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ALTERNATIVE SPECIFICATIONS AND EXTENSIONS OF THE ECONOMIC THRESHOLD CONCEPT AND THE CONTROL OF LIVESTOCK PESTS

by

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Alternative Specifications and Extensions of the Economic Threshold Concept and the Control of Livestock Pests

Rex Davis and Clem Tisdell

Abstract

Outlines economic threshold models developed by various authors as an aid to decision-making about pest management. Particular attention is given to the models proposed by Stern et al. (1959) and by Headley (1972) and the major differences in their concepts of the economic threshold. Limitations and scope for applying these models is discussed as well as differences in the extent of their applications are reviewed. After considering general issues in this respect, particular matters are given attention such as difficulties raised by complexities in the nature of yield loss function due to uncertainty in pest densities, the presence of multiple-pests, and the occurrence of pesticide resistance. An extension is provided for multiple species pest models to incorporate both multiple-pest species and pest resistance. The presence of fixed costs and the complexities in determining actual cost functions for pest control are also raised as additional qualifications to existing economic models of decision-making about pest control. The combination of these factors limits the applicability of profit-maximising thresholds for livestock management, especially compared to other strategies such as prophylaxis, although improvements in dynamic biological modelling and computer simulations are increasing the scope for applying profit-maximising models.

Alternative Specifications and Extensions of the Economic Threshold Concept and the Control of Livestock Pests

Introduction

The economic threshold is the most frequently applied technique in the field of economic pest management. The concept of linking the pest population to a treatment decision was first formalised by Stern, et al. (1959). A key to the popularity of the original concept has been the combination of practicality and simplicity. This has made it the natural choice of applied entomologists and agronomists. The variety and quantum of economic threshold applications have been outlined by Peterson (1996). He finds that the vast majority (81.9%) of the reviewed scientific literature relates to insect pests, with the majority of these applications focused on cropping situations. Of the other applications by pest-types, weeds and plant diseases have also received considerable attention, again with a focus on crop protection.

The popularity of the concept of the economic threshold for pest control decisions has emerged despite divergent definitions. In particular, the work of Headley (1972), and subsequent modifications by Hall and Norgaard (1973) present a definition that is substantially different to the original concept defined by Stern et al. (1959). Interestingly, the concept of the economic threshold has never been as popular in livestock pest management as in crop management. Certainly research on the economics of managing the cattle tick *Boophilus microplus*, a major pest species in Australia, has focused on strategic (prophylaxis) treatments rather than identifying threshold levels. Nevertheless, Jonsson and Matschoss (1998) indicated that threshold-style decisions for treatments of cattle ticks are taken by 50% of dairy farmers in Queensland.

Given the complexities of modern agriculture, such as the presence of multiple-pest species and insect resistance, do threshold-based treatments provide satisfactory economic theories for pest management or are they simple, broad rules of thumb which represent the best alternative from a small list of alternative strategies?

This paper discusses the usefulness of the economic threshold concept to the modern management of pests of livestock. The paper analyses these issues by examining the scope of threshold treatment strategies amongst all pest management options. It then examines the definitional divergence and confusion in the economic threshold literature and the importance of specification, in both functional forms and in the variables included. Conclusions and future research potential are then provided.

Economics of a Pest Management Strategy

Norgaard (1976) provides a base model of the economics of pest management. The term 'pest management' in this present context encompasses all actions undertaken by producers against pests. For an individual producer, the returns from conducting pest control are the increases in the net monetary value of yield resulting from the pest management technique. A monetary value for yield normally also involves issues about product quantity and quality. The total costs of a pest management strategy can include the costs of acquiring information, the costs of pest management inputs and the costs of applying those inputs. The economics of the firm state, *ceteris paribus*, that a producer will use a variable input up to the point where the marginal revenue product from that input is equal to the marginal cost of using that input. Fox and Weersink (1995) observed that inputs designed to prevent damage provide unique problems for economists because in contrast to conventional inputs, damage control inputs operate through an indirect effect on output. The choice of damage control inputs will depend upon the strategy used by the producer in a given period.

Cousens (1987) suggests that there are three distinct pest management strategies:

- *eradication* – this is a strategy in which extensive efforts and costs are provided in the short term to completely remove the pest and therefore provide unhindered produce development in future periods;
- *prophylaxis* – this is a strategy of insurance, in which pest controls are applied systematically, periodically and generally preventively regardless of the pest population;

- *containment* – the intention is to ensure the pest population stays below a specific level. The producer in this situation accepts some loss of yield (and therefore revenue) and controls the pest when it is cost-effective to do so.

Usually no single pest management strategy is dominant for any given pest. In cattle tick control in Queensland for example, a prophylactic or strategic dipping program has been shown in research trials in certain areas to be economically superior to a containment strategy (see Burns et al., 1977). However in other regions across the State, variance in the tick population may mean that cattle are only chemically treated when pest populations reach a certain threshold.

In many situations, technical constraints limit the number of alternative approaches available to a producer. For example, in the control of the cattle tick because of tick mobility and therefore externalities, eradication for an individual producer is unlikely to be successful without the assistance of neighbours and is disregarded as a viable pest management method (Cattle Tick Control Commission, 1973). The essence of economic pest management is to determine which pest management strategy class is viable or preferred, and then optimise the actions taken by using that strategy. For example, if a containment strategy is determined to be the only practical solution for pest management, then the role of economic pest management models is to determine what level of pest population should be tolerated and treated with what intensity. Generally this will involve calculating an economic threshold.

Two points can be derived from the above discussion. First, from the point of view of an economic analyst, it is vital to have appropriate methodologies to compare the relatives strengths and weaknesses between the different strategies, and then determine the optimal application within the preferred strategy. Secondly, the importance of economic threshold treatments are limited to a sub-class of pest management strategies, although containment is generally the dominant form of pest management strategy undertaken by agricultural producers.

