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A Review and Extension of Economic Pest Control Model Incorporating Multi-Pest Species and Insect Resistance

by

Rex Davis

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The Commissioned Organization is the Queensland Department of Primary Industries. Collaborating institutions in Australia are CSIRO-ANHL, Geelong, Victoria and the University of Queensland (Department of Economics; Department of Geographical Sciences and Planning). In Thailand, the collaborating institutions are the Department of Livestock Development (National Institute of Animal Health; Disease Control Division), Chiang Mai University (Department of Agricultural Economics; Department of Animal Husbandry) and Thammasat University (Faculty of Economics). The collaborating institution in Laos is the Department of Livestock and Veterinary Services. Dr F.C. Baldock, Senior Principal Epidemiologist, Queensland Department of Primary Industries is the Project Leader in Australia and Dr P. Chamnanpood, Senior Epidemiologist, Thai Department of Livestock Development is the Project Leader in Thailand. Professor Clem Tisdell and Dr Steve Harrison, Department of Economics, University of Queensland are responsible mainly for the economic component of this project.

'The overall goal of this project is to develop and evaluate the .necessary tools to provide decision-makers with reliable animal health information which is placed in context and analysed appropriately in both Thailand and Australia. This goal will be achieved by improving laboratory diagnostic procedures; undertaking research to obtain cost-effective population referenced data; integrating data sets using modern information management technology, namely a Geographical Information System (GIS); and providing a framework for the economic evaluation of the impact of animal diseases and their control.

A number of important diseases will be targeted in the project to test the systems being developed. In Thailand, the focus will be on smallholder livestock systems. In Australia, research will be directed at the northern beef industry as animal health information for this sector of livestock production is presently scarce.'

For more information on *Research Papers and Reports Animal Health Economics* write to Professor Clem Tisdell (c.tisdell@economics.uq.edu.au) or Dr Steve Harrison,(s.harrison@uq.edu.au) Department of Economics, University of Queensland, Brisbane, Australia, 4072.

A Review and Extension of Economic Pest Control Model Incorporating Multiple-Pest Species and Insect Resistance

ABSTRACT

Most pest control models are extensions of classical production theory which states that a producer will increase the use of a variable input to the point where the marginal cost of the input is equal to the marginal benefit. There have been several useful and sophisticated extensions of this model that incorporate complexities of agricultural production such as pesticide externalities, insect resistance and multiple- insect species. These extensions have generally been developed incrementally from separate applications of pest-control economics to diverse agricultural situations.

There is a need, however, to develop a general framework that combines some of these important extensions to classical production theory into the one model. The aim of this paper is to develop a general framework in which the situations of insect resistance and multi-pest species are examined simultaneously. This framework will form the basis of a bio-economic computer simulation which will examine the pest- control decision of producers in the tick-infested area of Queensland where both cattle-tick (*Boophilus microplus*) and buffalo-fly (*Haematobia irritans exigua*) are simultaneously effecting cattle, and resistance to pesticides occurs with use in both pests.

The model is developed from a general framework by Harper and Zilberman (1989). The paper also examines some of the issues and possible implications that may emerge from the model.

Keywords: pest management, production theory, insect resistance

JEL Codes: Q16,

A Review and Extension of Economic Pest Control Model Incorporating Multiple-Pest Species and Insect Resistance

1. Introduction

Economic theory has been applied extensively to the field of pest control where classical production theory has been used to examine individual producers' pest control decisions. This model has been modified, with successive applications to diverse agricultural situations, to include factors such as risk, environmental externalities resulting from pesticide use, the divergence between private and social costs from a producer's pest-control decision, the effect of insect resistance and the effect of multiple pest species. These applications have made the model more practical and have utilised sophisticated techniques such as dynamic programming and bio- economic computer simulation.

There is a need, however, to develop a general framework that combines some of these important extensions to classical production theory. The aim of this paper is to develop a general framework that specifically relates to the pest-control decision confronting many agricultural producers, namely the problem of determining the optimum level of pest management where there are multiple pest species to control and one or more of the pest species develops resistance to the control technique. This framework will form the basis of a bio-economic computer simulation which will examine the situation relating to cattle producers in the tick infested area of Queensland who have to determine pest-control responses for both cattle-tick (*Boophilus microplus*) and buffalo-fly (*Haematobia irritans exigua*), and resistance to pesticides occurs with both pest.

To develop this framework, the paper is broken into six parts:

1. Introduction.
2. The Classical Production Theory Pest-Control Model.
3. Extensions of the Classical Pest-Control Model, (including multiple-pest species and insect resistance).

4. A Dynamic Pest-Control Model for Livestock Incorporating Multiple-Pest Species and Insect Resistance.
5. Issues and Implications from the Model.
6. Conclusion.

