Bio-economic analysis of foot-and-mouth disease transmission between wildlife and livestock populations in Limpopo Province, South Africa

by

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Dedication

To my husband Stefano, our daughter Masase and son Masana Tempia

Declaration

I declare that this thesis I hereby submit for the degree of PhD in Agricultural Economics at the University of Pretoria is entirely my own work and has not been submitted anywhere else for the award of a degree or otherwise.

Parts of the thesis have been published and submitted for publication in journals.

Any errors in thinking and omissions are entirely my responsibility.

Signed: ……….
Name:

Sikhweni NP

July 2014

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Abstract

This study contributed to the existing body of literature on the economics of smallholder livestock systems and management of conflicts between livelihood objectives of local livestock farming communities and neighbouring conservation parks in the presence of animal disease transmission such as foot-and-mouth disease (FMD). Published literature on the economics of animal disease and its control focused on a small number of developed countries, concentrating on the economic impact of animal disease on the commercial farming sector and neglecting the plight of small-scale farmers. Limiting economic analysis of animal disease to the commercial farming sector implies that the economic impact of animal disease on small-scale farmers is considered similar. In Sub-Saharan Africa, where 70% of the population is poor and depends on smallholder agricultural activities such as livestock farming for its livelihood, analysis of the economic consequences of animal disease on small-scale producers is therefore badly needed. This study investigated ways to better manage the trade-offs between keeping buffalo in the Kruger National Park (KNP) for the sake of conservation and for their recreational value and the livelihood objectives of the cattle

farmers who have to contend with the transmission of FMD. Furthermore, the study assessed the factors associated with cattle herd size in the study area in order to understand the underlying reasons, challenges and opportunities for the farming community in keeping livestock.

A negative binomial regression model was applied to analyse determinants of cattle ownership (eg cattle herd size) in the study area. The results of the analysis indicated that, contrary to the popular belief that rural households in developing countries own large herds of livestock for social reasons, the majority of communal livestock farmers in the study area kept livestock for economic/commercial reasons. However, limited access to marketing channels was found to be a major constraint on keeping large herds. Moreover, livestock farmers owning large herds experienced higher losses due to theft and mortality associated with diseases or predation. Given the fact that farmers in the study area keep livestock for economic reasons, but face constant challenges due to losses associated with livestock diseases, including FMD transmitted from infected buffalo from the KNP, the control of FMD could enhance the livelihood of this livestock farming community. A bio-economic model was accordingly developed to assess trade-offs between wildlife conservation and the livelihood objectives of the small-scale farmers dealing with FMD transmission (negative externality) from buffalo to cattle populations.

The theoretical model was solved using optimal control techniques to evaluate the trade-off between keeping buffalo in the park and the economic impact on the livelihood objectives of the cattle farmers in the presence of the negative externality of FMD transmission. Three different scenarios, namely (1) a conservation scenario with no unified resource management policy, (2) a social planner scenario and (3) a no-disease scenario, were compared. In the model formulation it is assumed that the stock of buffalo influences the size and the composition of cattle herds through disease transmission, and ultimately the benefit and livelihood of cattle farmers, but not *vice versa*. Accordingly, while the conservation agency can optimise its situation without being influenced by the harvest and the cattle holding of the farmers, farmers must adjust their harvest and stocks to the stock size of buffalos.

In contrast, the social planner scenario takes into consideration the interest of both agents and a socially optimal resource management policy is achieved. Analytical study results show that when the social planner allocates common resources, benefits to the farmers increase compared to the conservation scenario. While culling of buffalo is not currently practised at the park, analytical study results demonstrated that culling would be beneficial to farmers if practised in the KNP. Results of the empirical simulation analyses also confirm that when culling of buffalo is implemented, the unified management scheme (social planner scenario) would yield fewer buffalo and less disease transmission (hence fewer infected cattle), as well as higher overall economic benefits than the pure conservation scenario.

An important implication of the study findings is the great potential for economic policy to enhance the welfare of smallholder cattle farmers in the country. Investment in farmers' education and awareness of new technological innovations, appropriate measures and practices in breeding and veterinary services are proposed to be critical for improving small livestock farmers' welfare. In addition, the study also proposes policy interventions to improve access to marketing channels and information and increased public investment in efficient game-proof fences that will effectively deter wildlife from escaping from game parks to come into contact with adjacent communal livestock, as well as more effective protection measures against theft.

Results of the sensitivity analyses indicate that overall, higher benefits would be achieved when intervention measures contributing to a reduction in the proportion of buffalo that escape from the park, as well as a reduction in cattle-to-cattle transmission, are introduced simultaneously. However, comparing the two measures, investing more in preventing infection among cattle populations through quarantine and vaccination programmes would yield higher benefits to the farmers compared to decreasing FMD transmission from buffalo to cattle populations through culling of buffalos and/or increased investment in maintenance of the fence. Thus, the main policy implication of this study involves weighing up the costs and benefits of the two intervention measures. While this study assessed the impact of these interventions on farmers' livelihood, the costs of such intervention measures were not considered, which represents a gap requiring further future research work.

This study is the first to use bio-economic modelling to examine the impact of FMD on small-scale farmers within the wildlife-livestock interface in a developing economy. The model developed in this study is widely applicable to many other similar situations where transmission of animal disease from wildlife populations poses serious threats to the livelihood of small-scale livestock farmers. In addition, the policy interventions proposed in the study contribute to the search for feasible management solutions and policy measures for balancing the trade-off between environmental and economic benefits from keeping wildlife and the livelihood objectives of small-scale farmers living adjacent to conservation areas.

Nonetheless, this study has limitations ranging from the simplified assumptions made to the availability of suitable data. Firstly, the optimisation model treats farmers as a homogeneous group, whereas in reality the impact in terms of benefits and costs will differ across various farmer groups depending among others on location and distance to the park. The model also incorporates non-market variables such as social status attached to cattle ownership and tourist value attached to buffalo viewing, which will require better valuation methods than the overly simplified assumptions made in this study. In addition, while the study quantifies the economic benefits of proposed FMD control measures, it does not assess the cost of such measures. While the construction of proper fencing can be expensive, there are other instruments that can be implemented to reduce the transmission between wildlife and livestock. For example, a tax on the entrance fee can be imposed, which may be used for maintaining the fence around the park.

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ACRONYMS AND ABBREVIATIONS

AHT	Animal Health Technician
bTB	Bovine Tuberculosis
BWH	Bicknell, Wilen and Howitt
BZNV	Buffer Zone without Vaccination
BZV	Buffer Zone with Vaccination
CBA	Cost-benefit Analysis
CGE	General Equilibrium Models
DAFF	Department of Agriculture, Forestry and Fisheries Agriculture
FMD	Foot-and-mouth Disease
FMDV	Foot-and-mouth Disease Virus
GCIS	Government Communication and Information System
GDP	Gross Domestic Product
I-O	Input-output
KNP	Kruger National Park
OIE	World Organisation for Animal Health
StatsSA	Statistics South Africa
SAT	South African Territories
TA	Traditional Authority
USAID	United States Agency for International Development

CHAPTER 1: INTRODUCTION

1.0 Background

In most African countries, agriculture is still the largest contributor to gross domestic product (GDP); the biggest source of foreign exchange, accounting for about 40% of the continent's hard currency earnings; and the main generator of savings and tax revenues (Ruane & Sonnino, 2010). As 70% of the continent's extremely poor depend on agriculture for their livelihood, it is estimated that growth in agriculture is about four times more effective in raising the income of extremely poor people than growth originating from other sectors (World Development Report, 2008).

Although in South Africa the agricultural sector contributes less than 4% of GDP, this sector contributes 10% of total reported employment (Organisation for Economic Cooperation and Development), 2006). In addition, the sector is highly export-oriented, exporting about one third of total production, thereby generating a significant amount of foreign exchange for the country. Within the sector, livestock plays a crucial role in sustaining the livelihood of people living in rural areas; 40% of livestock in South Africa is owned by small-scale communal farmers (Department of Agriculture, Forestry and Fisheries [DAFF]), 2010). Nevertheless, this group of farmers remains poor. Their level of poverty can be attributed to the inability of small-scale farmers to extract maximum profits from their livestock assets, especially when dealing with outbreaks of animal diseases such as foot-and-mouth disease (FMD).

The current situation in Limpopo Province, South Africa, where the Kruger National Park (KNP) has been established to conserve wildlife, is a typical example of the above. According to the World Organisation for Animal Health (OIE), the KNP is an FMD infection zone in which the FMD virus (FMDV) is present in free-ranging buffalo (DAFF, 2010). While buffalo in the KNP offer recreational value to tourists and economic benefits to the park agency, they also transmit FMDV to livestock grazing adjacent to the park. FMD is known to have devastating effects on the health of cloven-hoofed animals, including domesticated animals such as cattle, pigs, sheep and goats. This disease spreads rapidly and if not controlled quickly, its economic effects can be substantial. In a susceptible non-vaccinated population, morbidity (the proportion of animals that will get the disease) could be as high as 100% (Vosloo *et al.*, 2009). The disease is rarely fatal in adult animals but mortality can be high in young animals. In addition, losses in milk and meat production are a common feature of FMD infection. Because of its potential to spread rapidly within a short time, its virulence that can induce severe livestock production losses locally, especially for the poor who depend on livestock for their livelihood, and its far-reaching implications for international trade, the OIE ranks FMD as a priority disease for global control(Forman *et al.*, 2009).

In spite of its large economic effects, especially for the poor, limited research has been conducted to assess its impact on small-scale livestock farmers and the way in which they can use their livestock asset base to enhance their livelihood. Thus, there is an urgent need to assess the impact of animal disease such as FMD on the livelihood of small-scale farmers. In addition, it is essential to formulate an appropriate resource management policy such that the trade-off between keeping wildlife as a recreational asset generating income for the park and livestock that supports the livelihood of small-scale farmers is determined in an optimal way to the maximum benefit of both groups. Unless the park agency policy makers consider the negative externality they are imposing on local farmers, conservation policy has the potential to lead to a reduction in social welfare for society as a whole. In this regard the positive role that livestock plays in the livelihood of small-scale farmers may be undermined if policies fail to take these interactions into consideration.

1.1 Statement of the Problem

Epidemiology with economic outputs (economics of disease transmission) has been used widely to assess the economic impact of animal disease such as FMD on large commercial farmers, especially in developed countries (Rich *et al.*, 2005). Analysis of the impact of animal disease has rarely been used to assess the impact on small-scale farmers in the context of developing countries. Given the operation of different production systems, the impact of animal disease is likely to vary between small-scale and commercial farmers. For example, whereas commercial livestock farmers own and keep stock for commercial reasons, small-scale farmers own and keep livestock for both commercial and non-commercial reasons. Non-commercial reasons may include owning livestock to mitigate unforeseen and unplanned events, as a store of value, as a means of draught power or as a source of social standing within their communities: the more livestock they have, the more enhanced is their social status (Perry & Randolph, 2003). In case of an outbreak of FMD, small-scale farmers might suffer a significant loss if the disease wipes out their entire herd, thereby destroying their source of livelihood. In fact, it has been observed that small-scale farmers are generally reluctant to sell their livestock and would only do so under extreme circumstances such as during droughts, difficult economic conditions or disease outbreaks (Bengis, 2011). In the instances where they are forced to sell by circumstances, they would normally receive lower prices than otherwise, hence failing to extract maximum potential profits.

In addition, the impact of animal disease on small-scale farmers is exacerbated by the establishment of parks to conserve wildlife, which are often erected next to communal areas where small-scale farmers graze their livestock. Several studies have demonstrated the conflict that arises between local communities and conservation park agencies in the context of grazing competition (Skonhoft, 1998; Borge-Johannesen & Skonhoft, 2005; Fischer *et al.*, 2010; Barnes, 1996). Conflict, however, may also arise in response to protected wildlife escaping from the park into the communal areas adjacent to the park where they mingle with livestock, transmitting diseases. Contrary to commercial farmers who keep their livestock in protected areas with a certain level of biosecurity measures, the livestock of small-scale farmers is subject to constant risk of disease transmission because they graze in open areas with fewer biosecurity measures where they can mingle with infected wildlife. As said above, this represents the current situation in Limpopo Province, where FMD-infected buffalo escape from the KNP into adjacent areas, thereby transmitting the FMDV to livestock. It is therefore important to assess the optimal trade-off between keeping FMD infected buffalo in the park for their recreational value and the livelihood objectives of the small-scale farmers living adjacent to the park.

1.2 Objectives of the Study

The main objective of this study is to assess the economic significance of livestock ownership among communal cattle farmers next to the KNP and to determine how transmission of FMD from the park wildlife to cattle affects the welfare of this group of farmers. Under the main objective, the following specific goals will be pursued:

1. To analyse the determinants of livestock ownership (herd size) for the small-scale cattle farmers living adjacent to the KNP, Limpopo Province.
2. To analyse the trade-off between wildlife conservation in terms of keeping FMD-infected buffalo in the park and livestock ownership of small-scale farmers in the study area in the presence of FMD (negative externality) that affects their livelihood through the use of a bio-economic model.
3. To use the developed bio-economic model to determine the optimal regime for managing these conflicts by comparing a socially optimal resource management scheme to situations with no unified resource management policy and no disease transmission.
4. To distil implications of the study results for improved resource management and policy design that promote conservation at minimal externality costs to the livelihood of adjacent communities.

1.3 Hypotheses of the Study

1. Socio-economic factors influence the herd size of small-scale farmers and consequently their livelihood.
2. The presence of a negative externality (FMD) from buffalo to cattle populations will lead to a lower number of healthy cattle, a higher number of infected cattle and lower benefits to small-scale cattle farmers.
3. Internalising the source of the externality through relevant policy instruments such as adjusting the proportion of buffalo escaping from the park or reducing the interaction between infected and healthy cattle will lead to a higher number of healthy cattle, lower number of infected cattle and hence higher benefits to the cattle farmers

1.4 Approaches and Methods of the Study

The study will use two analytical techniques to attain the above objectives. Firstly, a negative binomial regression model will be estimated to analyse the determinants of cattle ownership (herd size) among communal cattle farmers living adjacent to the KNP. This model will be implemented empirically based on cross-section data to be collected from surveys of communal livestock owners in the study area. Secondly, optimal control techniques will be employed to develop a bio-economic model with ecological interactions between wildlife and livestock populations. The developed model will be employed to determine the optimal disease management strategy that ensures that the trade-offs between keeping wildlife in the park for tourist and recreational benefits and the livestock that supports the livelihood of small-scale farmers is managed in an optimal way. The model will be constructed using parameters (ecological, economic and epidemiological) from previous studies. Primary data will be obtained through a household survey questionnaire, interviews with local veterinarians and the livestock committees of the selected villages in the study area.

1.5 Organisation of the Thesis

The thesis is organized as follows: Chapter 2 reviews literature of relevance to the study. Background to the importance of livestock in the economy of South Africa and the study area is given in Chapter 3, as well as an analysis of the main determinants of livestock ownership (herd size) for small-scale farmers living adjacent to the KNP in Limpopo Province. The analytical framework for optimal control of FMD transmission between wildlife (buffalo) kept in the KNP and livestock of adjacent small cattle farmers is developed in Chapter 4. Chapter 5 presents numerical illustration of application of the optimal control model developed in Chapter 4 to the case study area. Chapter 6 summarises the methods used in the study, derives conclusions and implications of the study findings for optimal management and policy design of wildlife conservation projects under disease transmission situations and defines the limitations of the study and areas of potential future research.

CHAPTER 2: REVIEW OF RELEVANT LITERATURE

2.0 Introduction

Given the devastating economic effects that FMD can have for livestock farmers and the economy at large, various models have been developed and used by economists to estimate the costs of FMD to commercial farmers and consumers under alternative control strategies. Models used to analyse the economics of animal disease span a wide range of formulations from partial equilibrium to multi-sector and general equilibrium approaches. This chapter reviews literature on various methods used to assess the economic impact of animal disease, specifically focusing on FMD. The latter part of the chapter reviews literature on studies that assess the economic impact of animal disease within a wildlife-livestock interface. It will be clear from the literature that the existing studies have come mainly from a small number of developed countries, have concentrated on particular commodities and have often been associated with the specific occurrence of an outbreak or an epidemic. In addition, these studies have focused mainly on the economic impact of animal disease on commercial farming, while neglecting the impact on small-scale farmers.

2.1 Partial Equilibrium Models

Three types of partial equilibrium models have been employed to analyse the economic implications of animal disease and its management and control. The first category of these models employed cost-benefit analysis (CBA) methods. The two other categories made use of either econometric estimation or optimisation models.

2.1.1 Cost-benefit Analysis Methods

Animal health economics frequently use CBA methods to evaluate strategies for the prevention and control of diseases (Berentsen *et al.*, 1992). CBA is popular for its ability to provide valuable information on the effects of the disease on revenues from livestock production and the cost of public intervention (Rushton *et al.*, 1999). CBA is generally used to assess the economic impact of animal disease at farm or herd level and the results are aggregated to reflect costs and benefits at a macro-level. A significant number of studies have been conducted in developed countries, examining the economic impact of FMD on the commercial livestock sector, while a limited number of studies have been conducted in developing countries to determine the economic impact of FMD outbreaks on commercial and small-scale farming systems. Some studies examined only direct costs of FMD control or compared the direct benefits and costs of the diseases, but neglected indirect impacts. Other studies compared the impacts of acute and chronic forms of FMD.

Studies conducted in developed countries include that of Ekboir (1999) who examined the potential effects of an FMD outbreak on the commercial livestock industry in California and calculated direct, indirect and induced output losses in the range of \$8.5-\$13.5 billion. A significant amount of the estimated effects, \$6 billion, resulted from the assumption that United States (US) meat exports would be banned from international markets. Paarlberg et al. (2003) estimated that an FMD outbreak would result in a direct and indirect loss in US farm income of \$14 billion and a reduction in national consumer expenditure of 7%. In another study, Krystynak and Charlebois (1987) estimated that an FMD outbreak would cost Canadian agriculture \$2 billion if exports were banned for one year and an additional \$2 billion if the export ban lasted six months longer. Thompson et al. (2002) estimated direct and indirect losses from FMD in the United Kingdom (UK) at £5.8 billion to £6.3 billion. In a similar study, Bates et al. (2003) estimated total eradication costs of FMD in the USA at \$61 million to \$551 million. The authors found that vaccination strategies were economically viable, yielding benefit cost ratios ranging from 5.0 to 10.1.

Limited application of CBA methods has been documented in some developing countries of South-east Asia and Africa. The nature and economic impact of FMD in developing countries vary considerably with the production systems in which the disease occurs, and the degree of risk of re-introduction from outside sources (Randolph *et al.*, 2002). The spread of FMD is often limited in developed countries because livestock is primarily kept in protected feedlots to avoid contact with potential FMD carriers or infected animals. In contrast, the spread of FMD in developing countries is through smallholder farming due to the high frequency of animal movement, which often results in livestock coming into contact with infected cattle and wildlife.

In Thailand, for example, FMD is prevalent primarily in village cattle, buffalo and pigs and can be continuously re-introduced by the high frequency of animal movement from neighbouring countries. In the Philippines FMD is currently endemic in the backyard pig system, which threatens the presence of a strong commercial pig sector. The pig sector generates a significant amount of revenue for the country, thus calling for disease control efforts that will assist the country to capitalise on opportunities to develop export trade (Randolph *et al.*, 2002).

Randolph et al. (2002) evaluated the impact of FMD and control of the disease in the Philippines and estimated benefit-cost ratios for public investment in eradication as ranging between 1.6 (under the assumption that the country does not export) and 12.0 (under the assumption that the country exports its livestock product). Commercial cattle producers were estimated to capture 84% of the benefits generated by the public investment in eradication, backyard cattle producers 4% and the government 12%. However, because of data unavailability, the study did not capture the indirect impact of FMD outbreaks. A similar study conducted in Thailand found that eradication of FMD would be economically viable, even without exports, with a predicted benefit-cost ratio of 3.73. On the assumption that exports were included in the analysis, the economic justification for FMD eradication was much stronger, giving a benefit-cost ratio of up to 15.1 (Perry *et al.*, 1999).

While some studies did not distinguish between the impact of the chronic and acute form of FMD, others did. Barasa et al. (2008) conducted a CBA study on FMD vaccination in South Sudan, examining the impact of FMD that occurred during 2004-2005 in the extensive pastoralist systems of Koch County. They examined the impact of FMD vaccination using measures such as FMD prevalence (acute or chronic), mortality and milk production. The study estimated a benefit-cost ratio of FMD vaccination of 11.5. Losses due to the chronic form of FMD accounted for 28.2% of the total FMD losses and losses due to the acute form accounted for 71.8%. The contribution of losses due to chronic FMD highlights the need for future studies to consider the impact of the chronic form of FMD, which is often persistent among pastoralists' herds in Africa and frequently neglected when assessing the impact of FMD.

