AN APPLICATION OF
DYNAMIC MICROECONOMIC THEORY
TO BOVINE TUBERCULOSIS CONTROL
IN NEW ZEALAND CATTLE

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AN APPLICATION OF DYNAMIC MICROECONOMIC THEORY TO BOVINE TUBERCULOSIS CONTROL IN NEW ZEALAND CATTLE

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Capital theory has been used in a wide range of economic applications to provide valuable insights into intertemporal trade-offs. This research uses an optimal control framework to model a livestock disease control problem in which there are movements of livestock into and out of a herd. Movement control regulations are important in reducing the transmission of bovine tuberculosis (Tb) between cattle herds and farming areas in New Zealand. The analysis focuses on a representative breeding-store beef cattle production system in a Tb vector risk area under mandatory movement control testing. The hypothetical producer has the objective of maximising net revenue from the cattle enterprise while being faced with control decisions concerning marketing cattle to store sale or slaughter, purchasing replacement cattle, and harvesting a wildlife Tb vector population. Non-linear programming is used to find the steady state values for the control variables. Numerical results disclose that economic incentives may exist for risk neutral producers to purchase cattle from infected herds. A major policy implication is that some form of regulatory response may be required to assist the market in transforming the price discount for cattle from infected herds from an incentive into a disincentive.

KEYWORDS: Dynamic optimisation, optimal control theory, bioeconomics, animal health economics, livestock disease control.

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1.1 Introduction

Bovine tuberculosis is a bacterial disease caused by the bacillus *Mycobacterium bovis* (*M. bovis*). The disease can affect all animal species and age groups, and is present in every country of the world (Radostits *et al.*, 1994). The bacteria is responsible for the majority of tuberculosis found in cattle and is of particular concern worldwide with respect to dairy cattle (Blood and Radostits, 1989). In New Zealand *M. bovis* is listed as a notifiable organism under the Biosecurity (Notifiable Organisms) Order (1993). Recent statistics show that Tb levels in New Zealand are the highest in beef cattle herds (MAF, 1996).

Epidemiological research suggests that airborne transmission of *M. bovis* is the most important route for bovine tuberculosis infections in cattle (Pritchard, 1988; Morris *et al.*, 1994). While in many countries the disease is primarily transmitted to cattle from other infected cattle (Radostits *et al.*, 1994), in New Zealand wildlife vectors such as the brush tailed possum (*Trichosurus vulpecula)* are identified as a major source of infection in some areas (Boland and Livingstone, 1986; Tweedle and Livingstone, 1994).[1]

The development of bovine tuberculosis in cattle depends on the route of infection and the animal's immune response (Pritchard, 1988). In a generalised account of the disease's pathology Radostits *et al.* (1994) state that bovine tuberculosis is a progressive cattle disease which spreads in two stages known as the primary complex and post-primary dissemination. During these two stages the characteristic tubercles which develop in the lymph nodes and organs give rise to toxemia which causes increasing morbidity and eventually the death of the animal.

Bovine tuberculosis is a significant disease of cattle for several reasons. Firstly, it is claimed that of all cattle diseases tuberculosis has been the most destructive in terms of cattle deaths (Myers and Steele, 1969). Secondly, the impact of the disease on cattle is not solely restricted to high levels of mortality, the productive efficiency of infected animals is estimated to decline by 10-25% (Radostits *et al.*, 1994). Thirdly, if herd Tb infection levels are relatively high compared to other countries then exports of beef and veal products may be adversely affected by the establishment of trade barriers or reduced demand from foreign consumers in response to either perceived risk or inferior quality (Animal Health Board, 1995). Fourthly, bovine tuberculosis is an important zoonosis that can be transmitted to humans in unpasteurised milk and through infection arising from close contact with infected animals (Radostits *et al.*, 1994).

Bovine Tb control in New Zealand has developed into an integrated approach involving different tactics and methods. To appreciate the role and significance of movement control in current policy the economics and evolution of Tb control need to be understood. This chapter provides an economic interpretation of Tb control and overviews past approaches towards control to provide a context for a discussion of the current Tb control strategy. The details and economic issues relating to movement control regulations are then highlighted and the objectives of the study outlined.

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[1] Other significant wildlife and feral vectors include deer, pigs, cats and ferrets (Allen, 1991; Hickling, 1995).

1.2 The Economic Rationale for Government Involvement in Tb Control

The well known market failures associated with controlling an infectious disease in livestock suggest an active role for government (Umail *et al.*, 1994). Economic theory supports such an approach. When goods or services are non-exclusive and/or non-rival in consumption private markets may fail to provide an efficient allocation of resources (Randall, 1983). Non-exclusiveness gives rise to external costs or benefits being incurred by agents third party to a transaction, and non-rivalry produces inefficient pricing due to the marginal cost of supplying another consumer being zero. Private market solutions to market failure are often impeded by high transaction costs required to internalise externalities, inefficient property rights, and agents free riding by not disclosing their true willingness to pay for the good or service (Stiglitz, 1988). As a consequence, public sector involvement may be required to achieve a more efficient allocation of resources.

There are several negative impacts associated with cattle herds being infected with bovine Tb. Firstly, producers with infected herds may incur reduced productivity as a result of the disease. Secondly, other producers with uninfected herds are subject to an increased risk of disease being spread into their herds, either through natural spread or management practices, and associated reductions in productivity. Thirdly, the cattle industry as a whole may face an increased risk of export market closure due to the level of Tb being unacceptable to trading partners. Finally, there is an increased risk that the general public will become exposed and infected with Tb.

Economic theory suggests that individual producers will respond to infection in their herds by undertaking efforts to control Tb to a level where the marginal benefits of control, in the form of increased productivity, equal the marginal costs of control. As highlighted above, some of the benefits of control are not exclusive to the producer undertaking the control activity. Neighbouring properties, those purchasing or grazing cattle, the cattle industry, and the general public all benefit to some degree from the reduced level of disease. Because there are no payments for these benefits the producer's decision regarding the level of control to undertake relates solely to the private benefit of control. Government involvement may therefore be necessary to achieve a more socially optimal level of control.

Several approaches are available to Government for correcting market failures. The government could intervene to modify producer behaviour by establishing systems of taxes, charges, fines, or subsidies (Randall, 1972; Stiglitz, 1988). Tb control programmes in New Zealand have used subsidies to a limited extent in the form of subsidised testing and compensation for reactor cattle. More recently, fines have also been used to ensure producers present accurate Tb declaration cards when moving cattle off their properties. Although economic instruments are generally favoured by economists, factors such as distributional implications, implementation costs, information requirements, uncertainty and variance of costs and benefits, and political manipulation may constrain their application (Stiglitz, 1988).

An alternative approach that does not rely on direct government intervention is the use of market solutions following the creation of well defined property rights. However, internalising the benefits of control by reducing transaction costs and/or establishing more efficient property rights in order to arrive at a market solution to Tb control is problematic due to the non-exclusive and non-rival characteristics of the external benefits.

Government involvement in New Zealand Tb control has mainly relied on a third approach to market failure: interventions in the form of regulations. Regulations such as compulsory Tb testing, slaughtering of reactors, and movement control restrictions attempt to ensure coordination of control activities and producer compliance with required standards. Using regulations and standards could be regarded as a pragmatic approach to achieving a suitable level of control given some of the difficulties associated with economic instruments and market solutions.

In the most recent Tb control programme the Animal Health Board has disclosed an interest in moving away from regulations towards a greater reliance on market mechanisms to achieve more socially optimal levels of control. As a consequence, the latest Tb control programme introduces some market incentives to modify producer behaviour but still uses regulations to a large extent to meet its objectives. To appreciate the evolving role of the public sector in New Zealand Tb control and the move towards placing more responsibility for control in the domain of the private sector the history of Tb control in New Zealand cattle needs to be appreciated.

1.3 A Brief History of Tb Control in New Zealand Cattle

In most countries motivation for bovine tuberculosis control was initially based on public health concerns, however, over time adverse economic implications associated with the disease became increasingly dominant (Myers and Steele, 1969). In New Zealand bovine tuberculosis control has largely been motivated by possible reductions in livestock production, reduced access to export markets, and negative implications for public health that would arise if the disease was uncontrolled (Tweedle and Livingstone, 1994).

Following McFadyean's identification in 1888 that tuberculosis was a significant disease for humans and animals, various methods of controlling the disease in cattle such as, the removal of clinical cases, tuberculin testing and separation of reactors from non-reactors, testing and slaughtering reactors, and vaccination, have been used in different countries (Pritchard, 1988). Of these methods, testing and slaughtering is acknowledged as a necessary component of any effective control policy (Myers and Steele, 1969; Pritchard, 1988; Radostits *et al.*, 1994).

Bovine tuberculosis control in New Zealand cattle originated with voluntary testing of town supply dairy herds in 1945 in response to public health concerns (Jackson, 1993). The voluntary scheme was expanded to include factory supply dairy farmers in 1958 and became compulsory in 1961 with the introduction of area testing for all dairy cattle (Boland and Livingstone, 1986). The move to compulsory participation was primarily undertaken to meet expectations regarding Tb control from importers of New Zealand's dairy products (Janson, 1990). Although surveillance was extended to all dairy cattle in 1970 the control of tuberculosis in beef cattle had only begun two years earlier, in 1968, with the introduction of voluntary testing (Boland and Livingstone, 1986). The voluntary scheme was soon replaced by compulsory area testing in 1971 (Boland and Livingstone, 1986). The move to a compulsory scheme was undertaken to address concerns that beef cattle may be responsible for reinfection of dairy herds (Tweedle and Livingstone, 1994). By 1977 all cattle were subject to compulsory testing or surveillance (Boland and Livingstone, 1986). This brought to a culmination the progressive recognition that the public good aspects of Tb control, and the expectations from New Zealand's trading partners regarding control efforts, required a collective approach between Government and the cattle sector to ensure effective control. The evolution of Tb control from a voluntary to compulsory programme motivated by trade implications parallels the history of Tb control in many other developed countries (Neill, 1995).

Tb control programmes were initially very successful at reducing apparent infection levels in cattle. Comparisons between national reactor rates at the commencement of testing and those for the 1979/80 season show declines from 8.6% to 0.05% and 0.8% to 0.1% for dairy and beef cattle, respectively (Boland and Livingstone, 1986). These figures do, however, disguise two important epidemiological findings relating to the failure of the test and slaughter policy in progressively containing and eliminating infection from some areas. The first was in the early 1970's when the brush tailed possum (*Trichosurus vulpecula)* was identified as a wildlife vector of bovine tuberculosis (Tweedle and Livingstone, 1994). The second finding concerns movements of infected stock being implicated in cases of infection in areas where *M. bovis* was not present in wild animal populations. (Boland and Livingstone, 1986). In response to these findings Tb related possum control operations were undertaken in the 1970's and in 1977 movement control restrictions were established (Batcheler and Cowan, 1988). Favourable results were initially obtained through the adoption of these additional control tactics with the number of herds on movement control falling from 1275 in 1977 to a low of 504 at the beginning of 1981 (Boland and Livingstone, 1986). This trend towards lower numbers of herds on movement control was soon reversed in the early 1980's after reductions in Government funding of possum control. (Boland and Livingstone, 1986).

Wildlife vector control and livestock movement control have remained prominent components of Tb control strategies and have been successively modified in accordance with increased insight gained into the epidemiology of the disease (Morris *et al*., 1994). The general trend in these changes has been towards an expansion of wildlife vector control and a tightening of livestock movement control (Animal Health Board, 1996). While concern was expressed in recent years at the lack of progress in reducing annual reactor rates in cattle from levels experienced in the mid 1980's (Jackson, 1993), recent reporting on the status of the bovine Tb eradication programme is optimistic that favourable results are beginning to be achieved (Animal Health Board, 1996).

1.4 The National Pest Management Strategy for Bovine Tuberculosis

New Zealand bovine Tb control policy makers recognise the need for a collective approach and continue to rely on regulations and an associated national level focus. This is reflected in the proposed National Pest Management Strategy for bovine tuberculosis (NPMS) developed under Part V of the Biosecurity Act (1993).[2]

The purpose of the strategy remains consistent with previous motivations for Tb control and focuses on reducing Tb transmission to and within domestic livestock herds over a five year period. Section 5.4 of the proposed strategy specifically seeks the following objectives:

- A reduction in the percentage of infected herds from 0.7% to 0.2% of the total herds in Tb Vector-Free Areas.
- Prevent the establishment of new and/or existing Tb Vector Risk Areas.
- A reduction in the percentage of infected herds from 17% to 11% of the total herds in Tb Vector Risk Areas.
- Create an environment whereby individuals are encouraged to take responsibility for the Tb status of their area and herds.

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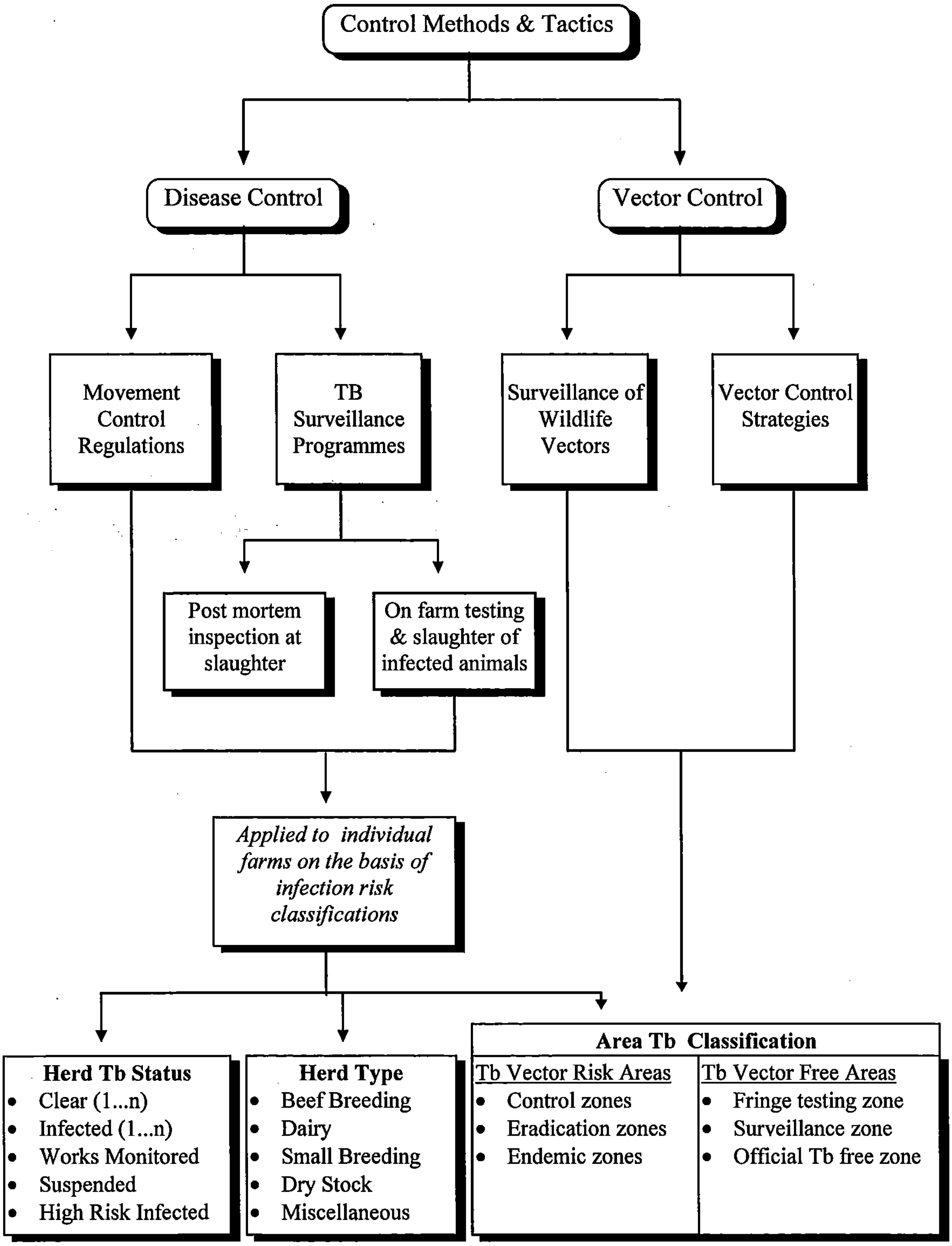
[2] Most of the strategy was implemented on 1 November 1996 under existing legislation.

In the process of developing the strategy the Animal Health Board took the opportunity to review current control policies and, as a consequence of consultation with affected groups, identified risk management “as an overarching theme” (Livingstone, 1996: p.10). This is reflected in the principle focus of control programmes which is the management and elimination of *disease risk.* The strategy acknowledges that areas currently clear of Tb must be kept clear and infection must be reduced in infected areas in order to achieve its objectives. Figure 1.1 illustrates how Tb control is approached under the NPMS using both disease control and vector control.

Disease control is directed at reducing infection levels within herds and preventing the spread of Tb between herds. Vector control focuses on restricting the transmission of infection from wild vectors. Herd Tb status and the area Tb classifications serve to convey information as to the risk of disease. Herd Tb status is determined by the current and past incidence of herd infection, and area Tb classification is determined by the local Tb risk from Tb vectors together with the recent history of herd infection. These classifications jointly determine the appropriate surveillance programme for a particular herd, whether and to what extent movement control is applied, and the vector control strategy.

Animal disease control authorities are aware that an increased Tb control effort is required to prevent greater risk of infection for livestock (Animal Health Board, 1995). The NPMS addresses this need by bringing about several changes to both the philosophy and current policies used in Tb control. Although the public good aspect of Tb control is still acknowledged, and a collective approach to management and funding is maintained to ensure control coordination and compliance, the NPMS moves towards imposing greater individual responsibility for control.

Figure 1.1 NPMS Tb Control Methods & Tactics



The management approach under the proposed strategy reinforces the use of economic instruments to promote desirable producer behaviour by encouraging the link between herd Tb status, and both market prices for cattle and associated disease control costs. Funding responsibilities are based on the identification of beneficiaries of the strategy and exacerbators of the Tb problem and the extent to which they benefit or contribute. The management and funding framework maintains a general trend evident in control approaches over recent years towards more market based approaches to market failure. It facilitates this by fostering an environment in which individual producers face the economic consequences arising from their decisions.

The change in philosophy provides the foundation for changes to the policies and tactics employed in the strategy's disease and vector control programmes. With respect to disease control, the changes are aimed at increasing the detection of Tb and increasing the efficiency of control. Detection is increased through more intensive herd testing. Previously testing frequency was determined by the Tb area classification, type of herd and movement control status of a herd. Under the new system Tb area classification and herd type are still used to determine testing frequency, however, a more refined system for classifying herd Tb status is also used. The new herd Tb status classification permits testing frequency to depend on factors such as the period a herd has retained a "Clear" or "Infected" status and whether an infected herd is considered to be "High Risk".

To increase the efficiency of control, changes are directed at making the producer bear more of the costs associated with an infected herd. This is brought about through the limited introduction of direct payment for discretionary testing, reduced reactor compensation, the new herd Tb status classification, and tighter movement control regulations. Efficiency gains are expected to come from increased incentives for farmers to reduce disease risk and improve testing facilities as they become confronted with the costs of not adequately controlling the disease (Livingstone, 1995). Although direct payment for testing only relates to discretionary testing, there is the provision for direct payment for all testing if it is considered at some future time to be in the best interests of the scheme. Compensation for reactor cattle identified at surveillance and movement control testing, and subsequently slaughtered, is reduced from 85% to 65% of fair market value. The new classification for herd Tb status together with the Tb management area classification are intended to provide producers with better information as to the risk of Tb and an incentive to improve their risk status. The Animal Health Board expects that the improved information on Tb risk will assist producers in incorporating Tb risk into their livestock purchasing and grazing decisions and consequently lead to lower market prices for stock from "Infected" herds relative to stock from "Clear" herds. Movement control requirements are also tightened to lower the risk of infection being spread through livestock movement.

Economic analysis of the costs and benefits of the proposed NPMS has been undertaken to satisfy the requirements of Schedule One of the Biosecurity Act (1993) (Nimmo-Bell, 1995). Cost benefit analysis was used to compare the NPMS with the strategies of doing nothing and the current control programme which has existed since 1992/93 (Animal Health Board, 1995). The results of the analysis supported the NPMS on the basis that benefits significantly outweighed costs when the potential for loss in trade was included.

The above cost benefit analysis was concerned with identifying whether the NPMS was more efficient than the two selected alternatives using a fairly restricted set of relevant costs and benefits. It does not, however, provide a detailed analysis of the tradeoffs encompassed within the NPMS and therefore ignores other important issues such as the likely behavioural responses of individual producers to the strategy and the equity implications. As a consequence many questions remain regarding the economic tradeoffs surrounding the methods and tactics employed in the proposed strategy.

1.5 Economic Issues Surrounding the NPMS

It is acknowledged by Tb control experts that the effectiveness of control programmes depends on individual producer's decisions being consistent with control objectives (Livingstone, 1996; Morris *et al.*, 1994). While the NPMS seeks to achieve compliant producer behaviour by positively associating control costs with herd Tb status, uncertainty exists as to whether control costs are an incentive or disincentive for producers to behave desirably (Livingstone, 1995).

Concern has been expressed that moves toward increased individual responsibility for control may result in greater non-compliance (Livingstone, 1995). This concern is borne out in a recent study by Bicknell (1995), who highlighted the possibility that increasing the financial burden of Tb control may elicit either non-compliant producer behaviour with respect to regulated Tb testing or less than socially optimal levels of testing when testing is unregulated. Two of the policy changes considered by the study were the removal of reactor compensation and a requirement that producers pay for their Tb testing. Exploratory analysis indicated that there may be a trade-off between accurate market signals and testing compliance. The study inferred that although reactor compensation gives a false price signal to producers through the positive value it places on diseased animals, if market signals result in the cost of diseased animals becoming too high then producers may be encouraged to take non-compliant action such as "hiding" infected animals from authorities.

Other potentially negative economic impacts associated with the NPMS have been identified by animal health officials. Some producers, especially in vector risk (endemic) areas, may incur substantial increases in costs which could require the adoption of alternative farming systems, and there may also be a general increase in transaction costs associated with producers adjusting cattle production under a regime emphasising greater individual responsibility for control (Livingstone, 1995). The relevant transaction costs include testing as well as related costs such as reduced compensation for reactor cattle and direct payment for discretionary testing, and greater discounting of cattle from infected herds.

With the recent implementation of most of the control tactics and methods under the NPMS, knowledge regarding the effects of significant components of the strategy on producer behaviour and their associated costs is warranted. Such a focus is consistent with recent calls by epidemiologists for increased examination of livestock producer behaviour in order to achieve effective tuberculosis control (Morris *et al.*, 1994). A component of the strategy which will give rise to an increased incidence of control costs for some producers and for which producer behavioural responses remain uncertain are the methods and tactics associated with movement control.

1.6 Movement Control Regulations

1.6.1 The Importance of Movement Control

The tightening of movement control requirements is identified as a major change to disease control tactics and a key feature of the National Pest Management Strategy (Animal Health Board, 1995; Livingstone, 1996). Results from recent studies suggest that the movement of infected cattle is a cause of many herd breakdowns (Pfeiffer *et al.*, 1991; Ryan *et al.*, 1995; Ryan *et al.*, 1996). Movement control has therefore been recognised as a necessary instrument in reducing Tb breakdowns in cattle herds and limiting the possible contribution by infected cattle to the establishment of new Tb endemic areas (MAF, 1977; Allison, 1992; Morris *et al.*, 1992).

Movement control regulations were originally introduced under the Animals Amendment Act 1976 on 1 April 1977 (MAF, 1977). Several key components of the initial regulations have remained integral in movement control regulations over the last two decades:

(1) A minimum age of cattle to which the regulations apply;

(2) Testing requirements for the movement of cattle;

(3) The spatial focus of the regulations;

(4) The form of identification required to accompany cattle moved; and

(5) The necessary requirements for a herd to be removed from movement control.

Since the early 1990's changes to movement control regulations have generally related to one or more of these components.

1.6.2 Movement Control Under the NPMS

Under the NPMS once Tb infection is suspected or identified in a herd it is classified as 'Infected'. During the period a herd has the 'Infected Herd' status it is subject to movement control regulations. The focus of movement control is on the herd, although a provision is retained for area movement control where the aggregate percentage of reactors exceed 0.1% in a declared vector risk area. Any movement of livestock from a herd subject to movement control must be supported by a permit to move. If cattle from an infected herd, aged one month and older, are being moved other than to slaughter then there is a requirement for movement control ear tags to be inserted prior to movement, and pre- and post-movement Tb tests performed. The testing interval for pre-movement testing is reduced to within 60 days of being moved for cattle from both infected herds and area controlled herds. Cattle from infected herds are required to undergo a post-movement test no sooner than 90 days after the pre-movement test and within 60 and 120 days following the arrival of cattle onto the new property. For a herd to be removed from movement control, excluding area movement control, its Tb status must change from infected to clear. This requires the herd passing 2 whole herd tests administered at a minimum of 6 months apart.

Movement restrictions have been tightened for cattle from 'infected' herds. If reactors are found at a pre-movement test then the balance of the tested cattle may only be permitted to go either to slaughter or to another infected herd in a vector risk area. These restrictions can be avoided if the reactor rate is no greater than 1% with 100 cattle or more being tested or infection is removed from the cattle to be moved through more testing and slaughtering. A new category of 'high risk infected' herd is established for herds with an annual incidence of Tb of 5% or more. Depending on the outcome of an epidemiological investigation into the risk of infection presented by the herd, or groups of cattle within the herd, high risk herds will be placed into one of three sub-categories which will determine the pre-movement testing requirements and options for movement.

1.6.3 Justification for Tighter Controls

The tighter movement control restrictions in the NPMS have been justified along two distinct lines. Firstly, they move towards addressing farmers' concerns regarding previous policy deficiencies in protecting herds clear of Tb infection in clear areas, and secondly, they are consistent with the Animal Health Board's philosophy of using market signals and economic incentives to elicit appropriate behavioural responses from individuals (Livingstone, 1995).

Previous attempts to tighten movement control, such as the introduction of area movement control in 1992 and the compulsory requirement in 1994 for Tb status declaration cards to accompany all cattle being moved, were motivated by farmers' concerns over the ease at which bovine Tb could spread from infected herds (NZ Farmer, 1992; Animal Health Board, 1993). Epidemiological research identified two possible contributors to herd breakdowns. Some farm management practices were found to be inconsistent with efforts to control the disease (Pfeiffer *et al.*, 1991). The lack of sensitivity of the skin tests also posed problems for containing the spread of disease because infected animals could return false negative reactions and be moved to other properties as infection free (Ryan *et al.*, 1991). The compulsory requirements for pre-movement testing of all cattle from areas assessed to present a high risk of infection from wildlife vectors, and provision of information as to the Tb status of cattle being moved were policy responses aimed at reducing the spread of infection into clear areas.

Notwithstanding these tougher movement controls, recent research into Tb breakdowns in non-endemic areas highlights that the movement of cattle from endemic to non-endemic areas, as a result of purchasing or grazing decisions, as a significant factor in the spread of infection (Ryan *et al.*, 1995). The role of management decisions in the spread of Tb is reinforced in a recent study into livestock movements in the Waikato veterinary district (Ryan *et al.*, 1996). The study suggests that there is still "much opportunity for spread of infectious diseases" due to the high proportion of herds open to introductions, the amount of movement between herds, and inadequacies inherent in the current confirmatory testing programmes which are prescribed according to wildlife vector risk (p.19).

To encourage cattle management practices which reduce the spread of Tb infection, the NPMS creates incentives for producers to take the risks of Tb seriously. The new classification systems and tighter movement control regulations are intended to provide producers with infected herds with increased costs arising from lower market valuations of cattle and increased Tb control compliance costs. This reflects the strategy's philosophy that better disease control can be achieved if producers are confronted with the economic consequences of their decisions.

1.7 Objectives of the Study

Despite a significant investment of time and effort, only minor progress has been made in recent years to reduce bovine tuberculosis levels in cattle herds. Movement control policies play a prominent role in influencing cattle producer behaviour in order to achieve the objectives of the NPMS. However, very little is known about likely effects of movement control regulations on individual producer behaviour.

Economic analysis of movement control regulations at the producer level achieves two broad objectives. Firstly, it provides insight into whether behavioural responses by cattle producers are likely to be consistent with the objectives of the NPMS. Secondly, it provides an indication of the costs of movement control for affected cattle producers and thus facilitates a deeper understanding of the distributional implications of the legislation.

This study attempts to answer three specific research questions concerning the effect of movement control regulations on cattle producers.

- What are the likely producer behavioural responses to movement control under the NPMS at various levels of store cattle price discount, in terms of decisions regarding the purchase and sale of cattle, and vector control, for a representative cattle production system?

- What is the economic impact of movement control under the NPMS, in terms of the difference in discounted net revenue, for a representative cattle production system?
- Given the tighter movement control restrictions and use of market signals employed under the NPMS, what is the likely impact on Tb infection levels for a representative cattle herd?

In addition to answering these specific questions, exploratory analysis sheds light on the role of price signals in meeting the objectives of the Animal Health Board.

1.8 Outline of the Study

Chapter 2 reviews the literature on animal health economics to gain direction on how the study will be approached. Given the dynamic nature of the research problem the literature on dynamic optimisation, particularly its application to production and policy problems, is evaluated to identify an appropriate methodology. A theoretical model of a representative breeding-store beef cattle production system in a Tb vector risk area is developed using an optimal control framework in Chapter 3. The necessary conditions of the model are also presented and interpreted. The theoretical model is transformed into a discrete time optimal control model in Chapter 4. Store cattle production and Tb control parameters relevant to the Clarence/Waiau area of the South Island of New Zealand are then presented and explained, along with preliminary results for the empirical model. The results of the model under various policy and market scenarios, and a sensitivity analysis are reported in Chapter 5. Chapter 6 concludes the study by presenting answers to the research questions and highlighting limitations of the study and areas for further research.

Chapter 2: Review of the Literature

2.1 Introduction

Before undertaking an analysis of bovine tuberculosis movement control restrictions at the producer level it is necessary to gain an appreciation of how the economic analysis of producer behaviour has been approached in the past. Animal health economics and in particular the economic analysis of livestock disease control provide specific direction for the proposed research. Additional guidance is found in the economic literature on dynamic optimisation applied at the producer level.

2.2 Economic Analysis of Livestock Disease Control

2.2.1 Cost Benefit Analysis

Economic theory is acknowledged as providing quantitative insights into livestock health issues (Dijkhuizen *et al.*, 1991). With respect to livestock disease control, these insights are often obtained from economic evaluations in the form of cost benefit analyses undertaken at the national or regional level. Economic evaluations at these levels tend to either narrowly focus on a current control program, or adopt a wider approach and analyse a number of alternative control programs. An example of the later approach is the cost benefit analysis by Habtemariam and Ruppaner (1982) in which various disease control methods were evaluated for trypanosomiasis in Ethiopian livestock and human populations. Their analysis identified insecticide application as the most efficient form of disease control.

Cost benefit analyses have been used not only to evaluate alternative disease control programs but also to highlight the economic trade-offs arising from particular programs. Bech-Nielsen *et al.* (1982) applied cost benefit analysis to four programs for the control of the cattle nematode *Parafilaria bovicola* in Sweden. Their evaluation resulted in the recommendation that although individual producers would prefer to treat only young livestock destined for slaughter, from a social perspective control should be directed at treating cows serving as a disease reservoir in order to eradicate the disease and thereby remove impediments to Sweden's livestock exports.

Export markets often impose an important constraint on animal health programs. Johnston and Matuska (1981) emphasised the substantial benefits associated with bovine brucellosis and tuberculosis eradication in terms of averting potential export market restrictions. In a recent cost benefit analysis of the proposed National Pest Management Strategy for Bovine Tuberculosis in New Zealand it was concluded that when trade was excluded from the analysis the costs of the strategy exceeded the benefits (Nimmo-Bell, 1995). However, when the potential trade implications were included, the benefits of the strategy not only outweighed the costs but net benefits exceeded both doing nothing and the control program that was operational at the time.

