cost per ha application method of controlling a pest by pesticide use. Represent this relationship function by $C(z)$.

Extensions for previous threshold models

Now the previous models in which the cost of controlling a pest were assumed to be independent of its density can be given greater generality because $C(z)$ can be substituted for C in Equation 1. In the illustration shown in Figure 1 the line EAH will be lower the larger is z. It follows then that the larger the area to be treated to control a pest, the lower is the level of infestation at which it is economic to control it, This is so, provided $V(x)$ is monotonically increasing, for instance, provided $V(x)' > 0$ for all values of x. This relationship is, however, reversed if $C(z)$ increases with z. It seems likely that economies of scale for controlling pests exist in many cases at farm level. Consequently, those with larger sized farms are more likely to find the spraying of pesticides more economical than smaller landholders. This implies that those with larger landholdings would be more likely to undertake pest control than those with smaller holdings as a matter of routine.

Further extension of this type of analysis is possible. For example, the optimal choice of technique to control a pest may in some cases depend on its density and the area to be treated. Then the cost minimizing technique depends on both x and z. Hence, Equation (1) in this case becomes

$$G = V(x) - C(x, z) \qquad (8)$$

And the choice of the pest control technique which minimizes costs is sensitive to both x and z.

An additional important extension has to do with the effectiveness of alternative techniques in reducing the density of a pest. Often a pest is not entirely eliminated by a control method. Consequently, the following decision rules can be applied. Does the gain in gross economic returns from using a particular technique exceed its costs taking into account its effectiveness in reducing the density of the targeted pest? If yes, its use is profitable and otherwise not. If several alternative techniques are available compare their additions to profit taking into account the factors just mentioned and select the one making the greatest addition to profit. Note that the economically optimal technique may not be the one resulting in the greatest reduction in density of the pest, because the private benefit-cost ratio may be highest for a technique which does not result in the maximum achievable reduction in a pest population. The mathematical analysis of this can be formalized, but this will not be done here. It should, however, be kept in mind that private decisions about the choices of a pest control technique may not be socially optimal.

5. The Economics of the Timing of Pest Control and the Optimal Choice of Techniques given Uncertainty

Uncertainty can influence the optimal choice of pest control techniques as well as the optimal timing of pest control. First, let us briefly consider some of the factors that may influence the timing of pest control and subsequently, how uncertainty about the level of pest infestation can influence decisions to adopt the use of herbicide-resistant crops rather than the non-resistant ones, and about whether to use Bt modified seed rather than unmodified seed.

Timing of pest control

The timing of pest controls often influence their ecological effectiveness and the level of their economic benefits (Keller et al., 2014). For some techniques, flexibility exists about the time at which pest control can be undertaken. If the likely level of the pest infestation is uncertain, delay will increase information about its distribution and density within the landscape. As a result of delaying a control, it may, for example, become clear that the level of the pest infestation is going to be too low to warrant pest control. However, the benefit of this information needs to be weighed against possible economic penalties which may be increased by delay. For example, the longer the delay, the lower can be the yield of the crop because the pest may have already damaged the produce. Furthermore, applying a pesticide at a late stage may add to application costs, damage to the crop or create problems if there is a withholding period before marketing. Therefore, the extra benefits from delaying the control of a pest need to be compared with any loss in the economic value of the crop caused by the delay and any extra cost involved in applying the control.

In the case of mung beans and other legumes, the control of insects needs to occur before the seed pod is compromised. While insects may only cause cosmetic damage to the seedpod, the weakening of this protective layer allows fungus, pathogens and moisture into the seedpod, ruining the grain. Once the seedpod has been compromised, pesticides are economically ineffectual due to the difficulty of getting the active ingredient into the seedpods.

Choice of herbicide-resistant crops versus non-resistant ones

The choice of planting a genetically modified herbicide-resistant crop rather than a non-resistant one can be expected to be influenced by uncertainty about the density of weeds in the crop. The purchase of seed for a herbicide-resistant crop will usually cost more than for a non-resistant one. However, the economic benefit for the farmer is that it adds to flexibility in his or her decision-making about pest control. It keeps open the option of eradicating weeds in a crop if their density is found after planting to be high enough to warrant it. For several crops, the only economic way to control weeds after planting is by use of herbicides.