Although CBA generates useful information for decision-making in evaluating the impact of the disease on a given herd or farm, it suffers from several drawbacks. CBA is often conducted at farm or herd level and the results are aggregated to reflect the costs at macro-level. The aggregation of results is based on the assumption that economic agents (consumers and producers) are homogeneous, implying that consumers and producers face the same demand and supply curves. Assuming homogeneity among economic agents might lead to misrepresentation of welfare changes because an FMD outbreak is likely to induce different reactions from different producers and consumers, which would in turn affect prices and hence their economic welfare. However, CBA can be designed to assess different types of scenarios that would easily accommodate different responses from different agents.

In addition, CBA methods may be inappropriate when the effects of the disease spill over to other sectors of the economy that are indirectly linked to livestock sectors. Linkages across levels of analysis (say from commercial to small-scale farmers) and across sectors (from farming to tourism) are not explicitly modelled in CBA methods. Moreover, CBA methods may not be well-suited to measure longer-term dynamic effects or impacts because a longer time period has more uncertainty associated with the benefits and costs of a particular project (Otte *et al.*, 2004). The shortcomings of CBA methods have prompted economists to develop alternative methodologies.

2.1.2 Econometric Response Models

As discussed above, one important shortcoming of CBA is that it has been applied to representative farm level cases. Econometric response models addressed this weakness by adopting demand and supply relationships for a specific commodity at a national level. By defining the relationships between demand and supply, econometrics response models have the ability to measure welfare changes in private benefits and costs to producers (producer surplus) and consumers (consumer surplus) (Just *et al.*, 1982).

Several studies have been conducted in developed countries to estimate the cost of an FMD outbreak at national level. Schoenbaum and Disney (2003) simulated the cost to the US government and the welfare effects of alternative control strategies in a hypothetical FMD outbreak in the country and estimated national-level economic impacts, including potential losses associated with lost meat exports. They estimated the total cost of an FMD outbreak by specifying the demand and supply functions for FMD-affected product markets (cattle, hogs, sheep, beef and pork). The study found that the median government cost plus net welfare change in terms of producer and consumer surplus varied from $260 to $327 million depending on the scenarios, which involved combinations of three demographic populations of herds, two rates of FMD spread, slaughter strategies and three vaccination strategies.

In addition, another shortcoming of CBA is that it assumes that economic agents are homogeneous and this has led to aggregation problems and inaccurate estimates of changes in economic wellbeing by agents from an FMD outbreak. Econometric response models have often addressed this shortcoming by decomposing welfare changes for agents, as demonstrated in Paarlberg et al. (2003). This process has led to more accurate measures of changes in national economic welfare for a livestock disease outbreak. Contrary to CBA methods that assume homogeneity among economic agents, econometric response models have the ability to estimate separate demand and supply functions for each category of economic agent.

A study by Paarlberg et al. (2003) demonstrated how standard welfare measures, such as consumer and producer surplus, could be disaggregated by estimating different supply functions of beef for different cattle producers. In his study, Paarlberg measured the welfare effects of an FMD outbreak by disaggregating the effects between commercial farmers who quarantined and those who did not quarantine their animals during the outbreak. Using their respective demand and supply functions, he estimated that producers with quarantined animals experienced a loss of $516.6 million in lost sales. Producers without quarantined animals experienced a producer surplus gain of $264.4 million. His study highlights that welfare effects are not the same even within the same category of economic agents, such as producers. Thus, it can be argued that it is more appropriate to report separately the effects of an outbreak within a group, since this will give more detailed information for policy makers, which can also lead to better comparisons of alternatives (Berentsen *et al.*, 1992)

The two studies mentioned have been conducted in developed countries Lack of studies in developing countries can be attributed to the difficulty in obtaining data needed to estimate demand and supply relations for economic agents. In developing countries where small-scale farmers are not well integrated into the formal markets, obtaining reliable data to construct demand and supply functions can prove cumbersome.

2.1.3 Optimisation Models

Optimisation models have primarily been developed to address the inability of CBA to capture how economic agents can adapt to different strategies as the situation evolves. By its very nature, CBA typically considers pre-determined levels of disease control measures, leaving out the possibility of incorporating other control strategies. For example, Bates et al. (2003) assessed the relative costs and benefits of vaccination and pre-emptive herd slaughter to control FMD in the Central Valley of California. The authors specified the radius ring vaccination for FMD at 5, 10, 25, and 50 km and that of ring depopulation at 1, 3 and 5 km, and CBA was performed on the simulation of output under each specification. Under these specifications, CBA was able to evaluate only pre-determined control strategies (Kobayashi *et al.,* 2007). By contrast, optimisation models overcome this weakness by allowing all possible control strategies achievable, given the objective function. This is possible because optimisation techniques derive optimal or efficient solutions to a maximisation and minimisation problem subject to certain constraints. Thus, in an optimisation model, the levels of decision variables or control strategies such as vaccination to be chosen are determined endogenously in the process of maximising or minimising the objective function.

Application of optimisation models has occurred in a number of studies, particularly aimed at finding optimal control strategies for animal diseases. Some studies used stochastic linear programming techniques (Stott *et al.*, 2003), while others used a deterministic optimisation framework (Bicknell *et al.*, 1999; Kobayashi *et al.*, 2007). Stott et al. (2003) used a stochastic linear program, Minimization of Total Absolute Deviation, to assess the relative contribution of disease prevention to whole-farm income and to farm income risk. In their model, they combined epidemiological and economic parameters to integrate animal health into whole-farm business management to aid farm-management decisions associated with bovine viral diarrhoea in cow-calf herds in Scotland. The model found that the total costs related to optimal disease control level varied according to the level of risk of contraction associated with each herd.

By contrast, models implemented by Kobayashi et al. (2007) and Bicknell et al. (1999) were deterministic in nature, implying that they did not consider risk and uncertainty (variability) around model parameters, as each model parameter is uniquely determined by a single value. In contrast, stochastic models make use of a set of probable values (obtained from probability distributions of potential outcomes) for each model parameter, allowing for random variation in one or more inputs over time. Thus, stochastic models depend on the chance variations in risk of exposure, disease and other transmission dynamics.

Variation in parameters' values is very likely because of uncertainty of estimates or variation in transmissibility characteristics of host and pathogen sub-populations and individuals. As a consequence, deterministic models do not internalise the impact of disease control strategies outside the area of analysis because they assume an equal and constant risk of infection for each transmission event. This in turn limits the use of such optimisation models as a predictive tool because each disease outbreak follows a unique pattern, which is most likely different from the population average (Tiongco, 2005). However, in spite of the above limitation, optimisation approaches offer some advantages.

Contrary to CBA methods, which specify strategy parameters during the entire simulation run, dynamic optimisation models allow flexible strategies to be incorporated during the process of minimising or maximising the objective function. This is the main advantage over CBA, which would require running the simulation for several different scenarios to achieve a comparable goal. Thus, optimisation models offer more feasible options for deciding optimal allocation strategies when available resources for control strategy implementation are limited (Kobayashi *et al.*, 2007).

2.2 Multi-sector models

A number of studies employed different multi-sector model formulation to analyse the economic impact of animal disease. This section reviews case applications of the multi-sector models approach.

2.2.1 Input-output Models

In simple terms, the essence of input-output (I-O) analysis is that in any economy there are thousands of firms producing various products and these firms require inputs for their production processes from other firms in the national economy (Leontief, 1936). If an increase in export demand for a particular product occurs, the export-oriented firms will then increase their production in response, demanding more inputs from input suppliers. Input suppliers in turn will also demand additional inputs from other firms in the national economy in order to produce the extra inputs required by the export-oriented firms. Through this process, a chain of reactions occurs throughout the economy in response to the initial export demand stimulus, generating an increase in output, income and employment for the whole economy. Thus, an important role of I-O analysis is the measurement of the change in output, income and employment of the entire economy as the result of an initial stimulus.

Based on the linear relationship between the inputs required and outputs produced by different sectors, an I-O model that accounts for all economic transactions within the economy during a particular period can be developed, following the original work of Leontief (1936). Traditional I-O analysis requires a number of assumptions about the production of goods and services. It is not the intention of this study to give a detailed account of the mechanics of the I-O models, but it is important to recognise some of these limiting assumptions.

Studies that have used I-O models to determine the economic impact of FMD include those of Garner and Lack (1995), as well as Mahul and Durand (2000). In both studies, the authors combined epidemiological and I-O economic models to examine the efficient management of FMD in Australia and France, respectively. These studies were applied using data from the commercial farming sector to highlight the impact of international trade restrictions on livestock sectors, as well as on their respective economies as a whole through interactions among economic sectors that are directly or indirectly linked to the livestock sector.

Garner and Lack (1995) used a stochastic FMD simulation model to generate outbreak scenarios and an economic model to estimate direct and indirect economic impacts of the disease. I-O analysis was used to determine the extent and the nature of the indirect economic effects by using a transaction table or I-O table. Direct and indirect output, income and employment multipliers were generated for each sector directly and indirectly affected by the disease. The model found that slaughtering of infected herds reduced economic impacts and vaccination was effective in reducing the size and duration of outbreaks. A similar study by Mahul and Durand (2000) found that slaughtering of infected herds reduced the economic consequences of FMD outbreaks. Vaccination was found to be socially optimal if additional export losses associated with the delay of slaughtering vaccinated animals were offset by the gains of reducing the duration of an FMD outbreak. The use of stochastic epidemiologic models allowed better simulation of the occurrence and spread of FMD by accounting for the variability of transmission parameters in heterogeneous pathogen and host populations at national level. This in turn led to a better evaluation of the effectiveness of different interventions.

While I-O models have the ability to capture linkages between the sectors in the economy, they suffer from certain limitations. Their accuracy to measure or capture these linkages depends on the level of aggregation in the I-O table. This has the implication that if livestock is not accurately disaggregated, the analysis will overstate the potential impact of a shock. The challenges inherent in disaggregating data, as well as complex accounting systems required in collecting data from economic sectors indirectly affected by the outbreak, clearly explain the lack of studies conducted in developing countries. Even in simple CBA studies, authors have often neglected the indirect impacts of an outbreak because of the difficulty of measuring and attaching value to them (Randolph *et al.*, 2002)

Moreover, I-O models lack the ability to allow for changes in prices owing to fixed coefficient relationships that the model specifies. The inability of I-O models to capture dynamic changes in prices that accompany a shock is due to two fundamental assumptions in the framework. Firstly, production technology is specified as a Leontief fixed coefficient technology, which implies no substitution between inputs and constant returns to scale. Thus, I-O models are fixed price models and do not allow for substitution responses either in consumption or production. Secondly, I-O models assume that any changes in the economy are only due to shifts in the demand curve, and the supply curve is assumed to be perfectly elastic (Hastings & Brucker, 1993; Shaffer, 1989; Miller & Blair, 1985; Rich *et al.*, 2005). This assumption is problematic in agriculture where supply constraints are real, particularly in sectors subject to long production lags, such as livestock. Thus, the focus of I-O models is on demand side adjustments and supply responses are taken as exogenous or inadequately modelled.

2.2.2 General Equilibrium Models

The limitations or shortcomings of I-O models have prompted economists to expand I-O models to address disaggregation problems. Similar to I-O models, computable general equilibrium (CGE) models are also used to capture the economy-wide effects of a shock and are highly disaggregated, allowing a comprehensively detailed, quantitative grasp of the structured linkages between various economic system components. CGE models are developed to address the shortcomings of fixed coefficient, linear multiplier models that tend to be completely demand-driven and do not incorporate supply constraints or substitution possibilities (Robinson & Ronald-Holst, 1988). Among the advantages of CGE over I-O models is the ability to incorporate macro-variables and mechanisms for achieving balance among aggregates. In addition, CGE models can address questions concerning macro-economic impacts across sectors, and distributional effects on various categories of households and employment groups. This is possible because CGE models use flexible functional forms between actors of the economy that allow for substitution in production and consumption, making them able to analyse or address price changes, substitution between inputs and outputs and longer-term impacts resulting from a shock such as an FMD outbreak (Rich *et al.*, 2005).

Various studies have applied CGE techniques to animal health issues. Perry et al. (2003) conducted a CBA, which combined information on income and costs with a CGE model to calculate the trade effects of alternative FMD control strategies in Zimbabwe. The results of CBA showed that FMD control measures would be of considerable benefit to the national economy. The study suggested that if Zimbabwe were to invest in infrastructure and veterinary services, there would be a return of $1.5 on every $1 invested, compared to $5 lost for every $1 disinvested.

CGE models have also been applied to examine the impacts of FMD outbreaks in the UK and Ireland. O'Toole et al. (2002) used the CGE model to assess the impact of FMD on agriculture, government expenditure and tourism in Ireland. The study found that the overall impact on the agricultural sector was positive because of higher prices for meat products arising from the FMD outbreak, but a significantly adverse impact on tourism was found. The results of the simulations showed that the onset of FMD had little impact on the quantity of output of agricultural produce in the short run, but that the beneficial price increases were considerable and led to an economy-wide increase in private and public expenditure of 0.11%. A similar study was conducted by Blake et al. (2002) to assess the economy-wide effects of FMD in the UK, with particular attention to the tourism sector. The study found that total tourism revenue would fall by almost £7.b billion and GDP would be reduced by £1.93 billion as a result of reductions in tourism expenditure and £2.50 as a result of the FMD crisis.

Despite the appeal of CGE models in analysing the economy-wide effects of a shock, they suffer from certain weaknesses. Firstly, CGE models are complex in terms of data requirements and suffer the same weakness as I-O models because their accuracy in measuring macro-economic impacts depends on the level of disaggregation in the I-O table. This implies that if livestock is not accurately disaggregated, the analysis will overstate the potential impact of a shock. This is true in livestock applications where a number of sectors are directly or indirectly linked to the livestock sector. Secondly, most of the CGE models used to analyse the economic impact of FMD are not explicitly linked to the epidemiological model (see, for example, O'Toole *et al.*, 2002; Perry *et al.*, 2003). Changes in the economy resulting from a disease outbreak were measured exogenously as a supply or demand shock rather than through a disease model. This is because the focus of CGE models has been on the economic impact of animal disease, and there appears to be a need to link the epidemiological model directly to economic models. It is also difficult to build the inter-temporal and spatial dynamics of animal disease into CGE.

2.3 Studies on the Economics of Animal Disease within Wildlife-livestock Interface

Relatively little research has been conducted in the area of the economics of disease control within the wildlife-livestock interface. The establishment of parks aimed at conserving wildlife has noticeably led to interesting debates between conservationists and economists, as these parks have often led to conflicts between these economic agents. While the establishment of national parks and other protected areas has noticeably conserved some of the wildlife that could be nearly extinct and has certainly preserved biodiversity (Bruner *et al.*, 2001), conservation policy has been received with resentment by local people as a policy alienating wildlife from their livelihood and transforming what was previously a valuable commodity into a threat (Borge-Johannesen & Skonhoft, 2005). Conservation policy is accordingly often seen as denying local people traditional rights to harvest wildlife to support their livelihood, as well as loss of cultivation and grazing land or pasture for their livestock (Skonhoft, 1998). Conservation policies are therefore generally viewed by local communities to conflict with livelihood and poverty reduction goals.

Several authors employing bio-economic models have studied the role of communities in wildlife conservation and the way in which conservation policies can be managed in a manner that improves the welfare of local people. Most of these studies focused on evaluating the effect of different property-sharing schemes on park managers' incentives and the welfare of local people, inducing changes in nuisance (roaming wildlife) and consequent community welfare impacts. Market solutions have been compared where local people are given property rights in the form of fixed shares of profits from harvesting wildlife or from tourism activities (Skonhoft, 1998). Solutions have also been evaluated under integrated conservation and development projects with income transfers from non-consumptive tourism and safari hunting (Johannesen & Skonhoft, 2005). Fischer et al. (2010) found that mere sharing of resources does not necessarily improve community welfare or incentives for wildlife conservation, as those incentives depend critically on the type of resource activity generating the shared profits, the size of benefits compared with agricultural losses (grazing land and crop production) and also the way in which benefit sharing and community responses affect the resource management practices of the park agency.

The above studies addressed problems of grazing competition between wildlife and livestock and crop damage associated with wildlife conservation. In some instances, intruding wildlife roaming the lands adjacent to protected areas may also transmit various diseases, including FMD or brucellosis, to livestock (Fischer *et al.*, 2010). Such disease transmission may be costly to farmers in terms of loss of livestock, milk and meat production and can thus lead to serious conflict between conservation and the welfare of local people. A few recent studies (Bicknell *et al.*, 1999; Horan & Wolf, 2005; Fenichel & Horan, 2007; Horan *et al.*, 2008; Horan *et al.*, 2010) have attempted to pay more attention to the disease transmission dimensions of an apparent conflict between wildlife conservation and the economic interests of commercial farmers. Bicknell et al. (1999) developed a multi-host bio-economic model to analyse a bovine tuberculosis (bTB) problem in New Zealand in which TB was spread by Australian brush-tailed possums to dairy (cattle farmers') herds. In their model, they determined optimal disease control strategies such as testing at farm level and hunting of possums off farm from the perspective of a single farmer. However, optimising an economic problem that affects many agents as a single-farmer problem can lead to suboptimal solutions that do not improve the overall welfare of society. For example, an individual farmer may under-invest in wildlife control measures because of the public good nature of these controls (Horan *et al.*, 2011).

In response to this, Horan and Wolf (2005) developed a single-host bio-economic model to analyse bTB among Michigan white-tailed deer. Unlike Bicknell et al. (1999), they developed a bio-economic model to determine the socially optimal management strategies that wildlife managers would select to control the spread of bTB and prevent the high mortality caused by the disease. Their approach highlighted that wildlife disease problems affected not only wildlife managers but also other economic agents such as hunters and possibly the livestock sector, although they did not explicitly model the damage to the livestock sector. This has led to a change in perception on how to manage wildlife-transmitted diseases optimally.

Traditionally, wildlife disease control has been concerned with harvest, vaccination or culling of infected wildlife to control the disease without considering the economic damage to other sectors, such as livestock. A recent study by Horan et al. (2008) demonstrated the importance of including ecological interactions between wildlife and livestock. They used a bio-economic model to analyse a population management and disease control strategy that a social planner will choose in order to maximise the discounted net benefits of deer hunting and cattle management. Their results suggest a mix of livestock and wildlife control measures in an effort to suppress the wildlife reservoir as being the most effective at reducing disease prevalence. In addition, their results warrant significant on-farm biosecurity investments to reduce wildlife disease status because of the potential to reduce cross-species transmission. Similar to Horan and Wolf (2005), they found that if wildlife imposes fewer externalities on livestock, farmers might not have the incentives to control the disease in wildlife directly. These findings further validate an argument that the ability to target effective controls in managing disease transmission requires consideration of other economic agents who may potentially have a crucial role in managing the spread and control of the disease. Thus in a case where disease affects multiple economic agents, the choices to control the disease should clearly be interdependent. This implies that within wildlife-livestock disease interaction, choices that a cattle farmer takes must also be considered because economic damage to this sector depends on both wildlife management choices and responses to the threat of livestock infection by infected wildlife (Horan *et al.,* 2008).

However, studies conducted by Bicknell et al. (1999) and Horan and Wolf (2005), for example, involved the transmission of bTB between deer and livestock. It appears that the economics of other type of animal disease, such as FMD, within the wildlife-livestock interface remain under-researched. In addition, most of the studies assessing the impact of animal disease transmission focused on commercial farmers in developed countries.

2.4. Conclusion

This chapter has reviewed studies that assessed the economic impact of animal disease, with specific focus on FMD. Various methods that have been used to assess this impact address different aspects of the economic problem. While some methods are well-suited to address the costs and benefits of alternative disease control strategies at herd or farm level, some are suitable to address these questions at national level. Others are more suitable to examine the economy-wide effects of the disease. Bio-economic models that allow ecological interactions between wildlife and livestock have also been employed to analyse population management and disease control strategies. However, a limited number of studies have been conducted in developing countries using either of the methods presented in this chapter. In contrast, most of the available studies in the literature have been conducted in developed countries and have focused mainly on the economic impact of animal disease (eg FMD) on the commercial farming sector, while neglecting the plight of small-scale farmers. The reasons cited range from data unavailability to lack of monetary value attached to the herds in backyard farming systems (Kobayashi *et al.*, 2007).