Cost benefit analysis has also been used as a general framework from which to analyse the distributional consequences of selected animal health programs. Liu's (1979) analysis of brucellosis control programs in the United States provided an estimate of the welfare changes resulting from disease control programs. The distributional impacts arising from disease eradication were identified by estimating changes to consumer and producer surplus. Liu concluded that the increased benefit to consumers from greater production of beef and milk, and lower prices when brucellosis was eradicated outweighed the increased costs of eradication to producers. The finding that consumers benefited from disease control programs through a positive supply response, while producers were adversely affected by increased costs of control, was supported in a later cost benefit analysis of bovine brucellosis control in the United States by Dietrich *et al.* (1987). However, a recent study into pseudorabies eradication in the United States found that while eradication increased consumer surplus, its impact on producer surplus depended on a number of factors such as whether hog herds were infected, the level of prevalence, price elasticity, and the overall scale of hog production in the state (Ebel *et al.*, 1992).

The importance of considering the impacts of disease control programs on different groups of livestock producers was specifically acknowledged by Andrews and Johnston (1985). They applied cost benefit analysis to the eradication of bovine tuberculosis from northern Australia. Their analysis estimated and compared the costs and benefits for cattle producers whose cattle management and production systems differed by geographical region. Results showed that although many producers benefited from the disease eradication program, net costs were incurred by producers in two of the three areas.

Cost benefit analyses at the regional and nation levels have contributed to disease control and eradication decisions by permitting economic evaluations of control methods and entire programs. The literature suggests, however, that treating all livestock producers as a homogenous group can mask the distributional implications arising from disease control programs. Furthermore, the broad focused analysis, whether at a national or regional level, has been undertaken using a static framework and thereby precludes any detailed insight into how producers are likely to respond to the economic incentives or disincentives arising from the implementation of control or eradication programs over time.

2.2.2 Producer Level Analysis

Although most of the economic analyses of livestock disease control are undertaken at the national level, the importance of identifying tradeoffs at the producer level has also been emphasised. As McInerney (1996) suggests, livestock disease control is very similar to any other input problem confronted by the producer and therefore raises questions about efficiency and the optimal allocation of resources.

The objective of most of the producer level economic analyses of animal health issues have been to gain insight into the economic consequences for producers of either control programmes or diseases. An example is Miller *et al.*'s (1982) farm budgeting analysis of the economic impact of transmissible gastroenteritis (TGE) on swine producers. Another example is found in Walker *et al.*'s (1985) use of simulation modeling to analyse Johne's disease control strategies. Neither of these studies took into account feedback between disease control decisions, the state of livestock production and other production decisions. Treating disease control as unrelated to livestock production decisions is surprising, given the acknowledgment within the animal health economics literature that animal health outcomes are influenced by producers making decisions which are fundamentally economic in nature (Morris, 1969; Morris and Blood, 1969; McInerney, 1996).

Including disease control as part of the production process has an important implication with respect to the economic analysis of disease control policy. By modelling disease control as another input into the livestock production system the analyst is permitted to highlight trade-offs between disease control and other inputs. This information can be used to refine disease control policy.

2.2.3 Identifying Producer Behavioural Responses

There have only been a few studies which have taken into consideration the likely behavioural responses of producers to disease control policies. Rubinstein's (1977) study of foot-and-mouth disease in Columbia provides an early example of how *ex-ante* economic analysis at the producer level could be used in the evaluation of alternative disease control strategies. The analysis used epidemiological and farm simulation sub-models to represent the interaction between the disease's progression, cattle production, and either vaccination or eradication control strategies. Stoneham and Johnston's (1986) economic evaluation of Australia's brucellosis and tuberculosis eradication campaigns also used producer level simulation models in conjunction with a model of disease transmission to predict how pastoralists would respond to different policy requirements. In a more recent study, Bicknell (1995) used a bioeconomic model of livestock disease control to capture important production and disease interrelationships. Bicknell's analysis provided insight into the effect of New Zealand bovine tuberculosis control policies on individual cattle producer behaviour and the implications of this behaviour for policy outcomes. The interaction between the production and disease environments is also present in Hall *et al.*'s (1996) analysis of treatment options for controlling East Coast fever in Zebu cattle in Malawi. Their model permitted producer responses in the form of culling and selling decisions relating to each treatment option to be obtained.

These studies demonstrate that economic analysis can provide policy relevant insight into disease control by including the producer's behavioural response to control in the modelling. It is important now to identify how movement control has been incorporated into the economic analysis of disease control.

2.2.4 Analysing Livestock Movement Control

Two important insights into analysing movement control at the producer level are provided in the literature. In an overview of cost benefit analysis applied to quarantine Hinchy and Fisher (1991) emphasise that the economic impact of disease on the producer arises from production losses brought about by deaths and reduced conversion efficiencies. Mitigation against impaired production requires an increased level of inputs which will increase total variable cost and marginal cost. They suggest the economic impact of disease can be analysed by comparing the level of net revenue when disease is present to the level when disease is absent.

Stoneham and Johnston's (1986) study included an estimation of the benefits of removing cattle movement restrictions in Australia. Their study highlights that the cost of movement control includes components such as the preparation of livestock for testing rather than just the direct testing costs. They also highlighted that when movement control is enforced a welfare loss results from producers having to fatten cattle on marginal pastures.

The literature provides only limited guidance on how movement control can be analysed. More general directives are sought for how research into the economics of disease control at the producer level should be undertaken.

2.2.5 Research Issues Relating to Producer Analysis

A review of the literature suggests several research issues relevant to the economic analysis of livestock disease control at the producer level. The main issues concern the focus and method of analysis.

The economic analysis of disease control at the producer level should focus on determining optimal strategies for 'hypothetical representative farms' to avoid any idiosyncratic problems associated with actual individual farms (Morris and Blood, 1969; Barros, 1982). Where data limitations are a problem, the research should initially be approached from a general context focusing on key behavioural variables and then expanded upon as more data becomes available (Barros, 1982). Data availability is often a problem in economic analyses of livestock disease control as a result of cost, time constraints, and collection difficulties (Dijkhuizen *et al.*, 1991). Consequently, analyses frequently rely on highly stylised models to predict how producers will react to livestock disease and its control, and the epidemiological and economic implications of those reactions (Dijkhuizen *et al.*, 1991).

Mathematical modelling is acknowledged as necessary to provide the relevant abstractions of the relationships between the epidemiological and economic systems being studied (Carpenter and Howitt, 1980; Beal and McCallon, 1982; Howitt, 1982). Practitioners have also been aware that economic analysis of livestock disease control should make explicit the optimal tradeoffs involved in decision making. Carpenter and Howitt (1980) demonstrated how dynamic optimisation using linear programming could produce dynamically efficient solutions to disease control problems and also allow the evaluation of non-optimal control programmes. Linear programming was adopted by Habtemariam *et al.*, (1984) in their analysis of the optimal allocation of resources in trypanosomiasis control in Ethiopia. However, as Howitt (1982) has highlighted, the underlying dynamic relationships in disease control are nonlinear and therefore economic analysis of animal disease policy requires a theoretically consistent optimisation method capable of capturing nonlinear features.

The above literature suggests that to adequately analyse a livestock disease control problem that is inherently dynamic, the method chosen should be capable of highlighting the optimal trade-offs being made by a producer who is making choices in a temporally dynamic environment. This requires the identification of an appropriate dynamic optimisation technique.

2.3 Dynamic Optimisation

2.3.1 Decision Making in a Dynamic Context

In dynamic settings the decision making being analysed is sequential and influenced by feedback in the form of past decisions impacting on future decisions (Rausser and Hochman, 1979). For these problems a dynamic framework is required to obtain meaningful results. The application of static analysis to dynamic problems is inadequate because it is incapable of yielding the time path of the variables and thereby forces the analyst to ignore important components of the problem (Silberberg, 1990; Chiang, 1992).

As outlined above very few analyses of livestock disease control have considered the influence of temporal dynamics on producer responses and fewer have applied the techniques of dynamic optimisation. However, the application of dynamic optimisation has been well developed in other areas of economics where it is considered relevant and necessary in order to gain insight into intertemporal tradeoffs when production response efficiency is a function of time.

2.3.2 Dynamic Analysis in Capital Theory

Dorfman (1969) demonstrated how the mathematics of optimal control theory could yield interesting results when applied to economic problems involving capital use and accumulation. His economic interpretation of the necessary conditions and costate variables resulted in control theory becoming recognised as a theoretically consistent method for undertaking dynamic analysis of problems in capital theory. The application of dynamic optimisation spread to other areas of economics where problems could be characterised in terms of use and accumulation (Clark and Munro, 1975).

The conceptualisation of problems in terms of capital theory is evident in economic analyses involving livestock management. In a seminal paper by Jarvis (1974) producer price response, with respect to cattle management decisions, was formulated as a problem in which cattle were considered capital goods and producers portfolio managers. Jarvis recognised that the empirically observed backward bending supply response could not be adequately modeled within a static framework, therefore the problem needed to be expressed dynamically. A recent econometric study into cattle cycles by Rosen *et al.* (1994) demonstrated that this approach is still relevant.

The economic literature on livestock management provides studies such as Chavas *et al.* (1985), Chavas and Klemme (1986), and Rosen (1987) which demonstrated that a more realistic understanding of agricultural production response was obtained by incorporating underlying dynamic processes into analysis, and focusing on dynamic efficiency rather than static efficiency. It is clear that capital theory has played a significant role in the conceptualisation of economic problems which are characterised by growth and/or depletion. As a consequence, dynamic optimisation is available as a theoretically consistent approach to analysing these problems.

2.3.3 Applications of Dynamic Optimisation at the Producer Level

Although three techniques are available for dynamic optimisation, the calculus of variations, optimal control theory, and dynamic programming, only the later two are prominent in the applied literature. Many applications of dynamic optimisation at the producer level are aimed at identifying the producer behaviour necessary to achieve an optimal allocation of resources. Extensive surveys of dynamic programming applications in agriculture, forestry and fisheries which seek to identify the optimal sequencing of inputs and outputs are provided by Kennedy (1981, 1986, 1988). There have also been a wide range of applications in which problems are formulated as optimal control problems and solved using gradient based solution algorithms in order to identify optimal resource allocations through time. Examples relating to the optimal management of biological resources include applications to broiler production (Talpaz *et al.*, 1988), aquaculture management (Talpaz and Tsur, 1982; Cacho *et al.*, 1991), shrimp fishery management (Onal *et al.*, 1991), and swine production (Chavas *et al.*, 1985).

Optimal control has also been used to analyse a wide range of bioeconomic problems at the producer level. Problems to which optimal control has been applied to identify the optimal management of resources include crop production and soil conservation (Burt, 1981; Segarra and Taylor, 1987), pest management (Huffaker *et al.*, 1992; Bhat *et al.*, 1993), rangeland management (Torrel *et al.*, 1991; Standiford and Howitt, 1992), and wetland protection and restoration (Stavins, 1990; Parks and Kramer, 1995).

Another area where dynamic optimisation has provided useful insight, and is of particular relevance to this research, is the analysis of feedback between the producer and his or her policy environment. Several recent applications have explored the effects of policy interventions on producer behaviour. In a theoretical study, Xepapadeas (1992) compared the impact of taxes and standards on a firm's behaviour and found that behaviour differed significantly under each regime. Empirical analysis has also been undertaken. Bicknell's (1995) study into the economic issues of bovine tuberculosis control highlighted a possible tradeoff between the payment of reactor compensation and subsidised testing policies in terms of reducing herd Tb prevalence if testing was not mandatory. Fleming and Adams (1995) identified that if transport time lags were not considered in economic studies of groundwater pollution policy, then the pollution taxes suggested by analysis may lead onion producers to generate pollution levels in excess of those socially desired. In an analysis of the impact of pricing policy on producer behaviour Gao *et al.* (1992) suggested that the supply of milk by dairy producers in Florida was highly sensitive to the pricing policy adopted. Van Kooten's (1993) analysis into wetland conversion identified government agricultural support programmes as being responsible for the relatively high depletion of Canadian wetlands. Jin and Grigalunas' (1993) study into the different environmental regulations placed on an oil and gas producer confirmed that more stringent regulations resulted in substantially less revenue to the producer.

The above applications of dynamic optimisation demonstrate that it is an appropriate method for gaining insight into producer responses and will permit the analysis of important feedback between the producer and relevant policy interventions.

2.4 Modelling the Cattle Herd

As previously highlighted, capital theory has been used successfully in applications relating to herd management. However, approaches to herd modelling are varied in terms of complexity. Jarvis (1974) used a relatively comprehensive age and sex structured model in his study of Argentinean cattle production. His justification for using six categories of cattle was that the problem required a model that permitted producer behaviour to differ depending on the age and sex of cattle. Chavas and Klemme's (1986) analysis of aggregate milk supply response and investment behaviour on US dairy farms focused only on the age structure and herd size of female cattle.

Their model was considered to be detailed enough to ensure the main determinants of milk production were captured. Rosen (1987) abstracted from both age and sex composition by assuming the herd was composed of homogeneous females in his study of market dynamics. This approach was taken to highlight the unusual consequences for market equilibrium dynamics of rational livestock management while avoiding the increased analytical complexity associated with a more detailed model. A cow-calf production system involving annual replacement decisions was used in Standiford and Howitt's (1992) study of rangeland management in a multiple use setting. Their herd model consisted of breeding females which were either raised as replacements or purchased off-farm and whose surplus calves were sold each period. Although their model was highly stylised, it captured the principle activities of the predominant type of livestock enterprise in the study area. In Bicknell's (1995) study, a closed herd was represented as a biomass of susceptible and infected cattle which grew in accordance with a logistic growth function. The simplified representation of the herd allowed producer responses to be identified and provided general results for the class of farm analysed.

The literature suggests that the complexity of the model is dependent on the requirements of the research question. The application of dynamic optimisation techniques to many problems has required conceptually simple models. An important issue arising from the literature is to insure the herd model is simple enough for the solution technique to solve while still allowing the analyst to capture the important characteristics of the problem under consideration.

2.5 Discussion and Implications for Modelling

The literature provides direction as to the requirements for producer level analysis. The problem should be based around a representative production system. Analysis should be consistent with economic theory and thereby identify optimal producer tradeoffs. Because the problem is likely to contain nonlinear dynamic relationships between the economic and epidemiological systems, the solution method will require the use of dynamic optimisation techniques capable of handling nonlinear equations. A complex model of the underlying economic and epidemiological system is not necessarily required to enhance understanding of producer responses, providing the model captures the key characteristics of interest. Only two empirical analyses of disease control, Bicknell (1995) and Hall *et al.* (1996), have conformed to these requirements.

Only recently have theoretically consistent attempts been made to gain insight into the economics of disease control at the producer level. While Bicknell's (1995) study provides a theoretically consistent empirical analysis of bovine Tb control it is based on a model of a closed herd. Consequently, it is unable to capture the two way movement of cattle and thereby identify the relevant behavioural responses of a producer to movement control regulations.

This study contributes to the empirical problem of bovine Tb control by analysing the impact of livestock movement control regulations on producers. It also contributes to the economic literature by providing an empirical extension of dynamic optimisation to livestock disease control problems involving regulations on stock movements.

Chapter 3: The Theoretical Model

3.1 Introduction

The review of the literature suggested important direction for the analysis of movement control policy. The analysis should: 1) be of a representative production system; 2) produce results consistent with economic theory; 3) be able to handle nonlinear dynamic relationships; and 4) permit disclosure of the important feedback between the production and policy environments. The literature also demonstrated that dynamic optimisation is a method of analysis that provides insight into a variety of production and policy problems exhibiting the above characteristics. As a consequence, producer level analysis using dynamic optimisation in an optimal control framework was selected as the method of analysis.

3.2 Beef Cattle Production in a Tb Vector Risk Area

In contrast to many other countries throughout the world bovine Tb levels in New Zealand are higher in beef than in dairy herds (MAF, 1996). New Zealand also has a relatively high incidence of newly infected herds compared to many of its trading partners largely as a result of wildlife Tb vectors (Animal Health Board, 1995). It is acknowledged that changes to Tb control under the NPMS are likely to place significant economic costs on beef cattle producers in areas where there is a high risk of Tb transmission from wildlife vectors (Livingstone, 1995). The epidemiological and economic implications of bovine Tb and its control in New Zealand therefore suggest that the analysis of movement control focus on beef cattle production in a Tb vector risk area.

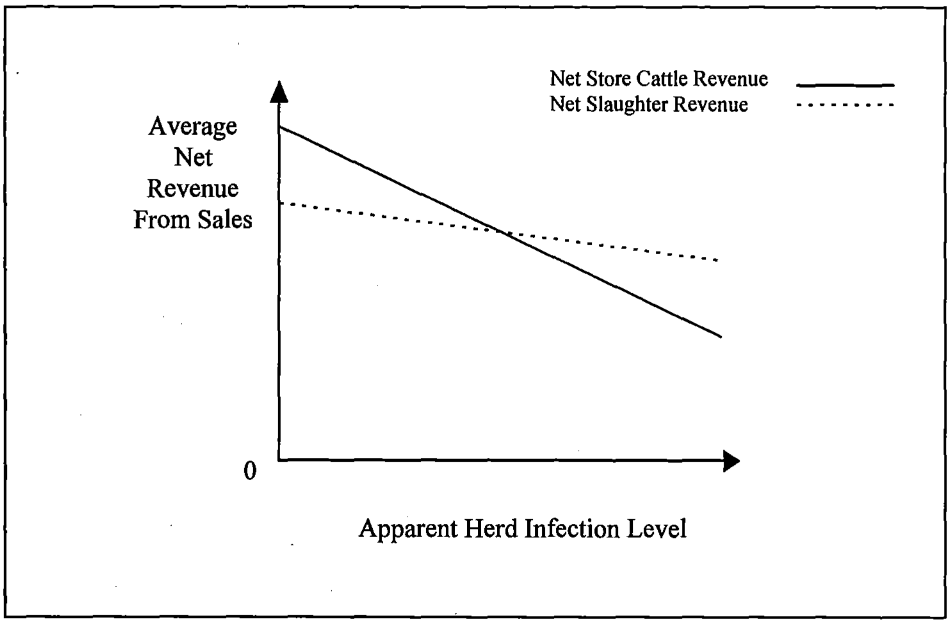
Beef cattle production in New Zealand can be loosely divided into beef breeding systems and finishing cattle enterprises which differ in objectives and management (Nicol and Nicoll, 1987). The primary role of the breeding herds is to produce calves for breeding replacements and sale as weaners. Cattle requiring further growing and finishing are maintained in finishing herds. Depending on the physical attributes of the farm, cattle are either retained and sold directly to slaughter or sold as "stores" to other producers who in turn "finish" the cattle off for sale to slaughter. Store cattle are distinguished from finished cattle in so far as the former have greater value to the producer in being kept alive and sold to other producers than being sent directly to slaughter. The difference in value is due to the potential for producers who can finish the cattle to achieve higher slaughter returns with additional feeding. Beef cattle production systems may be either comprised of a breeding herd, a finishing herd or both. It is also common for cattle production systems to be operated in conjunction with sheep production (Coop, 1987).

Previous economic analysis indicated that movement control had the largest impact on producers of store cattle (Dunham, 1995). Movement control regulations stipulate that all cattle from infected herds, or from non-infected herds in a Tb vector risk area, must be submitted to movement control Tb testing if cattle are moved to a destination other than to slaughter. Costs incurred by the producer include mustering the cattle for testing and test interpretation, as well as the cost arising from the slaughter and/or re-testing of any non-diseased cattle which test positive. Net revenue may also be adversely affected when movement controlled cattle are sent to sale as stores. Some store cattle buyers have discounted the price of movement controlled cattle in response to a perceived risk of spreading infection onto their properties (Kelly, 1992; Rawlings, 1996). The Animal Health Board anticipates that under the NPMS price discounting with respect to the risk of Tb infection will become a common feature of livestock markets.

Sending cattle to sale as stores is not necessarily the only marketing option available to store cattle producers. Cattle may be marketed to slaughter if they satisfy the minimum carcass weight requirements. Fattening stock destined for slaughter imposes extra costs on the producer in the form of feeding costs. Consequently, the producer, when considering the marketing options, compares the average revenue expected from cattle sold as stores with the average revenue expected from cattle sold to slaughter at a later date net of the cost of fattening the cattle. Society also incurs additional costs if cattle are marketed to slaughter because store cattle producers do not have a comparative advantage in fattening cattle.

The relationships between the net revenue of cattle, risk of infection, and marketing options are illustrated in Figure 3.1. The downward sloping net slaughter revenue line reflects an association between Tb risk and actual infection levels in a mob of cattle sold. Infected animals detected at slaughter only return to the producer a salvage value and therefore decrease the average price received) The slope of the net store revenue line illustrates that as the perceived risk of infection increases the average price declines. Unlike the slaughter situation where only infected cattle incur the reduced price, when cattle are sold as stores the price received for all animals is affected by the perceived risk of infection. Depending on the slopes of the two net revenue lines the relative difference between store and slaughter revenue is reduced as the risk of Tb infection increases. It is possible that beyond a certain level of Tb risk the producer may obtain a higher average net revenue if the cattle are marketed directly to slaughter.

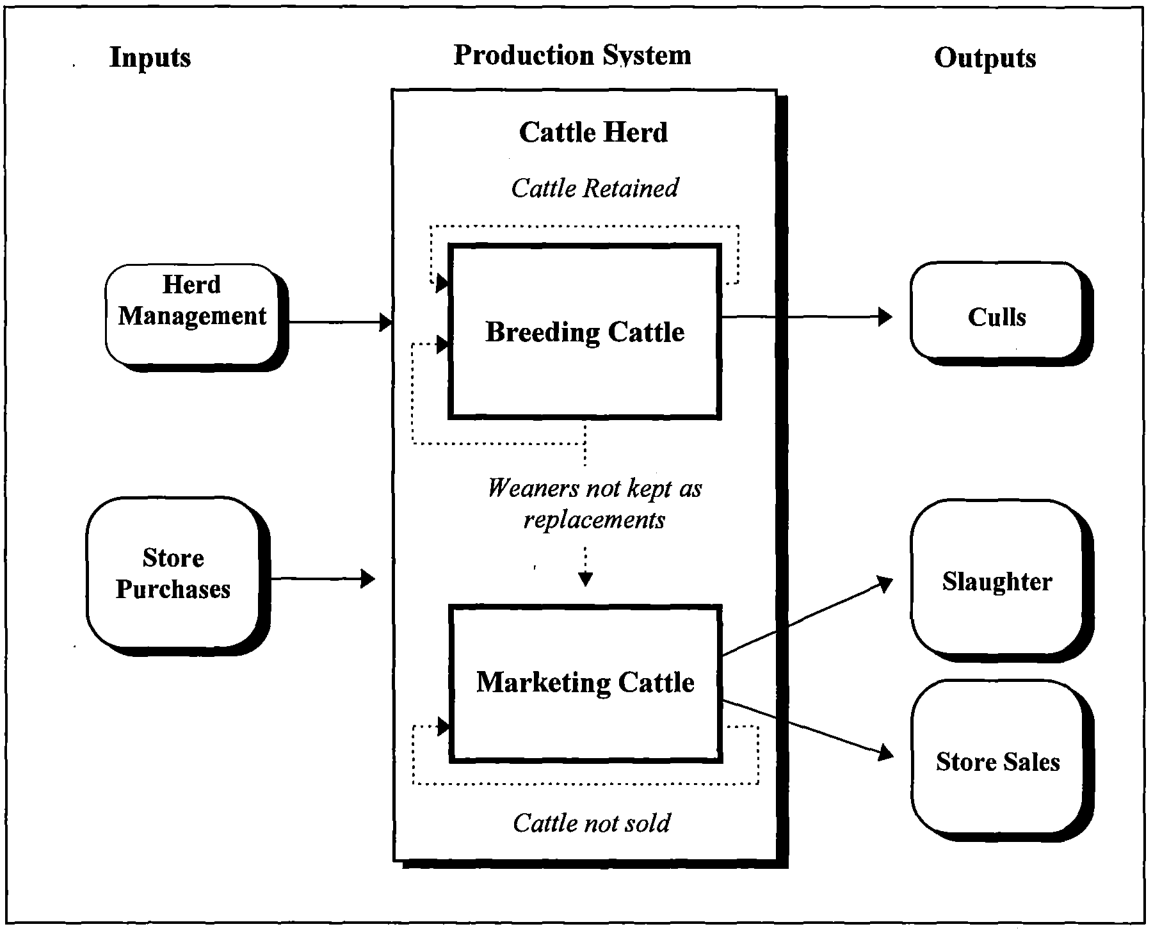
Figure 3.1 Herd Infection Level-Average Net Revenue Relationships



The producer's decision to market cattle as stores or directly to slaughter therefore depends on the impact of each marketing alternative on net revenue. The factors influencing the marketing decision are the difference between the store and slaughter market prices for the class of cattle being marketed, the magnitude of the discount in the store market, the risk of Tb infection, the actual level of Tb in the herd, and the impact on revenue of the movement control testing requirements.

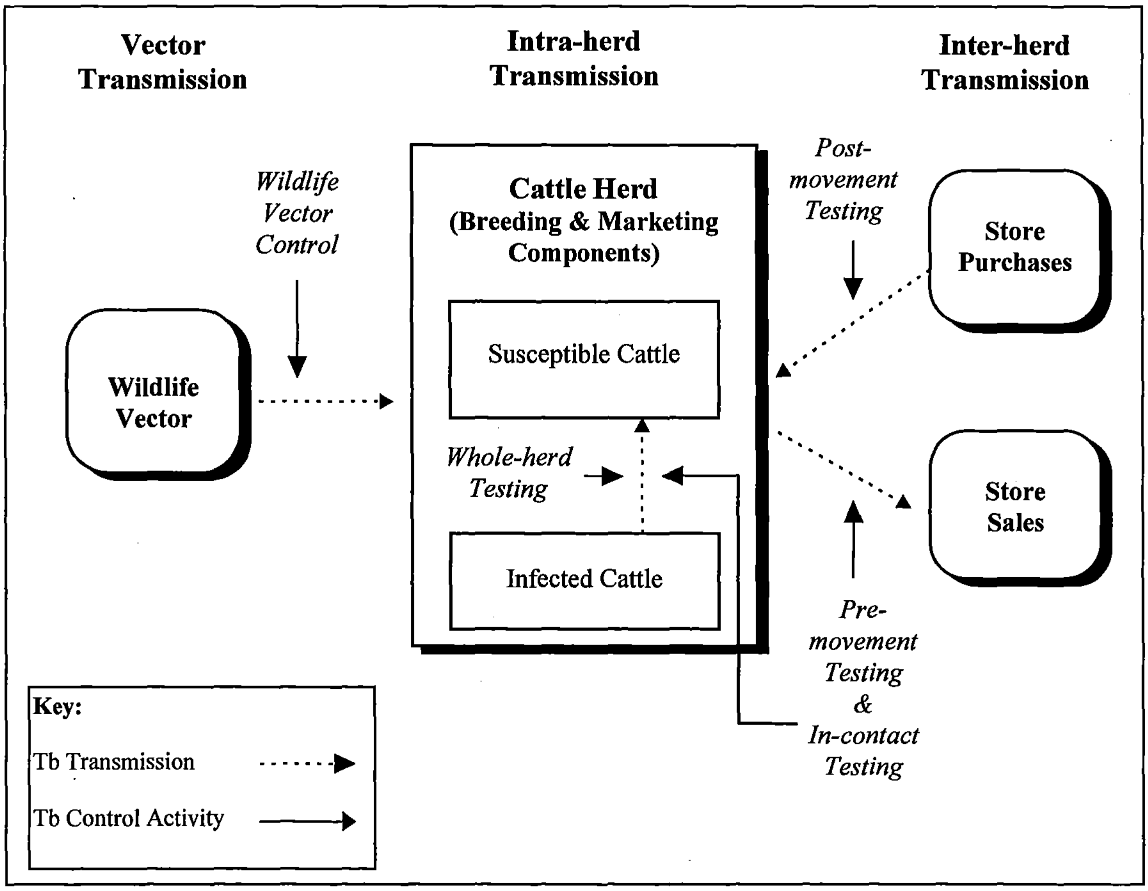
The potentially large impact of movement control on the production and marketing of store cattle further suggested that the analysis of movement control regulations should focus on a beef cattle breeding-store system. Given the variation in beef cattle production throughout New Zealand, and the complexity of undertaking analysis of a complete farming system, the analysis was based on a generic beef cattle breeding-store system and abstracts from all other production activities (Figure 3.2). The production system was separated into breeding and marketing cattle components reflecting the different herd objectives and management requirements. Age and sex structures in the herd were abstracted from to avoid unnecessary complexity. The breeding component comprises mature cows and replacement cattle obtained through the retention of weaner heifers. A proportion of mature cows are culled each period to improve the breeding herd's performance. Cattle entering the marketing component comprise weaners and cattle purchased as stores which are not required as replacements in the breeding herd. The marketing options available for cattle in the marketing component consist of selling store cattle requiring further finishing, or selling cattle directly to slaughter.

Figure 3.2 The Beef Cattle Production System



Tb and its control have an important impact on beef cattle production in Tb vector risk areas. The relationships between Tb control activities, disease transmission, and the production system are illustrated in Figure 3.3. Bovine Tb may be transmitted into a herd through susceptible cattle coming into contact with infectious animals from a wildlife vector population and infected cattle being moved into the herd from other properties. Susceptible cattle are defined as cattle that are not currently infected with Tb, but may become infected if they come in contact with infectious animals. Infected cattle are defined as cattle that are currently infected with Tb and are infectious. Once Tb infection is within the herd the disease may be transmitted from infectious cattle to susceptible cattle.

Figure 3.3 Tb Transmission Routes and Control Activities



Regulatory and voluntary control activities reduce the probability that Tb will spread throughout the herd. Vector control reduces wildlife vector transmission, movement control Tb testing which comprises pre-movement, "in-contact", and post-movement Tb testing events, and purchases of cattle from infection free herds, reduces the spread of Tb between properties. Periodic whole-herd Tb surveillance testing reduces transmission within the herd.

3.3 The Theoretical Optimal Control Model

The beef production system in a Tb vector risk area was formulated as an optimal control problem in which a representative beef cattle producer is faced with decisions regarding the purchase and sale of cattle. The producer was assumed to be risk neutral, and have the objective of maximising discounted net revenue from the cattle enterprise over time. The model specifies the relevant relationships associated with a breeding-store beef cattle production system in an environment where Tb infection is endemic in a possum population. To achieve the required objective, the producer chooses the optimal activity level for four control variables which impact on three state variables. Two state variables relate to the susceptible (S_t) and infected (I_t) cattle populations. The third state variable is for the possum population (P_t). Table 3.1 displays the variables and parameters contained in the model.