Assuming that the decision-maker aims to maximize profit, a simple model can be used to highlight factors which influence private decisions to plant a herbicide-resistant crop rather than a non-resistant one. Suppose the loss in economic value of the crop as a function of weed density, V(x), is the same for planting a genetically modified crop as for a non-modified one. However, GM seed is assumed to be more expensive than non-modified seed. Suppose also that if a non-herbicide resistant crop is planted, it is impossible to control the level of weed infestation in the crop once planted. In this case, the extra cost of GM seed is the price paid for increased flexibility of weed control. Once this cost is incurred, it is a sunk cost but it has an economic benefit because it keeps options open. If GM seed is planted, it allows the subsequent use of herbicides when this is economic.

Figure 7 illustrates the economic outcome from choosing to adopt a herbicide-resistant crop and or plant a conventional variety (i.e. non-GM). Although the benefit of weed control per ha is represented by a linear line OABD, the following argument is applicable provided that the function is upward sloping. OF represents the herbicide cost of producing a conventional crop and EF is the additional cost of using the GM seed (e.g. the seed costs and the license fee). In this case, if prior to planting all predicted values of x exceed x_k, it pays to plant GM seed but if all predicted values are less than x_k, it is more profitable to plant non-modified seed. It does not matter whether these values of x are uncertain. The weed density $x = x_k$ is the critical value in this case. If these predictions are correct, no spraying of herbicide will occur if $x < x_k$. However, if GM seed is wrongly selected (for any reason), then spraying will occur at a lower weed density, namely $x = x_r$ because the extra cost of GM seed is a sunk cost.

The use of herbicide resistant crops may themselves produce new weed problems (Kniss et al., 2011) as well as accelerate the evolution of herbicide resistant weed species (Vencill et al., 2012) thus producing a range of externality issues.[7]

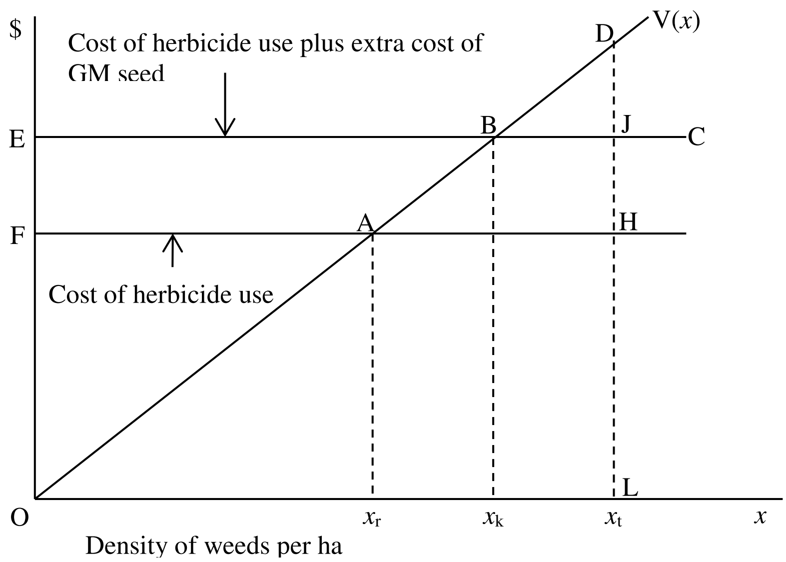

Figure 7: A diagram to illustrate the economics of choosing between a herbicide-resistant crop and one that is not

If the predicted levels of weed density straddle x_k, the decision about whether it pays to buy GM seed or not is more complicated. If $x < x_r$, the comparative loss in profit of GM seed is chosen rather than non-GM, is equal to the extra cost of GM seed, EF. If $x_r < x < x_k$, this loss is partially offset by a net gain from herbicide use. If $x > x_k$, there is a net gain in avoided loss of profit. For example, if $x = x_t$, it is equivalent to DJ. If expected profit is to be maximized, net values of losses and benefits (times their probability) in these ranges should be computed and summed. If the result is positive, the decision maker maximizes expected profit by planting a GM crop. If it is negative, the decision maker would maximize profit by planting a traditional crop.

A producer who has a desire for income security will favour planting a herbicide-resistant crop, unless all predicted values of $x < x_k$. If $x > x_k$, the minimum possible reduction in profit if a herbicide-resistant crop is planted, is C. If a non-herbicide resistant crop is planted, it is V(x) > C. So the maximum possible loss in possible loss in profit is minimized when the herbicide-resistant crop is chosen. For example, if the highest predicted possible level of $x = x_t$, the loss in profit if a non-herbicide resistant crop is planted, is equal to an amount equivalent to the distance DL. However, the planting of a herbicide-resistant crop reduces this by an amount equivalent to the distance JL. Consequently, this will lower the loss in profit by an amount equivalent to the distance DJ.