CHAPTER 3 : DETERMINANTS OF LIVESTOCK OWNERSHIP AMONG SMALL-SCALE FARMERS LIVING ADJACENT TO THE KNP IN LIMPOPO PROVINCE

3.0 Introduction

The main aim of this chapter is to analyse the determinants of livestock ownership (herd size) among small-scale cattle farmers in selected villages at Mhinga Traditional Authority (MTA), in Limpopo Province. Section 1 gives a brief account of the economic significance of the livestock sector in South Africa. Section 2 describes the materials and methods of the study. The results of the study are presented and discussed in section 3. Section 4 concludes the chapter.

3.1 Economic Significance of the Livestock Sector in South Africa

Livestock farming is one of the viable agricultural activities in most parts of the country, with approximately 69% of South African agricultural land being used for extensive grazing. More specifically, according to statistics from DAFF (2010), cattle production has increased by nearly 1 million head from 12.6 million in 1994 to 13.5 million in 2004 (DAFF, 2010). However, beef cattle producers vary from commercial operators who rely on highly sophisticated technology to communal subsistence producers who rely on indigenous knowledge. Three major groups of beef cattle farmers co-exist in South Africa. Commercial farmers are estimated at 50 000, emerging farmers at 240 000 and communal farmers at 3 million; 60% of the 14.1 million cattle available in South Africa are owned by commercial farmers and 40% by emerging and communal farmers (DAFF, 2010).

A report by DAFF (2010) estimated approximately 70 feedlots in South Africa and 495 abattoirs, which employed about 500 000 people. Thus, the livestock sector is a major source of livelihood, creating employment for many of the poor who lack the necessary skills to be employed in other sectors of the economy. In addition to creating employment and serving as sources of livelihood for the rural poor, the sector is increasingly export-oriented, generating a significant amount of foreign exchange revenue for the country. Beef exports reached 3 987 million tons in 2010, yielding an export value of R156 million. The main destination of South African beef in 2010 was Mozambique (36%), followed by Angola (18%), then the Democratic Republic of Congo (12%) (DAFF, 2010). The average gross value of beef produced during the period 2000/01 to 2009/10 amounted to R881 million.

In spite of these potential benefits, communal farmers in rural areas continue to face many challenges that constrain them in generating income from owning livestock. These challenges include both social and economic factors. Economic factors may include lack of access to land and water, lack of access to efficient marketing channels, risk-associated factors such as drought and theft, as well as animal diseases such as FMD (Montshwe, 2006). Social factors may include gender, age, marital status and even social motives associated with livestock ownership. Studies by Musemwa *et al.* (2007) and Hangara et al. (2011) have demonstrated that in spite of these challenges, livestock ownership among cattle farmers has the potential to enhance their income.

3.2 Materials and Methods

3. 2.1 Study Area

The study was conducted in five communal villages that fall under MTA in the Vhembe district in Limpopo Province, South Africa. According to Statistics South Africa (StatsSA), Limpopo Province covers an area of 12,46 million hectares, which accounts for 10,2 % of the total area of South Africa (StatsSA, 2003; DAFF, 2012). Like the rest of South Africa, Limpopo Province is characterised by two distinct types of agricultural production systems, namely large-scale commercial and smallholder farming systems (StatsSA, 2002; Aliber & Hart, 2009). Commercial farmers who practise large-scale farming using advanced production technology occupy approximately 70% of the land (DAFF, 2012). At present, there are approximately 2 934 commercial farming units in Limpopo Province (StatsSA, 2007)

Limpopo had its highest average real economic growth rate of 3.8% between 1995 and 2001 (Government Communication and Information System [GCIS], 2004). However, StatsSA (2012a) indicates the real average growth of 2.2% for Limpopo Province as the lowest of the nine provinces. The province is also characterised by high unemployment levels estimated at 20,2% (StatsSA, 2012b), but unemployment specific to the study area (MTA) ranges between 60% and 80% (Chaminuka, 2012).

MTA has 10 villages under its jurisdiction, namely Mhinga 1, Mhinga 2, Mhinga 3, Ka-Matiana, Joseph, Botseleni, Maphophe, Mabililigwe, Makuleke and Nthlaveni. These villages fall under the Thulamela municipality situated 180 km north-east of Polokwane, the capital city of Limpopo Province, which is the gateway to the KNP, the second largest park in the world (http://www.golimpopo.com/municipalities/thulamela.html). MTA covers an area of about 20 000 ha, mainly comprising communal grazing areas and village settlements with an estimated 6 880 households and 43 450 people (Chaminuka, 2012).

The villages mentioned above are populated by smallholder communal farmers who mainly depend on agricultural and livestock farming for their livelihoods. However, only five villages were chosen as the target populations for conducting the survey, namely Matiyani, Josefa, Botseleni, Maphophe and Mhinga (Mhinga 1, 2 and 3) (Figure 1). These villages were selected because they are representative of the demographics and socio-economic conditions of most villages bordering the KNP on the northern and western sides (Anthony, 2007). All the above villages are between 0 and 9 km from the KNP (Chaminuka, 2012).

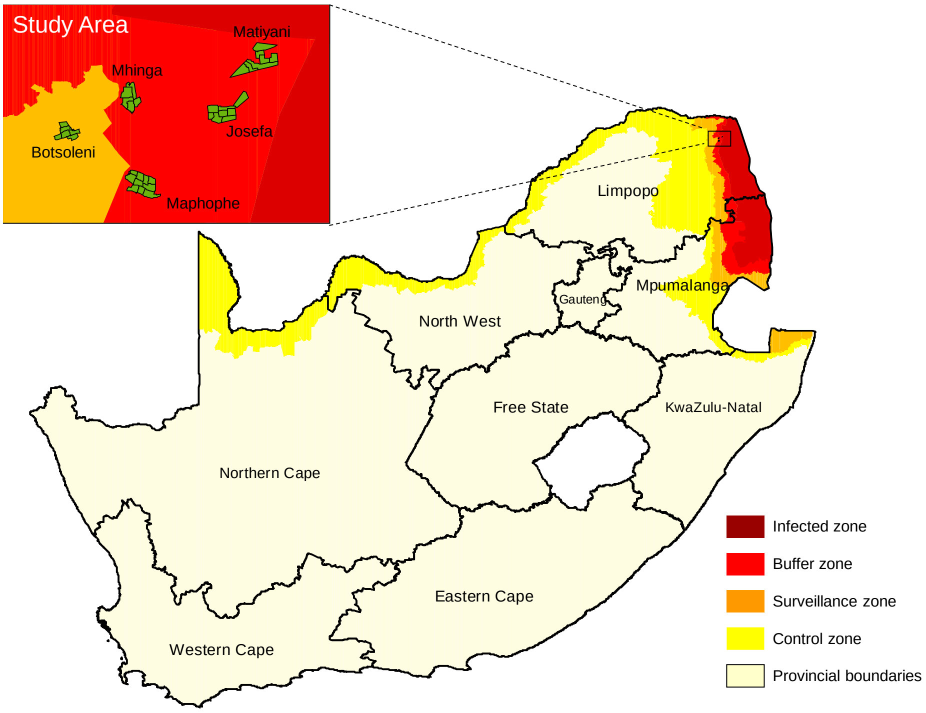

Figure 3.1: Map of South Africa and the study area

Adapted from Department of Agriculture, Forestry and Fisheries (2012)

3.2.2 Data Collection Methods

A cross-sectional survey was conducted using a semi-structured questionnaire that was administered to the livestock farmers in the study sites. The main aim of the questionnaire was to gather information on the demographic and economic characteristics of the farmers, livestock and land ownership, marketing channels used by farmers to sell their livestock and factors leading to losses in livestock (Appendix 1). The study was based on a simple random sampling design. A list of all farmers from the target villages was obtained from the Department of Agriculture of the local municipality, Thulamela. The cattle-owning farmers were identified through the dip register kept by the local animal health authorities. Farmers were then randomly selected, using the farmer's identity card number from the available list, and interviewed. The interviews were conducted using local languages, which were either Tshivenda or Xitsonga. The estimation of the sample size for the survey was based on the method proposed by Cochran (1977), assuming a 95% confidence interval, ie 5% desired absolute precision. Fieldwork for data collection was conducted between June and August 2011 and 253 questionnaires were successfully completed.

3.2.3 Empirical model and variables

In addition to understanding the main attributes of small-scale cattle farmers in the study area, the research also examined the main determinants of herd size among this particular group of farmers in the selected villages at MTA. The response (dependent) variable of the study was measured as the number of cattle owned by an individual farmer (count variable). Count data are best modelled using Poisson or negative binomial models and the choice between the two models depends on the distribution of the response variable. Negative binomial models (that can be considered as a generalisation of Poisson regression) are best suited for the analyses of over-dispersed count data, ie when the conditional variance exceeds the conditional mean (Osgood, 2000). For this analysis the study used a negative binomial model because significant over-dispersion in the number of cattle owned by farmers in the study area was observed (α: 0.4; χ^2: 818; p<0.001).

The general empirical model for the study was specified as an additive multivariate model:

$$\hat{Y} = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \ldots + \beta_n X_n + \varepsilon_i \tag{1}$$

where Y denotes the number of cattle owned by an individual farmer, the Xi's refer to explanatory variables, the βi's are model parameters' estimates and ε is the random error term. Equation 1 suggests that livestock ownership by small-scale farmers is affected by multiple factors. Definitions of factors influencing herd size are shown in Appendix 2. The literature suggests that livestock ownership differs widely among ecological zones, production systems (small-scale or commercial) and social factors such as gender and marital status (Niamir, 1990). Generally, men and women tend to own different animal species. In many societies, cattle and larger animals are usually owned by men, while animals such as goats and backyard poultry are more women's domain (Yisehak, 2008). This could be due to the fact that women lack capital to purchase larger animals. It is therefore hypothesised that male farmers will tend to have larger numbers of cattle than their female counterparts. The study also hypothesised a positive relationship between marital status and herd size in that married farmers would tend to have larger herd sizes compared to unmarried farmers. This association could be attributed to the observation that married farmers might use their livestock as a source of income for their families.

Other social factors such as family size also have an effect on the number of cattle that farmers own. Because of the relatively larger family size in most rural areas, the study hypothesised a positive relationship between herd size and family size. De Bruyn *et al.* (2001) argue that older producers will tend to have larger herds of cattle than younger farmers. Accordingly, the study hypothesised a positive relationship between age and herd size. Teweldemedhin and Kafidi (2009) indicated that access to other sources of income may give farmers more buying power and hence the ability to purchase additional stock of cattle. It is also argued that access to other forms of income may in fact discourage farmers from selling their cattle to meet their daily needs and production costs, which may in turn increase their existing herds, as they use the extra income to buy additional cattle (Nthakheni, 2006). Accordingly, the study hypothesised a positive relationship between off-farm employment and herd size. By contrast, the study hypothesised a negative relationship between welfare grants and herd size. This association is based on the argument that recipients of welfare grants in rural communities often depend on the grants as their main source of income, without alternative sources of income they can use to buy additional stock of cattle.

The study also hypothesised a positive relationship between land ownership and herd size. A study conducted by Rahman *et al.* (2001) found a positive relationship between land and livestock ownership for farmers in the semi-arid area of Bangladesh. Similar results were also reported by Baset *et al.* (1997), who observed significant differences between land ownership and the number of animals owned by farmers.

It has been argued that farmers who received an education are able to adapt to new technological innovations relating to cattle production and are able to acquire skills faster than those who received no education. This tends to translate into higher productivity, often resulting in larger herd sizes (Musiguzi, 2000). Thus a positive relationship between herd size and education is hypothesised in this study.

Lack of marketing facilities imposes a serious constraint on small-scale farmers' ability to market their cattle (Mahabile *et al.*, 2002). Having access to market facilities and information can have a significant impact on the ability of small-scale farmers to generate sustainable profits (Hobbs, 1997). Moreover, market accessibility in terms of access to infrastructure and better roads will boost farmers' ability to negotiate better prices for their cattle and thus boost production in terms of quantity and quality (Musemwa, 2007). It is therefore hypothesised that increased access to marketing facilities in terms of reduced distance and improved roads will encourage farmers to have larger herd sizes.

The study also hypothesised a positive relationship between herd size and various motives for livestock ownership. As already alluded to in the introduction, several authors studying the behaviour of cattle farmers in Africa have found that in many nomadic societies, as well as in pastoral and agro-pastoral communities with less mobile herds, in addition to market benefits such as an important insurance asset, herd size can also provide other important non-market benefits (Perrings, 1993; Perrings, 1994). For instance, in traditional pastoral societies the herd size is often of greater importance for cultural reasons, as well as an asset signalling social status. The study also hypothesised a positive relationship between livestock losses (due to theft, livestock predation and death) and herd size. It is expected that a higher incidence of losses due to the above risk factors will encourage farmers to have larger herds in order to minimise the effects of the losses. Incidences of livestock losses for farmers living adjacent to national parks were also reported in other parts of Africa, such as Botswana and Tanzania (Holmern *et al.*, 2007; Kgathi *et al.*, 2012). Following Montswhe (2006) and Hangara *et al.* (2011), who found a positive relationship between an increase in the number of cattle owned by an individual farmer and an increase in the sales volume, the study hypothesised a positive relationship between herd size and sales volume.

3.3 Results

3.3.1 Attributes of the Population in the Study Area

Descriptive information on the main attributes of the population in the study area is presented in Table 3.1. Both men and women were involved in cattle farming and men constituted 77% of the livestock farming community in the study area. This figure is similar to that reported for other areas in South Africa. For example, Musemwa et al. (2007) reported that 80% of men were engaged in cattle farming in Kamastone village, Eastern Cape, while Spies (2012) reported that 98% of farmers in the Free State Province engaged in cattle farming were men. The average age of the head of the family was 58, while the average family size for the study area was six. Most farmers in the study area had some form of schooling. About 51%, 26% and 4% had primary, secondary and college education respectively. Only 19% of the farmers in the study area had no form of education. This figure clearly differs from the one reported for Kamastone village in the Eastern Cape, where 57% of farmers were not educated (Musemwa *et al.*, 2007). The majority of farmers (67%) in the study were married. Similar findings were reported for the Free State Province where 88% of farmers were married (Spies, 2012).

Besides cattle farming, some farmers were involved in other forms of employment. About 67% of the farmers interviewed were solely committed to cattle farming, while 33% had employment outside farming, such as working as government officials. As one would expect in communal areas, most farmers own land that is allocated to them by the local chief. In the study area, about 63% of farmers owned an average of 2 hectares of land each. The herd size of the farmers varied between a minimum of one (1) to a maximum of 134 cattle with a mean of nine head of cattle, thus suggesting that the majority of farmers had small herds. Similar figures are reported in other parts of South Africa, such as in Rustenburg, where herd size varies between five and 149, with a mean of 29 head of cattle per household (Schwalbach, 2001); the average number of head of cattle per farmer in Thaba Nchu and Botshabelo was 10.8 and 7.2, respectively (Moorosi, 1999) and a mean herd size of eight was reported in Venda (Nthakheni, 1996). The herd structure of the farmers interviewed in the study area was distributed as follows: 44% had one to five cattle, while 32% had six to 10 cattle; 12% of the farmers had 11-15 cattle while another 12% had more than 16 cattle. This confirmed that the bulk of farmers in the study area had smaller herds.

Farmers in the study area kept livestock for various reasons. Almost all farmers kept livestock to provide income (99%) and as insurance against unforeseen conditions such as loss of employment or severe drought (100%). Similar numbers were reported by Schwalbach et al. (2001) for South Africa, indicating that 91% of farmers kept cattle to generate cash and 25% for the provision of financial security, while 17% kept livestock to provide for emergencies or insurance. In the study area, 96% kept livestock for social reasons such as acquiring social status in the community. This finding is in agreement with the thesis that communal farmers tend to keep large herds in order to gain social standing in society (Borge- Johannesen & Skonhoft, 2011).

Table 3.1: Attributes of small-scale cattle farmers in the study area

Attribute	Valid number	Percentage
Gender (N=251)		
Female	58	23
Male	193	77
Marital status (N=253)		
Married	170	67
Unmarried	83	33
Education (N=252)		
No schooling	47	19
Some schooling	205	81
Employment (N=253)		
On-farm employment (full-time)	169	67
Off-farm employment (part-time)	84	33
Welfare grants (N=253)		
Not receiving	30	12
Receiving	230	88
Land ownership (ha) (N= 159)		
No	92	37
Yes	159	63
Marketing channels (N=252)		
Local people	150	60
Local butcheries	102	40
Theft of livestock (N=253)		
No	245	97
Yes	8	3
Losses due to natural death (N=253)		
No	194	77
Yes	59	23
Losses due to predation (N=253)		
No		
Yes	225	89
Reasons for keeping livestock	28	11
Keeping livestock for income (N=252)		
No		
Yes	1	1
Keeping livestock for insurance (N=252)	251	99
Yes		

Keeping livestock for social status (N=251)	252	100
No		
Yes	9	4
Cattle sales	242	96
No		
Yes	133	53
Selling cattle for household consumption (N=251)	120	47
No	1	1
Yes	250	99

Attribute	**Min**	**Average**	**Max**
Age (N=253)	18	58	92
Family size (N=253)	1	6	22
Herd size (N=253)	1	9	134
Herding costs (N=252)	0	161	800
Private land (ha) (N=159)	0	2	6
Income from selling cattle (N=253)	0	6 400	120 000

While most of the farmers in the study area kept livestock to generate income, about 53% of the farmers surveyed had not sold any cattle during the past year, which could be attributed to their relatively smaller herds. Farmers who sold their cattle (47%) on average generated R120 000 per annum. Scholtz et al. (2008) found that 47% of the farmers in South Africa sold their cattle mainly to generate cash and provide food. Most farmers (99%) used the generated income for current household needs, such as buying groceries and paying school fees.

Communal farmers in the study area used various channels to market or sell their cattle. The most commonly used method was private sales to local people for slaughter for socio-cultural functions such as funerals, weddings or religious celebrations and butchers buying livestock for different reasons, such as retailing for income (USAID, 2003). About 60% of the farmers sold their cattle directly to local people, while 40% sold to local butcheries. By contrast, 25% of farmers in the Kamastone village in the Eastern Cape used private sales, while the largest group of the farmers (46%) used auctions (Musemwa *et al.*, 2007). These differences in the marketing channels used by farmers can be attributed to factors such as infrastructure or quality of the roads, high transactional costs and lack of information in different regions (Musemwa *et al.*, 2008).

In addition to challenges related to marketing channels, farmers in the study area faced risks such as losses due to theft and predation from wildlife that escaped from the KNP. Almost all farmers interviewed (99%) indicated seeing wildlife roaming in grazing areas. Interaction between livestock and wildlife often results in livestock predation. According to Holmern *et al.* (2007), 27% of the households interviewed in seven villages outside the Serengeti National Park in Tanzania reported that they had lost 4.5% of their livestock owing to predation. Much higher figures were reported for Shorobe village, northern Botswana, where 63% of respondents reported that predators had killed some of their livestock (Kgathi *et al.*, 2012). However, findings in the study area indicate that 11% of livestock losses were due to predation, 3% due to theft and 23% due to death as a result of animal disease such as FMD transmitted by wildlife (buffalo) that escaped from the park.

3.3.2 Empirical results and discussion

The statistical analysis was implemented using STATA® version 11 (StataCorp, Texas, USA). The estimation results of the negative binomial model indicate high statistical significance for all variables at a level of 5% (ie P-value of < 0.05) in Table 3.2. All variables retained the expected signs, except employment (off-farm) and social status, as motives for keeping livestock. Two-way interactions were assessed by inclusion of product terms for all variables remaining in the final additive models. No interaction terms were significant in the model.

Table 3.2: Negative binomial model estimation results for factors influencing herd size of small-scale farmers in the study area (dependent variable) N= 216

Explanatory Variables	Percentage	P-value*
Marital status (unmarried)	-0.32	<0.05
Education level [1]	0.59	<0.05
Off-farm employment	-0.21	<0.05
Receiving welfare grants	-0.23	<0.05
Livestock loss (theft)	0.80	<0.05
Livestock loss (death)	0.23	<0.05
Cattle sales	0.63	<0.05
Marketing to local butcheries	0.19	0.05
Social reasons for keeping livestock	-0.41	<0.05

*Level of significance at less than 5% (<0.05)

Results from the study show that education, high incidences of theft and death of livestock, cattle sales and access to markets have a positive influence on herd size, while being unmarried has a negative influence on herd size. The study found that unmarried farmers kept 32% less cattle than married farmers. This finding is not surprising, given that most farmers in rural communities are married and have larger families, compelling them to have larger herd sizes to support their livelihoods. Farmers with some form of schooling were found to have 59% more cattle compared to those without any form of schooling[1]. Almost universally, studies that analyse income, agricultural production and other forms of welfare measures, find that human capital available in a household (usually measured as the education of the head of the household) is strongly correlated with these welfare measures (World Bank, 1999). This result suggests that investing in farmers' education and awareness of new technological innovations such as breeding and detecting sick animals and treatment are critical for improving small livestock farmers' welfare.

