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A Review of the Economics of Controlling Diseases in Livestock and the Modelling of Control Policies

by

Thomas D Murphy

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'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 of the Economics of Controlling Diseases in Livestock and the Modelling Of Control Policies

ABSTRACT

International health organisations point to the need to improve the efficiency of prevention, control and eradication programs for animal diseases. In order to achieve this and justify national and international support it has become essential to apply techniques of economic analysis (Ellis, 1993). A review of the literature indicates that techniques of economic analysis such as cost benefit analysis and simulation modelling are commonly applied in assessment of disease control programs. It is argued however that such applications fail to satisfy the principles of optimal economic analysis. It is suggested in this paper that Mathematical programming techniques in principle help determine optimality better than competing techniques, appropriately integrating economics and epidemiology into the analysis. This paper will provide a review of the economics of controlling diseases in livestock and outline the possible application of optimal control modelling to assessing disease control policies. This review and application will be conducted with special reference to foot-and-mouth disease in Thailand.

Keywords: Foot and mouth disease, Thailand, control of livestock disease, control policies

JEL Classifications: Q160, I15

A Review of the Economics of Controlling Diseases in Livestock and the Modelling Of Control Policies

1. Introduction

The stated objectives of international health organisations such as the Office of International des Epizooties (O.I.E) and Thai organisations such as the Department of Livestock and Development (DLD), have identified the necessity to improve the efficiency of prevention, control and eradication programs for livestock diseases such as FMD. In order to achieve this and justify national and international support it has become essential to apply techniques of economic analysis (Ellis, 1993).

As Ozawa (1993) noted in his analysis of South East Asian regional control programs, the rising costs of FMD control programs in South East Asia requires the development of the most economically efficient strategy. The development of such strategies should be developed through rigorous evaluations and regular economic analysis of national control programs. As Thieme (1982) noted, from a national viewpoint, control of economically important diseases can represent potentially large benefits or alternatively large losses in personal welfare forgone through reduced consumption and lost export earnings if disease control programs are not optimal.

However relative to other fields of agricultural economics, there is little published literature on the economic assessment of animal diseases and control strategies. As noted in Anaman (1993) the work that is available is concentrated on major disease such as FMD and tuberculosis - a bias reflecting the damaging impact of these diseases on livestock production and international trade.

James and Ellis (1979) and McInerney (1988), noted that past approaches to disease control were an all-or-nothing affair, generally determined by the concept of disease as undesirable, and any measures that mitigated or eliminated its effects were to be adopted in its control. In recent times however the general approach to disease control has witnessed the integration of economics and epidemiology in order to determine the optimal management of control programs. While the number of documented ‘bio-economic’ studies on the modelling of disease control is increasing with time, they can be criticised on the appropriateness of the economic techniques applied and whether they sufficiently represent the appropriate epidemiological and economic features of disease (eg. FMD) control. This paper will discuss these issues, particularly where relevant to Thailand.

2. Mathematical Modelling of Disease.

An essential element in the evaluation of control programs has been the representation of disease dynamics through modelling techniques. While this process is often a difficult task the historical development of mathematical theories on the spread of endemic disease has formed the backbone for a more accurate assessment of the dynamics and impact of disease in many contemporary economic studies of disease control programs.

2.1 Epidemiological modelling

Bailey (1975) provided a comprehensive outline of the development of mathematical theory in relation to infectious diseases. In relation to deterministic models, it was Hamer (1906 in Bailey 1975) who considered that the course of an. epidemic depends on the number of susceptibles and the contact rate between susceptibles and infectious individuals the basic mathematical assumption of all deterministic theories.

The first to provide mathematical theory as a research tool in epidemiology was Ross (1911 in Bailey, 1975). Ross developed a deterministic model with some elements of probability included concerning the transmission of malaria. This model determined the future state of the epidemic process (given the initial numbers of susceptibles and infectives), together with the attack recovery, birth and death rates (Bailey, 1975, p 11).

Kermack and McKendrick (1927-1939, in Bailey 1975) were to extend such studies introducing more variable rates of infection and recovery and developing a notable principle- the threshold theorem, whereby if the density of susceptibles exceeds a critical level then introduction of an infection will result in an epidemic that will reduce the density of susceptibles as far below the threshold as it was originally above.

McKendrick extended his earlier deterministic work to a stochastic treatment of an epidemic’s dynamics. Modelling developments in epidemiology have been characterised by this transition from deterministic to stochastic approaches. Bailey (1975) noted that limitations of deterministic models in representing the variability and chance elements of the real world saw deterministic models frequently abandoned for probabilistic or stochastic representations. Deterministic models take the actual number of new cases in a short interval of time to be proportional to the number of both susceptibles and infectives. Stochastic models, such as those adopted by McKendrick, differ from those of a deterministic nature in that they determine the probability of one new case in a short interval of time was proportional to the same quantity (Bailey,1975, p. l2). These developments in the stochastic representation of disease have formed the basis for the Markovian approaches so often applied in contemporary modelling of disease. It was Greenwood (1931) and Reed and Frost (1928) (see Bailey, 1975) who were to extend the application of probability to contact rate estimation in determining frequency of infective cases. These latter stochastic modelling applications of Reed and Frost's (1928) model have been utilised recently by Baldock (1992) in determining the potential outbreak of FMD in regional Australia.

2.2 Optimal control theory

As the applications of epidemiological modelling has developed and broadened there has been increased focus on the implications of such approaches for animal health intervention and control. The design of optimal immunisation programs especially prevention via vaccination has been outlined in studies by Morton and Wickwire (1974).

