Effects of a Traceability System on the Economic Impacts of a Foot-and-Mouth Disease Outbreak

by

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Abstract

This thesis creates an epidemiological foot-and-mouth disease (FMD) spread model for Ontario. Disease simulations are constructed to reflect three levels of the cattle identification and movement recording system. The outputs generated by the epidemiological model are used to calculate the direct disease control costs a FMD outbreak. In addition, welfare effects caused by a FMD outbreak are also calculated for each level of cattle traceability using an equilibrium displacement model. Parameter sensitivity was tested for both the epidemiological and economic model results. It is found that the benefits to the beef cattle industry of increasing the ability to trace direct animal contacts during a FMD disease outbreak in Ontario are less than the lowest annual cost estimate of a cattle traceability system as estimated by Agriculture and Agri-Food Canada.

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Dedication

I dedicate the following research to my deceased friend, Kevin Ross. Our ambitious discussion concerning our goals, our hopes, and our future dreams will never be forgotten.

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Chapter 1 Introduction and Background

1.1 Objectives and Motivation

This thesis is designed to determine the short-run economic impacts of a livestock traceability system on a foot-and-mouth disease (FMD) outbreak in Ontario. The economic value of a livestock identification and recording system during a contagious disease outbreak is of extreme importance to both livestock producers and policy makers. Saatkamp et al. (1995) state the control and eradication of foot-and-mouth disease is the primary benefit of a livestock identification and recording system. Zhao, Wahl, and Marsh (2006) affirm that from an economic perspective, FMD is the most devastating type of disease outbreak in the livestock sector. Consultation with the Manitoba representative of the National Agriculture and Food Traceability Task Team also identified contagious disease control as the primary benefit of the cattle animal identification system (Hunt 2009).

The importance and timeliness of this study are considerable. The Canadian and several provincial Governments have financially committed to extensive animal identification and livestock movement recording programs. Producers in all affected livestock supply chains are currently experiencing new costs associated with these programs and related regulations. According to the Canadian Dairy Commission’s (CDC) 2005 Annual Report, design of an optimal and uniform traceability system for the dairy industry, including full product tracing from farm to final consumer is an important goal for the entire industry. The comparison of the benefits provided by the system to the costs of adopting and maintaining a livestock identification and recording system has important implications for the development of an informed animal identification related government policy.

1.2 Foot-and-Mouth Disease

According to the Canadian Food Inspection Agency (CFIA), FMD is a severe, highly contagious viral disease of cattle, sheep and swine (CFIA 2010). The disease can affect all cloven-hoofed animals, both wild and domestic, including but not limited to boar, goats, deer, elk and bison. FMD causes blister-like sores in the mouth, between the animals' hooves and on the teats. These sores cause a reduction in appetite and movement, significantly weakening the infected animal. FMD is among the most contagious of livestock diseases, spreading by direct, indirect and airborne transmission. (described further in chapter 4) FMD can not affect humans; however, humans can transmit the disease. The disease agent can survive in the human respiratory tract for up to 28 hours.

The last reported incidence of FMD in Canada was in Saskatchewan in 1952, and occurred from either the illegal importation of FMD-contaminated meat or via an East-German immigrant's clothes. Sellers and Daggupaty (1990) reported that a total of twenty-nine premises were infected and direct outbreak control costs were reported to be $1 million. FMD is currently endemic to many livestock populations throughout the world, including countries in South America, Asia, and Africa. The World Organization for Animal Health (OIE) maintains a list of countries that have FMD-free status. The most recent suspension of the disease-free status was of Japan on April 20th 2010. The world prices for beef and cattle from countries where FMD is prevalent are substantially lower than those in FMD-free countries. According to Ekboir et al. (2002), a premium of 50-60% exists for FMD-free fresh meat.

The UK experienced FMD outbreaks in both 2001 and 2007, with the former outbreak displaying the importance of disease control programs. According to the Department for Environment, Food and Rural Affairs (DEFRA) website, the 2001 outbreak in the UK infected 2,030 premises, resulting in the slaughter of 2,382,000 sheep, cows, pigs and goats (DEFRA 2010). Several other estimates of the number of animals slaughtered are even higher than the figure cited by DEFRA. The source of the outbreak was suspected to be the contamination of waste food, fed to a swine herd in the UK. Several factors are listed by DEFRA that contributed to the extent of the outbreak, including; delays in disease reporting, climate effects, increasing sheep herd sizes relative to the farm labor force and the large number of animal movements. The 2001 disease outbreak in the UK lasted 221 days, and required a further four months for the UK to obtain disease-free status by the OIE. The total economic losses from the 2001 FMD outbreak in the UK estimated by Thompson et al. (2002) was 5.8-6.3 billion British pounds. Other recent FMD outbreaks have occurred in South Korea, the Netherlands, and France.

1.3 Livestock Traceability

During the last several years, the value of resources devoted to ensuring Canada’s trading partners and domestic consumers the existence of a safe and accountable food supply chain has significantly increased. This has been the result of an attempt made by private firms to reduce their exposure to food safety risks, as well as the introduction of a number of government regulations and subsidy programs. Traceability within the livestock sector is comprised of three pillars, animal identification, premise identification and movement tracking. Animal identification involves the tagging of individual animals in addition to the animal inventory practices of the livestock operation. Premise identification refers to a system in which all operations that have livestock on the premise are documented. This system is primary managed by a government agency, as in the case of the Canadian Cattle Identification Agency (CCIA). When the information from these pillars is combined, livestock movement recording between premises becomes possible. This system, also managed by a government agency, enables the recording of all movements of individual animals between premises in the supply chain. Premise identification and livestock movement recording are systems that cannot be implemented by livestock producers individually.

The livestock sector has recently undergone significant food safety-related transformations relating to traceability. Factors within the beef and dairy supply chains subject these industries to both milk-borne pathogen and animal disease risk. Following the detection of an animal disease outbreak, government officials are required to discover how and where the disease entered the supply chain, in order to identify which animals and products have been affected by the outbreak and to adopt pre-emptive measures to avoid the occurrence of future livestock disease outbreaks. In addition to the benefit of improved management of disease outbreaks, functioning traceability systems improve supply management and allow for product differentiation in products with undetectable quality attributes (Golan et al. 2004). These benefits enable the producer to realize commercial value of a functioning traceability system.

The requirement for livestock traceability prompted the creation of the CCIA to harmonize cattle tagging systems across the country (Carlberg 2010). This system is designed to trace a particular animal's history of exposure with other animals, exposure to various premises, lineage and birth place. Traceability is defined as the ability to follow the movement of a food through specified stages of production, processing and distribution (Codex Alimentarius 2010). Animal identification and movement recording are important aspects of traceability in the supply chain of all livestock derived food products.

Traceability is a growing issue of importance in many other agribusiness sectors, due in part to the risks and associated costs of food safety outbreaks. The 2005-2006 CDC annual report stated the objective of investigating the need for a strategy on traceability for the purpose of providing leadership to the Canadian dairy industry (CDC 2009). Golan et al. (2004) note that traceability systems are designed to track the flow of product or product attributes through the production process or supply chain.

1.3.1 Livestock Traceability Abroad

The use of mandatory animal identification systems and animal movement recording systems is currently in place in several European countries as well as Australia. Radio frequency identification (RFID) tags are mandatory in Australia, but optional in Great Britain (Animal Health Australia 2010). The Netherlands have chosen to only use barcode and visual identification due to cost-benefit considerations. However, all animals are required to be tagged promptly after their birth in Great Britain and the Netherlands (Ministry of Agriculture and Forestry 2010). This is not the case in Australia, where tagging is only mandatory when the animal leaves its farm of origin.

Data on animal movement is digitally stored in The Netherlands, Great Britain, and Australia. The US proposed the National Animal Identification System (NAIS), however the program was terminated on February 5th 2010 (USDA 2010). NAIS was designed as a national mandatory livestock tagging and movement recording system. The termination of this program was primarily due to substantial producer criticism regarding violations in privacy policy and the cost-effectiveness of the system. Wisconsin, an important dairy producing state in the US, had mandated the use of NAIS for both dairy and beef cattle operations. In place of NAIS, the US is currently in the process of creating a livestock traceability system for animal movements between states. The US Department of Agriculture published a paper entitled "Benefit-Cost Analysis of the National Animal Identification System", which included monetary estimates of various forms of animal identification costs but failed to quantify the potential benefits from the system. The most important benefit of an animal identification and tracking system as stated in the USDA document is the systems impact on animal health.

1.3.2 Livestock Traceability in Canada

On January 1 2001, the Canadian Cattle Identification Program was formed, prompting legislation for the mandatory use of standardized ear tags to identify all dairy and beef cattle in Canada. The National Livestock Identification for Dairy (NLID) and CLTS were created as segments of the initial program to address the specific identification needs of the Canadian dairy and beef industry. A three-read tagging system was implemented that included RFID, barcode and visual medians for identification. The standardized animal identification system complies with the International Organization for Standardization (ISO) regulation number 22005:2007.

Animal movements are not electronically recorded in the CLTS. The current system only stores the birthplace and current location data is stored. Contrary to the rest of Canada, Quebec has a cattle traceability system which records and stores data on all cattle movement within the province. Alberta has also adopted limited movement tracking of animal movements as of March 1st, 2010 (Government of Alberta 2010).

Canada's federal and provincial governments have recently shown increased interest in the area of food traceability. This has been represented by an announcement made on July 2008 in Quebec City to adopt a "Growing Forward" program over the next five years. This compilation of federal and provincial initiatives includes a program of partial reimbursement for traceability investments for processors and producers in most provinces and across all food industries. For example, the Ontario "Food Safety and Traceability Program" offers 75% reimbursement for traceability or food safety related capital investments up to a maximum of $20,000 per applicant.

Federal, provincial and territorial agriculture ministers have also committed to the National Agriculture and Food Traceability System (NAFTS). This prompted Agriculture and Agri-Food Canada (AAFC), the CFIA and each province and territory to collectively assemble a Federal-Provincial-Territorial Traceability Task Team. The team's purpose is to create a national traceability information management system supported by a legislative and regulatory framework, beginning with beef and dairy cattle. The traceability goal set by the Canadian government is to have NAFTS fully operational by 2012. All three of the essential pillars of traceability were incorporated into this system. It is unclear how this will affect current traceability practices currently used in the Canada but the goal of NAFTS is to build upon what currently exists in the agriculture and agri-food sectors. (AAFC 2009) Both federal and provincial governments have committed to phasing-in NAFTS.

In addition to NAFTS, Can-Trace, an initiative created by AAFC, is focused on developing minimum requirements for national traceability standards within food and agricultural sectors. The traceability standard currently required within the Canadian agrifood industry in order to comply with Can-Trace guidelines is “one up/one down” sharing of product traceability information within the supply chain. However, this implies that no formal requirement for internal traceability has been established, so by extension this thesis only examines a specific aspect of the complete traceability system. Traceability systems have complementary impacts on stakeholders both up and down stream, resulting in the existence of additional benefits of a livestock traceability system to the supply chain as a whole.

The cost of implementing an animal identification and recording system in Canada has been estimated. AAFC published “Costs of Traceability in Canada: Developing a Measurement Model” in March 2007 (Hobbs 2007). The purpose of this publication was to estimate the cost of establishing a RFID traceability and recording system for sheep, cattle and hogs. The research revealed significant equipment, labor, communications and operational costs exist. The per-head cost for a beef cattle producer ranged from \$3.12 to \$10.35 (Hobbs 2007). The study included cost estimates for each segment of each respective industry’s supply chain.

1.4 Benefits of Livestock Traceability

Traceability benefits within livestock-related industries are not limited to the control of contagious livestock disease outbreaks. Traceability benefits have been explored at other levels of cattle-related supply chains. Sparling et al. (2005) conducted a survey of private firms within the Canadian dairy processing sector regarding their perception of the costs and benefits of the implementation of traceability systems. They concluded the majority of firms believe the private benefits are equal to or greater than costs associated with implementation.

Traceability systems generate a number of positive effects including regulatory, market and customer response, recall and risk-management, and supply-chain benefits (Sparling and Sterling, 2004). According to a USDA document entitled “Benefit-Cost Analysis of the National Animal identification System”, benefits to trade are also believed to exist due to increased market access (Blasi et al. 2009). However, due to the limited accessibility of herd information to producers and consumers, other private benefits to producers are considerably limited. This is especially relevant to Canadian beef cattle producers, whose potential export market losses are substantial relative to those possible to the dairy cattle industry.

Government agencies such as the CFIA could experience significant cost-savings associated with the Canadian Livestock Tracking System (CLTS). According to a CFIA veterinarian, a full cattle traceability system would provide significant cost savings to the CFIA in relation to carrying out the Agency's regulatory disease investigation mandate for diseases other than FMD (Koller-Jones 2010). The CFIA senior veterinarian also stated that in the last few years regulatory disease investigations were carried out for BSE, bovine tuberculosis, brucellosis and anaplasmosis, all of which tapped into the CLTS for valuable tracing assistance that reduced costs for CFIA, resulting in a more rapid resolution of the investigation, and reduced the impact of the occurrence/investigation on the cattle industry. Numerous Canadian studies have listed the various benefits and costs of a livestock traceability system but few attempts have been made to assign any value to the stated benefits.

1.5 Thesis Outline

A spatial, stochastic disease simulation model is employed to generate disease outbreak statistics for several livestock traceability system scenarios. A detailed description of the epidemiological disease spread model is provided in chapter 3, with the equilibrium displacement model (EDM) used to determine the resulting economic impact in Canada illustrated in chapter 4. Included in the model is the derivation of exogenous shocks to the cattle and beef market caused by an Ontario FMD outbreak. A negative supply shock to feeder and fed cattle markets is computed for each scenario, dependent on the direct disease control costs and the fraction of animals slaughtered as a result of the disease containment strategy. In addition, a negative demand shock is included in the economic model to incorporate the loss of wholesale beef and cattle export markets. Chapter 5 outlines the parameterization and data sources for both the epidemiological and economic models. Chapter 6 presents results with, Feeder cattle, fed cattle, wholesale beef and retail beef market welfare changes determined and compared for each livestock traceability scenario. The seventh and final chapter presents discussion regarding model limitations, implications of model findings and potential topics for future research.

Chapter 2 Literature Review

This chapter will provide a review of the epidemiological-economic modeling literature. This will include previously employed frameworks used to calculate the epidemiological and economic impacts of livestock traceability systems. In addition, the economic frameworks used to compute the direct and indirect outbreak costs will be reviewed. The economic frameworks used by Saatkamp et al. (1996a), Saatkamp et al. (1996b), Disney et al. (2001), Stott et al. (2003), Krystynak and Charlebois (1987), and Zhao, Wahl, and Marsh (2006) will be summarized. In addition, a brief backgrounder of the EDM framework will be included. A review of previous literature that has employed an EDM framework will also be incorporated into this chapter. The studies included in this review are: Wohlgenant (1985), Piggott, Piggott, and Wright (1995), Sumner (2005), Brester, Marsh, and Atwood (2004), Pendell (2006), and Pendell et al. (2010).

2.1 Traceability Impact on FMD Outbreaks

Saatkamp et al. (1996a) constructed an epidemiological contagious disease spread model for classical swine fever. The model was constructed by the authors using a Markov chain approach to simulate a classical swine fever outbreak in Belgium. Parameters reflecting Belgium's animal identification and recording system were varied to create a variety of identification and recording scenarios. The parameters used to reflect the status of the animal identification and recording system were refined to compare current and proposed states of an animal tracing system in Saatkamp et al. (1996b). This framework was adopted by Disney et al. (2001) to quantify the impact of animal traceability systems on a FMD outbreak in cattle and swine in the US. They find the benefits of the system include limiting the spread of disease, decreasing production losses, minimizing trade losses, and reducing the costs associated with government control of the disease.

The conceptual framework used by Disney et al. (2001) involves the manipulation of an epidemiological contagious disease spread model for FMD in both cattle and swine to represent different levels of livestock identification and recording. The epidemiological disease spread model used by Disney et al. (2001) allowed for parameters that reflect the ability to trace back an infected animal. A livestock traceability system affects the ability to control a contagious disease outbreak by increasing the ability to successfully trace the direct contacts of an infected herd. The different animal identification and recording scenarios generated unique disease outbreak outputs. The mean output values generated by a contagious disease spread model are used as inputs into an economic consequence model.

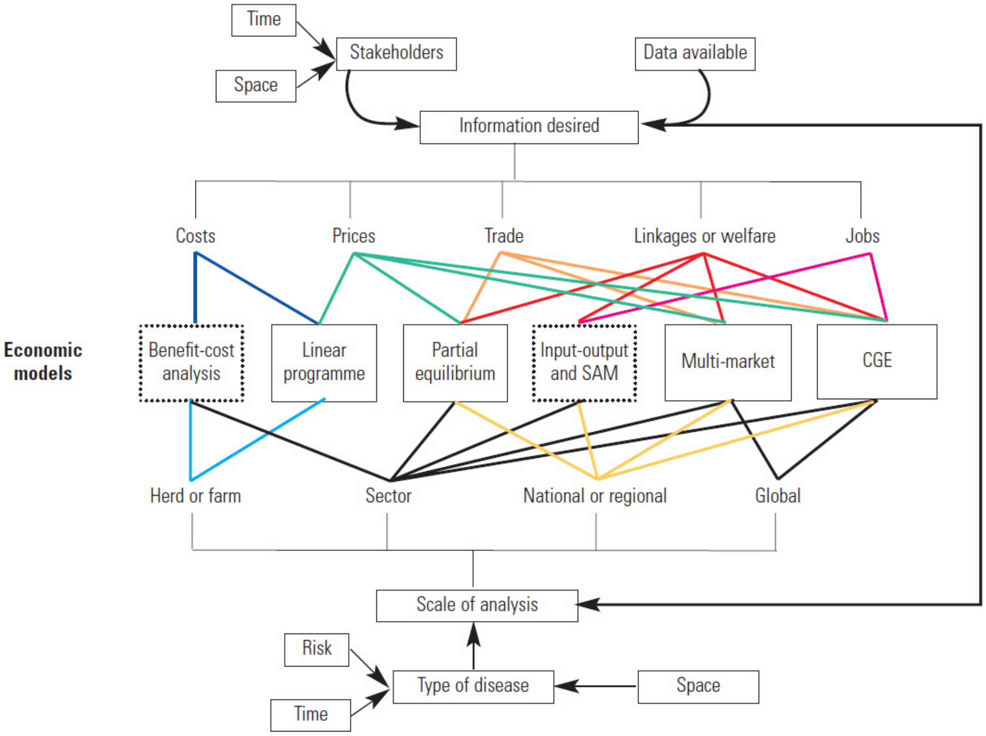
Pendell (2006) included livestock traceability scenarios by adjusting the probability of a successful trace of an infected herd to susceptible herds that have been exposed to the FMD virus. Both studies utilized a scenario-style approach that reflected three different levels of animal traceability. The low level, medium level and high level of traceability scenarios used 30%, 60%, and 90% respective probabilities of a successful trace. These studies used the same epidemiological framework that was implemented in this thesis.

Looney (2009) used the Texas AusSpread model derived by Elbakidze et al. (2009) to assess the impact of a livestock traceability system on direct outbreak costs. The parameter reflecting the level of livestock traceability, “days till dangerous contacts are found” was varied to create eight different traceability scenarios. Disease management costs that included slaughter, destruction, disposal, surveillance and disinfection were compared across scenarios to inform the decision on the NAIS system. It was found that the “days till dangerous contacts are found” did not impact the disease spread model results enough to show statistically significant differences in outbreak length or total outbreak costs. It should be noted that the author held the probability of a successful trace parameter constant at 90%.

2.2 Epidemiological-Economic Modeling

Epidemiological-economic modeling is becoming increasingly popular within the agricultural economics literature. Rich, Miller, and Winter-Nelson (2005) focused on reviewing the economic tools for the assessment of animal disease outbreaks. They created the typology shown in Figure 2.1 to illustrate the scale of analysis for each economic framework, in addition to a description of which is best suited for the information desired from the economic model. The economic models included are benefit-cost analysis, linear program, partial equilibrium, input-output, multi-market and computable general equilibrium. The paper lists the information provided by, appropriate scale for each, and the data required for each model. Ekboir (1999) states that a complete analysis of the economic implications of a FMD outbreak is comprised of four components. These components include; the direct cost of controlling an outbreak, production losses, induced price changes, and the effects across sectors in the economy.

Figure 2.1. Typology of economic models for animal disease analysis



Source: Rich, Miller, and Winter-Nelson (2005)
Notes: Models boxed in solid line are more capable of accommodating time considerations than those boxed in dashed line. CGE – computable general equilibrium. PAM – policy analysis matrix. SAM – social accounting matrix.

Rich, Winter-Nelson, and Miller (2005) reviewed the use of benefit-cost analysis in the circumstance of analyzing the economic effects of contagious animal disease, ultimately favoring the use of this method given several suppositions. The authors recommended that this model is best suited to gauge the short-fun, farm-level impacts of a contagious livestock disease outbreak. Long-term dynamic effects cannot be accurately depicted by this method since the model ignores endogenous changes in producer behavior (an optimal response). This issue becomes more important as the model attempts to explain effects further into the future. The paper also states that due to, the lack of endogenous links to other sectors in the economy, the impact of a disease outbreak may be overstated. In the long term, producers ascertain an optimal response behavior, spillover effects into other markets occur, and price effects become increasingly evident. These factors, as explained by Rich, Winter-Nelson, and Miller (2005), encourage cautious use of the benefit-cost analysis framework, particularly when calculating the long-term effects.

Derivation of a measure that captures the direct cost of controlling a disease outbreak has been common practice in previous work. Some studies that have included a computation of direct outbreak costs from an epidemiological FMD spread model are Garner and Lack (1995), Mahul and Durand (2000), Disney et al. (2001), Pendell (2006) and Pendell et al. (2007). Direct cost computations are most commonly found in research using the benefit-cost methodology. However, partial equilibrium models also require this estimation to derive the magnitude of an adverse supply shock. Economic studies have combined this basic accounting method with a range of other economic frameworks in an attempt to capture both direct and indirect economic effects. This section will review the economic consequence frameworks within the literature, including; benefit-cost analysis, linear program, partial equilibrium, and computable general equilibrium.