Defining the economic threshold

Having considered the economic threshold in terms of its relationship within overarching pest management strategy alternatives, we now turn to a definition of the economic threshold itself. The definitional debate and confusion that has existed since the seminal work by Stern et al. (1959) is ironic given the conceptual simplicity of the original model. To calculate an economic threshold a practitioner needs to first estimate the economic injury level (EIL). The economic injury level is the pest population density that will result in economic damage. Stern et al. (1959) defined economic damage as the point at which the "amount of injury justifies the cost of artificial control measures". The economic threshold is the pest population density at which control measures should be adopted to prevent an increasing pest population reaching the EIL.

In essence, although the Stern et al. (1959) models are described as "economic threshold" models, the major component of economic calculations occurs in estimating the EIL. The economic threshold is simply the operational criteria for administering pest control action (Higley and Pedigo, 1996). The generalised form of the EIL described by Pedigo et al. (1986) is:

$$EIL = \frac{C}{VDIK} \qquad (1)$$

where *EIL* is the economic injury level described in injury equivalents per production unit, such as insects/ha,

C is the management costs per production unit ($/ha),

V is the market value per unit of production ($/kg),

D is the damage per unit injury (kg reduction/ha/injury),

I is the injury per pest equivalent (injury/insect) and

K is the proportional reduction in injury with control.

The resulting measure from an EIL calculation will be a pest population which relates to the point at which the costs and benefits of control are equal.

There are three non-exclusive issues that have led to an array of subsequent extensions following the model outlined by Stern et al. (1959):

1. *What constitutes “economic damage”?* Stern et al. (1959) presented a form of break-even analysis. Should a threshold model be viewed as a break-even analysis for a single input or should it be a profit-maximising input (marginal benefits equals marginal costs) as defined by Norgaard (1976) above?

2. *What defines the point of action?* How crucial is the economic threshold, the point of action, to the economic quantification of the EIL? If the threshold is surpassed are the implications catastrophic or incremental? In other words, what functional form does the model of yield damage follow.

3. *What other variables should be considered in threshold models?* If other variables are considered, such as a producer’s attitude to risk, multiple-pest species, or chemical resistance, does the EIL or the economic threshold increase or decrease?

These issues are discussed in order in the proceeding sections.

Defining “economic damage”

The first of these issues was initially raised by Headley (1972) who observed that the Stern et al. (1959) break-even definition of “economic damage” was deficient as a profit-maximising model. The alternative model developed by Headley (1972), in its most basic form, consisted of three variables. These being damage to the product caused by the pest, the pest population and time. The economic threshold as defined by Headley (1972a) is described graphically in Figure 1. The upper half of the diagram depicts the overall cost of pest control and the value of production at each pest population level. The value of production is highest with a pest-free environment and then remains constant until the pest population reaches a critical mass of which it then begins to reduce the yield of the product. The cost of control is highest when the population is kept to zero and follows entomological observations that the cost of reducing a pest population increases substantially if attempts are made to achieve very high kill rates (Headley 1972).

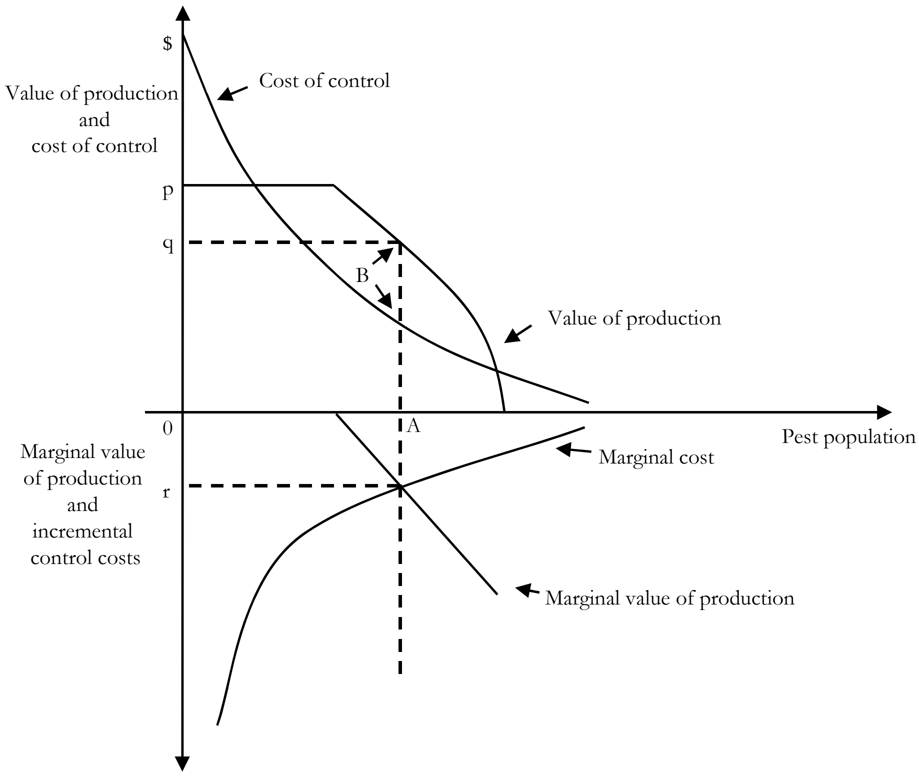

Figure 1 **The economic threshold for pest control**
Source: Based on Headley (1972a, p.103).

The lower half of the diagram displays the marginal values of production and control costs. The economic threshold (according to Headley's (1972) viewpoint), corresponds to the pest population at which the marginal value of production is equal to the marginal cost of pest control. In this case, this implies a value of *r* for these functions. In Figure 1, the corresponding economically optimal pest population is *0A*. In this model, it is better to sacrifice the value of production between *p* and *q* then to try to maintain yield at level *p* as the costs of reducing the pest population to this point expands exponentially.