Wickwire (1977) saw developments in the theory of optimisation and its ‘dynamic analogue’ *optimal control theory* go through similar phases to that of epidemiology. The theory emerged through attempts to develop solutions to problems in the physical sciences which heralded the invention of calculus and calculus of variations. According to Wickwire (1977) the theory however only really progressed by applications by Pontryagin and Bellman - where the methods of dynamic programming based on Pontryagin’s optimising principles were well used by the fields of engineering and mathematics. Recently however we have seen the application of such theories to the biological sciences and in particular to the optimal or efficient control of pests and infectious diseases. Wickwire (1977) provided overviews on formal control theory methods of writers referred to in Bailey (1975) such as Jacquette, Sanders, Abakuks, and Hethcote and Waltman. Bailey (1975) saw the application of such methods as of considerable practical importance to the whole disease treatment process.

Given the development of many of these modelling approaches to disease and disease control it is notable that many economic studies are criticised for their inability to sufficiently represent the dynamics of the disease. - the principles of epidemiology in the analysis (Anaman, 1993). Berentsen (1992a), Dijkhuizen (1992) and Anaman (1993) have attempted to address what has been criticised as an inability in previous documented studies on disease control to adequately incorporate the biological features of the spread of animal disease over time and/or space in determining the economic impact of disease. Some of these studies have attempted to solve this problem by utilising epidemiological modelling that simulates disease spread and in doing so estimate costs associated with' the epidemic. These outputs then feed into a benefit-cost framework.

These integrated applications provide a very useful manageable approach to evaluating control programs particularly on a national basis. However they do not in themselves represent what they claim as strictly bio-economic approaches and often do not represent basic economic principles of optimality. How economic principles are applied to analysis of disease and the role of economics in optimal control strategies is an area of little analysis in the literature.

3. Economic Evaluation of Disease

Dijkhuizen and Huime (1992) stated that animal health economics can be described as “the discipline that aims to provide a framework of concepts, procedures, and data to support the decision making process in optimising animal health management” (p. 145). The scientific foundation for the discipline of animal health economics, was according to Dijkhuizen and Huime (1992), laid 20-25 years ago in Australia and England by Morris (1969) and Ellis (1972) respectively. Their studies highlighted the essential economic principle in making veterinary decisions - *the equimarginal principle* that states disease control input should be increased to a level where the *cost of an additional input equals the return from the additional output*.[1] This has been seen as a fundamentally different approach from the previous traditional opinion about disease control being an all-or-nothing affair and has been the basis for the approaches to animal health economics outlined in other literature (McInerney (1988), Dijkhuizen (1992), Howe (1988)). Essentially this approach forms the basis for analysing disease control within an economic framework.

3.1 Techniques applied in economic evaluation of disease control

Many economic studies on disease control generally try to combine approaches of epidemiology and economics and to apply them to animal health problems in order to either

1) evaluate the causal relationships,
2) predict and measure the losses and,
3) prescribe preventive and or control measures (Ngategize and Kaneene, 1985, p. 153).

Studies on the quantitative techniques applied to analyse animal health problems have been classified in a variety of ways in the literature. In respect to animal health, Ngategize and Kaneene (1985), Dijkhuizen (1988) and Bennett (1992) have provided comprehensive assessments of a broad range of quantitative modelling approaches utilised in economic assessments. The former two studies considered the modelling of animal health within two broad headings 1) statistical and/ or epidemiological models, 2) economic models. Under the first category they had included a range of techniques that are predominantly statistical such as regression, discriminant variance and path analysis. Under the ‘Economic’ category, Ngategize and Kaneene (1985) include Cost benefit analysis, partial budgeting and the ‘equimarginal’ principle. Other economic modelling approaches applied to animal health that were analysed in this study were decision analysis, linear programming, markov chains, systems simulation[2] and dynamic programming. Bennett (1992) considered a similar range of quantitative economic modelling approaches that in many ways overlapped with the former studies mentioned. The major categories in Bennett's (1992) study were

1) mathematical programming,
2) network analysis,
3) decision analysis
4) simulation
5) cost-benefit analysis.

James and Ellis (1979) simply categorised the modelling approaches into positive and normative approaches. The positive approach is essentially a description of relevant processes by statistical epidemiological data analysis (ie empirical modelling). The normative approach to the economic effect of animal disease requires a conceptual model of the animal production system and the economic system on which it operates on purely theoretical grounds. This is then used to predict the effect of the disease on the system (James and Ellis, 1979, p 366). Put simply, the positive approach is all data and no model and the normative approach is all model with no data (James and Ellis, 1979). Generally the approaches undertaken contain elements of both. Livestock disease models which appear to be normative in practice contain many elements which have been estimated by empirical methods (James and Ellis, 1979, p367)

Therefore, it must be understood there is considerable overlap between these modelling approaches, particularly where they are applied in several of the same applications. While studies by Bennett (1992) and Ngategize et al. (1985) included a broad range of approaches, the major applications and particularly those applied in control of FMD in Thailand will be highlighted.

3.2 Statistical/epidemiological models

Statistical/Epidemiological models have been applied in the literature to identify factors that contribute to development of disease conditions, magnitude and direction of contribution and relationship between disease and other conditions (Ngategize and Kaneene, 1985). The varying types of these kind of models are,

a. Regression Analysis

b. Path Analysis

c. Discriminant Analysis

d. Analysis of Variance

e. Time Series

Statistical analysis of factors affecting the levels of infection in Thai villagers was undertaken by Cleland et.al (1992). While these applications are important this paper will concentrate on the more direct economic modelling approaches that have been applied to FMD control in developing countries.