Results also suggest that farmers who experience livestock losses due to risk factors such as theft or death resulting from wildlife-livestock transmission diseases (eg FMD) tend to keep

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[1] Respondents were first grouped into different education levels (primary, secondary and tertiary) but there were no significant statistical differences in performance between the three groups and hence the sample was subsequently split into only two groups, namely those with and those without any education.

larger herd sizes. This is possibly motivated by the need to minimise the impact of losses due to these above-mentioned risk factors. The loss due to disease transmission from wildlife to livestock calls for the government to erect efficient game-proof fences that will effectively prevent wildlife escaping from the park, which will result in a reduction in livestock predation and herding costs to small-scale farmers.

The study findings also show that farmers who sold their cattle to local butcheries had larger herd sizes (19% increase in herd size) compared to those who did not sell to local butcheries. This could be due to the fact that farmers are able to command relatively higher prices when selling to a butcher compared to an ordinary individual. This finding is consistent with the findings by Musemwa *et al.* (2007) who reported that the ability of farmers to participate in the market was heavily dependent on marketing channels available to them. This implies that the availability of efficient and well-functioning markets is vital for market participation by farmers and improving the potential of farmers to earn higher incomes. This finding is also in agreement with that of Hangara *et al.* (2011), who found that an increase in the number of cattle owned by an individual farmer in Namibia led to an increase in sales volume. This implies that a larger herd size has a direct influence on the economic development of communal farmers. Thus, it is important to assist farmers both to expand the size of their herds and to manage them in optimal ways.

Contrary to previous research, which reported a positive relationship between non-market benefits for owning livestock and large herds of cattle, the findings from the study show a negative relationship between herd size and social reasons for owning livestock. Farmers who kept cattle for social reasons had 41% smaller herds compared to those who did not. This could be attributed to the poverty and unemployment levels in the study area, rendering social reasons as the main motive to keep livestock less important. In other words, farmers in the study area generally kept livestock for economic reasons or market benefits rather than for social reasons.

Contrary to the hypothesised statement, the results from the study show that farmers with off-farm employment have smaller herds (21% less) compared to farmers who depend solely on farm employment. This finding contradicts the results of Teweldemedhin and Kafidi (2009), who report that farmers are able to generate additional income from off-farm employment, which is then used to purchase additional stock. This finding can be attributed to the fact that farmers in the study area are relatively poor so that any extra income they generate from off-farm activities is used to buy necessities such as food for daily consumption instead of buying additional stock of cattle. Similarly, the results from the study show that farmers receiving welfare assistance in the form of disability grants or pensions have smaller herd sizes (23% less) compared to those not receiving assistance. This finding is in disagreement with Nthakheni (2006), who reports that access to other sources of income such as a pension or disability social grants may present farmers with more buying power at their disposal, which enables them to purchase livestock, thus expanding their existing stock. It is, however, important to note that receiving welfare grants may serve as a disincentive for farmers to look for alternatives to sustain their livelihoods or increase their incomes.

3.4. Conclusions and implications of the study

This study analysed determinants of herd size among communal livestock farmers in Mhinga district, in the Limpopo Province of South Africa. A negative bionomial model was chosen to implement the empirical analyses, given the over-dispersed count data measuring the response variable (herd size). Contrary to the popular belief that rural households in developing countries generally own large herds of livestock for social reasons, communal livestock farmers in the study area who kept livestock for social reasons were found to own smaller herds of cattle. The research indicates that economic reasons for livestock ownership are more important than social reasons among smallholder livestock farmers in the study area. An important implication of this finding is the great potential this presents for economic policy to enhance the welfare of this and similar groups of small-scale cattle farmers in the country. This is because livestock in the study area is a major source of cash income for farmers, as 99% keep livestock to provide income for their household. However, this potential of welfare gains from promoting larger herd sizes must be weighed against sustainability objectives in terms of what would be an optimal herd size, given the current carrying capacity of the supporting ecosystem. Although subsequent chapters address aspects of optimal stock size, the current analyses point to some key challenges and obstacles.

The study found that access to marketing channels, such as selling to local butcheries, encourages farmers to keep larger herds. This reinforces the potential for economic policy interventions, such as the establishment of efficient and well-functioning markets, including improved access to better roads as well as other market information such as current market prices for their products. However, while the study area resembles most regions in rural South Africa where smallholder livestock farming is practised, these findings need to be carefully assessed and validated through replication of similar studies in other rural areas of the country.

Measures to provide protection against livestock predation and death from transmission of diseases such FMD from wildlife will contribute to a reduction in stock losses and in turn to the welfare of these small-scale cattle farmers. This justifies public investment in efficient game-proof fences that will effectively deter wildlife from escaping from game parks from coming into contact with adjacent communal livestock. The study results also suggest that investing in farmers' education and awareness of new technological innovations and appropriate measures and practices in breeding and veterinary services are critical for improving small livestock farmers' welfare. It is also noted that theft is a major challenge in the farming community living adjacent to the KNP because of shared borders with Zimbabwe, as well as the lack of designated fenced grazing areas for their livestock. Policy proposals to address theft could include government being actively involved in policing the criminals or establishing fenced grazing areas.

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CHAPTER 4: ANALYTICAL FRAMEWORK FOR OPTIMAL CONTROL OF FMD TRANSMISSION FROM WILDLIFE TO LIVESTOCK POPULATIONS IN THE STUDY AREA

4.0 Introduction

This chapter provides the methodological approach used to analyse the trade-off between wildlife conservation in terms of keeping FMD-infected buffalo in the park and livestock ownership of small-scale farmers in the study area in the presence of FMD (negative externality) that affects their livelihood. This chapter is organised as follows: Section 1 presents the FMD problem in the study area. Section 2 outlines the FMD transmission between buffalo and cattle populations, which then lays the foundation for the analytical model to be developed in section 3. Section 4 develops the costs and benefit functions of the park agency and the cattle farmers. In section 5, the model is solved analytically under three scenarios (conservation, social planner and no-disease scenarios). Section 6 concludes the chapter.

4.1 FMD problem in the KNP area

FMD is an animal disease, which affects the health of animals with cloven hooves including cattle, pigs, sheep, and goats (Bastos *et al.*, 2003). In wildlife, all species of deer and antelope are susceptible to FMD, with some of them, such as African buffalo, acting as carriers of the virus without showing clinical symptoms (Thomson *et al.*, 2003). The typical clinical sign is the occurrence of blisters (or vesicles) on the muzzle, tongue, lips, mouth, between the toes, above the hooves, teats and potential pressure points on the skin (Hedger, 1976; Thomson *et al.*, 2003). The virus that causes FMD is an aphthovirus of the family *Picornaviridae* and there are seven immunologically distinct types of FMDV: A, O, C, Asia-1 and the South African Territories (SAT) 1, 2 and 3 (Vosloo *et al.*, 2009

The most common viruses found in South Africa are the three SAT serotypes of FMDV (Hedger, 1976; Thomson *et al.*, 2003). These are maintained in the free-living buffalo population in the KNP, which is situated in the north-eastern corner of South Africa (see Figure 3.1). Adjacent to the western and southern borders of this infected zone is the buffer zone, which has two sections: a portion where livestock is vaccinated twice yearly, referred to as the buffer zone with vaccination (BZV), and a portion where animals are not vaccinated but where increased surveillance and movement control are implemented, known as the buffer zone without vaccination (BZNV). Adjacent to the latter is an inspection zone, where increased surveillance is implemented through the inspection of domestic livestock. Free movement of animals is permitted within the inspection zone and from it to the FMD-free zone. In the infected zone, BZV and BZNV (together comprising the FMD-control zone), various levels of restriction on animal movement are enforced, while in the FMD-free zone restrictions are not applied (Bengis, 2011; Jori *et al.*, 2009).

However, efforts to contain the disease are often undermined or diminished by elephants that frequently destroy fencing around the park, leading to buffalo escaping into communal lands adjacent to the park, where they mingle with livestock grazing, thus transmitting the disease. The magnitude of buffalo escaping from KNP had been documented by the Directorate of Veterinary Services in the KNP. Their estimates suggest that more than a thousand fence breaks occur every year, and at least 70% of all fence breaks occur on the western boundaries of the KNP (Du Plessis, 2007). Prior to November 2000, the last FMD outbreak in livestock in the buffer zone happened in 1983. Since the floods in 2000, a string of fence breaks have occurred, eventually leading to FMD outbreaks. Between 2000 and 2007 five outbreaks, with confirmed epidemiological connection to the KNP, occurred along the western boundaries of the KNP (Jori *et al.*, 2009).

Furthermore, reports from the Directorate of Veterinary Services in the KNP estimate that between 1996 and 2006 an average of 80 buffalo escaped each year (Du Plessis, 2007). Those buffalo spotted outside the park were either chased back to the park if the herd size that escaped was large or killed if the herd size was small. While the number of buffalo that escape might appear small, or even negligible, given the current estimated population size of 39 000 buffalo (Bengis, 2011), the negative impact they have on farmers who depend on their livestock for their livelihood is significant. As a consequence of FMD infection, livestock will lose weight, which eventually leads to lower slaughter market prices as well as loss in milk production. In some instances where livestock is used for draught power, the blisters on the muzzle and between the toes make it impossible for an animal to walk (Bengis, 2011). In a susceptible population, the infection rate can be as high as between 80% and 90% (Coetzer *et al.*, 1994). However, the mortality due to FMD is quite low, typically lower than 10 % (Bengis, 2011).

The current situation in the Limpopo Province in South Africa where the KNP has been established to conserve wildlife represents a typical case of this phenomenon where FMD-infected buffalo escape from the KNP into adjacent areas, thereby transmitting FMD to livestock of small-scale cattle farmers. According to OIE, the KNP is an FMD-infected zone in which FMDV is present and persistent in free-ranging buffalo (Department of Agriculture, Fisheries and Forestry (DAFF), 2010). While buffalo represent a conservation value to society and recreational value to tourists, they also present a negative externality to small-scale cattle farmers living adjacent to the park by transmitting FMD to their livestock. The wildlife-livestock interface scenario in Limpopo Province provides an opportunity to assess the economic impact of FMD transmitted by wildlife on small-scale cattle farmers living adjacent to the KNP conservation area and investigate how to balance the conflicting interests between small-scale cattle farmers and the park agency.

4.2. The FMD transmission mechanism between buffalo and cattle populations

The model of FMD disease transmission to be studied in this chapter extends the model developed by Bicknell, Wilen and Howitt (BWH) (1999) and builds on the work of Anderson and May (1981, Chap 7). Similar to BWH’s model, the model in this study has two economic agents and includes a conservation agency managing the national park where the buffalo have their primary living area, and a group of small-scale cattle farmers living adjacent to the protected park area. However, this model differs from the BWH one in terms of how harvesting takes place. BWH assumes non-selective harvesting, while this study assumes selective harvesting. Selective harvesting is possible in this model because FMD is a symptomatic disease, making it easy to distinguish between healthy and infected cattle. In addition, the BWH model was carried out in a developed country context where the impact of TB on the cattle of commercial (large-scale farmers) was assessed. The model undertaken in this t study is the first to be conducted in a developing country using dynamic optimisation techniques to assess the impact of animal disease such as FMD on the livestock of small-scale farmers. While it is acknowledged that FMD has many negative economic effects on livestock, such as lower milk production, weight loss, etc, the main economic impact to be studied in this model is lower slaughter value. Thus, the objective of this study is to use the formulated model of FMD transmission between cattle and buffalo populations to assess the effects of FMD on the welfare of small-scale cattle farmers.

Based on the FMD situation presented above, a simplified ecological model between wildlife and cattle populations is formulated, where buffalo interact with cattle populations through disease transmission. Therefore, the ecological model in this study considers three stocks, the healthy and infected cattle populations and infected buffalo population, whereby cattle are subject to FMD infection from buffalo, but not *vice versa*. Thus the interaction between cattle and buffalo is considered unidirectional. This conclusion is based on the scientific evidence that all buffalo in the KNP are infected with and carriers of FMDV, showing no symptoms. Therefore, the negative impact of FMD is always from infected buffalo that escape from KNP to healthy livestock grazing in adjacent areas. In addition, there is currently no evidence showing the mode of FMD transmission from infected cattle to infected buffalo (Vosloo & Thompson, 2004). Hence, infection between infected cattle and infected buffalo is not analysed in the study. However, infection within cattle populations is possible, irrespective of the strong surveillance and control measures in place; hence transmission between cattle populations is included in the model, as illustrated in Figure 4.1 below. For the sake of the analysis, the model also assumes that cattle farmers cannot bring their livestock into the park and buffalo that are spotted outside the park are driven back to the park or killed before they can reproduce.

4.3. The Basic Model

Infected wildlife stock (buffalo) X at time (year) t that inhabits the protected area (KNP) is considered first. The natural growth function of buffalo is given by $F(X_t)$ and $0 \leq y \leq y^{\max}$ denoting harvesting or culling (hereafter, the time subscript is omitted to minimise clutter in the mathematical presentation). The harvesting/culling is non-negative because the possibility of restocking is ignored and it is assumed here that it cannot exceed a certain maximum y^{max}. Buffalo population growth is thus defined as:

$$dX/dt = F(X) - y. \tag{4.1}$$

The density dependent natural growth function is assumed to be a humped curve increasing to a peak value for an intermediate value of stock size such that $\partial F/\partial X = F' \geq 0$ for $X \leq X_{MSY}$ and $F' < 0$ for $X > X_{MSY}$, where X_{MSY} represents the population that gives the maximum sustainable yield. In addition, the model assumes strict concavity, $F'' < 0$. In the numerical analysis and in theoretical reasoning a standard logistic model is used to represent this function, ie $F(X) = rX(1 - X/K)$, where $r > 0$ is the maximum specific growth rate and $K > 0$ is the carrying capacity. It is further assumed that a proportion of buffalo, $0 \leq \theta < 1$, escapes from the park and hence θX number of buffalo mingle with the livestock and negatively influence livestock growth through disease transmission[2].

The livestock (cattle) population Z consists of healthy cattle (S) and infected cattle (I) such that $Z = S + I$ inhabit a particular fixed grazing land area adjacent to the park where they interact with the buffalo that escape from the park due to damaged fencing, lack of management, etc. The population growth of healthy cattle S is given by:

$$dS/dt = G(S + I) - \sigma\theta XS - \tau IS - \alpha_S S. \tag{4.2}$$

With $G(Z) = G(S + I)$ being the natural growth function, assumed to be density dependent, and where growth is governed by the whole cattle population[3], $\sigma\theta XS$ is the disease transmission from the buffalo to livestock with $\sigma > 0$ as the disease transmission rate, or interaction coefficient, and τIS is the disease transmission from infected cattle to healthy

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[2] As indicated above, buffalo that are spotted outside the park are driven back or destroyed before they reproduce. At the cost of considerable notational and analytical clutter, the stock size and hence the natural growth function of the buffalo should have been corrected owing to stock loss outside the park. That is, $(1-\theta)X$ should possibly have replaced X as the actual stock size within the park. However, as a quite small fraction of the buffalo escapes from the park, this discrepancy is ignored.

[3] Density *in*dependent natural growth is often postulated for cattle and other grazing livestock. However, because cattle in the study area are grazing on communal land with limited vegetation quantity, density dependent growth is assumed.

cattle, whereas $\tau > 0$ is the transmission coefficient term from infected cattle to healthy cattle. Finally, $h_s = \alpha_s S$ is the number of healthy cattle harvested, or slaughtered, with $0 \leq \alpha_S \leq \alpha_S^{\max}$ as the harvesting fraction.

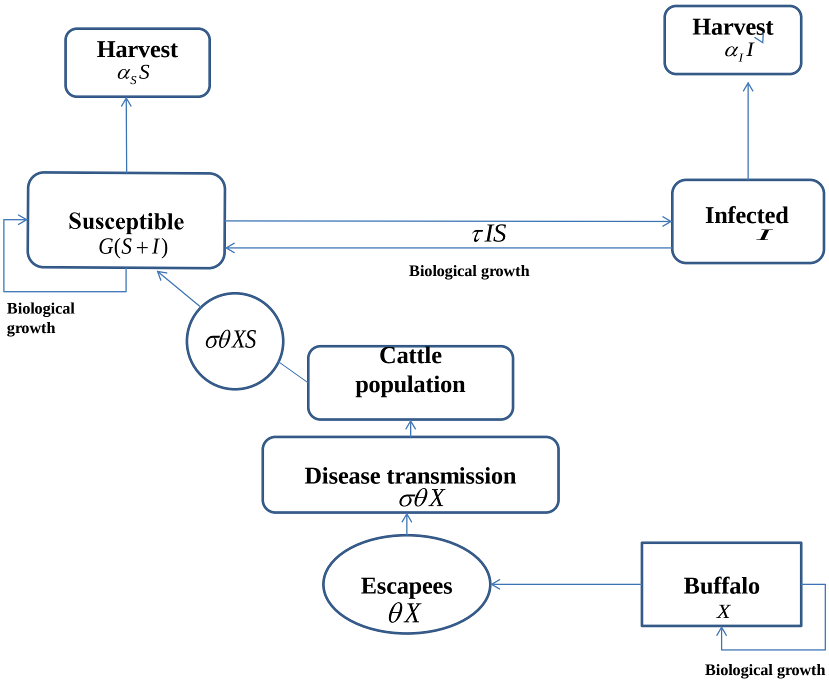


Figure 4.1: The analytical framework showing ecological interaction between buffalo and cattle populations

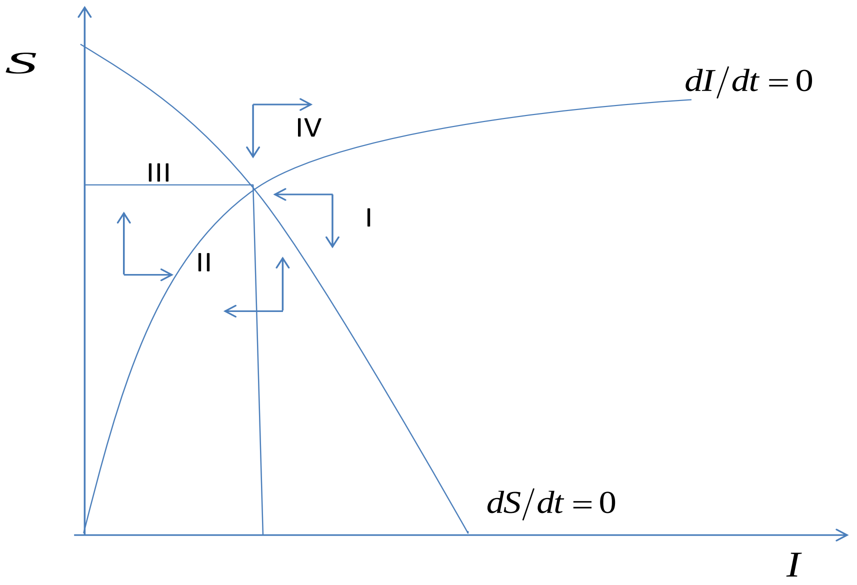
The natural growth function of the healthy cattle population is also assumed to be a humped curve increasing to a peak value for an intermediate value of own stock size such that $G' \geq 0$ for $Z \leq Z_{MSY}$ and $G' < 0$ for $Z > Z_{MSY}$. Strict concavity is also assumed for the livestock growth function, $G'' < 0$. In the numerical analysis this is represented by the logistic function $G(Z) = gZ(1 - Z/L)$, or $G(S+I) = g(S+I)\left[1-(S+I)/L\right]$, where $g > 0$ is the livestock maximum growth rate and $L > 0$ is the carrying capacity.

Finally, the infected cattle population growth is governed by:

$$dI / dt = \sigma\theta XS + \tau SI - mI - \alpha_I I \ . \tag{4.3}$$

In equation 4.3 mI is natural mortality, with $m > 0$ as the mortality rate of infected cattle and $h_I = \alpha_I I$ the number of infected cattle slaughtered with $0 \le \alpha_I \le \alpha_I^{\max}$ as the slaughtering fraction. As already indicated, slaughter of healthy and infected cattle occurs in a selective manner because it is easy to distinguish infected from healthy cattle before slaughter. Therefore, α_I and α_S are generally different.

For a given level of buffalo stock and disease transmission from buffalo $\sigma\theta X$ and given harvesting activity α_S and α_I, one can construct the isoclines of the above equations 4.2 and 4.3. The S-isocline for the healthy cattle is given as $G(S+I) = \sigma\theta XS + \tau IS + \alpha_S S$. By taking the total differential it can be confirmed that this isocline slopes downwards in the $I-S$ plane, except for high values of the harvesting parameter α_S. A downward-sloping S-isocline is depicted in Figure 4.2. The I-isocline for the infected cattle is given by $\sigma\theta XS + \tau SI = mI + \alpha_I I$ and will always be upward-sloping and approach $(m+\alpha_I)/\tau$ when I approaches infinity. Arrows indicate dynamics outside equilibrium.