Choice of Bt modified crops versus non-modified ones.

Consider economic factors which can be expected to influence the choice of Bt crops versus non-modified crops. An important influence on the optimal economic decision will be the uncertainty about possible levels of pest infestations. These levels are influenced by environmental conditions. Figure 8 can be used to illustrate the relevant choice problem assuming that if a non-modified crop is planted, alternative means (such as spraying insecticide) to kill the pest are available. It is supposed that the use of this alternative is more costly than control which is achieved by planting a Bt modified crop but maintains greater flexibility in deciding whether controlling the pest is warranted economically. Adoption of the alternative form of management is responsive to the level of pest infestation but planting a Bt modified crop is assumed to eliminate flexibility.

The economics of these alternative forms of pest management can be illustrated by Figure 8. The extra cost of relying on a Bt crop (such as the extra cost of seed, provision of refuges) compared to planting the same conventional crop is indicated by OF. If the conventional crop is planted and pest control is undertaken, the cost of controlling the pest is assumed to be equal to OE. The economic benefit from controlling the pest is shown by the line OB and for simplicity, the alternative means of pest control are assumed to be equally effective in eliminating the pest. Therefore, if it is certain that $x < x_k$, it is less profitable to plant Bt modified seed than conventional seed. If $x > x_k$, this relationship is reversed.

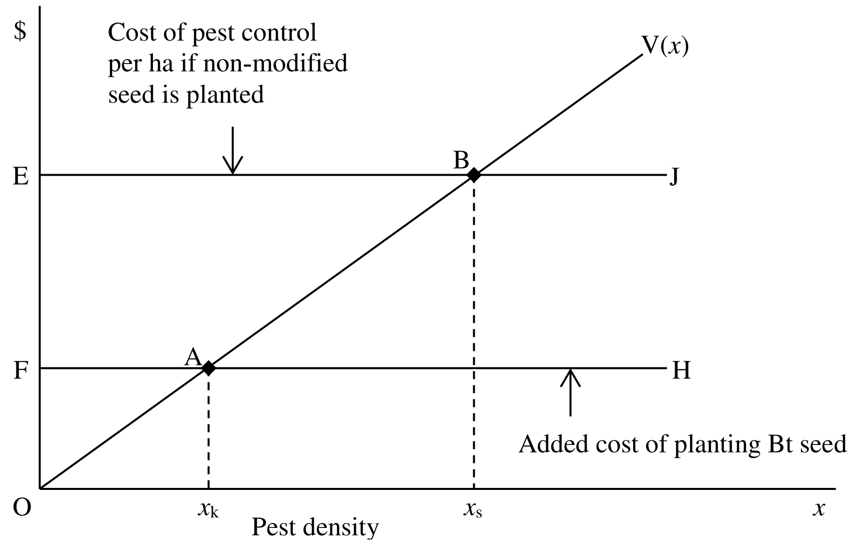

Figure 8: An illustration of the economics at farm level of choosing between Bt seed and conventional seed when a pest is to be managed. Planting of Bt seed involves inescapable upfront costs once it is decided to plant it whereas the option of controlling the pest remains open if conventional seed is planted.

If uncertainty about the level of pest-infestation exists, this complicates the optimal decision, unless of course all uncertain values of x are less than x_k or they are larger than x_k. Suppose that possible values of x may be less than x_k or greater than x_k. If the farmer places a very high emphasis on income security, the minimax loss rule may be adopted. In that case, if there is any possibility that $x > x_k$, the farmer should decide to plant Bt seed because this minimizes the largest possible reduction in profits taking into account pest management options. However, if the (mathematically) expected value of the reduction in profit is to be minimized, the optimal choice is not so clearcut. Suppose that at the time when conventional pest control may be undertaken the level of pest infestation will be known. Then the reduction in profit (as a result of pest management for $x < x_k$ for the planting of conventional seed) will be V(x) where $x < x_k$. This is a smaller reduction than if Bt seed is planted because then this loss is equal to V(x_k). However if $x > x_k$, the use of conventional seed results in a greater reduction in profit than if Bt seed is planted. In this case, the reduction in profit is V(x) for $x_k < x < x_s$ and V(x_s) for $x > x_s$ compared to OF = V(x_k) if the Bt crop is planted. Consequently, the greater is the skew of probable x-values towards larger values of x above x_k, the more likely is the expected reduction in profit to be minimized the adoption of a Bt crop. On the other hand, the more marked is the skew in the opposite direction, the greater is the likelihood that the planting of conventional seed will minimize the expected reduction in the profit of the farmer.