A report entitled “Potential Economic Impacts of a Foot and Mouth Disease Outbreak in British Columbia” by Serecon Management Consulting Inc. written for the Investment Agriculture Foundation of BC was completed on February 2010 (Serecon Management Consulting 2010). The economic framework used in the report was not entirely clear, primarily obtaining the economic impacts from basic per-unit cost estimates, similarly to the techniques applied in previously conducted benefit-cost research, described below. This report determined the economic impact of three hypothetical FMD outbreak situations, involving 5, 100, or 1,000 herds. According to the report’s authors, these situations were based on previous outbreaks throughout the world occurring in the last 15 years. The “large outbreak” scenario assumed a 25% domestic price decrease in beef and a 20% domestic demand decrease. The total cost of the “large outbreak” scenario was estimated at $47.8 billion dollars. The results from this scenario valued Ontario trade losses due to FMD at $10.9 billion.

The linear program is the least common economic consequence model in modern epidemiologic-economic literature. This framework allows for the minimization or maximization of an objective function given a set of constraints. Stott et al. (2003) used this framework to asses precautionary control strategies for bovine virus diarrhea in a representative 100-cow cow-calf herd. The level of risk experienced by the farm was set as the objective function, while income level and farm business decisions were included as model constraints. The largest draw-back associated with the linear program methodology is the scale of analysis. Linear programs are commonly applied to model an individual farm’s cost minimizing or profit maximizing behavior and cannot be used to represent entire sectors. This limits the linear program to assessing farm-level disease control strategies while incorporating farm income constraints.

The use of a computable general equilibrium model to assess the economic impacts of a livestock disease outbreak has been conducted in a Canadian context by Krystynak and Charlebois (1987). This framework requires the derivation of pre-and-post outbreak equilibrium prices across the entire agriculture industry. Within a general equilibrium model, farm income, farm input quantities, and farm input prices are treated as endogenous. In addition, all commodity prices and quantities of interrelated markets are included. Krystynak and Charlebois were granted the use of Agriculture Canada’s

FARM model, a 655 equation model of the Canadian agricultural sector. The construction of this type of model requires extensive linkage data between markets (Input-Output matrix) and elasticities. A general equilibrium model can capture the economic effects across a wide range of markets and subsequent marketing levels. This model type involves substantial data requirements, limiting its attractiveness.

Zhao, Wahl, and Marsh (2006) utilize a partial equilibrium approach when interpreting disease spread simulation results. This methodology derives price change information, linkages across markets, and welfare measures of the market participants. Similarly to the previous studies, the epidemiological model utilizes the traditional Markov-Chain state transition process however the economic consequence analysis adopts an alternative approach. Dynamic livestock production, domestic consumption and trade models are included in the framework. Consumer and producer behavioral responses to the outbreak are calculated as well as the groups resulting welfare for each control strategy. Similarly to both Saatkamp et al. (1996a) and Disney et al. (2001), different scenarios were tested for various tracing and surveillance efforts, vaccination plans, and depopulation methods.

Market reactions to animal disease outbreaks have been computed for diseases other than FMD. A PhD dissertation by Hu (2008) determined the market affects and biosecurity risks given the existence of bovine spongiform encephalopathy (BSE) in the North American cattle markets. Data from the 2002 BSE outbreak in Canada and the US was used to represent US; welfare impacts, livestock production and beef price responses. Hu (2008) constructed six scenarios of various combinations of Canada-US disease related trade restrictions and decreasing market demand. The worst case scenario, which included the largest decrease in trade and domestic demand, found a US beef price decrease of 26% and a decrease in US beef production of 16%.

2.3 Equilibrium Displacement Model Overview

The use of an EDM was first demonstrated by Muth (1964), who extended Hicks' (1948) analysis of the factors affecting the elasticity of derived demand for the case of variable input proportions. Muth (1964) derived a factor demand schedule and elasticity of industry supply given a number of underlying assumptions, including production of a homogeneous product across all producers, identical production functions, and an individual firm's production being independent of industry output. He also assumed all firms within the market are 'price takers' in both product and factor markets; this is commonly known as the 'perfectly competitive' market assumption. He derived a series of differential equations that demonstrated the effect of exogenous shifts on one or more of the structural supply and demand equations. Displacements from the initial equilibrium can be determined using elasticities to reflect the relationships between changes in the endogenous variables. Shift equations were expressed on the price axis, demonstrating an increased price at any quantity on the new demand schedule given an exogenous shock. Following the inclusion of elasticities and the exogenous supply and demand shifts, the system relative change equations is then solved for changes in all endogenous variables.

The term "equilibrium displacement model" was first used by Sumner and Wohlgenant (1985) in a paper that calculated the economic impacts of a cigarette tax increase on manufacturers and tobacco producers. An EDM was used by Piggott, Piggott, and Wright (1995) to determine the farm-level returns to incremental changes to beef advertising. The study converted the demand and supply shift equations into matrix form to determine the impact on baseline prices and quantities due to an exogenous shock. More recently, Sumner (2005) used a framework that incorporated equilibrium displacement methods in a Cato Institute paper that determined the trade policy effects of US commodity subsidies.

Brester, Marsh and Atwood (2004) used an EDM framework to estimate the economic impacts of country-of-origin labeling in the US meat industry across four beef and cattle marketing levels. The beef, pork and poultry sectors were included along with cross-sector linkages to account for intra-sector effects. Multiple marketing levels were used within each sector, including two in the poultry sector, three in the pork sector, and four in the beef sector. The beef sector model was comprised of farm, slaughter, wholesale beef, and retail beef marketing levels. Production quantities were permitted to vary across marketing levels to allow for variable input proportions. Consumer substitution among beef, pork and poultry is also included in the Bester, Marsh, and Atwood (2004) paper through the use of cross-price elasticities within the primary demand functions. Imports are incororated into the demand and supply functions within their modeling framework, requiring the assumption of a global homogenous commodity. Exogenous supply shocks due to an increase in producer costs from the implementation of country-of-origin labeling are included in the model. These supply shocks are only imposed on the beef and pork markets at the retail levels. The structural supply and demand relationships are totally differentiated using log differentials to produce relative change equations. In addition, the system of relative change equations is solved by conversion into matrix form. Brester, Marsh, and Atwood (2004) observe that the accuracy of the EDM is directly reliant on the level of nonlinearity of the true demand

and supply functions. Also, assuming the supply shocks are relatively small, the authors state that the linear approximations of the supply and demand functions are appropriate for determining the changes in consumer and producer welfare.

Most recently, Pendell et al. (2010) use an EDM to determine the economic impacts of adopting animal identification and recording systems on the US cattle, swine, lamb, poultry, and meat sectors. Exogenous shifts to supply are included in the model to account for the increased costs of the livestock traceability system, independent from a livestock disease outbreak. These shifts are imposed on the farm level markets and vertical market linkage parameters to convey the effects of the supply shift on the other marketing levels. In addition, horizontal linkages in the form of cross-price elasticities capture these effects across sectors. Potential increases in export demand were also investigated within the study, also using the EDM. The authors assumed that an animal livestock traceability system would have a positive effect on the retail demand for beef. Demand shift scenarios were included in the model to determine the percentage increase in beef demand necessary to justify the costs of the livestock traceability system. Assuming the livestock traceability adoption rate was 90% in the US, it was found that a retail beef demand increase of 1% would be sufficient to cover all costs associated with animal identification.

Pendell (2006), used the NAADSM epidemiological software and employs an EDM to assess welfare consequences. The equilibrium displacement model is derived from a partial equilibrium framework; however, exogenous shocks can be included in the former. An epidemiological-economic model is employed to derive the local economic impact of a hypothetical FMD outbreak in southwest Kansas. A partial equilibrium model that included US beef, pork and poultry markets was used in conjunction with the equilibrium displacement model framework. The model included four marketing levels for beef, three marketing levels for swine and two marketing levels for poultry. Quantity transmission elasticities were used in the model to permit variable input proportions across marketing levels. Welfare measures and trade impacts at each of the marketing levels were derived in the study.

Chapter 3 Epidemiological Model

3.1 Introduction

An epidemiological livestock disease spread model is required to generate estimates of the scale and duration of a FMD outbreak in Ontario. Epidemiological modeling of contagious livestock disease is conducted globally using a wide range of modeling techniques. Attempts have been made to construct models that explain the direct contact, indirect contact and airborne spread of FMD. Airborne transmission models for FMD have been constructed for New Zealand, Australia, Denmark, UK, US and Canada. Glostera et al. (2010) published a report that compared these atmospheric dispersion models, concluding the models predicted similarly with any differences being attributed to regional atmospheric conditions. Keeling (2005) compared different types of disease spread models used to simulate the 2001 UK FMD outbreak. The models compared in this research include; a susceptible-infected-removed (SIR) differential equation model, an explicit spatial model, and a complex (stochastic, state-transitional, temporal, spatial) computer model. The model developed to model FMD outbreaks in the UK, InterSpread, was developed by the UK's Department for Environment, Food and Rural Affairs to include all possible routes of disease transmission and disease mitigation strategies (DEFRA 2010). The three model types compared in the study had all made similar predictions about the types of disease control strategies that were needed to prevent the spread of the disease however Keeling (2005) failed to identify what type of model provided the greatest predictive power by comparing the estimates to the actual outbreak data. In addition, he stated that the more complex models rely more heavily on the accuracy of parameters, thus calling for more collaboration between epidemiologists, veterinarians and modelers.

Computer modeling of contagious livestock disease has existed as early as the mid nineteen-seventies within the academic literature. Hugh-Jones (1976) used a spatial computer simulation model to mimic the 1967-1968 FMD outbreak in the UK. Computer simulation models since this time have become much more complex, allowing for increased accuracy, flexibility, and applicability. However, the structure of these complex models has a negative effect on model transparency. As more features are included in the model, it becomes more difficult for the system of equations to be summarized in a concise manner, therefore limiting the benefits of academic scrutiny from the scientific community. The model feature most significant to this investigation is the degree of animal identification and recording systems can impact a livestock disease outbreak. This feature can only be included in a complex spatial simulation model. In a paper by Dubé et al. (2006), three spatial simulation models were compared using eleven scenarios, all with different levels of complexity. The models included were; *AusSpread* – Australia, *InterSpread* – New Zealand and Canada/US – *The North American Animal Disease Spread Model*. The outputs generated by all three models were found by Dubé et al. (2006) to be quite similar. The computer model used in the current analysis for modeling a FMD outbreak in Ontario is the North American Animal Disease Spread Model (NAADSM).

3.2 NAADSM Overview

NAADSM is a framework for the development of contagious livestock disease spread models, formally presented in Harvey et al. (2007). The computer framework was developed through collaboration between Guelph University, Colorado State, United States Department of Agriculture (USDA) and the Canadian Food Inspection Agency (CFIA). It is a predecessor of a model developed for the Australian Government Department of Agriculture, Fisheries and Forestry, published in Garner and Lack (1995) to model FMD in Australia. The early NAADSM framework is also based on '*SpreadModel'* in Schoenbaum and Disney (2003).

NAADSM is generally used to model FMD outbreaks at the regional level, due to the challenge of obtaining herd demographic information and NAADSM's inability to randomize disease introduction scenarios. NAADSM requires an assumption regarding exactly where the disease is introduced into a livestock population. For instance, Australia is in the process of building an FMD model that includes every animal on the entire continent. If NAADSM was selected as the modeling framework, thousands of disease introduction scenarios would be required to generate robust outbreak results for the entire country. NAADSM is widely used by the USDA and CFIA to determine the relative importance of regional disease control strategies, biosecurity and farm related government policy.

As mentioned in chapter 2, NAADSM has also been utilized by the academic community, appearing in numerous veterinary and agricultural economic peer-reviewed journals. NAADSM becomes a working epidemiological model when specific disease parameters, animal movement information, a disease control strategy and herd demographic data is integrated into the framework. The parameters used in the construction of the epidemiological model are discussed in detail within chapter 5.

3.3 Stochastic Process

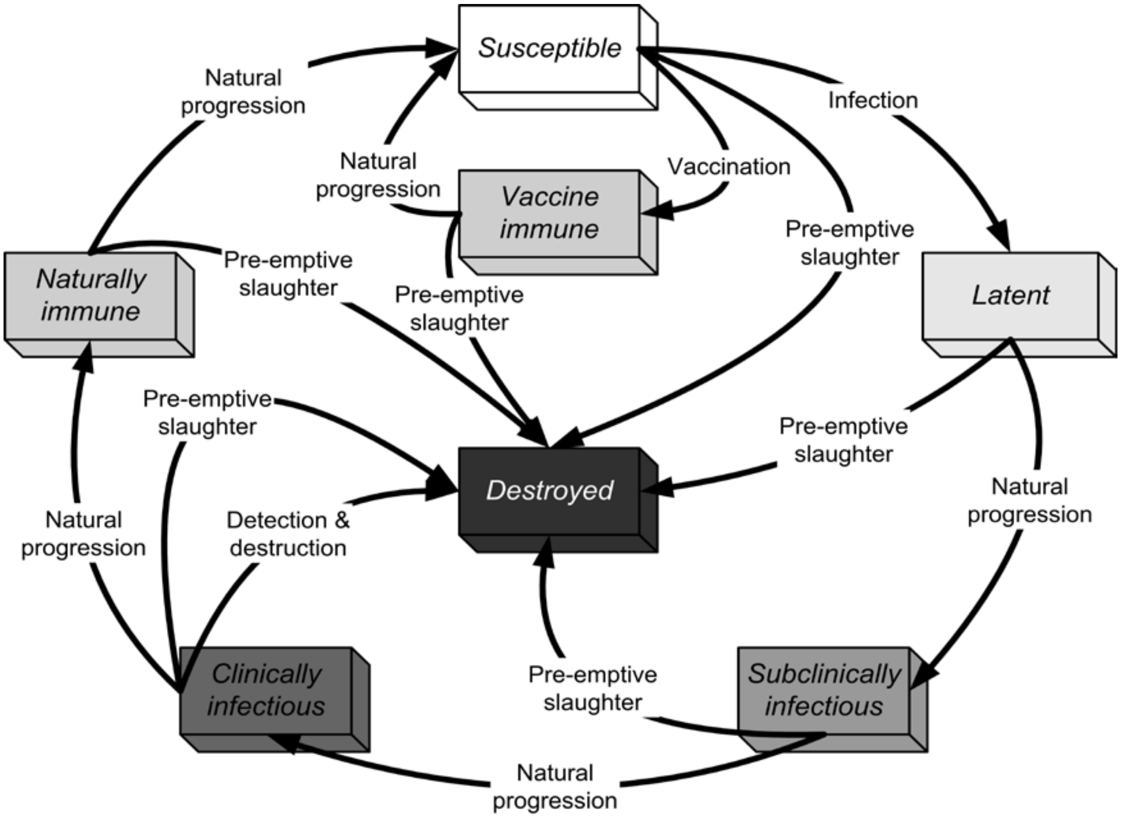
NAADSM is a stochastic simulation model, allowing for the inclusion of probabilistic parameters to predict the disease spread. This feature allows for parameter variability and uncertainly, providing a random element to the disease outbreak process. When scientific data is provided in the form of a distribution, it becomes much more valuable to incorporate this into the model rather than using the mean value. Parameters that can be incorporated into the model in the form of probability distributions include; the time a herd is in each disease state, the distance of live animal shipments, shipping delay of live animal shipments, and the transport delay of airborne disease spread. For example, rarely are live animals shipped long distances within Ontario, but by including this as a possible factor in the model using a probability distribution, uncommon events can be taken into consideration. Direct animal contact rates between farm types are also stochastic in nature ranging both seasonally and between farms. The NAADSM framework allows for a normal distribution to be included around a selected mean for these parameters. This is less accurate relative to model parameters where the distributional properties can be selected.

The non-deterministic framework requires many disease outbreak iterations to provide robust model outputs. Disney et al. (2001), Dubé (2009), Pendell (2006), and Pendell et al. (2007) have used 1,000 iterations of the disease spread to provide sufficient convergence of the output values' statistical means. This thesis will follow this trend and conduct 1,000 iterations of each disease outbreak scenario. The stochastic nature of NAADSM allows for the generation of statistical measures for each disease outbreak output statistic. This provides a more robust analysis of the extreme cases of a livestock disease spread. Although the economic analysis in the current study does not utilize the statistical properties of the disease spread model outputs, value exists in the ability to assess the probability and severity of worst case scenarios.

3.4 State-Transitional

NAADSM requires that the entire livestock population included in the outbreak scenario be divided into mutually exclusive disease state categories. The NAADSM framework is a herd based model, therefore the following classification system applies to the entire herd rather than to an individual animal. This feature has many implications that will be discussed both later in this chapter and with regards to model parameterization, in chapter 5. Similar to the framework used in a classical swine fever model by Saatkamp et al.

Figure 3.1. NAADSM disease states and disease transmission routes



Source: Reeves (2010)
Note: The Ontario model used in this thesis ignores the vaccine immune state.

(1996a), herds can be classified as either; susceptible, latent, clinical, subclinical, destroyed or non-susceptible. The movements between these herd classifications are summarized in Figure 3.1. Susceptible herds are those that are vulnerable to FMD infection. There are three paths a herd can follow from the susceptible state; remain susceptible, become infected or be preemptively destroyed.. Herds that are in the latent stage are infected but do not have the ability to spread the virus to other herds. Animals in this stage of FMD show no clinical signs of infection and are therefore undetectable. Latent herds can transition to the sub-clinically infectious or destroyed state.

The duration a herd exists in a particular disease state is determined stochastically from a probability density function. These probability density functions are derived using clinical data from individual animal trials. Individual animal data is used because a herd is no longer classified as susceptible when the first animal becomes infected. Following the latent stage, a herd naturally progresses to the subclinical disease state. The only scientific difference between subclinical animals and latent animals is that sub-clinically infectious animals have the ability to spread the disease. An issue does arise in the case of a latent animal being transported to a susceptible herd and this will be discussed in section 3.6. When the first animal within a herd naturally progresses from the latent to sub-clinical state, the entire herd is then reclassified. Following the natural progression from latent to subclinical, animals begin to show signs of the FMD and become classified as clinically infectious.

It is also the case that the entire herd is reclassified immediately after the first animal shows clinical signs of the disease. Clinically infectious herds can naturally progress to the naturally immune stage or be destroyed from ether pre-emptive/detection or destruction slaughter. Both subclinical and clinical herds have the ability to infect susceptible herds through airborne, direct and indirect contacts, all of which will be discussed in section 3.6. Herds within the naturally immune stage can also naturally return to the susceptible state, an occurrence that is common within countries where FMD is epidemic to the livestock population.

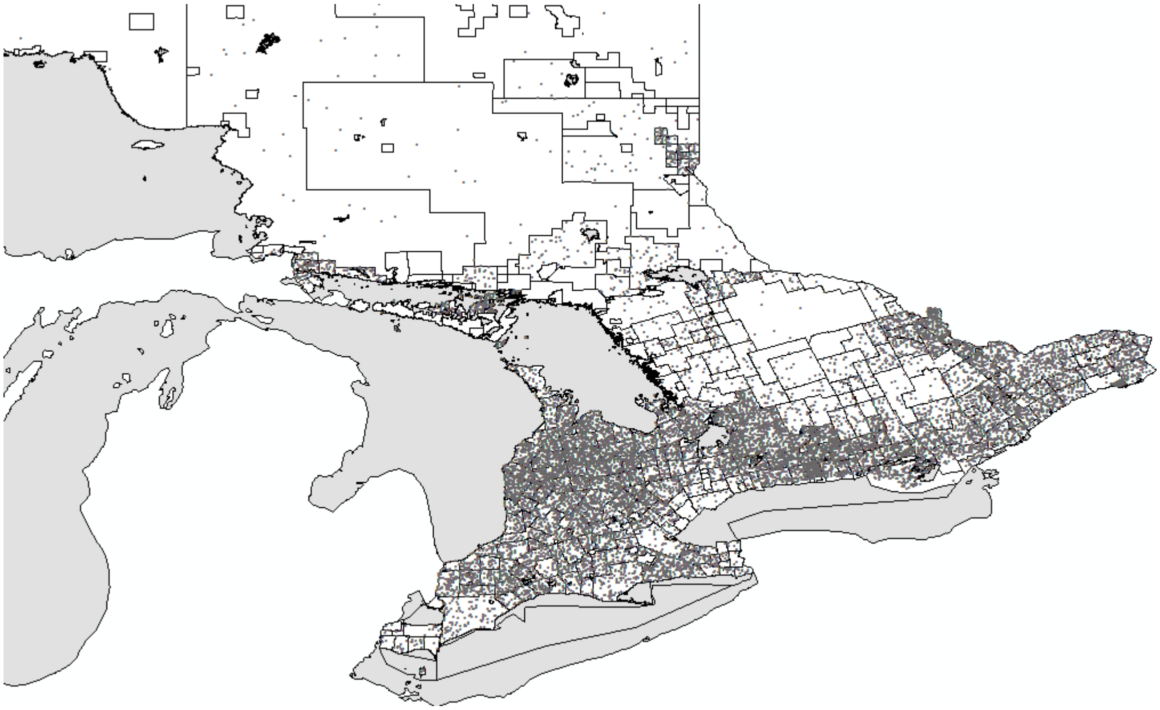
The trend where the first animal is responsible for reclassifying the disease state of entire herd is not the case for the transition from clinical infectious to naturally immune. In this situation, the herd can still spread the disease even after some of the animals have transitioned to becoming naturally immune. This reasoning requires the use of a ‘within herd prevalence’ model to derive an estimate for how long a herd will remain in a clinically infectious state. The previously mentioned disease states were able to use individual animal disease state duration data because it was always the first animal that transitioned that would be responsible for the entire herds’ re-classification. The ‘within herd prevalence’ model was developed by Aaron Reeves with Colorado State University, to estimate the prevalence of FMD within a single representative herd (Reeves 2010). Chapter 5 will discuss how this disease-state duration is derived and the data were used for the Ontario FMD model.

3.5 Spatial

Specific herd geographical information is required for the disease outbreak region. This is the case because all forms of contact rates (explained in section 3.6) and surveillance zones (explained in section 3.9) are also a function of distance within the NAADSM framework. The geographical coordinates, farm type, and the number of animals at each farm are required by the NAADSM framework.

Figure 3.2 depicts a representation of the demographic input data used by NAADSM. This data allows for livestock operation densities and the relative distances between operations to be included in the disease spread model framework. Herd geographical information is also required to determine what operations are affected through the movement controls imposed by the creation of infected and high risk zones.

Figure 3.2. Geographical representation of cow-calf operations in Southern Ontario



Notes: Each grey dot represents a single operation. Consolidated census regions and major bodies of water are included in the illustration. Dairy coordinates are excluded from this representation due to a confidentiality agreement with Dairy Farmers of Ontario.