Table 3.1 Variable and Parameter Definitions

Variable/ Parameter	Definition	Units
S_t	Density of susceptible cattle (state variable)	hd/ha
I_t	Density of infected cattle (state variable)	hd/ha
P_t	Density of possums (state variable)	hd/ha
F_t	Cattle sold to other producers (control variable)	%
APP_t	Average price paid for cattle purchased (control variable)	$/hd
MC_t	Movement control testing (control variable)	#
H_t	Possums harvested (control variable)	hd/ha
SR_t	Revenue from cattle marketed as stores	$/ha
SL_t	Revenue from cattle marketed to slaughter	$/ha
WHT_t	Net proceeds from whole herd Tb surveillance testing	$/ha
$MT1_t$	Net proceeds from pre-movement & in-contact Tb testing	$/ha
$MT2_t$	Net proceeds from post-movement Tb testing	$/ha
PC_t	Weaner cattle purchase cost	$/ha
VC_t	Variable cost of maintaining the herd	$/ha
B	Proportion of the herd that are breeding cattle	%
$s_1(S_t,I_t)$	Within herd infection transmission function	hd/ha
$s_2(S_t,P_t)$	Possum infection transmission function	hd/ha
$w_1(APP_t)$	Proportion of susceptible cattle purchased	%
$w_2(APP_t)$	Proportion of infected cattle purchased	%
δ	Annual discount rate	%
p_1	Average price for clear herd weaners	$/hd
p_2	Average price for clear herd store R2 cattle	$/hd
p_3	Average price for non-infected R2 cattle slaughtered	$/hd
p_4	Average price for non-infected cull cows	$/hd
$r(D_t)$	Average price function for store R2 cattle	$/hd
l	Slaughter levy	$/hd
μ	Average proportion of infected cattle salvaged	%
ρ	Proportion of cows culled	%
ψ	Annual whole herd testing frequency	#

Table 3.1(Continued)

$z(F_t)$	"In-contact" testing function	%
τ_1	False positive reactor cattle	%
τ_2	True positive reactor cattle	%
α	Cost of testing cattle	\$/hd
γ_1	Compensation non-lesioned cattle	%
γ_2	Compensation lesioned cattle	%
$K1$	Profit maximising stocking rate	hd/ha
$g_1(S_t)$	Susceptible breeding herd calves	hd/ha
$g_2(I_t)$	Infected breeding herd calves	hd/ha
v_1	Variable cost of cattle	\$/hd
v_2	Variable cost of fattening slaughter cattle	\$/hd
$PH(P_t,H_t)$	Possum control cost function	\$/ha
$g_3(P_t)$	Possum population growth function	hd/ha

3.3.1 Objective Function

The cattle producer's objective is represented mathematically in Equation 3.1. Revenue each period arises from the sale proceeds of cattle marketed as stores (SR_t) or to slaughter (SL_t), and the net proceeds obtained from whole herd Tb surveillance (WHT_t) and movement control Tb testing ($MT1_t$ and $MT2_t$) when total reactor compensation payments exceed total testing costs. Costs are comprised of weaner cattle purchases (PC_t), the variable costs of maintaining the herd (VC_t), and possum control costs (PH_t). To achieve the optimal net revenue the producer has control over decisions regarding the percentage of marketing herd cattle selected for sale as stores each period (F_t), the market price paid for cattle purchased (APP_t) and consequently the Tb infection status of the herd from which cattle are purchased, whether movement control testing is undertaken (MC_t), and the number of possums harvested (H_t).

$$\begin{aligned}\underset{F_t, APP_t, MC_t, H_t}{Maximise}\ \pi = \int_{t=0}^{T} e^{-\delta t}(& WHT_t(S_t, I_t) + MT1_t(S_t, I_t, F_t, MC_t) + \\ & SR_t(S_t, I_t, F_t, MC_t) + SL_t(S_t, I_t, F_t, MC_t) - \\ & PC_t(APP_t, S_t, I_t, F_t, MC_t) + MT2_t(APP_t, S_t, I_t, F_t, MC_t) - \\ & VC_t(S_t, I_t, MC_t) - PH_t(P_t, H_t))dt\end{aligned} \tag{3.1}$$

The model assumes that the proportion and implied composition of breeding and marketing components of the herd remain constant over time through biological reproduction and cattle purchased each period. This assumption permitted the breeding and marketing sub herds to be distinguished by the relationships $B(S_t+I_t)$ and $(1-B)(S_t+I_t)$, respectively. Where B is the proportion of the total herd that are breeding cattle, S_t is the number of susceptible cattle in the herd, and I_t is the number of infected cattle.

Surveillance testing of cattle herds for tuberculosis is mandatory. Cattle producers are required to present all cattle in a herd for a compulsory whole herd Tb test which is administered at a frequency specified in regional Tb plans. Whole herd testing was assumed to occur at a frequency ψ prior to all marketing activities and cattle purchases. As a result, all cattle in the breeding and marketing herds at the beginning of each period are exposed to whole herd Tb testing.

The tuberculin test used in surveillance and movement control Tb testing of cattle is the caudal fold test (CFT). The accuracy of any diagnostic test is influenced by its sensitivity and specificity which describe the test's power to discriminate between diseased and non-diseased animals, respectively (Martin *et al.*, 1987). The percentage of infected cattle at a testing event that test positive, termed true positives, is determined by the test's sensitivity (τ_2). Correspondingly, false positives, the percentage of susceptible cattle testing positive at a testing event, is determined by one minus the test's specificity (τ_1). Consequently, $\tau_2 I_t$ cattle are removed as true positives from a Tb testing event while $\tau_1 S_t$ are removed as false positives. With respect to *M. bovis* infections the sensitivity and specificity of the caudal fold test changes as infection progresses (Neill *et al.,* 1995). The sensitivity of the Tb test also changes depending on the interval between re-testing (Ryan and Cameron, 1995). In response to the possibility of a decline in the sensitivity of the Tb test through increased frequency of testing, ancillary testing has not been permitted in most Tb vector risk areas (O'Neil and Pharo, 1995). The model assumes that the frequency of whole herd Tb testing ensures infection is at the same stage of development each period and that ancillary Tb testing is not undertaken on reactors detected at any Tb testing event. Therefore τ_1 and τ_2 were assumed to remain constant over time.

Testing cost (α) was assumed to be the average cost of presenting an animal for Tb testing and the subsequent test interpretation. If cattle return a positive reaction at testing then compensation, as a percentage of fair market value, is paid to producers. The percentage of fair market value paid as compensation is currently the same for false positive reactors (γ_1) and true positive reactors (γ_2) due to difficulties in distinguishing between them. The parameters γ_1 and γ_2 were distinguished in the model to permit analysis of the impact of compensation on the producer's decisions. It was assumed that fair market value corresponds to the relevant sale price for cattle of a particular class. The surveillance testing revenue associated with breeding and finishing herd cattle is given by Equation 3.2.

$$\begin{aligned} WHT_t = {} & \psi(B(S_t((p_4 - l)\gamma_1\tau_1 - \alpha) + I_t((p_4 - l)\gamma_2\tau_2 - \alpha)) + \\ & (1 - B)(S_t((p_2 - l)\gamma_1\tau_1 - \alpha) + I_t((p_2 - l)\gamma_2\tau_2 - \alpha))) \end{aligned} \tag{3.2}$$

The number of cattle remaining in the herd after whole herd Tb testing was represented by the relationships $(1-\psi\tau_1)S_t$ and $(1-\psi\tau_2)I_t$. Movement control regulations require cattle to have a pre-movement Tb test prior to being sent to sale as stores. Testing in accordance with movement control regulations enters the model as a control variable (MC_t). Producers can be forced to Tb test prior to moving cattle by setting MC_t equal to 1. Alternatively, MC_t can be treated as a decision variable by specifying upper and lower bounds, and letting the model choose the optimal level. Any cattle which have been in contact with a group of sale animals testing positive at a pre-movement test must also be submitted to an "in-contact" test. Cattle required to be in-contact Tb tested are those not involved in the pre-movement Tb test and not removed as reactors at the whole herd Tb test. The proportion of cattle in the breeding and marketing sub herds requiring "in-contact" testing was assumed to be dependent on the proportion of the marketing herd being selected for sale as stores ($z(F_t)$). The net Tb testing revenue attributable to pre-movement and "in-contact" testing is expressed as,

$$\begin{aligned} MT1_t = {} & MC_t((1-B)(F_t+(1-F_t)z(F_t))((((p_2-l)\gamma_1\tau_1-\alpha)S_t(1-\psi\tau_1)+ \\ & ((p_2-l)\gamma_2\tau_2-\alpha)I_t(1-\psi\tau_2))+Bz(F_t)((((p_4-l)\gamma_1\tau_1-\alpha)S_t(1-\psi\tau_1) \\ & +((p_4-l)\gamma_2\tau_2-\alpha)I_t(1-\psi\tau_2))) \end{aligned} \tag{3.3}$$

Cattle can only be marketed for sale as stores providing the risk of Tb infection is acceptable to animal health authorities. The price received for store cattle is also dependent on the risk of Tb infection. The NPMS uses both the incidence and duration of Tb infection as measures of herd Tb risk (Animal Health Board, 1995). Animal health authorities determine whether herds are classified as "infected" or "high risk infected" by their annual Tb incidence. With respect to how producers evaluate Tb risk, it is envisaged by the Animal Health Board that risk will be related to the number of years a herd has been infected with Tb. These two approaches to measuring Tb risk focus on the level and persistence of disease, respectively. Epidemiologists suggest that in situations where the disease does not result in high mortality, or animals do not make speedy and frequent recoveries, prevalence information may be used as a substitute for the incidence of disease (Martin *et al.*, 1987). The proxy for disease risk adopted in the model was the level of Tb in the herd as indicated by its annual true prevalence. The relationship between price and disease risk was included in the model by assuming that buyers discount the price of store cattle based on the cattle herd's annual Tb prevalence (D_t).

The percentage of marketing cattle selected for sale (F_t) each period is reduced by the percentage of true positive ($MC_t\tau_2$) and false positive ($MC_t\tau_1$) cattle reacting to the pre-movement Tb test. Consequently, sale revenue is dependent on how much the average sale price ($r(D_t)$) is discounted due to the risk of Tb infection and the number of cattle actually sent to sale (Equation 3.4).

$$SR_t = r(D_t)F_t(1-B)((1-MC_t\tau_1)S_t(1-\psi\tau_1)+(1-MC_t\tau_2)I_t(1-\psi\tau_2)) \qquad (3.4)$$

The producer also has the option of marketing cattle directly to slaughter. Because the cattle production system was assumed to have a comparative advantage in breeding and the production of store cattle, it was assumed that marketable cattle will only reach the minimum carcass weight category necessary for slaughter. Slaughter revenue is expressed mathematically in Equation 3.5. Cattle slaughtered each period comprise a fixed percentage of the breeding herd which are culled (ρ) and marketing herd cattle which have not been removed as positive reactors at prior tuberculosis testing events and/or not sold to other producers as stores. The average price received for breeding cattle culled is p_4 and the average price for marketable cattle slaughtered is given by p_3. The price parameters reflect the assumptions that cattle producers face perfectly competitive prices and that for both groups of cattle the attributes of the average of all cattle selected for slaughter remain constant over time. The price of all adult cattle sent directly to slaughter is reduced by a slaughter levy (l) which funds the cattle industry's share of costs associated with running the tuberculosis control programme.

$$\begin{aligned}SL_t = {} & (p_3 - l)(1 - B)(S_t(1 - \psi\tau_1)(1 - (F_t + MC_t(1 - F_t)z(F_t)\tau_1)) + \\ & \mu I_t(1 - \psi\tau_2)(1 - (F_t + MC_t(1 - F_t)z(F_t)\tau_2))) + (p_4 - l)\rho B(S_t(1 - \psi\tau_1) + \\ & \mu I_t(1 - \psi\tau_2))\end{aligned} \tag{3.5}$$

It was assumed that Tb infection can only be detected in cattle as a result of Tb testing or surveillance at slaughter facilities and that all infected cattle sent to slaughter were identified. The revenue received by producers for an infected animal identified at slaughter depends on the extent to which the carcass can be salvaged for further processing. The price received for infected cattle slaughtered was therefore represented in the model as a proportion (μ) of the price for susceptible cattle.

The cost of cattle purchased (Equation 3.6) is expressed as product of the average price paid by the producer for weaner cattle (APP_t) and the number purchased. In each time period the producer was assumed to purchase the number of cattle that would ensure the herd was maintained at its profit maximising stocking rate (K1). Surplus stocking rate was formulated as the difference between the profit maximising stocking rate less the net flow of cattle out of the herd during the period. The relevant flows include marketing cattle sold and breeding cattle culled, positive reactors at Tb testing events, and new calves entering from the breeding herd.

$$
\begin{aligned}
PC_t = {} & APP_t(K1-((S_t+I_t)-(1-B)((F_t(1-MC_t\tau_1)+ \\
& (1-(F_t+MC_t(1-F_t)z(F_t)\tau_1)))S_t(1-\psi\tau_1)+(F_t(1-MC_t\tau_1)+ \\
& (1-(F_t+MC_t(1-F_t)z(F_t)\tau_2)))I_t(1-\psi\tau_2))-\rho B(S_t+I_t)- \\
& MC_t((1-B)(F_t+(1-F_t)z(F_t))+Bz(F_t))(\tau_1 S_t(1-\psi\tau_1)+\tau_2 I_t(1-\psi\tau_2))- \\
& \psi(\tau_1 S_t+\tau_2 I_t)+g_1(S_t)+g_2(I_t)))
\end{aligned}
\tag{3.6}
$$

The net revenue from post-movement Tb testing is comprised of compensation received from test positive cattle (Equation 3.7). Under movement control regulations a post-movement Tb test must be administered to cattle arriving on the property if the cattle are from a herd with an "infected" herd Tb status or from a herd in a Tb vector risk area. The model assumes that all cattle purchased are from herds in Tb vector risk areas thereby avoiding the need to include a relationship for discounting due to area status. The proportion of each group of cattle purchased that is susceptible ($w_1(APP_t)$) and/or infected ($w_2(APP_t)$) was assumed to be a function of the purchase price.

$$
\begin{aligned}
MT2_t = {} & (K1-((S_t+I_t)-(1-B)((F_t(1-MC_t\tau_1)+ \\
& (1-(F_t+MC_t(1-F_t)z(F_t)\tau_1)))S_t(1-\psi\tau_1)+(F_t(1-MC_t\tau_2)+ \\
& (1-(F_t+MC_t(1-F_t)z(F_t)\tau_2)))I_t(1-\psi\tau_2))-\rho B(S_t+I_t)- \\
& MC_t((1-B)(F_t+(1-F_t)z(F_t))+Bz(F_t))(\tau_1 S_t(1-\psi\tau_1)+\tau_2 I_t(1-\psi\tau_2)) \\
& -\psi(\tau_1 S_t+\tau_2 I_t)+g_1(S_t)+g_2(I_t)))(w_1(APP_t)\tau_1((p_1-l)\gamma_1-\alpha)+ \\
& w_2(APP_t)\tau_2((p_1-l)\gamma_2-\alpha))
\end{aligned}
\tag{3.7}
$$

Equations 3.3 to 3.7 highlight the marketing and purchase tradeoffs faced by the producer. With respect to marketing cattle, the producer's marketing decision was presented as choosing the percentage of marketing cattle to be sold as stores, for which the average price received for all cattle sold is negatively correlated to the apparent infection status of the herd. Once the producer had chosen the proportion of marketing cattle to be sold as stores the remaining proportion, less cattle removed as reactors at in-contact Tb testing, are sold to slaughter. When cattle are sold to slaughter the producer receives only a salvage value for stock identified as infected. Cattle that are sold or removed from the herd as reactors within a period must be replaced. The producer decides on the average purchase price paid for cattle (APP_t) and, because of an assumed relationship between price and Tb infection, trades off a lower price with an increase in the apparent risk of infection.

The variable cost of holding cattle (VC_t) was comprised of two components. The first cost represented by ν_1 is the average direct expenditure incurred in managing a cattle beast for a period. The second cost ν_2 is the cost of fattening a cattle beast to a carcass weight suitable for slaughter. This cost is only applied to marketing cattle retained for sale to slaughter. Total variable cost is expressed in Equation 3.8 as a function of the starting number of cattle in the herd each period.

$$\begin{aligned} VC_t = (&\nu_1(S_t + I_t) + \nu_2(1-B)(S_t(1-\psi\tau_1)(1-(F_t + MC_t(1-F_t)z(F_t)\tau_1)) + \\ &I_t(1-\psi\tau_2)(1-(F_t + MC_t(1-F_t)z(F_t)\tau_2)))) \end{aligned} \tag{3.8}$$

Possum control is undertaken to reduce the opportunity for transmission of Tb into the herd from the local possum population. Possum harvest cost (PH_t) was assumed to be a function of the size of the possum population on the farm (P_t) and the number of possums harvested each period (H_t).

3.3.2 Equations of Motion

The objective function (Equation 3.1) is constrained by equations of motion for the three state variables. These are the equations in the model which describe the evolution of the state variables, S_t, I_t, and P_t. Two of the equations relate to the populations of the susceptible cattle (Equation 3.9) and infected cattle (Equation 3.10) in the herd. Because the total herd size was assumed to be constant, activities specific to either the breeding or marketing components of the herd are captured in each equation using the terms B and (1-B) as restrictions on the proportion of the susceptible and infected cattle populations affected.

$$\begin{aligned}\dot{S} = {} & -s_1(S_t, I_t) - s_2(S_t, P_t) - (1-B)(F_t(1-MC_t\tau_1) + \\ & (1-(F_t + MC_t(1-F_t)z(F_t)\tau_1)))S_t(1-\psi\tau_1) - \rho BS_t + (K1 - ((S_t + I_t) - \\ & (1-B)((F_t(1-MC_t\tau_1) + (1-(F_t + MC_t(1-F_t)z(F_t)\tau_1)))S_t(1-\psi\tau_1) + \\ & (F_t(1-MC_t\tau_2) + (1-(F_t + MC_t(1-F_t)z(F_t)\tau_2)))I_t(1-\psi\tau_2)) - \\ & \rho B(S_t + I_t) - MC_t((1-B)(F_t + (1-F_t)z(F_t)) + Bz(F_t))(\tau_1 S_t(1-\psi\tau_1) + \\ & \tau_2 I_t(1-\psi\tau_2)) - \psi(\tau_1 S_t + \tau_2 I_t) + g_1(S_t) + g_2(I_t)))(w_1(APP_t)(1-MC_t\tau_1)) + \\ & g_1(S_t) - \psi S_t\tau_1 - MC_t((1-B)(F_t + (1-F_t)z(F_t)) + Bz(F_t))S_t(1-\psi\tau_1)\tau_1\end{aligned} \tag{3.9}$$

$$\begin{aligned}\dot{I} = {} & s_1(S_t, I_t) + s_2(S_t, P_t) - (1-B)(F_t(1-MC_t\tau_2) + \\ & (1-(F_t + MC_t(1-F_t)z(F_t)\tau_2)))I_t(1-\psi\tau_2) - \rho BI_t + (K1 - ((S_t + I_t) - \\ & (1-B)((F_t(1-MC_t\tau_1) + (1-(F_t + MC_t(1-F_t)z(F_t)\tau_1)))S_t(1-\psi\tau_1) + \\ & (F_t(1-MC_t\tau_2) + (1-(F_t + MC_t(1-F_t)z(F_t)\tau_2)))I_t(1-\psi\tau_2)) - \\ & \rho B(S_t + I_t) - MC_t((1-B)(F_t + (1-F_t)z(F_t)) + Bz(F_t))(\tau_1 S_t(1-\psi\tau_1) + \\ & \tau_2 I_t(1-\psi\tau_2)) - \psi(\tau_1 S_t + \tau_2 I_t) + g_1(S_t) + g_2(I_t)))(w_2(APP_t)(1-MC_t\tau_2)) + \\ & g_2(I_t) - \psi I_t\tau_2 - MC_t((1-B)(F_t + (1-F_t)z(F_t)) + Bz(F_t))I_t(1-\psi\tau_2)\tau_2\end{aligned} \tag{3.10}$$

The functions $s_1(S_t,I_t)$ and $s_2(S_t,P_t)$ capture the periodic transmission of Tb from infectious cattle and infectious possums to susceptible cattle within the herd, respectively. The spread of Tb infection in a cattle population has been modeled elsewhere as a flux term in which the spread of Tb in the herd is specified as a function of the density of the susceptible cattle population and an infected animal population (Stoneham and Johnston, 1986; Kean, 1993; Bicknell, 1995). It is therefore assumed that the spread of Tb infection from cattle is a function of the density of susceptible and infected cattle, while the spread of infection from possums is a function of the density of susceptible cattle and possums. Support for this specification is found in the epidemiological literature which suggested that the risk that *M. bovis* will be transmitted from infectious cattle increases with the concentration of cattle in a herd (Neill *et. al.*, 1989; Radostits *et al.*, 1994).

The model reflects implicit assumptions concerning the movement of cattle into each of the susceptible and infected cattle populations. Replacement cattle for the breeding component were assumed to come from annual calving and, when required, weaners purchased. It was further assumed that cattle entering the marketing component comprised surplus weaners from the breeding component and weaner cattle purchased.

The risk of interuterine transmission is considered to be very low (Morris *et al.*, 1994). However, it was assumed that infected cows will transmit Tb to their offspring sometime prior to weaning because calves normally remain with their mothers for between seven and nine months (Coop, 1987). The annual increase in the susceptible cattle population ($g_1(S_t)$) and infected cattle population ($g_2(I_t)$), arising from calves each period, is dependent on the number of breeding cows remaining after the whole herd Tb test because testing was assumed to occur prior to calving.

The proportion of cattle purchased that are susceptible and infected are determined by the market price paid. The relationship between the market price for store cattle purchased (APP_t) and the level of Tb infection in the group purchased are given by the functions $w_1(APP_t)$ and $w_2(APP_t)$ for susceptible and infected cattle, respectively.

Cattle are removed from the susceptible and infected populations through the culling of breeding cattle, the sale to store or slaughter of marketing cattle, and the removal of true and false positive reactors at Tb testing events. The Tb testing events, which reduce the transmission of Tb infection in the herd, influence each population depending on the particular herd component affected. Surveillance testing through compulsory whole herd Tb testing is administered to both breeding and marketing cattle. The number of true and false positive reactor cattle removed at whole herd Tb testing is given by the terms $\psi I_t\tau_2$ and $\psi S_t\tau_1$, respectively. Pre-movement Tb testing is administered only to marketing cattle that are selected for sale as stores. The number of cattle removed as true positive reactors at pre-movement Tb testing is determined by the equation $MC_t(1\text{-}B)F_t(S_t(1\text{-}\psi\tau_1)\tau_1)$. Correspondingly, the number of false positive cattle removed is determined by $MC_t(1\text{-}B)F_t(I_t(1\text{-}\psi\tau_2)\tau_2)$. If reactors are detected at pre-movement Tb testing then cattle in both the breeding and marketing components are subject to "in-contact" Tb testing. The number of cattle removed as false and true positive reactors at "in-contact" testing are expressed mathematically by the equations $MC_t((1\text{-}B)((1\text{-}F_t)z(F_t))+Bz(F_t))(S_t(1\text{-}\tau_1)\tau_1)$ and $MC_t((1\text{-}B)((1\text{-}F_t)z(F_t))+Bz(F_t))(I_t(1\text{-}\tau_2)\tau_2)$, respectively. Only cattle which are purchased undergo post-movement Tb testing. The expression $1\text{-}MC_t\tau_2$ determines the proportion of infected cattle purchased that are removed as true positive reactors at post-movement Tb testing. The proportion of false positive reactors identified and removed from susceptible cattle purchased is similarly determined by the expression $1\text{-}MC_t\tau_1$.

Mycobacterium bovis can infect a wide range of New Zealand wildlife species. Epidemiological research, however, suggests that the brushtail possum (*Trichosurus vulpecula)* plays a major role in wildlife vector transmission of Tb to cattle (Morris and Pfeiffer, 1995). To allow for Tb infection due to wildlife vectors, the model includes an equation of motion for a Tb infected possum population (Equation 3.11). The state of the possum population was assumed to be dependent on its natural biological growth ($g_3(P_t)$) and the number of possums killed through vector control operations (H_t). A logistic growth function was used to represent the density dependent population dynamics.

$$\dot{P} = g_3(P_t) - H_t \tag{3.11}$$

The objective function is also constrained by initial conditions for the state variables (Equation 3.12), non-negativity constraints on the state variables (Equation 3.13) and boundary constraints on the control variables (Equation 3.14).

$$S_0 = S(0),\ I_0 = I(0),\ P_0 = P(0). \tag{3.12}$$

$$S_t,\ I_t,\ P_t \geq 0 \tag{3.13}$$

$$0 \leq F_t \leq 1,\ APP_{Min} \leq APP_t, \leq \mathrm{p}_1,\ 0 \leq MC_t \leq 1,\ 0 \leq H_t \leq \mathrm{P}_t \tag{3.14}$$

3.4 First Order Necessary Conditions

The first order necessary conditions for optimal solutions to control problems are obtained by formulating the problem in terms of a Hamiltonian functional and ensuring the maximum principle is satisfied (Chiang, 1992). The current value Hamiltonian for the control problem above (Equation 3.15) was generated by pre-multiplying each equation of motion with a costate variable and then adding the equations to the objective function. The current value costate variables m_1 to m_3 are interpreted as the shadow prices (marginal values) of the state variables S_t, I_t, and P_t, respectively. The current value Hamiltonian therefore represents for each period the value of net revenue and the change in value of each state variable as given by its size and shadow price. The shadow price of susceptible cattle is expected to be positive as additional units positively contribute to net revenue. However, the shadow prices of infected cattle and possums are expected to be negative reflecting the contribution each of these populations make towards the spread of disease within the herd and the consequent reduction in net revenue.

$$
\begin{aligned}
H_{cv} = \{ & (p_3 - l)(1-B)(S_t(1-\psi\tau_1)(1-(F_t + MC_t(1-F_t)z(F_t)\tau_1)) + \\
& \mu I_t(1-\psi\tau_2)(1-(F_t + MC_t(1-F_t)z(F_t)\tau_2))) + (p_4 - l)\rho B(S_t(1-\psi\tau_1) + \mu I_t(1-\psi\tau_2)) + \\
& r(D_t)F_t(1-B)((1-MC_t\tau_1)S_t(1-\psi\tau_1) + (1-MC_t\tau_2)I_t(1-\psi\tau_2)) - \\
& (APP_t - MC_t(w_1(APP_t)\tau_1((p_1 - l)\gamma_1 - \alpha) + w_2(APP_t)\tau_2((p_1 - l)\gamma_2 - \alpha))) * \\
& (K1 - ((S_t + I_t) - (1-B)((F_t(1-MC_t\tau_1) + (1-(F_t + MC_t(1-F_t)z(F_t)\tau_1)))S_t(1-\psi\tau_1) + \\
& (F_t(1-MC_t\tau_2) + (1-(F_t + MC_t(1-F_t)z(F_t)\tau_2)))I_t(1-\psi\tau_2)) - \rho B(S_t + I_t) - \\
& MC_t((1-B)(F_t + (1-F_t)z(F_t)) + Bz(F_t))(\tau_1 S_t(1-\psi\tau_1) + \tau_2 I_t(1-\psi\tau_2)) - \psi(\tau_1 S_t + \tau_2 I_t) + \\
& g_1(S_t) + g_2(I_t))) + MC_t((1-B)(F_t + (1-F_t)z(F_t))(((p_2 - l)\gamma_1\tau_1 - \alpha)S_t(1-\psi\tau_1) + \\
& ((p_2 - l)\gamma_2\tau_2 - \alpha)I_t(1-\psi\tau_2)) + Bz(F_t)(((p_4 - l)\gamma_1\tau_1 - \alpha)S_t(1-\psi\tau_1) + ((p_4 - l)\gamma_2\tau_2 - \alpha) * \\
& I_t(1-\psi\tau_2))) + \psi(B(S_t((p_4 - l)\gamma_1\tau_1 - \alpha) + I_t((p_4 - l)\gamma_2\tau_2 - \alpha)) + \\
& (1-B)(S_t((p_2 - l)\gamma_1\tau_1 - \alpha) + I_t((p_2 - l)\gamma_2\tau_2 - \alpha))) - (\nu_1(S_t + I_t) + \nu_2(1-B)(S_t(1-\psi\tau_1) * \\
& (1-(F_t + MC_t(1-F_t)z(F_t)\tau_1)) + I_t(1-\psi\tau_2)(1-(F_t + MC_t(1-F_t)z(F_t)\tau_2)))) \\
& - PH(P_t, H_t)\} + \\
\\
& m_1\{-s_1(S_t, I_t) - s_2(S_t, P_t) - (1-B)(F_t(1-MC_t\tau_1) + (1-(F_t + MC_t(1-F_t)z(F_t)\tau_1))) * \\
& S_t(1-\psi\tau_1) - \rho BS_t + (K1 - ((S_t + I_t) - (1-B)((F_t(1-MC_t\tau_1) + \\
& (1-(F_t + MC_t(1-F_t)z(F_t)\tau_1)))S_t(1-\psi\tau_1) + (F_t(1-MC_t\tau_2) + \\
& (1-(F_t + MC_t(1-F_t)z(F_t)\tau_2)))I_t(1-\psi\tau_2)) - \rho B(S_t + I_t) - MC_t((1-B)(F_t + (1-F_t)z(F_t)) \\
& + Bz(F_t))(\tau_1 S_t(1-\psi\tau_1) + \tau_2 I_t(1-\psi\tau_2)) - \psi(\tau_1 S_t + \tau_2 I_t) + g_1(S_t) + g_2(I_t))) * \\
& (w_1(APP_t)(1-MC_t\tau_1)) + g_1(S_t) - \psi S_t\tau_1 - MC_t((1-B)(F_t + (1-F_t)z(F_t)) + \\
& Bz(F_t))S_t(1-\psi\tau_1)\tau_1\} + \\
\\
& m_2\{s_1(S_t, I_t) + s_2(S_t, P_t) - (1-B)(F_t(1-MC_t\tau_2) + (1-(F_t + MC_t(1-F_t)z(F_t)\tau_2))) * \\
& I_t(1-\psi\tau_2) - \rho BI_t + (K1 - ((S_t + I_t) - (1-B)((F_t(1-MC_t\tau_1) + \\
& (1-(F_t + MC_t(1-F_t)z(F_t)\tau_1)))S_t(1-\psi\tau_1) + (F_t(1-MC_t\tau_2) + \\
& (1-(F_t + MC_t(1-F_t)z(F_t)\tau_2)))I_t(1-\psi\tau_2)) - \rho B(S_t + I_t) - MC_t((1-B)(F_t + (1-F_t)z(F_t)) \\
& + Bz(F_t))(\tau_1 S_t(1-\psi\tau_1) + \tau_2 I_t(1-\psi\tau_2)) - \psi(\tau_1 S_t + \tau_2 I_t) + g_1(S_t) + g_2(I_t))) * \\
& (w_2(APP_t)(1-MC_t\tau_2)) + g_2(I_t) - \psi I_t\tau_2 - MC_t((1-B)(F_t + (1-F_t)z(F_t)) + \\
& Bz(F_t))I_t(1-\psi\tau_2)\tau_2\} + \\
\\
& + m_3\{g_3(P_t) - H_t\}
\end{aligned}
\tag{3.15}
$$

The maximum principle requires that three conditions are satisfied. Firstly, the value of H_{cv} must be maximised over all time periods for the control variables. Maximisation is achieved by differentiating the current value Hamiltonian with respect to each of the control variables. Secondly, a Hamiltonian system must be obtained by differentiating the current value Hamiltonian with respect to each of the state variables and current value costate variables, respectively. The Hamiltonian system comprises equations which specify the way control decisions impact on the state variables and the evolution of the costate variables over time. The third condition states that the problem must have the appropriate transversality conditions.

Equation 3.15 is linear with respect to the control variable for the average purchase price of cattle so the broader maximisation requirement, *Max* H_{cv}, was invoked (Chiang, 1992). The optimal solution for a control variable that enters the Hamiltonian linearly will be some combination of "bang-bang" and singular controls which are determined by the switching function associated with the control variable (Clark, 1990). The switching function for the average purchase price of cattle is presented in Equation 3.17.

$$
\begin{aligned}
&\frac{\partial H_{cv}}{\partial APP_t} = \sigma_{APP} = \Bigg\{ -(1 - MC_t(\frac{\partial w_1}{\partial APP_t}\tau_1((p_1 - l)\gamma_1 - \alpha) + \frac{\partial w_2}{\partial APP_t}\tau_2((p_1 - l)\gamma_2 - \alpha)))\; * \\
&(K1 - ((S_t + I_t) - (1 - B)((F_t(1 - MC_t\tau_1) + (1 - (F_t + MC_t(1 - F_t)z(F_t)\tau_1)))S_t(1 - \psi\tau_1) + \\
&(F_t(1 - MC_t\tau_2) + (1 - (F_t + MC_t(1 - F_t)z(F_t)\tau_2)))I_t(1 - \psi\tau_2)) - \rho B(S_t + I_t) - \\
&MC_t((1 - B)(F_t + (1 - F_t)z(F_t)) + Bz(F_t))(\tau_1 S_t(1 - \psi\tau_1) + \tau_2 I_t(1 - \psi\tau_2)) - \psi(\tau_1 S_t + \tau_2 I_t) \\
&+ g_1(S_t) + g_2(I_t)))\} + \\
&m_1\{(K1 - ((S_t + I_t) - (1 - B)((F_t(1 - MC_t\tau_1) + (1 - (F_t + MC_t(1 - F_t)z(F_t)\tau_1)))S_t(1 - \psi\tau_1) \\
&+ (F_t(1 - MC_t\tau_2) + (1 - (F_t + MC_t(1 - F_t)z(F_t)\tau_2)))I_t(1 - \psi\tau_2)) - \rho B(S_t + I_t) - \\
&MC_t((1 - B)(F_t + (1 - F_t)z(F_t)) + Bz(F_t))(\tau_1 S_t(1 - \psi\tau_1) + \tau_2 I_t(1 - \psi\tau_2)) - \psi(\tau_1 S_t + \tau_2 I_t) \\
&+ g_1(S_t) + g_2(I_t)))\frac{\partial w_1}{\partial APP_t}(1 - MC_t\tau_1)\Bigg\} + \\
&m_2\{(K1 - (S_t + I_t) - (1 - B)((F_t(1 - MC_t\tau_1) + (1 - (F_t + MC_t(1 - F_t)z(F_t)\tau_1)))S_t(1 - \psi\tau_1) + \\
&(F_t(1 - MC_t\tau_2) + (1 - (F_t + MC_t(1 - F_t)z(F_t)\tau_2)))I_t(1 - \psi\tau_2)) - \rho B(S_t + I_t) - \\
&MC_t((1 - B)(F_t + (1 - F_t)z(F_t)) + Bz(F_t))(\tau_1 S_t(1 - \psi\tau_1) + \tau_2 I_t(1 - \psi\tau_2)) - \psi(\tau_1 S_t + \tau_2 I_t) + \\
&g_1(S_t) + g_2(I_t)))\frac{\partial w_2}{\partial APP_t}(1 - MC_t\tau_2)\Bigg\}
\end{aligned}
\tag{3.16}
$$

The control conditions for the average purchase price are,

$$APP_t = \begin{cases} APP_{Min} & if\ \sigma_{APP} \langle 0 \\ APP_t^* & if\ \sigma_{APP} = 0 \\ p_1 & if\ \sigma_{APP} \rangle 0 \end{cases} \tag{3.17}$$

The switching conditions relate to the price interval bounded by the clear herd price and the fully discounted price for store cattle. The first term in brackets in Equation 3.16 shows that there is an inverse relationship between the average purchase price of weaners and net revenue each period. The magnitude of the impact on net revenue depends, however, on the cost of weaners purchased and the revenue received from any reactors that may be detected at post-movement Tb testing less the cost of testing all weaners purchased. The second and third terms describe the marginal changes to the implied future contributions to net revenue by susceptible and infected cattle, respectively, resulting from a marginal change in the average purchase price. Equations 3.16 and 3.17 suggest that the producer will pay the minimum purchase price for cattle if the current net cost of purchasing and post-movement testing cattle is greater than the change in the herd's future earnings potential. Because the minimum purchase price corresponds to purchasing cattle from herds with high apparent prevalence levels, the producer trades-off the short run benefit of a higher net revenue against the long run costs of infected cattle entering the herd. The decision to purchase cattle from herds with high apparent infection levels therefore depends on whether the maximum price discount provides producers with an economic incentive to trade-off short run benefits with long run costs.