Pedigo (1996) observed that when Headley described the economic threshold he in fact was describing the EIL. Hall and Norgaard (1973) observed that Headley's definition of the economic threshold level actually represents a post treatment population level rather than a trigger for action as defined by Stern et al (1959). Hall and Norgaard (1973) corrected the economic threshold to a pre-treatment population level and include timing of the treatment variable and the dosage of the control technique flexible and inherent components of the model.

The extension by Headley, Hall and Norgaard has led to a literature dichotomy in relation to economic thresholds, between approaches that establish EIL based on a profit-maximising model and those of the Stern et al. (1959) tradition based on break-even analysis. This point that has been observed by Hall and Moffitt (1985), Moffitt (1986), Plant (1986), Weersink et al. (1991), and Higley and Pedigo (1996).

Despite the theoretical strengths of the Headley-Hall-Norgaard concept in terms of its linkages to economic principle, the weight of literature has favoured the initial Stern et al. (1959) approach (Peterson, 1996). The dominance of the Stern et al (1959) approach has been explained by Moffitt (1986), Plant (1986) and Weersink et al. (1991), who state that the definition simply highlights differences in attitudes between entomologists and economists. This appears unsatisfactory as many economists also continue to define economic thresholds in terms of the Stern et al. (1959) concept, for example Auld and Tisdell (1987).

A possible reason for the popularity of break-even thresholds is that they provide simple and effective decision-rules that can be empirically derived and applied by practitioners in the field. On the other hand, the degree of knowledge required to establish an economic threshold suggested by Headley-Hall-Norgaard is considerable. For that threshold to be applied, information on the whole cost function is required as opposed to a discrete point for the Stern et al. (1959) threshold. Furthermore, in many situations dosage rates are prescribed thereby limiting the evaluation to a break-even analysis. While this may not maximise profit, it at least ensures that a control measure can be justified on some economic grounds.

Hall (1988) accepts this criticism and extends the argument by stating that the prescriptive value of the economic threshold models described above and many of the applications of the economic threshold are limited due to the specification and experiments on which the models are based being specific to individual situations. As Hall (1988, p.642) states: "It is difficult enough for Ph.D. agricultural economists and entomologists to develop these models, design experiments and estimate parameters, much less expect that each farmer will do so…"

A third and less discussed possibility is that thresholds are based on producer behaviour other than profit maximisation and are more related to a producer maximising expected utility. In these situations the producers attitude to risk becomes important.

According to Pannell (1990), several stochastic variables are likely to be observed in any economic pest management model. First, uncertainty can occur due to a lack of knowledge of the initial pest density or a lack of certainty in relation to the number of pests killed. Second, uncertainty can be attributed to a lack of knowledge of the pest-free yield as well as a limited understanding of the actual damage function as mentioned above. Uncertainty, therefore, has a direct and often major effect on profit. Furthermore, pesticides involve a form of insurance against pest damage and therefore a potential reduction of risk (Norgaard, 1976).

If uncertainty is present, attitudes of producers to risk need to be examined. Feder (1979) developed a comprehensive utility model that examined management techniques based on producers' risk profiles and finds that unlike other industries in which the presence of risk leads to a decrease in inputs, uncertainty is likely to increase pesticide use. Moffitt (1986) on the other hand examines risk based on Stern et al. (1959) economic thresholds. In his model, producers do not necessarily increase their inputs when considered over the course of a season, rather risk aversion will manifest itself in higher pesticide dosage. Tisdell (1986) and Auld and Tisdell (1987) indicate that there are a considerable variety of producer responses to pest management when uncertainty is present particularly when assumptions of risk aversion are relaxed and replaced with risk neutrality or a risk preference.

Plant (1986) and Szmedra et al. (1990) are highly critical of the use of economic thresholds in the presence of uncertainty. Plant (1986) finds that the critical value of pesticide dosage (economic threshold) increases with increasing uncertainty. However, as opposed to Feder (1979) this is claimed not to be due to risk-aversion but because the expected mortality rate of pests decreases with higher levels of uncertainty. That is, the level of variance in the model is reduced with increased pesticide dosages as nearly all the pests are killed. Plant (1986) questions the use of economic thresholds at all because inclusion of additional levels of uncertainty and taking into account the natural dynamics of pest control mean that techniques such as sequential decision theory are better equipped to provide pest management advice.

Cousens (1987) identified a number of additional types of threshold in relation to uncertainty and producer risk profiles. These include safety thresholds, which refer to producers tolerating lower pest population levels or damage when applying treatments due to their aversion to risk. Similarly visual thresholds refer to the fact that many producers will make their decisions on their own perceptions of the pest population regardless of scientific or extension advise.

The points made by Plant (1986) and the safety threshold identified by Cousens (1987) are particularly important. The implications of higher levels of risk aversion or satisficing behaviour in producers is that threshold models began to resemble a strategy of prophylaxis. That is, if a producer is aiming for a minimum outcome rather than a profit-maximising approach, pest treatments are more likely to based on calendar dates rather than with reference to the pest population.

The difficulty of functional form and thresholds

The issue of specification is important in terms of establishing both the EIL and economic threshold. For example, the models above have focused on the main cost of pest management being chemical control. In livestock issues one of the main costs is application. Mustering of the cattle, particularly on cattle stations with low cattle density provides the majority of costs.

Fox and Weersink (1995) observe that many damage functional forms can arise. Although conventional wisdom is to examine relationships that result in decreasing returns to pest management, situations may exist where increasing returns from the damage control input are possible depending on the model specification. They observe that increasing returns highlight the potential for corner point solutions such as that provided above.

Specification becomes more important in relation to the economic threshold. So far this paper has not discussed the importance of the difference between when the pest population is treated to avoid reaching the EIL. Depending upon complex issues of pest dynamics, the timing of the treatment may be crucial or unimportant.