2. The Classical Production Theory Pest-Control Model

Production theory states that a producer will use a variable input to the point where the marginal revenue product from that input is equal to the marginal cost of using the input, ceteris paribus. The classical production theory approach to a producer's profit-maximising pest-control decision has been described by Noorgard (1976).[1]

The returns to the individual farmer from pest-management are the increase in money value of the yield resulting from a particular pest management strategy. By expressing yield as dollars, quantity and quality items are simultaneously accounted for. The costs of a pest-management strategy are simply the costs of acquiring pest-control information, the costs of applying the inputs and the costs of the inputs themselves.

Expressed mathematically,

$$\pi = pF(x) - C(x) \tag{1}$$

where π represents profits, p is the price of the product, $F(x)$ is the quantity of product expressed as a function of x, x is a vector of pest management inputs and $C(x)$ is the cost of pest management inputs expressed as a function of x. Profits are maximised when the derivative of π with respect to x is set equal to zero.

$$\frac{(d\pi)}{(dx)} = p\,\frac{dF(x)}{(dx)} - \frac{dC(x)}{(dx)} = 0 \tag{2}$$

At this level, the marginal return from an increase in pest management intensity is equal to its marginal cost.

The classical production theory model can be seen in Figure 1. Marginal costs rise with increases in pest management intensity because of the costs of gathering more precise information and using more specialized materials[2]. Marginal revenue product[3] (marginal benefits) decreases with greater pest intensity as the remaining proportion of the crop to be saved decreases. Figure 1 shows that a profit maximizing farmer will choose to lose some of his crop to pests rather than forego the even higher costs of stricter pest management (Norgaard, 1976).

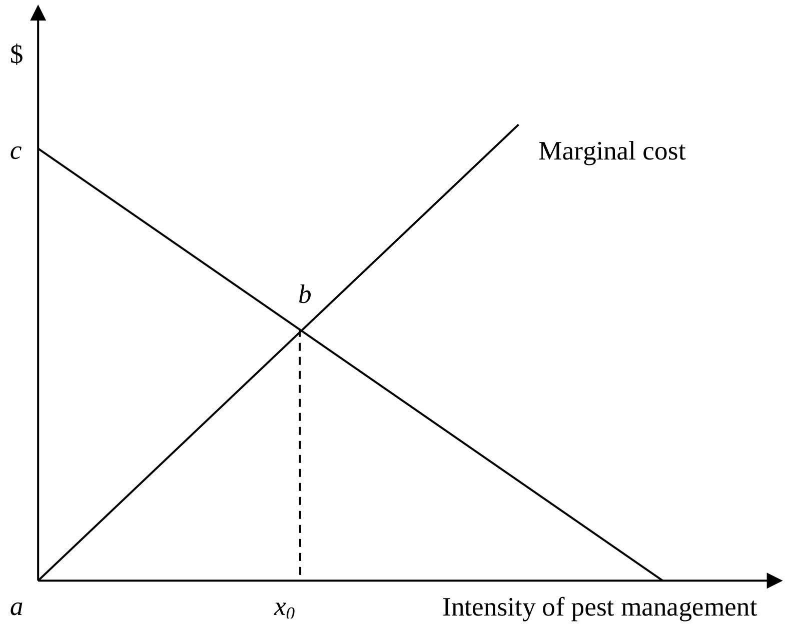

Figure 1: Based on Norgaard (1976, p.53)

Profits are maximised when these curves intersect at x_0, with the profits that the producer receives equal to the difference between these two curves represented by the area of the triangle *abc*.

An extension of the classical production theory model involves the concept of the economic threshold which has generally been accredited with Stem et al. (1959). According to Weersink et al. (1991, p.619), Stem et al. defines the economic threshold as the

> "...density at which control measures should be determined to prevent an increasing pest population from reaching the economic injury level." The economic injury level was defined by these authors as the "lowest population that will cause economic damage."

According to Weersink et al. (1991, p.619) many authors have substituted the terms economic threshold and economic injury incorrectly,

> "...the point at which profit from controlling pests exceeds the cost of doing so is the economic injury level and not the economic threshold level as is commonly inferred in the literature."