The Hamiltonian is non-linear with respect to the control variables for sales of store cattle, movement control Tb testing and possum harvest. The strong maximising condition *Max* H_{cv} was applied to the non-linear control variables to accommodate the possibility of boundary solutions. To derive the appropriate control conditions for a maximum Kuhn-Tucker conditions were formulated. Following the normal procedure for obtaining Kuhn-Tucker conditions, multiplier equations for the control constraints were added to the current value Hamiltonian which was in turn differentiated with respect to the control variable and set to zero (Kamien and Schwartz, 1981).

Boundary solutions must be expected for control decisions concerning store cattle sales. As shown in Figure 3.1 the trade-off between selling cattle as stores or to slaughter is based on each marketing option's contribution to current net revenue. It is reasonable to expect that the net revenue associated with store sales in a period may either favour selling all marketable cattle as stores or none. The necessary conditions for the maximisation of the current value Hamiltonian with respect to sales of store cattle are given by Equations 3.18-3.20.

$$\frac{\partial H_{cv}}{\partial F_t} = \left\{ -(p_3 - l)(1-B)(S_t(1-\psi\tau_1)\left(1 + MC_t\left((1-F_t)\frac{\partial z(F_t)}{\partial F_t}\tau_1 - z(F_t)\tau_1\right)\right) + \right.$$

$$\left. \mu I_t(1-\psi\tau_2)\left(1 + MC_t\left((1-F_t)\frac{\partial z(F_t)}{\partial F_t}\tau_2 - z(F_t)\tau_2\right)\right)\right) +$$

$$r(D_t)(1-B)((1-MC_t\tau_1)S_t(1-\psi\tau_1) + (1-MC_t\tau_2)I_t(1-\psi\tau_2)) -$$
$$(APP_t - MC_t(w_1(APP_t)\tau_1((p_1 - l)\gamma_1 - \alpha) + w_2(APP_t)\tau_2((p_1 - l)\gamma_2 - \alpha))) *$$

$$((1-B)\left(\left((1-MC_t\tau_1) - \left(1 + MC_t\left((1-F_t)\frac{\partial z(F_t)}{\partial F_t}\tau_1 - z(F_t)\tau_1\right)\right)\right)S_t(1-\psi\tau_1) + \right.$$

$$\left.\left((1-MC_t\tau_2) - \left(1 + MC_t\left((1-F_t)\frac{\partial z(F_t)}{\partial F_t}\tau_2 - z(F_t)\tau_2\right)\right)\right)I_t(1-\psi\tau_2)\right) +$$

$$MC_t\left((1-B)\left(1 + \left((1-F_t)\frac{\partial z(F_t)}{\partial F_t} - z(F_t)\right)\right) + B\left(\frac{\partial z(F_t)}{\partial F_t}\right)\right)(\tau_1 S_t(1-\psi\tau_1) + \tau_2 I_t(1-\psi\tau_2))\Bigg)$$

$$+ MC_t\Big((1-B)\Big(1+\Big((1-F_t)\frac{\partial z(F_t)}{\partial F_t}-z(F_t)\Big)\Big)\Big)(((p_2-l)\gamma_1\tau_1-\alpha)S_t(1-\psi\tau_1)+$$

$$((p_2-l)\gamma_2\tau_2-\alpha)I_t(1-\psi\tau_2))+B\Big(\frac{\partial z(F_t)}{\partial F_t}\Big)(((p_4-l)\gamma_1\tau_1-\alpha)S_t(1-\psi\tau_1)+$$

$$((p_4-l)\gamma_2\tau_2-\alpha)I_t(1-\psi\tau_2)))+$$

$$\nu_2(1-B)\Big(S_t(1-\psi\tau_1)\Big(1+MC_t\Big((1-F_t)\frac{\partial z(F_t)}{\partial F_t}\tau_1-z(F_t)\tau_1\Big)\Big)+$$

$$I_t(1-\psi\tau_2)\Big(1+MC_t\Big((1-F_t)\frac{\partial z(F_t)}{\partial F_t}\tau_2-z(F_t)\tau_2\Big)\Big)\Big)\Big\}-$$

$$m_1\Big\{(1-B)\Big((1-MC_t\tau_1)-\Big(1+MC_t\Big((1-F_t)\frac{\partial z}{\partial F_t}\tau_1-z(F_t)\tau_1\Big)\Big)\Big)S_t(1-\psi\tau_1)-$$

$$((1-B)\Big(\Big((1-MC_t\tau_1)-\Big(1+MC_t\Big((1-F_t)\frac{\partial z}{\partial F_t}\tau_1-z(F_t)\tau_1\Big)\Big)\Big)S_t(1-\psi\tau_1)+$$

$$\Big((1-MC_t\tau_2)-\Big(1+MC_t\Big((1-F_t)\frac{\partial z}{\partial F_t}\tau_2-z(F_t)\tau_2\Big)\Big)\Big)I_t(1-\psi\tau_2)\Big)-$$

$$MC_t\Big((1-B)\Big(1+\Big((1-F_t)\frac{\partial z}{\partial F_t}-z(F_t)\Big)\Big)+B\Big(\frac{\partial z}{\partial F_t}\Big)\Big)(\tau_1 S_t(1-\psi\tau_1)+$$

$$\tau_2 I_t(1-\psi\tau_2)))(w_1(APP_t)(1-MC_t\tau_1))+$$

$$MC_t\Big((1-B)\Big(1+\Big((1-F_t)\frac{\partial z}{\partial F_t}-z(F_t)\Big)\Big)+B\Big(\frac{\partial z}{\partial F_t}\Big)\Big)S_t(1-\psi\tau_1)\tau_1\Big\}-$$

$$m_2\Big\{(1-B)\Big((1-MC_t\tau_2)-\Big(1+MC_t\Big((1-F_t)\frac{\partial z}{\partial F_t}\tau_2-z(F_t)\tau_2\Big)\Big)\Big)I_t(1-\psi\tau_2)-$$

$$((1-B)\Big(\Big((1-MC_t\tau_1)-\Big(1+MC_t\Big((1-F_t)\frac{\partial z}{\partial F_t}\tau_1-z(F_t)\tau_1\Big)\Big)\Big)S_t(1-\psi\tau_1)+$$

$$\Big((1-MC_t\tau_2)-\Big(1+MC_t\Big((1-F_t)\frac{\partial z}{\partial F_t}\tau_2-z(F_t)\tau_2\Big)\Big)\Big)I_t(1-\psi\tau_2)\Big)- \qquad (3.18)$$

$$MC_t\Big((1-B)\Big(1+\Big((1-F_t)\frac{\partial z}{\partial F_t}-z(F_t)\Big)\Big)+B\Big(\frac{\partial z}{\partial F_t}\Big)\Big)(\tau_1 S_t(1-\psi\tau_1)+$$

$$\tau_2 I_t(1-\psi\tau_2)))(w_2(APP_t)(1-MC_t\tau_2))+$$

$$MC_t\Big((1-B)\Big(1+\Big((1-F_t)\frac{\partial z}{\partial F_t}-z(F_t)\Big)\Big)+B\Big(\frac{\partial z}{\partial F_t}\Big)\Big)I_t(1-\psi\tau_2)\tau_2\Big\}-\omega_1+\omega_2=0,$$

$$\omega_1 \geq 0, \qquad \omega_1(1-F_t^*)=0, \qquad (3.19)$$

$$\omega_2 \geq 0, \qquad \omega_2(F_t^* - 0) = 0. \tag{3.20}$$

Equation 3.18 mathematically describes the marginal benefits and costs of selling cattle as stores. The marginal benefit of store sales comprises the current revenue received for cattle sold, the net revenue received for any cattle reacting at movement control Tb testing, and the avoidance of additional grazing costs. The marginal cost includes the opportunity cost of not sending cattle to slaughter, and the reduction in the future earnings potential of the herd brought about through the removal of cattle not being offset by purchases due to the post-movement test. Another factor contributing to the herd's future earning potential relates to changes in the level of Tb infection in the herd. Changes in the size of each cattle population occur because the producer has some control over the disease status of cattle purchased through the price paid and therefore the status of purchased animals may not necessarily match those sold or removed at pre-movement and in-contact Tb testing. Given the expectation that m_1 and m_2 will be positive and negative, respectively, net decreases in the stock of susceptible cattle will adversely affect future earnings while net decreases in the stock of infected cattle will be beneficial for future earnings.

The control conditions for sales of store cattle suggest that the producer will not sell any marketable cattle as stores if the marginal impact on net revenue and the implied future contribution of the herd are negative. This may be shown by setting F_t^* to zero which implies that ω_1 in (3.19) is zero and ω_2 in (3.20) is positive. The results of (3.19) and (3.20) will only satisfy the maximising condition of (3.18) providing both the marginal value for current net revenue and the herd's implied future value are negative. Alternatively, if both marginal values are positive then all marketable cattle will be sold as stores ($F_t^* = 1$, $\omega_1 \geq 0$, $\omega_2 = 0$). If neither of these two conditions are satisfied ($\omega_1 = \omega_2 = 0$), then the producer will select a level of sales that ensures that the marginal change in net revenue equals the marginal change in future earnings brought about by changes in numbers and proportions of susceptible and infected cattle.

It is also reasonable to expect that when movement control Tb testing is a control variable the producer may decide to either undertaking testing consistent with the NPMS or undertaking none. Equations 3.21-3.23 provide the necessary conditions for the maximisation of the current value Hamiltonian with respect to movement control Tb testing.

$$\begin{aligned}
&\frac{\partial H_{cv}}{\partial MC_t} = \sigma_{MC} = \{-(p_3 - l)(1-B)(S_t(1-\psi\tau_1)(1-F_t)z(F_t)\tau_1 + \\
&\mu I_t(1-\psi\tau_2)(1-F_t)z(F_t)\tau_2) - r(D_t)F_t(1-B)(\tau_1 S_t(1-\psi\tau_1) + \tau_2 I_t(1-\psi\tau_2)) + \\
&(w_1(APP_t)\tau_1((p_1 - l)\gamma_1 - \alpha) + w_2(APP_t)\tau_2((p_1 - l)\gamma_2 - \alpha)))(K1 - ((S_t + I_t) - \\
&(1-B)((F_t(1 - MC_t\tau_1) + (1 - (F_t + MC_t(1-F_t)z(F_t)\tau_1)))S_t(1-\psi\tau_1) + (F_t(1 - MC_t\tau_2) + \\
&(1 - (F_t + MC_t(1-F_t)z(F_t)\tau_2)))I_t(1-\psi\tau_2)) - \rho B(S_t + I_t) - \\
&MC_t((1-B)(F_t + (1-F_t)z(F_t)) + Bz(F_t))(\tau_1 S_t(1-\psi\tau_1) + \tau_2 I_t(1-\psi\tau_2)) - \\
&\psi(\tau_1 S_t + \tau_2 I_t) + g_1(S_t) + g_2(I_t))) + (APP_t - MC_t(w_1(APP_t)\tau_1((p_1 - l)\gamma_1 - \alpha) + \\
&w_2(APP_t)\tau_2((p_1 - l)\gamma_2 - \alpha)))((1-B)((F_t\tau_1 + (1-F_t)z(F_t)\tau_1)S_t(1-\psi\tau_1) + \\
&(F_t\tau_2 + (1-F_t)z(F_t)\tau_2)I_t(1-\psi\tau_2)) - ((1-B)(F_t + (1-F_t)z(F_t)) + Bz(F_t)) * \\
&(\tau_1 S_t(1-\psi\tau_1) + \tau_2 I_t(1-\psi\tau_2))) + ((1-B)(F_t + (1-F_t)z(F_t))(((p_2 - l)\gamma_1\tau_1 - \alpha) * \\
&S_t(1-\psi\tau_1) + ((p_2 - l)\gamma_2\tau_2 - \alpha)I_t(1-\psi\tau_2)) + Bz(F_t)(((p_4 - l)\gamma_1\tau_1 - \alpha)S_t(1-\psi\tau_1) + \\
&((p_4 - l)\gamma_2\tau_2 - \alpha)I_t(1-\psi\tau_2))) + \nu_2(1-B)(S_t(1-\psi\tau_1)(1-F_t)z(F_t)\tau_1 + \\
&I_t(1-\psi\tau_2)(1-F_t)z(F_t)\tau_2)\} +
\end{aligned}$$

$$\begin{aligned}
&m_1\{(1-B)(F_t\tau_1 + (1-F_t)z(F_t)\tau_1)S_t(1-\psi\tau_1) - ((1-B)((F_t\tau_1 + (1-F_t)z(F_t)\tau_1) * \\
&S_t(1-\psi\tau_1) + (F_t\tau_2 + (1-F_t)z(F_t)\tau_2)I_t(1-\psi\tau_2)) - ((1-B)(F_t + (1-F_t)z(F_t)) + Bz(F_t)) * \\
&(\tau_1 S_t(1-\psi\tau_1) + \tau_2 I_t(1-\psi\tau_2)))(w_1(APP_t)(1 - MC_t\tau_1)) - (K1 - ((S_t + I_t) - \\
&(1-B)((F_t(1 - MC_t\tau_1) + (1 - (F_t + MC_t(1-F_t)z(F_t)\tau_1)))S_t(1-\psi\tau_1) + \\
&(F_t(1 - MC_t\tau_2) + (1 - (F_t + MC_t(1-F_t)z(F_t)\tau_2)))I_t(1-\psi\tau_2)) - \rho B(S_t + I_t) - \\
&MC_t((1-B)(F_t + (1-F_t)z(F_t)) + Bz(F_t))(\tau_1 S_t(1-\psi\tau_1) + \tau_2 I_t(1-\psi\tau_2)) - \\
&\psi(\tau_1 S_t + \tau_2 I_t) + g_1(S_t) + g_2(I_t)))(w_1(APP_t)\tau_1) - ((1-B)(F_t + (1-F_t)z(F_t)) + \\
&Bz(F_t))S_t(1-\psi\tau_1)\tau_1\} +
\end{aligned}$$

$$
\begin{aligned}
&m_2\{(1-B)(F_t\tau_2+(1-F_t)z(F_t)\tau_2)I_t(1-\psi\tau_2)-((1-B)((F_t\tau_1+(1-F_t)z(F_t)\tau_1)*\\
&S_t(1-\psi\tau_1)+(F_t\tau_2+(1-F_t)z(F_t)\tau_2)I_t(1-\psi\tau_2))-((1-B)(F_t+(1-F_t)z(F_t))+Bz(F_t))\\
&*(\tau_1S_t(1-\psi\tau_1)+\tau_2I_t(1-\psi\tau_2)))(w_2(APP_t)(1-MC_t\tau_2))-(K1-((S_t+I_t)-\\
&(1-B)((F_t(1-MC_t\tau_1)+(1-(F_t+MC_t(1-F_t)z(F_t)\tau_1)))S_t(1-\psi\tau_1)+(F_t(1-MC_t\tau_2)\\
&+(1-(F_t+MC_t(1-F_t)z(F_t)\tau_2)))I_t(1-\psi\tau_2))-\rho B(S_t+I_t)-MC_t((1-B)(F_t+(1-F_t)*\\
&z(F_t))+Bz(F_t))(\tau_1S_t(1-\psi\tau_1)+\tau_2I_t(1-\psi\tau_2))-\psi(\tau_1S_t+\tau_2I_t)+g_1(S_t)+g_2(I_t)))*\\
&(w_2(APP_t)\tau_2)-((1-B)(F_t+(1-F_t)z(F_t))+Bz(F_t))I_t(1-\psi\tau_2)\tau_2\}-\omega_3+\omega_4=0
\end{aligned}
\tag{3.21}
$$

$$\omega_3 \geq 0, \qquad \omega_3(1-MC_t^*)=0, \tag{3.22}$$

$$\omega_4 \geq 0, \qquad \omega_4(MC_t^*-0)=0. \tag{3.23}$$

The impact on current revenue from movement control testing stems from several factors. Aside from the direct cost of testing, revenue is foregone from reactor cattle removed at pre-movement and in-contact Tb testing because these animals are not available for marketing as stores or to slaughter. Offsetting the opportunity cost of movement control Tb testing is the revenue received from reactor cattle detected and subsequently slaughtered. The reactor cattle removed at pre-movement and in-contact Tb testing increase purchase costs as additional cattle have to be purchased to replace them. The adverse impact on net revenue from purchasing additional animals is reduced to the extent that compensation from post-movement testing outweighs the costs of testing all purchased cattle. With respect to the future earnings potential of the herd, movement control Tb testing reduces the herd size because post-movement testing removes reactors from the group of cattle purchased but these animals are not replaced within the current period. The future earnings potential is also affected by changes to the susceptible and infected cattle populations as a result of purchase decisions.

Equations 3.21-3.23 disclose that movement control Tb testing will not be undertaken by the producer if the current and future marginal contributions to net revenue are negative ($MC_t^* = 0$, $\omega_3 = 0$, $\omega_4 \geq 0$). The producer will, however, undertake movement control Tb testing consistent with the NPMS if both current and future marginal contributions are positive ($MC_t^* = 1$, $\omega_3 = 0$, $\omega_4 \geq 0$). If neither of these situations apply then an interior solution is optimal. The net revenue maximising level of movement control Tb testing will therefore occur where the marginal benefit from reduced infection levels in the future equals the marginal adverse impact on current revenue.

With respect to possum harvest, Equations 3.24-3.26 provide the necessary conditions for maximisation of H_{cv}. If the difference between the current marginal harvest cost and the marginal benefit of reducing Tb transmission into the herd is negative then no harvest will be undertaken ($H_t^* = 0$, $\omega_5 = 0$, $\omega_6 \geq 0$). Conversely, the entire possum population will be harvested if the combined net marginal impact of harvest is positive ($H_t^* = P_t$, $\omega_5 = 0$, $\omega_6 \geq 0$). When boundary solutions are not optimal the producer maximises net revenue by harvesting possums to a level H_t^* where the marginal cost of harvesting equals the marginal benefits of reducing Tb transmission into the herd.

$$\frac{\partial H_{cv}}{\partial H_t} = \frac{\partial PH}{\partial H_t} - m_3 - \omega_5 + \omega_6 = 0 \tag{3.24}$$

$$\omega_5 \geq 0, \qquad \omega_5(P_t - H_t^*) = 0, \tag{3.25}$$

$$\omega_6 \geq 0, \qquad \omega_6(H_t^* - 0) = 0. \tag{3.26}$$

The conditions imposed by the costate equations of motion on the Hamiltonian system ensure that the marginal change in the shadow price of each state variable equals each state variable's marginal contribution to current and future profits (Chiang, 1992). Rearranging the costate equations allowed these relationships to be expressed in terms of the opportunity cost of a state variable at a particular time. Equations 3.27-3.29 describe mathematically the conditions associated with the optimal evolution of the three costate variables. The interpretation ascribed to each equation is that if the costate variable is on its optimal path, then the opportunity cost of the associated state variable should equal the change in the states contribution to current and future net revenue plus the depreciation or appreciation in its shadow price.

Equations 3.27 and 3.28 relate to the susceptible and infected cattle populations, respectively. Both cattle populations contribute to current and future earnings of the cattle enterprise. Contributions to current revenue come from store cattle sales, cattle slaughtered, and reactor cattle detected at Tb testing when compensation is paid. Although the average store cattle price received and reactor compensation are the same for both susceptible and infected cattle, slaughter revenue is higher for susceptible cattle because infected cattle are detected at slaughter. With respect to future earnings, because it was assumed that the herd size remains constant, changes to earnings arise from changes in the relative proportion of the herd in each population. Biological reproduction adds to each population at the same rate each period. The significant factors that influence the size of the susceptible and infected cattle populations are purchase decisions and the spread of infection into the herd from either the possum population or within the herd through infected cattle. The infection level in the herd affects the apparent infection level which in turn impacts on the average price received for store cattle.

$$\begin{aligned}
\delta m_1 = \frac{\partial H_{cv}}{\partial S_t} + \dot{m}_1 = \{&(p_3 - l)(1-B)(1-\psi\tau_1)(1-(F_t + MC_t(1-F_t)z(F_t)\tau_1)) + \\
&(p_4 - l)\rho B(1-\psi\tau_1) + r(D_t)F_t(1-B)(1-MC_t\tau_1)(1-\psi\tau_1) + \\
&(APP_t - MC_t(w_1(APP_t)\tau_1((p_1 - l)\gamma_1 - \alpha) + w_2(APP_t)\tau_2((p_1 - l)\gamma_2 - \alpha))((1-(1-B)(F_t(1-MC_t\tau_1) \\
&+ (1-(F_t + MC_t(1-F_t)z(F_t)\tau_1)))(1-\psi\tau_1) - \rho B - MC_t((1-B)(F_t + (1-F_t)z(F_t)) + \\
&Bz(F_t))\tau_1(1-\psi\tau_1) - \psi\tau_1 + \frac{\partial g_1}{\partial S_t})) + MC_t((1-B)(F_t + (1-F_t)z(F_t))((p_2 - l)\gamma_1\tau_1 - \alpha) + \\
&Bz(F_t)((p_4 - l)\gamma_1\tau_1 - \alpha)) + \psi(B((p_4 - l)\gamma_1\tau_1 - \alpha) + (1-B)((p_2 - l)\gamma_1\tau_1 - \alpha)) - \\
&(\nu_1 + \nu_2(1-B)(1-\psi\tau_1)(1-(F_t + MC_t(1-F_t)z(F_t)\tau_1)))\} + \\
&\{m_1(-\frac{\partial s_1}{\partial S_t} - \frac{\partial s_2}{\partial S_t} - (1-B)(F_t(1-MC_t\tau_1) + (1-(F_t + MC_t(1-F_t)z(F_t)\tau_1)))(1-\psi\tau_1) - \\
&\rho B - ((1-(1-B)(F_t(1-MC_t\tau_1) + (1-(F_t + MC_t(1-F_t)z(F_t)\tau_1)))(1-\psi\tau_1) - \rho B - \\
&MC_t((1-B)(F_t + (1-F_t)z(F_t)) + Bz(F_t))\tau_1(1-\psi\tau_1) - \psi\tau_1 + \frac{\partial g_1}{\partial S_t}))(w_1(APP_t) * \\
&(1-MC_t\tau_1)) + \frac{\partial g_1}{\partial S_t} - \psi\tau_1 - MC_t((1-B)(F_t + (1-F_t)z(F_t)) + Bz(F_t))\tau_1(1-\psi\tau_1))\} + \\
&\{m_2(\frac{\partial s_1}{\partial S_t} + \frac{\partial s_2}{\partial S_t} - ((1-(1-B)(F_t(1-MC_t\tau_1) + (1-(F_t + MC_t(1-F_t)z(F_t)\tau_1)))(1-\psi\tau_1) \\
&- \rho B - MC_t((1-B)(F_t + (1-F_t)z(F_t)) + Bz(F_t))\tau_1(1-\psi\tau_1) - \psi\tau_1 + \frac{\partial g_1}{\partial S_t})) * \\
&(w_2(APP_t)(1-MC_t\tau_2)))\} + \dot{m}_1
\end{aligned} \tag{3.27}$$

$$\begin{aligned}
\delta m_2 = \frac{\partial H_{cv}}{\partial I_t} + \dot{m}_2 = \{&(p_3 - l)(1-B)\mu(1-\psi\tau_2)(1-(F_t + MC_t(1-F_t)z(F_t)\tau_2)) + \\
&(p_4 - l)\rho\mu B(1-\psi\tau_2) + r(D_t)F_t(1-B)(1-MC_t\tau_2)(1-\psi\tau_2) + \\
&(APP_t - MC_t(w_1(APP_t)\tau_1((p_1 - l)\gamma_1 - \alpha) + w_2(APP_t)\tau_2((p_1 - l)\gamma_2 - \alpha)) * \\
&((1-(1-B)(F_t(1-MC_t\tau_2) + (1-(F_t + MC_t(1-F_t)z(F_t)\tau_2)))(1-\psi\tau_2) - \rho B - \\
&MC_t((1-B)(F_t + (1-F_t)z(F_t)) + Bz(F_t))\tau_2(1-\psi\tau_2) - \psi\tau_2 + \frac{\partial g_2}{\partial I_t})) + \\
&MC_t((1-B)(F_t + (1-F_t)z(F_t))((p_2 - l)\gamma_2\tau_2 - \alpha) + Bz(F_t)((p_4 - l)\gamma_2\tau_2 - \alpha)) + \\
&\psi(B((p_4 - l)\gamma_2\tau_2 - \alpha) + (1-B)((p_2 - l)\gamma_2\tau_2 - \alpha)) - (\nu_1 + \nu_2(1-B) * \\
&(1-\psi\tau_2)(1-(F_t + MC_t(1-F_t)z(F_t)\tau_2)))\} + \\
&\{m_1(-\frac{\partial s_1}{\partial I_t} - ((1-(1-B)(F_t(1-MC_t\tau_2) + (1-(F_t + MC_t(1-F_t)z(F_t)\tau_2))) * \\
&(1-\psi\tau_2) - \rho B - MC_t((1-B)(F_t + (1-F_t)z(F_t)) + Bz(F_t))\tau_2(1-\psi\tau_2) - \psi\tau_2 + \frac{\partial g_2}{\partial I_t})) * \\
&(w_1(APP_t)(1-MC_t\tau_1))\} +
\end{aligned}$$

$$\begin{aligned}&\Big\{m_2(\frac{\partial s_1}{\partial I_t} - (1-B)(F_t(1-MC_t\tau_2) + (1-(F_t + MC_t(1-F_t)z(F_t)\tau_2)))(1-\psi\tau_2) - \\ &\rho B - ((1-(1-B)(F_t(1-MC_t\tau_2) + (1-(F_t + MC_t(1-F_t)z(F_t)\tau_2)))(1-\psi\tau_2) - \\ &\rho B - MC_t((1-B)(F_t + (1-F_t)z(F_t)) + Bz(F_t))\tau_2(1-\psi\tau_2) - \psi\tau_2 + \frac{\partial g_2}{\partial I_t})) * \\ &(\dot{w}_2(APP_t)(1-MC_t\tau_2)) + \frac{\partial g_2}{\partial I_t} - \psi\tau_2 - MC_t((1-B)(F_t + (1-F_t)z(F_t)) + Bz(F_t))\tau_2 * \\ &(1-\psi\tau_2))\Big\} + \dot{m}_1\end{aligned} \tag{3.28}$$

Changes in the possum population impact on the cost of harvesting possums and therefore affect current net revenue (Equation 3.29). The marginal change in possum harvest costs is indeterminate until the precise formulation of the harvest function is known. Possums spread infection into the herd and therefore the contribution to future earnings brought about through changes in possum numbers will be negative when m_1 is positive and m_2 is negative. The possum population's marginal contribution to future earnings is expected to be negative, given the expected sign associated with its shadow price.

$$\delta m_3 = \frac{\partial H_{cv}}{\partial P_t} + \dot{m}_3 = \frac{\partial PH}{\partial P_t} - m_1\frac{\partial s_2}{\partial P_t} + m_2\frac{\partial s_2}{\partial P_t} + m_3\frac{\partial g_2}{\partial P_t} + \dot{m}_3 \tag{3.29}$$

The control problem has a fixed endpoint *T* but the terminal values of the state variables are not specified. The transversality conditions appropriate to this formulation are given in Equation 3.30. These conditions state that the shadow price of each state variable should follow a path that ensures it is zero at the termination of the problem.

$$m_i(T)e^{-\rho T} = 0 \qquad\qquad i = 1, 2, 3. \tag{3.30}$$

3.5 Hypothesised Relationships

The specification of the model and the interpretations of the first order necessary conditions provide insight into how the hypothetical producer may respond to cattle marketing and purchase decisions. Whether cattle are marketed to sale as stores or to slaughter depends on the market prices associated with each alternative, the apparent and actual levels of Tb infection in the herd which determine the average price received for cattle under each option, the additional cost of carrying cattle through to slaughter condition, and the reduction in revenue arising from cattle reacting as false and true positives at pre-movement and in-contact Tb testing and the Tb testing costs. The difference between the average net revenue obtained from store cattle and slaughter sales is expected to favour the producer marketing cattle as stores at low infection levels. As illustrated in Figure 3.1, when herd infection levels increase and apparent infection increases the impact of the discount on the store cattle price will act as a disincentive to selling cattle as stores and the producer will prefer to incur the additional cost of carrying cattle through to slaughter condition.

With respect to purchasing replacement cattle, it is anticipated that the risk neutral producer has an incentive to pay the minimum price for cattle if movement control testing is undertaken. The minimum price maximises the difference between current purchase cost and potential net revenue. Although the minimum price implies cattle are from high apparent infection herds, pre-movement Tb testing by the seller and post-movement Tb testing by the purchaser reduces the actual number of infected cattle entering the herd. As a consequence the negative impact of infected cattle on future earnings is expected to be very low.

Chapter 4: An Empirical Model of Bovine Tuberculosis Control

4.1 Introduction

In the following sections the theoretical model described in the Chapter 3 is specified as a discrete time optimal control model to undertake the empirical analysis of movement control policy in New Zealand. This chapter provides an empirical context for the problem of store cattle production in a Tb vector risk area. The generalised functional relationships outlined in the theoretical model are specified and the selection of parameter values detailed. The chapter concludes with the presentation of preliminary results for the empirical model.

4.2 The Empirical Problem

Bovine Tb has been a long term problem for many farmers in the Clarence/Waiau Tb vector risk area of North Canterbury. The area contains several different cattle production systems which are common elsewhere in New Zealand. These systems include hill country breeding and all store finishing, hill country breeding and limited finishing, hill country and downlands breeding and finishing, and trading.

Relevant parameter values for a representative store cattle production system in the Clarence/Waiau were obtained from secondary data relating to beef cattle production in North Canterbury. The New Zealand Meat and Wool Board Economic Service (NZMWBES) produces average yearly production data for various classes of New Zealand farms from their annual farm surveys. The NZMWBES data for "South Island Hill Country" farms was most representative of cattle production in the study area (NZMWBES, 1992-1996). Supplementary data was obtained from Lincoln University's Financial Budget Manual (FBM) which collates commodity price and input cost information relating to most types of primary production in New Zealand (Burtt and Fleming, 1992 & 1994; Fleming and Burtt, 1993; Oliver and Burtt, 1995; Burtt, 1996). Variations in production data due to commodity prices and climatic conditions were smoothed out using five year averages from 1990/91 to 1994/95. Where necessary production characteristics not available from the NZMWBES and FBM data were obtained from Dunham's (1995) study of bovine tuberculosis control on six types of cattle farm in North Canterbury which relied on farmer interviews. All financial data was expressed in 1995 dollars using either Statistics New Zealand producers price index for agricultural output or the consumers price index. Averages obtained from the beef production data revealed that over the period from 1990/91 to 1994/95 a representative South Island Hill Country farm had an effective area of 1567 hectares on which 237 cattle were run with primarily sheep and other livestock such as deer and goats at a stocking rate of 3.6 stock units per hectare.