Cousens (1987) identifies a threshold which he calls the competition threshold. The competition threshold arises due to the possibility that a sigmoidal-like relationship can be observed between weed density (his field of interest) and yield as opposed to the normally observed hyperbolic yield – weed relationship. When a sigmoidal relationship is observed This differs from the classic hyperbolic yield function in which damage begins instantly and increases at a decreasing rate until only a limited level of produce is left to save. In a sigmoidal relationship, a period exists in which no damage is recorded until the weed density reaches a certain critical mass at which the level of damage increases significantly. The point at which damage begins in the sigmoidal response function is the competition threshold – named as the point at which weed density competition begins to effect yield. The important element from Cousens (1987) identification of competition thresholds is that it highlights the fact that yield response relationships can give rise to a range of critical density points that may be considered as catalysts for action[2].

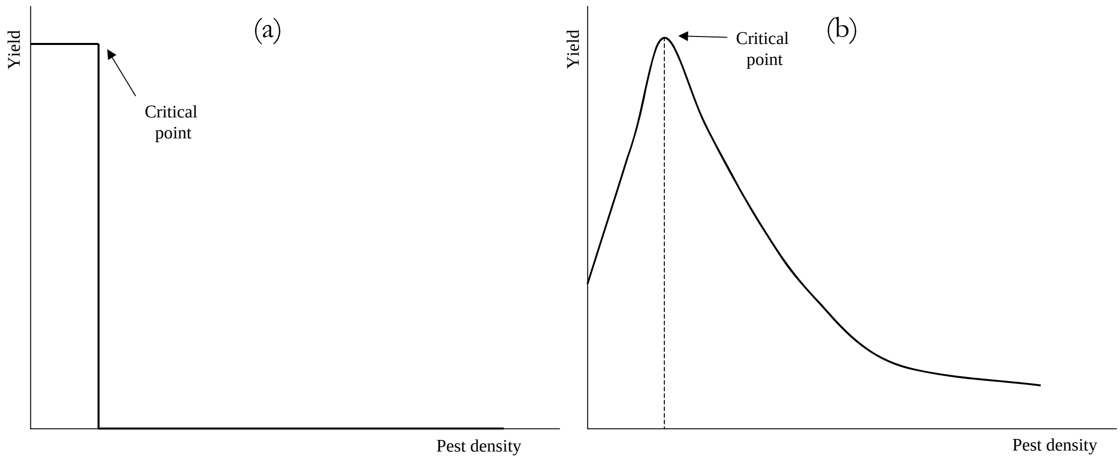

Figure 2 **Other conceptual response curve examples**

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2 **Cousens (1987) observes that models that do not include sigmoidal relationships have potential areas of application. He therefore identifies a category of thresholds known as "statistical thresholds" which are the points observed through research experiments and simulation which potentially do not correspond with thresholds observed in the field.**

Figure 4 displays two conceptual yield response curves which highlight the importance of identifying response relationships when specifying thresholds.

In *(a)* a situation is identified in which past a certain pest density all produce is lost, accentuating the importance of treating before a particular pest density. In (*b)* a situation is identified where at low levels the "pest" actually increases yield at low levels but beyond a certain point becomes unmanageable and decreases yield. While these examples are conceptual and extreme, they do raise interesting possibilities and may have some grounding in producer behaviour. If a pest is able to inflect mortalities once a certain density is reached then situation (*a)* would apply. Situation (*b*) could relate to evidence from some cattle producers in Queensland who indicate that a small tick presence ensures the maintenance of high levels of immunity to tick fever.

The difference in functional form relating to the damage function highlights one of the real difficulties in applying economic thresholds. For an application to be successful, the agronomist or other such practitioner needs to have at least some knowledge of the relationship between the pest and yield. In many cases, this condition will not be fulfilled making some thresholds applications as inappropriate. Campbell and Thomas (1996) observe one of the reasons why livestock economic threshold applications have been limited in their application to veterinary pests is that the damage function is likely to be both more complicated and more subtle than that observed in cropping as pests of livestock are often vectors for disease (such as ticks and the transmission of tick fever) and this relationship is difficult to quantify.

Extensions of Threshold Models

Aside from uncertainty mentioned above, other important variables often need to be incorporated into producer decision models about pest control especially:

1. **Chemical resistance** - each year the level of insect resistance to chemical control measures continues to rise. Part of this rise is due to inappropriate chemical control measures which intensify the problem.

2. **Multiple-pest species -** traditional economic thresholds only examine one pest species at a time. Treatments can be based not only on achieving control in a primary pest species but also in ensuring a reduced pest population in another pest species. The relationship treatment and the other pest species is often not considered.

Several papers have examined the role of pesticide resistance. Tisdell (1982) in a generalised framework observes that when the effectiveness of techniques decline over time, and the effect of this loss is known, then welfare maximisation over multiple time-frames may be maximised by reduced consumption of the technique in the current time period.

Specific resistance models have been developed by Hueth and Regev (1974) and Taylor and Headley (1975). In these models Hueth and Regev (1974) observe that the economic threshold not only changes between seasons, due to changing effectiveness of the pesticides, but within a particular season as well. They find that the economic threshold increases over a season as a producer is willing to forego more yield the closer the product is to harvesting. More importantly, the also find that the exclusion of the variable relating to increase resistance to control, only results in an overuse of chemicals with additional restrictive assumptions. In other words, as timing and dosage are able to be varied in their model, the actual effect on chemical use is unclear due to the varying incremental effects of the effectiveness of pest control applications across a season.

Taylor and Headley (1975) find that the use of pest population functions which incorporate resistance will result in an improved pest control decision, provided that the additional benefit of this decision (the benefits gained from making the greatest use of a control technique over time) is greater than the cost of acquiring the information necessary to provide greater pest population modelling.

The existence of multiple-pest species is an issue which has dogged the use of economic thresholds. Apart from difficulties in defining the damage function, Campbell and Thomas (1996) highlight multiple-pest species as a further factor behind the lack of economic threshold applications to veterinary pests.