3.6 Disease Transmission and Contact Rates

Disease transmission between operations and across operation types are divided into three mutually exclusive categories. First, airborne spread is included within NAADSM where the rate of disease transfer declines exponentially from the source. Only sub-clinically and clinically infectious units can spread the disease agent via airborne transmission. The probability of airborne disease spread within NAADSM is a function of the distance, the individual animals' probability of spread at 1km to a recipient animal type and the number of animals in the transmitting and receiving herds. Airborne spread is untraceable (further discussed in section 3.8) and is therefore unaffected by the animal identification system. NAADSM also allows for the inclusion of prevailing winds; however, this feature was not included in the Ontario FMD study.

Second, from Harvey et al. (2007), indirect contact in NAADSM accounts for the movement of people, materials, vehicles, equipment, animal products, etc. For example, veterinarians, federal inspectors or maintenance crews that contact multiple herds in a single day are a source of indirect contact. Similarly to airborne spread, only sub-clinically and clinically infected herds can contaminate the indirect contacts that move between farms. Also similar to airborne spread, animal identification and recording systems are assumed to not have any effect on the ability to trace indirect contacts. Individual operation recordkeeping and third party standard operating procedures impact the ability to trace this method of disease spread. The trace option is available in NAADSM for indirect contacts although no method to calculate the probability of a successful indirect trace is available in the literature. This investigation will allow for indirect contacts to be traced.

Lastly, direct contacts are the result of the movement or shipment of live animals from one herd to another. Unlike the previously mentioned methods of disease transmission, and based on earlier reasoning presented in section 3.4, if a situation arises where a latent animal is introduced to a susceptible herd, the infection will spread. Therefore, NAADSM allows for the option that direct contact by a latent herd can result in successful disease transmission. Contact rates for the Ontario model were derived from

Dubé (2009), Ontario auction barn interviews and consultation with CFIA livestock experts. Direct contacts between cattle and swine herds were not determined to exist from the sources listed, resulting in indirect and airborne transmission as being the only method of disease spread between cattle and swine.

Direct contacts are determined in the NAADSM framework by the ongoing generation of a shipment priority list for each operation in the model. Each individual operation samples from a distribution of likely shipping distances, and the largest farm at the chosen distance is selected as the recipient operation. Based on the probability that a given farm is shipping animals, direct contacts are made. A priority list of direct contacts is generated due to the possibility that a single farm may have multiple direct contacts in a single day. Following the largest farms at the originally chosen distance the list is populated in the following order; smaller farms at the originally chosen distance, then larger farms at a marginally closer distance. When a direct contact is made between a latent, subclinical or clinical herd and a susceptible herd, the probability that a successful disease transmission will occur will be applied and disease transmission may or may not occur. Newly infected herds will always start the disease cycle in the latent stage regardless of the classification of the herd that transmitted the disease. As this is the least transparent portion of NAADSM and further information may be required, the open source code including all model algorithms is available at www.NAADSM.org and further explanation can be found in Harvey et al. (2007).

3.7 Temporal

A step-time for the model is required, resulting in the calculation of a new categorical distribution of the cattle population after each day of the outbreak. This step-time is also used to compute the expected duration of the projected outbreak in days. In addition, many of the models input parameters are relational functions to time. These parameters include; the effect of movement controls within and outside of control zones following the detection of the outbreak, the probability of observing clinical signs given the number of days a herd is classified as clinically infectious, the probability of reporting an observed clinical unit given the days following disease detection, and the destruction capacity of the CFIA given the number of days since the disease was initially detected.

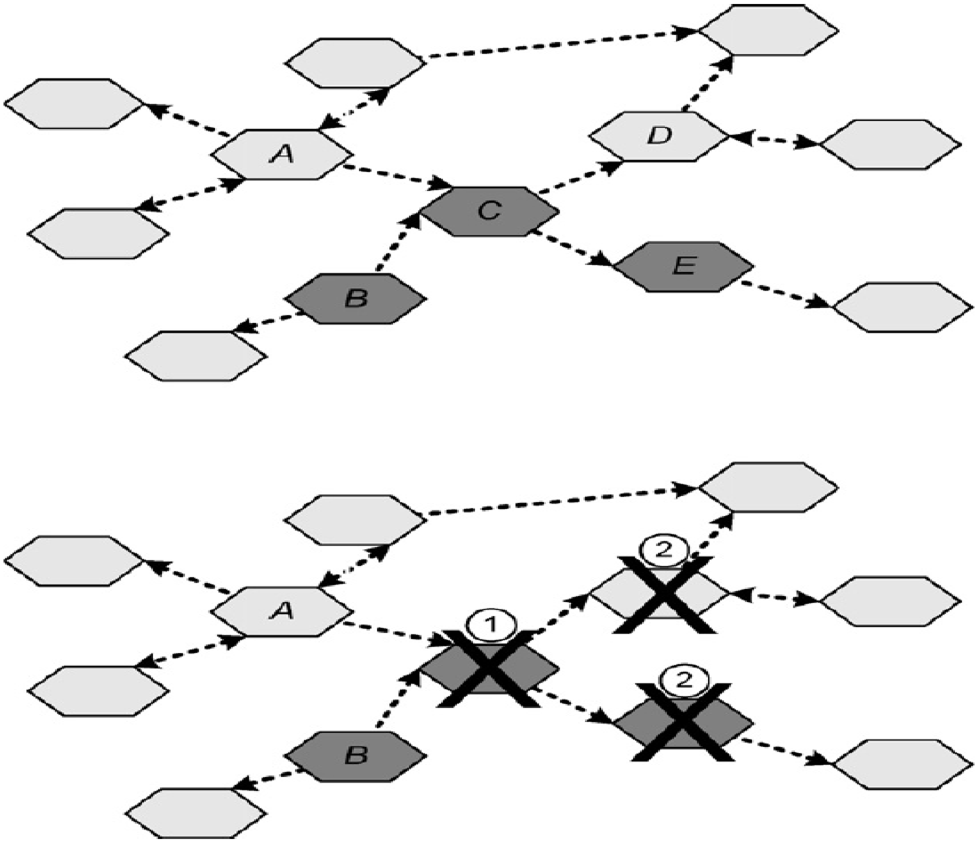
There are also two distinct periods of the model, a pre-period where the disease is unnoticed and a main period. Disease spread is more likely to occur during the pre-period due to the absence of movement restrictions and other disease control measures. The main period starts with the implementation of control measures following notification to CFIA officials of a FMD outbreak. NAADSM allows for a separation between the actual disease outbreak created by the model and the number of cases that were detected by animal health officials. The probability of an outbreak being detected and the probability that a farmer will report an outbreak are important model inputs that will be provided by the Canadian Food Inspection Agency from the FMD model created for the Maritime Provinces.

3.8 Livestock Traceability System

This model assesses the effect of animal traceability systems on the effectiveness of FMD control strategies. The Canadian FMD Hazard Specific Plan (2007) states that all movements of susceptible animals onto or off of positive FMD infected farms for 14 days (for cattle and pigs) prior to the onset of the oldest FMD clinical signs must be investigated (CFIA 2009). Tracing priority is given to direct animal contacts although indirect contacts must also be investigated.

The animal identification and animal movement recording system allows for an increased ability to trace potentially diseased animals to prevent further disease spread. The NAADSM framework incorporates the ability to assess, given disease detection has occurred, what herds an infected herd had made direct or indirect contact with. This process is displayed in Figure 3.3, showing the ability of NAADSM to trace contacts forward one level from a single herd. Indirect contact tracing is unaffected by the animal identification system. As mentioned in section 3.6, the accuracy of indirect tracing relies on farm specific and third-party (veterinarians, maintenance personnel, etc.) recordkeeping practices. NAADSM allows for the model traceability inputs to be production type specific. This allows for heterogeneity among the traceability systems for each animal type, enabling the benefits of a traceability system solely for cattle to be assessed. When a unit is identified to have come in direct or indirect contact with a diseased herd, NAADSM either quarantines or destroys the traced herd.

Figure 3.3. Trace-back instrument in the NAADSM framework



Source: Harvey et al. (2007)
Notes: Arrows show contacts (either indirect or direct) between herds. Given that unit C is detected positive for FMD (1), and given herds D and E and made contact with herd C (2), C,D and E are either quarantined or destroyed. NAADSM version 3.1 does not trace back (identify disease source as A or B) or further than a single step forward.

Previous NAADSM studies that have used expert opinion to derive the trace parameters include Disney et al (2001) and Ward et al. (2009). NAADSM requires the number of days an infected animal can be traced-forward with a specific probability of accuracy. These parameter estimates for direct contact would heavily rely on the situation of livestock movement recording. The version of NAADSM (Version 3.1) used in this study is only able to 'trace' the animal movements out of a diseased herd one level forward.[1] This is a significant limitation to the current study since CFIA veterinarians would utilize the traceability system to determine the origin of disease in an infected herd.

3.9 FMD Control Strategies

The Canadian FMD control strategies must be accurately depicted within the NAADSM framework. The Canadian FMD hazard specific plan would provide the specific implementation of disease control strategies in the event of a FMD outbreak in Canada. Vaccination, although included in the NAADSM framework, will not be incorporated in the Ontario FMD model. According to the Canadian FMD Hazard Specific Plan, the use of emergency vaccination will be determined at the time of an outbreak. Emergency vaccination effects export market access, creating a substantial cost of using this disease control. Due to the uncertainty of its use, emergency vaccination will be ignored in this study. FMD control strategies included in the current model include; decontamination activities, destruction activities, quarantine practices, movement restrictions and zoning strategies.

The Canadian FMD Hazard Specific Plan (2007) includes a list of disinfectants that are required for use in decontaminating an infected premise. A list of disinfectant products and the products' suppliers is currently under construction for North America, signaling similarities in decontamination protocol between Canada and the US. It should

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[1] A new version of NAADSM (Version 3.2) was set to be released in December of 2009, and include vast improvements in the way traceability systems can be included in the model to affect the control strategies. Version 3.2 includes a new trace back feature, allowing for an investigation into the source of infection for any infected herd. This would be common practice in the event of an FMD outbreak and this type of trace investigations' accuracy would heavily rely on the animal identification and movement recording system. Also, NAADSM version 3.2 allows for an array of options concerning what actions should be taken when a direct or indirect trace is conducted. These include; preemptive destruction, disease test, or quarantine. This new trace surveillance modeling approach is a much better representation of the options presented to CFIA officials in the event of an actual outbreak. The official release of version 3.2 has been postponed due to some technical issues and was not able to be used in this study.

be noted that the Canadian FMD plan states that if premise disinfection cannot be achieved quickly, then all contaminated materials, equipment, and buildings should be destroyed (CFIA 2009). NAADSM does not incorporate a disinfection capacity as an outbreak control parameter, whereas this situation could lead to significantly higher outbreak costs. However, the Canadian FMD Hazard Specific Plan does not define the timeline associated with rapid disinfection, requiring further assumptions to include such additional costs in the model.

The depopulation capacity and destruction priorities are included in the NAADSM framework. In accordance with the Canadian FMD Hazard Specific Plan, pre-emptive slaughter of all susceptible animals known to have come into contact with an infected herd (through tracing) will be slaughtered. This includes all animals on the premise. Infected animals are required to be slaughtered within 24 hours, whereas animals directly exposed to the virus are required to be slaughtered within 48 hours. The depopulation priorities according to the Canadian FMD Hazard Specific Plan are displayed in Table 3.1.

Table 3.1. Canadian FMD depopulation priorities

Priority Ranking	Depopulation Action
1	All clinical swine at the farm of origin
2	Other clinically affected animal species at the farm of origin
3	All known direct contact swine
4	All know direct contact susceptible animal species
5	Susceptible contact fractious/exotic game farm animals
6	High-risk swine in infected zone and indirect swine contacts
7	Other high-risk activity in infected zone and other animal indirect contacts

Source: CFIA (2009)

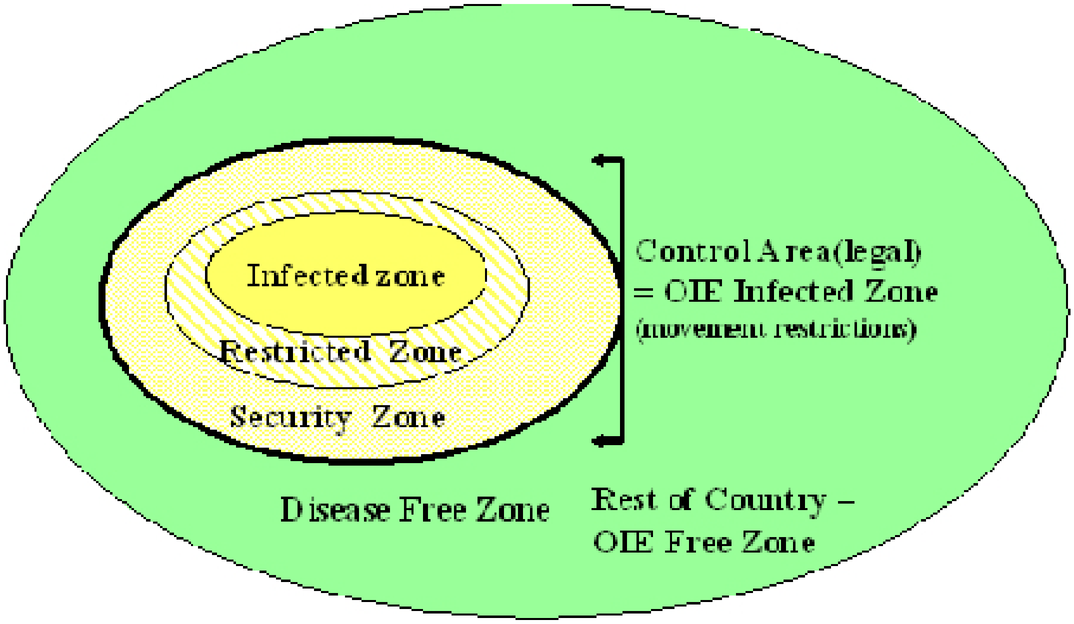
The destruction priority list is incorporated into the NAADSM model framework. However, fractious/exotic game farm animals are not included in the model. The destruction priority list is required when the number of herds that are required to be euthanized exceed the CFIA slaughter capacity. The slaughter capacity relational function depicts how many average sized herds can be humanely slaughtered by the CFIA as a function of days following disease detection.

Quarantine procedures heavily impact the number of direct and indirect contacts generated by each farm. This change in the contact rate has an immense impact on the severity of the disease outbreak, making quarantine practices among the most important of the disease control input parameters within the NAADSM framework. According to the Canadian FMD Hazard Specific Plan, immediately following the detection of FMD, the CFIA immediately sets a 5km ‘suspect infected place declaration’, halting all movements of animals and indirect forms of disease transmission in the area. The ‘suspect infected place declaration’ is a temporary control area until official zones can be established. The NAADSM framework ignores the ‘suspect infected place declaration’ and assumes the instantaneous creation of control zones.

The first requirement of setting up formal control zones is the CFIA’s determination of a control area, as displayed in Figure 3.4. The area of the country outside this control area is legally defined as disease free, according to the World Organization for Animal Health. Although this status legally defines animals and products outside of the control area as disease free by the *Terrestrial Animal Health Code* (OIE 2009), it is not guaranteed that the US would allow Canadian imports from this area into the country. The control area for this study will be assumed to be the province of Ontario. Within the control area is referred to as the security zone. In this area animal, equipment and livestock support personnel movement restrictions are implemented. This is included in the NAADSM framework as a relational function between the direct and indirect contact rate relative to the number of days following the creation of the security zone.

Where herds have been detected as positive for FMD, two zones are created surrounding the herd. An infected zone is created within a 3km radius of the infected herd, impacting; animal, equipment and livestock support personnel movements. Within the infected zone, the probability of a farmer observing clinical FMD signs during business as usual within their herd is multiplied by two. This is the result of an increased attentiveness following the existence of disease in the area.

Figure 3.4. A visual representation of Canadian disease control zones



Source: CFIA (2009)

The second zone that is created by the CFIA and modeled in NAADSM is the restricted zone, having a radius of 10km around the infected zone. Similar to in the infected zone, movement of any source of disease transmission is heavily restricted. The restricted zone is created for the purpose of containing airborne spread because 10km is the general limit for airborne spread of FMD. Also, increased consciousness of the disease increases the probability of observing clinical FMD signs by 1.5 times the probability during business as usual. The specific movement restrictions imposed in both the security, infected and restricted zones in the NAADSM model will be discussed in detail in chapter 5.

3.10 Epidemiological Model Limitations and Assumptions

Several assumptions and model limitations exist within the NAADSM framework. Spatial assumptions that must be noted when using this model include; the herd demographic estimation procedure, the point estimates of the farm locations and the inability for the disease to enter or exit the jurisdiction modeled. Obtaining the geographical coordinates of all beef cattle and swine operations in Ontario was not possible. This resulting estimation procedure of farm-level geographical coordinates that is later described in chapter 5 requires several model assumptions. In regions where livestock farms are so concentrated that some operations would be adjacent to one another, NAADSM only records the farm location as a geographical point, thus overestimating the distances between these operations. This limitation would underestimate the spread of FMD whereas farms that are across the road from one another and airborne transmission is almost guaranteed, are modeled as being a kilometer apart because the geographical coordinate identifies the center of the operation. This limitation was also evident in Gerbier et al. (2002), within an airborne FMD spread model. The AusSPREAD model is able to use either farm boundary or point-location demographic data inputs. Modelers at the USDA are in the process of dealing with this issue but it would further intensify the model’s data requirements, requiring a geographical polygon layer to represent the boundaries of each operation. It would also heavily complicate the algorithms that depict the relative distances between operations. Lastly, NAADSM does not have a method of incorporating the possibility that the disease may leave and re-enter the area under investigation. This situation is not extremely important in Ontario where the largest populations of livestock are either bordered by the Great Lakes or the St. Lawrence River.

In addition to the spatial assumptions in the NAADSM framework, animal movement issues also create model limitations worthy of discussion. NAADSM assumes that intra-herd contact rates and airborne spread rates are uncorrelated with seasonality and herd size. Seasonality can be addressed with the use of scenario analysis, having derived different contact rates given different seasons in the production cycle. In addition, seasonality can also impact airborne disease transmission rates, something also not addressed in the NAADSM framework. According to Ferguson et al. (2001), animal density has a direct impact on the airborne transmission of FMD. Herd size has also been found to impact the number of indirect contacts in a study by Bates et al. (2001) when investigating California direct and indirect contact rates. The NAADSM framework assumes a single direct and indirect contact rate for each production type regardless of the herd size.

For the case of an FMD outbreak, small ruminant operations should be included as an additional production type in the model. The epidemiological FMD outbreak model should optimally included all FMD susceptible animal types including lamb, sheep, goat, elk, boars and deer. Although these species are in Ontario, the Canadian Census of

Agriculture identifies 311,162 sheep and lambs, 76,114 goats, 3,550 elk, 1,006 wild boars and 8,031 non-wild deer on Ontario farms in 2006 (Statistics Canada 2010). However, relative to the 1.98 million cattle and calves and 3.95 million swine, small ruminant operations are a small fraction of the FMD susceptible population within the province.

Non-livestock animal populations should also be included in the model. Bates et al. (2001) found that fifty-five percent of large beef cattle herds observed deer or elk within 150 meters of their livestock at least once a month. This finding was from California and is heavily dependent on the wild-deer population in the area. These animals are an important factor due to their ability to make undetected and unrecorded contact with multiple livestock herds in an area. NAADSM currently does not have a methodology for including migratory animal populations. This study chooses to overlook this potential source of disease transmission due to data constraints and the restrictions generated by the NAADSM framework.

Lastly, it is important to note that NAADSM does not account for animal births, restocking, or natural animal deaths in this simulation model. The Canadian FMD Hazard Specific Plan (2007) allows for restocking before the end of an outbreak given no confirmed FMD cases within 10km of the farm in the last 14 days. This model assumption could significantly underestimate the number of susceptible animals and the number of animal movements in a given area. However, the CFIA requires the new stock of animals to originate from areas where movement restrictions have not been imposed.

3.11 Output Statistics

The NAADSM framework generates statistical measures for 67 different disease outbreak characteristics, listed in Table A.1 in the appendix. These outputs can be segregated by production type, for the purpose of identifying outbreak statistics for particular livestock species or operation types. The statistical nature of the outputs include the following for each statistic; mean values, standard deviation, lowest recorded value, highest recorded value and various percentile measures.

Chapter 4 Economic Model

The modeling strategy used to compute the indirect effects in the current analysis will involve the implementation of an equilibrium displacement model on a partial equilibrium framework of the Canadian live cattle and beef markets. Two exogenous shifts generated by a FMD outbreak will be incorporated into the equilibrium displacement model framework. A negative supply shock to feeder and fed cattle markets will be determined, dependent on the number of animals destroyed and the outbreak control costs realized by the producer. Secondly, the loss off export markets will be included as a negative demand shift, explained in chapter 4 of this paper. The welfare changes at each marketing level will be calculated using annual baseline quantity values. This annual change in welfare will be calculated based on the length of the FMD outbreak as determined by the epidemiological model. The length of time required after the destruction of the last FMD infected animal for Canada to be considered a disease-free country and international trade can be resumed will also be considered in the welfare calculation.

The determination of the benefits of the animal traceability and recording systems with regard to the economic consequences of the disease outbreak will be ascertained using scenarios that reflect different levels of livestock tracing abilities. These traceability scenarios will be compared to determine what effect traceability has on the epidemiological and economic results. The parameterization of each scenario will be detailed in chapter 5 of this study.

The plan for this thesis is to estimate the economic consequences for an outbreak in the present economic environment, a period in which conditions can be much more accurately depicted. It must also be noted that livestock traceability systems create other benefits not incorporated into the current study on producers and animal health officials. These factors prevent the current study from generating an all-encompassing benefit cost ratio of a livestock identification and recording system for Canada.

4.1 Economic Model Selection

The process of selecting an economic framework to monetize outputs from the epidemiological model was adopted from Rich, Miller, and Winter-Nelson (2005). This review of the various economic tools available to assess animal disease outbreak data provides an overview of several of the economic techniques' strengths and weaknesses.

The scope of the analysis is intended to examine changes in prices, output and welfare, given the economic shocks on the domestic cattle markets created by the onset of a FMD outbreak. Domestic cattle producers are interested in the expected costs experienced by a producer given a FMD outbreak, changes in feeder and fed cattle prices following the loss of the US export market, and the subsequent changes in welfare. The retail beef and wholesale beef market must also be included in the model to enable the computation of consumer surplus. In addition, the farm level markets are required for a producer surplus measure to be calculated.

Also of interest to policy makers responsible for livestock traceability is additional analysis regarding the sensitivity of these economic changes given different livestock traceability scenarios. The model used for this analysis must be calculated using the epidemiological disease outbreak data from three different traceability scenarios, providing comparable economic results for each scenario. Scenario analysis is also conducted with respect to the economic ramifications of who endures these direct outbreak costs; the producer or the government. These results are of interest to both domestic producers and government officials involved in agricultural production or livestock traceability policy.