4.3 The Empirical Model

The continuous time theoretical model developed in Chapter 3 (Equations 3.1-3.14) was formulated as a discrete time optimal control model (Equations 4.1-4.7). The time step in the discrete time model represents one year of production. The cattle producer chooses the appropriate levels for store cattle sales (F_t), the price paid for purchases (APP_t), the level of movement control testing if regulations are not imposed (MC_t), and numbers of possums harvested (H_t) in order to maximise the net present value of production over the period (Equation 4.1). Values and definitions for parameters and variables are shown in Table 4.1. The model is run over T periods to obtain average/steady state solution values.

$$
\begin{aligned}
&\underset{M_t, F_t, APP_t, MC_t, H_t}{Maximise\pi} = \sum_{t=0}^{T} \frac{1}{(1-\delta)^t} \Big\{ (p_3 - l)(1-B)(S_t(1-\psi\tau_1)(1-(F_t + MC_t(1-F_t)(1-e^{-\sigma F_t})\tau_1)) \\
&+ \mu I_t(1-\psi\tau_2)(1-(F_t + MC_t(1-F_t)(1-e^{-\sigma F_t})\tau_2))) + (p_4 - l)\rho B(S_t(1-\psi\tau_1) + \\
&\mu I_t(1-\psi\tau_2)) + \Bigg(\left(\frac{p_2 - p_2(1-\omega)}{-i} \right) \Bigg(\bigg(\left(\frac{\psi(\tau_1 S_t + \tau_2 I_t)}{(S_t + I_t)} \right) - \tau_1 \bigg) \Big/ (1-(\tau_1 + (1-\tau_2))) \Bigg) + p_2 \Bigg) * \\
&F_t(1-B)((1-MC_t\tau_1)S_t(1-\psi\tau_1) + (1-MC_t\tau_2)I_t(1-\psi\tau_2)) - \\
&\Bigg(APP_t - MC \Bigg(\bigg(1 - \left((APP_t - p_1) \Big/ \frac{(p_1 - p_1(1-\omega))}{-i} \right) (1-\eta\tau_2) \bigg) ((p_1 - l)\gamma_1\tau_1 - \alpha) + \\
&\bigg((APP_t - p_1) \Big/ \frac{(p_1 - p_1(1-\omega))}{-i} \bigg) (1-\eta\tau_2)((p_1 - l)\gamma_2\tau_2 - \alpha) \Bigg) \Bigg) (K1 - ((S_t + I_t) - \\
&(1-B)((F_t(1-MC_t\tau_1) + (1-(F_t + MC_t(1-F_t)(1-e^{-\sigma F_t})\tau_1)))S_t(1-\psi\tau_1) + \\
&(F_t(1-MC_t\tau_2) + (1-(F_t + MC_t(1-F_t)(1-e^{-\sigma F_t})\tau_2)))I_t(1-\psi\tau_2)) - \rho B(S_t + I_t) - \\
&MC_t((1-B)(F_t + (1-F_t)(1-e^{-\sigma F_t})) + B(1-e^{-\sigma F_t}))(\tau_1 S_t(1-\psi\tau_1) + \\
&MC_t((1-B)(F_t + (1-F_t)(1-e^{-\sigma F_t})) + B(1-e^{-\sigma F_t}))(\tau_1 S_t(1-\psi\tau_1) + \tau_2 I_t(1-\psi\tau_2)) - \\
&\psi(\tau_1 S_t + \tau_2 I_t) + g_1(S_t) + g_2(I_t))) + MC_t((1-B)(F_t + (1-F_t)(1-e^{-\sigma F_t})) * \\
&(((p_2 - l)\gamma_1\tau_1 - \alpha)S_t(1-\psi\tau_1) + ((p_2 - l)\gamma_2\tau_2 - \alpha)I_t(1-\psi\tau_2)) + B(1-e^{-\sigma F_t}) * \\
&(((p_4 - l)\gamma_1\tau_1 - \alpha)S_t(1-\psi\tau_1) + ((p_4 - l)\gamma_2\tau_2 - \alpha)I_t(1-\psi\tau_2))) + \\
&\psi(B(S_t((p_4 - l)\gamma_1\tau_1 - \alpha) + I_t((p_4 - l)\gamma_2\tau_2 - \alpha)) + (1-B)(S_t((p_2 - l)\gamma_1\tau_1 - \alpha) + \\
&I_t((p_2 - l)\gamma_2\tau_2 - \alpha))) - (\nu_1(S_t + I_t) + \nu_2(1-B)(S_t(1-\psi\tau_1)(1-(F_t + MC_t(1-F_t) * \\
&(1-e^{-\sigma F_t})\tau_1)) + I_t(1-\psi\tau_2)(1-(F_t + MC_t(1-F_t) * (1-e^{-\sigma F_t})\tau_2)))) - \left(\frac{h}{z} \right) \left(\frac{H_t}{P_t} \right)^2 \Bigg\}
\end{aligned}
\tag{4.1}
$$

Subject to:

$$
\begin{aligned}
S_{t+1} = {} & S_t - \beta_1 S_t I_t - \beta_2 S_t P_t - (1-B)(F_t(1-MC_t\tau_1) + (1-(F_t + MC_t(1-F_t)(1-e^{-\sigma F_t})\tau_1))) \\
& * S_t(1-\psi\tau_1) - \rho B S_t + (K1 - ((S_t + I_t) - (1-B)((F_t(1-MC_t\tau_1) + \\
& (1-(F_t + MC_t(1-F_t)(1-e^{-\sigma F_t})\tau_1)))S_t(1-\psi\tau_1) + (F_t(1-MC_t\tau_1) + \\
& (1-(F_t + MC_t(1-F_t)(1-e^{-\sigma F_t})\tau_2)))I_t(1-\psi\tau_2)) - \rho B(S_t + I_t) - \\
& MC_t((1-B)(F_t + (1-F_t)(1-e^{-\sigma F_t})) + B(1-e^{-\sigma F_t}))(\tau_1 S_t(1-\psi\tau_1) + \tau_2 I_t(1-\psi\tau_2)) - \\
& \psi(\tau_1 S_t + \tau_2 I_t) + \phi B(S_t(1-\psi\tau_1) + I_t(1-\psi\tau_2)))) * \\
& \Bigg(1 - \bigg((APP_t - p_1) \Big/ \frac{(p_1 - p_1(1-\omega))}{-i} \bigg) (1-\eta\tau_2) \Bigg) (1-MC_t\tau_1)) + \phi B S_t(1-\psi\tau_1) - \psi S_t\tau_1 \\
& - MC_t((1-B)(F_t + (1-F_t)(1-e^{-\sigma F_t})) + B(1-e^{-\sigma F_t}))S_t(1-\psi\tau_1)\tau_1
\end{aligned}
\tag{4.2}
$$

$$\begin{aligned}
I_{t+1} = {} & I_t + \beta_1 S_t I_t + \beta_2 S_t P_t - (1-B)(F_t(1-MC_t\tau_2) + (1-(F_t + MC_t(1-F_t)(1-e^{-\sigma F_t})\tau_2))) \\
& * I_t(1-\psi\tau_2) - \rho B I_t + (K1 - ((S_t + I_t) - (1-B)((F_t(1-MC_t\tau_1) + \\
& (1-(F_t + MC_t(1-F_t)(1-e^{-\sigma F_t})\tau_1)))S_t(1-\psi\tau_1) + (F_t(1-MC_t\tau_1) + \\
& (1-(F_t + MC_t(1-F_t)(1-e^{-\sigma F_t})\tau_2)))I_t(1-\psi\tau_2)) - \rho B(S_t + I_t) - \\
& MC_t((1-B)(F_t + (1-F_t)(1-e^{-\sigma F_t})) + B(1-e^{-\sigma F_t}))(\tau_1 S_t(1-\psi\tau_1) + \tau_2 I_t(1-\psi\tau_2)) - \\
& \psi(\tau_1 S_t + \tau_2 I_t) + \phi B(S_t(1-\psi\tau_1) + I_t(1-\psi\tau_2)))) * \\
& \left((APP_t - p_1)\Big/\frac{(p_1 - p_1(1-\omega))}{-i}\right)(1-\eta\tau_2)(1-MC_t\tau_2) + \phi B I_t(1-\psi\tau_2) - \psi I_t\tau_2 - \\
& MC_t((1-B)(F_t + (1-F_t)(1-e^{-\sigma F_t})) + B(1-e^{-\sigma F_t}))I_t(1-\psi\tau_2)\tau_2
\end{aligned} \tag{4.3}$$

$$P_{t+1} = P_t + aP_t\left(1 - \frac{P_t}{K2}\right) - H_t \tag{4.4}$$

$$H_t \leq .95 P_t \tag{4.5}$$

$$S_t,\ I_t, \text{ and } P_t \geq 0 \tag{4.6}$$

$$0 \leq F_t \leq 1,\ 0 \leq APP_t \leq p_3,\ 0 \leq MC_t \leq 1,\ 0 \leq H_t < .95 * P_t. \tag{4.7}$$

Table 4.1 Variable Definitions and Parameter Values

Variable/ Parameter	Definition	Value
S_t	Density of susceptible cattle (state variable)	hd/ha
I_t	Density of infected cattle (state variable)	hd/ha
P_t	Density of possums (state variable)	hd/ha
F_t	Cattle sold to other producers (control variable)	%
APP_t	Average price paid for cattle purchased (control variable)	$/hd
MC_t	Movement control testing frequency	1
H_t	Possums harvested (control variable)	hd/ha
δ	Annual discount rate (%)	8.7
p_1	Average price for clear herd weaners purchased ($/hd)	349
p_2	Average price for clear herd R2 store cattle ($/hd)	482
p_3	Average price for non-infected R2 cattle slaughtered ($/hd)	516
p_4	Average price for non-infected cull cows ($/hd)	327
l	Slaughter levy ($/hd)	8.71
μ	Average proportion of infected cattle salvaged (%)	35
ρ	Proportion of breeding herd culled (%)	16
ψ	Annual whole herd testing frequency	1
η	Pre-movement test parameter for cattle purchased	1
σ	"In-contact" testing parameter	250
τ_1	False positive reactor cattle (1-test specificity) (%)	1
τ_2	True positive reactor cattle (test sensitivity) (%)	75
α	Cost of testing cattle ($/hd)	3.53
γ_1	Compensation for non-lesioned cattle (%)	65
γ_2	Compensation for lesioned cattle (%)	65
β_1	Cattle to cattle Tb transmission parameter	3
β_2	Possum to cattle Tb transmission parameter	.003
ω	Maximum store cattle price discount (%)	10
i	Maximum apparent true infection level for store cattle (%)	4.99

Table 4.1(Continued)

$K1$	Profit maximising stocking rate (hd/ha)	0.15134
ϕ	Percentage of breeding herd that are productive (%)	67
v_1	Variable cost of cattle ($/hd)	13.48
v_2	Grazing costs of R2 cattle sent to slaughter ($/hd)	52.00
B	Proportion of the herd that are breeding cattle (%)	65
$K2$	Carrying capacity of possum population (hd/ha)	3
h	Cost of time hunting possums ($/hunt)	94.26
a	Intrinsic rate of growth for possum population (%)	30
z	Possum harvest parameter	6.449

4.3.1 Objective Function

4.3.1.1 Annual Discount Rate

Cash flows were discounted at an annual real rate of 8.7%. The rate was derived from the average base rate and margin charged for secured working capital for a farming business by the major farm lenders (Burtt and Fleming, 1992 & 1994; Fleming and Burtt, 1993; Oliver and Burtt, 1995; Burtt, 1996).

4.3.1.2 Cattle Prices

Average cattle prices were obtained for mature cows culled, marketing cattle sold as stores, marketing cattle sold to slaughter, and weaners purchased. The price for cull cows (p_4) was set at the slaughter price for M grade cows which was $349 (Burtt and Fleming, 1992 & 1994; Fleming and Burtt, 1993; Oliver and Burtt, 1995; Burtt, 1996). Reproductive and breeding herd replacement assumptions, which are discussed below, implied a sex composition for the marketing herd of approximately one third heifers and two thirds steers. It was assumed that all marketing cattle are sold each period as rising two year olds and that purchase decisions ensure the sex composition remains constant over time. These assumptions permitted price data for one to one and a half year old steers and heifers sold in Marlborough and Canterbury to be weighted and combined into an average store cattle price (p_2) of $482 (Burtt and Fleming, 1992 & 1994; Fleming and Burtt, 1993; Oliver and Burtt, 1995; Burtt, 1996). The price of clear herd weaner cattle purchased (p_2) was similarly derived producing a value of $349.

The average prices for store cattle purchased and sold are either chosen by the producer (APP_t) or determined by the market discount regime as introduced in Chapter 3, respectively. Producers currently obtain information relating to a herd's Tb status and history from MAF Quality Management. The model assumes producers use the whole herd testing information to determine the apparent Tb prevalence (D_t) for herds from which they purchase cattle. Apparent Tb prevalence is defined as the percentage of cattle identified as being infected at whole herd testing (Equation 4.8).

$$D_t = \frac{\psi(\tau_1 S_t + \tau_2 I_t)}{S_t + I_t} \tag{4.8}$$

Problems arise in developing a relationship between apparent Tb prevalence as formulated in Equation 4.8 and risk of infection. Due to the lack of sensitivity and specificity of the Tb test, apparent Tb prevalence does not reflect the actual level of disease in the herd. At the levels of Tb prevalence for which cattle are permitted to be sold as stores whole herd testing information will overstate the herd infection level due to the lack of specificity of the test. Adopting a measure of apparent prevalence which takes into account information obtained from reactor cattle slaughtered is also problematic. All cattle reacting at a Tb test, that are not presented for an ancillary Tb test, must be subsequently slaughtered and subjected to further inspection at slaughter to assist in clarifying their disease status. Given the assumption that the Tb infection status of cattle is identifiable at slaughter, using whole herd testing information together with diagnostic results from reactors subsequently slaughtered will understate herd infection levels due to the lack of sensitivity of the test. The epidemiology literature does, however, offer a solution to finding an appropriate measure of disease risk based on apparent prevalence. When the sensitivity and specificity of the test are known, apparent prevalence may be converted into apparent true prevalence (ATP_t), using Equation 4.9, which in turn will provide an estimate of the actual prevalence of disease in the herd of origin (Martin *et al.*, 1987). To overcome the problems mentioned above apparent true prevalence was used in the model as a proxy for disease risk. This approach assumes that producers use all available information to estimate the herd infection level. Direct comparisons are therefore permitted between a producer marketing cattle to sale as stores and slaughter without assuming an information bias associated with either marketing option.

$$\mathit{Actual\ Level\ Of\ Disease} \approx ATP_t = \frac{D_t - \tau_1}{(1-(\tau_1+(1-\tau_2)))} \tag{4.9}$$

The relationship between the average price for store cattle and the apparent true Tb prevalence in the herd was assumed to be a linear function (Equation 4.10). The price of store cattle is discounted according to the cattle herd's apparent true Tb prevalence (Equation 4.10). Herds with an apparent true Tb prevalence of zero would attract a market price equal to the maximum average price available for cattle of their class (p_2).

$$r_t = p_2 + \xi ATP_t \tag{4.10}$$

The price-infection parameter (ξ) was obtained by manipulating Equation 4.10 and substituting in the minimum average price for r_t and maximum apparent true Tb prevalence (i) for ATP_t to give,

$$\xi = \frac{p_2 - r_{Min}}{-i}. \tag{4.11}$$

The NPMS makes it increasingly difficult for cattle from herds with a high Tb incidence to move other than to slaughter. High risk herds are initially classified as those with an annual Tb incidence of 5% or greater. It was assumed that cattle from a herd with an apparent infection level of greater than i would only be permitted to be marketed to slaughter. As a consequence, the highest apparent true Tb prevalence associated with cattle sent to sale as stores (i) was set at 4.99%. At this level of herd infection the sale price (r_{Min}) would equal the maximum discounted average price available for the relevant class of cattle from infected herds. To reflect the price-infection risk response in the store cattle market the model includes an equation for the average price of cattle sold as stores (Equation 4.12) based on Equation 4.10.

$$r_t(D_t) = \left(\frac{p_2 - p_2(1-\omega)}{-i}\right)\left(\frac{\left(\frac{\psi(\tau_1 S_t + \tau_2 I_t)}{S_t + I_t}\right) - \tau_1}{(1-(\tau_1 + (1-\tau_2)))}\right) + p_2 \tag{4.12}$$

The amount by which store cattle from movement controlled herds in the study area have been discounted at sale range between zero and \$100 per head (Dunham, 1995; Nicol, personal communication). Information on maximum discounts in recent years suggest a base run level for ω of 10% of the clear herd sale price or approximately $47.

Although the cattle production system does not have a comparative advantage in fattening cattle it was assumed that cattle can be sold to slaughter. To avoid many additional assumptions, and to overcome difficulties in obtaining a consistent data set for the price of low weight cattle slaughtered, the price of prime cattle sold at the regional sale yards was used as a proxy for slaughter price. Combining information on the lowest price per kilogram for prime cattle sold at Addington with appropriate cattle live weight profiles and dressing out ratios resulted in an average price per head for cattle slaughtered (p_3) of $516 (New Zealand Farmer, 1995-1996; Beef New Zealand, 1997).

4.3.1.3 Slaughter Levy

A levy of $8.71 is charged on all adult cattle slaughtered to recover the beef cattle sector's share of Tb disease control costs. The slaughter levy (l) was set at this level.

4.3.1.4 Salvage Value

The carcass of an infected cattle beast sold to slaughter may either be entirely condemned, for which the producer is paid nothing, or partially condemned and the producer receives payment for the portion of the carcass graded as manufacturing beef. In previous studies, the average value to the producer of an infected carcass has ranged from 35% (Scott and Forbes, 1988) to 37.5% of market value (Dunham, 1995). Given that Scott and Forbes used survey data, a salvage value of 35% was selected.

4.3.1.5 Variable Costs

Variable cost data was obtained from the Financial Budget Manual. Gross margin analysis for the Canterbury area indicated a direct expenditure of \$2.73 per stock unit for a cattle breeding system that carried marketing stock through to rising two year olds (Burtt and Fleming, 1992 & 1994; Fleming and Burtt, 1993; Oliver and Burtt, 1995; Burtt, 1996). Applying stock unit equivalents used in the gross margin analysis to the hypothetical production system resulted in an average cattle beast being approximately 4.9 stock units. Because the herd size and proportions of different cattle classes were assumed to be constant in the model the variable cost of cattle (v_1) was set at \$13.48.

The model includes an additional component to variable costs to reflect the cost of fattening marketing cattle to a condition required for slaughter (v_2). Grazing charges were assumed to represent the opportunity cost of fattening cattle. The cost per week for grazing steers in Canterbury was calculated at \$3.25 (Burtt and Fleming, 1992 & 1994; Fleming and Burtt, 1993; Oliver and Burtt, 1995; Burtt, 1996). The grazing cost per week was multiplied over 16 weeks, the assumed additional fattening period, to give a total grazing cost for marketable cattle slaughtered of \$52.00 per head.

4.3.1.6 Tb Testing Costs and Compensation

Two types of Tb testing are distinguished in the model; whole herd testing and movement control testing. The Tb testing programme for cattle from infected herds requires the interval between whole herd tests to be greater than two months but not exceed twelve months. The model assumes a whole herd test interval of twelve months and accordingly ψ is set at 1. With respect to movement control Tb testing, the base-run reflects a policy environment where testing is mandatory and therefore the control variable MC_t and the pre-movement test parameter for cattle purchased (η) were initially set at 1. Consequently, when MC_t and η are set at 1 all eligible cattle in the herd are subjected to movement control Tb testing events and all cattle purchased are treated as having undergone pre-movement Tb testing prior to being sold.

The direct costs of Tb testing are currently funded by the cattle slaughter levy. There is, however, the opportunity cost of time involved in moving cattle to and from the yards for an injection of tuberculin and then returning at a later date for the injection site to be interpreted. A survey of representative cattle production systems in North Canterbury suggested a Tb testing cost of $3.53 per animal for a farm of approximately 1500 hectares when the opportunity cost of time is valued at $10 per hour (Dunham, 1995). The cost of Tb testing (α) was therefore set at $3.53.

Compensation is paid for reactor cattle at 65% of the fair market value for all test positive animals slaughtered. The rate at which susceptible and infected cattle react to the tuberculin test (τ_1 and τ_2) is determined by the test's specificity and sensitivity, respectively. Recent field estimates of the sensitivity of a single intra-dermal caudal fold tuberculin test ranged from 75% to 85% while the test's specificity was estimated to be greater than 99.6% (Pharo and Livingstone, 1997).[3] Animal health specialists familiar with the study region suggest, however, a more conservative range for test sensitivity of between 70% and 80% and specificity of 95% to 99% (Crews, personal communication). Based on these estimates, the values for true and false positive reactor cattle (τ_1 and τ_2) were set at 75% and 1%, respectively.

---

[3] Earlier estimates from field trials suggested that the single intra-dermal caudal fold tuberculin test had a sensitivity of 66% and a specificity of 98% (Ryan, de Lisle and Wood, 1991). A more recent study into the within herd spread of Tb by Kean (1993) adopted a higher value for test specificity of 99.7% as suggested by Livingstone and Davidson (1993).

4.3.1.7 Possum Control Cost

Tb vector risk areas may be comprised of several vector control zones. The possible zones are vector buffer zones, endemic zones, vector control zones, and vector eradication zones. The application and form of coordinated vector control operations varies according to the zone. Notwithstanding the possibility of coordinated vector control, the NPMS places responsibility for on farm vector control primarily with the cattle producer. The control of on farm possum populations using shooting, poisoning and trapping is a common activity amongst cattle producers in North Canterbury (Dunham, 1995).

The objective function includes a cost function for possum harvest, Equation 4.13, which was specified and estimated in an earlier study by Bicknell (1995). The specification was based on a general harvest function and parameter estimates used data on possums killed, harvest effort and initial possum density relating to ground control activities in New Zealand. The harvest function describes an inverse relationship between the density of possums and the cost of harvest. An additional constraint has been added to the model (Equation 4.5) to prevent the entire possum population being harvested in a single period. This constraint is not considered unduly restrictive as eradicating the possum population would be prohibitively expensive.

$$PH_t = \frac{h}{6.449}\left(\frac{H_t}{P_t}\right)^2 \qquad (4.13)$$

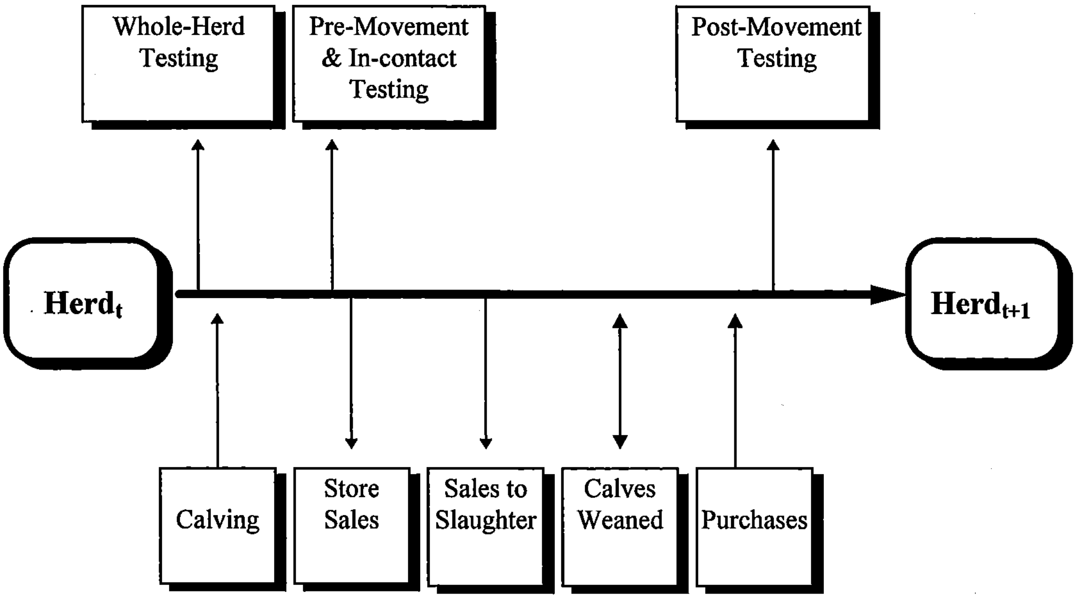
An estimate of the average cost of time hunting possums (h) was obtained from Dunham's (1995) study. Results from farmer interviews showed that for a 1500 hectare hill country farm total annual labour and material costs for Tb vector control were \$9,895 and \$2,301, respectively. Using hourly labour costs of \$10 for farm labour and

$15 for contract labour the average hourly labour cost for vector control was $12.75. Averaging annual material costs over the number of hours spent on vector control produced a material cost per hour of $2.96. Assuming an average control session of 6 hours duration *h* was set at $94.26.

4.3.2 Equations of Motion

A year of cattle production is assumed to commence at the beginning of July and run through to the end of June. The periodic events leading to changes in the herd are described mathematically by the equations of motion and illustrated in Figure 4.1. Not all the events portrayed in Figure 4.1 are relevant to both breeding and marketing components of the herd. For instance "calves weaned" entering the herd relates solely to marketing cattle while "calves weaned" leaving the herd relates to the breeding group.

Figure 4.1 Sequencing of Production and Tb Testing Events



4.3.2.1 Herd Composition and Natural Growth

Cattle are assumed to be managed in a single herd in which the breeding and marketing components are distinguished as fixed proportions. Decomposition of similar representative cattle systems used in gross margin analysis indicated that 65% of cattle were in the breeding component and 35% were in the marketable component (Burtt and Fleming, 1992 & 1994; Fleming and Burtt, 1993; Oliver and Burtt, 1995; Burtt, 1996). The value of B was therefore set at 65%.

The natural reproductive growth of breeding cattle depends on the percentage of the "breeding cattle" which are productive and their corresponding calving rate (Equation 4.14). Survey data indicated breeding herd replacement rates of approximately 16% and death rates due to natural mortality of 3% for adult cattle (NZMWBES, 1992-1996). On properties in North Canterbury it is not uncommon for breeding herd replacement heifers to be mated in their second year and calve in their third year (Dunham, 1995). A percentage for the breeding herd which are potentially productive of 81% was obtained by deducting from the breeding component the 19% replaced in the previous period. The percentage of the breeding cattle which are actually productive (ϕ) was calculated as 67% using a calving percentage of 83% (NZMWBES, 1992-1996). It was further assumed that 50% of calves would be heifers.

$$g_1 = \phi B(S_t + I_t) \tag{4.14}$$

4.3.2.2 Tb Transmission

The flux terms $\beta_1 S_t I_t$ and $\beta_2 S_t P_t$ are used in the model to capture the transmission of Tb from infectious cattle and infectious possums to susceptible cattle within the herd, respectively. Following Bicknell (1995) the study used a parameter for cattle to cattle transmission (β_1) of 3 and a possum to cattle transmission parameter (β_2) of 0.003.[4]

4.3.2.3 Cattle Purchases

Survey data indicated that the average stocking rate for cattle on a South Island hill country farm was 0.15134 head per hectare (NZMWBES, 1992-1996). It was assumed that this stocking rate represented the profit maximising level for this class of farm. To avoid the need for another control variable in the model the producer was assumed to purchase each period the number of cattle required to maintain the herd at its profit maximising stocking rate (K1). This assumption also ensures that the breeding and marketable proportions of the herd remain constant over time.

As identified previously, cattle from herds classified as "infected" may be sold to producers with "infected" herds in vector risk areas providing apparent infection is less than 5%. The relationship between herd infection levels and cattle price posited in Chapter 3 and in Section 4.3.1.2 is used in the mathematical representations of the proportions of cattle purchased that are susceptible (Equation 4.15) and infected (Equation 4.16).

$$w_1(APP_t) = \left(1 - \left(\left(APP_t - p_1\right) \Big/ \frac{(p_1 - p_1(1-\omega))}{-i}\right)(1 - \eta\tau_2)\right) \tag{4.15}$$

$$w_2(APP_t) = \left(\left(APP_t - p_1\right) \Big/ \frac{(p_1 - p_1(1-\omega))}{-i}\right)(1 - \eta\tau_2) \tag{4.16}$$

Assuming the same relationships between maximum and minimum store cattle prices and apparent true herd infection levels for sales and purchases of cattle, the

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[4] In Bicknell's (1995) study β_1 was based on modelling results from Kean (1993) and β_2 was calibrated to match observed prevalence levels given a lack of empirical research which would support a more precise measure.

equations for susceptible and infected cattle purchased were derived from Equations 4.10 and 4.11. The market price paid for weaner cattle (APP_t) is substituted for the store cattle price received (r_t) and the price of clear herd store weaners (p_1) is substituted for the price of clear herd rising two year olds (p_2) (Equation 4.17). Rearrangement of Equation 4.17 permits the apparent true prevalence in the herd from which cattle are purchased to be obtained (Equation 4.18) using the relationship expressed in Equation 4.19. The term $p_1(1-\omega)$ is the fully discounted market price of weaner cattle and replaces r_{Min} in Equation 4.11.

$$APP_t = p_1 + \xi ATP_t \tag{4.17}$$

$$ATP_t = \frac{APP_t - p_1}{\xi} \tag{4.18}$$

where,

$$\xi = \frac{p_1 - p_1(1-\omega)}{-i}. \tag{4.19}$$

The factor $1-\eta\tau_2$ in Equations 4.15 and 4.16 acknowledges that if cattle purchased have been subjected to a pre-movement test then the proportion of diseased animals, as indicated by the apparent true prevalence, will be reduced by the percentage of true positive reactors.

It was assumed that apparent true infection corresponds to actual infection levels for cattle purchased. Therefore while the actual true prevalence adjusted for pre-movement testing gives the proportion of infected cattle purchased the remaining proportion relates to susceptible cattle entering the herd. Modeling cattle purchases in this manner provided a direct relationship between the purchase price chosen by the producer and the proportions of infected and susceptible cattle entering the herd. The producer's decision to purchase discounted cattle was therefore presented as the decision to "buy-in" infection.

4.3.2.4 In-Contact Testing

In-contact testing was incorporated into the model using Equation 4.20 which describes the relationship between the percentage of the herd presented for in-contact testing and the percentage of marketable cattle selected for sale as stores. It was assumed that a positive relationship existed between these two mobs of cattle. Equation 4.20 provides a general specification of the relationship between store sales and cattle in-contact tested while allowing testing to switch off when there are no stores sold. If no cattle are marketed ($F_t = 0$) then $z = 0$ which implies that no in-contact Tb testing is undertaken. The implication for herd Tb prevalence arising from producers separating cattle into smaller groups is explored by adjusting the value of the in-contact test parameter (σ). As σ increases from zero the percentage of the herd not being sold as stores that are in-contact tested increases. For large values of σ the percentage of the herd tested approaches 100%. An in-contact test parameter of 250 was selected for the base-run to ensure that the simplest scenario of all cattle in one herd.

$$z = (1 - e^{-\sigma F_t}) \tag{4.20}$$

4.3.2.5 Possum Population Growth

Following previous studies on the impact of control and harvest on possum populations, Equation 4.21 was used to describe the growth of the possum population (Clout and Barlow, 1982; Barlow and Clout, 1983; Hickling and Pekelharing, 1989). The parameters *a*, K2, and θ provide values for the intrinsic growth rate of the population, the carrying capacity, and an adjustment to the shape of the curve to reflect the impact of resource constraints, respectively.

$$g_2 = aP_t\left(1-\frac{P_t}{K2}\right)^{\theta} \tag{4.21}$$

Clout and Barlow (1982) estimated a value for *a* of 0.3 and for K2 of 3. These values were adopted in the model. With respect to the value of the impact of resource constraints Barlow and Clout (1983) suggested that for New Zealand possum populations θ is likely to be greater than one, and therefore more control effort is required to maintain a low population density than indicated by symmetric logistic models. Preliminary modelling indicated that a symmetric logistic function could be used without materially affecting results and thereby reduce non-linearity. Clark (1990) and Hone (1994) state that analyses of the control and harvesting of vertebrate species often employ a symmetric logistic function in which θ is equal to one. Consequently θ was set equal to 1.