4.2: Cattle isoclines and the equilibrium with fixed slaughter fractions α_S and α_I and fixed number of wildlife θX that mingles with the cattle population

The effects of more buffalo θX mingling with the livestock are two-sided. Firstly, it reduces the growth of healthy cattle stock, and secondly, the number of infected cattle increases. It can be verified that both isoclines in Figure 4.2 will shift down with a higher density of mingling buffalo and hence result in a lower equilibrium number of healthy cattle, while the effect on the number of infected cattle generally is ambiguous. Both these effects are in line with intuitive reasoning. The total equilibrium cattle stock will generally decrease except when the natural mortality of the infected animals is small and negligible; that is, when $m \approx 0$. Under this assumption and when the slaughter fractions of the two stocks are identical, the number of infected cattle will increase by the same number as the reduction in the equilibrium number of healthy cattle (see also below). A higher value of α_I will shift up the I -isocline, indicating a lower number of infected and higher number of healthy cattle at equilibrium. On the other hand, a higher value of α_S will shift down the S -isocline, indicating that both stocks will be reduced at equilibrium. One also finds that a lower value of the disease transmission parameter within cattle populations τ reduces the equilibrium number of infected cattle, while both the number of healthy cattle and the total cattle population increase. Lower mortality of infected cattle m works in an opposite manner. If the mortality rate of the infected stock is small and negligible, combination of the two isoclines yields $G(S+I) = \alpha_S S + \alpha_I I$. Therefore, as stated above, if $m \approx 0$ and in addition $\alpha_S = \alpha_I = \alpha$, the number of mingling buffalo has no influence on the total equilibrium cattle stock. When inserting the logistic growth function, one further finds $(S+I) = L(1-\alpha / g)$. The total equilibrium cattle population is then simply governed by the two natural growth parameters g and L together with the slaughter parameter α under these assumptions.

4.4. Cost and Benefit Functions

Two agents are included in the model, a group of small-scale cattle farmers acting as a single agent, meaning that any possible conflicting interest among them is neglected, and a conservation agency (or park manager). The cattle farmers derive market and non-market benefits from livestock. However, farmers suffer two direct negative economic effects as a result of FMD transmission. Firsly, infected cattle will generally command a lower price compared to healthy cattle, which in turn reduces income for the farmers through the lower market value of the infected cattle. Secondly, FMD-infected cattle will have lower milk production as well as loss of traction, leading to a reduction in their value. However, the second effect was not considered because information from the survey indicates that this effect is quite insignificant (Sikhweni, 2011). With $p_S > p_I > 0$ as the market prices (net of slaughtering costs) for healthy and infected cattle, respectively, prices are assumed to be determined under perfect competitive conditions; the total income is defined by $p_S h_S + p_I h_I = p_S \alpha_S S + p_I \alpha_I I$. It is also assumed that prices are fixed over time and are not contingent upon the number of cattle sold (slaughtered).

In addition, farmers incur herding costs depending on the total number of cattle. These costs are represented by the increasing, convex function $A(S+I) = A(Z)$ with $A'(Z) > 0$, $A''(Z) \geq 0$ and $A(0) = 0$.

In addition to the income derived and costs incurred, farmers also derive non-market benefits from the total cattle stock, which are given by $W(Z)$, indicating a measure of social status, draught power as well as possible insurance motives (eg Bromley & Chavas, 1989; Perrings, 1994**,** Fafchamps *et al.*, 1998; McPeak, 2004; Borge-Johannesen & Skonhoft, 2011). It is also believed that the more cattle the farmers own, the more benefits, implying that $W' > 0$ and $W(0) = 0$, but at a non-increasing rate; that is, $W'' \leq 0$. This stock effect is hence similar to the so-called 'wealth-effect' in models of optimal growth (eg Kurz, 1968). In addition to the market and non-market benefits above, farmers do not pay for vaccination costs and other related disease control measures such as dipping and quarantine of infected cattle, but rather the government incurs these expenditures (Jori *et al.*, 2009). Assuming that these costs are fixed and incurred by the government, the current net benefit for the group of cattle farmers in year t is given by:

$$U = p_S \alpha_S S + p_I \alpha_I I - A(S+I) + W(S+I). \tag{4.4}$$

On the other hand, the conservation agency derives non-consumptive benefits from tourism (wildlife viewing). It is believed that more wildlife means a more attractive park and higher benefits for the park and this is presented by the function $B(X)$, with $B'(X) > 0$ and $B(0) = 0$. In addition, $B''(X) \leq 0$ is the conservation value, which is typically non-increasing at the margin (Schulz & Skonhoft 1997). Although there are certainly many species of fauna in the park, the interest in this study is in the buffalo stock causing disease transmission to the livestock and the conservation value of buffalo stock.

The conservation agency also incurs costs related to keeping buffalo in the park (Starfield & Bleloch, 1986). This cost component is represented by an increasing, convex function, $V(X)$, with $V'(X) > 0$, $V''(X) > 0$ and $V(0) = 0$ implying that marginal maintenance cost increases with the number of buffalo. While culling of buffalo is currently not practised in the KNP (Bengis, 2011), it is assumed that the conservation agency may find it beneficial to cull. Thus, the conservation agency would also incur the cost of culling buffalo to keep the stock at an acceptable maximum level. For simplicity, this cost function is assumed to be stock-independent and constant per animal culled; that is, cy, with $c > 0$ as the unit culling cost. Therefore, the current net benefit to the conservation agency is defined by:

$$\pi = B(X) - cy - V(X) \tag{4.5}$$

Taking into consideration that safari hunting and selling of hunting licences are not allowed in the park, it is considered that harvesting of buffalo always comes at a cost to the conservation agency. Therefore, if the conservation agency, or the social planner, should find it at all beneficial to cull the stock in the model, as in reality, the marginal stock cost $V(X)$ must exceed the marginal stock benefit $B(X)$ at some level. Specification of $V(X)$ and $B(X)$ will ensure this, such that the concave function $[B(X) - V(X)]$ will reach a peak for a value of the stock below that of the carrying capacity of the animals (see also section 4.5 below).

4.5. Solving the Model Theoretically

4.5.1. The Conservation Perspective

Equations 4.1 – 4.5 are the basic equations of the model. As indicated, without a unified resource management policy, both agents follow their narrow self-interests and optimise independently. The stock of buffalo influences the size and the composition of cattle herds through disease transmission, and ultimately the benefit and the livelihood of cattle farmers, but not *vice versa*. Accordingly, while the conservation agency can optimise its situation without being influenced by the harvest and the cattle holding of the farmers, the farmers must adjust their harvest and stocks to the stock size of buffalo. Therefore, the economic problem of the conservation (park) agency is defined as follows:

$$\underset{y}{Max} \int_{t=0}^{\infty} [B(X) - cy - V(X)]e^{-\delta t} dt \, , \qquad (4.6)$$

$$\text{s.t} \;\; dX/dt = F(X) - y, \; \text{X>0} \; .$$

Note that the (4.6) defines a constrained optimisation problem. The constraint is called the 'equation of motion' because it describes the motion in time of the state variable, while $\delta \geq 0$ is the discount rate and the planning horizon is infinite, indicating that one is looking for steady state. It is possible use Pontryagin's maximum principle to find the optimal harvest (Conrad and Clark 1987). The first step to apply the maximum principle is to define the Hamiltonian. The current value Hamiltonian for problem (4.6) is given by:

$$H_{cv} = [B(X) - cy - V(X)] + \mu(F(X) - y) \qquad (4.7)$$

where μ is the shadow price (costate variable) of the buffalo population. This may be thought of as the value of having an additional unit of buffalo stock at the margin or the intertemporal opportunity of harvesting an additional buffalo immediately. Assuming an interior solution, there are three necessary conditions for optimisation of the Hamiltonian. These conditions, which define the optimal solution path, are the equation of motion (4.1), the first order conditions (FOC) and the adjoint condition.

The FOC are derived as follows:

$$\partial H / \partial y = -c - \mu \overset{\geq}{\underset{\leq}{=}} 0 \text{ with}$$

$$y = \begin{cases} 0 & \\ y^* & if \\ y^{\max} & \end{cases} \begin{matrix} -c < \mu \\ -c = \mu \\ -c > \mu \end{matrix} \qquad (4.8)$$

$d\mu / dt - \delta\mu = -\partial H / \partial X$.

Equation (4.8) represents a bang-bang or singular control, y^*, as is expected with an objective function that is linear in the control variable and where the instantaneous buffalo culling cannot exceed the maximum $y^{\max}$. In addition, equation (4.8) states that at the optimum the marginal intertemporal cost of harvesting (μ) must be equal to the marginal net benefit from harvesting in the current period.

The adjoint condition is derived as follows:

$$d\mu / dt - \delta\mu = -\partial H / \partial X = -B'(X) + V'(X) - \mu F'(X) \quad . \qquad (4.9)$$

Equation 4.9 is the adjoint condition, which indicates that the sum of the cattle capital gain $d\mu/dt$ and the net stock effect $[B'(X) - V'(X) + \mu F'(X)]$ resulting from maintaining one unit of buffalo must be equal to the marginal benefit of harvesting one unit of buffalo and putting the proceeds in the bank, $d\mu$. This condition further ensures that the planner will be indifferent at the margin between reallocations of harvests across time; in essence it is an intertemporal arbitrage condition.

The analysis below confirms that the optimal interior steady state solution is unique. The steady state will, as indicated, be approached by bang-bang control, either through no harvesting at all, ie $y = 0$, or harvesting at the maximum level, $y = y^{\max}$. The sufficient condition for the above problem is that the maximised Hamiltonian is concave in the stock variable X, ie the weak Arrow sufficiency condition is satisfied. This requires that $\partial^2 H / \partial X^2 = (B'' - V'' + \mu F'') \leq 0$. With singular control $-c = \mu$, this also reads as $cF'' \geq (B'' - V'')$ and implies that at the optimum the harvest costs associated with buffalo must decline less than the combined value of the marginal t value and buffalo stock maintenance cost.

The optimal steady state is defined by $dX/dt = d\mu/dt = 0$. Therefore with singular control and inserting this into condition 4.9 one finds that the optimal state is described as:

$$F'(X) = \delta + \frac{B'(X) - V'(X)}{c} \quad . \tag{4.10}$$

Equation 4.10 is the 'golden-rule' management for the conservation agency (See Appendix 2) and determines the long-term buffalo target population X^* when the conservation agency steers the resource allocation in the absence of a unified management policy. With minor arrangements, the left-hand side is simply the discount rate representing the opportunity cost of holding the buffalo in situ, as the buffalo stock could otherwise be harvested and the proceeds invested in the bank. The right-hand side represents the rate of return from holding the stock in situ. The first term represents the cost effect due to a larger stock while the second term represents the stock's marginal growth.

In equation 4.10, the concave net stock value function $(B'-V')$ should reach a peak value below the buffalo carrying capacity because harvesting always comes at a cost. The sign of $(B'-V')$ can be either positive or negative at the optimum. However, the important thing from the sufficient condition is that $(B''-V''-cF'') \leq 0$ should hold. The solution is then unique and less than the carrying capacity, that is, $0 < X^* < K$. The singular, or steady state, harvest follows from $y^* = F(X^*)$. Because buffalo are harvested (culled) not for their value, but for keeping the stock at an acceptable maximum level, the comparative static results were found to be different from the standard bio-economic model (ie Clark, 1990). When differentiating equation 4.10 , one thus finds $(B''-V''-cF'')dX = -cd\delta$, which indicates that for a higher value of the discount rate, δ, the conservation agency will find it beneficial to keep more buffalo and hence invest more in the buffalo stock, and not in 'the bank'. The effect of a higher culling price c is ambiguous, and a negative effect occurs if X^* is larger than the stock size determined by $F' < \delta$.

The preceding section analyses the problem of cattle farmers with the aim to maximise the net present-value of cattle with perfect harvesting selectivity. When assuming that the discount rate is similar to that of the conservation agency, the economic problem for the group of farmers is then to maximise:

$$\underset{\alpha_S,\alpha_I}{Max}\int_0^{\infty}[(p_S\alpha_S S + p_I\alpha_I I) - A(S+I) + W(S+I)]e^{-\delta t}dt \tag{4.11}$$

s.t $dS/dt = G(S+I) - \sigma\theta XS - \tau IS - \alpha_S S \;\; , S > 0$

$dI/dt = \sigma\theta XS + \tau SI - mI - \alpha_I I \;\; , I > 0$.

The constraints are represented by the population growth equations 4.2 and 4.3 for healthy and infected cattle, respectively. A similar process as before will be followed in order to reach the steady state solution.

The current–value Hamiltonian of this problem is then given by:

$$H_{cv} = [(p_S\alpha_S S + p_I\alpha_I I) - A(S+I) + W(S+I)] + \tag{4.12}$$

$$\lambda[G(S+I) - \sigma\theta XS - \tau IS - \alpha_S S] + \eta(\sigma\theta XS + \tau SI - mI - \alpha_I I)$$

where λ and η are the shadow prices (costate variables) of the healthy and infected cattle stock, respectively.

The necessary conditions for a maximum are the following: $\partial H / \partial\alpha_S = S(p_S - \lambda) \overset{\geq}{\underset{\leq}{=}} 0$ with:

$$\alpha_S = \begin{cases} 0 & \\ \alpha_S^* & if \\ \alpha_S^{\max} & \end{cases} \begin{matrix} p_S < \lambda \\ p_S = \lambda \\ p_S > \lambda \end{matrix} \tag{4.13}$$

$\partial H / \partial\alpha_I = I(p_I - \eta) \overset{\geq}{\underset{\leq}{=}} 0$ with:

$$\alpha_I = \begin{cases} 0 & \\ \alpha_I^* & if \\ \alpha_I^{\max} & \end{cases} \begin{matrix} p_I < \eta \\ p_I = \eta \\ p_I > \eta \end{matrix} \tag{4.14}$$

Similar to the park agency, cattle farmers also have bang-bang control or singular controls; here the slaughtering of the healthy cattle and the infected cattle cannot exceed the maximum values $\alpha_S^{\max}$ and $\alpha_I^{\max}$, respectively.

The adjoint equations when still assuming $S>0$ and $I>0$ are:

$$d\lambda/dt-\delta\lambda=-\partial H/\partial S=-[p_S\alpha_S-A'+W'+\lambda(G'-\sigma\theta X-\tau I-\alpha_S)+\eta(\sigma\theta X+\tau I)] \quad (4.15)$$

and

$$d\eta/dt-\delta\eta=-\partial H/\partial I=-[p_I\alpha_I-A'+W'+\lambda(G'-\tau S)+\eta(\tau S-m-\alpha_I)]. \quad (4.16)$$

Equation 4.15 indicates that the sum of the healthy cattle capital gain $d\lambda/dt$ and the net stock effect $[p_S\alpha_S-A'+W'+\lambda(G'-\sigma\theta X-\tau I-\alpha)+\eta(\sigma\theta X+\tau I)]$ resulting from maintaining one unit of cattle must equate the marginal benefit of harvesting one unit of the cattle stock and putting the proceeds in 'the bank', $\delta\lambda$. Condition 4.16 for the infected cattle stock is given a similar interpretation.

In order to analyse the optimal steady state solution, the possibility when an interior solution with singular controls exists was considered. The steady state is defined by $dS/dt=dI/dt=d\lambda/dt=d\eta/dt=0$. Inserting the singular controls $p_S=\lambda$ and $p_I=\eta$ into conditions 4.15 and 4.16, the steady state may be characterised as:

$$G'(S+I)=\delta+\frac{A'(S+I)-W'(S+I)}{p_S}+\frac{(\sigma\theta X+\tau I)(p_S-p_I)}{p_S}$$

and $G'(S+I)=\dfrac{p_I(\delta+m)}{p_S}+\dfrac{A'(S+I)-W'(S+I)}{p_S}+\dfrac{\tau S(p_S-p_I)}{p_S}$.

The sufficient conditions of this interior steady state require that the maximised Hamiltonian is concave in the two stock variables S and I (.e again the weak Arrow sufficiency condition). This requires that

$\partial^2 H/\partial S^2=\partial^2 H/\partial I^2=(p_S G''-A''+W'')\le 0$ and

$$(\partial^2 H/\partial S^2)(\partial^2 H/\partial I^2)-(\partial^2 H/\partial S\partial I)^2=(p_S G''-A''+W'')^2$$
$$-[(p_S G''-A''+W''-\tau(p_S-p_I)]^2\geq 0\,.$$

However, because the slaughter value of healthy cattle is above that of infected cattle, the last inequality of the equation does not hold. Therefore, this interior solution does not represent a maximum, but is rather of the saddle type solution. Other options for an optimal steady state are to set the controls at the boundary. There are several possibilities for boundary solutions. Both controls may be set at their maximum values, or one control set at a maximum and the other control at zero. Alternatively, one control can be set to bind either at zero or maximum, while the other control may be an interior. However, among these different possibilities, the most likely path to follow should be to slaughter the infected cattle at the maximum $\alpha_I^{\max}$ while the healthy stock, depending on the size of the maximum constraint, should be slaughtered at its maximum, or at an interior value, $0<\alpha_S<\alpha_S^{\max}$. The reason that slaughtering of the infected stock at its maximum may represent an optimal strategy is that this strategy will boost the growth of the healthy stock as the number of infected cattle decreases. While this has not been proven mathematically, numerical illustration supports this conclusion (Chapter 5). In a steady state with singular control for the healthy stock $p_S=\lambda$ and maximum harvest of the infected cattle such that $p_I>\eta$ the golden rule equations are as follows:

$$G'(S+I)=\delta+\frac{A'(S+I)-W'(S+I)}{p_S}+\frac{(\sigma\theta X+\tau I)(p_S-\eta)}{p_S} \qquad (4.17)$$

and

$$G'(S+I)=\frac{\eta(\delta+m)}{p_S}+\frac{A'(S+I)-W'(S+I)}{p_S}+\frac{\tau S(p_S-\eta)}{p_S}-\frac{\alpha_I^{\max}(p_I-\eta)}{p_S}\,. \qquad (4.18)$$

Therefore, equations 4.17 , 4.18, 4.2, equation 4.3 as well as equation 4.10 determine the steady state stock values for healthy cattle, S^* and infected cattle, I^*, as well as the singular harvest for heathy cattle, α_S^*, and the shadow price of the infected cattle stock η^* (* indicates the steady state solution for cattle farmers). Because $(p_S G''-A''+W'')\leq 0$ and the term $(\sigma\theta X+\tau I)(p_S-\eta)/p_S$ in 4.17 is positive, the total cattle stock (S^*+I^*) will be smaller than without disease. The disease prevalence hence represents a two-sided steady state effect; fewer cattle and lower slaughtering value of the animals.

Approaching this steady state in an optimal way is complicated for the following reasons: Firstly, the growth of the cattle populations is contingent upon the dynamics of the buffalo population. Secondly, cattle slaughter controls may take place by a combination of extreme and singular controls. The complexity of analysing the approach paths in multi-dimensional models is exemplified by the predator-prey model of Mesterton-Gibbons (1996), where it is shown that a combination of bang-bang and singular strategy is not generally optimal. For a more recent example see Fenichel and Horan (2007).. However, one may suspect that because of the strong degree of linearity in the model, together with density dependent regulation through both the wildlife stock growth equation and the cattle growth equations in the model, a stable equilibrium is approached quite fast. This is confirmed by the numerical results presented in the following chapter.

4.5.2. Social planner scenario

The following section analyses overall optimality or a social planner solution. Under this scheme there is a unified management policy so that the trade-offs between keeping buffalo in the park for their tourist value and the livestock supporting the livelihood of small-scale farmers are determined in an overall optimal way. The negative externality through disease transmission from wildlife to cattle is then internalised. Therefore, the goal of the social planner is to maximise joint net present value or benefit given as:

$$\underset{\alpha_s,\alpha_I,y}{Max}\int_0^{\infty}\{[(p_S\alpha_S S+p_I\alpha_I I)-A(S+I)+W(S+I)]+[B(X)-cy-V(X)]\}e^{-\delta t}dt \qquad (4.19)$$

s.t $dX/dt = F(X)-y,$ X>0

$$dS/dt = G(S+I)-\sigma\theta XS-\tau IS-\alpha_S S \quad , S>0$$

$$dI/dt = \sigma\theta XS+\tau SI-mI-\alpha_I I \quad , I>0.$$

The equation of motion is given by the population dynamics of buffalo (4.1) and the healthy and infected cattle stock growth equations (4.2) and (4.3), respectively. The model assumes the same weighting of the net benefits between the park agency and the cattle farmers such that on the margin, the value of an extra unit of benefit is the same for both. This obviously represents a normative valuation, but it is beyond the scope of this study to look further into distributional issues of this type.