During a livestock contagious disease outbreak, prices of the affected agricultural commodities change. This price change is amplified if large export markets are closed due to international disease spread concerns. Measuring the sensitivity of a negative shift in farm-level supply caused by outbreak costs realized by the producer is critical in the development of outbreak control policy. The determination of who should endure these direct outbreak costs directly impacts the magnitude of the negative supply shock. If producers bear the entire outbreak costs, output would be negatively affected and prices would increase. The selected model must have the ability to compare these scenarios to provide an understanding of the sensitivity of model outputs to the previously mentioned input parameters.

According to Rich, Miller, and Winter-Nelson (2005), the scale of the economic analysis is dependent on the nature of the disease itself. Disease characteristics heavily influence model selection due to temporal and spatial considerations. For the case of FMD, it is unrealistic to constrain the economic model to a single farm because of the highly contagious nature of the disease. FMD disease outbreaks can span across multiple livestock production sectors, affect different livestock operation types within each sector and result in international trade restrictions. National and regional analyses have been conducted for previous FMD economic consequence studies. For instance, national and regional scopes of analysis were used by Serecon Management Consulting in a study conducted for the Investment Agriculture Foundation of BC in February 2010 (Serecon Management Consulting 2010). Both national and provincial economic impacts of several disease outbreak scenarios were explored. Assuming the international trade restrictions are imposed on the entire country, national economic consequences should be considered.

The model used for this thesis assumes a FMD outbreak in Canada would immediately halt all Canadian exports of beef and live cattle. This assumption requires a model that can estimate the effect of losing export markets at the beef wholesale, fed cattle and feeder cattle market levels. Discussions between Canadian and US animal health and trade officials are taking place, primarily concerning the possibility of zoning initiatives. Zoning initiatives would partition the country with respect to Canada's disease-free status in a FMD outbreak situation, and would allow parts of the country that are unaffected and have no-risk of becoming contaminated to be interpreted as disease-free internationally. The disease-free status would thus allow international trade to continue in these areas, reducing the overall economic impact. These initiatives cannot be incorporated into this study due to the uncertainty surrounding their implementation in the event of a FMD outbreak. Canadian live cattle export data including province of origin exists for recent years and could possibly be used in future research to assess the economic impacts of zoning. The same data for wholesale beef were unavailable; therefore this study does not include this scenario.

An economic analysis at a national scale is also justified by the nationwide scope of current government livestock traceability initiatives. Sectoral considerations must be addressed due to the existence of different operation types within the cattle industry. An investigation should be conducted to determine the effect on feeder and fed cattle markets if producers were to assume the direct costs of a FMD outbreak. Although the outbreak costs are unlikely to result in a permanent shift in the cattle market supply, it is assumed that the aggregate producer supply curve would be impacted in the short-run. An example of how this cost could be shared across the cattle market would be the use of a per-unit tax across the industry to reimburse the government for outbreak associated costs. Direct outbreak costs, used to determine a supply shock to cattle producers, would be best calculated within a simple accounting framework. This would generate cost estimates for surveillance, testing, destruction, disinfecting, disposal, compensation, and movement control practices.

The disaggregated market effects on retail beef, wholesale beef, feeder and fed cattle markets are important for analyzing the distributional effects on the domestic beef and livestock industry. These requirements call for an economic model that can derive welfare changes for the entire industry, measure distributional effects across sectors, and allow for both supply and demand shocks at different market levels. A partial equilibrium model that includes retail beef, wholesale beef, fed cattle and the feeder cattle market is ideal for determining the economic effects of a FMD outbreak. Trade would also be required within each marketing level, except domestic retail beef. The changes in prices and quantities generated by the supply and demand shifts are best calculated using an EDM, as described in the following section. Previous implementation of EDMs in a similar context to this study will be described in section 4.2 of this chapter.

4.2 Modeling Strategy

The economic modeling strategy used in this analysis will involve the use of an EDM within a partial equilibrium framework of the Canadian cattle and beef markets. The most recently available supply and demand elasticities will be used in conjunction with annual baseline values for prices, quantities and exports. Baseline annual values will be computed using 2009 data. Live cattle imports will be ignored in this model for both the feeder and fed cattle markets. According to CANFAX, live cattle imports constituted less than 1% of total supply in 2009 (Canfax 2010). Therefore, the domestic supply curve for live cattle is assumed to be equal to the total supply curve.

The EDM framework requires the derivation of linear approximations of all supply and demand functions in order to compute changes in welfare. This requirement entails a number of assumptions pertaining to production conditions, market aggregation, technological effects and product homogeneity. These assumptions will be outlined in detail in section 4.9. EDMs are designed to assess the effects of supply and demand shifts on commodity prices, commodity output levels and the subsequent changes in welfare across marketing levels.

In order to use an output quantity that can be comparable across feeder cattle, fed cattle and wholesale beef markets, a common unit must first be derived. Differences in feeder and fed cattle animal value limit the effectiveness of a ‘per-animal’ vertical linkage between markets. The model must compare a homogeneous product at all market levels. This follows the approach used by Pendell et al. (2010), where individual animal prices and quantities are converted into dollars per cwt of beef and live weight pounds of beef, respectively. The average weight of feeder and fed animals will be used to determine quantity levels in the live cattle markets. This will also enable a vertical linkage with the wholesale and retail beef markets.

Primary demand is calculated at the retail beef marketing level and primary supply is calculated for the feeder cattle marketing level. All remaining supply and demand curves included in the model are vertically related to these functions, defined as derived demand and derived supply. These vertical linkages are represented in the structural model through the use of transmission elasticities, a parameter reflecting the percentage change in a market level quantity given a 1% change in another market level quantity. These measures can only reflect the relative quantity changes in a single direction, requiring the use of two separate measures at the wholesale beef and fed cattle levels to include intra-market relationships in both directions.

Transmission elasticities are used to relate all derived supply and demand functions to their primary counterparts. For instance, in the model used here, a transmission elasticity is used to relate the derived domestic demand for feeder cattle to the quantity of fed cattle. In addition, the derived demand for fed cattle is related through a transmission elasticity to the derived demand for wholesale beef. Furthermore, the derived domestic demand for wholesale beef is related to the primary demand for domestic retail beef through a transmission elasticity, thus relating all derived demand functions, directly or indirectly, to a primary domestic demand function. The same situation is seen in the other direction for derived supply functions, whereas the derived retail and wholesale beef supply are related to the quantity of fed cattle through a transmission elasticity. Moreover, the derived supply function of fed cattle is related to the primary supply of feeder cattle through a transmission elasticity.

OLS regression estimates from Pendell (2006) will be used to describe the relationship of quantities across the respective marketing levels. An explanation regarding the specific derivation procedure of these estimates and the source data used for their computation will be explained in detail in section 4.7 below. Transmission elasticities that are statistically different from one allow for non-fixed relative changes in input proportions among market levels. The baseline output quantities are permitted to be different among market levels; however, relative changes in these quantities are bound by these elasticities.

Two effects generated by an FMD outbreak will be incorporated into the EDM framework. First, the negative supply shock to feeder and fed cattle markets will be computed, dependent on the number of animals destroyed and the outbreak control costs borne by the producer. Assumptions will be made regarding the fraction of outbreak control costs faced by Canadian cattle producers and the resulting changes will be compared. The EDM requires percentage shocks, which in turn requires computation of a cost relative to the entire industry's value. The details regarding the computation of this supply shock are discussed in section 4.4. Second, a negative trade demand shock is also included in the model to incorporate the loss of US cattle export markets. It is important to distinguish that the trade demand shock included in the current model is different from a traditional demand shock, one realized by a change in consumer behavior at the retail marketing level. The trade demand shock will be included at the feeder cattle, fed cattle and wholesale beef marketing levels. Due to the existence of a significant quantity of imports at the wholesale beef marketing level, the shock caused by export market loss will only be included as the loss of net exports. This implies an assumption that all previously imported beef will be replaced by cheaper domestic product. Computation of the trade demand shocks is discussed in detail in section 4.5 of this chapter.

Disney et al. (2001) used the value of exports as a proxy for the indirect trade-related costs of a FMD outbreak. This approach assumes the number of animals and quantity of wholesale beef originally produced for output simply disappear from the market; having no impact on domestic prices and having no impact on the surplus of domestic consumers. It is unlikely that this assumption would hold in any realistic scenario. The EDM will allow these animals that were originally produced with the expectation of being sold abroad to be introduced into the domestic market. The post-FMD live cattle and beef markets are expected to experience significant price reductions due to the inflated supply; however, the proposed model allows for the inclusion of a “consumer effect” of a change in retail beef price and the economic implications of a subsequent change in domestic consumption.

The welfare changes for each marketing level based on the effects of FMD will be calculated. Since the baseline quantities reflect annual values, this change in welfare will be divided by 365 then multiplied by the length of the FMD outbreak (as determined using the epidemiological model) plus the length of time required after the destruction of the last FMD infected animal for Canada to be considered a disease-free country and international trade can be resumed. Scenarios are constructed to reflect different levels of animal identification and movement recording. The benefits of animal traceability will be assessed by comparing the number of animals culled, the disease outbreak costs, the length of time the border remains closed and the welfare effects generated from each scenario.

This analysis only includes short-run elasticities, thus only incorporating a short-run analysis due to unavailability of long-run elasticities and the temporary nature of the loss of the export market. Pendell (2006) used both long and short-run elasticities to determine long and short-run prices, quantities and subsequent welfare effects. He found that long-run changes in consumer and producer welfare were much smaller than those found in the short-run. This is primarily the result of differences in supply and demand elasticities, representative of the ability over the long-run to more easily adjust output based on market conditions.

Table 4.1. Parameter definitions used in the economic analysis

Parameter	Definition
Q^j_i	Quantity at the *j*th marketing level in market i
P^j_i	Price at the *j*th marketing level in market i
Z^j_i	Demand shift at the *j*th marketing level in market i
W^j_i	Supply shift at the *j*th marketing level in market i
η^j_i	Own-price demand elasticity *j*th marketing level in market i
ε^j_i	Own-price supply elasticity *j*th marketing level in market i
τ^{jy}	Transmission elasticity between two marketing levels
Markets (i)	Definition
CAN	Domestic Canadian market
E	Export market
NE	Net export market
Marketing Levels (j)	Definition
r	Retail beef
w	Wholesale beef
s	Fed cattle (slaughter)
f	Feeder cattle

Note: The term y is a marketing level $\neq j$.

Table 4.2. Welfare change equations

Economic Measure		Equation
Change in consumer surplus for retail marketing level	=	$-P^rQ^r(EP^r - z^r)(1 + 0.5EQ^r_{CAN})$
Change in total producer surplus	=	$\sum^j(\Delta PS^j)$
Change in producer surplus at marketing level j	=	$P^jQ^j(EP^j - w^j)(1 + 0.5EQ^j)$

Source: Alston, Norton, and Pardey (1995)

Table 4.1 defines the model variables used in economic analysis. The retail beef, wholesale beef, fed cattle and feeder cattle marketing levels are denoted by the superscript j, defined as r, w, s, and f, respectively. Markets are depicted by the subscript i; CAN denoted as the domestic Canadian market, E denoted as the export market, and NE denoted as the net export market. When a subscript is not included, it is assumed that the parameter represents the total Canadian output level or price. Exogenous parameters also included in the model are domestic demand and supply elasticities denoted as η^j_{CAN} and ε^j_{CAN} for each market level *j*, respectively. Lastly, as described in the two previous sections, the exogenous demand and supply shifts parameters are included denoted as z^j_{CAN} and w^j_{CAN} for each market level *j*, respectively.

Consumer surplus, defined as the difference between consumers' willingness-to-pay and the actual price paid at each output level, is calculated only at the retail level. Producer surplus, defined as the difference between marginal cost and price for each level of output, is calculated at each marketing level. Producer surplus at the retail level is representative of the surplus generated by the beef retailer, most commonly the grocery store. Alston, Norton, and Pardey (1995) show changes in surplus using the equations in Table 4.2. The E term in the change in surplus equations denotes a relative change operator (i.e. $EQ^r_{CAN} = \partial Q^r_{CAN}/Q^r_{CAN} = \partial \ln Q^r_{CAN}$).

4.3 Structural Model

The research reported in this study uses an EDM framework that follows the approach used by Pendell (2006). That thesis's objective was to calculate the economic impacts associated with various animal identification and traceback scenarios in the event of a highly contagious outbreak of FMD. This research determined these impacts using a

FMD simulation for southwest Kansas, a region with a large and dense cattle population. Following the framework of Brester, Marsh, and Atwood (2004), that study included beef, pork and poultry sectors, including cross-sector linkages to account for intra-sector effects. In addition, multiple marketing levels were used within each sector, including two in the poultry sector, three in the pork sector, and four in the beef sector. Unlike that used by Brester, Marsh, and Atwood, Pendell (2006) includes beef exports and cattle imports at different marketing levels. The beef sector included farm, slaughter, wholesale beef, and retail beef marketing levels. The loss of the export wholesale beef market was assumed in the model as an effect of the onset of FMD. Feeder and fed cattle markets in the US are net importers, primarily from Mexico and Canada, respectively. These import markets were assumed to be unaffected by the change in US livestock disease-free status. Similar to Brester, Marsh, and Atwood (2004), a negative supply shock was included in the EDM to incorporate the increased costs faced by producers and the number of animals destroyed due to the FMD outbreak. Pendell (2006) derived three different scenarios that resembled low, medium and high levels of livestock traceability. The economic consequences were measured using welfare changes and were compared for each livestock traceability scenario.

Following the studies cited above, in this research supply and demand equations are created for each marketing level within the beef supply chain. The equations in Table 4.3 outline the structural model. Previous studies included pork and poultry markets; however, this study will only include a beef market model. Pork and poultry markets were excluded from this analysis due to the unavailability of primary supply elasticities for the Canadian hog and poultry markets. The implications of ignoring the cross-market effects are discussed in section 4.9.

Vertical linkages between Canadian feeder cattle, fed cattle, wholesale beef and retail beef markets are incorporated into the model through the use of quantity transmission elasticities. The quantity of exports within the structural model is treated as exogenous, due to the model's trade demand shock assumption, which assumes all exports will equal zero immediately following a FMD outbreak. Section 4.5 describes the exogenous treatment of export quantity and the trade demand shock. A primary supply equation is specified for the feeder cattle market; this equation is not dependent on any other marketing level. The derived supply equations for all other marketing levels require downstream relationships that link the supply of each marketing level to the quantity domestically available in the underlying market. For instance, fed cattle supply is related to the quantity of feeder cattle available domestically. Therefore, supply linkages in this model relate market supply to the total quantity supplied in the underlying market minus the quantity provided to that marketing level's export market.

Vertical market linkages also exist on the demand side; however, total demand (domestic + exports) is included in the intra-market demand relationships for all cases. All upstream demand linkages are related to the primary demand function for beef at the retail level. Transmission elasticities are also included to relate the output quantities in each marketing level and will be discussed in further detail below.

Table 4.3. Equation structure of the partial equilibrium model

Retail Beef Market			
Primary Domestic Demand	Q^r_{CAN}	=	$f_1(P^r_{CAN})$
Derived Total Supply	Q^r_{CAN}	=	$f_2(P^r_{CAN},Q^w_{CAN})$
Wholesale Beef Market			
Derived Domestic Demand	Q^w_{CAN}	=	$f_3(P^w_{CAN,}Q^r_{CAN})$
Net Exports	Q^w_{NE}	=	$f_4(Z^w_E)$
Total Demand	Q^w	=	$Q^w_{CAN} + Q^w_{NE}$
Derived Total Supply	Q^w	=	$f_5(P^w_{CAN},Q^s_{CAN},W^w_{CAN})$
Fed Cattle Market			
Derived Domestic Demand	Q^s_{CAN}	=	$f_6(P^s_{CAN},Q^w)$
Exports	Q^s_E	=	$f_7(Z^s_E)$
Total Demand	Q^s	=	$Q^s_{CAN} + Q^s_E$
Derived Total Supply	Q^s	=	$f_8(P^s_{CAN},Q^f_{CAN},W^s_{CAN})$
Feeder Cattle Market			
Derived Domestic Demand	Q^f_{CAN}	=	$f_9(P^f_{CAN},Q^s)$
Exports	Q^f_E	=	$f_{10}(Z^f_E)$
Total Demand	Q^f	=	$Q^f_{CAN} + Q^f_E$
Primary Total Supply	Q^f	=	$f_{11}(P^f_{CAN},W^f_{CAN})$

A further assumption is required in the wholesale beef market, where both exports and imports are present in the market. Instead of using an ‘exports’ measure, a ‘net exports’ term is included that subtracts the level of imports from the quantity exported. In order to treat the ‘net exports’ quantity as exogenous to the model, an assumption regarding effects upon imports in the case of a FMD outbreak is required. This model assumes that following a FMD outbreak, all wholesale beef imports are immediately substituted with domestic beef, as discussed in sections 4.5 and 4.9.

4.4 Outbreak Cost Supply Shift

The supply shift parameter, W^j_{CAN}, represents the negative production effects generated by the FMD outbreak at the *j*th market level. This shift is comprised of two primary impacts; the direct disease control costs that are assumed to be borne by the producer and the percentage of feeder and fed cattle destroyed. The direct disease control costs are the summation of all costs associated with disease containment and eradication. The current analysis focuses on the short-run economic impacts of a FMD disease outbreak, thus in order for direct disease control costs to shift the supply curve of the entire industry, several assumptions are required. Current policy in Canada does not require firms in the cattle industry to internalize the monetary risks of controlling a foreign disease outbreak. However, if firms were expected to internalize these uncertain costs into their production decision, the marginal cost of production would be affected due to the fact that exposure to this risk increases with the number of animals owned. The direct outbreak cost scenarios discussed in this section do not assume that a single fixed cost shock would alter the short-run marginal cost of production but reflect situations in which producers were to internalize these risks into their production decisions. The expected direct disease control costs are used, implying that all producers are risk neutral.

A partial budgeting framework will be developed to aggregate the direct short-run costs of the hypothetical disease outbreak. These direct costs include surveillance, disinfection, slaughter, and government reimbursement. In a similar framework used by Disney et al. (2001), the mean output values generated by the contagious disease spread model were used to compute these direct outbreak costs. The disease outbreak model outputs are multiplied by the per-unit costs for disinfection, slaughter, government reimbursement and surveillance costs. For clarification, slaughter costs include the removal, euthanasia and disposal of the infected herds and surveillance costs. The contagious disease spread model provides 28 output parameters in both per-animal or per-herd form (Table A.1), and when combined with the disease eradication procedures in the Canadian FMD hazard specific plan, these costs are easily calculated. The specific derivation of these costs is described in detail in section 5.2.3.

The direct disease outbreak cost shock is required by the EDM framework as a percentage change of the total market. The percentage change in the cost of supplying output in the *j*th market level, $EW^{j}_{CAN,}$ is calculated using the methodology of Pendell (2006), separately for both the disease outbreak costs and culled animal costs. Firstly, the direct disease outbreak cost impact is calculated. The total industry value is approximated for both feeder and fed cattle markets using the average animal weight multiplied by the price per animal type in $/cwt. The percentage change in cost is calculated as the direct cost of the disease outbreak divided by the total value of the industry.

Some of the most pressing questions pertain to the assignment of the direct outbreak costs. A sensitivity analysis is conducted in this thesis on various scenarios of who bears these direct outbreak costs. Three situations will be analyzed: (1) producers bear the entire cost; (2) producers split the cost with the government 50-50; and (3) government bears the entire direct control cost of the disease outbreak. In the first two scenarios, a distinction must be made with respect to which operation types should be responsible. This model will assume the costs are borne by feeder and fed cattle producers' proportional to the relative number of animals affected by FMD on each operation type. Also, because the total value of feeder and fed cattle markets are different, the direct cost impacts on the percentage change supply shifters should differ between EW^{f}_{CAN} and EW^{s}_{CAN}. Since the supply functions in the model are representative of the entire country, it may also be unrealistic to assume that producers in geographically distant regions should be financially responsible for a disease outbreak in a specific location. However, the existence of a disease-free cattle supply in Canada benefits every producer regardless of their location or production type.

It is assumed that the view of Canada’s FMD-free status as a public good among producers is the rationale that supports government funded animal health programs. However, this ignores the fact that consumers are excluded from realizing the benefits from these government funded programs. FMD-free status allows all producers in Canada the ability to trade with other FMD-free status countries regardless of their individual concern for animal health, signifying a non-excludability characteristic. An individual producer’s trade with an FMD-free status country is minimally affected by the actions of other producers. However, this would not be the case if Canadian exports did affect world prices. The perception that Canada’s FMD-free status is a public good among producers does not justify government funded programs that benefit animal health. The required non-rivalrous and non-excludability characteristics only exist among producers, whereas taxpayers are expected to subsidize the industry. This sensitivity analysis is constructed to demonstrate the economic effects of producers having to internalize the realized monetary risk of experiencing an FMD outbreak.

The portion of the supply shock caused by the destruction of animals is computed by calculating the percentage change in total animals before and after the disease outbreak. Unlike the direct cost estimates, where costs were assumed to be split equally between feeder and fed cattle producers, the NAADSM disease spread framework allows for the number of feeder and fed animals destroyed during the FMD simulation scenarios to be separated. The percentage of feeder and fed cattle destroyed in a particular traceability scenario outbreak relative to the total Canadian feeder and fed cattle supply is calculated.

4.5 Derivation of Demand Shift Parameters

A negative trade demand shift is included in the model to portray the effects of losing export markets at the feeder cattle, fed cattle and wholesale beef market levels. This model assumes an FMD outbreak in Canada would immediately halt all Canadian exports of live cattle and beef. In the feeder and fed cattle markets, the total quantity demand at each market level is assumed to equal the quantity exported to the United States plus the quantity used in the domestic market. This assumption ignores the small number of feeder animals imported from the US each year, totaling less than 0.5% of the Canadian total feeder cattle supply (Canfax 2009). For the case of the wholesale beef market, the negative trade demand shock is set equal to the total quantity of exports minus total imports, totaling net exports. Using the measure of net exports in this situation implies that domestic wholesale beef prices will drop below international market clearing prices, and imports will be completely replaced by domestic production.

The export demand price and elasticity are not included in the export demand equation due to the complete loss of this market following the disease outbreak. Previous partial equilibrium models involving a country whose trading practices impact the international price incorporate the export price as an endogenous variable. In this case, the exogenous shock of a FMD outbreak is assumed to immediately set the export price and quantity equal to zero. When EDMs incorporate international trade, a new export quantity would be computed based on the relative changes in foreign and domestic prices. In a situation where exports are disallowed entirely, the production decision, domestic price, export quantity and domestic demand are not correlated to the international price.