4.4 Solution Technique

The empirical problem was specified in a non-linear programming format whereby control and state variables were represented as activities and non-linear equations of motion were represented as constraints linking activities in subsequent periods. The empirical model represented by Equations 4.1-4.7 was solved numerically over a 70 year period (T=70) using GAMS/MINOS (Brooke *et al.*, 1988 and 1996) software on an IBM-PC clone.

4.5 Preliminary Results

The preliminary results for the empirical model are displayed in Table 4.2. The simulation assumes a Tb policy environment in which movement control Tb testing is mandatory. It is also assumed that the herd is currently classified as Tb infected with an initial actual Tb prevalence of 2%.

Total herd size at the beginning of each period averages 237 cattle which implies that the number of cattle in the breeding and marketing components is 154 and 83, respectively. Marketing decisions follow a "bang-bang" control approach with on average 80.37 marketing cattle sold as stores and none marketed to slaughter. When cull cows are added to sales, a total of 104.5 cattle are sold each period. NZMWBES survey data for the period 1990/91 to 1994/95 show that an average of 87 cattle were sold with annual sale numbers ranging from 84 to 91 (NZMWBES, 1992-1996). The slightly higher sales in the base run is due to the assumption that all marketable cattle are sold in their second year. The average price received for store cattle is $470.56, which is $11.44 lower than the maximum average price for this class of cattle, reflecting an average apparent true Tb prevalence for the total herd of 1.18%.

An average of 11.27 weaner cattle are purchased each period as a result of surplus stocking capacity due to sales of marketable and cull cattle and reactors detected at whole herd, pre-movement and in-contact testing. The NZMWBES five year average for cattle purchases is 12 with a range of 7 to 17 (NZMWBES, 1992-1996). The purchase price of $314.10 also corresponds to a "bang-bang" control at the maximum discounted price for weaner cattle. The fully discounted market price of store cattle applies to cattle from herds with the highest permissible level of infection. This purchase price implies therefore that the producer has chosen to allow the maximum possible amount of infection into the herd through store cattle purchased. Possum numbers average 1.97 per hectare with 10.25% of the possum population harvested annually through control activities. As a result of all the cattle production activities average net revenue is $24.66 per hectare which corresponds to $38,643 per year for the cattle enterprise.

Table 4.2 Preliminary Results

Variable	**Steady State Values**
Herd Size	237
Possums/Hectare	1.97
Possum Harvest Rate	10.25%
Marketable Cattle Slaughtered	0
Susceptible Cattle Sold as Stores	80.31
Infected Cattle Sold as Stores	0.06
Susceptible Cattle Purchased	11.13
Infected Cattle Purchased	0.14
Average Store Cattle Sale Price	$470.56
Average Weaner Purchase Price	$314.10
Annual Net Revenue	$38,643
Actual Herd Tb Prevalence	1.18%
Apparent True Herd Tb Prevalence	1.18%
Apparent Herd Tb Prevalence at WHT	1.88%
Reactors at Whole Herd Test	4.45
Reactors at Pre-Movement Test	1.00
Reactors at In-Contact Test	1.85
Reactors at Post-Movement Test	0.22
Marginal Value of Susceptible Cattle	$484.83
Marginal Value of Infected Cattle	-$562.33
Marginal Value of Possums	-$1.65

The marginal values in Table 4.2 represent the average marginal change to current and future net revenue from a marginal change in each of the state variables. The marginal values for susceptible and infected cattle are influenced by the current level of herd prevalence, the rate at which infection is spread within the herd, the average store cattle price, the number of reactors removed at testing events, and the reproductive growth in the herd. The marginal value for susceptible cattle is $484.83, which is slightly higher than the price for clear herd store cattle, while the marginal value for infected cattle is - $562.33.

The marginal value for susceptible cattle reflects the positive contribution susceptible cattle make to the value of the herd through reproduction and a higher average store cattle price arising from the reduction in the apparent true infection level. The increased value of the herd is offset to an extent by the negative contribution susceptible cattle make to the future spread of infection through the herd by increasing density and the reduced value arising from false positive reactors at Tb testing.

The large negative marginal value for infected cattle is due to an additional infected animal increasing apparent Tb prevalence both currently and in the future by increasing the spread of Tb through the herd. The higher apparent prevalence negatively affects the store cattle price for all cattle sold. Both susceptible and infected cattle incur reductions in value when they react at a Tb testing event because compensation is only 65% of fair market value and therefore less than the average store cattle price. Although the compensation for false and true positive reactors is the same, the sensitivity and specificity of the Tb test results in an infected animal impacting more on the value of the herd because it has a greater chance of reacting than a susceptible. The greater reduction in value caused by a true positive reactor is offset to a degree by a reduction in the spread of infection in the herd. The net revenue from cows culled is also affected because infected cull cows only return their salvage value while susceptible culls return their full value. As with susceptible cattle, an additional infected cattle beast contributes to the natural growth of its population. However, because the whole herd test is assumed to occur prior to calving and the reactor rate for infected cattle is greater than that for susceptible cattle, infected cows which are in-calf react and are removed form the herd at a relatively greater rate than is the case for susceptible cows. Although the loss of the cow is compensated for no compensation is received for the calf. As a consequence of these factors the marginal value of infected cattle is substantially negative.

The possum population has a marginal value of -$1.65. This reflects the positive relationship between the number of possums and both the cost of possum control activities together with their contribution to reduced cattle values as a result of Tb transmission into the herd. An additional possum only has a small effect on the spread of infection into the cattle herd because the rate of Tb transmission from possums is very low. Consequently, the marginal value of possums is slightly negative in line with the low level of costs arising from increased infection in the herd and the producer's response in the form of increased harvesting effort.

Chapter 5: The Economics of Bovine Tuberculosis Movement Control Policy

5.1 Introduction

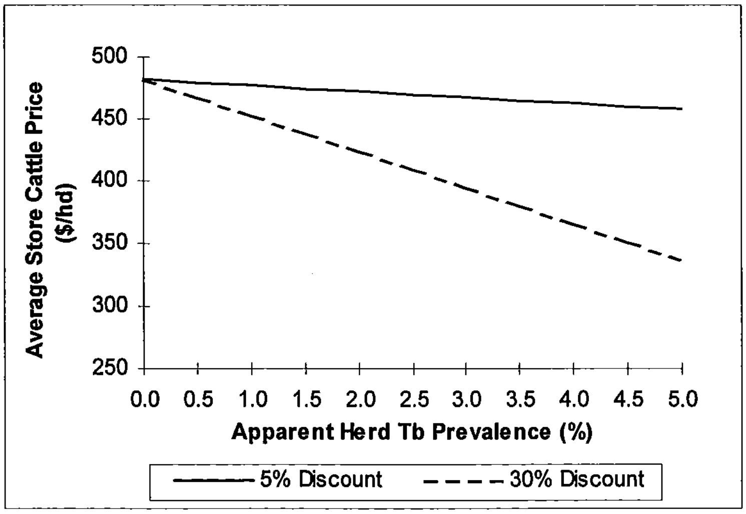
Preliminary results from the empirical model showed that herd Tb prevalence was reduced from initial levels of 2% through the Tb testing requirements imposed on the producer by the NPMS, together with the decision by the producer to undertake possum control. This chapter considers the behavioural responses of a cattle producer who is constrained by movement control restrictions and the implications, if any, for bovine Tb control policy objectives. The factors influencing cattle production and Tb control that are considered include; the level of infected herd price discounting in the store cattle market, the producer's response to "in-contact" testing, the impact of the "High Risk" infected herd threshold level, and the role of reactor compensation. An attempt is also made to estimate the costs of complying with movement control restrictions. The policy simulations are followed by an exploratory analysis into the association between price discounting and herd infection levels in an environment where movement control Tb testing is voluntary. The chapter concludes with sensitivity analysis of the key parameters.

5.2 Store Cattle Price Discounting

As discussed in Chapter 3, cattle sold as stores are often discounted if the cattle have come from an infected herd. Economic theory suggests that the discount on the price of cattle from infected herds should equal the expected cost of bringing disease into the herd. The expected cost of disease includes the reduced value of infected cattle purchased when they are either identified at testing or at slaughter, and the cost arising from susceptible cattle in the herd becoming infected.

Following observed behaviour the empirical model assumes that a risk neutral producer would discount the average price of a group of cattle purchased by a maximum of 10% if the corresponding herd had an apparent prevalence of 4.99%. The preliminary results indicated that when the maximum market discount is 10% the producer sends all marketed cattle to sale as stores, thereby incurring some discount on the price, and avoiding the additional grazing costs that would be incurred if the cattle were fattened for sale to slaughter. Given that the price of cattle from infected herds has been discounted to varying extents on occasions, the assumption of a 10% discount is relaxed and replaced by maximum discounts to the store cattle price of 5%, 15%, 20%, 25% and 30%.

Figure 5.1 Store Cattle Price Discount-Infection Relationship



For each of the percentage discounts mentioned above, the appropriate maximum discount parameter (ω) is entered in the model. The effect of these changes on the price-infection relationship for the 5% and 30% discount regimes is illustrated in Figure 5.1. Increasing the discount increases the slope of the price-infection line. Therefore, for any given level of apparent herd Tb prevalence, a higher discount will result in a lower average store cattle price.

Table 5.1 Steady State Values for Store Cattle Price Discount Regimes

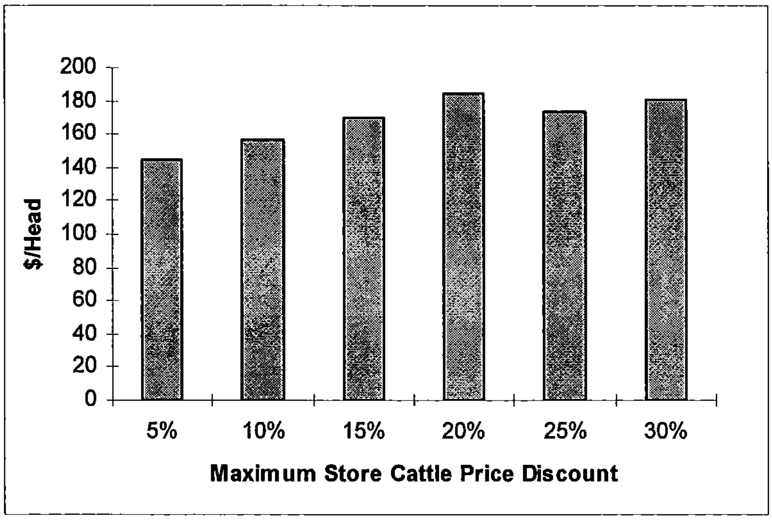
Variable	Store Cattle Price Discount (Maximum)					
	5%	10%	15%	20%	25%	30%
Possums/Hectare	2.21	1.97	1.76	1.56	2.51	2.54
Possum Harvest Rate	7.89%	10.25%	12.43%	14.41%	4.93%	4.61%
Cattle Slaughtered	0	0	0	0	80.91	80.90
Cattle Sold as Stores	80.27	80.37	80.47	80.56	0	0
Cattle Purchased	11.57	11.27	11.00	10.74	10.85	10.90
Average Store Cattle Sale Price[1]	$475.63	$470.56	$466.67	$463.76	$435.26	$425.23
Average Weaner Cattle Purchase Price[2]	$331.55	$314.10	$296.65	$279.20	$261.75	$244.30
Net Revenue/Hectare	$24.80	$24.66	$24.56	$24.49	$24.77	$24.89
Actual Tb Prevalence	1.32%	1.18%	1.06%	0.94%	1.94%	1.96%
Marginal Value Susceptible Cattle	$503.07	$484.83	$467.13	$449.86	$430.91	$413.99
Marginal Value Infected Cattle	-$277.64	-$562.33	-$849.27	-$1138.14	-$43.53	-$28.45
Marginal Value Possums	-$1.13	-$1.65	-$2.25	-$2.94	-$0.62	-$0.57

[1] The average price the producer receives if cattle are sold as stores.
[2] Always purchased at the maximum discounted price.

Table 5.1 displays results for the different levels of discount. The producer markets all marketable cattle to sale as stores for all discount regimes up to and including 20%. With respect to cattle purchases, the producer has an incentive to purchase cattle at the maximum discounted price and therefore chooses to allow infected animals to enter the herd.

When cattle are sold as stores, the actual Tb prevalence in the herd is inversely related to the level of store cattle price discount. As highlighted in Table 5.1, increases in the price discount lowers the average price received for any given level of herd Tb prevalence. Under a 10% discount regime, when the herd's actual prevalence is 1.18%, the producer receives an average price of $470.56 per head of store cattle. When the price discount is 20% infection in the herd becomes more costly and therefore greater effort is taken to control it. Although actual prevalence is lowered to 0.94% the average price received for store cattle is reduced to $463.76. Figure 5.2 illustrates that it is in the producer's best interest to continue to purchase cattle at the maximum discount and reduce herd Tb prevalence as the maximum price discount increases. The lower purchase price of weaner cattle from Tb infected herd's, and the higher store cattle sale price arising from reducing Tb infection in the herd, provide an increasing margin between the sale and purchase price of store cattle as the price discount increases.

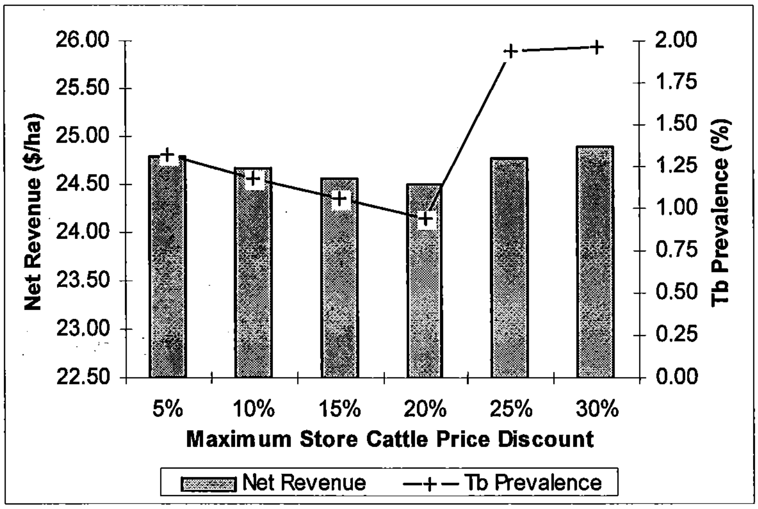
Figure 5.2 Margin Between Store Cattle Price and Weaner Purchase Price



The lower average price associated with a higher store cattle price discount regime is reflected in the increasingly negative marginal value of an infected cattle beast (Table 5.1). Although the producer has an incentive to purchase cattle at the maximum price discount, it is the higher cost of infection that arises as the store cattle price discount increases that motivates the producer to reduce the herd's Tb prevalence. Reductions in the transmission of infection into the herd can be achieved either through purchasing mobs of weaner cattle with lower infection risk at a higher price or by undertaking greater levels of possum control. Results suggest that the opportunity cost of not purchasing weaner cattle at their maximum discount is too large and therefore the producer reduces transmission of infection into the herd by increasing the possum harvest rate. Figure 5.3 illustrates the steady state impact of the store cattle price discount regime on annual net revenue and herd Tb prevalence.

In response to the lower average prices that would be received if cattle were sold as stores under the 25% and 30% discount regimes the producer chooses to incur the additional grazing costs and send cattle to slaughter. Taking into account grazing costs the average price received for slaughtered cattle is $401.29 when the maximum discount is 25% and $401.33 under the 30% discount regime. When cattle are marketed to slaughter the herd's Tb infection level does not impact on net revenue to the extent it does when cattle are sold as stores. Susceptible cattle return their full market value to the producer while infected cattle return only a salvage value. The value of a susceptible cattle beast sent to slaughter is not affected by the presence of infected cattle. The producer therefore trades-off the benefits of sending less infected cattle to slaughter, the difference between salvage value and full slaughter value, with the costs of achieving lower herd infection levels. Results show that when marketing cattle are sent to slaughter the steady state herd Tb prevalence is higher. The increase in Tb prevalence is due to a greater number of possums arising from a reduction in the possum harvest rate, and the removal of fewer infected cattle because fewer Tb testing events are undertaken.

Figure 5.3 Steady State Net Revenue and Herd Tb Prevalence Under Maximum Store Cattle Price Discount Regimes



The marginal values relating to the cattle and possum populations also disclose interesting information when the different discount regimes are compared. The marginal values for susceptible and infected cattle decline as the store cattle price discount increases, when cattle are sold as stores. Recall that the marginal values relate to each cattle population's contribution to current and future earnings of the cattle enterprise. The inverse relationship between the marginal values of susceptible and infected cattle, and the magnitude of the store cattle price discount is due to the impact of an additional cattle beast on the average price received for store cattle

Susceptible and infected cattle affect the current level of Tb prevalence within the herd and therefore impact on current net revenue. An additional susceptible cattle beast reduces the current level of herd Tb prevalence and thereby increases the average price received for store cattle (Figure 5.1). The marginal increase in the average store price resulting from a reduction in herd Tb prevalence becomes larger as the store cattle price discount increases. However, *ceteris paribus* the average store cattle price decreases as the maximum price discount increases if the herd has an apparent Tb infection level greater than zero. As a consequence of the change in, and the actual level of, the store cattle price the marginal contribution of a susceptible cattle beast to current revenue is positive but declines as the maximum store cattle price discount increases.

Conversely, an additional infected cattle beast increases the current level of Tb prevalence in the herd. The higher herd Tb prevalence reduces the average store cattle price received. The average store cattle price is also adversely impacted by increases in the maximum price discount. As a result, the negative marginal value of infected cattle increases, when cattle are sold as stores, as the store cattle price discount becomes larger.

The marginal values of susceptible and infected cattle are their lowest and highest, respectively, under the 30% discount regime. An additional infected animal has relatively less impact on the marketing proceeds when cattle are sent to slaughter compared to when cattle are sold as stores. Unlike the situation when cattle are sold as stores, the adverse impact on herd Tb prevalence does not affect the price received for all other marketing cattle sold to slaughter. Correspondingly, an additional susceptible cattle beast will not bring about the same degree of change to the average marketing revenue, through a lower herd prevalence, as would be achieved if cattle were sold as stores.

In addition to the marginal impacts on current revenue, both susceptible and infected cattle contribute to the future spread of Tb within the herd and therefore adversely impact on future net revenue. The extent of the impact on future revenue from additional susceptible and infected cattle increases as the maximum level of price discount increases.

The marginal value of the possum population is negative under all discount regimes reflecting the role possums have in spreading Tb into the herd. The marginal value of a possum is related to the transmission of infection into the herd. As the price discount on store cattle increases the cost of an extra possum becomes greater if cattle are sold as stores. The producer therefore increases the harvest rate to reduce the transmission of infection and lower herd Tb prevalence. The marginal value (or economic cost) of possums is lowest when cattle are marketed to slaughter because an infected cattle beast does not impact on the price of all cattle marketed. It is under the 30% price discount regime that the possum population reaches its greatest number. The producer trades-off the high level of price discount on cattle purchased and reduction in possum control costs against the costs incurred through higher herd Tb prevalence levels.

5.3 Splitting the Herd

It has been suggested that cattle producers may respond to in-contact testing requirements by dividing herds further and thereby reducing the proportion of the herd exposed to a testing event (Crews, personal communication). The most extreme case of herd splitting is when the cattle to be marketed in each period are kept separate from the remainder of the herd. This situation is modeled by setting the value of the "in-contact" test parameter (σ) to zero.[5] Steady state values are presented in Table A.1.

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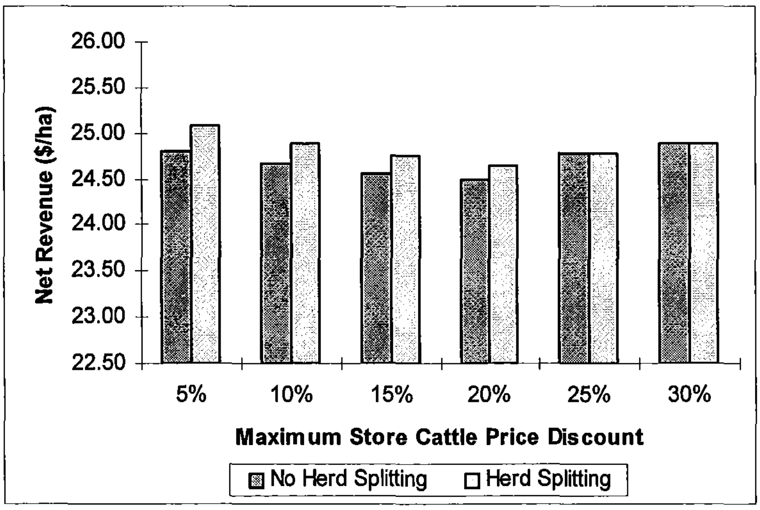
[5] Other potential management costs such as those resulting from increased mustering effort and sub-optimal grazing regimes which may result from maintaining an in-farm quarantine system are ignored.

Numerical results disclose there is an economic incentive for the producer to avoid the in-contact test (Figure 5.4). Higher revenues than those occurring under the base scenarios arise from reductions in the cattle management costs associated with testing cattle in the herd that are not being sold, the value of false positive cattle that would have been removed and slaughtered at the "in-contact" test, and the purchase cost of cattle to replace them. Elimination of the in-contact test, however, provides a greater opportunity for an infected animal to persist in the herd and hence Tb prevalence is greater when cattle destined for store sale remain separated from the rest of the herd. This observation highlights a conflict between the social and private objectives of Tb control. Producers can increase their revenue (private benefit) by avoiding Tb testing even though herd infection levels increase (social cost).

Figure 5.4 Steady State Net Revenue: No Herd Splitting vs Herd Splitting



5.4 A Lower "High Risk" Herd Infection Threshold

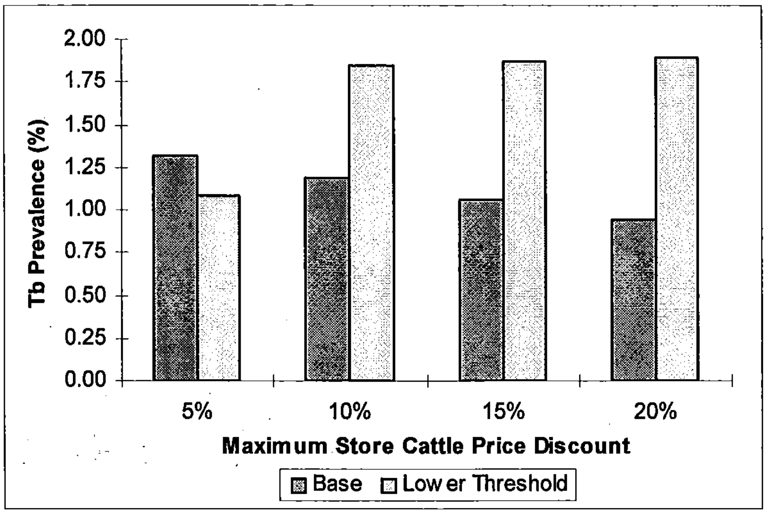
A major implication for the producer of having a herd classified as "High Risk" is that it may be not possible to market cattle as stores, or if it is possible, additional herd testing conditions must be satisfied. The NPMS states that the "High Risk" herd infection threshold level may be adjusted over the term of the strategy (AHB, 1995). To determine the consequences of a lower threshold level for the producer, the maximum apparent infection level parameter was reduced from 4.99% to 1.99%. At this level, the hypothetical herd would be classified as "High Risk" at the beginning of each simulation given an initial value for Tb prevalence of 2%. With respect to the store cattle price-infection relationship illustrated in Figure 5.1, lowering the "High Risk" herd infection threshold to 1.99% increases the slope of the price-infection line and thereby increases the extent to which the price discount impacts on the average store cattle price for a given level of herd Tb prevalence.

The steady state values obtained from numerical results are detailed in Table A.2. The increased impact of the price discount on the average store cattle price results in the decision to switch from marketing cattle as stores to marketing to slaughter being made at a lower price discount than that in the base scenario. Figure 5.5 shows the impact of lowering the threshold on herd Tb prevalence.

In response to the greater marginal effect of infection on the store cattle price, the producer ceases to market cattle as stores when the price discount regime is 10% or greater. When cattle are sold as stores, under a 5% discount, the producer is motivated to reduce herd Tb prevalence to 1.08%, which is below the base scenario's steady state level of 1.32%, in order to avoid too large a reduction in the average sale price ($468.88). Under the lower threshold scenario the producer still chooses to reduce herd

Tb prevalence by controlling possums rather than through the purchase of mobs of cattle with lower infection status.

Figure 5.5 Steady State Herd Tb Prevalence: Base Run vs Lower "High Risk" Threshold



The cost of reducing herd Tb prevalence to levels which would make marketing cattle to sale as stores attractive becomes too great when price discount levels are 10% and above. By adopting the strategy of sending cattle to slaughter the producer can offset the additional grazing costs with lower possum harvest costs and a higher value for susceptible cattle not removed as false positive reactors at pre-movement and "in-contact" Tb testing.

5.5 No Reactor Cattle Compensation

The Animal Health Board has stated that reactor cattle compensation will be reviewed annually after the first two years of the NPMS (AHB, 1995). Several options for alternative reactor compensation schemes were considered by the Animal Health Board during the formulation of the current NPMS. These options ranged from the payment of a fixed percentage of fair market value plus cartage for all reactor cattle slaughtered, through to producers receiving only the carcass value of reactors slaughtered and paying their own cartage (Livingstone, 1995).

To examine the impact of a change to reactor compensation policy on the production environment a "no compensation" scenario is simulated. Under the no compensation scenario it is assumed that the actual disease state of reactor cattle is identified at slaughter and therefore the producer either receives the full value of the animal's carcass if it is non-infected or its salvage value if it is infected. It is further assumed that under the no compensation option the producer will not have to pay for cartage of any reactor cattle sent to slaughter because the specificity of the tuberculin test will result in some non-infected cattle being sent.

To reflect the change in basis from fair market value to carcass value, the live weight of a generic marketable cattle beast at the time of Tb testing is calculated and converted into a carcass value. The carcass value calculations used live weight and carcass weight data for a 12-14 month cattle beast (Beef New Zealand, 1997). The conversion uses the same price per kilogram as applied to marketing cattle that are slaughtered (New Zealand Farmer, 1995-1996; Beef New Zealand, 1997). Rather than create additional compensation parameters, the values for false positives and true positives (γ_1 and γ_2) are changed from 65% and based on the percentage of the clear herd store cattle price (p_2) that would correspond to a full payment of the carcass value or the salvage value, respectively. The salvage value of a carcass was assumed to be 35% of the carcass value (Scott and Forbes, 1988). Assuming the relationship between the carcass proceeds and the store cattle price is fixed, the carcass proceeds for weaner cattle are determined similarly. Consequently, the compensation parameter values under the no compensation scenario are set at 0.77 for false positive reactors and 0.27 for true positive reactors.

Table A.3 provides details of the steady state results obtained. The absence of compensation does not change the optimal marketing activities or purchasing strategies for any of the discount regimes analysed. Under a no compensation policy, the values of false and true positive reactor cattle increase by 18.46% and decline by 58.46%, respectively. The reduced value of a true positive reactor motivates the producer to lower actual Tb prevalence in the herd from levels in the base scenarios for all price discount regimes by increasing the possum harvest rate (Figure 5.6).

Figure 5.6 Steady State Herd Tb Prevalence: Reactor Compensation vs. No Reactor Compensation

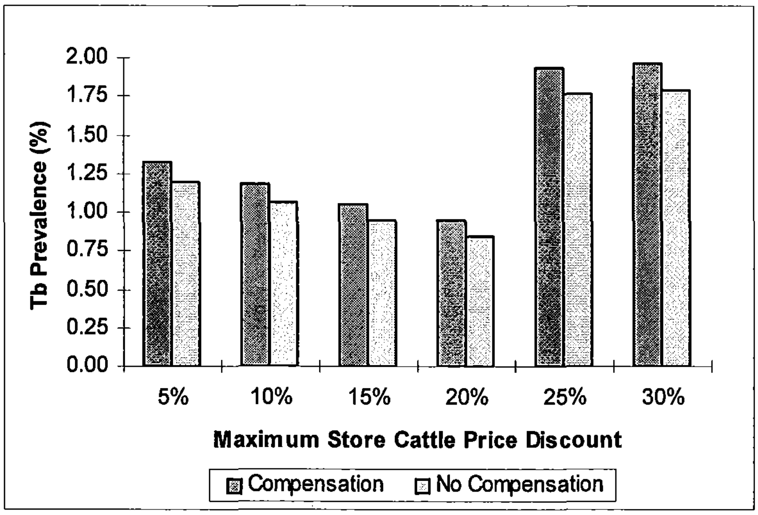
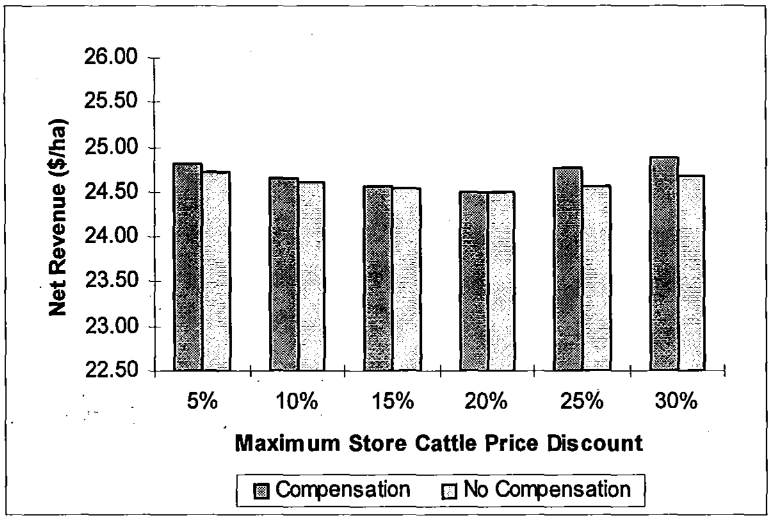


Figure 5.7 shows net revenue is slightly less for all discount regimes, apart from the 20% price discount, when no compensation is paid. Although the average store cattle price is higher when compensation is absent it is not enough to offset increased possum harvest costs and the reduced value of infected cattle detected at testing. With respect to the 25% and 30% discount regimes, a significant cause of the lower net

revenue is the higher cost arising from a 47% and 51% increase in possums harvested annually at the steady state, respectively.

Figure 5.7 Steady State Net Revenue: Reactor Compensation vs. No Reactor Compensation

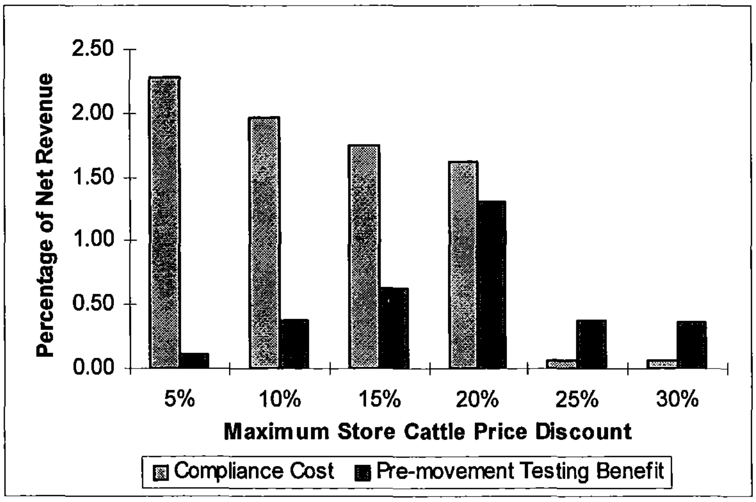


5.6 The Economic Impact of Movement Control Regulations

Under the NPMS producers with infected herds incur a number of costs. Some costs are the result of either restrictions placed on the movement of cattle, as discussed in Chapter 2, or the extent of the market discount imposed on the price of store cattle. There are also costs associated with undertaking the required Tb testing activities; pre-movement, in-contact and post-movement testing. The simplifying assumptions employed in the model concerning the age and sex structure of the herd, and the homogeneity of the cattle sold, do not permit the non-testing costs to be fully captured. The model does, however, allow insight to be gained into the direct and indirect compliance costs of movement control Tb testing.