3.3 Quantitative economic models

Quantitative economic models applied in the literature use mathematical expressions to represent aspects of the real world. The term is usually applied to models whereby an equation or a set of equations are used to represent the behaviour of livestock production systems and the impact of disease on these systems. Some of the major modelling techniques outlined in the literature include partial budgeting, decision analysis, simulation, cost benefit analysis and mathematical programming.

3.3.1 Partial budgeting

A partial budget is a description of economic consequences of a specific change in farm planning. The partial budget can be categorised into four sections in response to change, i.e 1) additional revenue, 2) reduced cost, 3) revenue foregone, and 4) extra cost of implementation of the change. A change may be related to a new approach to disease control or methods. The decision rule to adopt the change is determined by whether the sum of 1) and 2) is greater than 3) and 4). Ellis (1993) provided a very simple though useful illustration of this technique in relation to increased vaccination of Thai cattle on farms.

3.3.2 Decision analysis

Decision analysis considers likely outcomes resulting from alternative courses of action under possible states of nature (Bennet,1992, p.68). Often decision trees or network diagrams are used to graphically represent the decision problem. This tree is defined as a “graphical method of expression, in chronological order, of the alternative actions available to the decision maker and the choices determined by chance.” (Hiller and Lieberman, 1980 in Ngategize et al., 1985 p.157)

3.3.3 Simulation

Simulation is a method for analysing a problem by creating a simplified mathematical model of the system under consideration. The objective of simulation is to essentially emulate reality through a simplified model that can be manipulated by input modification. These models represent the likely outcome associated with different situations or states of nature (Bennet,1992). They allow experimentation with a model of a system rather than the system itself and generally use probability distributions associated with events.

In terms of the epidemiology of livestock disease and economic models, simulation is relatively popular given its flexibility in the utilisation of other techniques and its ability to represent the dynamic and uncertainty aspects of livestock disease. The Markovian approach has been particularly concentrated on in the economic studies applied to disease over the last few years (Anaman, 1993). Baldock (1992) and Dijkhuizen (1988) utilised Markov processes in simulation models evaluating pestilence and FMD control. Markov processes or ‘chains’ use transitional probabilities between possible states in a system, e.g. between susceptible to infective animals from one period to the next. These epidemiological simulation models generally link to a form of economic analysis or evaluation (loosely termed ‘bio-economic’) rather than the simulation being also applied to economic considerations such as prices and interest rates as noted in Bennet (1992). In respect to FMD, simulation approaches have been conducted by Carpenter and Thieme (1980) in measuring the economic effects of Foot and Mouth disease on beef and dairy cattle. Their model was designed to simulate the economic costs and benefits associated with controlling FMD in beef and dairy cattle herds where disease is considered to be endemic.

For Thailand, specific studies have been conducted on various aspects of disease control in recent times. Cleland et al (1992) introduced a study examining the effects of different vaccination coverage rates and timing of the first vaccination. The study adopted a simple state transition (Markov) model constructed to determine the change over time in the percentage of animals immune to FMD in a village.

3.3.4 Cost-benefit analysis (CBA)

Cost-benefit analysis is by far the most popular economic analysis technique applied in order to analyse disease control programs. The main elements of cost-benefit analysis according to Ngategize and Kaneene (1985) involve:

1. enumeration of benefits and costs,
2. determination of discount rate,
3. specification of a decision criterion (i.e. net present value, benefit-cost ratio or internal rate of return) (Ngategize et.al. 1985).

It is applied at the private (producer), industry (cattle producer) and society (national) levels (Bennet, 1992). At the national level social cost benefit analysis (SCBA) is carried out considering the costs and benefits to producers and consumers (using concepts of consumer and producer surplus). This process takes into account distortions in market prices in any valuations (such as subsidies, taxes etc.) to provide some measure of the true costs and benefits to society of a resource allocation decision (Bennet, 1992).

Benefit-cost analysis is essentially the major modelling approach to large disease control programs. Anaman et al. (1993) applied benefit-cost analysis in the case of eradicating screw worm fly in the event of invasion in Australia. Power and Harris (1973) provided one of the first published applications of SCBA to animal health in the UK in an evaluation of two alternative strategies for controlling Foot and Mouth disease in Britain. In respect to Thailand, Bartholomew and Culpit (1992) applied cost-benefit analysis to identifying producer benefits to disease control in Thai villages.

3.3.5 Mathematical programming

Mathematical programming techniques are essentially quantitative planning techniques which involve trying to achieve an objective given various alternative courses of action and resource constraints. The objective, the alternative ways of achieving it and constraints require mathematical specification (Bennet 1992). The programming technique then involves the search for an optimal solution to the decision problem. Mathematical programs can be used to determine disease control strategies where the primary objective is to maximise the net benefit of the control program given possible alternatives for control and subject to a number of ecological epidemiological and economic constraints.

A central feature in programming, as in most mathematical techniques is the correct specification of the model, the assumptions contained within it, and the value of parameters. Many of these models such as dynamic programming can become very large and costly to compute. This paper however will apply a simplified framework for analysing the nature of relevant control strategies in Thailand. The greatest strength in mathematical programming is its ability to search for an optimal solution amongst a number of alternatives, under a number of constraints (Bennet 1992, p. 67).