6. A Discussion of the Modelling of the Economics of Pest Management at the Farm Level

The above models only cover a limited set of factors which can influence the economics of pest control at the farm level. Other factors that can be relevant include:

- The possibility that multiple pest control measures are needed serially.
- The speed with which a pest population recovers from a control
- The likelihood of immigration of a pest population occurring when its on-farm population is reduced. This may depend on the extent to which other farmers and agencies control the pest.
  - In the case where immigration is reduced by a government agency, it is a public benefit;
  - In the case where immigration is reduced by an individual and the farmer costs are reduced it is a positive externality

    - In the case where immigration is reduced and the farmer takes no pest management, the farmer become a free-rider
    - In the case where migration from one farm to another increases a decision makers costs, this is a negative externality
- The likelihood that populations of secondary pests will increase if populations of primary pests are controlled.
- The economically optimal concentration of a pesticide assuming higher concentration involves higher costs (farm, health and ecosystem costs, see chapter on Externalities).
- Optimal annual management techniques at a farm level may increase the rate at which pests develop resistance to pesticides

From the above modelling, it is clear that farmers face many environmental uncertainties which affect the type of pest controls they adopt and whether or not they undertake pest control at all. Changing environmental conditions lead to uncertainty about the effectiveness of different types of pest control and to uncertainty about crop yields (Jones et al., 2006). Furthermore, uncertain environmental conditions influence the prices received for agricultural produce because there are major factors changing the (aggregate) market supplies of this produce. The pest control strategies adopted by farmers to respond to these uncertainties depend on their attitudes to risk-bearing and their economic returns.

The farm-level models outlined above assume that the basic objective of farmers is to maximize their profit. Under conditions of uncertainty, this narrows the range of pest control measures which it is rational to adopt, and in some circumstances (as was demonstrated using the above models), the presence of uncertainty is irrelevant for making optimal choices. However, in 'straddle-type' cases (which may be common), this is not so. In these cases, the attitudes of individual farmers to risk-bearing need to be taken into account and usually attention needs to be paid to the nature of the probability distribution of relevant uncertain events. In these circumstances (but not in all, as was shown), increased risk-aversion tends to increase the likelihood of pest control measures being adopted, and probably favours pest control techniques which show greater reliability in controlling pests than other methods. However, the decision-making process is made more complicated by the need to take account of the flexibility which different techniques allow in responding to changes in environmental conditions which among other things, includes changes in estimates of likely levels of pest infestation. Although an economic premium is usually placed on flexibility (for example, if with the passage of time, knowledge improves about the variables which influence the profitability of pest controls), there are often extra costs associated with adopting techniques that permit greater flexibility in pest control as relevant conditions change. The costs and benefits therefore need to be compared, as was demonstrated by considering two types of GMO-based strategies for pest control, namely the planting of herbicide resistant crops (which permit significant flexibility in weed control) and the growing of Bt modified crops which result in less flexibility in pest control than possible alternatives.

GMO crops can provide additional benefit for producers including a reduction in time allocated to crop management, transaction costs associated with regulations designed to internalise externalities, improving relationships with neighbours from using fewer chemical pesticides and a reduction in stress associated with worry about crop management (Back and Beasley, 2007). However, the planting of GM crops can also add to social conflict, for example, between growers of GM crops and GM-free crops.

As mentioned above economic behaviour depends on motives. In some cases, farmers may engage in income-satisficing behaviours rather than profit maximization. This is liable to alter their choice of pest control strategies (Doohan et al., 2010). These choices can be quite different to those based on profit maximization. For example, suppose that a farmer seeks a particular level of income and no more. Then, if the price of a relevant product rises, this increases the likelihood that a profit-maximizing farmer will undertake pest control but it reduces the likelihood that the income-satisficing farmer will do so. The latter case is believed to occur in some LDCs.