This renders the inclusion of an export price and the subsequently required export demand elasticity as irrelevant in the current model. If domestic prices were to increase to a level higher than the international price following a FMD outbreak, foreign prices would then become a factor due to the existence of imports into the supply chain. In addition, in many countries such as China, India and Russia, FMD is endemic to the domestic livestock population. This model also assumes that trade with countries that have a positive FMD status will not occur.

It is important to note that since the export market is not modeled in this framework, an accurate calculation of the change in consumer demand is possible at the retail level only because of the absence of exports in this market. By excluding information regarding the slope of the total demand curve from feeder, fed and wholesale beef markets, changes in welfare can only be computed beneath the price line. The initial baseline quantity in the feeder, fed and wholesale beef markets is included only as a point of reference to compute producer surplus. For these markets, only the slope of the domestic demand function is needed to determine the changes in price and quantity. In the retail beef market, the total demand function is required to determine consumer surplus changes; however, total demand is equal to domestic demand in this market.

4.6 Percentage Change Equations

Within the percentage change equations, the domestic and export market quantity fractions are exogenous to the EDM. These fractions represent the portion of the total demand either consumed domestically or exported as a fraction of total market output. These fractions are included for the purpose of relating percentage changes in either situation to the total demand.

Table 4.4. Percentage change equation structure

Retail Beef		
EQ^r_{CAN}	=	$\eta^r_{CAN} EP^r_{CAN}$
EQ^r_{CAN}	=	$\varepsilon^r_{CAN} EP^r_{CAN} + \tau^{rw}(Q^w_{CAN} / Q^w) EQ^w_{CAN}$
Wholesale Beef		
EQ^w_{CAN}	=	$\eta^w_{CAN} EP^w_{CAN} + \tau^{wr} EQ^r_{CAN}$
EQ^w_{NE}	=	Ez^w_{NE}
EQ^w	=	$(Q^w_{CAN} / Q^w) EQ^w_{CAN} + (Q^w_{NE} / Q^w) EQ^w_{NE}$
EQ^w	=	$\varepsilon^w_{CAN} EP^w_{CAN} + \tau^{ws}(Q^s_{CAN} / Q^s) EQ^s_{CAN} + Ew^w_{CAN}$
Fed Cattle		
EQ^s_{CAN}	=	$\eta^s_{CAN} EP^s_{CAN} + \tau^{sw} EQ^w$
EQ^s_E	=	Ez^s_E
EQ^s	=	$(Q^s_{CAN} / Q^s) EQ^s_{CAN} + (Q^s_E / Q^s) EQ^s_E$
EQ^s	=	$\varepsilon^s_{CAN} EP^s_{CAN} + \tau^{sf}(Q^f_{CAN} / Q^f) EQ^f_{CAN} + Ew^s_{CAN}$
Feeder Cattle		
EQ^f_{CAN}	=	$\eta^f_{CAN} EP^f_{CAN} + \tau^{fs} EQ^s$
EQ^f_E	=	Ez^f_E
EQ^f	=	$(Q^f_{CAN} / Q^f) EQ^f_{CAN} + (Q^f_E / Q^f) EQ^f_E$
EQ^f	=	$\varepsilon^f_{CAN} EP^f_{CAN} + Ew^f_{CAN}$

Note: The term E denotes a percentage change operator, e.g. $EQ^r_{CAN} = \partial Q^r_{CAN} / Q^r_{CAN} = \partial \ln Q^r_{CAN}$.

The percentage change equations were derived from total differentiating the structural model. The E term represents a percentage change operator, e.g. $EQ^r_{CAN} = \partial Q^r_{CAN} / Q^r_{CAN} = \partial \ln Q^r_{CAN}$. It is important to note that the percentage change equations relate changes amongst the models endogenous variables. As an example for clarification, the first equation in the framework below asserts the percentage change in the quantity of retail beef is equal to the domestic demand elasticity multiplied by the percentage change in the domestic price of retail beef. The system of supply and demand equations in Table 4.4 represents the EDM framework.

These percentage change operators can be rearranged to form equations that can be easily converted to matrix form. It is important to note that when the elasticities are moved to the left hand side of the equation, they must be included in the later described matrix as a negative value. Negative own-price demand elasticities will subsequently become positive in the matrix.

Table 4.5. Re-arrangement of percentage change equations for matrix form

Cattle Market Equations		
$EQ^{s}_{CAN} - \eta^{s}_{CAN} EP^{s}_{CAN} - \tau^{sw} EQ^{w}$	=	0
EQ^{s}_{E}	=	Ez^{s}_{E}
$EQ^{s} - (Q^{s}_{CAN} / Q^{s}) EQ^{s}_{CAN} - (Q^{s}_{E} / Q^{s}) EQ^{s}_{E}$	=	0
$EQ^{s} - \varepsilon^{s}_{CAN} EP^{s}_{CAN} - \tau^{sf} (Q^{f}_{CAN} / Q^{f}) EQ^{f}_{CAN}$	=	Ew^{s}_{CAN}
$EQ^{f}_{CAN} - \eta^{f}_{CAN} EP^{f}_{CAN} - \tau^{fs} EQ^{s}$	=	0
EQ^{f}_{E}	=	Ez^{f}_{E}
$EQ^{f} - (Q^{f}_{CAN} / Q^{f}) EQ^{f}_{CAN} - (Q^{f}_{E} / Q^{f}) EQ^{f}_{E}$	=	0
$EQ^{f} - \varepsilon^{f}_{CAN} EP^{f}_{CAN}$	=	Ew^{f}_{CAN}
Beef Market Equations		
$EQ^{r}_{CAN} - \eta^{r}_{CAN} EP^{r}_{CAN}$	=	0
$EQ^{r}_{CAN} - \varepsilon^{r}_{CAN} EP^{r}_{CAN} - \tau^{rw} (Q^{w}_{CAN} / Q^{w}) EQ^{w}_{CAN}$	=	0
$EQ^{w}_{CAN} - \eta^{w}_{CAN} EP^{w}_{CAN} - \tau^{wr} EQ^{r}_{CAN}$	=	0
EQ^{w}_{NE}	=	Ez^{w}_{NE}
$EQ^{w} - (Q^{w}_{CAN} / Q^{w}) EQ^{w}_{CAN} - (Q^{w}_{NE} / Q^{w}) EQ^{w}_{NE}$	=	0
$EQ^{w} - \varepsilon^{w}_{CAN} EP^{w}_{CAN} - \tau^{ws} (Q^{s}_{CAN} / Q^{s}) EQ^{s}_{CAN}$	=	Ew^{w}_{CAN}

Note: The term E denotes a percentage change operator, e.g. $EQ^{r}_{CAN} = \partial Q^{r}_{CAN} / Q^{r}_{CAN} = \partial \ln Q^{r}_{CAN}$.

A system of equations that depicts the relationship between marginal changes in the model's endogenous variables, percentage changes of the systems endogenous variables can be derived. The relative change equations in Table 4.4 are rearranged to become the equations in Table 4.5 to then be converted into matrix notation. Using the matrix algebra framework from Piggott, Piggott, and Wright (1995), Brester, Marsh, and Atwood (2004), Pendell (2006), and Pendell et al. (2010), the equations in Table 4.5 can be written in matrix notation as A·B=C, where A is an {14x14} matrix of elasticities depicting the relationships between all endogenous variable changes, B is a {14x1} vector of changes to the price and quantity variables given different exogenous shock scenarios, and C is a {1x14} vector of exogenous supply and export demand shifters determined within the epidemiological model. Matrix notation allows for the derivation of the changes in all endogenous variables given different changes in the exogenous shock variables z^j_i and w^j_i. Solving for vector B, the equation becomes $B= A^{-1} \cdot C$.

4.7 Elasticities

In order to construct the relative change system of equations in Table 4.4, supply, demand and quantity transmission elasticities are required. Quantity transmission elasticities are simply a statistical relationship between output levels across marketing levels. The derivation of these parameters is conducted using time-series output data from two marketing levels in a regression framework. The choice to use short-run supply and demand elasticity estimates in this study is made due to the dynamics of the FMD outbreak economic consequences. Preliminary results from the FMD spread model have produced disease outbreaks with durations that do not exceed six months. The World Organization for Animal Health (OIE) has recommended that no FMD-susceptible products or animals be exported for three months following the destruction of the last infected animal (OIE 2009). Since the supply and trade demand shocks are temporary, a long-run analysis using long-run elasticities cannot be justified. Using a static form of an EDM only depicts the immediate short-run effects of the outbreak. The model framework described in this chapter investigates how output and prices will respond based on elasticity relationships derived from FMD-free conditions, prompting the need to investigate model sensitivity of the elasticity estimates.

4.8 Sensitivity Analysis

EDMs are heavily reliant upon the accuracy of the supply and demand elasticity parameters. For the purpose of providing a robust analysis, all elasticities used in the model will be increased and decreased by fifty percent. This analysis will create four elasticity scenarios, including; all supply functions become 50% more inelastic, all demand functions become 50% more inelastic, all supply functions become 50% more elastic, and all demand functions become 50% more elastic. The value of 50% was arbitrarily chosen to represent the relative importance of the accuracy of the elasticity measures used in the EDM. This sensitivity analysis will be conducted due to discrepancies in the time-frames used to derive each elasticity estimate. The next chapter will discuss the sources of all of the elasticities used in the study. Optimally a Monte Carlo simulation would be conducted, using the elasticity estimates explained in chapter 5 as the central tendency in a distribution. A stochastic economic consequence model was not employed in the current analysis; however, investigating model sensitivity with regards to the elasticity estimates is of considerate value.

4.9 Model Limitations and Assumptions

EDMs employ the use of linear approximations of unknown supply and demand functions. This requires several assumptions regarding production conditions, market aggregation and product homogeneity. As stated by Muth (1964), the EDM requires that the production function of each individual firm and the market as a whole is homogenous of degree one relative to all production inputs. This implies that the production technology has constant returns to scale for all firms. In addition, to ignore aggregation problems, firms are assumed to have identical production functions and the productivity of input factors are regarded as equal across firms. According to Muth, these conditions imply that the average cost curve for each firm is the same.

The primary domestic beef demand equation (4.4) implies that the cross-price elasticities between the direct substitutes of beef are zero. This is a limiting assumption due to the fact that a FMD will also affect the pork market, surely resulting in changes of the pork retail price. According to Statistics Canada (2010), over 5 million head of swine were exported to the US in 2003, a shock in domestic demand similar to that investigated in this study. Pendell (2006) and Brester, Marsh, and Atwood (2004) both included both pork and poultry markets to include this effect. These markets were excluded from this investigation for reasons explained above. The effect of not including these cross market effects depends on the severity of the expected decline in retail pork prices in the event of a FMD outbreak. In addition, in the case that beef prices experience a substantial decline, consumers would alter their consumption bundle by reducing the quantity of poultry consumed and increasing the amount of beef consumed. This would result in a positive shift on the primary domestic beef demand function. The retail price changes modeled in this framework ignore this effect.

Lastly, it is important to note that the EDM provides a poor framework for the computation of total consumer and producer surplus. This problem stems from the assumed linear form of supply and demand functions. Calculation of the changes in consumer and producer surplus can only be accurately computed when the distance from the original data derived baseline values are minimal. The further the model strays from these baseline prices and quantities, the more reliant it becomes on the accuracy of supply and demand elasticities. The degree of non-linearity of the true supply and demand functions also affects the accuracy of surplus change measures. Wohlgenant (1993) advised that shocks must be small for the EDM to accurately predict endogenous variable changes. This recommendation was the motivation for using net exports as the trade demand shock for the wholesale beef market. This required a further assumption that imported beef would be replaced with domestic beef; this is seen as minor relative to including a negative trade demand shock that exceeded one third of the Canadian wholesale beef market.

Chapter 5 Model Data

5.1 Epidemiological Model Data

The NAADSM framework requires extensive herd demographic, disease attribute, and livestock movement data. In addition, parameter estimates are also needed to model disease detection, disease control strategies and animal tracing capabilities. This section describes the parameterization of the disease spread model, also identifying the source of each model input. Although disease spread models have been previously used by the CFIA to model disease outbreaks in the Ontario livestock population, the parameters employed were not publically available. Many of the disease spread model parameters are spatially sensitive, prompting the need for Ontario-specific data. An example of this region-specific data is the Ontario herd demographic information. The following section describes the use of and sources of all data and parameter estimates obtained for use in the FMD spread model.

Snowball sampling was used to select an expert whom could provide the best disease control parameter estimates for the NAADSM FMD spread model framework. This technique involves the selection of a group of professionals in the industry, which of whom are then asked to identify an individual who would have the most accurate opinion of a particular incident. In this study, senior staff members in both Agriculture Canada and the Canadian Food Inspection Agency were contacted and follow-ups were conducted of those experts recommended by these individuals. This method of selecting an expert to provide parameter estimates for the model was recommended in Garabed et al. (2009). According to the authors, this process ensures that the final selection of an expert is not directly determined by the researcher.

5.1.1 Herd Demographics

Herd demographic data is required by NAADSM to incorporate spatial considerations in the models' indirect contacts, direct contacts, zone controls, and the probability of airborne disease spread. The specific demographic data required by the model is the geographical coordinates and herd size of every; cow-calf, feedlot, dairy and swine operation. This data was only available in Ontario for dairy operations, provided by the Dairy Farmers of Ontario organization (Lane 2009). Therefore, an estimation procedure was needed to approximate the distribution of both beef cattle and swine operations, as well as the distribution of animals among these operations.

An approximation technique that utilized 2006 Census of Agriculture data combined with geographical information system software was implemented. This technique required data on the total number of operations and animals within each of Ontario's census division districts. The 2006 Census of Agriculture divided Ontario into over 250 districts, providing the number of operations (for each operation type) and the total number of animals for each district. Statistics Canada also provides geographical information system boundary files that create a layer of polygon shapes that represent each of these census districts in geographical space. Using the geographical information system software package ArcGIS®, the boundary file and the number of operations within each district, a random point generator created a number of geographical points in each boundary equal to the number of operations for each production type. This process was further refined using an ArcGIS® add-on program called "Hawth's Analysis Tools" that enabled the inclusion of a geographical layer where points could be excluded. Due to the inclusion of several large bodies of water in the Statistics Canada census division boundary file, a “lakes, rivers and streams” layer was used to prohibit the creation of geographical points in major bodies of water. Although the use of census divisions limit the number of points generated in urban areas, future research should use a geographical information systems program that can include multiple geographical layers that restrict the creation of data points in areas where cattle farms cannot exist (urban areas, national parks, etc.).

Following the creation of a number of geographical points equal to the number of operations in each census division, an assumption was required that the number of animals on each operation is equal to the average number of animals per operation within each census division. The 2006 Census of Agriculture included several regional data amalgamations for the purpose of respecting farmer privacy. A total of 70 census divisions were amalgamated into 20 representative regions; however, the data regarding the number of operations in each individual region was still available. Since only the total number of animals in these amalgamations was provided, the average number of animals in the amalgamated district was used for each component of the amalgamation. This is the most commonly used practice within the CFIA and USDA for estimating livestock demographic data at the time of writing; however, improvements can be made. If statistical measures were available concerning the distribution of animals within each region, the uniformity created by assuming the number of animals on each operation is equal to the average could be relinquished.

5.1.2 Disease Spread Parameters

The parameters used in NAADSM to determine the rate of disease spread includes the direct animal contact rate, the indirect contact rate, and the herd-level disease state durations. The direct animal contact rates were obtained from an average of a survey of Ontario livestock auction houses and the parameters used by the CFIA in a NAADSM model of a FMD outbreak in the Maritimes. Due to the non-existence of a formal publication of the CFIA Maritime FMD model, the parameters adopted from this model have been referenced as personal communication with the model designer, Dr. Emery Leger, a senior veterinarian with the CFIA. The data used in the CFIA Maritimes study were obtained based on expert opinion within the Canadian animal health community and industry personnel. The Ontario livestock auction house survey obtained estimates from four of the seven auction house managers surveyed. The questions regarded the frequency of animal shipments between different operation types. The survey was implemented to account for differences in livestock industry practices between the Maritimes and Ontario.

The medium and high direct contact rates are displayed in Table 5.1.1, representing the number of animals per day that come in contact with a particular recipient operation type. The high estimate was calculated in a similar fashion to the high contact estimate used in the CFIA Maritimes study, multiplying the data derived medium contact rate estimates for each production type combination by 2.5. The contact rate among dairy operations was obtained from the academic literature. Dubé et al. (2008) provided an estimated direct animal contact rate among dairy farms that was nearly eight times greater then what was found by the auction house survey and the Maritime parameters. This finding signifies the possibility of underestimations of the direct contacts among all operations; a disease spread parameter that greatly impacts the effects of animal traceability on the outbreak result. The number of days between contacts

(DBC) is calculated from the contact rate to illustrate the contact frequency in a more comprehensible form.

Table 5.1.1. Direct contact spread parameters used in epidemiological model

Source To Recipient	Direct Contact Rate*		DBC** (days)	Distance Distribution (km)
Dairy to dairy[a]	Medium	0.0790	13	BetaPERT(1,150,700)
	High	0.1975	5	
Dairy to cow-calf	Medium	0.0039	256	BetaPERT(1,150,700)
	High	0.0098	103	
Dairy to feedlot	Medium	0.0710	14	BetaPERT(1,150,700)
	High	0.1775	6	
Cow-calf to cow-calf	Medium	0.0115	87	BetaPERT(1,150,700)
	High	0.0288	35	
Cow-calf to feedlot	Medium	0.0038	263	BetaPERT(1,150,700)
	High	0.0095	105	
Feedlot to feedlot	Medium	0.0029	350	BetaPERT(1,150,700)
	High	0.0072	140	
Swine to swine	Medium	0.0340	29	BetaPERT(1,50,100)
	High	0.0850	12	

Notes: * Number of direct animal contacts per herd per day. ** Number of days between each contact for an average sized operation.

The distance distribution function represents the distance direct animal contacts travel from the source operation. Due to the spatial differences between Ontario and the Canadian Maritime provinces, this parameter was modified to include a longer positive tail. The maximum distance traveled used by the maritime study was 600km, whereas this was extended for all cattle operation types to 700km in the Ontario model. Swine direct contact distance distribution data was taken directly from the Maritime model.

Table 5.1.2 illustrates the indirect contact rates and distance distributions between the various operation types. Indirect contact rates and distance distributions were adopted directly from the CFIA study conducted in the Maritimes. The 'high' estimates were used for this study. Multiple scenario analysis for this parameter could not be conducted due to time constraints. The indirect contact rate signifies the frequency of non-animal contacts between herds, most commonly in the form of veterinarians, maintenance personnel, and milk collection trucks.

Table 5.1.2. Indirect contact spread parameters used in epidemiological model

Source to recipient	Indirect Contact Rate*	DBC** (days)	Distance distribution (km)
Dairy to dairy	3.5350	< 1	30
Dairy to cow-calf	0.0950	11	30
Cow-calf to Dairy	0.0950	11	30
Cow-calf to cow-calf	0.0350	29	30
Cow-calf to feedlot	0.0650	15	30
Feedlot to cow-calf	0.0650	15	30
Feedlot to feedlot	0.8000	1	30
Swine to swine	0.5000	2	30

Notes: * Number of indirect contacts per herd per day. ** Number of days between each contact for an average sized operation.
Source: Personal Communication with Emery Leger of the CFIA.

Unlike the case of direct contacts, the distance distribution for indirect contacts is much shorter, resulting in much more localized indirect spread. Unlike in the case of direct contacts, the distance distribution function is a point estimate of 30km.

Assuming direct or indirect contact is made between a diseased source and a susceptible recipient does not ensure successful disease transmission. NAADSM also requires a “probability of infection transfer” parameter. The NAADSM framework allows for the prevalence of FMD within a herd to affect this probability each time a contact is made, however insufficient data was available to include this into the Ontario framework. A relative frequency of disease graph is required to display the relationship between the percentage of animals infected within a herd and the number of days the herd has been infected. Therefore, a probability of infection transfer parameter was assigned for both direct and indirect contacts. The probability used for direct and indirect contacts was chosen to be 0.95 and 0.2 respectively. These parameters were adopted from Ward et al. (2009), although no data source is provided in this study to justify the parameter selection. Similar parameter estimates of 0.89 and 0.1 were used in Pendell (2006).

Animal level disease state durations were obtained primarily from the literature and displayed in Table 5.1.3. These animal level disease state durations were assumed to be equal to the herd-level disease state due to the construction of the epidemiological model. As described earlier in chapter 4, the disease state of the entire herd is reclassified when a single animal progresses disease states. The only situation where this is not true is the transition from clinically infectious to naturally immune. This is due to the fact the herd remains infectious regardless of the fact a single animal has made the transition to the naturally immune stage.

Table 5.1.3. Duration of animal-level disease states

Disease State	Production Type	Duration of State (days)
Latent	Cattle	Gaussian (4.1,1.1)[a]
	Swine	Gaussian (1.2,0.5)[b]
Subclinical	Cattle	Gaussian (2.2,0.8)[a]
	Swine	Gaussian (1.1,0.7)[b]
Immune Period	Cattle	BetaPERT (180,270,360)[c]
	Swine	BetaPERT (180,270,360)[c]

Sources: [a] Alexanderson (2003), Bouma (2004), Cox (2005,2006) [b] Alexanderson (2003), Eble (2004,2006,2007), Orsel (2007) [c] Personal communication with Dr. Emery Leger

Due to the previously mentioned drawbacks of using an animal-level clinically infectious disease state, a herd-level clinically infectious state is required. This parameter would depend on the individual animals' level clinically infectious disease state, the livestock operations' configuration and the number of animals on the operation. Each operation type implies a different internal arrangement of animals, thus affecting the ability for disease to spread within the herd. Aaron Reeves at Colorado State University designed a "within-herd prevalence model" to determine the length of the herd-level clinically infectious disease state given assumptions about internal animal-to-animal contacts, herd size and the number of animals initially infected (Reeves 2010). This non-spatial "susceptible-infected-immune" model does not exist in the academic literature; however, it has been used by the USDA and CFIA to derive herd-level clinically infectious disease states. Table 5.1.4 displays the results of the "within-herd prevalence model" model for the CFIA epidemiological model of the Maritimes. Although the herd size distributions for Ontario and the Maritimes are not identical, these estimates were deemed appropriate for use in Ontario by CFIA personnel.