Multiple-pest models have been developed by several authors. Palis et al. (1990) use iso-loss lines to determine multiple-pest species economic thresholds. Iso-loss lines indicate combinations of the pest species that result in the same loss of yield. When a combined pest population exceeds the iso-loss line, then treatment is justified.

Control e.g. chemical control of one pest, can damage other neutral or friendly species. For example, a chemical control may kill natural predators of a pest species, which may lead to a secondary pest outbreak, or have other similar consequences that reduce the yield. A version of this problem was examined by Auld et al. (1987) and is discussed graphically using Figure 3.

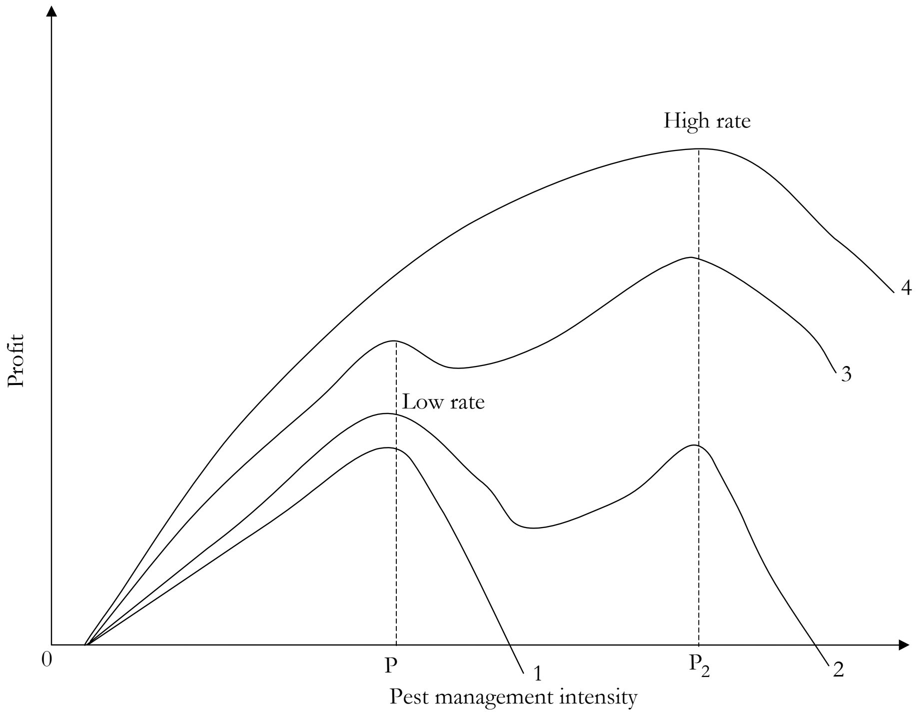

Figure 3 **Possible pest functions for pest management where a non-target and predatory pest species is effected by increasing pest management intensity.**
Source: Adapted from Auld et al. (1987).

In Figure 3, a series of conceptual net profit functions are presented. Profit functions *1* and *4* are classical situations in which increased pest management intensity brings increasing benefits to a maximum (such as the low rate of control, P_1 for profit function *1* or a high rate of control P_2 for profit function *4*), and then the benefits decrease with increased pest management intensity as the proportion of additional yield protected declines. Complicating factors, such as natural predators of the pest, which are also susceptible to control mechanisms, indicate that other possibilities such as profit functions *2* or *3* may exist. In these situations, low levels of pest management intensity do not damage the predator of the secondary pest species. However, increasing pest management intensity, aimed at the primary pest, gradually begins to impact on the predator of the secondary pest past P_1 and its reduction results in a secondary pest outbreak that reduces yield. Given profit function *3*, this reduced yield may be rectified and profit increased by intensifying the level of pest management i.e. to ensure treatment impacts on the secondary pest as well. By contrast, the increased pest management intensity for the secondary pest outbreak if profit function *2* applies, results in a maximum profit less than that attainable before the secondary pest outbreak is triggered.

Profit functions *2* and *3* highlight another situation involving multiple maxima. The humped profit curves, indicate a low local profit maximum at P_1, and a high maximum at P_2. The issues involving multiple maxima can be considered in more detail by use of Figure 4. In this example, a marginal cost function, MC_1 represents the marginal cost from controlling the primary pest and increases exponentially as it is becomes more difficult to provide 100% protection[3]. The marginal benefit curve, MB_1, has two humps, with marginal benefits initially increasing with greater protection of the crop from the primary pest, and then decreasing as the natural predator of the secondary pest is destroyed and a secondary pest outbreak occurs. The curve then increases as the higher pest management intensity results in protection from the secondary pest also, and then decreases to zero as 100% crop protection is provided and no additional benefit from pest management is possible.

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[3] The original example from which this analysis was inspired was discussed in terms of a reduction in yield through damaging a product that could potentially increase yield in this season or future seasons. As the area of interest of Auld et al. (1987){*Auld, et al. 1987} were weeds, their example was discussed in relation to under sown legumes that could be damaged and would reduce yield. In livestock, an example is that increased pest management intensity may result in some sickness in the animal or indeed secondary pest outbreaks through damage to a primary or secondary pest predatory