Note also that the most economic choice of pest control techniques is liable to differ between countries. In LDCs, where labour is abundant and capital is scarce, labour-intensive pest control techniques are likely to be more economic than in developed countries. Lack of availability of finance for smallholders may further reinforce this effect. It is also possible that in some LDCs that a greater weight will be placed on food supplies rather than on the negative environmental and health effects associated with the use of some pesticides if they are inexpensive.

7. Industry-wide Economic Benefits of Pest Control

Consider now an economic model which may be used to assess the net benefit of pest control at the industry level. This model is based on supply and demand analysis and the application of comparative statics. It has been used previously in the relevant literature (see, for example, Auld et al., 1987, Ch.8). In this modelling, the assessment of whether pest control results in a net economic benefit depends upon whether it increases the economic surplus of suppliers of a product (producers' surplus) plus that of buyers of a product (consumers' surplus). Producers' surplus is equal to the difference between the payments they receive for their supply of a product and the minimum payments they would require to supply it. Consumers' surplus is the difference between the maximum payments consumers would be willing to pay for the supply of a product and the amount they actually have to pay for it. Neoclassical economic modelling assumes that both consumers and producers are fully informed, and that consumers act to maximize their utility and producers act to maximize their profit.

Initial application of this neoclassical model is frequently based on the assumption that market failures of various kinds are absent. This includes the assumption that no adverse environmental spillovers occur in pest control. Also the assumption that all parties to economic exchange are well informed, rules out the possibility of asymmetric knowledge about their food purchases, for example, consumers being unaware of the presence of pesticides in their food purchases. Further economic analysis is then usually undertaken to allow for market failures. At that stage, judgment is needed to decide (particularly if public policies are to be formulated), how important these failures are. Moreover, some limitations of the modelling need to be taken into account before prescribing public policies.

Let us consider the welfare implications of pest control when it is assessed using the basic neoclassical industry model. Possibly unsurprisingly, it results in the conclusion that pest control which is profitable for producers is bound to increase economic welfare if it is judged by the level of total economic surplus obtained; consumers' surplus plus producers' surplus. It implies that relative to the available technologies, economic welfare is maximized in a competitive market system. However, this does not occur in practice because there are important failures in market systems. Despite this, the neoclassical model is a very useful basis for comparative economic analysis by comparing the effects on economic welfare of deviations from the neoclassical theoretical ideal.

With this background in mind, consider the application of neoclassical economics to the pest management problem. First, the case where pest control only increases the productivity of the industry will be considered and then the case is examined where pest control increases both productivity and improves the quality of the industry's produce. Quality changes do not appear to have been given much attention previously in the relevant economic literature.

Higher productivity as a result of pest control

Consider the welfare consequences (using the neoclassical industry model) of pest control which increases the yield of a crop. Let X designate the quantity of output of this crop. In the absence of pest control, the supply function of the output of this crop might be as represented by line S_1S_1 in Figure 9. D_1D_1 might represent the demand schedule for this output. In that case, the market equilibrium is established at E_1, X_1 of the product is supplied and it sells at P_3 per unit. Consumers' surplus is equivalent to the area of the dotted triangle and producers' surplus is equal to the area of the flecked triangle. Therefore, the total economic surplus is equivalent to the area of triangle AE_1B. Now, if producers adopt a pest control strategy which profitably increases their yield, the industry supply schedule moves downward. It costs them less to supply a given quantity of produce. As a result, if there is no change in the quality of the produce, the new industry equilibrium is established at E_2. Total economic surplus increases by an amount equivalent to the hatched area in Figure 9. Therefore, neoclassical economic analysis implies that economic welfare increases as a result of pest control.