However they also observe that regardless of whether an author is using the economic threshold level or the economic injury level to describe the lowest population that will cause damage, the main confusion in economic threshold literature is in the definition of economic damage. Using Stem et al.'s definition of economic damage as "the amount of injury that will justify control", Weersink et al. observe that there are two schools of thought in what is meant by 'will justify'. This observation has also been made by Plant (1986) who notes that economists and entomologists refer to two different thresholds in justifying control. The economist's definition can be called the 'optimising threshold'. It is based on the premise that a producer will use an application rate (including timing, number of applications and dosage) that will maximise profits (in the manner referred to in Figure 1). The issue in determining an optimal rate of control is "...what level of control is most profitable for that particular pest density?" (Weersink et al., 1991, p.620)

Entomologists on the other hand have a 'discrete-choice' definition of the economic threshold. Their model is based on the fact that if pest control is to be undertaken, it will be undertaken at the maximum application rate, or the rate prescribed on the pesticide label or information sheet. The issue for the discrete-choice threshold is "...what pest population density level should a particular control be undertaken." (Weersink et al., 1991, p.620)

The difference between the two definitions can be seen in this model derived from Weersink et al. (1991, p.620-622). The following equations represent the profit, damage and control functions respectively.

$$\pi = pX - wZ - a \tag{3}$$

$$X = f(D) \tag{4}$$

$$D = d(Z, D_0) \tag{5}$$

where π: is profits, p is the output price, X is yield, w is the unit price of the pesticide Z, a is the cost of application, D is the pest population after the pesticide treatment and D_0 is the pest level before pesticides are applied[4]. Without detailing specifications, in the damage function (4) it is assumed that yield decreases with pest density, and in the control function (5) it is assumed that pest density decreases when pesticide is applied but increases when it is uncontrolled. Substituting equations (4) and (5) into (3) results in the following profit function which is dependent on the amount of pesticide applied and the initial pest population,

$$\pi(Z,D_0) = p\,F(d(Z, D_0) - wZ - a \tag{6}$$

In the discrete-choice threshold employed by entomologists, the pesticide dosage is constrained to be at the prescribed or labelled dosage rate (X^L). The economic injury level (D^{EIL}) is the population at which the profits from treating at level X^L are equal to the costs of not treating, that is ($\pi(X^L, D^{EIL}) = \pi(0,D^{EIL})$). The decision rule is then to apply pesticide at X^L if the pest density is greater than D^{EIL} and not to apply otherwise.

For an economist's evaluation, the pesticide dosage may take any value up to X^L. The focus is then on what level of application maximises the producer's profit. The producer determines the level of dosage in which the marginal revenue product of the application is equal to the marginal cost. This level of dosage becomes the optimal pesticide dosage Z^* and is dependent on the initial pest population. However, according to Plant (1986) the optimal rate is not the optimising threshold level. The level of the optimising threshold is the smallest level of infestation in which the optimal application rate is greater than zero, Z^c. This can be seen in Figure 2.

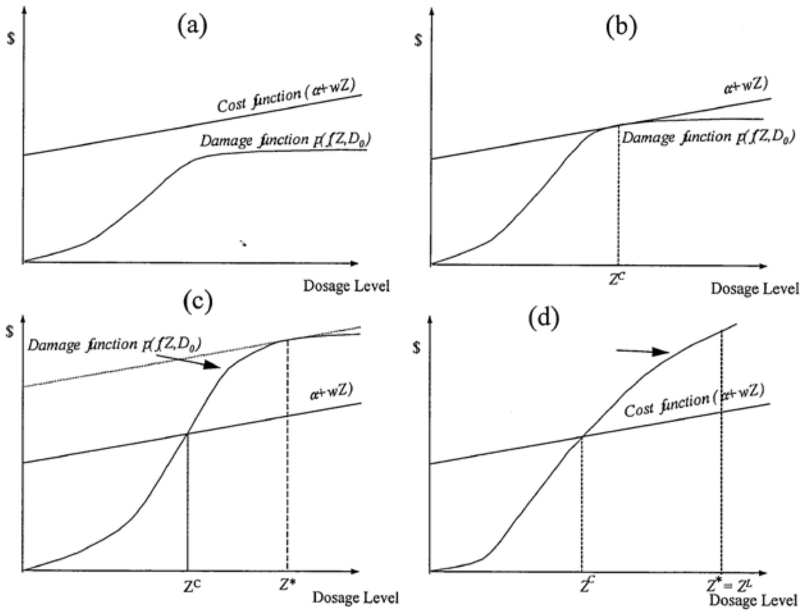

Figure 2: Based on Plant (1986, p.2)

The four plots in Figure 2 correspond to four different levels of D_0. The cost and damage functions (derived from losses to potential yield) are expressed as functions of the rate of pesticide Z applied. In Figure 2a, the costs of controlling the pest are never recovered as the cost function never surpasses the damage function (benefit curve) so the optimal pesticide level is zero, $Z^* = 0$. In Figure 2b the pest population is at the level in which the damage caused by the pest is touching the cost function. This level is the optimising threshold, Z^c as this is the first point at which the optimal level of control is greater than 0. In Figure 2c, the pest population density is such that a greater level of dosage is optimum and the producer will choose the level of dosage, Z^*. This level of pesticide is greater than the economic threshold dosage but still less than the label level, Z^L. In Figure 2d, the pest density is so great that the producer has no choice but to apply the maximum amount of pesticide Z^L.