3.4 Selection of Techniques

A review of the literature suggests there are no definite guidelines for the choice of appropriate techniques to assist in decisions about livestock disease control programs. As noted in Ngategize et al. (1985) and Bennet (1992), the choice depends on many factors such as,

- The decision problem being modelled
- The complexity of the system involved
- Information available about disease parameters
- Uses to which model will be put and the preference and capabilities of the model builder and the decision maker
- Resources available

As noted above in the case of disease in Thailand many different approaches have been utilised and combined in both epidemiological and economic contexts. Simulation can be applied where the system can be well represented by a mathematical model and performance relies on a number of known factors. Cost-benefit analysis, particularly social cost-benefit analysis is particularly useful when evaluation is required especially in regard to national policy. Mathematical programming techniques can be applied where disease control programs can be well defined in terms of a clear objective and methods for achieving the objective and constraints can be specified mathematically.

However while many of these approaches are useful in given situations, the literature has identified faults in the way many of these applications represent optimal economic behaviour. Studies into the economic principles of disease and disease control highlight problems in the approach of many traditional methods in providing optimal answers. The following section will outline the fundamentals of the economics of disease control.

4. Economic Framework of Livestock Disease

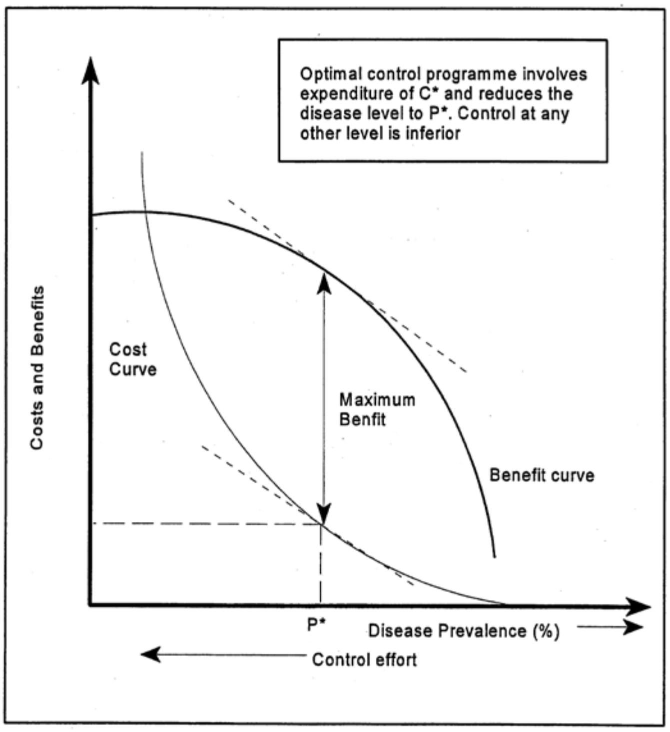
Studies by Dijkhuizen (1992), McInerney (1988) and Howe (1988) provide interrelated studies on the economic framework of disease. The basic conceptual model put forward by Dijkhuizen (1992) and McInerney (1988) that underlies economic analysis includes three major components: people, products, and resources. It is people who want things and make decisions which provide the driving force for economic activity. Products are goods and services that satisfy what people want and may be regarded as the outcome of economic activity. Resources are the physical factors and services that are the basis for generating the products and as such are the starting point for economic activity. Based on this conceptual framework put forward by McInerney (1988) and Dijkhuizen (1992) animal disease has been seen as an influence which affects the resource transformation process and causes extra resource use and/or less production to result then before .

4.1 *Disease as an economic process*

This concept of reduced production has been highlighted by Howe (1985) McInerney (1978) and Dijkhuizen (1992) in their approach to the concept of disease as an economic process. To represent disease as an economic influence both Howe (1988) and McInerney (1988) have begun with the model of production to represent the essential process that disease effects. In terms of economic analysis the production function states that there is a systematic relationship between the quantity of input factors used (i.e. feed labour) and the quantity of output produced (i.e. live weight gain). Given the nonlinear nature of output, production is often not represented as a physical quantity but a relationship between input and output. Taking the production system to represent a livestock production process, the effect of disease is portrayed as a downward shift in that relationship as described by McInerney (1988). This reflects lower livestock output from the inputs used compared with the healthy herd or animal-output possibilities are scaled down at all levels of input.

4.2 *Disease control as an economic process*

McInerney (1988) and Howes (1988) indicate the best disease level and therefore the most economically effective control program is where benefits associated with the level of prevalence exceed costs by the greatest amount. This is where the gradient of both curves is identical - the *economic optimum condition*. That is where marginal benefits and marginal costs are equal - satisfying the *equimarginal principle* (see Figure 1). McInerney believes that this principle lies at the heart of economic analysis.



Source: McInerney (1988, p.73)

Figure 1: Economically efficient disease control (and the optimum level of disease)

5. Status of the literature

The approach and validity of the literature on the economic evaluation of disease can be reviewed well within the framework provided in sections 4.1 and 4.2 concerning the economic principles of disease and optimal disease control. While popular approaches such as cost-benefit analysis provide a useful and manageable application in evaluating disease control programs, and in terms of national analysis are often the sole way of providing a form of economic evaluation, they can be criticised in their adherence to the economic principles of optimality.

There is often conflict in the literature on the precise role of economics in disease control and the best method and technique to determine economic efficient decisions. It is particularly evident with cost-benefit analysis as the most common form of ‘economic’ technique utilised in the control of foot and mouth disease. While Ngategize et al. (1985) claim cost-benefit is “the only real economic technique” (p.347), McInerney (1991) claims cost-benefit techniques are basically accountancy procedures with no real economic grounding. While a common problem in these assessments may be the source of studies criticised, McInerney (1988, 1991) makes a valid point.