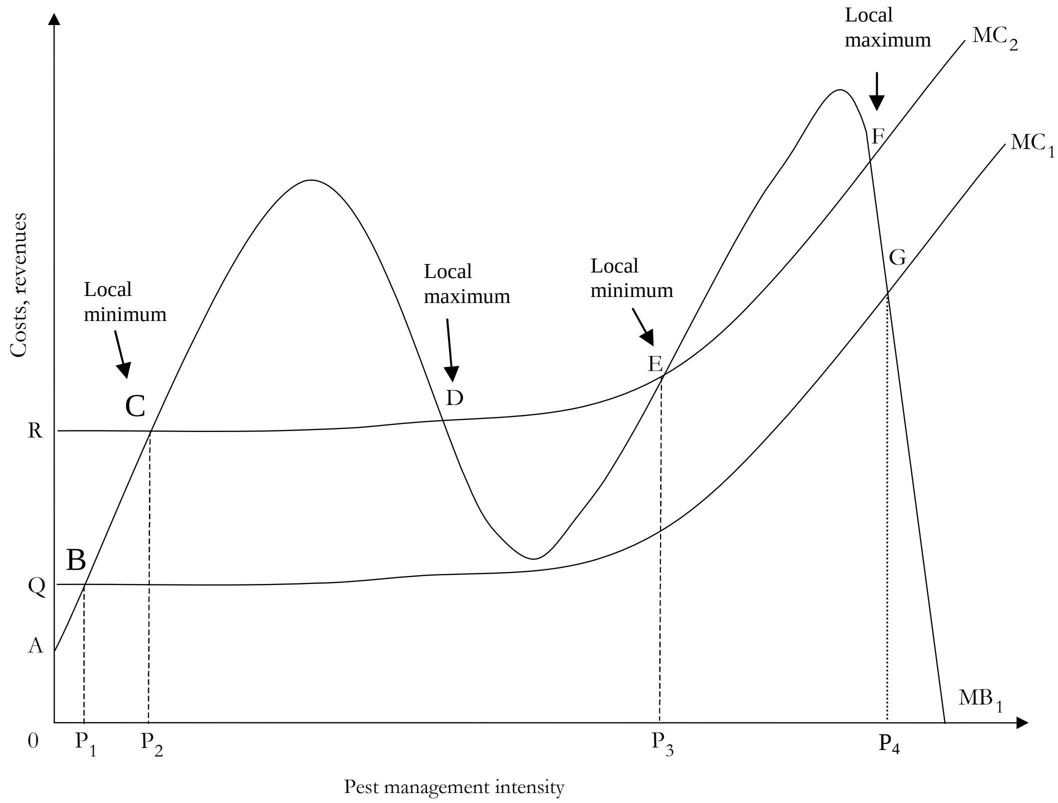

Figure 4 **Marginal analysis for an individual producer faced with two pest species where a predator of the secondary pest species is affected by higher levels of pest management intensity, or where the secondary pest is otherwise favoured by control of primary pest e.g. by less interspecies competition.**

Consider the marginal cost curve marked MC_1. The intersection of MC_1 with MB_2 occurs at a local profit minimum corresponding to *B* and the optimum level of pest management intensity is P_4 corresponding to a local profit maximum at G. This local profit maximum is also a global one. In this situation, the producer would operate at a high level of pest management intensity and severely damage the predator of the secondary pest species. If, on the other hand, the marginal cost curve of control marked MC_2 applies, there are two minima at *C* and *E* (with associated levels of pest management of P_2 and P_4) and two local maxima at *D* and *F*. The profit-maximising level of pest management can then only be determined by examining the difference in total profit between *D* and *F*. It is possible that profit could be maximised in such a case by a 'low' level of control of the primary pest, a level corresponding to point *d*, because this low level of control is less favourable to proliferation of the secondary pest.

Szmedra et al. (1988) uses a simulation model to examine the interactions of two-pest species in a pest decision framework. However in their simulation model natural predators of certain pest species are also killed by the main pesticide leading to additional outbreaks. Harper and Zilberman (1989) provide a model that examines secondary pest outbreaks caused by chemical treatments killing not only the primary pest but predators of the secondary pest.

In none of these models are the implications of multiple-pest species and chemical resistance examined together. The framework present by Harper and Zilberman (1989) is extended to examine potential resistance implications for producers stemming from multiple-pest species management decisions. The Harper-Zilberman approach has been selected as it is a production theory approach which examines damage as a proportion of potential yield, and allows the incorporation of pest populations into the damage function. An important element of the model presented below is to examine the scenarios arising from different cost structures.

The initial assumptions of the model are that there is an agricultural producer whose product is attacked by two different species of pest. At this stage there is no assumption as to which species is the predominant pest. It is also assumed that the main form of pest-control is through pesticide applications

The grazier's production function is equal to:

$$Q = f(X)[1 - D\{S_1, S_2\}], \qquad (2)$$

where Q is equal to quantity, X is the non-pesticide input and $f(X)$ is the potential output without any damage from pests with $f'>0$, $f'''<0$, $D\{S_1, S_2\}$ is the damage function where S_1 represents the population of pest species *1* and S_2 represents the population of pest species *2.*

The damage function D expresses the fraction of yield lost because of both pests. It is assumed that damage is directly related to the size of the population and expresses the yield lost because of both pests[4].

$$D = D\{S_1, S_2\} \tag{3}$$

where D_{S1}, $D_{s2} > 0$[5]. The population equations for the two pest species are:

$$S_1 = k_1(X)[1 - M_{1i}(Z_i)]R_{1i} \tag{4}$$

$$S_2 = k_2(X)[1 - M_{2i}(Z_i)]R_{2i} \tag{5}$$

where k_i is the carrying capacity that would be achieved by the insect population if no pesticide is used, M_{1i} is the mortality rate caused by the dosage of pesticide i for species *1*, M_{2i} is the mortality rate caused by the dosage of pesticide i for species *2*, Z_i is the dosage of pesticide i, R_{1i} is a measure of pesticide resistance by species *1* to pesticide i where $R_{1i}>1$, and R_{2i} is a measure of pesticide resistance by species *1* to pesticide i where $R_{2i}>1$.

The purpose of the variables R_{1i} and R_{2i} is to offset the decreases in population from the term $[1-Mi(Zi)]$. For example, if the mortality rate for $M_1(Z_1)$ is 0.9 then $1 \leq R_{11} \leq 10$.