Both definitions of the economic threshold level have their shortcomings. The economist's optimising threshold definition is difficult to utilise in practice as most of the parameters have to be known with certainty. The entomologist's discrete-choice threshold definition means that profits will not be maximised but is more useful in an environment of prescribed pesticide dosages. In this paper, the economic threshold definition utilised is that of the optimising threshold or as Palis et al. (1990, p.229) state "the pest damage level where the value of the incremental reduction in yield is equal to the cost of preventing its occurrence."

However, the policy conclusions derived from the model developed in section 4 of this paper are relevant in different degrees to both definitions of the economic threshold level.[5]

3. Extensions of the Classical Pest-Control Model

Noorgard (1976) states that basic economic models of pest control are limited by the assumptions that are required to make the model work. Economists have not been able to capture the complex relationships surrounding pest-control as they assume elements such as perfect competition and costless transactions. The assumption of minimal decision-costs is inadequate as a producer will have a number of information gathering and research costs in evaluating the effectiveness of different forms of pest control.

The major obstacle for a producer in determining an optimal pest control strategy is the environment of uncertainty in which he/she operates. Producers have to determine threshold levels from sampling and rely on the previous experiences of the control strategy success of particular pest densities. The problem of uncertainty has been examined by a number of authors including Feder (1979), Tisdell (1986), and Parnell (1991).

In this paper however, the main focus is on pest-control models that have examined either insect resistance or multiple pest species in an attempt to make the classical pest control model more applicable to different agricultural situations.

3.1 Models incorporating insect resistance

An element of risk for the producer in choosing a pest-control strategy is the effectiveness of the pest-control technique. This can depend on a number of elements, such as the suitability of the form of control for the pest-species, the climatic conditions at the time of application, and the range in the estimated population level of the pest species. One of the main forms of pest control, chemical applications, can decline in effectiveness as pests develop resistance to the chemical, reducing the mortality rate in successive generations. Extending the classical model to incorporate this problem requires a multiple-season approach to determine what the optimum pest-control level is for the present season. A general economic framework for techniques that decline in effectiveness with use[6] has been developed in Tisdell (1982).

Figure 3 and 4, show the case of a technique that is effective for a set number of uses. When this technique surpasses the maximum number of exposes the technique becomes totally ineffective. It is also assumed that the stock is common property. In a competitive market situation the technique will be used to the point where the marginal cost equals the marginal product of 'doses' of that technique.

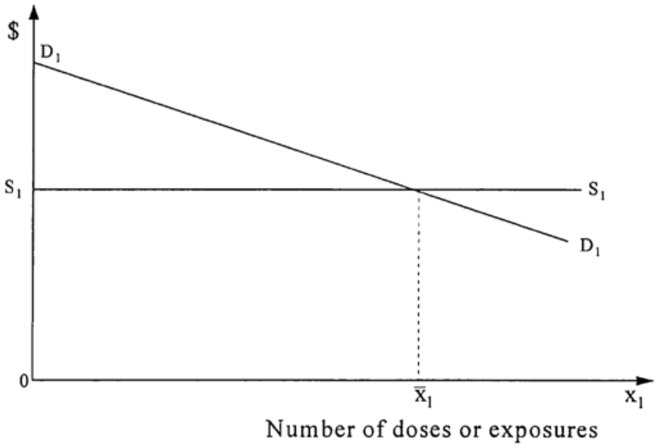

Figure 3: Based on Tisdell (1982, p.431)

Figure 3 shows the single-period situation. *D_1D_1* is the demand for doses and *S_1S_1* is the per-unit cost of supplying the doses[7]. In the single-period case the producers will use $\bar{x}_1$. However if $\bar{x}_1$ is the entire amount of possible dosages of the technique then that will not leave any for future periods. Figure 3 examines the use of the technique over a two period planning sequence. If the aim is to ensure the greatest social benefits over the whole planning period then the Government should intervene in period 1 to ensure that there is an adequate stock of the technique available in period 2. If the demand and supply curves[8] are the same for both periods then the amount of exposure to the technique in each period should be $0.5\bar{x}_1$. Government intervention could achieve this by setting a tax of *AB* in the first period and the present value equivalent of that tax, *JH*.