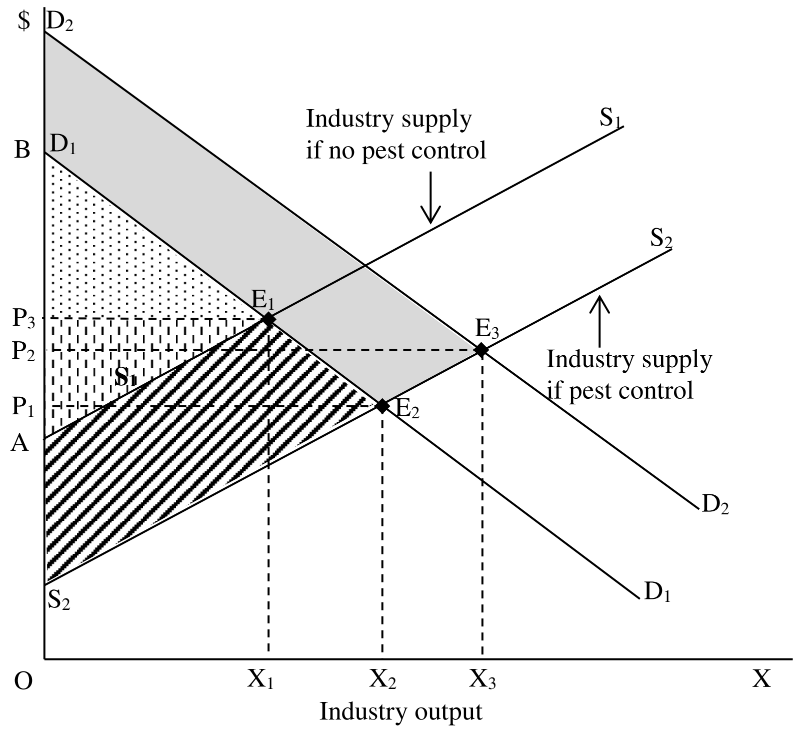

Figure 9: Illustration of community-wide economic benefits of pest control using neoclassical and economic modelling based on industry analysis

Changes in the quality of produce as a result of pest control

Pest control often not only affects the yield of a crop but also the quality of the produce. In many cases, but not all, it is believed to enhance the quality of the crop. It is possible for both the yield of a crop and its quality to be raised by pest control. In that case, improved quality of the produce adds to economic welfare. This is illustrated in Figure 9. An increase in the quality of the produce can be expected to increase the amount consumers are willing to pay for it. This results in the demand schedule shifting upward. In Figure 9, this is reflected in a shift upward of the demand schedule from D_1D_1 to D_2D_2. Taking this into account and given that the pest control raises yield, a new market equilibrium is established at E_3. Quality improvement as a result of pest control enables a further addition to economic surplus (equivalent to the lightly shaded area) to be achieved. While this is not illustrated in the case shown, improved product quality adds to both consumers' and producers' surplus.

In some circumstances, increased yield as a result of pest control may be obtained at the expense of reduced quality of the products. In other cases, improved quality may be achieved by altering pest management at the expense of lower yield. If these changes are profitable, the neoclassical model implies that they will be adopted in the market system, and will raise the total economic surplus. The model implies that production systems respond perfectly to the demands of consumers. This is sometimes described as the principle of consumers' sovereignty. This however, ignores all the possible sources of imperfections that can arise in the operation of market systems. These can be very marked for several forms of pest control, as is evident from other contributions in this book.

8. Further Discussion of Community-wide Economic Benefits of Pest Control and Consideration of Other Issues Worthy of Attention

The above neoclassical economic model only partially models real situations. For example, it assumes that the only stakeholders in pest control in an industry are producers and consumers of its products. However, because of the environmental spillovers from pest controls, other parties may have an interest in these, such as workers in the industry, those residing in neighbourhoods where pesticides are used, nature conservationists and those in other industries. Even within the same industry, producers can experience unwanted spillovers, for example, from the planting of GMO crops and the use of insecticides.

In some case too, the frequency and duration of a pest control technique influences its long-term effectiveness. In many cases, as the frequency and duration of a pest control techniques increases, its effectiveness in controlling a focal pest declines. Therefore, some communal controls on collective use may be called for in order to achieve maximum economic benefits from these methods of pest control.

It should also be noted that most social economic cost-benefit analysis adopts the Kaldor-Hicks criterion, also known as the potential Paretian gain criterion. If there are gainers and losers from a pest control strategy, the strategy is deemed to be economically desirable if the economic gains of those adopting the strategy exceed the economic losses of those disadvantaged by the strategy. However, this rule ignores the distributional consequences of economic change. This test of the social desirability of economic change has strong advocates, such as Richard Posner (1981), who favour it on the basis that it fosters economic growth. Nevertheless, in practice, it is often politically impossible to ignore the distributional consequences of different forms of pest control, even though in some cases, they may be of minor importance and be able to be politically ignored. For example, the introduction of the Calicivirus (commonly known as rabbit haemorrhagic disease) to Australia to control rabbit pest populations resulted in huge economic benefits for most agricultural industries, as well as benefits to protected areas, but it has disadvantaged commercial producers of rabbits for the meat trade and consumers of rabbit meat. No compensation was paid to these groups. However, the net economic gain from the introduction of the Calicivirus in Australia has been large, and greatly outweighs the losses experienced by those disadvantaged by the introduction of this virus. Thus, in this case, it is reasonable to argue that this pest control has resulted in a net social economic gain in Australia (Vere et al., 2004).