The model therefore states that a producer's production function will be determined by the potential yield, which is dependent on the non-pesticide inputs into the production process, and the fraction of the crop that is lost in damage to the two pest species. The amount of damage is determined by the population equations for the two pest species which are in turn determined by the carrying capacity achieved due to the non-pesticide

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[4] **Harper and Zilberman (1989) have the secondary pest species effected by a third insect species which is a natural predator. In this paper the role of natural predators is not considered.**

[5] **Harper and Zilberman (1989) add that it is natural to regard *D* as cumulative as only values between one and zero are meaningful. As this is a general framework they do not specify the functional form of *D* but note that two of the most commonly used functional forms are: $D=(1-e^{-\alpha 1S1})(1-e^{-\alpha 1S1})$; and $D=1-e^{-\beta 1S1-\beta 2S2}$.**

production input, the mortality rates of the pest species resulting from pesticide applications, and the subsequent level of resistance to the pesticide used.

It is also assumed that the producer has a choice of three chemicals, Z_1 represents the quantity of a pesticide that is used to control pest species *1* but this pesticide has a negligible effect on pest species *2*. Z_2 is the quantity of a pesticide that is used to control pest species *2* but this pesticide has a negligible effect on pest species *1*, and Z_3 is the quantity of the pesticide that can control both pest species. The producer's cost function is equal to

$$C = uX + a_1 + a_2 + a_3 + w_1 Z_1 + w_2 Z_2 + w_3 Z_3 + y_1 + y_2 + y_3 \qquad (6)$$

where u is the cost of the non-pesticide input, a_i are the fixed costs associated with applying pesticide i, w_i is the cost of pesticide i and y_i is the cost of applying pesticide i.

If π is profit, and p is the price received for the producer will aim to maximise profits subject to the pest population levels, so that

$$\max \pi = pf(X)[1 - D\{S_1, S_2\} - uX - a_1 - a_2 - a_3 - w_1 Z_1 - w_2 Z_2 - w_3 Z_3 - y_1 - y_2 - y_3 \qquad (7)$$

subject to

$$S_1 = k_1(X)[1 - M_{1i}(Z_i)R_{1i} \qquad (8)$$

$$S_2 = k_2(X)[1 - M_{2i}(Z_i)R_{2i} \qquad (9)$$

To examine the possible implications of this model a number of situations are examined. In the first instance let us assume that the fixed, application and unit costs of the three pesticide chemicals are the same, that is, $w_1Z_1 = w_2Z_2 = w_3Z_3$, $a_1 = a_2 = a_3$, and $y_1 = y_2 = y_3$. Let us also assume that pesticide *3* has the same effect over S_1 as does pesticide *1*, and that pesticide *3* has the same effect over S_2 as pesticide *2*, $M_{11}=M_{13}$ and that $M_{21}=M_{23}$. Finally, it is also assumed that there is no resistance, $R_{ii}=1$ and does not increase over time.

In this situation the producer will always choose pesticide *3* in every circumstance. If both pests required control in their own right, then pesticide *3* produces the saving of the fixed, application and unit costs of a second application of chemicals. Even if there is only one pest causing significant damage to the product, the choice of pesticide *3* still brings about more benefits through its ability to reduce the population of the second pest species. However, with the incorporation of different mortality rates, different cost structures and chemical resistance the choice is less obvious. To show the possibilities that emerge when these factors are considered two examples are considered. The first example examines the situation of a primary economically significant pest species that requires treatment in its own right, while the second situation example examines the situation where the cumulative damage function of both species requires treatment, however, control of a pest species when examined in isolation is not justified.

Example 1

In the first situation it is assumed that pest species *1* is the primary pest, that is $D_{S1} > D_{S2}$ and that the damage inflicted by Species *1* on the product is sufficient enough to warrant its control, so that:

$$pf(X) - pf(X)[1 - D\{S_1\}] > a_i + y_i + w_i Z_i \qquad (10)$$

where $i=1$ or 3. It is also assumed that although Species *2* is damaging the product, its population level does not justify control in its own right[6]:

$$pf(X) - pf(X)[1 - D\{S_2\}] < a_2 + y_2 + w_2 Z_2 \qquad (11)$$

In this situation the producer has two options which are detailed in Table 1.

6 It is also assumed that the producer from time to time has circumstances whereby S_2 becomes the primary pest.

Table 1 Control options for a producer where damage is accumulating through 2 pest species with only 1 justifying control in its own right.

Option A	***Option B***
Apply pesticide 1 which controls just species 1. The producer's cost function is:	Apply pesticide 3 which controls both pest species. The producer's cost function becomes:
$C=uX+a_1+y_1+w_1Z_1$	$C=uX+a_3+y_3+w_3Z_3$
with the population equations for the initial time period:	with the population equations for the initial time period:
$S_1 = k_1(X)[1-M_{11}(Z_1)]R_{11}$ $S_2 = k_2(X)[1-M_{21}(Z_1)]R_{21}$	$S_1 = k_1(X)[1-M_{13}(Z_3)]R_{13}$ $S_2 = k_2(X)[1-M_{23}(Z_3)]R_{23}$
where $0<M_{11}(Z_1)<1$, $M_{21}(Z_1)=0$, $R_{11}=1$ *and* $R_{21} = 1$	where $0<M_{13}(Z_3)<1, 0<M_{23}(Z_3)<1$, $R_{13}=1$ *and* $R_{23} = 1$

To concentrate on the effect of resistance, the assumption that $M_{11}=M_{13}$ is retained as is $w_1Z_1 = w_3Z_3$, $a_1 = a_3$, and $y_1 = y_3$ so that there is no cost advantage involved for either pesticide. Let us also assume that resistance in the primary pest S_1 is negligible, however, $R_{21}^{t+1} > 1$. In this situation, the producer has to determine whether the present value of benefits from controlling S_2 justify the decreased effectiveness of the technique at a later date. This situation is made more interesting if $M_{23}(Z_3)>M_{22}(Z_2)$ and that $a_3 + y_3 + w_3Z_3 < a_2 + y_2 + w_2Z_2$. In this situation, increased resistance to pesticide *3* by S_2 has a much higher cost, as pesticide *3* is the most effective and less expensive form of control against S_2. In this circumstances, the producer may decide to choose pesticide *1* and this is even more likely if $a_1 + y_1 + w_1Z_1 < a_3 + y_3 + w_3Z_3$.