The fundamental principles of economics (as outlined in any introductory economic text) lie in determining the *best use of resources for optimal decisions*. Cost-benefit analysis essentially does not determine this optimality. It only provides magnitudes in net revenue to relate to other programs in order to determine or prioritise programs. Sensitivity analysis allows a weak form of optimality in enabling a prioritising of outcomes given different inputs - still within a benefit cost framework. While these priorities are important and essential in determining choices they do not fully meet the principles of optimal economic analysis. Simulation procedures can represent the real world and provide estimates and predictions of certain policies and can be mechanistically adjusted to provide a variety of scenarios - they do not *in themselves* however determine the optimal solution to an objective.

Mathematical programming techniques in principle help determine optimality better than competing techniques. Mathematical optimising techniques developed in the literature purport to provide the solution to the objective of the policy maker based on the constraints he faces in these objectives. Their difficulty as noted in the literature however is sufficiently representing the system and correctly specifying the model. It is suggested in this paper that the application of optimal control techniques, while suffering its own deficiencies in application may actually address the important economic principle of optimality better than traditional approaches.

This paper will provide a simple framework for an economic analysis of a disease control program (such as zoning), using optimal control theory.

6. Modelling Disease Control Programs

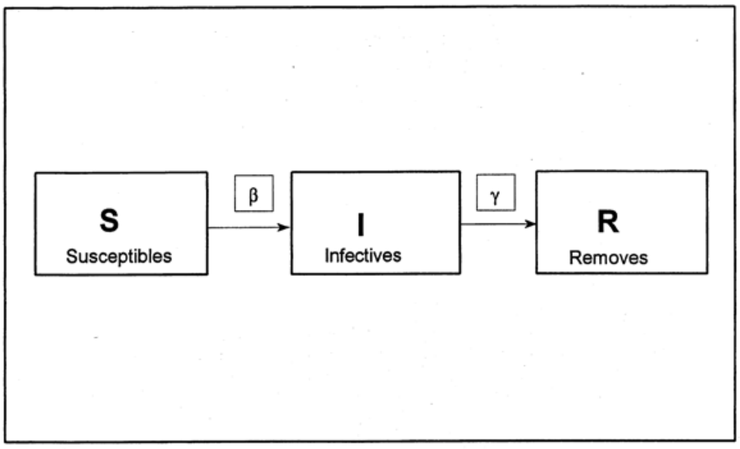
The previous section has outlined the literature on economic evaluation of disease control and has generally focused on the integration of epidemiological and economic techniques in order to correctly evaluate disease and control programs. These loosely termed ‘bio-economic’ models applied to control programs have often failed to integrate appropriately the two fields into a cohesive model that intrinsically determines optimality in disease control programs. Given the increasing costs associated with FMD control, the correct integration of epidemiology and economic modelling is necessary in order to provide optimal solutions to control.

This section will provide a simple, though valid bio-economic modelling approach to the disease control strategy of zoning. It will integrate the principles behind the deterministic modelling of epidemics by Kermack and McKendrick (1927 in Wickwire, 1977) with the optimal control approaches applied to biological populations and control of disease outlined in Wickwire (1977) and Clark (1990). This simple model combines the dynamics of a biological (process) within a constrained economic optimising technique. Essentially this provides a formal 'bio-economic' assessment of a control strategy in order to outline important policy implication related to optimal control through zoning.

6.1 Deterministic model of disease

In order to understand the control of a disease and develop relevant economic assessment of disease control programs, it is important to specify the features of disease and conditions for how disease spreads (epidemic). This section will outline the deterministic modelling of disease based on work by Kermack and McKendrick (Wickwire 1977). As noted in Bailey (1975), while not as precise as stochastic applications, deterministic modelling is a good foundation for the initial analysis of disease dynamics and is able to highlight striking features that can be represented more precisely through stochastic representations.

Epidemiological models of infectious disease represent the course of epidemics over time and are generally simplifications of complex biological systems. While this simplification is considered a limitation, mathematical models are useful tools in examining theoretical disease behaviour under assumptions derived from existing knowledge. The theoretical work on epidemic modelling by Kermack and McKendrick (outlined in Wickwire 1977) has had a major influence in the development of mathematical models. Figure 2 provides a simple illustration of the S.I.R model of infectious disease, described as a flow chart and an associated mathematical relationship.



Source: Based on Baldock (1992)

Figure 2: The S.I.R. Model

Figure 2 represents a schematic relationship in the flow of animals or herds between different possible stages of the disease. The β and γ terms represent the rate of change between the various disease stages, β is the contact rate per infective unit of time that is required to effect transmission from one animal or herd to another, while γ is the recovery rate from the particular disease per unit of time. The capital letters represent the proportion of animals or herds in each stage of the disease: *Susceptible (S), Infective, (I) Recovered (R).* Therefore S, I, and R obviously change with time as the disease spreads through the population (Baldock 1992, p 177).

In the model applied in this paper, population (*N*) is considered to be constant. If a small group of infected individuals are introduced into a large population, the basic problem is to describe the spread of the infection within the population as a function of time (*t*). This depends on a variety of circumstances, including the actual disease involved. For example, FMD is a highly infectious disease and would therefore have a high infectious rate (β). However for a basic modelling approach, this is not an unreasonable general assumption (Murray 1989, p 611).

Considering a disease that, after recovery, confers immunity (which includes deaths as dead individuals are still counted) the population is then divided up into three distinct classes, the susceptibles (S) who can catch the disease, the infectives (I) that have the disease and can transmit it and the removed class (R) that have either had the disease or are recovered, immune or isolated until recovered. The progress of individuals is schematically described by the S-1-R relationship (Murray, 1989, p.611).