The Hamiltonian of this problem is written as:

$$H_{cv} = [B(X) - cy - V(X)] + \mu(F(X) - y) \qquad (4.20)$$
$$[(p_S\alpha_S S + p_I\alpha_I I) - A(S+I) + W(S+I)] +$$
$$\lambda[G\left(S+I\right) - \sigma\theta XS - \tau IS - \alpha_S S] + \eta(\sigma\theta XS + \tau SI - mI - \alpha_I I)\ .$$

Assuming that that the upper boundary control of the infected cattle stock $\alpha_I^{\max}$ and singular control for the healthy stock still represent optimal steady state harvesting strategies and singular control of the buffalo population still holds, it can easily be verified that the steady state, or golden rule, conditions are described by equations 4.17 and 4.18., together with the buffalo equation:

$$F'(X) = \delta + \frac{B'(X) - V'(X)}{c} - \frac{\sigma\theta S(p_S - \eta)}{c}\ . \qquad (4.21)$$

Equation 4.21 replaces equation 4.10 when the disease externality is internalised. Equations 4.17, 4.18, and 4.21, together with the stock growth conditions 4.2 and 4.3 in equilibrium, now determine the steady state buffalo stock X^p, the cattle stocks S^p and I^p, the harvest for healthy cattle , α_S^p and the shadow price of healthy cattle, η^p (superscript ‘p’ indicates social planner steady state solution). In addition, just as above, the singular harvest of buffalo follows from the wildlife natural growth equation 4.1 in equilibrium while the buffalo shadow price, just as above, is $\mu^p = -c$.

With the knowledge that the market slaughter price for healthy cattle is higher than that of infected cattle and the slaughter price of the infected animals exceeds their shadow price when $\alpha_I^{\max}$, the last term in equation 4.21 is positive, $\sigma\theta S(p_S - \eta)/c > 0$. This term works in the opposite direction as the discount rate δ by increasing the slope of the growth function and thereby lowering the buffalo stock. Therefore, not surprisingly, the social planner scenario yields fewer buffalo because the negative externality has been internalised, compared to the conservation scenario without a unified resource management policy, such that $X^p < X^*$. Lowering the buffalo stock with a similar slaughtering fraction means that the equilibrium schedule of the infected cattle stock, or the I -isocline in Figure 4.2 above, shifts up compared to the conservation scenario. A smaller number of buffalo also means that the S -isocline partially shifts up. However, as the slaughter fraction of the healthy stock generally changes compared to the conservation scenario, the net effect here is generally ambiguous. However, as long as the net effect represents a non-negative shift, one will not find it surprising that the total cattle population will be higher compared to the conservation scenario; that is, $S^p + I^p > S^* + I^*$. One then also finds $S^p - S^* > 0$, while the difference $I^p - I^*$ is ambiguous (see also section 3 above). For this reason the difference $h_I^p - h_I^* = \alpha_I^{\max}(I^p - I^*)$ is ambiguous as well.

Assuming that the social planner distributes the conservation profit and cattle farmer benefit according to harvest and stocks of buffalo and cattle, respectively, the steady state profit of the park manager will then be lower under the social planner scenario. This will be so at least when the discount rate is zero, δ=0, because the steady state solution then coincides with the problem of maximising profit in ecological equilibrium (eg sustainable rent maximisation; see Clark, 1990). For the group of cattle farmers one finds the opposite and $U^p > U^*$ because $(\pi^p + U^p) > (\pi^* + U^*)$. Thus, when the social planner manages resources allocation, the net benefits of the park agency will increase while the net benefits of the cattle farmers will increase.

4.5.3. Hypothetical Situation with No Disease Transmission

The final scenario considers a hypothetical situation where there is no disease transmission, and hence the term $\sigma\theta XS$ becomes zero in the cattle growth equations 4.2 and 4.3. This may be the case if buffalo are effectively prevented from entering the adjacent areas of the conservation area; that is, no fences are destroyed, etc, or cattle vaccination is totally preventing the cattle stock from being infected. When also assuming that no cattle are infected initially, or that is it is possible to stamp out all infected cattle, the livestock equations 4.2 and 4.3 collapse into:

$$dZ/dt = G(Z) - \alpha Z \,. \tag{4.22}$$

The benefit function of the cattle farmers changes accordingly, since farmers only slaughter healthy animals such that the slaughter price is p_S . As there are no externalities in this model, there is no interaction among the agents. Therefore, when the conservation agency optimises its situation, the buffalo stock under a no-disease scenario will be identical to what was found under the conservation perspective, $X^n = X^*$ (superscript ‘n’ denotes the no disease transmission scenario). The steady state profit for the conservation agency will also be similar under these two scenarios.

The optimisation problem facing the cattle farmers is now to maximise

$$\underset{\alpha}{Max} \int_{t=0}^{\infty} [p_S \alpha Z - A(Z) + W(Z)] e^{-\delta t} dt \tag{4.23}$$

s.t

$$dZ/dt = G(Z) - \alpha Z \;\; , Z > 0 \,.$$

The equation of motion is given by equation (4.22). The steady state for cattle population with singular control Z^n (golden rule) is then determined by:

$$G'(Z) = \delta + \frac{A'(Z) - W'(Z)}{p_s} \quad . \tag{4.24}$$

The steady state singular optimal slaughter policy α^n follows through $\alpha Z = G(Z)$. This solution Z^n and α^n indicates the optimal size of the cattle stock and slaughtering when there are no resource conflicts due to disease transmission between the conservation agency and cattle farmers. In addition, assuming that there is no discounting, the steady state benefit under this scenario exceeds the previous cases, $U^n > U^p > U^*$.

4.6. Conclusions

This chapter developed a model that incorporates a disease transmission mechanism between buffalo and cattle populations within a dynamic optimisation framework. The disease transmission and interaction between buffalo and cattle populations are assumed to be unidirectional such that disease transmission always comes from infected buffalo to livestock and not *vice versa*. The important economic effect of the disease transmission considered in the model is the reduction in the value of the cattle through a reduced slaughter price, hence reduction in the net benefits of the cattle farmers.

The model is solved under three different scenarios in order to assess the conflicting interests of cattle farmers and the park agency. Under the conservation scenario there is no unified resource management policy and the conservation agency pursues its own selfish interests without taking into account the negative externality imposed on the livestock farmers. The social planner solution takes into consideration the interests of both the agency and farmers in order to achieve a unified optimal management strategy. The third scheme is a hypothetical situation of no disease transmission between buffalo and cattle populations. The model characterised the different scenarios analytically and the factors affecting cattle and wildlife stocks, harvest and net benefit in the various steady states were scrutinised.

As expected, the unified management scheme (social planner) yields fewer buffalo and less disease transmission than under a pure conservation strategy (hence fewer infected cattle). If the social planner distributes conservation profits such that the farmers benefit according to the harvest of buffalo and stocks of cattle, the steady state profits of the park manager will be lower but benefits to cattle owners will be higher under the unified management scenario than under the pure conservation scenario. Most importantly, the above results confirm that when the negative externality resulting from FMD is internalised, a social optimal solution will be reached such that there is a balanced trade-off between keeping buffalo in the park for their tourist value and as an income-generating asset and the livestock that supports the livelihood of small-scale farmers.

CHAPTER 5: EMPIRICAL RESULTS AND DISCUSSIONS

5.0 Introduction

This chapter presents results of the application of the analytical model developed in chapter 4 and derives conclusions and the implications of the study. In addition, the chapter looks at both the transitional dynamics and steady states under all three scenarios considered in the analytical model, with the main emphasis on the steady state under the conservation scenario where the park agency optimises the situation without being influenced by the actions of the farmers. In contrast, small-scale farmers must adjust their harvests and stock sizes to the stock size of the buffalos. Section 1 outlines the specification of functional forms and the parameters to be used in the simulation. Section 2 presents the results and section 3 derives the conclusion and policy implications of the study.

5.1 Data and specification of functional forms

The standard logistic forms were used for the natural growth functions of the buffalo as well as the healthy and infected cattle populations, as specified in Chapter 4. The disease transmission mechanisms are as given in the analytical model specifications of chapter 4. The culling cost function for the conservation agency is assumed to be linear in the harvest and does not include any stock effect. With the exception of the stock cost function to control the herd size of buffalo in the park, all other cost and benefit functions are assumed to be linear. Thus, the maintenance cost function for farmers is specified as $A(Z) = aZ = a \cdot (S + I)$ with $a > 0$ and the cattle stock value function as $W(Z) = wZ = w \cdot (S + I)$ with $w > 0$. The tourist value function for the conservation agency is measured by $B(X) = bX$ with $b > 0$, while the cost function for buffalo stock is specified as strictly convex and represented by $V(X) = (v/2)X^2$ with $v > 0$.

The values of the biological and economic parameters are taken either from previous studies, from South African National Parks and the Directorate of Veterinary Services in the KZN, or based on qualified guess work and calibration (Table 5.1). The carrying capacity for the cattle population in the open grazing area is $L = 32\ 5000$ (animals) while the carrying capacity for the buffalo population is $K = 50\ 000$ (animals). The baseline value proportion of buffalo escaping the park is assumed to be $\theta = 0.003$, indicating that about 150 buffalo escape the park if the buffalo stock is close to its carrying capacity. The associated disease interaction coefficient between buffalo and livestock is $\sigma = 0.0001$. With a healthy cattle population of, say, 200 000 animals, the number of healthy cattle that becomes instantaneously infected because of the 150 buffalo mingling with the cattle population is then $\sigma\theta XS = 3000$ animals. The disease transmission coefficient within the cattle populations, τ, is assumed to be far lower than the disease transmission coefficient between wildlife and healthy cattle. This assumption is based on the rapid response by the local Veterinary Services Department when an FMD outbreak is reported. Immediately after an outbreak has been reported, infected animals are kept in quarantine areas in order to avoid further transmission within the cattle populations (Personal communication with the local animal health technician). The disease coefficient within cattle populations was set at $\tau = 0.000001$. Based on the values of the disease interaction coefficient terms as well as stock levels, one finds that with a healthy cattle stock of 200 000 animals and an infected stock of 3 000 animals, the instantaneous loss of healthy cattle due to interaction with infected cattle is $\tau IS = 600$ animals. The mortality rate (m) of infected cattle is rather small, and its baseline value is fixed at 5% (0.05). As indicated in the steady state analysis of chapter 4, it will be beneficial for the cattle farmer to slaughter as many of the infected animals as possible to reduce disease transmission and extract benefits from sales. Thus, the slaughter fraction of infected cattle is arbitrarily set at $\alpha_I^{\max} = 0.90$ under the conservation as well as the social planner scenarios.

It is, however, difficult to assess the conservation cost and benefit values of the buffalo, because buffalo is just one of the many species present in the park. Based on the entrance fee of R196 ($1=ZAR7.562) and the annual number of tourists, 1.4 million people (SanParks, 2011), the total (gross) tourist value of the park is known. In addition to assessing the number of the other key species in the park and adding some intrinsic, or existence, value of the buffalo, one ends up with the arbitrary assumption of a baseline value of 175 (rand/animal). The culling cost per animal is assumed to be 1000 (rand/animal). This estimate is based on the contraceptive method that is currently used to manage the elephant population in the Greater Makalali Private Game Reserve in Limpopo Province, using a contraceptive vaccine derived from Pig Zona Pellucida (Delsink *et al.*, 2007). The maintenance cost for the buffalo stock is calculated taking into consideration that South Africa has a complicated system of fencing along its national park borders, which are regularly supervised and maintained. Some estimates of these costs do not include the capital investment in constructing fences (Perry *et al.*, 2003). Based on these considerations, the cost to keep the buffalo in the park v is then calibrated to ensure that the net stock buffalo value $[B(X)-V(X)]$ reaches a peak value below that of the carrying capacity.

The slaughter market price for healthy cattle and infected cattle is based on survey, where the healthy animal price is $p_S = 4030$ (rand/animal). The infected animal price is assumed to be 25% lower. The maintenance cost of the cattle is based on survey information where the farmers have assessed the average monthly cost of holding, or herding cattle. Based on a monthly cost of R300 per flock and assuming an average herd size of nine, one arrives at a yearly cost of about 500 (rand/animal). The non-market benefit for livestock (eg draught power) is estimated through the weighting proportion of male and female cattle (the herd size) as well as the market prices of male and female cattle; male cattle are more valuable. Finally, the baseline discount rate δ is assumed to be zero, indicating that the steady states, or target populations, are similar to what is found when the current benefit in biological, or ecological, equilibrium is maximised (see Clark, 1990). The analysis has also studied the consequences of other values for some of the key parameters.

Table 5.1: Baseline values of the ecological and economic parameters

	Parameter	Value	Source
Intrinsic growth rate buffalo	r	0.12	Jolles (2007)
Carrying capacity buffalo	K	50 000 (no of animals)	KNP
Intrinsic growth rate livestock	g	0.67	Horan et al. (2008)
Carrying capacity livestock	L	325 000 (no. of animals)	Vosloo et al. (2009)
Natural mortality disease infected livestock	m	0.05	Bengis (2011)
Disease interaction coefficient wildlife – livestock	σ	0.0001 (infected animals)	Bicknell et al. (1999)
Disease interaction coefficient livestock – livestock	τ	0.000001 (infected animals)	Bicknell et al. (1999)
Proportion of buffalos escaping park	θ	0.003	Bengis (2011)
Slaughter price for healthy livestock	p_S	4030 (R/animal)	Survey
Slaughter price for infected livestock	p_I	3000 (R/animal)	Survey
Maintenance cost for livestock	a	500 (R/animal)	Survey
Value of livestock (non-market benefit)	w	800 (R/animal)	Survey
Wildlife stock value (tourist benefit)	b	175 (R/animal)	Calculated
Unit cost of wildlife culling	c	1000 (R/animal)	Assumption
Wildlife stock cost (maintenance cost)	v	0.0064 (R/animal^2)	Calibrated
Discount rate	δ	0.00	Assumption

5.2 Results

5.2.1 Steady states and economic results

The empirical analysis and simulations of model scenarios were conducted using Microsoft Excel. Model solutions for ranges of key parameters' values have been obtained under various scenarios to test the sensitivity of the specifications to key determinants of the system performance.

Assuming a zero discount rate, Tables 5.2 and 5.3 report the steady state results for the three different scenarios specified in chapter 4. Specifically, table 5.2 shows the optimal harvest and stock levels under the conservation scenario. The buffalo stock is well below its carrying capacity of K= 50 000 and about 1 300 buffalo are culled yearly to keep the stock at an acceptable level. The optimal stock of the cattle population is slightly higher than $Z = 179\ 000$, consisting of 177 000 and 2300 healthy and infected cattle, respectively. The total stock of cattle is thus above $Z_{MSY} = 162\ 500$ animals because the positive stock value, which represents social status and draught power, dominates the maintenance cost and the negative externality effect of infected buffalo (Equation 4.13). The slaughter fraction of the healthy cattle is about 0.29, while the maximum harvesting fraction imposed on the infected cattle is $\alpha_I^{\max} = 0.90$.

Table 5.2: Steady state stock levels and their associated slaughter fractions

	Buffalos (X)	Culling (Y)	Healthy cattle (S)	Infected cattle (I)	$Z = S + I$	α_S	α_I
Conservation scenario	34 400	1300	177 000	2300	179 300	0.29	0.90
Social planner scenario	32 000	1400	177 300	2200	179 500	0.29	0.90
No disease transmission scenario	34 400	1300	180500	-	180500	0.30	-

Contrary to the conservation scenario, the buffalo stock declines (equation 4.15) under the social planner scenario where the negative externality is taken into consideration. In addition, the total cattle population, as expected, increases, albeit just slightly. Also as expected, the number of healthy cattle increases slightly, and the steady state fraction of infected cattle under the social planner scenario decreases by about 1.2%. The situation under the no-disease scenario paints a more attractive picture where the total cattle stock becomes slightly higher compared to the conservation and social planner scenarios. This increase can be attributed to the optimal harvest fraction $\alpha^* = 0.30$. In addition, under the no-disease scenario, the buffalo stock and harvest are expected to be similar to the conservation perspective scenario because there are no externalities and no interaction among the agents.

Table 5.3 reports the associated economic benefits at steady state for different scenarios. Under the conservation scenario, the yearly profit of the park manager is about R0.8 million while the monetary value for the utility of cattle farmers is about R267.5 million. The utility of cattle farmers under this scenario is made up of income generated from selling cattle (R213 million); the non-monetary benefits such as draught power and social status of R143 million less the herding costs (R89.7 million). These benefits are compared to the net benefits gained by the farmers under the social planner scenario, which is slightly higher (R268.9 million).

Table 5.3: Net benefits at the steady state (ZAR million)

	Park agency (π)	Farmers (U)	Total benefits ($\pi + U$)
Conservation scenario	0.8	267.5	268.4
Social planner scenario	0.9	288.0	268.9
No disease transmission scenario	0.9	271.0	271.9

In general the differences in the economic values between the different scenarios appear to be very small. The main reason for these small differences could be that the economic activity of the conservation agency, which includes only buffalo holding, is small compared to the livestock sector. Therefore, the economic effect imposed on farmers as a result of the negative externality becomes small because the effect is spread over a larger group.

The reduction in cattle farmers' benefits is even smaller between the social planner solution and the conservation scenario. However, it should be remembered that for simplicity, the model treats farmers as a homogeneous group, and as such each farmer's cattle stock is affected similarly by disease transmission. In reality these benefits/effects will differ across various farmers, depending on location, distance to the park and so forth and the model developed does not control for these variations.

Figures 5.1 to 5.3 show how steady state stock sizes approach a stable equilibrium. As already indicated, because of the strong degree of linearity in the model, together with density dependent population growth equations for both buffalo and cattle populations, the model approaches a stable equilibrium quite fast without any overshooting/undershooting. The culling of buffalo and harvesting values of the cattle stocks are adjusted such that the steady states are approached within three to five years.