The analysis of movement control testing compliance costs is undertaken by removing the restriction which imposes movement control testing on the system and permitting it to become a choice variable (MC_t) in the model. The difference between the net revenue obtained under mandatory and voluntary movement control testing regimes provides an estimate of compliance costs that captures the direct and some of the indirect costs. Because the relationship between price and apparent infection used in the model assumes cattle purchased have been pre-movement tested, this assumption is extended to the voluntary movement control testing regime. However, to capture the value to the producer of the pre-movement test on cattle purchased (pre-movement testing benefit), two voluntary movement control testing scenarios are compared. The first assumes the cattle purchased have undergone a pre-movement test and the second assumes they have not. These scenarios are represented in the model by setting the movement control parameter (η) to one and zero, respectively. Comparative results for movement control compliance costs and pre-movement testing benefits for the different price discount simulations are shown in Figure 5.8 and presented in Table A.4.

Figure 5.8 Annual Movement Control Compliance Costs and Pre-movement Testing Benefits



Numerical results suggest that the cost imposed on the producer from mandatory movement control testing is negatively correlated with the level of price discount when cattle are sold as stores. This relationship arises because under the discount regimes in which cattle are sold as stores, Tb prevalence declines as the price discount increases. When prevalence is high more cattle react at Tb testing events and are subsequently slaughtered due to changes in the composition of false and true positive reactors. Because the value of a cattle beast sold as a store is greater than the amount of reactor compensation received, the total opportunity cost of reactor cattle at high prevalence levels is greater than at lower prevalence levels. If movement control testing is voluntary, results indicate that the producer will not choose to undertake the full range of tests that are required under mandatory movement control testing (Table A5). Given the assumption employed in the model that either all movement control tests are performed or none, this decision amounts to no movement control testing being undertaken. Consequently, cattle that would have been removed under mandatory movement control testing generate a higher return to the producer from being sold as stores.

The value to the producer of the pre-movement test on cattle purchased is disclosed by the pre-movement testing benefit in Figure 5.8. The value of the pre-movement test on cattle purchased is positively related to the level of discount when cattle are sold as stores. If a pre-movement test is not undertaken the actual level of infection that is brought into the herd is higher if cattle are purchased at the maximum discount. When purchased cattle are not pre-movement tested the producer cannot trade-off the costs arising from infected cattle entering the herd with the benefits of the maximum discounted price and therefore buys mostly clear herd cattle at the full price (Table A.7). The trade-off between the discounted price and infection is, however, worthwhile when purchased cattle are pre-movement tested. The benefit obtained by the producer from the price discount therefore increases with the magnitude of the discount and as a result the value of the pre-movement test increases as the discount increases.

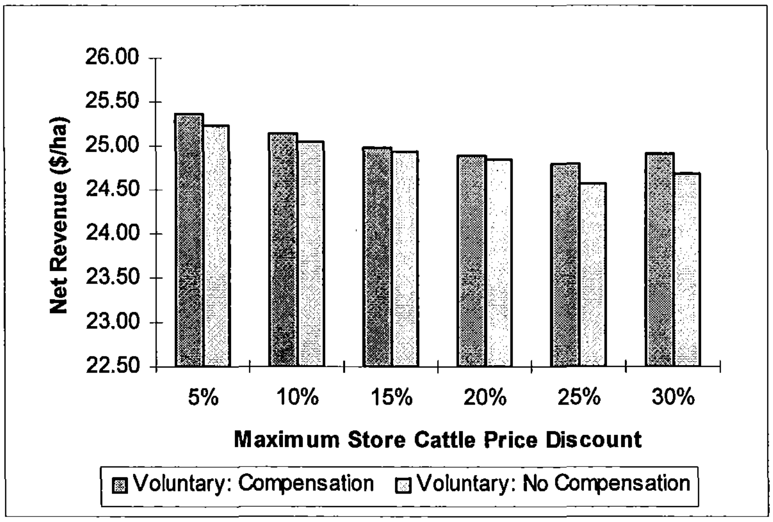
At higher discounts, when cattle are sold to slaughter, there is a negative relationship between the value of the pre-movement test and the price discount regime (Figure 5.8). Because the level of herd Tb prevalence does not impact on the average slaughter price to the extent it does on the average store price the producer is motivated to purchase cattle at the maximum discounted price and undertake post-movement testing to reduce infection levels. As the price discount increases, the correspondingly lower purchase price of weaner cattle reduces purchase costs. The lower purchase cost helps reduce the adverse impact on net revenue arising from a higher level of infection entering the herd.

5.7 Price Discounting and Herd Infection Levels

The Animal Health Board anticipates that the information provided by the new herd Tb classification system will establish economic incentives that influence producer decisions regarding cattle purchases and management, and vector control, that may reduce the reliance on movement control regulations in the future (AHB, 1995). The economic incentives referred to relate to the livestock market valuing store cattle according to their disease risk. An interesting issue requiring exploratory analysis concerns the likely behavioural responses of producers and the implications for Tb prevalence when movement control testing is voluntary. Simulations are undertaken for voluntary movement control testing under reactor compensation and no compensation policies. The latter policy is included to provide a scenario in which producers incur more fully the true cost of Tb infection in their herds. Steady state results are displayed in Tables A.5 and A.6.

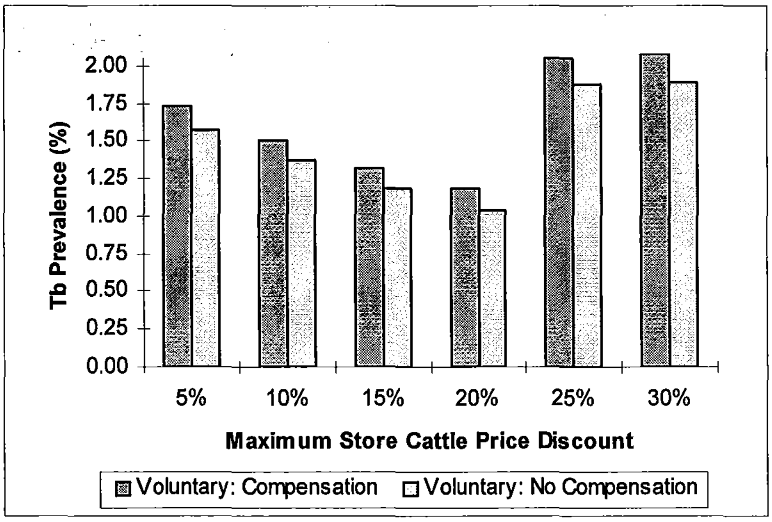
As was observed in Section 5.6, when compensation is paid, the producer increases net revenue by not undertaking movement control testing and thereby avoiding the opportunity cost of true and false positive reactor cattle. In response to an increase in Tb prevalence arising from a reduction in infected cattle removed from the herd as true positive reactors, possum harvest rates are increased from base run scenarios when cattle are marketed as stores. The increase in the possum harvest is not enough, however, to prevent herd Tb prevalence increasing relative to the mandatory movement control testing scenario.

Figure 5.9 Steady State Net Revenue for Voluntary Movement Control Testing: Reactor Compensation vs. No Reactor Compensation



Steady state results for voluntary movement control testing under a policy of no compensation for reactor cattle show that marketing and purchasing strategies remain the same as under a policy of reactor compensation. The significant difference between the two compensation policies is that herd Tb prevalence is lowered for all price discounts analysed when no compensation is paid (Figure 5.10). However, Tb prevalence is still higher than under a policy of mandatory testing. A comparison of the marginal value of infected cattle under the 5% to 30% discount regimes reveals large increases in the cost of an infected cattle beast when only a salvage value is returned to the producer. The producer's response to the higher cost of infection is to increase the possum harvest rate for all store cattle price discount regimes. No attempt is made to trade-off the cost of weaners purchased with lower levels of infection.

Figure 5.10 Steady State Herd Tb Prevalence for Voluntary Movement Control Testing: Reactor Compensation vs. No Reactor Compensation



Numerical results indicate that when movement control testing is voluntary and cattle are sold as stores, the benefits obtained by the producer from not undertaking a complete movement control testing program outweigh the benefits of maintaining lower herd infection levels. This observation suggests that under a voluntary movement control testing regime, producers are unlikely to pre-movement test cattle marketed as stores. Exploratory analysis into purchased cattle not being pre-movement tested ($\eta=0$), reveals that when purchased cattle intended for subsequent sale as stores are not pre-movement tested, the costs arising from infected cattle entering the herd cannot be traded-off against the benefits of the maximum discounted price (Table A.7). Under these conditions the producer responds by purchasing clear herd cattle at the full price to prevent higher levels of Tb prevalence. This behavioural change may, however, be the result of the assumption that either all movement control testing is undertaken or none.

Table 5.2 Producer's Behavioural Responses Under Voluntary Movement Control Testing

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	Purchased Cattle Pre-movement Tested		**Purchased Cattle Not Pre-movement Tested**	
	Cattle Sold as Stores	**Cattle Sold to Slaughter**	**Cattle Sold as Stores**	**Cattle Sold to Slaughter**
Infection Status of Cattle Purchased	Highest Risk Permissible	Highest Risk Permissible	Clear Herd	Highest Risk Permissible
Movement Control Testing	None	None	None	Post-movement

Table 5.2 discloses how the purchasing and movement control testing strategies adopted by the producer under a voluntary movement control testing regime depend on whether cattle are pre-movement tested and where they are eventually marketed. It is important to note that when pre-movement testing is not undertaken by the seller there is an incentive to purchase untested cattle from high risk herds and post-movement test if cattle are to be sold to slaughter. If the producer chooses to post-movement test cattle purchased then the specification of the model assumes that the producer will also choose to pre-movement test cattle sold as stores and in-contact test the remainder of the herd The costs of a complete movement control testing program when cattle are sold as stores are therefore likely to outweigh the benefits from obtaining a discounted price.

Numerical results imply that it is possible that producers marketing cattle as stores would continue to purchase cattle from infected herds and take advantage of the price discount if only post-movement testing could be performed. Results in Table A.7 disclose that there is an incentive for producers marketing cattle to slaughter to purchase and post-movement test cattle from herds with the highest permissible infection. Given that the gains to the producer from reducing infection in the herd are higher when cattle are marketed as stores, the incentive to purchase cattle at the maximum price discount and post-movement test is expected to be larger. It is therefore unlikely that producers would refrain from purchasing discounted infected herd cattle under voluntary movement control testing even if the cattle were not pre-movement tested.

5.8 Sensitivity Analysis

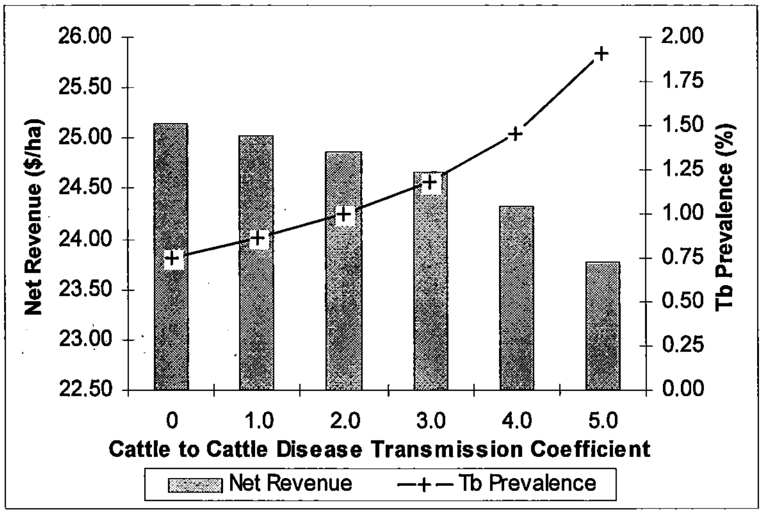
Sensitivity analysis is conducted on the key parameters in the model to identify their material impact on steady-state/average results. The value of each parameter is changed while holding the values of all other parameters at the 10% price discount base run levels. The parameters examined are the disease transmission coefficients, the sensitivity and specificity of the tuberculin test, and possum harvest costs.

5.8.1 Disease Transmission Coefficients

Cattle to Cattle Disease Transmission

The cattle to cattle disease transmission coefficient (β_1) was set at values from zero to five. An increase in the rate at which Tb spreads between cattle lowers net revenue and increases herd Tb prevalence at the steady state (Figure 5.11). The reduction in net revenue arises from an increase in the possum harvest rate undertaken to reduce the adverse impact on herd prevalence, and a lower average store cattle price. There is no change to the replacement cattle purchasing strategy and all cattle are bought at their fully discounted price.

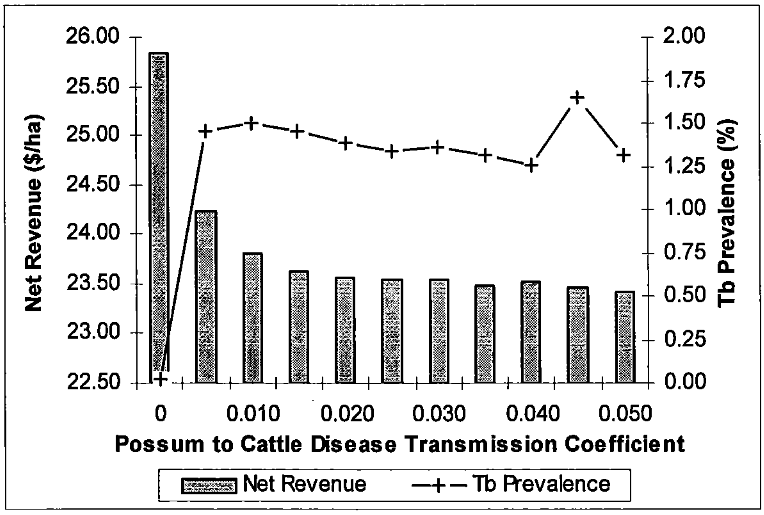
Figure 5.11 The Impact of Cattle to Cattle Transmission on Net Revenue and Herd Tb Prevalence



Possum to Cattle Disease Transmission Coefficient

Figure 5.12 illustrates the sensitivity of net revenue and herd Tb prevalence to changes in the possum to cattle disease transmission coefficient (β_2). The relationship between the value of β_2, and net revenue and Tb prevalence is complex. Changes to the magnitude of the possum to cattle disease transmission coefficient have a significant influence on herd Tb prevalence and consequently the marketing strategy adopted by the producer. Temporal results highlight that as β_2 is increased the producer changes marketing strategies in response to higher levels of herd prevalence. For values of β_2 of 0.015 and greater, the producer switches between marketing options. For most of the values analysed, cattle are marketed to slaughter in early periods and then sold as stores for the remaining periods. The switching strategy at high values of β_2 allows the producer to tradeoff lower current net revenue in some periods, from a low average store price, with the future benefits of lower prevalence obtained through removing infected cattle reacting at in-contact testing. The pattern of switching is not uniform for all values analysed. When of β_2 is set at 0.03 and 0.045 switching between slaughter and store sales becomes more frequent. Although the possum harvest rate increased substantially over the range of values analysed, weaner cattle were always purchased at their fully discounted price.

Figure 5.12 The Impact of Possum to Cattle Transmission on Net Revenue and Herd Tb Prevalence

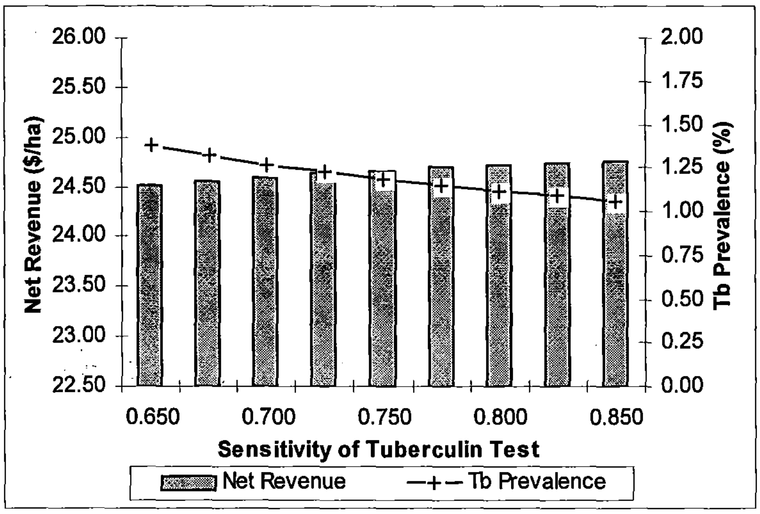


5.8.2 Sensitivity and Specificity of the Tuberculin Test

Sensitivity

Figure 5.13 shows that increasing the sensitivity of the Tb test from 65% to 85% reduces herd prevalence by 0.32%. As sensitivity is raised, a greater percentage of infected cattle are identified at testing events and as a result, the average store cattle price increases. The higher marketing revenue combined with a decline in the possum harvest rate slightly increases annual net revenue by 1.02% over the values of τ_2 analysed.

Figure 5.13 The Impact of Tb Test Sensitivity on Net Revenue and Herd Tb Prevalence

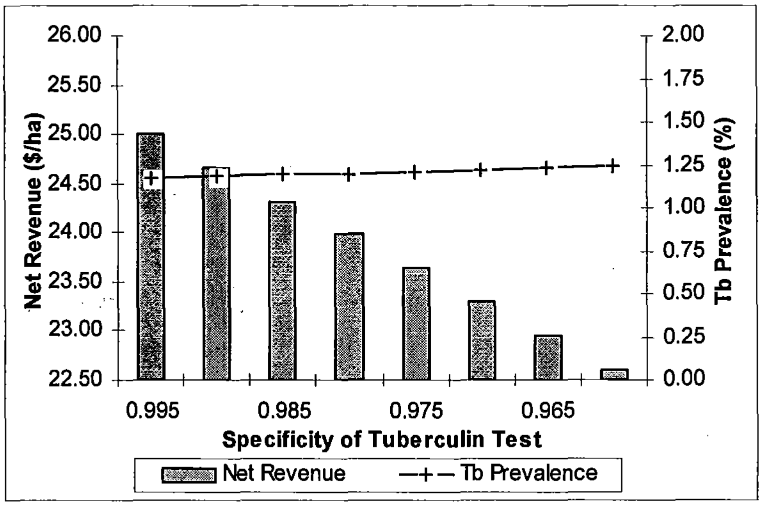


Specificity

False positive reactor rates ranging from .05% to 4% were analysed. Increasing the rate at which susceptible cattle react to the test produces only minor changes to prevalence, possum harvest rate and average store cattle price. However, results displayed in Figure 5.14 show a substantial reduction in net revenue arising from more susceptible cattle reacting at Tb testing events for which only 65% of fair market value is received. The adverse impact on net revenue from a reduction in the specificity of the test is not large enough to motivate the producer to market cattle to slaughter and thereby avoid false positive reactors at pre-movement and in-contact Tb testing.

The relationship between the specificity of the Tb test and net revenue highlights another important tradeoff between private and public objectives. The producer benefits from a reduction in the cost of false positive reactors arising from an increase in the specificity of the test.

Figure 5.14 The Impact of Tb Test Specificity on Net Revenue and Herd Tb Prevalence

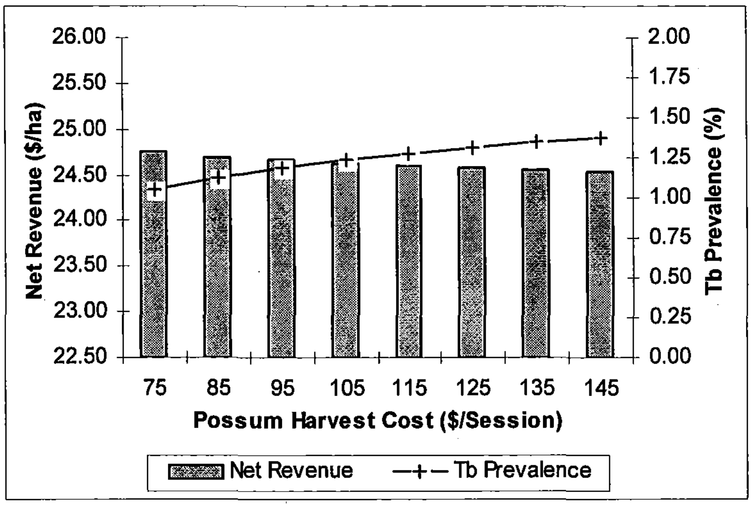


5.8.3 Cost of Time Harvesting Possums

The cost of time harvesting possums is analysed for values between $75 and $145. Results disclose that this parameter has only a minimal affect on net revenue and increases herd Tb prevalence by 0.30% over the range (Figure 5.15). In response to the higher cost of hunting time the possum harvest rate declines.

There are no changes to the producer's base run cattle marketing and purchasing strategies. An important observation gained from this series of simulations is that possum control has a relatively minor impact on the level of Tb infection in the herd when there is the opportunity to purchase cattle from infected herds.

Figure 5.15 The Impact of Possum Harvest Costs on Net Revenue and Herd Tb Prevalence



5.9 Summary of Results

The numerical results presented in this chapter provide insights into the producer's response to controlling herd Tb prevalence under policies of mandatory and voluntary movement control testing. Tb testing costs, vector control costs, and the prevailing level of price discount in the store cattle market all have an important influence on how actively the producer will control the disease. The analysis indicates that movement control compliance costs are not high and that the level of price discount in the store cattle market has a substantial impact on the producer's decisions concerning marketing and purchasing cattle, and possum control.

At low levels of price discount, the producer is motivated to sell cattle as stores and the discount acts as an incentive to reduce herd Tb prevalence. When the discount on the store cattle price is high, the impact of the discount creates a disincentive to marketing cattle as stores, and a strategy of holding cattle and selling directly to slaughter is adopted. By marketing cattle directly to slaughter, the producer can avoid the price discount as a penalty and yet still receive the benefit of a reduced purchase price for cattle from infected herds. The price discount therefore provides the producer with an economic incentive to purchase cattle from herds with the highest permissible Tb prevalence.

Chapter 6: General Discussion and Conclusions

6.1 Introduction

Research into bovine Tb in New Zealand acknowledges the significant role that cattle producer behaviour plays in efforts to control the disease. A common source of Tb infection in cattle is the introduction of infectious cattle from other herds. The policy response to the movement of infectious cattle between herds has been the implementation of tighter regulations on the movement of cattle.

Economic analysis of bovine Tb policy has generally focused on the national level, using static assumptions regarding the disease and producer behaviour. Livestock disease and its control is often, however, a dynamic process involving interactions between the state of disease and the producer's response through disease control. It is important therefore to understand how cattle producers are likely to react over time to changes in Tb control policy. As has been shown in previous chapters, economic methodology using dynamic optimisation can highlight the important temporal tradeoffs associated with cattle production and Tb control in either a policy constrained or unconstrained environment.

This chapter discusses the results of the empirical model in terms of answering the research questions posited in Chapter 1. General conclusions are then presented regarding the results and their implications for movement control policy. The chapter concludes by stating the study's limitations and areas for further research.

6.2 Answers to the Research Questions

What are the likely producer behavioural responses to movement control under the NPMS at various levels of store cattle price discount, in terms of decisions regarding the purchase and sale of cattle, and vector control, for a representative cattle production system?

The analysis demonstrates that the cattle producer's response to current movement control policy is heavily influenced by the cost of controlling Tb infection levels in the herd and the prevailing level of price discount in the store cattle market. The producer affects the level of Tb prevalence in the herd through the amount of possum control undertaken and the infection risk of cattle purchased. As the price discount in the store cattle market increases a marginal change in apparent herd prevalence has a larger adverse affect on the average price received for store cattle. The inverse relationship between the average store cattle price and apparent herd prevalence, and the greater marginal impact of a higher discount regime, results in the producer responding to higher price discount regimes by lowering herd Tb prevalence if cattle are marketed as stores.

When cattle are marketed as stores actual herd prevalence is lowered successively through increased possum control as the discount increases. No attempt is made to reduce the amount of infection brought into the herd through cattle purchases and therefore all cattle are purchased at the maximum discount. As the price discount becomes larger the marginal cost of preventing a decline in the average store cattle price by reducing Tb prevalence in the herd is high. The producer responds by fattening cattle to a condition suitable for sale directly to slaughter. Undertaking this strategy permits a trade-off between the additional grazing costs incurred and reductions in both possum harvest costs and the opportunity cost of false positive reactors identified at pre-movement and in-contact testing. As a consequence of the producer's change in behaviour, and because cattle are still purchased at the maximum discount, there is only a small reduction in herd Tb prevalence from its initial level. Results highlight that if the marginal change in the store cattle price with respect to a change in Tb risk is too large then the discount can switch from an incentive to a disincentive for the producer to lower herd Tb prevalence. The change in marketing preferences is facilitated by the producer being able to sell cattle directly to slaughter. In this situation, the discount does not act as a penalty on sales of cattle from Tb risk herds but does provide the producer with an opportunity to reduce cattle purchase costs.

Exploratory analysis suggests that if the producer can not sell cattle to slaughter then increases in the price discount reduce levels of herd Tb prevalence through higher possum harvest but do not result in the eradication of the disease from the herd because of the greater incentive to purchase infected cattle. An issue arising from this behaviour, but unable to be clarified by the model, is whether the opportunity cost of producing cattle relative to other land uses would become too large to make cattle production sustainable.

There are several other important insights into producer behaviour gained from the analysis. The compensation received for reactor cattle at Tb testing is a significant influence on the producer's decision making. When compensation is not paid for reactor cattle, the lower opportunity cost of false positive reactors and absence of financial benefit for true positive reactors results in higher levels of possum control and lower levels of herd Tb prevalence under all discount regimes analysed. This finding is consistent with Bicknell's (1995) closed herd study which also identified that a policy of no compensation for reactor cattle resulted in lower levels of herd prevalence. The incentive for the producer to increase expenditure and lower Tb prevalence arises from a substantial decrease in the value of infected cattle under a policy of no reactor compensation.

The effect of movement control Tb testing on net revenue also impacts on the producer's decisions. If movement control testing is reduced each period by the producer managing cattle to avoid the in-contact test when cattle are sold as stores, then net revenue is increased. Higher net revenue is obtained from reductions in the annual cost of presenting cattle for movement control testing and its subsequent interpretation and fewer false positive reactors slaughtered. Although extra possum control is undertaken it does not offset the increase in herd Tb prevalence resulting from removing fewer infected cattle each period at testing and consequently the average store cattle price is lower. The producer responds to the higher herd Tb prevalence by sending cattle to slaughter at a lower store cattle price discount. Imposing more Tb testing events on the producer lowers herd Tb prevalence, but in doing so increases the level at which the price discount prevents the sale of infected stock to other producers.

The preceding observations highlight that the producer's response to movement control depends on the costs imposed on cattle from infected herds by Tb control policy, the cost in terms of the market discount on store cattle, and the producer's ability to avoid these costs. The level of discount on the price of store cattle from infected herds determines whether cattle are marketed as stores or sold to slaughter. The opportunity to sell cattle directly to slaughter allows the producer to switch marketing strategies and avoid the adverse impact on sales revenue when the discount on store cattle becomes large. With respect to cattle purchases, the price discount provides an economic incentive for cattle to be purchased from herds with the highest permissible levels of infection. The significant benefit obtained from the lower store cattle purchase cost provided by the price discount results in the producer managing herd Tb prevalence levels through possum control rather than buying cattle from less infected herds. These observations imply that the producers most affected by movement control testing and price discounting are those, who due to constraints on their production system, can not fatten cattle for direct sale to slaughter.

What is the economic impact of movement control under the NPMS, in terms of the difference in discounted net revenue, for a representative cattle production system?

Under current Tb control policy, almost all Tb testing of cattle is funded by the cattle slaughter levy. The cost of administering and interpreting the Tb test is therefore not directly incurred by the producer. The costs which are incurred by the producer relate to presenting the cattle for the test and its subsequent interpretation, and a reduction in the expected proceeds of false positive reactors. There are also benefits derived from Tb testing cattle. The producer receives compensation at 65% of fair market value for infected cattle that react at the test and the removal of infected cattle lowers the spread of infection within the herd.

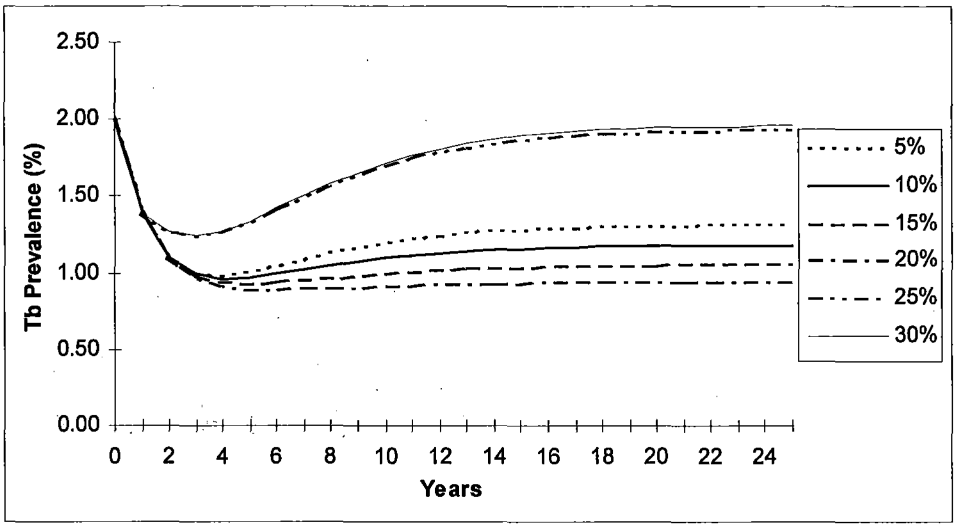
Comparison of net revenue per hectare between mandatory and voluntary movement control testing policy regimes suggests that compliance costs, in terms of the impact on net revenue, are low when Tb surveillance testing is mandatory. For the store cattle price discounts analysed, annual movement control testing compliance costs range from 1.63% to 2.28% of net revenue when cattle are sold as stores and cattle purchased are pre-movement tested. Compliance costs decline as the price discount increases because the opportunity cost of reactor cattle at movement control testing events becomes less as the discount increases. Decomposition of the compliance costs indicates that the annual benefit received by the producer if purchased cattle have been pre-movement tested ranges from 0.10% to 1.31% of net revenue as the price discounts adopted in the study were increased. The positive correlation between the value of the pre-movement test and the price discount is due to the difference between the cost of purchasing mobs of cattle with relatively low infection levels and the benefit of a lower purchase price becoming greater as the discount increases.

Given the tighter movement control restrictions and use of market signals employed under the NPMS, what is the likely impact on Tb infection levels for a representative cattle herd?

The objectives set out in the NPMS require the number of infected herds in Tb vector risk areas to decline and cattle producers in general to take measures to reduce both the risk and actual levels of Tb infection in their herds. The model suggests that when the maximum price discount in the store cattle market is 10% herd prevalence will decline from 2% to a steady state of 1.18%. The reduction in Tb prevalence is achieved by movement control and surveillance Tb testing events identifying and removing infected cattle. Tb infected cattle are not eradicated from the herd because cattle are purchased from herds with the highest permissible risk of infection and the steady state harvest rate of possums is not high enough to prevent the spread of infection from the possum population.

Figure 6.1 illustrates that under all of the store cattle discount regimes analysed, Tb testing has a large impact initially on reducing Tb prevalence and that the producer's optimal level of herd Tb infection is greater than zero. For the discount regimes in which cattle are sold as stores there is an inverse relationship between the magnitude of the price discount and the herd's Tb prevalence. This relationship arises because as the price discount increases the marginal value of an infected cattle beast becomes more negative and provides the producer with an incentive to reduce prevalence levels. The producer chooses to reduce Tb prevalence by increasing levels of possum harvest rather incurring higher purchase costs for cattle from herds with lower infection levels.

Figure 6.1 Trajectory of Tb Prevalence Under Movement Control Testing and Store Cattle Price Discounting



At higher levels of store cattle price discount there is an initial reduction in Tb prevalence because in the first period cattle are marketed as stores and the balance of the herd not marketed are "in-contact" Tb tested. The increase in herd prevalence back to levels close to 2% in the steady state occurs because after the initial period, cattle are marketed to slaughter. This highlights the impact on herd prevalence of not exposing cattle to the in-contact test and reductions in the possum harvest rate.