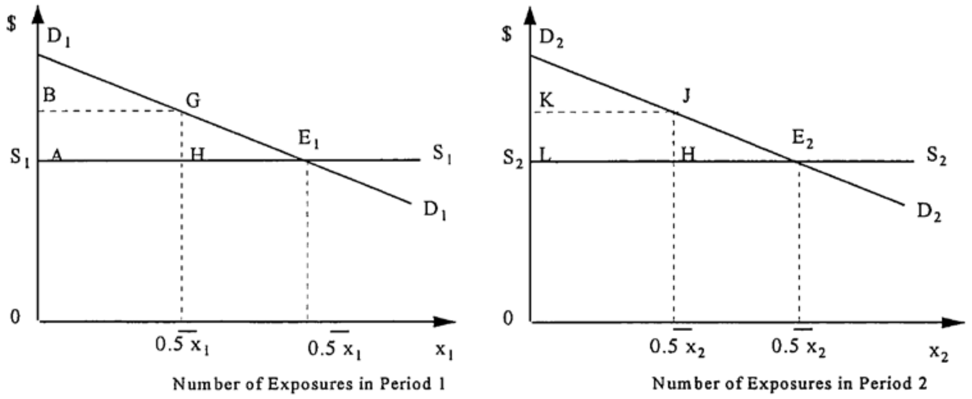

Figure 4 - Based on Tisdell (1982, p.432)

Tisdell's framework is designed to highlight the policy implications and the possible need for government intervention to ensure the optimum use of a technique with declining effectiveness. In practice, pesticides decrease slowly and inconsistently in effectiveness, making policy more difficult to determine.

Pest-control models that include pest resistance to control methods have been developed by several authors. Two of the most important models of pest-resistance are those developed by Rueth and Regev (1974) and Taylor and Headley (1976)[9].

Taylor and Headley's model is a comprehensive bio-economic model of insect resistance to control techniques. The model is driven by the pest population, with the costs and benefits of pest-control defined as a function of the population level and the damage levels that the population causes. The model is derived around the population genetics of three sub-populations: R_t, members of the population that are genetically resistant to pest-control; I_t, members of the population that are intermediate (have some genetic resistance); and S_t, members of the population that are susceptible to pest-control (no genetic resistance).

The mortality rates of these sub-populations then determine the number of pests in successive generations. The model develops three equations for successive generations that link the three sub-population levels to the initial generation and the dosage of pesticides. The benefits, B_t, from controlling pests is a function of the three sub-populations so that, $B_t = f_t(S_t, I_t, R_t)$ and the costs, C_i, of controlling the pests is a function of the dosage of insecticides, $X_t, C_t = c(X_t)$.

Determining the optimum level of benefits can be found through an optimisation program and simulated through dynamic programming. Taylor and Headley (1976, 240), note that the model is best examined at a regional level as it is unlikely that the individual producer would be able to incorporate resistance issues into a production function.

The Hueth and Regev (1974) model does not have the same bio-economic rigour but has a more extensive economic analysis. This model is more similar to the classical production theory approach, as opposed to Taylor and Headley's population based damage function model[10]. Hueth and Regev (1974) state also describe the similarity between the economics of pest-control where there is insect resistance and the literature relating to the economics of exhaustive resources. The Hueth-Regev model incorporates resistance as part of a optimisation problem subject to constraints. The main consequence of this model is that it provides insights into the nature of the economic threshold. Hueth and Regev (1974, 549);

> "It has usually been assumed that the economic threshold is constant over the growing season, or it is implied by the analysis when only one application is allowed for the season. It is shown below that the economic threshold varies over time and under certain assumptions increases with time so that, the closer the harvest time, the higher is the level of pest population that will be tolerated before controls will be applied."

The concept of a fluctuating economic threshold can be seen in Figure 5.

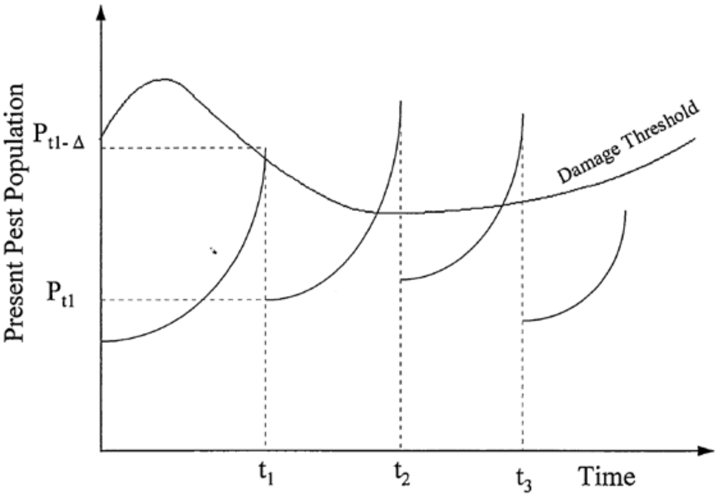

Figure 5: Based on Norgaard (1976, p.54)

Chemical applications occur at t_1, t_2 and t_3 with the population level decreasing with the control measure and then increasing with time between applications. The damage threshold changes with seasons, the price of pest-control inputs, and yield[11].