If a pest is not already in a country or region, there is also the problem of assessing the economics of measures to exclude it. Furthermore, if it is introduced, the economics of containing or eradicating it needs to be considered. Industries established in the absence of trade restrictive pests are able to gain a comparative advantage over trading rivals in terms of lower production costs and receive a higher price for its produce. In this case the welfare in both the exporting and importing country can be reduced if a biosecurity event occurs. The exporting country may no longer be able to supply a commodity under existing cost structures and may lose the price premium. While the importing country may not be able to purchase goods with the specification it desires.

In extreme situations the invasion of an exotic species can prevent a country from engaging in international trade (e.g. Bovine spongiform encephalopathy (BSE)), increase public health costs (e.g. fire ants) and cause ecosystem failure (e.g. the snakehead fish and the cane toad). By preventing the establishment of exotic species the economic debate is centred on the concepts of public benefits, where government expenditure prevents market failure in control occurring and society as a whole benefits (Adamson et al., 2014).

A further policy issue is the need to assess the economic risks associated with introducing an organism (predator) for the classical biological control of a pest. A similar problem is the risk that the introduction of some exotic plants from abroad could result in these becoming invasive with unwanted economic effects. There are also environmental risks from the release of some GMOs which should be considered. Economic factors need to be taken into account in determining whether it is wise to introduce new genetic material to a region..

9. Concluding Comments

Pest management situations are very diverse in relation to the type of pests to be controlled, the various techniques available for their management and prevailing economic and environmental conditions. Moreover, several techniques may be employed in an integrated pest management approach to individual or multiple problems serially or simultaneously (Harker and O'Donovan, 2012). In addition, pest management is frequently the source of social conflict, subject to communal constraints, and it is further complicated by uncertainties. Consequently, a variety of economic and ecological models are needed to effectively analyse the optimality of decisions about pest control. It has only been possible to introduce a few of these in this chapter. In later chapters, attention will be given to several pest management issues which involve market failure and which have only been touched on here. These include the importance of various types of environmental externalities or spillovers and the consequences of pest control for the supply of public (non-marketed) goods, for example, the conservation of wildlife. Another issue considered is the degree of awareness of consumers about the extent to which their purchases have been subjected to pest controls and their consequences, for instance, for human health. Economic analyses have been developed that do take some account of these issues which involve market failure.

A major constraint on economically optimal decision-making is controlling pests in the bounded rationality of all parties with an interest in it. For example, farmers often have limited knowledge about the effects and cost-benefits of alternative methods of pest control. They are therefore, liable to be heavily influenced in their decisions by information provided by suppliers of saleable pesticides and pest control products. This information naturally tends to be one-sided. Some studies in China revealed that farmers were quite ignorant about the economic benefits of the pest controls which they had adopted (Zhao et al., 2011).

Notes

1. This type of economic threshold model is sometimes presented differently. An alternative formulation focusses on the cost-benefit ratio of pest control (Brown, 1997). If this ratio exceeds unity it is uneconomic to control the pest, but if it is less than this, control is

economic. In the relevant literature, this ratio is usually referred to as the economic injury level (EIL) (Brown, 1997; Peterson and Hunt, 2003).

2. Elimination is assumed in the initial models but many controls only result in reducing the density of the pest. Adjustments to the basic model can be made to allow for this (see later).
3. Cut and paint is when each stem is cut and then the residual stump is brushed with a herbicide.
4. Yokomizo et al. (2009) have explored some of the economic applications of incorrect specification of the density-impact curve.
5. There is also an associated economic problem, namely to find the most economic method of assessing the population of a pest, for example, thrips (Sutherland and Parrella, 2011).
6. There is considerable scope for extending the analysis of the economic value of information gathering and dissemination in relation to pest control. In doing this, it needs to be kept in mind that the additional economic benefits from extra information (and its communication) should be weighed against the extra cost incurred (Tisdell, 1996, Ch. 1).
7. Various economic aspects of pest resistance to controls (including the use of GM crops) are discussed in Tisdell (2015, Chs. 7 and 9).

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