Table 5.1.4. Duration of herd-level clinical disease states

Production Type	Duration of Clinical State (days)	Assumptions	
Cow-calf	BetaPERT (12,18,27)	Herd Size:	BetaPERT (16,52,70)
		Initially infected:	Uniform (1,3)
		Effective Contact Rate:	BetaPERT (0,2,10)
		Number of Iterations:	1000
Feedlot	BetaPERT (9,18,25)	Herd Size:	BetaPERT (12,251,1618)
		Initially infected:	Uniform (1,3)
		Effective Contact Rate:	BetaPERT (2,10,25)
		Number of Iterations:	1000
Dairy	BetaPERT (14,23,34)	Herd Size:	BetaPERT (11,90,211)
		Initially infected:	Uniform (1,3)
		Effective Contact Rate:	BetaPERT (1,2,4)
		Number of Iterations:	1000
Swine	BetaPERT (12,16,20)	Herd Size:	BetaPERT (2,654,1833)
		Initially infected:	Uniform (1,3)
		Effective Contact Rate:	BetaPERT (10,20,30)
		Number of Iterations:	1000

Source: Personal Communication with Aaron Reeves of the USDA and Dr. Emery Leger of the CFIA.

Previous studies have obtained the disease state durations directly from expert opinion. Ward et al. (2009) surveyed ten animal health experts and obtained a 50% response rate.

The five experts that responded provided estimates for the duration of herd-level disease states to create a triangular distribution for the state durations. The median of the five survey responses are similar to the disease state durations used in the current study.

Airborne disease spread parameters were adopted from the CFIA Maritime study and are similar to those used in Pendell (2006). Unlike the AusSPREAD model used by Ward et al. (2009), the NAADSM framework does not included such factors as temperature and humidity. The only atmospheric condition included in NAADSM that impacts airborne disease spread is wind direction, assumed in this model to be completely random. The probability of airborne spread at 1km from the source is 0.01, taken from the CFIA Maritime model’s high estimate. The NAADSM framework allows this probability to decline exponentially or linearly from the source. Following Pendell (2006) and the CFIA’s Maritime model, the exponential option was selected. These NAADSM parameters are listed in Table A.2 in the appendix. Pendell (2006) assumed the probability of airborne spread at 1km to be 0.02, a higher estimate than used in the Maritimes, due to the difference in climate between the Canadian Maritime provinces and the US state of Kansas. The Ontario climate is assumed to be closer in relation to the Canadian Maritime provinces, prompting the use of 0.01. It must be noted that in theory and practice this parameter is greatly related to the season in which the outbreak occurs.

Aside from the airborne spread parameters used in the model, Table A.2 in the appendix includes several other important parameters required by the NAADSM framework. These parameters were all adopted from the CFIA’s Maritime NAADSM model. Included in this table is the shipping delay for both direct and indirect contacts, assumed to be 24 hours in both instances. This parameter is required by NAADSM to approximate the length of time required for animals or indirect contacts to transition from one premise to another. Similarly, an airborne transport delay is also included as 24 hours, signifying the length of time it takes for the disease agent to travel from an infected farm to a susceptible farm. The final NAADSM disease spread input is the ability of latent units to cause infection by direct contact. As mentioned earlier in section 3.6, when a latent unit is transferred from one premise to another, successful disease spread should result, regardless of the fact the animal is not currently in a contagious disease stage. NAADSM models this scenario of disease transmission as an immediate infection of the susceptible herd, regardless of the fact that a delay should exist, equal to the time required for the latent animal to progress to an infectious state. The use of this setting in the NAADSM framework is recording in Table A.2 in the appendix.

5.1.3 Disease Control Parameters

Several relational functions are required by the NAADSM framework to illustrate the probability of observing clinical signs, probability of reporting FMD disease, herd destruction capacity, and the effectiveness of movement restrictions. Table 5.1.5 depicts the probability of a livestock operator observing the clinical signs of FMD as a function of the number of days an animal has been in the clinical disease state. The clinical signs of FMD are commonly mistaken for symptoms of other animal diseases and conditions, as was the case in the recent FMD outbreak in Japan. This relational function varies among operation types due to different levels of attention by farm operators to the individual animals. These parameters are represented in Table 5.1.5, and were adopted from the CFIA Maritime study data.

Table 5.1.5. Relation functions of the probability of observing clinical signs

Production Type	Number of Days in Clinical State	Probability of Observing Clinical Signs
Dairy	0	0
	1	0.8
	2	0.9
	6	0.99
Feedlot	0	0
	1	0.8
	2	0.9
	6	0.99
Cow-calf	0	0
	2	0.5
	3	0.6
	5	0.8
	6	0.99
Swine	0	0
	1	0.8
	2	0.9
	6	0.99

Source: Personal Communication with Dr. Emery Leger of the CFIA.

A relational function is also required to identify the probability of an operation manager reporting the disease outbreak to CFIA officials. These parameters illustrated in Table 5.1.6 were also adopted from the CFIA Maritime study. It is assumed that the probability of reporting the existence of FMD is equal across all production types. Similarly to the probability of a farmer observing clinical signs, this function depicts further farmer uncertainly regarding the animals' condition. This uncertainly exists because since farm operators do not have the ability to directly test animals for FMD.

Table 5.1.6. Relational function of the probability of reporting disease

	Number of Days Following Disease Detection	Probability of Reporting Disease
All production types	0	0.7
	5	0.99

Source: Personal Communication with Emery Leger of the CFIA.

The herd destruction capacity is also an important NAADSM parameter used to reflect the ability of the CFIA to disinfect, destroy and dispose of infected herds. Table 5.1.7 displays the relational function of how the destruction capacity of an average sized herd increases in the days following initial FMD detection. These parameters were adopted from the CFIA Maritime study. It was originally assumed that Ontario would have a higher destruction capacity relative to the Maritime Provinces, due to Ontario's central location in Canada, differences in CFIA resources and differences in livestock populations. The leader of the CFIA's 'Humane Destruction Working Group" was contacted with regard to this matter.

Table 5.1.7. Destruction capacity relational function

Number of days following outbreak detection	Number of herds destroyed per day
1	0.5
2	1
3	1.5
4	3

Source: Personal Communication with Brad Gesinghaus, leader of the CFIA's humane destruction working group.
Note: Destruction capacity remains constant at 3 after 4 days

This individual believed that the destruction capacity in Ontario would be the same as that used in the CFIA Maritime model. The relational function assumes that the herd destruction capacity reaches a maximum of three average sized herds per day, four days after initial disease detection. Greathouse (2010) also used a destruction capacity of three herds per day in a US outbreak simulation. The NAADSM framework assumes the destruction capacity is equal across production types.

The NAADSM framework also requires information regarding what herds take priority for destruction during an outbreak. This information was extracted from the Canadian FMD contingency plan on the CFIA's website. The priority sequence for production type is as follows; swine, feedlot, and cow-calf. This sequence is justified by the production types relative disease spread capabilities. If two farms of the same production type are awaiting destruction, the herd that has been positive for FMD the longest will be culled first. The herd destruction delay is listed in the appendix in Table A.2. This delay of 24 hours depicts the length of time following outbreak detection required to mobilize CFIA personnel and equipment. As mentioned earlier in this section, the destruction capacity relational function signifies further personnel and equipment mobilization (disinfectants, bio-gear, etc.) in the days following initial disease detection. The identification and construction of adequate animal disposal sites are also factored into this estimate.

The Canadian Hazard Specific Plan for FMD identifies the use of movement control zones around FMD infected premises. As identified in chapter 3 of this paper, this disease control measure includes the creation of infected, restricted and security zones. The effectiveness of zoning on reducing animal movements and indirect contacts are displayed in Table 5.1.8. Direct and indirect contact rates of operations within these zones are multiplied by the percentage of movements still permitted given the number of days following zone creation. These movement restriction estimates were obtained from the CFIA's Maritime study.

Table 5.1.8. Relation functions of the effectiveness of movement restrictions

Movement Restriction	Number of Days Following Zone Creation	Percentage of Movements Permitted
Direct contacts in disease free and security zones	0	100%
	1	25%
	5	5%
Indirect contacts in disease free and security zones	0	100%
	1	60%
	5	30%
Direct contacts in infected zone	0	5%
	1	3%
	2	0%
Indirect contacts in infected zone	0	10%
	1	5%
	2	3%
Direct contacts in restricted zone	0	100%
	1	13%
	5	3%
Indirect contacts in restricted zone	0	100%
	1	30%
	5	15%

Source: Personal Communication with Dr. Emery Leger of the CFIA.

These parameter estimates heavily impact the number of direct and indirect contacts in the disease spread simulation, subsequently impacting the effectiveness of livestock traceability on the outbreak results. Therefore, a scenario will be included in the study to gauge the sensitivity of these parameters on the effect of animal traceability. Table A.3 in the appendix displays parameters for a situation where the original effectiveness of direct and indirect movement controls are reduced by one half. These parameters also include the situation where direct contacts in the infected zone cannot be controlled entirely and 1% of the original movement is still permitted.

5.1.4 Traceability Scenarios

The probability of successfully tracing an indirect contact was held constant across all traceability scenarios at 50% for all production types, equal to the parameter chosen for the CFIA Maritime model. Pendell (2006) assumed that the level of animal identification and recording system would affect the tracing of indirect contacts. The current study assumes that the probability of a successful indirect contact would be impacted by individual farm-level and farm-related personnel record keeping practices rather than by the animal identification and movement recording system. NAADSM is a herd-based model, and indirect contacts between herds are modeled as contact between premises that do not directly involve the movement of animals. When a veterinarian, milk-truck, or maintenance individual completes an indirect contact between an infected and susceptible herd, this study assumes that the probability of successfully tracing that contact would be independent of the animal identification system. This implies that the animal identification system only stores information regarding individual animals' current and previous premises. If the traceability system also linked indirect contacts with the premise, the animal identification and movement recording system would impact the ability to trace indirect contacts. This assumption significantly reduces the impact of the traceability system on controlling the disease outbreak.

Three scenarios were used in this study to represent different levels of animal identification and recording systems. The NAADSM parameter that reflects the probability of a successful trace following an animal movement between herds was set to;

30% for low, 60% for medium and 95% for high. Pendell (2006) used the same set of parameters; however, the high estimate used in the study was 90%. The current paper uses the parameter of 95% to reflect the high traceability scenario due to the parameterization of the CFIA Maritime model. Since the current study is designed to deduct the benefit of an animal traceability system for cattle, the probability of a successful trace was held constant for swine operations at 95% for all scenarios. The parameter used in the model for the probability of a successful trace for swine was adopted from the CFIA Maritime model.

Figure 5.1. Density of cattle and calves in Southern Ontario

Note: Number of beef cattle and calves per hectare of farm land.
Source: Statistics Canada (2010). Original figure produced by Remote Sensing and Geospatial Analysis, Agriculture Division, Statistics Canada, 2010.

The epidemiological model used in this study will generate a FMD disease outbreak originating in the most heavily populated livestock region of Ontario. The spread model will assume that the disease is introduced into a dairy operation in the general proximity of Listowel, Ontario. As displayed in Figure 5.1, this region of Ontario has the highest number of cattle and calves per-acre. In terms of cattle density, this region is only contested by small areas in Alberta and British Columbia. The cattle and calf density for all of Canada is illustrated in Figure 5.2. Similar representations are also included in this paper for swine, displayed in Figure A.1 and Figure A.2. Manitoba and South-Eastern Quebec are the only provinces that have areas of higher swine density relative to South-Eastern Ontario. Although not included as a figure in this paper, visual representations of the density of dairy animals illustrate that the areas surrounding Listowel and Ottawa are among the most populated dairy cow regions in Canada, challenged only by South-Eastern Quebec and South-Western British Columbia. The location selected as the FMD disease introduction site has high concentrations of dairy cattle, beef cattle and swine relative to the rest of Ontario and Canada.

Figure 5.2. Density of cattle and calves in Canada

Note: Number of beef cattle and calves per hectare of farm land.
Source: Statistics Canada (2010). Original figure produced by Remote Sensing and Geospatial Analysis, Agriculture Division, Statistics Canada, 2010.

5.2 Economic Model Data

The data required for the calculation of the direct costs of a FMD outbreak and the resulting welfare changes includes elasticity parameters, baseline domestic output levels, baseline prices and the per-unit disease control cost estimates. The following section will outline the parameters and data implemented for the economic sections of this analysis. Data sources and the implications of parameter use will also be addressed in this section.

5.2.1 Elasticities

The equilibrium displacement model requires supply and demand elasticities for each marketing level in the beef supply chain. Supply and demand elasticities are thus required for Canadian; feeder cattle, fed cattle, wholesale beef and retail beef markets. Table 5.2.1 illustrates the elasticity parameters used in the economic analysis. Many of these estimates were derived from US market data due to the inexistence of these parameters for the Canadian market. The availability of elasticity estimates that are derived from Canadian data is limited to the own-price elasticity for retail beef demand and the own-price elasticity for feeder cattle supply. The availability of these estimates is important because Canadian retail beef demand and Canadian feeder cattle supply represent the primary functions of the partial equilibrium model, while the remaining supply and demand equations represent derived functions. Furthermore, all derived supply and demand functions are dependent on primary functions, strengthening the model's relationship to the Canadian context.

Due to the inexistence of Canadian quantity transmission elasticity estimates, the current study assumes that quantity transmission elasticities are equal between Canada and the US. This parameter is included to allow for non-fixed proportions technology. The quantity transmission elasticity relates changes in output quantities at the various marketing levels to the quantity changes in both the primary feeder cattle supply and the primary retail beef demand functions.

Table 5.2.1. Short-run elasticity definitions, sources, and values

Parameter	Definition	Value
η^{r}_{CAN}	Own-price elasticity for Canadian retail beef demand[a]	-0.23
η^{w}_{CAN}	Own-price elasticity for wholesale beef demand[b]	-0.57*
η^{s}_{CAN}	Own-price elasticity for fed cattle demand[c]	-0.6*
η^{f}_{CAN}	Own-price elasticity for feeder cattle demand[c]	-0.887*
ε^{r}_{CAN}	Own-price derived retail beef supply elasticity[d]	0.36*
ε^{w}_{CAN}	Own-price derived wholesale beef supply elasticity[d]	0.28*
ε^{s}_{CAN}	Own-price derived Canadian fed cattle supply elasticity[c]	0.26*
ε^{f}_{CAN}	Own-price derived Canadian feeder cattle supply elasticity[a]	0.2
τ^{rw}	% change in retail beef quantity given a 1% change in wholesale beef quantity[e]	-1.02*
τ^{wr}	% change in wholesale beef quantity given a 1% change in retail beef quantity[e]	-1.03*
τ^{ws}	% change in wholesale beef quantity given a 1% change in fed cattle quantity[e]	-0.94*
τ^{sw}	% change in fed cattle quantity given a 1% change in wholesale beef quantity[e]	-1.02*
τ^{sf}	% change in fed cattle quantity given a 1% change in feeder cattle quantity[e]	-0.97*
τ^{fs}	% change in feeder cattle quantity given a 1% change in fed cattle quantity[e]	-0.78*

Note: * Elasticities were unavailable for Canada and are assumed to be the same as the US.
Sources: [a] FAPRI (2010); [b] Marsh (1992); [c] Marsh (1994); [d] Brester, Marsh, and Atwood (2004); [e] Pendell (2006)

The quantity transmission elasticities reflect the percentage change in the quantity of a specific marketing level given a 1% change in quantity in an adjacent market level. These parameters are included in Table 5.2.1, derived by Pendell (2006) using ordinary least square regressions of US annual quantity data from 1970-2005. The method used by Pendell (2006) for calculating quantity transmission elasticities was adopted from earlier work by Brester, Marsh, and Atwood (2004).

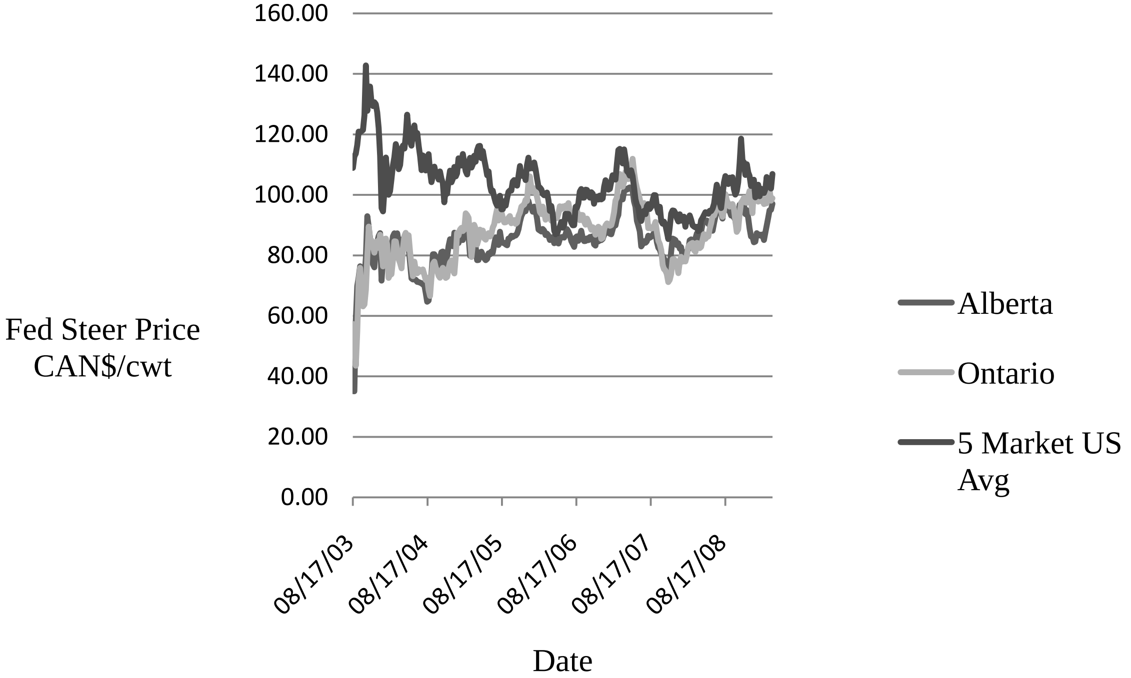
Previous literature has used US supply and demand elasticity estimates to model Canadian cattle and beef markets. Brester, Marsh, and Smith (2002) used US elasticity estimates as proxies for Canadian supply and demand responses in various cattle markets. In addition, Rude, Carlberg, and Pellow (2007) used US elasticities to estimate Canadian cattle supply response functions. According to Young and Marsh (1998), the appropriateness of the use of US elasticity parameters is related to the level of integration between the US and Canadian cattle and beef markets. Miljkovic (2006) used cointegration methods to compare the Alberta market with the United States market. This paper concluded that the Alberta and United States slaughter cattle markets were integrated between 1996 and 2004; however, the effects of the 2002 bovine spongiform encephalopathy (BSE) crisis were ignored. Young and Marsh (1998) also concluded that the US and Canadian beef and cattle markets were highly integrated prior to the 2002 BSE crisis.

The Canadian elasticities used in the economic model for the own-price elasticity of retail beef demand and the own-price elasticity of feeder cattle supply were obtained from the Food and Agricultural Policy Research Institute (FAPRI) elasticity database. FAPRI is a dual-university research group, headquartered at Iowa University and the University of Missouri-Columbia. The US supply and demand elasticities used in the model are obtained from Marsh (1992, 1994), and Brester, Marsh, and Atwood (2004). The own-price elasticity for wholesale beef demand was derived in Marsh (1992), using

1975-1989 quarterly data. Similarly, Marsh (1994) used monthly US cattle data from 1978-1991 to derive own-price elasticities for feeder and fed cattle demand. The intermediate run estimate determined by Marsh (1994) of eighteen months was used for this analysis. The use of the estimates derived by Marsh (1994) in a Canadian context follows previous research by Rude, Carlberg, and Pellow (2007). Lastly, Brester, Marsh, and Atwood (2004) calculated the derived elasticity for retail beef supply by multiplying the primary farm-level supply elasticity by a price transmission elasticity that related the feeder cattle price with the retail beef price. The primary farm level supply elasticity used by Brester, Marsh, and Atwood (2004) for this calculation was 0.22, similar to the parameter used in the current study of 0.2.

The BSE crisis of 2003 resulted in a complete US-Canada border closure for all live cattle from May 2003 to July 2005. Border closers with the US were also implemented for non-processed beef products. In January 2004, Canadian cattle farms had approximately one million more animals on farm than during the same time in the previous year. On December 23rd, 2003, a dairy cow in Washington State was found to have BSE. It was soon discovered that the animal had originated in Canada, causing increased biosecurity concerns from US officials. These factors caused an immense segregation of the US and Canadian beef and cattle markets. Figure 5.3 illustrates the prolonged effect of BSE on relative fed cattle prices between Canada and the US. However, price convergence has occurred after 2005. The use of US market elasticities to model the Canadian markets assumes that US and Canadian markets have reestablished the level of integration that existed prior to the BSE crisis of 2003.

Figure 5.3. Fed steer prices in the US and Canada following the 2003 BSE crisis



Note: The 5 market US average is converted into Canadian dollars using weekly exchange rate data. Canadian weekly prices for August 2003-Feburary 2009 provided by Canfax. The average of weekly fed-steer prices in Texas, Kansas, Colorado, Nebraska, Iowa and Minnesota from August 2003-Feburary 2009 was provided by the Livestock Marketing Information Center.
Source: Canfax (2010), LMIC (2010)

Lastly, the elasticity estimates used in the equilibrium displacement model are chosen to represent short-run changes in prices and output quantities. Although long-run effects of the loss of export markets would exist, as witnessed during the BSE crisis, the equilibrium displacement model framework assumes that prices and quantities would return to pre-outbreak equilibrium levels following the re-opening of export markets. This is an implication of the assumption that the supply and trade demand shocks caused by a FMD outbreak are temporary. Thus, short-run elasticities are required to determine the immediate effects on prices, quantities and subsequent welfare effects during, and immediately following the outbreak. The economic consequences of a FMD outbreak after the reinstatement of the export markets cannot be determined by the static equilibrium displacement model used in the current analysis.