3.2 Models incorporating multiple-pest species

A problem facing many agricultural producers is the existence of multiple-pest species. Palis et al. (1990, p.229),

> "Currently, economic thresholds assume only one pest, when in fact an array of pest species are usually present in the field at the same time. Cumulatively damage caused by a combination of pests may be above an economic level, even though each pest is below its individual economic threshold."

The approach adopted by Palis et al. involved determining the level of the multi-pest species economic threshold can be seen in Figure 6.

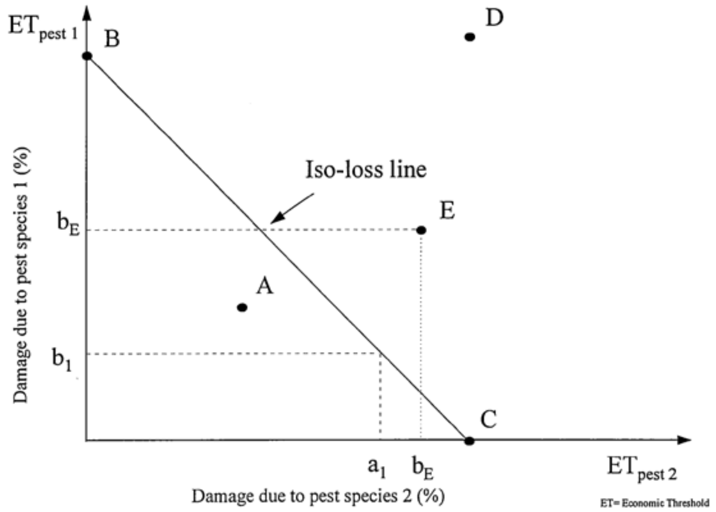

Figure 6: Based on Palis et al. (1990, p.233)

In the situation above, a producer is confronted by two different pest species and is to control them both through a single pesticide. In their model it is essential to determine the combination of damages due to the two pests and examine what pest control strategies should be undertaken by the producer in response to this situation. Palis et al. do this through the use of iso-loss lines. An iso-loss line shows combinations of damage by the two pest species, such as a_1b_1 that result in the same reduction in yield. Points below the iso-loss line, such as at point *A* relate to sub economic combinations of the two pest densities (similar to that shown in Figure 2a for the single pest case). For any combination of pest population densities to the right of the iso-loss line such as point *E* control is justified.

Iso-loss lines do not have to be linear. The shape will depend on the form of interaction that occurs between the two pests[12]. If a producer undertook a single pest threshold approach, rather than a multiple-pest threshold, then the only incidences in which control would be undertaken would be at point *B* for pest 1, point *C* for pest 2 and at point *D* for both pests. A point such as *E* would not reach the economic threshold for either pest 1 or pest 2, even though the combined damage at point *E* is higher than at point *B* or *C*. The multi-pest methodology as outlined by Palis et al. (1990) is an effective way of examining the single chemical - single season - multiple pest problem. Although the methodology can be extended to take into account two pest species controlled by different chemicals, the iso-line approach losses its relevance and use. It is also limited to a season by season approach to decision-making.

Szmedra, McClendon and Wetzstein (1988, p.l642) noted that there were many papers that examined the economic threshold for pest-control, however,

> "... the models developed assumed (a) highly simplified situations with a single pest, (b) a controlled environment, (c) a lack of pest-plant interaction, and (d) unstructured pest population dynamics. A more useful and appropriate area of investigation would be to consider the total cropping system."

Szmendra, McClendon and Wetzstein (1988), like, Boggess, Cardelli and Barfield (1985), extend a bio-economic model written by Wilkerson et al. (1983). In the Wilkerson model, classical pest-control theory is extended with the incorporation of multiple-pest species into the analysis. Wilkerson et al. (1983) was one of the first to build on the single-species model which was called the Florida Soybean Integrated Crop Management Model (SICM) is a bio-economic computer simulation model, Boggess, Cardelli and Barfield (1985, p.44) state that,

> "This modelling approach avoids two of the major limitations of the neoclassical theory of the firm as it relates to the problem of evaluating multiple-species management strategies. In this approach the simulation model replaces the

> classical production and is used to empirically derive the relationships between the various insect management strategies, yields and pesticide applications. These empirical relationships are used to determine the profit-maximising strategies, the demand for pest control and the marginal cost of pest control under various influx and price conditions.”

The importance of simulation models to the development of pest-control theory is that they aim to mimic the dynamic production process at the same time as maintaining a base of orthodox economic theory. Simulation models enable a benefit curve to be derived as they are able to compare crop potential to what actually occurs under a number of managerial strategies. They also provide useful information by simulating losses to a particular species, rather than a general loss.