6.1.1 Assumptions of deterministic epidemiological models

The assumptions made about the transmission of the infection and incubation period are critical in any model. Frauenthal (1980) in his study on deterministic modelling outlined the assumptions common to all deterministic models.

- Disease is contacted between an infected individual and a susceptible individual.
- There is no latent period for the disease therefore the disease is transmitted instantaneously upon contact.
- All susceptible individuals are equally susceptible and all infected individuals are equally infectious.
- Population under consideration is fixed in size – no births or migration occurs and all deaths are taken into account.

The various classes therefore are considered universally mixed, that is every pair of individuals has equal probability of coming into contact with each other.

6.1.2 Dynamics of the disease

The model mechanism that represents the different stages of the disease is then,

- $dS/dt = -\beta SI$
- $dI/dt = \beta SI - \gamma I$
- $dR/dt = \gamma I$

Where $\beta > 0$ is the infection rate and $\gamma > 0$ is the removal rate of infectives. These equations are known as *first order ordinary differential* equations and express changes in the proportion of animals or herds in each stage of the disease per unit of time. For example, the dS/dt is the rate of change in the proportion of susceptibles with time. Numerical solutions to the problems provide model outputs (Baldock, l992).

The constant population size is built into the system since on adding the equations

- $dS/dt + dI/dt + dR/dt = 0$, *that is*, $S(t) + I(t) + R(t) = N$

Where N is the total size of the population. Thus $S - I - R$ are all bounded above by N. The mathematical formulation of the epidemic problem is completed given *initial* conditions for the Susceptibles (S_0), Infective (I_0) and Removes (R_0) such that,

- $S(0) = S_0 > 0$,
- $I(0) = I_0 > 0$,
- $R(0) = 0$.

This is Kermack and McKendrick's S-I-R model.

6.1.3 Conditions for an epidemic

The fundamental issue in any analysis of a disease control programme, is what effect would such a control have on the outbreak of an epidemic, that is what conditions are necessary for an epidemic and therefore, what the basic requirements in control of a disease.

The key elements in any epidemic are the approximate infection rate β, relative removal rate γ, and initial number of susceptibles S_0 and Infectives I_0 whether infection will spread or not and how it will develop with time, and when will it start to decline. Murray (1975, p 612) provides a good summary of this scenario. From the second differential,

- $[dI/dt] = 1_0 (\beta S_0 - \gamma) < 0$, *if* $S_0 <$ *then* $\gamma/\beta = \rho$.

For the first differential $dS/dt \leq 0, S \leq S_0$ we have if $S_0 < \gamma/\beta$

- $dI/dt = I(\beta S - \gamma) \leq 0$ *for all* $t \geq 0$.

In which case $I_0 > I(t) \rightarrow 0$ *as* $t - {}^{\infty}$ and therefore the infection dies out and no epidemic occurs.

The alternative scenario is if $S_0 > \gamma/\beta$ then $I(t)$ initially increases and we have an epidemic. The term epidemic means that $I(t) > I_0$ for some $t > 0$. There is therefore a *Threshold Phenomena*. If $S_0 > S_c$ (*critical level of susceptibles*) $= \gamma/\rho$ there is an epidemic while if $S_0 < S_c$ there is not. The critical parameter $\rho = \gamma/\beta$ is called the relative removal rate and its reciprocal $\sigma = \beta/\gamma$ the infections contact rate (Murray, 1975. p. 612).

A further extension of these conditions is applied to the term R_0 – *the basic reproduction rate* *of the infection*. This means the number of secondary infections produced by one primary infection in a wholly susceptible population. It is defined as $R_0 = \beta S_0/\gamma$. The important point to be derived from these conditions therefore is that the basic epidemiological criteria that must be met by all effective eradication control programs is that $R_0 < 1$. A graphical simulation of Kermack and McKenrick's S-I-R model and the conditions for an epidemic and its dynamics can be seen in Figures 1 and 2 in Appendix 1.

The graphical simulation in Figures 1 and 2 in Appendix 1 indicates a scenario where 100% of animals are initially susceptible prior to infection. The infectious nature of the disease is defined by a contact rate (β) of .005 and as in Baldock (1992), the simulation assumes that animals remain infectious for a certain period of time, in this case 10 days (γ = 0.l), until they begin to recover as removes. With lower contact rates, outbreaks may fail to eventuate despite an initial level of susceptibility (if below ρ). This is known as herd immunity (Baldock, 1993). As can be noted in Figure 2 in Appendix A, a decrease in infection occurs once the critical value p is reached. This is the point where susceptibles fall below a certain critical number for the spread of the outbreak to increase in relative terms.

6.1.4 Objective of control measures

In the example used above the contact and recovery rates were assumed to remain constant over time with the course of the epidemic being affected by the availability of susceptibles in relationship to the number of recovered animals.

As Baldock (1993) noted the purpose of control measures to stamp out an outbreak is to reduce the effective contact rate of infectives with susceptibles through either zoning or slaughter, destroying virus in the environment through cleansing and disinfection and prevent contact of infectives with susceptibles through movement control. The following section will provide an economic optimising technique that seeks to determine the optimal level that the particular control will take given the dynamics of the disease.

6.2 Optimal control theory applied to disease

The modelling of infectious disease, as noted in the earlier section, has been an important process in the quantifying of the biology of epidemics from what was once qualitative analysis. This quantification of biological processes has assisted the application of economic techniques to the practical problems of controlling biological populations. Optimal control theory, outlined in Wickwire (1977) and Clark (1990), provides a mathematical optimising techniques that provides economic optimality in the control of dynamic systems, in this case biological populations.