Example 2

In this situation it is assumed that:

$$pf(X) - pf(x)[1 - D\{S_1\}] < a_1 + y_1 + w_1 Z_1 \quad (12)$$

$$pf(X) - pf(x)[1 - D\{S_2\}] < a_2 + y_2 + w_2 Z_2 \quad (13)$$

However:

$$pf(X) - pf(x)[1 - D\{S_1; S_2\}] < a_3 + y_3 + w_3 Z_3 \quad (14)$$

If the remaining assumptions utilised at the beginning of Example 1 are retained, then for this situation producer is more likely to trade-off future resistance to chemical control of pesticide *3* for the extra benefits of pest control in this current season. The producer also knows that pesticides *1* and *2* are available if required at a future date if pesticide *3* proves ineffective in the long run. As in the last example, adjusting the costs of application, the relative mortality rates of the pesticides, and the rate of resistance may provide different outcomes.

This extension examines potential producer behaviour when their choices in a current season are complicated by the existence of multiple-pest species and lead to a reduced efficacy of a pest control technique in the future. Developing the examples above further, would lead to an incremental analysis which would determine the points at which the marginal benefits of treating species *1*, species *2* or both species, would equate to the marginal cost of using pesticide *1*, pesticide *2* or pesticide *3* plus the cost of the declined effectiveness of the control technique in future seasons.

Fixed or Start-up Costs

What is clear however is that the role of fixed cost can have a major impact on pest control decisions. In this case, the choice of pesticide 3 is more appealing in many cases as the fixed costs and application costs in providing two separate treatments for each pest may be substantially larger than that for one. This applies in livestock situations as the cost of mustering cattle and treatment facilities is the greatest expense for cattle producers conducting treatments. It is also relevant to aerial cropping situations where the major expense is not the chemical costs but the cost of the plane and pilot.

In these situations, the choice of dosage, as discussed in such detail in economic threshold models above, few producers having to outlay hundreds of dollars to muster cattle are going to trade off lower pesticide application dosages and pesticide efficacy for the sake of small sums of money. In other words, when chemical costs are a minor component of the overall pesticide cost function, *ceteris paribus*, it is unlikely that producers would choose anything other than the recommended dose.

A further component to be considered is the role of other farm management practices on producer pest control decisions. Again using the example of livestock, other management practices can be utilised jointly with the control technique as was discussed earlier. The way in which costs are allocated with the existence of joint or common costs[7] in the production process will therefore have an effect on the pest management decision as indicated in Figure 4. The level of difference will depend upon the means by which costs are allocated across joint production processes (see for example, Billera et al. (1981) and Gal-Or (1993)). The existence of joint production costs are a major determinant in the establishment of economies of scope which result from the ability of a firm to produce two products in combination than it is for them to be produced individually (Panzar and Willig, 1981). In pest control situations however, only one end product is usually being developed, such as meat, however economies of scope apply to the production of goods that are inputs into the production of the agricultural product.

The above model indicates that there is another complexity that needs to be considered in economic threshold decisions. Aside from the complexity in determining pest dynamics, which is the focus of most economic threshold applications[8] there is potentially an equally complex procedure involved in determining the cost function.

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7 **Joint costs are those that are expended in the production of two or more goods but cannot be separated. Common costs are used in the production of both commodities but are able to be used in separate proportions for the production of each good (Billera, et al., 1981)**

8 **See Peterson (1996) for a comprehensive review of economic threshold applications.**

Conclusions

This paper has examined the role of economic thresholds both generally and specifically in the management of pests of livestock. Where thresholds have been established they have been the break-even methods identified by Stern et al. (1959) rather than profit maximising applications in the tradition of Hall-Headley-Norgaard.

Economic thresholds have had limited use in livestock pest management. The question that this paper has asked is whether limited applications for livestock are a peculiarity and there a gap in the literature needs to be filled, or alternatively, that economic thresholds are simply not useful in terms of livestock pest management.

The answer to this question is that while, theoretically economic thresholds have much to offer, there are limited situations in which they will offer producers much assistance. First, economic thresholds are a form of containment strategy, which is one of three overall strategies that a producer may adopt. Second, as issues such as uncertainty and a producer's risk profile are considered the current and future level of the pest population becomes less relevant and a producer's strategy merges towards one of prophylaxis.

Second, the complexity in establishing the correct specification of the threshold model, both in terms of the form of the damage and yield functions, but also the cost function, is considerable, especially for a profit-maximising function. This complexity is escalated almost to the unworkable, by the presence of complicating factors such as multiple-pest species

This issues highlight the potential for major prescriptive discrepancies between economic threshold models. Again, this leads to the possibility that strategic treatments, based on calendar dates, or other decision techniques based without reference to a pest population are potentially superior strategies even in situations of inconsistent and occasional pest populations simply due to the lack of acceptable threshold advice.

When situations of much additional complexity have been recognised, authors have often turned to simulation models to support their decisions. On face value, simulation models would appear to improve and extend the use of economic thresholds as they make it possible to allow for greater complexities in the interactions between the pest species and producer decisions then otherwise possible. Many of the issues raised above, particularly multiple-pest species and chemical resistance could be incorporated and trialed with computer simulation models. This would provide producers with better information on the timing of pest applications. This is certainly the case for irregular or occasional pest populations.

On the other hand, model validation through simulation is also likely to encourage a greater use of prophylaxis or strategic treatments. In situations where certain pests are constant in terms of their density, then simulation models are likely to highlight key dates which have the greatest impact on the control of the pest(s). In these situations it is the timing, rather than the pest population that will have the greatest impact. Such situations, are common in terms of livestock pest management.

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