One of the advantages of this model is the inclusion of the indirect effects such as pesticides killing natural predators of pests. The computer model incorporates the cost of such actions by determining how many insects would have been killed by these pests naturally, to how many exist after pesticides have been applied. The program then compares situations by evaluating different returns to the producer[13].

The externality elements of multiple-species pest-control are addressed in an interesting paper by Harper and Zilberman (1989). In this article they specifically examine two very important externalities that have not been addressed in the literature.

a) Directing a pest-control policy against one pest-species may lead to outbreaks in a secondary pest-species. This may occur if the natural predators of the secondary pest are destroyed by the pesticide used to control the major pest.

b) Non-pesticide inputs may lead to higher pest populations than otherwise would have been possible. Over-intensified agricultural practices may cause a higher than otherwise pest-burden.

The aim is to determine profit-maximising yields for both pesticides, Z and the yield enhancing input X. The primary pest and the secondary pests are treated by different pesticides. The paper, applied to Imperial Valley cotton, finds considerable value in scouting and integrated pest management. They also show that when the effects of intensified agricultural production on the pest population are considered, the producer would be likely to adjust the level of non-pesticide inputs.

4. A Dynamic Pest-Control Model for Livestock Incorporating Multiple-Pest Species and Insect Resistance.

The framework developed by Harper and Zilberman (1989) forms the basis of the model developed here to examine multiple-species of pests with gradual resistance to pesticides. While a number of production theory models could have been chosen to develop this model, such as Rueth and Regev (1974) or Parnell (1991), the Harper- Zilberman approach has been selected as it is a production theory approach, presents damage as a proportion of potential yield, and allows the incorporation of pest populations into the damage function. The main initial difference between Harper- Zilberman's model and the model presented here, are that there are no predators and fixed and application costs are included because of their importance in the cattle industry. The emphasis of the model is to present a number of 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.[14]

The grazier's production function is equal to

$$Q = f(X)\,[1 - D\{S_1, S_2\}], \tag{7}$$

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_l 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.[15]

$$D = D\{S_1, S_2\} \tag{8}$$

where $D_{s1}, D_{s2} > 0.$[16] The population equations for the two pest species are:

$$S1 = k_l(X)[1 - M_{li}(Z_i)]R_{li} \qquad (9)$$

$$S_2 = k_2(X)[l - M_2(Z_i)]R_{2i} \qquad (10)$$

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

We also assume 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

$$C = uX + a_1 + a_2 + a_3 + w_1Z_1 + w_2Z_2 + w_3A_3 + y_1 + y_2 + y_3$$

where u is the cost of the non-pesticide input, a_i are the fixed costs associated with applying pesticide i[17], w_i is the cost of pesticide i and y_i is the cost of applying pesticide i.[18]

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

$$max\pi = pf(X)\ [1 - D\{S_1; S_2\} - uX - a_1 - a_2 - a_3 - w_1Z_1 - w_2z_2 - w_3Z_3 - y_1 - y_2 - y_3$$

subject to

$$S_1 = k_1(X)[1 - M_{1i}(Z_i)]R_{1i} \tag{11}$$

$$S_2 = k_2(X)[1 - M_{2i}(Z_i)]R_{2i} \tag{12}$$

5. Issues and Implications from the Model

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 this example, let us assume 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, that is

$$pf(X) - pf(X)[1 - D\{S_1\}] > a_i + y_i + w_iZ_i$$

where $i = 1$ or *3*. Let us also assume that although Species *2* is damaging the product, its population level does not justify control in its own right, $pf(X) - pf(X)[1 - D\{S_2\}] < a_2 + y_2$

+ w_2Z_2.[19] In this situation the producer has two options.

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,
$S_1 = k_1(X)[1 - M_{11}(Z_1)]R_{11}$	$S_1 = k_1(X)[1 - M_{13}(Z_3)]R_{l3}$
$S_2 = k_2(X)[1 - M_{2l}(Z_1)]R_{21}$	$S_2 = k_2(X)[1 - M_{23}(Z_3)]R_{23}$
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, we retain the assumptions that $M_{11} = M_{13}$ and that $w_1Z_1 = w_3Z_3$, $a_1 = a_3$, 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 these 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

$pf(X) - pf(X)[1 - D\{S_1\}] < a_1 + y_1 + w_1Z_1$,

$pf(X) - pf(X)[1 - D\{S_2\}] < a_2 + y_2 + w_2Z_2$, however,

$$pf(X) - pf(X)[1 - D\{S_1; S_2\}] > a_3 + y_3 + w_3Z_3$$

If the assumptions used at the beginning of example one are retained, in 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.