By integrating the basic epidemic theory with optimal control principles, a simple bio-economic model can be constructed that provides a conceptual outcome relevant for economic analysis of control programs. Wickwire (1977) outlines the components of optimal control policy in the following subsection.

6.2.1 Components of optimal control policy

1. A model describing the uncontrolled transition mechanism of a dynamic system whose operation generates some cost or reward. For example a model that represents the dynamics of disease and whose operation represents a reward or cost.

2. To this is added the specification at each time of a *control action* in a given class which alters the operation of the system and costs something to employ. For example, the application of immunisation or isolation to the control of infectious diseases.

3. A rule which prescribes which control action to use at each time is called a control policy. A control policy uses only information from the current state of the controlled system to prescribe controlled actions- it is called a *closed loop* or *feedback control*.

4. One specifies next an objective functional which assigns a net value or cost to the total operation of the system from a particular point in the system.

Clark (1990) outlines the theory. In optimal control theory therefore *one has to determine a feasible policy u(t) that maximises J(u) the objective functional, such that if a control exists it is called an optimal control*. The maximum principle (Pontryagin's maximum principle) gives the necessary conditions that must be satisfied by an optimal control.

The maximum principle can be formulated in terms of a Hamiltonian ($\mathcal{H}$).

1. **Hamiltonian Expression** $\mathcal{H}(x,t,u) = q\,(x,t,u) + \lambda f\,(x,t,u)$

$\lambda\,(t)$ is an adjoint variable, $q(.)$ the objective while $f(.)$ represents the dynamic system whose operation generates a reward. If $u(t)$ is an optimal control and $x(t)$ is the corresponding response the maximum principle asserts the existence of an adjoint variable $\lambda(t)$ such that the following equations are satisfied for all t, $0 > t < T$

2. $d\lambda/dt = -\ \mathcal{H}/dx = -\ dg/d(x) - \lambda(t)\ df/dx$

3. $\mathcal{H}[x(t),t,u(t),\lambda(t)] = \max \mathcal{H}[x(t),t,u:\lambda(t)]$

Equations 2 and 3 represents the maximum principle.

6.2.2 Necessary conditions

Equations refer to optimal control $u(t)$ its associated response $x(t)$ and the associated adjoint variables $\lambda(t)$ and $\rho(t)$. Equation 2 is called adjoint equation or maximum principle and equation 3 asserts that at every given time t the value $u(t)$ of the optimal control must maximise the value of the Hamiltonian expression over all admissible values u satisfying the control restraints. If control constraints are not binding then $\mathcal{H}/u = 0$ (Clark,1990).

The maximum principle is applied when three unknown equations are determined. The *state equation (1) when x = 0, the adjoint equation (2) and the maximum principle (3).*

6.2.3 Bio-economic interpretation of optimal control policy

Clark (1990) applies the maximum principle to a basic fisheries resource model, using harvesting effort *E(t)* as a control variable. This section will extend Clark’s application by applying these principles to a livestock zoning policy utilising isolation rate *(u)* and border control *(v)* as the control variables. This model represents the disease dynamics (or transition mechanism) outlined in section 5.1. Having explained the biological process of disease in section 5.1, the economic considerations arising from constructing disease control in an optimising framework need to be understood. Clark (1990), identifies these approaches as strictly ‘bio-economic’ and outlines an economic interpretation for each variable.

l. Adjoint variable λ

Because the objective functional *J(u)* represents the ‘value’ of the capital or resource stock (stock of susceptibles and removes at time *t*), λ is defined as the marginal value of the capital stock (eg. S, I, R *at time t*). For example if the stock level (of susceptibles or removes) is reduced by one unit (eg by immunisation) its value at time *t* will be reduced by λ.

J.M. Keynes described this as marginal user cost for the loss in value when a capital asset is reduced by one marginal unit (Clark,1990). Therefore the adjoint variable is the marginal user cost along the optimal trajectory. Clark (1990) noted that modern usage leaned toward the term “shadow price of capital” for the adjoint variable. The terms shadow price refers to the fact that the assets value is not the direct sale but the value imputed for its future productivity. Therefore the adjoint variable represents the marginal value of the asset at time *t*.

2. *Hamiltonian Expression* $\mathcal{H}(x,t,u) = q\ (x,t,u) + \lambda f\ (x,t,u)$

The economic interpretation of this function states that the two terms on the right side of the equation can be recognised as value flows $g\ (x,t,u)$, that is ,the flow of accumulated dividends to the objective functional $J(u)$, whereas $F(x,t)$ is the flow of investment in capital. To express the investment flow in value terms it must be multiplied by the shadow price of capital $\lambda(t)$. The Hamiltonian therefore represents the total rate of increase of total assets (accumulated dividends and capital assets) (Clark, 1990.p.106).The maximum principle then asserts that an optimal control $u(t)$ must maximise the rate of increase of total assets. In several cases before the optimal choice of control $u(t)$ can be made, the shadow price needs to be known. An optimal control approach can be applied to an FMD free zoning program to illustrate the potential viability of such a strategy to a disease endemic country such as Thailand.

7. Conclusion

An application of an optimal control model is applied in Murphy (1996c) in assessing the viability of establishing and maintaining disease free zoning within a simple bio-economic framework. The objective of the modelling procedure applied in Murphy(1996c) was to apply a control in the form of isolation of susceptible livestock and border controls that maximise export profits (of representative firm) subject to the dynamics of the disease (utilising Kermack and McKendrick’s S,I,R epidemic model). Applying an optimising (Hamiltonian) function the modelling solutions attempted to firstly provide an optimal level of isolation of susceptibles and secondly quarantine or border controls that maximised export profits.