5.2.2 Baseline Parameters

The equilibrium displacement model requires baseline price and quantity data for each marketing level. The year 2008 was chosen as the baseline year due to Statistics Canada export data inconsistencies in 2009. Table 5.2.2 displays the baseline prices and annual quantities used in the current study, determined using the same methodology as Pendell (2006). Baseline quantities were derived from Stats Canada (2010) and AAFC (2010). The equilibrium displacement model requires that the transmission elasticities relate the outputs from each marketing level in similar units. Therefore, total quantities in each market level are required to be in kg of beef. Total quantity of retail beef in Canada was determined by multiplying the Statistics Canada measure for beef available in 2008 (of 21 kg per person) by the total Canadian population in 2008. The total wholesale quantity of beef in carcass weight for Canada was determined by multiplying the total number of animals slaughtered in 2008 (3,524,200) by the average cold dressed weight of meat production in 2008 (355 kg). The total wholesale quantity of beef in carcass weight was then multiplied by the percentage of beef weight from carcass weight to determine a measure of total kilograms of wholesale beef. The percentage of beef weight from carcass weight was determined by dividing the Statistics Canada measure for beef available in carcass weight per person for 2008 by the beef available per person in 2008. This calculation determined that 73 percent of carcass weight is translated into beef weight. The total quantity of domestic wholesale beef in Canada was calculated by subtracting wholesale beef exports and adding wholesale beef imports to the total wholesale beef production in Canada. Import and export data for 2008 was provided by AAFC (2010).

Total fed cattle quantities were determined by multiplying the Statistics Canada 2008 estimate for “output of farm production” (4,964,900 head) by the average cold dressed weight of meat production. The number of feeder cattle exports to the US was subtracted from the farm production measure prior to this calculation. This number was then multiplied by the percentage of beef weight from carcass weight. Domestic fed cattle quantity in terms of kg of beef was then calculated by subtracting total fed cattle exports to the US in kg of beef terms from the total. An assumption regarding the average weight of a feeder animal was required to convert feeder cattle into per kg of beef terms. The average weight of a feeder animal was assumed to be 250 kg. In addition, a carcass weight percentage estimate was required to determine the percentage of total animal weight that would be converted into carcass weight; this measure was assumed to be 60 percent. The Statistics Canada measure for total calves under one year in 2008 (4,034,400) was converted into kg of beef terms using the assumed average animal weight, the carcass weight percentage, and the carcass weight to beef percentage. The same procedure was applied to total feeder animal exports to the US for 2008, obtained from Agriculture Canada.

Prices for the retail beef, wholesale beef, fed cattle and feeder cattle markets were obtained from Canfax (2010). The feeder cattle price was obtained from the average price of a 550 pound steer in Ontario and Alberta for 2008. The fed cattle price was determined as the average of Alberta and Ontario fed steer and heifer prices for 2008 (Canfax 2010). The average wholesale beef price was attained from the weighted average cutout value of AAA and AA boxed beef. The retail beef price obtained from a Canfax data specialist was the seven price Canadian average for 2008, used by the cattle and beef industry (Grant 2010).

Table 5.2.2. Canadian beef market baseline prices and quantities for 2008

Market	Quantity (million kg of beef*)	Price ($/kg)
Domestic Retail Beef	709.2[a]	12.17[c]
Domestic Wholesale Beef	677.3[a]	3.65[c]
Wholesale Beef Imports	151.3[b]	-
Wholesale Beef Exports	387.2[b]	-
Domestic Fed Cattle	891.1[a]	1.98[c]
Fed Cattle Exports	232.1[b]	-
Domestic Feeder Cattle	372.7[a]	2.31[c]
Feeder Cattle Exports	69.0[b]	-

Note: * Prices and quantities for feeder and fed markets converted into per kg of beef terms, the details of this conversion are described in 5.2.2
Sources: [a] Statistics Canada (2010); [b] AAFC (2010); [c] Canfax (2010)

5.2.3 Disease Control Costs

The per-unit direct cost parameters of controlling a FMD in Canada were obtained from a 2010 Serecon Management Consulting study. This study determined the economic impact of several FMD outbreak scenarios for British Columbia. The costs estimates included in the study were disposal, surveillance, euthanasia, indemnity, cleaning, and disinfection. The Serecon Management Consulting (2010) study derived these cost estimates from CFIA personnel and equipment cost estimates.

Table 5.2.3. Direct outbreak per-unit costs

Cost Type	Description	CAN $	Unit
Surveillance	Initial cost of creating an infected zone	2,500,000	per zone
	Variable cost per day of infected zone	6,250	per day
Indemnity	Reimbursement cost of beef cattle*	950	per head
	Reimbursement cost of dairy cattle	2,000	per head
	Reimbursement cost of swine[a]	67	per head
Euthanasia	Euthanasia cost of beef cattle	100	per head
	Euthanasia cost of dairy cattle	100	per head
	Euthanasia cost of swine	20	per head
Cleaning and Disinfection	Disinfection cost of beef operation	200	per head
	Disinfection cost of dairy operation	200	per head
	Disinfection cost of swine operation	25	per head
Disposal[b]	Disposal cost of beef cattle	400	per head
	Disposal cost of dairy cattle	400	per head
	Disposal cost of swine	40	per head

Notes: a Assuming average swine weight of 67kg. b Based on mass burial. Includes; site, haulage, labor, supplies, environmental testing.
Sources: Serecon Management Consulting (2010); * Statistics Canada (2010)

The disposal costs are based on mass burial techniques, including the costs of transport, labor, equipment, disposal site and the required environmental testing. The cost of government reimbursement for a swine animal is based on the assumption that the average animal weighs 67kg. The reimbursement cost of beef cattle was obtained from Statistics Canada data on the value of farm capital assets. It must be noted that the calculation of direct cost estimates used in this model do not include animal appraisal costs, animal tracing costs and feed disposal costs. These cost estimates were not included in the current analysis due to the non-existence of the data required for their computation.

Chapter 6 Results and Discussion

The following chapter presents the epidemiological and economic model results from a range of FMD spread simulation scenarios. All model outputs will include three results, representing the different levels of cattle traceability. In addition to using two direct animal contact rate scenarios, sensitivity of the epidemiological spread model results was investigated for a reduction in animal movement controls, no pre-emptive slaughter of direct animal contacts and an alternative disease introduction scenario. The sensitivity of the economic model outputs was investigated for changes in elasticity parameters and to differences in who bears the direct outbreak control costs. This chapter will also derive conclusions from the study as well as provide recommendations for future research in this area.

6.1 Epidemiological Model Results

The epidemiological model outputs most relevant to the current investigation will be presented and discussed in this section. These epidemiological model outputs include; outbreak duration, number of farms exposed through direct contact and successfully traced, number of farms infected by each disease transmission type, and the number of livestock destroyed. The effects of the low, medium, and high cattle traceability scenarios will be determined for each epidemiological model output in each scenario.

The epidemiological results for the medium direct contact rate scenario most relevant to the current analysis are displayed in Table 6.1. These results clearly depict an indeterminate effect of cattle traceability parameters on the disease spread model outputs. The difference in the mean value of the disease outbreak duration after 1,000 iterations between the low and high traceability scenarios is minimal. The low traceability scenario's mean outbreak duration is approximately one day longer than the high traceability scenario. However, the total number of animals destroyed is actually higher in the situation with higher cattle traceability.

Much of the ambiguity in the results for the medium contact rate scenario can be explained by the number of farms infected by the different forms of disease spread. As noted in Table 6.1, the number of farms infected by direct contact is small relative to the number of farms infected through indirect contact and airborne transmission.

Table 6.1. Epidemiological results of medium direct contact rate scenario

	Traceability Scenario		
Output Statistic	Low	Medium	High
Outbreak duration (days)	81.77	81.46	80.73
Standard deviation of outbreak duration	34.19	35.96	33.58
Number of infected zones	64.37	65.50	63.92
Number of farms directly exposed and successfully traced	0.73	1.46	2.15
Number of farms infected by direct contact	2.37	2.43	2.41
Number of farms infected by indirect contact	5.56	5.55	5.65
Number of farms infected by airborne transmission	55.91	57.30	56.06
Beef cattle destroyed (head)	3,876	3,949	3,895
Dairy cattle destroyed (head)	1,566	1,611	1,608
Swine destroyed (head)	9,512	9,847	9,766
Total animals destroyed (head)	14,953	15,407	15,269
Standard deviation of total animals destroyed	9,843	11,122	9,843

Note: Results display the mean output values of 1,000 iterations of the disease spread.

The low relative number of direct contact disease transmissions significantly reduces the impact of the traceability system on the model outputs, since the current study assumes that cattle traceability has no direct affect on other forms of disease transmission. When the number of direct animal contacts is compared to the total number of disease transmissions, three percent of the total disease transmissions are impacted by the traceability system in the medium contact rate scenario. The mean value of farms that were directly exposed and successfully traced in each outbreak also explains the minimal impact of cattle traceability within this scenario. Table 6.1 illustrates that on average, between 0.73 and 2.15 directly exposed farms were successfully traced, across all traceability scenarios.

The epidemiological results for the high contact rate scenario are illustrated in Table 6.2. Relative to the results from the medium contact rate scenario, it is evident that an increase in the number of direct animal contacts significantly impacts the effect of cattle traceability on the outbreak duration and number of animals destroyed. In the high contact rate scenario, an increase in direct contact rates causes the percentage of direct animal contacts relative to the total disease transmissions to increase to nine percent. The difference in the mean outbreak duration between the low and high traceability scenarios is also increased threefold relative to the medium contact rate scenario. The difference in mean outbreak duration between the low and high traceability scenarios is equal to approximately three days.

It is of interest to reiterate that the difference in direct animal contact rates between the medium and high direct contact rate scenarios is a multiplier of 2.5. However, the number of farms infected by direct contacts in the high contact rate scenario was not 2.5 times larger than in the medium contact rate scenario. In addition, the increase in direct contact rates positively impacted the number of farms infected through indirect and airborne transmission. This implies that the number of infected farms for each transmission route is not mutually exclusive, implying that although a livestock traceability system can only directly impact direct animal contacts, indirect effects are generated on the number of other disease transmission types. An increase in the direct contact rates also caused the total number of animals destroyed in all traceability scenarios to increase by an average of thirty-three percent. The difference in the mean total number of animals destroyed between the low and high traceability scenarios was 846 animals. The difference in the mean number of animals destroyed varied highly among animal types. The number of dairy and beef cattle destroyed decreased relative to increases in the level of cattle traceability. However, the number of swine animals destroyed was ambiguous across all cattle traceability scenarios.

The mean percentage of total farm-level cattle destroyed was less than 0.1% of all beef cattle. However, the number of animals destroyed in the largest outbreak from the 1000 iterations was 0.4% of all beef cattle, on both cow-calf and feedlot operations. These results were similar for all levels of traceability. However, the same statistic for high levels of cattle traceability for dairy farms was a mean percentage of 0.5% and a maximum of 2.8%, while the low traceability scenario generated a mean percentage of 0.6% and a maximum of 3.7%. Although this analysis fails to take into account the benefit of reducing worst case scenarios, the same drastic decreases generated by the traceability system toward maximum outbreak values were not witnessed on beef cattle destroyed or outbreak durations. In many instances, the outbreak durations were higher in the scenarios with higher levels of animal traceability. For instance, the high level of traceability for this scenario produced an outbreak of 283 days, while the largest outbreak produced in the low traceability scenario was 261 days. However, these positive tails on the outbreak duration distribution created by NAADSM are extremely thin, represented by a 95% percentile value of 160 days. Also represented in Table 6.2 is the standard deviation of the outbreak duration and the total number of animals destroyed. As the level of cattle traceability is increased the standard deviation of the outbreak duration is reduced.

Table 6.2. Epidemiological results of high direct contact rate scenario

	Traceability Scenario		
Output Statistic	Low	Medium	High
Outbreak duration (days)	87.21	85.91	84.59
Standard deviation of outbreak duration	36.44	36.43	34.38
Number of infected zones	87.31	85.60	81.83
Number of farms directly exposed and successfully traced	2.62	4.99	7.06
Number of farms infected by direct contact	8.20	8.46	7.82
Number of farms infected by indirect contact	9.93	9.88	9.16
Number of farms infected by airborne transmission	69.32	68.11	66.36
Beef cattle destroyed (head)	5,307	5,239	5,139
Dairy cattle destroyed (head)	2,454	2,424	2,295
Swine destroyed (head)	12,687	12,742	12,172
Total animals destroyed (head)	20,449	20,406	19,606
Standard deviation of total animals destroyed	15,082	15,204	13,936

Note: Results display the mean output values of 1000 iterations of the disease spread.

Several variations of the high direct contact scenario were generated to gauge the impact of livestock traceability given slight changes to the initial disease spread model assumptions. First, the movement control parameters provided by the CFIA were modified to reflect a situation where the control of indirect and direct contacts following disease detection was reduced. The specific movement control parameters used in the sensitivity analysis are presented in Table A.3. Table 6.3 displays the epidemiological results of the reduced movement control scenario. The mean values for outbreak duration, total disease transmissions, and total animals destroyed all increased relative to the initial high contact rate scenario. The difference in the mean outbreak durations between the low and high cattle traceability scenarios remained at approximately three days. However, the difference in total animals destroyed experienced substantial change relative to the initial high traceability scenario.

Unlike in the previous scenario, the number of dairy, cattle, and swine animals destroyed was now negatively correlated with the level of cattle traceability. The percentage of direct animal contacts relative to the total number of disease transmissions decreased relative to the initial high contact scenario, to eight percent. These results suggest that a reduction in indirect and direct movement controls has a positive relationship to the outbreak length and scale. However, the effect of decreasing movement controls on the effectiveness of cattle traceability is limited only to the scale of the outbreak. The initial high contact rate scenario experienced a four percent decrease in the total number of animals destroyed when comparing the low and high traceability scenarios. Comparatively, the scenario with reduced movement controls found an eight percent decrease in the total number of animal destroyed between the low and high scenarios. In addition, the standard deviation for both the outbreak duration and the total number of animals destroyed is decreased with increases in the level of cattle traceability.

A disease outbreak scenario was also constructed to depict the situation where rather than preemptively destroying direct animal contacts; all farms directly contacted by an infected herd are put under increased surveillance. The Canadian FMD Hazard Specific Plan states that intensive monitoring of direct animal contacts may be considered under exceptional circumstances rather than the use of pre-emptive slaughter only when warranted by a risk assessment, section 4.3.2 (CFIA 2010).

Table 6.3. Epidemiological results of the reduced movement control scenario

	Traceability Scenario		
Output Statistic	Low	Medium	High
Outbreak duration (days)	99.39	98.67	95.22
Standard deviation of outbreak duration	44.05	42.30	38.20
Number of infected zones	133.02	126.04	121.08
Number of farms directly exposed and successfully traced	3.23	5.96	9.08
Number of farms infected by direct contact	10.52	10.20	10.05
Number of farms infected by indirect contact	19.92	19.16	18.99
Number of farms infected by airborne transmission	103.23	98.09	94.19
Beef cattle destroyed (head)	7,752	7,480	7,246
Dairy cattle destroyed (head)	4,132	3,918	3,839
Swine destroyed (head)	20,217	19,151	18,380
Total animals destroyed (head)	32,101	30,549	29,466
Standard deviation of total animals destroyed	29,575	26,641	23,517

Notes: Results display the mean output values of 1,000 iterations of the disease spread. High direct contact rate scenario.

The results generated by this modification to the initial high direct contact rate scenario are displayed in Table A.4. This table illustrates that without pre-emptive destruction of direct animal contacts, cattle traceability has very little effect on the disease outbreak. The scenario produces outbreak results similar for all traceability levels to those generated by the low traceability situation in the initial high direct contact rate scenario.

The initial high direct contact rate scenario was also modified to determine the impact on outbreak results when changing the disease introduction scenario from a dairy operation to a feedlot operation. In the disease spread model framework, the feedlot operation has both lower direct and indirect contact rates. Table A.5 displays the substantial negative impact on the scale and duration of the outbreak when altering the disease introduction location and operation type. The mean number of animals destroyed was approximately ten times lower than in the initial introduction scenario. Also, the mean duration of the outbreak was approximately one third of the duration produced by the initial high direct contact rate scenario. Although the feedlot operation used was in the same general area, the significant reduction in the number of airborne transmissions signifies the possibility that the livestock density in the area was considerably different than in the previous scenario. The mean number of farms infected by direct contact for each outbreak iteration was 0.19, signaling a trivial effect generated for increases in cattle traceability in this outbreak scenario. These results were included in this study to signify the importance of disease introduction scenarios within the NAADSM framework. Table A.6 displays the results of the high contact rate scenario when the number of outbreak iterations is increased from 1,000 to 10,000. The results generated by this scenario are very similar to those found in the 1,000 iteration baseline situation, signifying that 1,000 iterations of the outbreak is appropriate for determining mean values.

The epidemiological results cannot be compared to previous research because there is no previous publically available FMD spread model outputs for Ontario. However, the effects of traceability on disease spread model outputs have been calculated by Pendell (2006). He found that increases in the animal identification level, depicted by changing the probability of a successful trace from 0.3, 0.6, and 0.9, changes the total percentage of beef cattle destroyed to 0.9%, 0.5% and 0.1%, respectively. Such drastic changes in the percentage of total cattle destroyed were not found in the current analysis, possibly due to different contact rates and herd demographics. In the high contact rate scenario, the mean number of beef cattle destroyed caused a negative; 0.01% shock to the Canadian feeder cattle supply and a 0.11% shock to the Canadian fed cattle supply. This was the same result in all three of the traceability scenarios. In the high contact rate with the reduced movement control scenario, high traceability produced a 0.02% negative shock to the Canadian supply of feeder cattle and 0.15% negative shock to fed cattle, due to the destruction of animals. The negative shock to the Canadian fed cattle market increased to 0.16% with low traceability; however, the shock to the feeder cattle market remained that same.

6.2 Economic Model Results

The economic results generated by disease outbreak scenarios include the derivation of both direct outbreak cost estimates and welfare changes. The direct disease control outbreak costs for the medium contact rate are presented in Table 6.4. The mean total direct cost of a FMD outbreak in Ontario for this scenario is determined to be between $205 million and $206.6 million Canadian dollars. Approximately 94 percent of these costs are attributed to the cost of enforcing movement restrictions through the setup of infected and restricted control zones. The direct disease outbreak costs for this disease outbreak scenario are not impacted by the level of cattle livestock traceability, shown by the increased costs in the medium traceability scenario relative to both the high and low traceability scenarios. The higher direct disease outbreak control cost in the medium traceability scenario is attributed to a larger number of animals destroyed and a higher number of control zones.

The direct disease outbreak costs produced for the high contact rate scenario are displayed in Table 6.5. Total direct outbreak control costs are higher when the direct contact rate is increased by a factor of 2.5.

Table 6.4. Direct disease outbreak costs generated by the medium contact rate scenario

		Traceability Scenario		
Disease Outbreak Cost	Operation Type	Low	Medium	High
Surveillance	All	193,822,093	197,097,688	192,051,635
Indemnity	Beef	3,682,096	3,751,094	3,699,946
	Dairy	3,131,400	3,222,960	3,216,740
	Swine	1,398,235	1,447,538	1,435,537
	Total	8,211,730	8,421,592	8,352,223
Euthanasia	Beef	387,589	394,852	389,468
	Dairy	156,570	161,148	160,837
	Swine	190,236	196,944	195,311
	Total	734,395	752,944	745,616
Cleaning and Disinfection	Beef	775,178	789,704	778,936
	Dairy	313,140	322,296	321,674
	Swine	237,795	246,180	244,139
	Total	1,326,113	1,358,180	1,344,749
Disposal	Beef	1,550,356	1,579,408	1,557,872
	Dairy	626,280	644,592	643,348
	Swine	380,472	393,888	390,622
	Total	2,557,108	2,617,888	2,591,842
	Total direct outbreak cost	$206,651,439.23	$210,248,291.90	$205,086,065.92

Note: Results displayed are calculated from the mean values of 1000 iterations of the disease spread.

Also, these results display that in the situation of a higher contact rate, an increase in the level of cattle traceability has a negative effect on the total direct outbreak costs. The difference in direct outbreak cost between the low and high traceability scenarios is $18.8 million Canadian dollars. Similarly to the findings in the medium contact rate scenario, this cost is comprised primarily of surveillance costs. In addition, it is of interest to note that although more swine animals were destroyed relative to the other livestock types, the direct outbreak costs for this livestock type are significantly lower in all disease outbreak cost category.

Table 6.5. Direct disease outbreak costs for high contact rate scenario

Disease Outbreak Cost	Operation Type	Traceability Scenario Low	 Medium	 High
Surveillance	All	265,864,407	259,961,850	247,837,498
Indemnity	Beef	5,041,812	4,977,497	4,881,955
	Dairy	4,908,980	4,848,820	4,590,020
	Swine	1,865,005	1,873,137	1,789,291
	Total	11,815,797	11,699,454	11,261,266
Euthanasia	Beef	530,717	523,947	513,890
	Dairy	245,449	242,441	229,501
	Swine	253,742	254,849	243,441
	Total	1,029,908	1,021,237	986,832
Cleaning and Disinfection	Beef	1,061,434	1,047,894	1,027,780
	Dairy	490,898	484,882	459,002
	Swine	317,178	318,561	304,301
	Total	1,869,510	1,851,337	1,791,083
Disposal	Beef	2,122,868	2,095,788	2,055,560
	Dairy	981,796	969,764	918,004
	Swine	507,484	509,697	486,882
	Total	3,612,148	3,575,249	3,460,446
	Total direct outbreak cost	$284,191,769.90	$278,109,126.26	$265,337,125.73

Note: Results displayed are calculated from the mean values of 1000 iterations of the disease spread.

The direct disease control costs were also generated for the scenario where the effectiveness of movement controls is reduced. As displayed in Table 6.6, these costs are significantly higher than in the previous scenarios, the result of an increase in the number of infected animals and in the number of zones required for containing the outbreak.

Table 6.6. Direct disease outbreak costs for the reduced movement control scenario

		Traceability Scenario		
Disease Outbreak Cost	Operation Type	Low	Medium	High
Surveillance	All	415,088,910	392,709,130	374,757,735
Indemnity	Beef	7,364,581	7,106,219	6,884,109
	Dairy	8,263,340	7,836,340	7,678,220
	Swine	2,971,880	2,815,185	2,701,857
	Total	18,599,800	17,757,744	17,264,186
Euthanasia	Beef	775,219	748,023	724,643
	Dairy	413,167	391,817	383,911
	Swine	404,337	383,018	367,600
	Total	1,592,723	1,522,858	1,476,154
Cleaning and Disinfection	Beef	1,550,438	1,496,046	1,449,286
	Dairy	826,334	783,634	767,822
	Swine	505,422	478,773	459,500
	Total	2,882,194	2,758,453	2,676,608
Disposal	Beef	3,100,876	2,992,092	2,898,572
	Dairy	1,652,668	1,567,268	1,535,644
	Swine	808,675	766,037	735,199
	Total	5,562,219	5,325,397	5,169,415
	Total direct outbreak cost	$443,725,846.34	$420,073,581.94	$401,344,096.86

Notes: Results displayed are calculated from the mean values of 1000 iterations of the disease spread. High contact rate scenario.