6. Conclusion

Many developments in the economics of pest-control literature have occurred because of the need to make the theory more relevant to a certain agricultural situation. The model developed in this paper is no different. It is developed for the examination of the pest-control decisions confronting cattle producers in the cattle tick (*Boophilus microplus*) infested areas in Queensland. With changing domestic and international attitudes towards chemical use, the decreasing effectiveness of pesticides to controlling cattle-tick and the lack of new chemical development, there has been a renewed interest in the cattle industry and Government attitude towards cattle-tick control. In particular, which long-term strategies should be adopted, such as eradication or partial eradication, to ensure the greatest level of net benefits?

A problem that has to be addressed in determining the optimal control strategy from a regional perspective, is what control decisions the producer is making in relation to other pests, such as buffalo-fly (*Haematobia irritans exigua*). The overall benefits of eradicating *Boophilus microplus* will be dependent on the interactions between the producer's pest control decision and the economic thresholds of the two pest populations.

A simulation model will be able to incorporate accurate representations of the rate of resistance to different chemicals, appropriate damage functions, actual levels of non-pesticide input and current commodity prices and effectiveness of different pesticides. However there are areas of further investigation that will need to be examined and modifications for when the framework is applied.

For example, as few pest-species are bound to one property, a further element of investigation is the level of externality caused by differing pest-control management strategies. For example, a neighbouring producer trading off long term resistance with a small present benefit for a particular chemical is also providing resistance to that chemical for his/her neighbours. This is particularly likely in situations where the producers have a wide range of production procedures and diverse products, such as producers with different breeds of cattle that have different levels of natural resistance to pests. With this situation a regional control model would be a preferable framework in which to examine pest-control decisions as it can examine the interactions and the externalities associated with diverse production systems.

7. Notes

1. This model examines benefits from pest-control in a single season and compares them to the cost. If there are fixed elements to the variable, such as a cattle-dip, this value is discounted to the level for that particular year.

2. An example would be paying higher money for choosing a highly resistant bull or rotating pastures and the opportunity cost of agriculture foregone.

3. This is because the producer is a price taker (constant price) and marginal physical product is assumed to be downward sloping.

4. The variables in this model have been changes from those used by Weersink et al. (1991) read somewhat consistently with the Harper and Zilberman (1989) model presented later in this paper.

5. To prevent problems such as resistance and ineffective control of cattle tick or buffalo fly, most manufacturers recommend the producers treat cattle at a prescribed rate. This adds weight to the discrete-choice economic threshold being the more utilised technique in practice, and the importance of the model developed later in the paper to be valid for both threshold definitions.

6. Tisdell presents two models one in which the effectiveness of the technique declines with the amount of use and the other with the duration of use. Only the first model is presented here. In practice the two models need to be considered simultaneously. In cases such as resistance, the effectiveness of the technique will be a function of the population dynamics of the pest.

7. The curve D_1D_1 can be interpreted as the marginal product of doses of the technique, Tisdell (1982, 431). The flat supply curve is indicative of the assumption of perfect competition.

8. Discounted demand and supply curves.

9. Taylor and Headley initially published their work on pest resistance in 1973 as "Resistance and the Optimal Control of Pest Populations", Working Paper, Department of Agricultural Economics, University of Missouri, Colombia.

10. The models also differ in their perspective. Hueth and Regev analyse costs and benefits for the individual producer while Taylor and Headley (1975, 240) suggest that their model would be much more suited for regional analysis.

11. Szmedra, McClendon and Wetzstein (1988) examine the concept of the economic threshold concept and its relationship to Integrated Pest Management schemes. They pointed to the works of Hueth and Regev (1974), Headley (1972), Hall and Norgaard (1973) and Talpaz and Borosh (1974).

12. Johnson (1990, p.206) observes that there are three possible outcomes of combined pest infestations on yield, no interaction, greater than additive (synergistic) or less than additive (antagonistic). The relationship between the pests will determine the shape of the iso-loss line

13. In the case of soybean the model initially addressed the main pest for soybean the velvetbean caterpillar (*Anticarsia gemmatalis*) and then was extended to include the com earwonn (*Heliothis zea*) and the southern green stinkbug (*Nezara viridula*). Pests are treated with different pesticides at different times.

14. This model is valid for pest-control management by strategic chemical applications as the costs and doseages can be incorporated into the model with the selection of the chemical being the primary concern.

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

16. Harper and Zilberman (1989,p.693) 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: $D = (l - e^{-alSl})\,(1 - e^{-alSl})$; *and* $D = l - e^{-\beta lS1\ -\ \beta 2S2}$.

17. These fixed costs are the discounted values for this particular season.

18. Fixed costs are important in the application of chemicals to livestock, however they are generally left out of pest-control models for simplicity.

19. It is also assumed that the producer from time to time has circumstances whereby S2 becomes the primary pest.

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