While the application in Murphy (1996c) is based on certain simplified (though standard) assumptions, it provides a simple integration of deterministic epidemiological modelling with economic optimising techniques. The study attempts to highlight important economic considerations in the optimal control of FMD within a zoning framework. However as outlined in Murphy (1996c), while this approach provides a useful conceptual framework for determining optimal economic conditions, it experiences difficulties in obtaining a closed form solution -particularly in determining a direct value for shadow prices. Due to such problems the optimal control approach even within a simplified framework is limited in its direct application, particularly to national control programs. It is within this framework where cost-benefit analysis, despite its inability to provide essentially optimum solutions, is better able to attribute values to such factors as shadow prices and can incorporate the distributional welfare issues associated with national programs (Murphy 1996c). The application of the optimal control approach and an assessment of a cost-benefit analysis applied by Dijkhuizen (1992) (incorporating simulation modelling on a national basis), can be seen in Murphy (1996c).

8. Notes

1. Marginal cost equals marginal benefit

2. As Ngategize and Kaneene (1985) indicate, this should not be confused with the broader and more philosophical concept of ‘systems’ approach.

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APPENDIX I

Figure 1. Deterministic model of disease
Infection of susceptible population

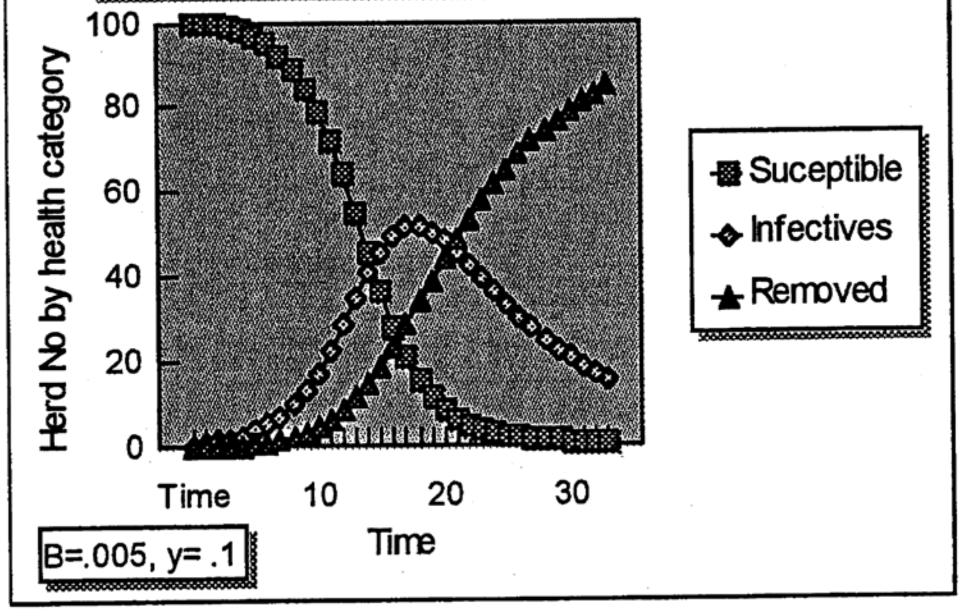
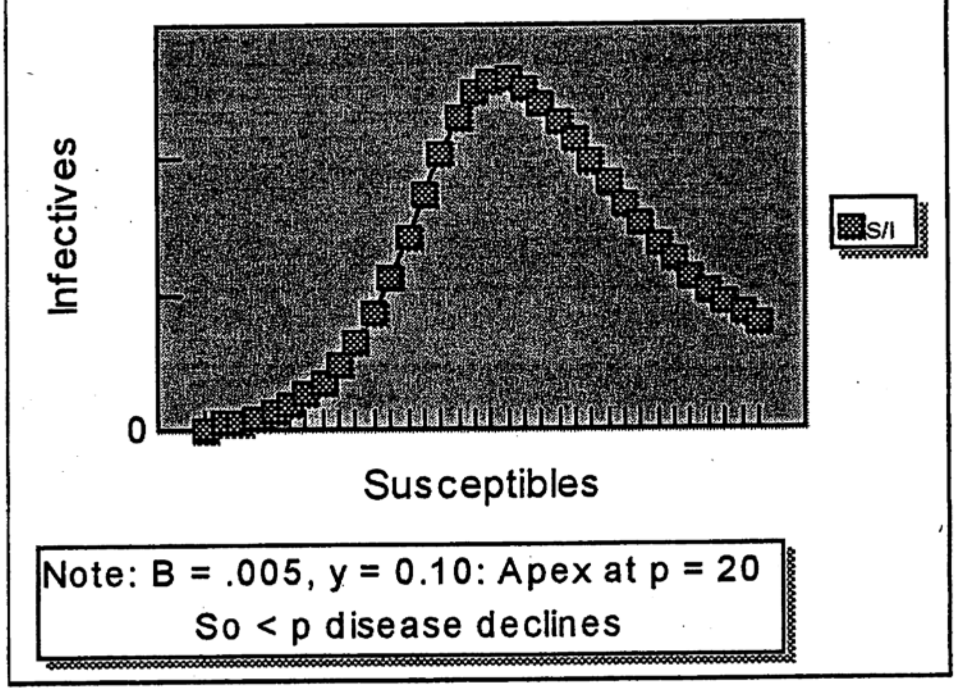


Figure 2. Phase Plane for Infectives and Susceptibles



Note: B = .005, y = 0.10: Apex at p = 20
So < p disease declines

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