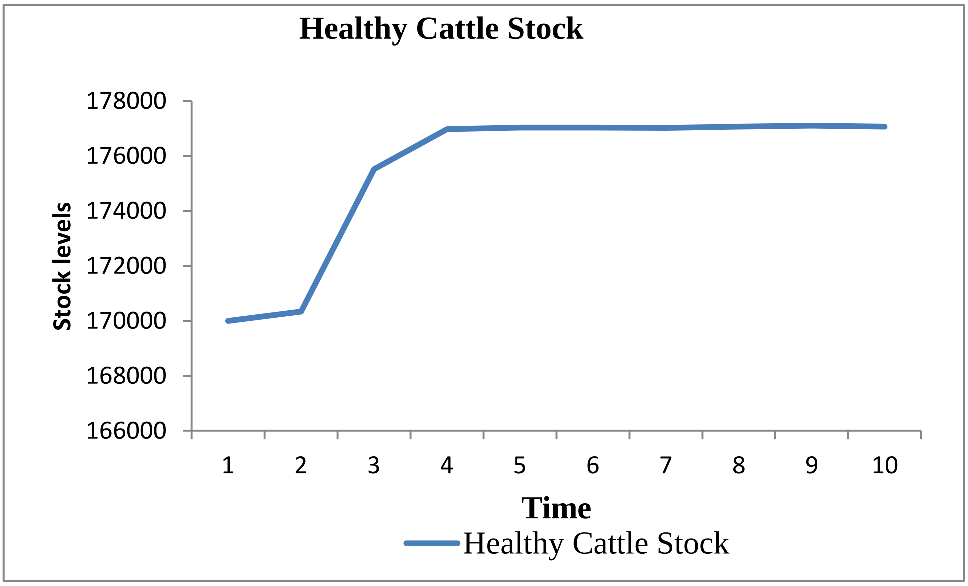


Figure 5.1: Steady state level for the stock of healthy cattle (S)

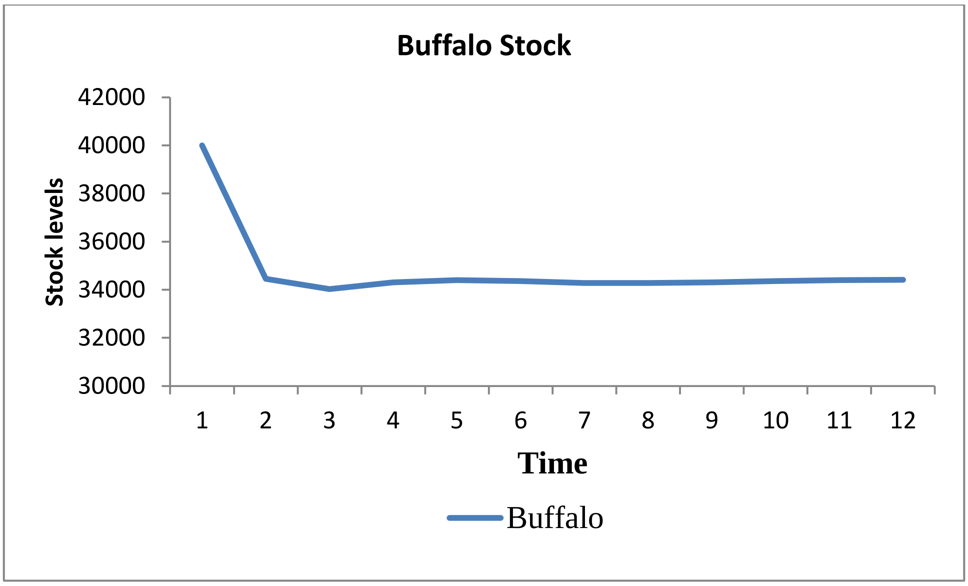


Figure 5.2: Steady state level for buffalo stock (X)

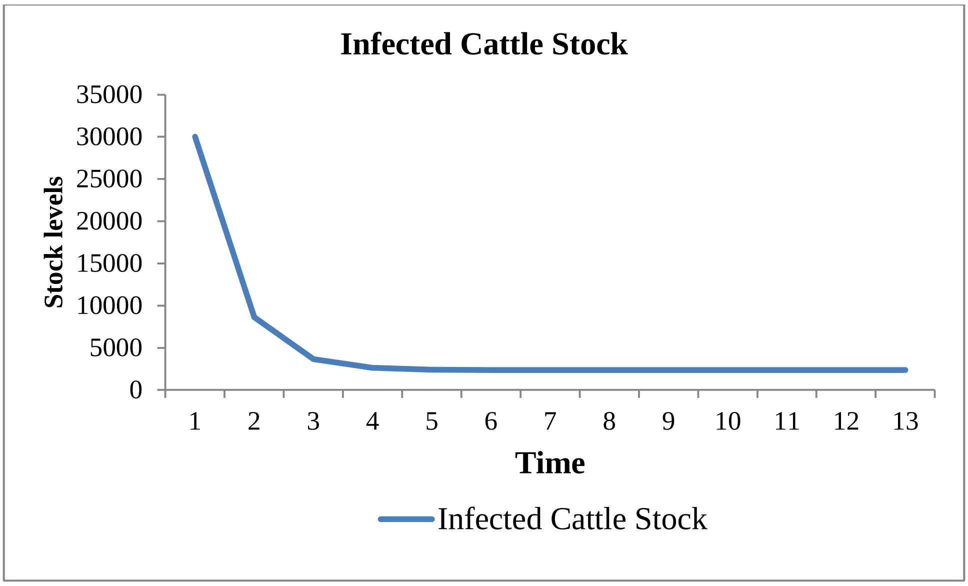


Figure 5.3: Steady state level for infected stock of cattle (I)

5.2.2 Sensitivity analysis

The steady states results above indicate that there are small differences between different scenarios, making it challenging to justify any government intervention. In order to assess the appropriate FMD control policies that will lead to optimal trade-offs between the conflicting interests of the park agency and cattle farmers, sensitivity analysis was conducted. Thus, the effects of changes in some of the key parameters, such as the proportion of buffalo escaping from the park, and the FMD control measures, such as quarantine or vaccination programmes aimed at reducing the infection between infected and healthy cattle in the model, were assessed under the conservation scenario (Table 5.4). It is important to assess how the negative externality will be minimised when these intervention measures are introduced.

Table 5 shows results of the sensitivity analysis of stock levels of buffalo and cattle populations to variations in the discounting rate. As explained in the theoretical reasoning, at higher discount rates the conservation agency will find it beneficial to keep more buffalo in the park. As the discount rate increases from the baseline value to 3%, the buffalo stock increases to 54% and 91%, respectively. Buffalo stocks therefore continue to increase as the discount rate is increased. This is because in this model buffalo are not culled to generate income but to keep the stock at an acceptable maximum level. By contrast, as the discount rate increases to 3%, the net benefits of the cattle farmers decrease by 9%. As the discount increases to 5%, 10% and 15%, the net benefits of the farmers decrease by 15%, 28% and 38%, respectively. The net benefits of farmers decrease owing to the higher number of buffalo in the park, which will lead to a higher proportion of buffalo escaping from the park and mingling with the cattle population, transmitting FMD. In addition, higher discount rates encourage farmers to sell more cattle immediately, as the opportunity cost of waiting increases with higher discounting of future income.

Table 5.4: Sensitivity of stock size and net benefits to discount rates under the conservation scenario

	$\delta = 0$	$\delta = 0.03$	$\delta = 0.05$	$\delta = 0.1$	$\delta = 0.15$
Buffalo	34 400	53 125	65 600	96 800	128 125
Infected	2 300	3 660	4 270	5 544	6 484
Healthy	17 700	171 600	166 571	148 246	134 684
Net benefits (ZAR millions)	268	243	228	194	165

Table 5.5 gives sensitivity results for buffalo and cattle populations as well as the net benefits to the farmers, when the interaction terms between livestock populations and the proportion of buffalo escaping from the park vary. The variation in the stock levels for cattle and buffalo populations, as well as the net benefits in Table 5.5, are compared to the net benefit (R268 million) in Table 5.4 when the discount rate is set at zero, without varying any parameter values (θ=0.003 and τ=0.000001). When the proportion of buffalo escaping from the park is reduced (θ=0.006) while holding the interaction coefficient with the cattle population constant, the net benefits to the farmers increase from R268 million (Tablen 5.4) to R270 million (Table 5.5). Obviously an opposite effect is realised when the proportion of the buffalo escaping from the park increases (θ=0.0015). It is important to note that while cattle are not allowed in the park, once the fence is compromised, animals can pass into each other's territory without a preference for being inside or outside the park (Brahmbhatt *et al*,. 2012). This kind of interaction between wildlife and livestock requires veterinary services and other governmental agencies in the study area to play an important role in preventing diseases in wildlife and domestic livestock. However, Brahmbhatt *et al.* (2012) acknowledge the

complexities and challenges associated with monitoring the park, collecting, storing and sharing data between field rangers, veterinary technicians and veterinary services in the KNP and adjacent provinces. Thus, there is a need for a systematic approach to collecting information on livestock and wildlife that will further enhance researchers' understanding of wildlife-livestock diseases.

By the same token, when the interaction coefficient between the cattle population increases (τ=0.000002), for example because of lack of quarantine measures, while holding the proportion of buffalo escaping from the park constant, the net benefits of the farmers decrease from R268 million to R267 million. This suggests that the action of the farmer who fails to adhere to quarantine measures during the outbreak increases the risk of FMD spreading to other holdings, thus generating a sizeable amount of negative externalities (Jones & Rushton, 2013) and losses to other farmers. Thus an opposite effect is obviously realised when the interaction coefficient term between the cattle populations is decreased (τ=0.0000005)

Table 5.5: Sensitivity analysis results for cattle stock sizes (healthy and infected) and net benefits with discount rate (δ) =0 while varying proportion of buffalo escaping from the park (θ) and livestock-livestock interaction (τ) under the conservation scenario

$\tau = 0.000001$	$\theta = 0.006$	$\theta = 0.0015$
Infected cattle (I)	4 660	1 211
Healthy cattle (S)	173 853	178 857
Net benefits for cattle farmers	266	270
$\theta = 0.003$	$\tau = 0.000002$	$\tau = 0.0000005$
Infected cattle (I)	3 234	2 126
Healthy cattle (S)	175 285	177 678
Net benefits for cattle farmers	267	269

Sensitivity results are also presented showing the effects on the net benefits of farmers when various intervention measures are considered (Table 5.6). A more realistic discount rate, 5%, is assumed for the purpose of the analysis. The variation in the stock levels for cattle and buffalo populations, as well as the net benefit values in Table 5.6, are compared to the baseline net benefits. Table 5.6 shows that when the proportion of buffalo escaping from the park is reduced (θ=0.0015), while holding the interaction coefficient term between the cattle population constant, the net benefits to the farmers increase from R228 million to R230 million. Holding the proportion of buffalo escaping from the park constant while decreasing the interaction coefficient term between the cattle population (τ=0.0000005) will increase the net benefits to the farmers from R228 million to R240 million. Decreasing both the proportion of buffalo escaping from the park (θ=0.0015) and the interaction coefficient between cattle populations (τ=0.0000005) yields the highest benefits for the farmers, indicated by an increase from R228 million to R249 million, which is about 9%. Obviously, the opposite will occur when the interaction between cattle populations and the proportion of buffalo escaping from the park is increased. Compared to the baseline benefits (R228 million) in Table 5.6, the net benefits gained when one reduces the proportion of buffalos escaping from the park by half while keeping the cattle interaction at baseline level is R2 million. This net benefits gain is six times lower than when one reduces the interaction between cattle populations by half while keeping the proportion of buffalos escaping from the park at baseline level (R12 million).

Table 5.6: Sensitivity results for stock sizes and net benefits with δ =0.05 while varying proportion of buffalo escaping from the park (θ) and livestock-livestock interaction (τ) under the conservation scenario

	Discount rate	θ	τ	Infected	Healthy	NPV
Baseline	$\delta = 0.05$	0.003	0.000001	4 270	166 571	228
		0.006	0.000001	7 820	157 028	214
		0.0015	0.000001	2 300	164 960	230
		0.003	0.000002	5 145	160 399	206
		0.003	0.0000005	4 122	162 736	240
		0.006	0.000002	9 484	153 688	202
		0.006	0.0000005	7 157	158 249	214
		0.0015	0.000002	2 768	163 949	208
		0.0015	0.0000005	1 900	165 756	249

Although the study has not been able to replicate the sensitivity analysis under the social planner scenario, the results clearly indicate the benefits of intervention measures in the presence of an externality under the conservative scenario. Given the initial situation resembling absence of government intervention, different simulation indicates that intervention measures such as quarantine measures and efficient fencing around the park will clearly increase the benefits of the farmers.

5.3 Conclusions

This chapter provides the results from the theoretical model under different scenarios developed in chapter 4. The steady state results from the model indicate that the net benefits that accrue to the farmers and the park agency are highest in a situation where FMD is eradicated (ie the no-disease scenario). However, this scenario may involve excessive culling of buffalos and all other potential wildlife species that can host the FMDV and reintroducing wildlife that is free of FMDV. However, from a practical and conservation perspective, eradication of FMDV from a wildlife reservoir may be challenging to achieve and the least preferred method to follow. The alternative options provided by the model involved comparing the steady state solutions for the social planner and conservation scenarios to determine the best optimal strategy to balance the trade-offs between keeping buffalos in the park against the livelihood objectives of the famers. Given the two scenarios, the benefits to the farmers were higher under the social planner scenario compared to the conservation scenario. This was due to the reduction in the number of buffalos through planned culling, which then led to a lower number of buffalos escaping from the park, and hence a reduction in the number of infected cattle.

In general the differences in the economic benefits between the different scenarios appeared to be very small, making it challenging to justify any government intervention. In order to assess the impact of two main FMD control approaches viv-à-vis the net benefit for the farmers, sensitivity analysis was conducted. Sensitivity analysis indicated that the economic benefits to farmers were higher when FMD intervention measures such as a reduction in the proportion of buffalo escaping from the park, as well as interaction between cattle populations, were introduced simultaneously. This implies that government would have to invest in effective fencing, vaccination and quarantine programmes with the aim to prevent and reduce further FMD outbreaks. Howerver, proportionally, higher benefits were achieved when interaction between cattle populations was reduced, compared to a reduction in the proportion of buffalos escaping from the park. This indicates that investing more in preventing infection between cattle populations, such as quarantine and a vaccination programme, would yield higher benefits to the farmers compared to decreasing FMD transmission from buffalo to cattle populations through culling of buffalos and/or increased maintenance of the fence. This finding indicates that increased veterinary services to reduce FMD transmission among the cattle population adjacent to the KNP would increase benefits to the farmers while preserving our wildlife heritage. Overall, this study indicates that improving FMD control measures will increase the income of the farmers, which may have implications for developing opportunities in livestock trade for this community, as well as achieving poverty alleviation and enhancing food security, as previously reported by Perry and Grace (2009). Nonetheless, while the model developed assessed the impact of the intervention on the farmers' livelihood, the costs of such intervention measures were not measured.

CHAPTER 6: SUMMARY, CONCLUSIONS AND IMPLICATIONS FOR POLICY AND FUTURE RESEARCH

6.0 Summary and Conclusions

This study was motivated by the lack of data on the economic impact of FMD on small-scale cattle farmers in the context of developing countries, with specific reference to the competing interests between wildlife conservation and livelihood objectives of the cattle-farming communities living adjacent to the conservation parks. Several studies have analysed the conflict between local communities and the conservation park agency with respect to competition over grazing resources (Skonhoft, 1998; Borge-Johannesen & Skonhoft, 2005; Fischer *et al*., 2010; Barnes, 1996). However, an adverse impact on livestock keeping can also arise owing to protected wildlife escaping from the natural reserves into the adjacent communal grazing areas and coming into direct contact with livestock, potentially transmitting diseases. Contrary to commercial farmers who keep their livestock in protected areas with varying levels of biosecurity measures, open-grazing livestock-keeping systems are vulnerable to disease transmission from infected wildlife. This situation is currently occurring in Limpopo Province, where FMD-infected buffalos escaping from the KNP into adjacent areas transmit FMDV to livestock.

While FMD and other livestock diseases can have an adverse economic impact on the livelihood of small-scale farmers, other socio-economic factors, such as the motives for owning livestock, can also affect people's ability to improve their livelihood through livestock keeping. For instance, it has been demonstrated that many rural communities in Africa tend to keep livestock for social status rather than economic reasons. Understanding the motives for owning livestock in the study area would provide insight into the use of healthier cattle by the farming community under an improved disease control scenario.

This study investigated better management of the trade-offs between keeping buffalo in KNP for their conservation and recreational value and the livelihood objectives of the cattle farmers in the presence of the negative externality of FMD. Further, the study assessed the factors associated with cattle herd size in the study area in order to understand the underlying reasons, challenges and opportunities for the farming community in keeping livestock.

To assess the factors associated with herd size, a randomised cross-section survey among livestock farmers living in five villages adjacent to the KNP was administered. Information on potential reasons, challenges and opportunities associated with livestock ownership was collected. A negative binomial regression model was applied to analyse determinants of cattle ownership (eg cattle herd size) in the study area. The results of the analysis indicated that, contrary to the popular belief that rural households in developing countries own large herds of livestock for social reasons, most communal livestock farmers in the study area kept livestock for economic/commercial reasons. However, limited access to marketing channels was found to be a major constraint on keeping large herds. Moreover, livestock farmers owning large herds experienced higher losses due to theft and mortality associated with diseases or predation.

Given the fact that farmers in the study area keep livestock for economic reasons, but face constant challenges due to losses associated with livestock diseases, including FMD transmitted from infected buffalo from the KNP, the control of FMD could enhance the livelihood of this livestock farming community. A bio-economic model was accordingly developed to assess such trade-offs between wildlife conservation and the livelihood objectives of the small-scale farmers in the presence of FMD transmission (negative externality) from buffalo to cattle populations.

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The bio-economic model allowed studying the transmission dynamics of FMD between wildlife and cattle populations, as well as the economic impact of the disease on small-scale farmers and the disease control implications for both farmers and park agencies. Three stock variables were considered in the model: healthy and infected cattle populations and an unhealthy buffalo population, where cattle were infected by the buffalos, but not *vice versa*, ie interaction between cattle and buffalo was considered to be unidirectional. This was under the assumption that infected buffaloes escaping from the park would transmit FMD to susceptible cattle, but the FMD prevalence in the buffalo population in the park would not be affected by the transmission of FMD among the cattle population grazing outside the park during outbreaks. The model of FMD transmission developed was an extension of the model developed by BWH (1999), which studied the impact of TB transmitted from possums to livestock in New Zealand. Similar to the BWH model, the model adapted for this study had two economic agents, namely a conservation agency managing the national park where the buffalo had their living area, and a group of small-scale cattle farmers living adjacent to the protected park area (KNP). The model differed from the BWH one in terms of how harvesting of infected livestock by farmers took place. While the BWH model assumed non-selective slaughtering of cattle irrespective of disease status, this study assumed selective harvesting. It was possible to make this assumption because FMD is a symptomatic disease, making it easy to distinguish between healthy and unhealthy cattle and for farmers to slaughter infected cattle preferentially during outbreaks. In addition, the BWH study was carried out in a developed country context where cattle of commercial (large-scale farmers) with biosecurity measures were affected by TB. In contrast, the model developed in this study assessed the economic impact of wildlife disease (FMD) on small-scale farmers in a developing country context, in the study area, Limpopo Province in South Africa.

The theoretical model was solved using optimal control techniques to determine the optimal trade-off between keeping buffalo in the park and the economic impact on the livelihood objectives of the cattle farmers in the presence of the negative externality of FMD transmission. Three different scenarios, namely (1) a conservation scenario with no unified resource management policy, (2) a social planner scenario and (3) a no-disease scenario, were compared. In the model, the conservation scenario is guided by narrow-selfish interests of both agents (park agency and cattle farmers) who optimise independently as per their separate objectives. More specifically, the park agency optimises its situation without taking into consideration the negative externality imposed on the farmers through the spread of FMD. In the model formulation it is assumed that the stock of buffalo influences the size and the composition of cattle herds through disease transmission, and ultimately the benefit and livelihood of cattle farmers, but not *vice versa*. Accordingly, while the conservation agency can optimise its situation without being influenced by the harvest and the cattle holding of the farmers, farmers must adjust their harvest and stocks to the stock size of buffalos.

In contrast, the social planner scenario takes into consideration the interest of both agents and a socially optimal resource management policy is achieved. Outcomes of a third scenario of no disease transmission were also evaluated, in which farmers maximise their benefits without any concerns about FMD transmission to their cattle (ie no externality effect). Analytical study results show that when the social planner allocates the common resources, the benefits to the farmers increase compared to the conservation scenario. This indicates that the unified management scheme (social planner) would yield a lower number of buffalo and less disease transmission (hence fewer infected cattle) than the pure conservation strategy. While culling of buffalo is not currently practised at the park, analytical study results demonstrated that culling would be beneficial to farmers if practised in the KNP. Results of the empirical simulation analyses also confirm that when culling of buffalo is implemented, the unified management scheme (social planner scenario) would yield fewer buffalo and less disease transmission (hence fewer infected cattle), as well as higher overall economic benefits than the pure conservation scenario.

Sensitivity analysis was then conducted to assess the impact of various FMD intervention measures on the livelihood of farmers. Results from sensitivity analyses indicated that the economic benefits to the farmers are highest when FMD intervention measures such as a reduction in the proportion of buffalo escaping from the park and the interaction between cattle populations are introduced simultaneously. However, proportionally, higher benefits were achieved when interaction between cattle populations was reduced, compared to the reduction of the proportion of buffalos escaping from the park.

6.2 Implications of the study

The results from this study have a number of implications for policy that could enhance the incomes and livelihoods of small-scale cattle farmers in rural areas. Firstly, results from the negative binomial regression model indicate that small-scale farmers in the study area keep cattle not for social reasons but rather economic reasons. This indicates that not all rural communities in Africa own livestock mainly for social reasons (eg paying a bride price or social standing in the community). An important implication of this finding is the great potential this presents for economic policy to enhance the welfare of this and similar groups of smallholder cattle farmers in the country. One policy proposal is for government to introduce appropriate livestock subsidy programmes that can assist farmers in expanding their herds. However, this potential of welfare gains from promoting larger herd sizes must be weighed against the ecological sustainability objectives in terms of what would be an optimal herd size, given the current carrying capacity of the supporting ecosystem. The study also proposes investment in farmers' education and awareness of new technological innovations, appropriate measures and practices in breeding and veterinary services critical for improving small livestock farmers' welfare. In addition, the study proposes policy interventions such as the establishment of efficient and well-functioning markets, including improved access to better roads, as well as other market information such as current livestock market prices. Access to such facilities and information has the potential to increase farmers' welfare through active participation in the market economy. Livestock losses due to theft and livestock mortality as a result of predation or diseases justify public investment in efficient game-proof fences that will effectively deter wildlife from escaping from game parks to come into contact with adjacent communal livestock and offer more effective protection measures against theft.