The analysis suggests that Tb testing requirements imposed by movement control regulations will reduce herd infection levels in Tb vector risk areas providing the maximum price discount does not motivate producers to send cattle to slaughter. An important implication of these findings is that if producers have the opportunity to purchase cattle from infected herds then under mandatory movement control testing discounting the price of store cattle is not likely to lead to the elimination of Tb infection from herds. The analysis also discloses that the extent to which Tb prevalence is reduced in the herd depends on the actual cost incurred by the producer for having infected cattle.

6.3 General Conclusions and Implications for Movement Control Policy

The methodology used in this study has permitted not only the specific research questions to be answered but has also allowed exploratory analysis to be undertaken on the likely producer responses to an environment where movement control testing is unregulated. The Animal Health Board has endeavoured to provide cattle producers with improved information on herd Tb infection. Their objective in doing so is to generate a market in which there is an incentive for cattle producers to more actively control disease.

Numerical results demonstrate that it may be rational for a risk neutral producer to behave in a manner under mandatory movement control testing that prevents the eradication of Tb from their herd when cattle from infected herds sell at a discount. The level at which Tb prevalence in the herd prevails is dependent on the magnitude of the price discount on store cattle. When movement control testing is voluntary the association between Tb prevalence and the store cattle price discount regime remains unchanged. At levels of discount that permit cattle to be sold as stores increases in the store cattle price discount reduce herd Tb prevalence. When the store cattle price discount results in cattle being marketed to slaughter, increasing the discount results in higher levels of Tb prevalence. Tb prevalence is, however, relatively higher than under mandatory movement control testing for all price discount regimes. The reason for the higher Tb prevalence is that fewer infected cattle are removed from the herd at annual testing events because movement control testing is not undertaken.

Of the two voluntary movement control testing scenarios explored, herd Tb prevalence is lower when reactor compensation is not paid. Because infected reactor cattle only return to the producer a salvage value, under a no compensation policy the implicit value of infected cattle declines substantially. The lower value of infected cattle provides the producer with an incentive to reduce herd Tb prevalence. In both voluntary scenarios, when cattle are sold as stores, increases in the store cattle price discount result in greater possum harvest rates to lower herd Tb prevalence.

The analysis indicated an interesting behavioural change when cattle purchased had not been pre-movement tested. The producer was motivated to purchase cattle from clear herds when the optimal marketing strategy was selling cattle as stores. This observed change in producer behaviour from the other scenarios may have been influenced by the assumption that when testing was voluntary the producer had to either undertake all movement control testing events (pre-movement, in-contact and post-movement) or none. Under the current formulation of the model it is not possible for the producer to undertake only one testing event. The model does not therefore permit firm conclusions to be drawn on how the producer would respond under a voluntary movement control testing regime if cattle purchased had not been subjected to a pre-movement test. The model does, however, permit some insights into whether cattle are likely to be pre-movement tested by the seller and the likely response of the purchaser if they are not.

The incentives and disincentives that exist for the seller to pre-movement test and the purchaser to post-movement test are presented in Table 6.1. Both the seller and the purchaser are faced with the same disincentives in the form of direct and indirect Tb testing costs. With respect to the incentives to post-movement test, the purchaser benefits from fewer diseased cattle entering the herd and therefore a lower probability of spread of infection. The economic benefits of fewer infected cattle entering the herd include the avoidance of reduced revenue from; a lower average store cattle price due to higher herd prevalence, the need for increased possum control to reduce herd prevalence, and a higher number of reactors removed at testing events if herd prevalence is not reduced. The incentive for the seller to pre-movement test depends on whether the market continues to accept cattle from infected herds if they have not been pre-movement tested which in turn depends on whether the purchaser is prepared to post-movement test. The exploratory analysis indicated that purchasers of store cattle would still be prepared to buy cattle at the maximum discounted price even if pre-movement testing had not be undertaken, providing they could conduct a post-movement Tb test on the cattle without engaging in other movement control Tb testing.

Table 6.1 Voluntary Movement Control Testing Incentives & Disincentives

	Incentives	**Disincentives**
Purchaser Post-movement Tests	• Lower the risk of Tb transmission into the herd and thereby reduce the adverse impact on future net revenue arising from higher herd infection levels.	• Opportunity cost of true positive and false positive reactors identified and removed at post-movement testing. • Testing costs.
Seller Pre-movement Tests	• Cattle may not be able to be sold as stores if they are not pre-movement tested and therefore current net revenue may be adversely affected.	• Opportunity cost of true positive and false positive reactors identified and removed at pre-movement testing. • Testing costs.

Based on the assumptions of the voluntary movement control testing analysis, the provision of accurate information concerning herd infection status is not likely to be a sufficient requirement to prevent the inter-herd transmission of Tb infection. This conclusion questions the probable success of a policy relying on market prices and indicates that a regulatory response may be required to assist the market in achieving Tb control policy outcomes. Justification for a regulatory response is found when the costs of Tb infection discussed in Chapter 1 are reconsidered. The economic impact for the producer of having infected cattle is the lower values of: false positive reactors slaughtered, cattle sold to store that are discounted and infected cattle slaughtered that only return a salvage value. The price discount on cattle purchased reduces the economic impact of these costs on the producer. Under the voluntary movement control testing scenarios considered, the producer does not have to bear any of the external costs relating to threats to New Zealand's meat trade and the adverse implications for public health which arise as Tb prevalence levels increase. Some regulatory intervention may therefore be required in order to reduce herd Tb prevalence.

The analysis undertaken in this study highlights that policies which lower the implicit value of infected cattle provide the producer with an incentive to lower herd Tb prevalence levels. A possible policy response consistent with this finding is the imposition of a disease tax on infected cattle. Under a disease tax producers would be fined for any infected cattle identified. To achieve the desired reduction in herd infection levels the fine would be set at an amount that reflected more accurately the marginal social cost of Tb infection. The producer would therefore be confronted with a more realistic cost of an infected animal. Previous research suggests that producers may respond to higher costs of infected animals by taking non-compliant action with respect to Tb control (Bicknell, 1995). Establishing the appropriate amount of the fine would require considering the strategic behaviour that would likely be adopted by producers to avoid the penalty imposed by a fine.

Another interesting issue concerns the development of the price discount within the store cattle market. Under the assumption of risk neutrality the price discount provides an incentive for producers to purchase cattle from infected herds. Such strategic behaviour, if adopted by a large proportion of store cattle buyers, would increase the market demand for cattle from infected herds and consequently reduce the amount of the discount on store cattle by increasing the price. Numerical results reveal that because it is optimal for producers to purchase cattle at the highest level of discount it is likely that the market price of cattle would be bid up to a level that reflected the expected cost of purchasing infected cattle. It should be noted that the analysis has focused on cattle being purchased and sold between movement controlled herds only. In markets dominated by producers with different herd types and Tb status, the expected cost of purchasing infected cattle will vary and therefore the level at which the store cattle price discount would persist would also vary.

A reason why the discount has been observed in store cattle markets is probably due to many producers being risk averse towards Tb infection entering their herds. Nevertheless as suggested previously the factors that will lead to higher levels of discount that are sustainable in a deregulated market remain unclear. The analysis indicates that to assist the market in creating and transforming the discount into a disincentive for those producers who are not risk averse some form of regulatory response, beyond the provision of information, is required.

6.4 Study Limitations and Opportunities for Further Research

This study has followed Bicknell's (1995) approach to the economic analysis of livestock disease control by representing the producer's response to cattle production and Tb control in a Tb vector risk area as an optimal control problem. The optimal control formulation has permitted numerical results to be obtained which provide insight into how risk neutral producers respond in different cattle price discounting regimes and policy environments. The use of non-linear programming to solve the optimal control problem has required several simplifying assumptions to reduce the complexity of the model and facilitate a numerical solution.

The hypothetical cattle production system is highly abstracted. Age and sex structures within the herd have been ignored and the herd size has been kept constant. Although these abstractions have simplified the mathematical representation of herd management and marketing options, they permit the analysis to focus on movement control.

With respect to the average price of store cattle sold, it is assumed that the price-infection relationship is linear. No empirical data was found that suggested the actual functional form of the relationship between price and infection except that it is inverse. The advantage of assuming linearity is that it reduces the amount of non-linearity in the control problem and hence assists in obtaining a solution. Empirical research is required to provide more accurate information on the impact of Tb risk on store cattle prices.

The results and conclusions presented in this study relate to a risk neutral producer. This assumption was considered the necessary starting point for a study into cattle producer behaviour. It is evident from anecdotal reports on the responses of cattle producers to Tb testing and store cattle purchasing decisions that a full spectrum of risk profiles exists. A useful role for future research is to gain empirical insight into how cattle producers respond to the risk of allowing Tb infection into their herds. Results obtained could then be used to construct behavioural models based on different risk profiles.

The final assumption is that the average price received for store cattle is a function of the apparent Tb infection in the herd only. The model does not allow for the determination of average price via interaction of supply and demand in the store cattle market. Further research into the dynamics of the store cattle market could provide insight into the optimal magnitudes of store cattle price discounts and whether they are likely to persist.

The sensitivity analysis in Chapter 5 identifies that changes to several key parameter values materially influence results. These observations highlight the importance of further empirical research into the rate of Tb transmission between cattle and from wildlife vectors, the sensitivity of Tb tests, and wildlife vector control costs. The methodology applied in this study is not a substitute for empirical research into bovine tuberculosis control but rather a complement to it. The optimal control model increases understanding of important economic issues concerning Tb control at a time when high quality empirical data is scarce. As the quality of parameter values are improved the model can be updated, new solutions obtained, and the relationships between cattle production and disease control that are identified in this research can be further clarified.

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Appendix 1: GAMS Input File for Base Run (10% Maximum Store Cattle Price Discount)

```
$OFFSYMLIST
$OFFSYMXREF
OPTION LIMROW = 0 ;
OPTION LIMCOL = 0 ;
OPTION ITERLIM = 10000 ;

*Model AGT2

 SETS
   T  time period   /0*70/

 SCALARS
   INITS     initial susceptible cattle                  /0.148313/
   INITI     initial infected cattle                     /0.003027/
   INITPOS   initial possum population                   /1.33/
   DELTA     annual discount rate                        /0.087/
   P1        price for weaners purchased                 /3.49/
   P2        price for clear herd store R2 cattle        /4.82/
   P3        price for R2 cattle slaughtered             /5.16/
   P4        price for cull cows                         /3.27/
   L         slaughter levy                              /0.0871/
   MU        salvage value                               /.35/
   RHO       breeding component culled                   /.16/
   GAMMA1 compensation non-lesioned                      /.65/
   GAMMA2 compensation lesioned                          /.65/
   PSI       annual whole herd test frequency            /1/
   ETA       MC parameter for cattle purchases           /1/
   OMEGA     maximum price discount                      /0.10/
   IOTA      maximum herd infection level for stores     /0.0499/
   SIGMA     in-contact testing parameter                /250/
   NU1       variable cost of cattle                     /0.1348/
   NU2       additional grazing costs R2 slaughtered     /0.52/
   ALPHA     testing cost                                /0.0353/
   BETA1     cattle-cattle disease transmission          /3/
   BETA2     possum-cattle disease transmission          /0.003/
   TAU1      false positives                             /.01/
   TAU2      true positives                              /.75/
   K1        profit maximising stocking rate             /.15134/
   PHI       breeding herd calving percentage            /.67/
   B         percentage of herd breeding cattle          /.65/
   K2        possum population carrying capacity         /3/
   W         cost of time hunting possums                /0.9426/
   Z         possum harvest parameter                    /6.449/
   A         possum growth rate                          /.30/
```

```
PARAMETERS

   STRT(T) ;

   STRT(T) = 1 ;
   STRT("0") = 0 ;

Display
   STRT ;

VARIABLES
   S(T)          susceptible cattle
   I(T)          infected cattle
   F(T)          proportion of marketable R2 cattle sold as stores
   MC(T)         movement control testing
   APP(T)        price paid for weaner cattle purchased
   POS(T)        possum population
   H(T)          possums harvested
   NREV          net revenue

PARAMETER
   DIS(T)        annual discount factor ;

   DIS(T) = (1/(1+DELTA))**(ORD(T)-1);


EQUATIONS
   NETREV        total discounted net revenue
   SUSCEP(T)     equation of motion for susceptible R2 cattle
   INFECT(T)     equation of motion for infected R2 cattle
   POSSUMS(T)        equation of motion for possums
   POSCON(T)     possum harvest constraint ;


NETREV.. SUM(T$STRT(T), DIS(T)*((P3-L)*(1-B)*(S(T)*(1-PSI*TAU1)*
(1-(F(T)+MC(T)*(1-F(T))*(1-EXP(-SIGMA*F(T)))*TAU1))+MU*I(T)*(1-
PSI*TAU2)*(1-(F(T)+MC(T)*(1-F(T))*(1-EXP(-SIGMA*F(T)))*TAU2)))+
(P4-L)*RHO*B*(S(T)*(1-PSI*TAU1)+MU*I(T)*(1-PSI*TAU2))+
(((P2-P2*(1-OMEGA))/(0-IOTA))*((((PSI*(TAU1*S(T)+TAU2*I(T)))/(S(T)+I(T)))-
TAU1)/(1-(TAU1+(1-TAU2))))+P2)*
F(T)*(1-B)*((1-MC(T)*TAU1)*S(T)*(1-PSI*TAU1)+(1-MC(T)*TAU2)*I(T)*
(1-PSI*TAU2))- (APP(T)-MC(T)*((1-((APP(T)-P1)/((P1-P1*(1-OMEGA))/(0-
IOTA)))*
(1-ETA*TAU2))*((P1-L)*GAMMA1*TAU1-ALPHA)+
((APP(T)-P1)/((P1-P1*(1-OMEGA))/(0-IOTA)))*(1-ETA*TAU2)*
((P1-L)*GAMMA2*TAU2-ALPHA)))*(K1-((S(T)+I(T))-(1-B)*((F(T)*(1-
MC(T)*TAU1)+
(1-(F(T)+MC(T)*(1-F(T))*(1-EXP(-SIGMA*F(T)))*TAU1)))*S(T)*(1-PSI*TAU1)+
(F(T)*(1-MC(T)*TAU2)+(1-(F(T)+MC(T)*(1-F(T))*
```

```
(1-EXP(-SIGMA*F(T)))*TAU2)))*I(T)*(1-PSI*TAU2))-RHO*B*(S(T)+I(T))-
MC(T)*((1-B)*(F(T)+(1-F(T))*(1-EXP(-SIGMA*F(T))))+B*(1-EXP(-
SIGMA*F(T))))*
(TAU1*S(T)*(1-PSI*TAU1)+TAU2*I(T)*(1-PSI*TAU2))-
PSI*(TAU1*S(T)+TAU2*I(T))+PHI*B*(S(T)*(1-PSI*TAU1)+I(T)*(1-
PSI*TAU2))))+
MC(T)*((1-B)*(F(T)+(1-F(T))*(1-EXP(-SIGMA*F(T))))*
(((P2-L)*GAMMA1*TAU1-ALPHA)*S(T)*(1-PSI*TAU1)+
((P2-L)*GAMMA2*TAU2-ALPHA)*I(T)*(1-PSI*TAU2))+
B*(1-EXP(-SIGMA*F(T)))*(((P4-L)*GAMMA1*TAU1-ALPHA)*S(T)*(1-
PSI*TAU1)+((P4-L)*GAMMA2*TAU2-ALPHA)*I(T)*(1-PSI*TAU2)))+
PSI*(B*(S(T)*((P4-L)*GAMMA1*TAU1-ALPHA)+I(T)*((P4-L)*GAMMA2*TAU2-
ALPHA))+(1-B)*(S(T)*((P2-L)*GAMMA1*TAU1-ALPHA)+I(T)*
((P2-L)*GAMMA2*TAU2-ALPHA)))-(NU1*(S(T)+I(T))+NU2*(1-B)*
(S(T)*(1-PSI*TAU1)*(1-(F(T)+MC(T)*(1-F(T))*(1-EXP(-SIGMA*F(T)))*TAU1))+
I(T)*(1-PSI*TAU2)*(1-(F(T)+MC(T)*(1-F(T))*(1-EXP(-SIGMA*F(T)))*TAU2))))-
(W/Z)*((H(T)/POS(T))**2))) =E= NREV ;

SUSCEP(T)$STRT(T)..  S(T) =E=  S(T-1)-BETA1*S(T-1)*I(T-1)-
BETA2*S(T-1)*POS(T-1)-(1-B)*(F(T-1)*(1-MC(T-1)*TAU1)+
(1-(F(T-1)+MC(T-1)*(1-F(T-1))*(1-EXP(-SIGMA*F(T-1)))*TAU1)))*
S(T-1)*(1-PSI*TAU1)-RHO*B*S(T-1)+(K1-((S(T-1)+I(T-1))-(1-B)*((F(T-1)*
(1-MC(T-1)*TAU1)+(1-(F(T-1)+MC(T-1)*(1-F(T-1))*
(1-EXP(-SIGMA*F(T-1)))*TAU1)))*S(T-1)*(1-PSI*TAU1)+
(F(T-1)*(1-MC(T-1)*TAU2)+(1-(F(T-1)+MC(T-1)*(1-F(T-1))*
(1-EXP(-SIGMA*F(T-1)))*TAU2)))*I(T-1)*(1-PSI*TAU2))-
MC(T-1)*((1-B)*(F(T-1)+(1-F(T-1))*(1-EXP(-SIGMA*F(T-1))))+
B*(1-EXP(-SIGMA*F(T-1))))*(TAU1*S(T-1)*(1-PSI*TAU1)+TAU2*I(T-1)*
(1-PSI*TAU2))-RHO*B*(S(T-1)+I(T-1))-PSI*(TAU1*S(T-1)+TAU2*
I(T-1))+PHI*B*(S(T-1)*(1-PSI*TAU1)+I(T-1)*(1-PSI*TAU2))))*
(1-((APP(T-1)-P1)/((P1-P1*(1-OMEGA))/(0-IOTA)))*(1-ETA*TAU2))*
(1-MC(T-1)*TAU1)+PHI*B*S(T-1)*(1-PSI*TAU1)-PSI*S(T-1)*TAU1-
MC(T-1)*((1-B)*(F(T-1)+(1-F(T-1))*(1-EXP(-SIGMA*F(T-1))))+
B*(1-EXP(-SIGMA*F(T-1))))*S(T-1)*(1-PSI*TAU1)*TAU1 ;

INFECT(T)$STRT(T)..  I(T) =E=  I(T-1)+BETA1*S(T-1)*I(T-1)+
BETA2*S(T-1)*POS(T-1)-(1-B)*(F(T-1)*(1-MC(T-1)*TAU2)+
(1-(F(T-1)+MC(T-1)*(1-F(T-1))*(1-EXP(-SIGMA*F(T-1)))*TAU2)))*
I(T-1)*(1-PSI*TAU2)-RHO*B*I(T-1)+(K1-((S(T-1)+I(T-1))-(1-B)*((F(T-1)*
(1-MC(T-1)*TAU1)+(1-(F(T-1)+MC(T-1)*(1-F(T-1))*
(1-EXP(-SIGMA*F(T-1)))*TAU1)))*S(T-1)*(1-PSI*TAU1)+
(F(T-1)*(1-MC(T-1)*TAU2)+(1-(F(T-1)+MC(T-1)*(1-F(T-1))*
(1-EXP(-SIGMA*F(T-1)))*TAU2)))*I(T-1)*(1-PSI*TAU2))-
MC(T-1)*((1-B)*(F(T-1)+(1-F(T-1))*(1-EXP(-SIGMA*F(T-1))))+
B*(1-EXP(-SIGMA*F(T-1))))*(TAU1*S(T-1)*(1-PSI*TAU1)+TAU2*I(T-1)*
(1-PSI*TAU2))-RHO*B*(S(T-1)+I(T-1))-PSI*(TAU1*S(T-1)+TAU2*
I(T-1))+PHI*B*(S(T-1)*(1-PSI*TAU1)+I(T-1)*(1-PSI*TAU2))))*
((APP(T-1)-P1)/((P1-P1*(1-OMEGA))/(0-IOTA)))*(1-ETA*TAU2)*
(1-MC(T-1)*TAU2)+PHI*B*I(T-1)*(1-PSI*TAU2)-PSI*I(T-1)*TAU2-
```

```
MC(T-1)*((1-B)*(F(T-1)+(1-F(T-1))*(1-EXP(-SIGMA*F(T-1))))+
B*(1-EXP(-SIGMA*F(T-1))))*I(T-1)*(1-PSI*TAU2)*TAU2 ;

POSSUMS(T)$STRT(T).. POS(T) =E= POS(T-1)+A*POS(T-1)*(1-(POS(T-1)/K2))-
H(T-1) ;

POSCON(T)$STRT(T).. H(T) =L= .95*POS(T) ;


* BOUNDS FOR VARIABLES
   S.LO(T) = 0.0001 ;
   I.LO(T) = 0 ;
   POS.LO(T) = 0.0 ;
   F.LO(T) = 0 ;
   MC.LO(T) = 1 ;
   APP.LO(T) = P1*(1-OMEGA) ;
   H.LO(T) = 0 ;
   S.UP(T) = .15134 ;
   I.UP(T) = .15134 ;
   POS.UP(T) = 3 ;
   F.UP(T) = 1 ;
   MC.UP(T) = 1 ;
   APP.UP(T) = P1 ;
   H.UP(T) = 3.0 ;

* FIXED INITIAL VALUES
    S.FX("0") = INITS ;
    I.FX("0") = INITI ;
    POS.FX("0") = INITPOS ;
    F.FX("0") = 1 ;
    MC.FX("0") = 1 ;
    APP.FX("0") = P1*(1-OMEGA) ;
    H.FX("0") = .2 ;

* STARTING INITIAL VALUES
    S.L(T) = INITS ;
    I.L(T) = INITI ;
    POS.L(T) = .8*INITPOS ;
    F.L(T) = .5 ;
    MC.L(T) = 1 ;
    APP.L(T) = P1*(1-(.8*OMEGA)) ;
    H.L(T) = .2 ;

 MODEL AGT2 /ALL/ ;

 SOLVE AGT2 USING NLP MAXIMISING NREV ;
```

Appendix 2: Steady State Results for Policy Scenarios and Discount Regimes

Table A.1 Steady State Values for Herd Splitting Simulation ($\sigma = 0$)

Variable	Store Cattle Price Discount (Maximum)					
	5%	**10%**	**15%**	**20%**	**25%**	**30%**
Possums/Hectare	2.07	1.79	1.54	2.47	2.51	2.54
Possum Harvest Rate	9.30%	12.11%	14.61%	5.25%	4.93%	4.61%
Cattle Slaughtered	0	0	0	80.93	80.91	80.90
Cattle Sold as Stores	80.06	80.21	80.36	0	0	0
Cattle Purchased	10.23	9.82	9.46	10.80	10.86	10.90
Average Store Cattle Sale Price[1]	$474.21	$468.44	$464.37	$445.05	$435.26	$425.23
Average Weaner Cattle Purchase Price	$331.55	$314.10	$296.85	$279.20	$261.75	$244.30
Net Revenue/Hectare	$25.08	$24.89	$24.76	$24.65	$24.77	$24.89
Actual Tb Prevalence	1.61%	1.40%	1.22%	1.91%	1.94%	1.96%
Marginal Value Susceptible Cattle	$504.01	$485.57	$467.96	$447.84	$430.91	$413.99
Marginal Value Infected Cattle	-$436.39	-$793.57	-$1155.37	-$58.64	-$43.53	-$28.45
Marginal Value Possums	-$1.43	-$2.15	-$3.02	-$0.67	-$0.62	-$0.57

[1] The average price the producer receives if cattle are sold as stores.

Table A.2 Steady State Values for Lowering the "High Risk" Threshold ($i = 0.0199$)

Variable	**Store Cattle Price Discount (Maximum)**					
	5%	**10%**	**15%**	**20%**	**25%**	**30%**
Possums/Hectare	1.83	2.41	2.45	2.48	2.51	2.54
Possum Harvest Rate	11.71%	5.84%	5.53%	5.22%	4.90%	4.59%
Cattle Slaughtered	0	80.98	80.98	80.96	80.95	80.93
Cattle Sold as Stores	80.48	0	0	0	0	0
Cattle Purchased	10.99	10.62	10.66	10.71	10.75	10.79
Average Store Cattle Sale Price[1]	$468.88	$437.23	$414.02	$390.26	$365.93	$341.03
Average Weaner Cattle Purchase Price	$331.55	$314.10	$296.65	$279.20	$261.75	$244.30
Net Revenue/Hectare	$24.45	$24.44	$24.55	$24.67	$24.78	$24.90
Actual Tb Prevalence	1.08%	1.85%	1.87%	1.89%	1.92%	1.94%
Marginal Value Susceptible Cattle	$498.24	$479.64	$462.83	$446.02	$429.23	$412.44
Marginal Value Infected Cattle	-$725.55	-$87.33	-$72.28	-$57.25	-$42.25	-$27.28
Marginal Value Possums	-$2.03	-$0.77	-$0.72	-$0.67	-$0.62	-$0.57

[1] The average price the producer receives if cattle are sold as stores.

Table A.3 Steady State Values for No Reactor Cattle Compensation ($\gamma_1 = 77, \gamma_2 = 0.27$)

Variable	Store Cattle Price Discount (Maximum)					
	5%	**10%**	**15%**	**20%**	**25%**	**30%**
Possums/Hectare	1.99	1.77	1.57	1.40	2.27	2.30
Possum Harvest Rate	10.07%	12.26%	14.25%	16.03%	7.26%	6.96%
Cattle Slaughtered	0	0	0	0	81.02	81.01
Cattle Sold as Stores	80.37	80.47	80.55	80.63	0	0
Cattle Purchased	11.30	11.02	10.76	10.53	10.51	10.56
Average Store Cattle Sale Price[1]	\$476.23	\$471.68	\$468.19	\$465.57	\$439.40	\$430.23
Average Weaner Cattle Purchase Price	\$331.55	\$314.10	\$296.65	\$279.20	\$261.75	\$244.30
Net Revenue/Hectare	\$24.71	\$24.61	\$24.54	\$24.50	\$24.56	\$24.67
Actual Tb Prevalence	1.19%	1.07%	0.95%	0.85%	1.76%	1.79%
Marginal Value Susceptible Cattle	\$503.74	\$485.99	\$468.69	\$451.74	\$430.15	\$413.15
Marginal Value Infected Cattle	-\$522.68	-\$808.80	-\$1096.92	-\$1386.67	-\$286.24	-\$270.96
Marginal Value Possums	-\$1.61	-\$2.20	-\$2.88	-\$3.65	-\$1.01	-\$0.96

[1] The average price the producer receives if cattle are sold as stores.

Table A.4 Movement Control Compliance Costs for Store Cattle Production

Store Cattle Price Discount Regime	Steady State Annual Net Revenue			Steady State Annual Costs & Benefits	
	Mandatory MC Testing	**Voluntary MC Testing (1)**	**Voluntary MC Testing (2)**	**MC Testing Compliance Cost**	**Voluntary Pre-Movement Testing Benefit**
5%	$38,864	$39,752	$39,711	$887.16	$40.29
10%	$38,643	$39,402	$39,255	$759.03	$146.83
15%	$38,483	$39,153	$38,913	$670.04	$240.04
20%	$38,379	$39,003	$38,499	$624.03	$503.14
25%	$38,812	$38,839	$38,692	$27.11	$147.13
30%	$37,997	$39,025	$38,885	$27.42	$139.11

(1) Cattle purchased have been pre-movement tested by the seller.
(2) Cattle purchased have not been pre-movement tested by the seller.

Table A.5 Steady State Values for Voluntary Movement Control Testing: Reactor Compensation*

Variable	Store Cattle Price Discount (Maximum)					
	5%	**10%**	**15%**	**20%**	**25%**	**30%**
Possums/Hectare	2.09	1.79	1.54	1.33	2.51	2.54
Possum Harvest Rate	9.13%	12.04%	14.63%	16.49%	4.87%	4.55%
Cattle Slaughtered	0	0	0	0	80.91	80.90
Cattle Sold as Stores	81.11	81.24	81.36	81.47	0	0
Cattle Purchased	10.26	9.83	9.46	9.14	10.87	10.91
Movement Control Testing	No	No	No	No	No	No
Average Store Cattle Sale Price[1]	$473.65	$467.43	$463.00	$459.83	$432.55	$421.97
Average Weaner Cattle Purchase Price	$331.55	$314.10	$296.65	$279.20	$261.75	$244.30
Net Revenue/Hectare	$25.37	$25.14	$24.99	$24.92	$24.79	$24.90
Actual Tb Prevalence	1.73%	1.51%	1.31%	1.15%	2.05%	2.07%
Marginal Value Susceptible Cattle	$505.28	$489.87	$475.39	$460.11	$427.97	$411.09
Marginal Value Infected Cattle	-$416.28	-$781.02	-$1150.17	-$1403.27	-$40.72	-$25.69
Marginal Value Possums	-$1.39	-$2.13	-$3.03	-$3.33	-$0.61	-$0.57

*Reactor compensation is paid at 65% of Fair Market Value.

[1] The average price the producer receives if cattle are sold as stores.

Table A.6 Steady State Values for Voluntary Movement Control Testing: No Reactor Compensation[*]

Variable	Store Cattle Price Discount (Maximum)					
	5%	10%	15%	20%	25%	30%
Possums/Hectare	1.87	1.61	1.37	1.18	2.28	2.31
Possum Harvest Rate	11.24%	13.92%	16.24%	18.21%	7.23%	6.92%
Cattle Slaughtered	0	0	0	0	81.02	81.01
Cattle Sold as Stores	81.21	81.33	81.45	81.54	0	0
Cattle Purchased	9.95	9.56	9.22	8.94	10.53	10.57
Movement Control Testing	No	No	No	No	No	No
Average Store Cattle Sale Price[1]	$474.42	$468.81	$464.79	$461.97	$436.80	$427.11
Average Weaner Cattle Purchase Price	$331.55	$314.10	$296.65	$279.20	$261.75	$244.30
Net Revenue/Hectare	$25.22	$25.04	$24.92	$24.85	$24.56	$24.68
Actual Tb Prevalence	1.57%	1.37%	1.19%	1.04%	1.87%	1.89%
Marginal Value Susceptible Cattle	$506.74	$492.00	$478.01	$464.56	$428.34	$411.38
Marginal Value Infected Cattle	-$663.52	-$1030.66	-$1401.58	-$1775.25	-$284.35	-$269.11
Marginal Value Possums	-$1.91	-$2.75	-$3.75	-$4.91	-$1.01	-$0.95

[*] No reactor compensation is paid: false positives return their full carcass value, true positives return a salvage value.
[1] The average price the producer receives if cattle are sold as stores.

Table A.7 Steady State Values for Voluntary Movement Control Testing: Reactor Compensation and No Pre-Movement Test for Cattle Purchased*

Variable	Store Cattle Price Discount (Maximum)					
	5%	**10%**	**15%**	**20%**	**25%**	**30%**
Possums/Hectare	2.07	1.76	1.49	2.46	2.49	2.52
Possum Harvest Rate	9.28%	12.39%	15.09%	5.40%	5.07%	4.74%
Cattle Slaughtered	0	0	0	80.76	80.74	80.73
Cattle Sold as Stores	81.20	81.34	81.47	0	0	0
Cattle Purchased	9.98	9.54	9.15	11.29	11.35	11.40
Movement Control Testing	No	No	No	Yes	Yes	Yes
Average Store Cattle Sale Price[1]	$474.36	$468.94	$465.34	$443.16	$432.86	$422.32
Average Weaner Cattle Purchase Price	$349.00	$349.00	$349.00	$279.20	$261.75	$244.30
Net Revenue/Hectare	$25.34	$25.05	$24.83	$24.57	$24.69	$24.82
Actual Tb Prevalence	1.58%	1.35%	1.15%	2.01%	2.03%	2.06%
Marginal Value Susceptible Cattle	$512.36	$510.11	$508.79	$457.35	$439.72	$422.09
Marginal Value Infected Cattle	-$424.95	-$803.25	-$1186.16	-$65.83	-$50.15	-$34.52
Marginal Value Possums	-$1.43	-$2.23	-$3.22	-$0.70	-$0.65	-$0.60

*Reactor compensation is paid at 65% of Fair Market Value; η equals 0.

[1] The average price the producer receives if cattle are sold as stores.