Results of the sensitivity analyses indicate that overall, higher benefits are achieved when intervention measures contributing to a reduction in the proportion of buffalo that escape from the park and a reduction in cattle-to-cattle transmission are introduced simultanously. However, comparing the two measures, investing more in preventing infection among cattle populations through quarantine and vaccination programmes would yield higher benefits to the farmers compared to decreasing FMD transmission from buffalo to cattle populations through culling of buffalos and/or increased investment in maintenance of the fence. Thus, the main policy implication from this study involves weighing the costs and benefits of the two intervention measures. While this study assessed the impact of these interventions on farmers' livelihood, the costs of such intervention measures were not considered, which represents a gap requiring further future research work.

6.3 Contributions and limitations of the study

This study made a number of contributions to the existing body of literature on the economics of smallholder livestock systems and management of conflicts between the livelihood objectives of local livestock-farming communities and neighbouring conservation parks in the presence of animal disease transmission, such as FMD. Published literature on the economics of animal disease and its control has focused on a small number of developed countries, concentrating on particular commodities and often the specific occurrence of an outbreak or an epidemic. In particular, studies conducted in developed countries have focused mainly on the economic impact of animal disease on the commercial farming sector, neglecting the plight of small-scale farmers. The reasons cited ranged from data unavailability to lack of monetary value attached to the herds in backyard farming systems (Kobayashi et al., 2007). Limiting economic analysis of animal disease to the commercial farming sector implies that the economic impact of animal disease on small-scale farmers is considered similar. In Sub-Saharan Africa, where 70% of the population is poor and depends on smallholder agricultural activities such as livestock farming for its livelihood, analysis of the economic consequences of animal disease on small-scale producers is therefore badly needed.

In addition, conventional economic methods have been used to estimate the costs of animal diseases but have neglected analysis of social costs and benefits of controlling disease transmission between wildlife and livestock. Although a few studies (eg Horan and Wolf, 2007; Horan, 2011) have highlighted the significance of this interface by building bio-economic models incorporating ecological interactions between livestock and wildlife, none of these studies has been applied to the FMD case in a developing country context. This study is the first to use bio-economic modelling to examine the impact of FMD on small-scale farmers in the wildlife-livestock interface in a developing economy. The model developed in this study is widely applicable to many other similar situations where transmission of animal disease from wildlife populations poses serious threats to the livelihood of small-scale livestock farmers. In addition, the policy interventions proposed in the study contribute to the search for feasible management solutions and policy measures for balancing the trade-off between environmental and economic benefits of keeping wildlife and the livelihood objectives of small-scale farmers living adjacent to conservation areas.

Nonetheless, this study has limitations ranging from the simplified assumptions made to the availability of suitable data. Firstly, the optimisation model treats farmers as a homogeneous group, whereas in reality the impact in terms of benefits and costs will differ across various farmer groups, depending among others on location and distance to the park. The model also incorporates non-market variables such as social status attached to cattle ownership and tourist value attached to buffalo viewing, which will require better valuation methods than the overly simplified assumptions made in this study. In addition, while the study quantifies the economic benefits of proposed FMD control measures, it does not assess the costs of such measures. While the construction of proper fencing can be expensive, other instruments can be implemented to reduce transmission between wildlife and livestock. For example, a tax on the entrance fee can be imposed, which may be used for maintaining the fence around the park.

However, in spite of the limitations of the study, the model developed here provides a solid foundation for future analysis of similar diseases that affect the livelihoods of small-scale farmers and avenues to suggest policies that will enhance the income of the rural poor. The ecological model developed provides avenues for a multidisciplinary approach in solving economic problems. Thus, further work may involve collaborating with veterinarians as well as epidemiologists to understand the impact of FMD on various stakeholders better.

APPENDICES

Appendix 1: Household questionnaire administered to small-scale farmers in five villages at Mhinga District in Limpopo Province

I. Demographics

1. Village	1	2	3	4	5

2. Gender	Male	Female

3. Marital status	Married	Divorced	widowed	Separated	Never married

4. What is your year of birth	

5. If you have a spouse, what is his/her year of birth	

6. Please write the number of persons in your household at present and at the beginning of the three preceding years.	Now	2010	2009	2008

7. Please write the number of household members in each of the following age categories?	0-4yrs	5-15ys	16-25yrs	26-35yrs	35+years

8. Please write the number of people in your household that are currently in education at:	Primary school	Secondary school	College	University	No schooling

9. What is your highest completed education level?	Primary school	Secondary school	College	University	No schooling

10. What is your spouse's highest completed education level?	Primary school	Secondary school	College	University	No schooling

11. Is the house you live in your own or rented?	Your own	Rental

12. What is your current occupation? Choose the one(s) relevant to you.	Employed for wages	Self-employed (e.g., family business or farm)	Out of work and looking for work	Out of work but not looking for work	Retired	Unable to work

13. What is your spouse's current occupation? Choose the one(s) relevant to you.	Employed for wages	Self-employed (e.g., family business or farm)	Out of work and looking for work	Out of work but not looking for work	Retired	Unable to work

14. If you are employed for wages, what kind of employment do you have (mark one box only)	Employee of a business or an individual for a salary	Employee of a charitable organisation	Government employee	An employee at a farm

15. If you spouse is employed for wages, what kind of employment does he/she have? (mark one box only)	Employed for wages	Self-employed (e.g., family business or farm)	Out of work and looking for work	Out of work but not looking for work	Retired	Unable to work

16. Indicate the average monthly income of your household from each category below at the present and in each of the following past years:

	2011	2010	2009	2008
Child grants				
Old-age pensions				
Disability grants				
Others grants (specify)				

II: LAND OWNERSHIP

1. Do you have access to privately owned land for agricultural purposes (crop production, livestock keeping) from 2008 and up to the present?	Yes	No

2. How many acres of land do/did your household own in each of the years 2008-2011?

	2011	2010	2009	2008
Number of acres				

3. How many acres of land do/did your household rent in the years 2008-2011?

	2011	2010	2009	2008
Number of acres				

4. Does your household have access to communal land?	Yes	No

5. How many acres of communal land do/did your household use for crop production?

	2011	2010	2009	2008
Number of acres				

6. Have you used communal land to graze your livestock in 2011?	Yes	No

7. If Yes, which of your animals graze on communal land?

Cattle	Goats	Sheep	Others (specify)

8. How would you characterise your access to communal grazing land? Answer on a scale from 1 to 6, where 1 is "strongly disagree" and 6 is "strongly agree".

	Strongly disagree					Strongly disagree
There is enough grazing land for all households in this village	1	2	3	4	5	6
There are no conflicts between the households in this village on the use of the communal grazing land.						
My household is satisfied with our access to communal grazing land.						
The communal grazing land is distributed based on old traditional uses.						
The village administration sets rules for the use of communal grazing land.						
My household is satisfied with the way the communal grazing land is used.						

9. If communal grazing land is divided into individual parcels and distributed between households?	Yes	No

10. If yes how many acres are distributed to your household at the present?	

III. LIVESTOCK OWNSERSHIP

1. How many animals does your household have at the present and how many animals did your household have at the beginning of each of the preceding years?

	At present	2010	2009	2008
Cattle				
Goats				
Sheep				
Pigs				

2. Indicate the present number of animals your household have in each of the following categories:

	0-2yrs	3-5yrs	Over 5yrs
Cattle			
Goats			
Sheep			
Pigs			

3. How many female adult animals does your household have at present, and how many female adult animals did you have at the beginning of each of the preceding years?

	Now	2010	2009	2008
Cattle				
Goats				
Sheep				
Pigs				

4. How many male adult animals does your household have at present, and how many male adult animals did you have at the beginning of each of the preceding years

	At present	2010	2009	2008
Cattle				
Goats				
Sheep				
Pigs				

5. On the scale from 1 to 6, to what extent do you agree or disagree with the following statements about herd size.

	Strongly disagree					Strongly disagree
A large herd is important to provide current income to the household	1	2	3	4	5	6
A large herd is important to gain social status in the community						
A large herd is important as insurance against adverse herding conditions (e.g., disease outbreak, severe drought)						
A large herd is important as a buffer against income shocks (e.g., drought destroying crops, loss of employment)						

A large herd is important for cultural reasons like bride's payment						

IV. SLAUGHTER

1. How many female animals did you sell for household consumption in each of the last past years?

	2010	2009	2008
Cattle			
Goats			
Sheep			
Pigs			

2. How many male animals did you sell for household consumption in each of the last past years?

	2010	2009	2008
Cattle			
Goats			
Sheep			
Pigs			

3. Please indicate the selling price for each of the male animals in each of the last three years.

	2010	2009	2008
Cattle			
Goats			
Sheep			
Pigs			

4. Please indicate the selling price for each of the female animals in each of the last three years.

	2010	2009	2008
Cattle			
Goats			
Sheep			
Pigs			

5. To whom do you usually sell your animals? Mark the one alternative most relevant to you.

Local butchers	Local people	Commercial farmers	Local auctioneers

6. Which season of the year do you sell most of your animals? Mark the one most relevant to you.

Rainy season	Dry season

7. On scale from 1 to 6, how important was each of these reasons for selling or slaughtering animals in the last three years

	Not important					Very important
To earn income	1	2	3	4	5	6
To get meat for household consumption						
To get rid of sick or old animals						

8. If earning income was at all important to you, how important were ewach of these reasons for earning income

	Not important					Very important
To pay for household consumption	1	2	3	4	5	6
To pay school fees						
To pay loans						
To pay bride's price						

9. Would you sell more animals if herd size increased?	Yes	No

IV. LOST ANIMALS

1. How many cattle did you lose in each of the last three years due to the following causes?

	2010	2009	2008
Theft			
Old age			
Killed by wildlife			
Other causes (specify)			

2. How many goats did you lose in each of the last three years due to the following causes?

	2010	2009	2008
Theft			
Old age			
Killed by wildlife			
Other causes (specify)			

3. How many sheep did you lose in each of the last three years due to the following causes?

	2010	2009	2008
Theft			
Old age			
Killed by wildlife			
Other causes (specify)			

4. How many pigs did you lose in each of the last three years due to the following causes?

	2010	2009	2008
Theft			
Old age			
Killed by wildlife			
Other causes (specify)			

VI. WILDLIFE INDUCED DAMAGE AND DISEASE TRANSMISSION

1. Have you seen wildlife from Kruger National Park roaming in the grazing areas?

	2010	2009	2008
Yes			
No			

2. Has wildlife caused damage to your crops or livestock during the past three years?

Yes	No

If yes, what type(s) of damage have wildlife caused to your household?

	Yes	No
Wildlife has infected some of my livestock with disease		
Wildlife has injured (but not killed) some of my livestock		
Wildlife have damaged my crops		

3. How many of your animals are/were infected by diseases from wildlife now and in the last three years?

	2010	2009	2008
Cattle			
Goats			
Sheep			
Pigs			

4. How many of your animals were injured by wildlife now and in the last three years?

	2010	2009	2008
Cattle			
Goats			
Sheep			
Pigs			

5. Please indicate how much damage wildlife caused to your livestock in each of the following past years.

	No damage	Some damage	A lot of damage
2010			
2009			
2008			

6. Please indicate how much damage wildlife caused to your crops each of the following past years.

	No damage	Some damage	A lot of damage
2010			
2009			
2008			

VII. COSTS OF THE SMALL SCALE FARMER

1. Who herds your cattle?

Members of my household herd our cattle	
We hire people to herd our cattle	

2. How many workers (hired and household members) do you have to herd your cattle?	

3. How much do you pay each worker per month?	R

4. Do you pay for vaccination costs for your cattle**?**	Yes	No

5. If yes, how much do you pay per cattle?	R

6. Do you pay for dipping costs for your cattle?	Yes	No

7. If yes, how much do you pay per cattle?	R

Appendix 2: Definition of variables influencing herd size of small-scale cattle farmers

Variables	Variable description	Expected sign
Household characteristics		
Gender	Male=1, 0 otherwise	+
Age of the farmer	Categorical: 19-40; 41-60; 61-80; 81+	+
Marital Status	Unmarried=1, 0 otherwise	-
Family size	Categorical: 1-5; 6-10; 11+	+
Level education	Schooling (primary, secondary and college) =1, 0 otherwise	+
Source of income/livelihood		
Employment	Off-farm-employment=1, 0 otherwise	+
Access to welfare grants	Access welfare grants=1, 0 otherwise	-
Access to marketing channels		+
Selling to local people or local butcheries	Local people=1, 0 otherwise	
Land ownership	Yes=1, 0 otherwise	+
Cattle sale	Categorical : 0; 1+	+
Livestock losses		
Theft	Yes=1, 0 otherwise	+
Death (diseases)	Yes=1, 0 otherwise	+
Livestock predation	Yes=1, 0 otherwise	+
Reasons for livestock ownership		
Provision for income	Yes=1, 0 otherwise	+
Social status	Yes=1, 0 otherwise	+

Appendix 3: Derivation of golden rules in equations (4.10), (4.17), (4.18), (4.21) and (4.24)

The economic problem for the park agency is defined by

$$\max_{y} \int_{t=0}^{\infty} [B(X) - cy - V(X)]e^{-\delta t} dt$$

s.t $dX/dt = F(X) - y,$ X(0) is given

The current value Hamiltonian for the above problem is

$$H_c = [B(X) - cy - V(X)] + \mu\big(F(X)\big) - y)$$

where μ is the co-state variable. .

Assuming an interior solution, there are three necessary conditions for optimisation of the Hamiltonian. These conditions, which define the optimal solution path, are the equation of motion or the constraint, the first order condition and the adjoint condition.

Then, the first-order condition is derived as follows:

$$\frac{\partial H_c}{\partial y} = 0 \rightarrow -c - \mu = 0$$

Then, $\mu = -c$

The adjoint condition is derived as follows

$$d\mu / dt - \delta\mu = -\partial Hc / \partial X = -B'(X) + V'(X) - \mu F'(X) \quad (7)$$

At steady state $\frac{d\mu}{dt} = \dot{\mu} = 0 \Rightarrow -\delta\mu = -[B'(X) + V'(X) - \mu F'(X)]$

Substituting$-c = \mu$, if we substitute –c for μ in equation (7), we get

$$-\delta(-c) = -B'(X) - V'(X) - cF'(X)$$

$$\delta c = -B'(X) + V'(X) + cF'(X)$$

Solving for $F'(X)$ we obtain

$$cF'(X) = \delta c + B'(X) - V'(X)$$
$$F'(X) = \delta + \frac{B'(X) - V'(X)}{c}$$

After some few manipulations, we obtain the following equation

$$\delta = \frac{B'(X) - V'(X)}{c} + F'(X) \qquad (4.10)$$

Deriving conditions (4.17) and (4.18)

The current value Hamiltonian for the maximisation problem for the group of farmers is given by:

$$H_c = [(p_S \alpha_S S + p_I \alpha_I I) - A(S+I) + W(S+I)] + \lambda[G\left(S+I\right) - \sigma\theta XS - \tau IS - \alpha_S S]$$
$$+\eta(\sigma\theta XS + \tau SI - mI - \alpha_I I)$$

Where λ and η are the co-state variables for healthy and infected cattle

The two FOC for the control variables α_s and α_I

$$\partial H_c / \partial \alpha_S = 0 \Rightarrow S(p_S - \lambda) = 0$$

Simplifying this, then $p_s = \lambda$

$$\partial H_c / \partial \alpha_I = 0 \Rightarrow I(p_I - \eta) = 0$$

Simplifying this, then $p_I = \eta$

The adjoint conditions

$$d\lambda / dt - \delta\lambda = -\partial H_c / \partial S = -[p_S\alpha_S - A' + W' + \lambda(G' - \sigma\theta X - \tau I - \alpha_S) + \eta(\sigma\theta X + \tau I)] \quad (11)$$

Knowing that at steady state $\frac{d\lambda}{dt} = \frac{d\eta}{dt} = 0$ and substituting conditions (4.8) and (4.13 into (4.14)

$$-\delta p_s = -[p_S\alpha_S - A' + W' + \lambda(G' - \sigma\theta X - \tau I - \alpha_S) + \eta(\sigma\theta X + \tau I)]$$

$$-\delta p_s = -p_S\alpha_S - A' + W' + p_s G' - p_s\sigma\theta X - p_s\tau I - p_s\alpha_S) + p_I\sigma\theta X + p_I\tau I$$

$$-\delta p_s = -p_S\alpha_S + A' - W' + p_s G' + p_s\sigma\theta X + p_s\tau I + p_s\alpha_S - p_I\sigma\theta X - p_I\tau I$$

$$p_s G' = \delta p_s + A' - W' + p_s\sigma\theta X + p_s\tau I - p_I\sigma\theta X - p_I\tau I$$

Then after some minor arrangements, the golden rule for the healthy cattle stock reads as follows

$$G'(S+I) = \delta + \frac{A'(S+I) - W'(S+I)}{p_S} + \frac{(\sigma\theta X + \tau I)(p_S - p_I)}{p_S} \quad ($$

Applying the same steady state conditions and singular controls the adjoint conditions for infected cattle stock:

$$d\eta / dt - \delta\eta = -\partial Hf / \partial I = -[p_I\alpha_I - A' + W' + \lambda(G' - \tau S) + \eta(\tau S - m - \alpha_I)] \quad (12)$$

$$-\delta p_I = -p_I\alpha_I + A' - W' - p_s G' + p_s\tau S - p_I\tau S + p_I m + p_I\alpha_I$$

$$p_s G' = \delta p_I - p_I\alpha_I + A' - W' + p_s\tau S - p_I\tau S + p_I m + p_I\alpha_I$$

After some minor arrangements, we arrive at the golden rule for infected cattle stock given by:

$$G'(S+I) = \frac{p_I(\delta + m)}{p_S} + \frac{A'(S+I) - W'(S+I)}{p_S} + \frac{\tau S(p_S - p_I)}{p_S}$$

Inserting $p_s = \lambda$ and $p_I > \eta$, the healthy and infected stock will be presented by the following equations

$$G'(S+I) = \delta + \frac{A'(S+I) - W'(S+I)}{p_S} + \frac{(\sigma\theta X + \tau I)(p_S - \eta)}{p_S} \qquad (4.17)$$

$$G'(S+I) = \frac{p_I(\delta + m)}{p_S} + \frac{A'(S+I) - W'(S+I)}{p_S} + \frac{\tau S(p_S - \eta)}{p_S} - \alpha_I^{\max}\frac{(p_I - \eta)}{p_s} \qquad (4.18)$$

Deriving equation (4.21)

The current-value Hamiltonian for the maximisation problem of the social planner is given by:

$$H_c = [B(X) - cy - V(X)] + \mu(F(X) - y) +$$

$$[(p_S\alpha_S S + p_I\alpha_I I) - A(S+I) + W(S+I)] +$$

$$\lambda[G(S+I) - \sigma\theta XS - \tau IS - \alpha_S S] + \eta(\sigma\theta XS + \tau SI - mI - \alpha_I I)$$

The adjoint condition for is then given as

$$\frac{d\mu}{dt} - \delta\mu = -\frac{\partial H_c}{\partial X} = -\left[B'(X) - V'(X) + \mu F'(X) - \lambda\sigma\theta S + \eta\sigma\theta S\right]$$

Substitution conditions (4.8), (4.13) and (4.14) we arrive at the following expression

$$-\delta(-c) = -\left[B'(X) - V'(X) - cF'(X) - p_s\sigma\theta S + p_I\sigma\theta S\right]$$

$$\delta c = -B'(X) + V'(X) + cF'(X) + p_s\sigma\theta S - p_I\sigma\theta S$$

$$cF'(X) = \delta c + B'(X) - V'(X) - p_s\sigma\theta S + p_I\sigma\theta S$$

After some minor arrangements

$$F'(X) = \delta + \frac{B'(X) - V'(X)}{c} - \frac{\sigma\theta S(p_s - p_I)}{c} \qquad (4.21)$$

Deriving equation 4.24

The current-value Hamiltonian for the group of cattle farmers when there is no disease transmission is given by:

$$H_c = [p_s \alpha Z - A(Z) + W(Z)] + \lambda [G(Z) - \alpha Z]$$

The first order condition for the control is given by

$$\frac{\partial H_c}{\partial \alpha} = 0 \Rightarrow p_s Z - \lambda Z = 0$$

Then, $\lambda = p_s$

The adjoint condition is then given by

$$\frac{d\lambda}{dt} - \delta\lambda = -\frac{-\partial H_c}{\partial Z} \Rightarrow -[p_s \alpha - A'(Z) + W'(Z) + \lambda G'(Z) - \lambda \alpha]$$

Substituting for the FOC, we obtain

$$-\delta p_s = -p_s \alpha + A'(Z) - W'(Z) - p_s G'(Z) + p_s \alpha$$

After some minor arrangements, we obtain the golden rule condition

$$G'(Z) = \delta + \frac{A'(Z) - W'(Z)}{p_s} \qquad (4.24)$$

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