Also, the difference in total direct costs between the low and high traceability scenarios in this circumstance is $42.2 million, more than double the value found in the initial high contact scenario. Included in the analysis was the calculation of the direct outbreak costs for the feedlot disease introduction scenario. The smaller scale and duration generated by this disease introduction scenario caused a drastic decrease in the direct disease outbreak costs, as shown in Table A.7.

The exogenous supply shocks to the Canadian fed and feeder cattle markets are displayed in Table 6.7. The values in this table represent a percentage shock to the entire Canadian fed and feeder cattle markets. Table 6.7 represents the situation where direct disease control costs are divided equally between producers and the government. These shocks were affected when the assumptions regarding who bears the direct disease outbreak costs were changed to either the producer or government. The number of animals destroyed as a percentage of the entire Canadian markets was minimal for both the fed and feeder cattle markets. The effect of traceability on this type of supply shock represented less than one-hundredth of a percentage point for both markets.

Table 6.7. Exogenous supply shocks generated by the high contact rate scenario

	Traceability Scenario		
	Low	Medium	High
Direct Disease Control Costs			
Fed cattle	-0.68%	-0.66%	-0.65%
Feeder cattle	-0.08%	-0.08%	-0.07%
Animals Destroyed			
Fed cattle	-0.11%	-0.11%	-0.11%
Feeder cattle	-0.01%	-0.01%	-0.01%

Notes: Results displayed are calculated from the mean output values of 1000 iterations of the disease spread. Outbreak costs are split between producer and government 50-50. Exogenous shocks are displayed as a percentage of the Canadian market.

Lastly, the changes in producer and consumer welfare measures generated by the EDM are discussed. Consumer welfare is defined as the difference between all consumers willingness to pay for a product minus the actual price paid for a product by consumers. Since all consumers have different prices they are willing to pay for a product, this computation represents an aggregated measure of consumer well-being for the total quantity consumed. Consumer surplus is represented graphically by the area under the demand function that is above the selling price. Producer surplus represents the difference between all producers' willingness to produce a product and the price of the respective product. The willingness of producers to produce a product at any given price level is dependent on the marginal costs of production. This measure is not related to the profitability of consumers to the exclusion of fixed costs in this analysis. Graphically, producer surplus is represented by the area above the supply function and below the selling price.

Table 6.8 illustrates the welfare changes generated by FMD from the medium contact rate scenario, totaling a negative change in welfare of approximately $4.2 billion across all marketing levels. Total consumer welfare, as measured by the change in consumer welfare at the retail level, experienced a larger positive welfare change in the low traceability scenario relative to the scenario with high traceability. This is caused by the slightly longer outbreak duration. The supply shock in this scenario was too small to produce a measurable effect on the entire Canadian market. Relative to the high traceability scenario, the medium traceability situation had a higher number of animals destroyed and had higher direct disease outbreak costs. However, the medium contact rate scenario had a smaller negative total change in welfare. The mean difference in welfare changes between the low and high traceability situations for the medium contact rate scenario was $22 million, a difference of half of one percent.

Table 6.8. Welfare changes generated by the medium contact rate scenario

	Traceability Scenario		
	Low	Medium	High
Change in consumer welfare	659,478,325	658,546,996	655,030,642
Change in producer welfare			
Retail	-2,413,723,557	-2,408,934,263	-2,400,146,828
Wholesale beef	-851,771,437	-850,067,692	-847,013,136
Fed cattle	-1,143,955,447	-1,141,251,878	-1,138,469,676
Feeder cattle	-415,369,830	-414,794,811	-412,647,119
	-4,824,820,271	-4,815,048,645	-4,798,276,760
Total change in welfare	-$4,165,341,946	-$4,156,501,648	-$4,143,246,117

Notes: Results displayed are calculated from the mean output values of 1000 iterations of the disease spread. Direct disease control costs are barred by the producer.

The welfare changes produced by the high contact rate scenario are shown in Table 6.9. The model indicates that consumers will experience a positive change in welfare between $677-689 million and producers will experience a decrease in welfare between $4.8-4.9 billion. Similarly to the results for the medium contact rate scenario, the low traceability situation causes the positive effect on consumer welfare and the negative effect on producer welfare to amplify relative to the high traceability scenario. The drastic decrease in prices at all marketing levels cause retailers and fed cattle producers to be affected the most in real value terms. This remains the case across all livestock traceability scenarios. The difference in the total change in welfare between the high and low traceability situations is $50.6 million, just over one percent of the total change.

Table 6.9. Welfare changes generated by the high contact rate scenario

	Traceability Scenario		
	Low	Medium	High
Change in consumer welfare	689,548,965	683,638,583	677,717,443
Change in producer welfare			
Retail	-2,469,611,667	-2,453,654,472	-2,437,074,291
Wholesale beef	-870,849,756	-865,290,595	-859,501,036
Fed cattle	-1,151,589,510	-1,146,080,739	-1,140,011,621
Feeder cattle	-432,863,449	-429,376,253	-425,802,324
	-4,924,914,381	-4,894,402,059	-4,862,389,272
Total change in welfare	-$4,235,365,417	-$4,210,763,476	-$4,184,671,828

Note: Results displayed are calculated from the mean output values of 1000 iterations of the disease spread. Direct disease control costs are barred by the producer.

Welfare changes were also calculated for the scenario with reduced movement controls, illustrated in Table 6.10. Similar findings were observed with regards to the relative changes in welfare among market participants across all traceability scenarios. However, the total negative change in welfare was greater than in the high and medium contact rate scenarios. With reduced movement controls, consumer welfare is predicted to increase between $732-752 million and producer welfare is predicted to decrease between $5-5.1 billion. The total welfare losses are decreased $70 million when comparing the low and high traceability scenarios. Across all outbreak and traceability scenarios (excluding the feedlot introduction scenario) the feeder cattle market is expected to have the smallest decrease in producer welfare, between $412-469 million. The welfare changes generated by the feedlot introduction scenario are displayed in Table A.8. These results show a total decrease in welfare of $2.9 billion across all traceability scenarios.

Table 6.10. Welfare changes generated by the reduced movement control scenario

	Traceability Scenario		
	Low	Medium	High
Change in consumer welfare	752,572,953	747,946,349	732,094,520
Change in producer welfare			
Retail	-2,602,813,580	-2,597,500,187	-2,554,426,247
Wholesale beef	-916,688,778	-914,959,760	-899,924,717
Fed cattle	-1,180,467,221	-1,182,165,302	-1,166,780,201
Feeder cattle	-469,439,958	-467,047,104	-457,320,099
	-5,169,409,537	-5,161,672,353	-5,078,451,263
Total change in welfare	-$4,416,836,584	-$4,413,726,005	-$4,346,356,743

Notes: Results displayed are calculated from the mean output values of 1000 iterations of the disease spread. High contact rate scenario. Direct disease control costs are barred by the producer.

This section also includes the scenario results of different assumptions regarding who bears the direct outbreak costs discussed above. The three scenarios discussed in this section that illustrate the effects of dividing the direct outbreak costs were all derived by modifying the initial high contact rate scenario. The three scenarios analyzed were; producers bear the entire outbreak cost associated with controlling FMD within beef operations, producers and the government split these costs 50-50, and government bears the entire outbreak cost. The welfare changes decomposed by marketing level for the 50-50 cost split scenario and the government bears the entire outbreak cost, are displayed in Table A.9 and Table A.10, respectively.

The scenario where producers bear the entire outbreak cost was previously presented in Table 6.9. The total changes in welfare for each scenario is presented in Table 6.11. In the first scenario, cattle producers bear a weighted average of the surveillance costs and the remaining costs that were experienced in the disease control of beef animals. This cost is then divided between cow-calf and feedlot operations depending on the relative number of operations affected. The direct outbreak cost with high traceability totaled 0.15% of the Canadian cow-calf market value and 1.30% of the Canadian fed cattle market value. The low traceability situation generated negative supply shocks to the cow-calf and fed cattle markets of 0.16% and 0.37%, respectively.

These negative shocks described above were combined with both the negative demand shock from the loss of export markets and the negative supply shock from the number of animals destroyed, to generate the following results from the EDM. In all traceability scenarios, the above shocks caused prices in all of the modeled marketing levels to fall drastically. In the high traceability scenario, when producers bore the entire outbreak cost; retail beef prices dropped 55.4%, wholesale beef prices decreased 52.3%, fed cattle prices fell 35.9%, and feeder cattle prices decrease 15.5%. When producers split the direct outbreak costs with the government; retail beef prices declined 56.2%, wholesale beef prices decreased 53.0%, fed cattle prices fell 36.5%, and feeder cattle prices decrease 15.1%. Lastly, in the situation where the government bears the entire direct outbreak cost; retail beef prices dropped 56.9%, wholesale beef prices dropped 53.7%, fed cattle prices fell 37.2%, and feeder cattle prices fell 14.7%. The level of traceability had less than half a percentage impact on any price change.

It is evident from the above price change information that price decreases are larger in the marketing levels closer to the retail level as the government covers more of the direct outbreak costs. As shown in Table 6.11, the larger decreases in price cause the total negative change in surplus as a result of an FMD outbreak to increase. This is because when feeder and fed cattle supply is negatively shocked, the price decrease caused by the loss of export markets is reduced.

Table 6.11. Welfare changes generated by direct outbreak cost bearing scenarios

	Traceability Scenario		
Direct Outbreak Cost Scenario	Low	Medium	High
Producers Bear Outbreak Costs	-$4,235,365,417	-$4,210,763,476	-$4,184,671,828
Costs Split Between the Government and Producers 50-50	-$4,341,319,940	-$4,312,822,769	-$4,283,380,896
Government Bears All Outbreak Costs	-$4,447,686,983	-$4,415,267,653	-$4,382,453,326

Notes: Results displayed are calculated from the mean output values of 1000 iterations of the disease spread. High contact rate scenario.

Since all of the underlying supply curves are derived with inelastic own-price supply elasticities, the changes in price have proportionally smaller negative effects on the quantities. Also, the fact that demand is inelastic in the model causes the negative shift in supply to have a more pronounced positive effect on prices relative to the negative effect on quantity. So in the case where prices are forced upwards by a proportionally larger degree than quantity is decreasing, the negative shift in supply generated by bearing direct outbreak costs causes a reduction in the producer welfare losses initially caused by the loss of export markets. This affect is echoed in the upstream markets whose derived supply curves are dependent on the underlying cattle markets.

Finally, a sensitivity analysis was conducted on the elasticities used in the EDM. Supply and demand elasticities in all four marketing levels were fluctuated together by 50% to gauge the sensitivity of elasticity selection on model results. This sensitivity analysis creates four scenarios, including; all four supply functions become 50% more inelastic, all four demand functions become 50% more inelastic, all four supply functions become 50% more elastic, and all four demand functions become 50% more elastic. The value of 50% was chosen to represent the relative importance of the accuracy of the elasticity measures used in the EDM. The total changes in welfare produced by the elasticity scenarios are presented in Table 6.12. These results depict that the sensitivity of the model results is much greater with respect to changes in the supply elasticity parameters rather than the demand elasticities.

When all of the supply elasticities become more inelastic, the predicted total decrease in welfare generated by a FMD outbreak nearly doubles from $4.2 billion to $7.1 billion, in the low traceability scenario. The opposite effect occurs when all of the supply elasticities become more elastic, causing the total welfare loss to decrease $1.4 billion, to $2.8 billion. Table A.11 and Table A.12 illustrate the welfare effects generated at each market level by the supply elasticity sensitivity analysis. Changes in the demand elasticities cause the total welfare loss to decrease in both instances. However, represented in Table A.13 and Table A.14, each situation causes very different effects at each marketing level. When demand elasticities become more inelastic, consumer welfare is substantially increased while producers experience much larger decreases in welfare.

When individual supply and demand elasticities are tested for model sensitivity the effect on the change in welfare is significantly reduced. The most pronounced effect is observed when the retail beef supply elasticity estimate becomes 50% more inelastic, resulting in $5.5 billion welfare loss, compared with the baseline loss of $4.2 billion. The retail beef supply elasticity also causes the most pronounced decrease in welfare losses when the parameter becomes 50% more elastic, resulting in a $3.6 billion loss. When all other elasticity parameters are individually varied by 50% in both directions, the resulting changes in welfare losses are between those generated by the sensitivity analysis of the retail beef supply elasticity. The results of the sensitivity analysis of the individual elasticity parameters are displayed in Table A.15.

This analysis is consistent with that mentioned by Kohls and Uhl (2002) where because the demand for most farm products is inelastic, a reduction in prices will reduce total revenue and rising prices will increase revenue. When demand becomes more elastic, producers in the feeder cattle, fed cattle, and wholesale beef levels face lower welfare losses, and retail producers encounter substantially larger welfare declines. Overall, the effect generated by the traceability on the economic model outputs was not significantly changed given different elasticity scenarios. In the inelastic supply situation, the total welfare loss was decreased by $88 million between the low and high levels of traceability, relative to the $50.6 million change in the baseline high contact rate scenario.

Table 6.12. Welfare changes generated by elasticity scenarios

	Traceability Scenario		
Elasticity Scenario	Low	Medium	High
50% more-inelastic supply	-$7,146,573,777	-$7,103,427,910	-$7,058,002,407
50% more-elastic supply	-$2,785,262,064	-$2,769,871,988	-$2,753,386,880
50% more-inelastic demand	-$3,939,314,496	-$3,917,313,798	-$3,893,821,735
50% more-elastic demand	-$3,918,656,622	-$3,895,823,176	-$3,871,612,309

Notes: For the situation of 50% more-inelastic, elasticities were multiplied by 0.5. For the situation of 50% more-elastic, elasticities were multiplied by 1.5. Results displayed are calculated from the mean output values of 1000 iterations of the disease spread. High contact rate and producers bear direct outbreak costs scenario was used for this sensitivity analysis.

Chapter 7 Conclusions, Limitations, and Suggestions for Future Research

7.1 Conclusions and Summary

This thesis research involved the construction of an epidemiological FMD spread model for Ontario using the NAADSM framework. Disease simulations were produced to reflect different levels of cattle traceability. This was accomplished using variations of the parameter that reflects the probability of a successful direct animal trace. The epidemiological model outputs were then used to calculate the direct disease control costs of an FMD outbreak in Ontario. Indirect costs of an FMD outbreak were then calculated for each level of cattle traceability using an EDM framework that incorporated negative demand shocks from to the loss of export markets and negative supply shocks caused by the disease outbreak. Parameter sensitivity was investigated within both the epidemiological and economic model.

The findings presented in this thesis regarding the effectiveness of cattle traceability at reducing the costs associated with an FMD outbreak for the high contact rate baseline scenario illustrate an $18.8 million decrease in direct outbreak costs and a decrease in total beef market welfare losses of $50.6 million. When the effectiveness of movement controls is reduced by one half, traceability reduces the direct outbreak cost by $42.2 million and the total beef market welfare loss by $70 million. Hobbs et al. (2007) estimated the cost of a national animal traceability system for cattle to be $85.5-$155.9 million per year. Also, in the majority of outbreak scenarios, the standard deviations for the total number of animals destroyed and the outbreak duration is reduced with higher levels of cattle traceability. It is important to note that the benefits mentioned above are only realized in the event of a FMD outbreak occurring, and cannot be directly compared to the costs of a traceability system. It is strikingly obvious that unless the probability of a FMD outbreak occurring each year was equal to one, investment in a national cattle traceability system solely to affect a FMD outbreak may not be warranted. Also, it is important to note that this analysis only derives the benefit of a national livestock traceability system with respect to FMD outbreaks, whereas other benefits exist.

The results found in this thesis are comparable to the economic impacts derived for the 2003 BSE crisis. Mitura and Di Pietro (2004) find that the 2002-2003 loss of live beef cattle exports caused an overall loss to the Canadian economy of $5.7 billion. This estimate does not include the restriction of beef exports; however this would have generated a much lower economic loss due to a much shorter export ban. A Serecon Management Consulting (2003) paper found that the total impact of BSE to the beef industry by early 2004 was $6.3 billion. As an average among the different scenarios, this thesis finds that total welfare losses of a hypothetical FMD outbreak in Canada to be $4.2 billion, less significant than BSE estimates due to the expectation of a shorter export ban of live cattle to the US.

7.2 Model Limitations and Future Research

The research presented in this paper provides a valuable starting point for future epidemiological-economic modeling research in Canada. The stochastic nature of the outputs generated by the NAADSM framework allows for future research to incorporate the statistical properties of the disease spread model outputs, rather than only using the mean model outputs. This approach would allow the economic model to take account of the possibility of worst case disease outbreak scenarios. Incorporating an economic model with stochastic inputs would generate a distribution of direct costs and welfare changes for each scenario. The version of NAADSM used in this analysis only incorporates a trace-forward instrument in the framework. This fails to include the potential benefit generated by a full cattle traceability system with regard to improving the ability to trace the source of an infected herd. Also, future versions of NAADSM want to include more options regarding cattle tracing in the event of a disease outbreak, such as allowing for diagnostic testing of traced herds. Future research should attempt to obtain the most recent version of the software when deriving the benefits of such a traceability system.

In addition, this research demonstrated that model results are highly sensitive to the supply elasticity parameters used in the EDM. Stochastic elasticity parameters can also be incorporated into the current framework to reduce the dependency of model outputs on the accuracy of the elasticity parameters. A major drawback of using stochastic elasticity parameters is that a distributional form must be assumed. Depending on the number of different elasticity estimates available for each marketing level, the selection of this functional form is highly arbitrary and cannot be easily justified. The use of US elasticities as proxies for several of the derived marketing levels should also be listed as a model limitation.

Future EDM models used in a similar context to the current study should include swine and poultry markets. When relative prices change between beef, pork and poultry, product substitution would occur towards products with a reduced relative price. This effect is not incorporated in the current analysis, causing potential overestimates of the reduction in beef market welfare. Lastly, the economic model should optimally include dynamics to incorporate the re-opening of export markets. Rich and Winter-Nelson

(2007) used a five year period to capture the impacts of changing access to export markets. The current model is designed to evaluate the economic effects up until the time that the boarder is re-opened. However, as demonstrated by the Canadian BSE crisis in 2003, market distortions caused by the closure of export markets would not be corrected instantaneously.

References

Agriculture and Agri-Food Canada Website. *"National Agriculture and Food Traceability System"* Internet Site: http://www.ats-sea.agr.gc.ca/trac/sys-eng.htm (Accessed September 11th 2009).

Agriculture and Agri-Food Canada Website. *"Red Meat Market Information"* Internet Site: http://agr.gc.ca/redmeat/main.htm (Accessed September 14th 2010).

Animal Health Australia Website, *"History of livestock identification and traceability."* Internet Site: http://www.animalhealthaustralia.com.au/programs/drm/nlis/history-of-livestock-identification-and-traceability.cfm (Accessed September 12th 2010).

Alexanderson, S., Z. Zang, A.I. Donaldson, and A.J.M. Garland. "The Pathogenesis and Diagnosis of Foot-and-Mouth Disease." *Journal of Comparative Pathology* 129(2003):1-36.

Alston, J.M., G.W. Norton, and P.G. Pardey. *Science under Scarcity: Principles and Practice for Agricultural Research Evaluation and Priority Setting*. Ithaca, NY: Cornell University Press, 1995.

Bates, T.W., M.C. Thurmond, and T.E. Carpenter. "Direct and indirect contact rates among beef, dairy, goat, sheep, and swine herds in three California counties, with reference to control of potential foot-and-mouth disease transmission." *American Journal of Veterinary Research* 62(2001):1121-1129.

Blasi, D., G. Brester, C. Crosby, K. Dhuyvetter, J. Freeborn, D. Pendell, T. Schroeder, G. Smith, J. Stroade, and G. Tonsor. *"Benefit-Cost Analysis of the National Animal Identification System."* Washington DC: U.S. Department of Agriculture/Animal and Plant Health Inspection Service, January 2009.

Bouma, A., A. Dekker, and M.C.M. de Jong. "No foot-and-mouth disease virus transmission between individually housed calves." *Veterinary Microbiology* 98(2004):29-36.

Brester, G.W., J.M. Marsh, and J.A. Atwood. "Distributional Impacts of Country-of-Origin Labeling in the U.S. Meat Industry." *Journal of Agricultural and Resource Economics* 29(2004):206-227.

Brester, G.W., J.M. Marsh, and V.H. Smith. "The Impacts on U.S. and Canadian Slaughter and Feeder Cattle Prices of a U.S. Import Tariff on Canadian Slaughter Cattle" *Canadian Journal of Agricultural Economics* 50(2002):51-66.

Buse, Rueben, C. "Total Elasticities. A Predictive Device." *The Journal of Farm Economics* 40(1958): 881-891.

Canadian Diary Commission Website. *"Canadian Diary Commission Annual Report 2005-2006"* Internet site: http://www.cdc-ccl.gc.ca/DCPCDC/app/filerepository/1B99D3ABC17B4AB18B19162CE0F721BA.pdf (Accessed September 22nd 2009).

Canadian Food Inspection Agency Website. *"Foot-and-Mouth Disease Hazard Specific Plan"* Internet site: http://www.inspection.gc.ca/english/anima/heasan/man/fmdfie/fmdfiee.shtml (Accessed October 4th 2009).

Canadian Food Inspection Agency Website. "*Foot and Mouth Disease – Fact Sheet"* Internet site: http://www.inspection.gc.ca/english/anima/disemala/fmdfa/fmdfafse.shtml (Accessed March 25th 2010).

Canadian Food Inspection Agency Website. "*Traceability in Canada."* Internet site: http://www.inspection.gc.ca/english/anima/trac/traccane.shtml (Accessed September 25th 2009).

Canfax Website. Internet site: http://www.canfax.ca/Main.aspx (Accessed July 2nd 2010).

Codex Alimentarius Website. "*Principles for Traceability / Product Tracing as a Tool Within Food Inspection and Certification System.*" Internet Site: http://www.codexalimentarius.net/download/standards/10603/CXG_060e.pdf (Accessed July 1st, 2010).

Cox, S.J., C. Voyce, S. Parida, S.M. Reid, P.A. Hamblin, G. Hutchings, and D.J. Paton. "Protection against direct-contact challenge following emergency FMD vaccination of cattle and the effect on virus excretion from the oropharynx." *Vaccine* 23(2005):1106-1113.

Cox, S.J., C. Voyce, S. Parida, S.M. Reid, P.A. Hamblin, G. Hutchings, D.J. Paton, and P.V. Barnett. "Effect of emergency FMD vaccine antigen payload on protection, sub-clinical infection and persistence following direct contact challenge of cattle." *Vaccine* 24(2006):3184-3190.

Department for Environment, Food and Rural Affairs Website. "*FMD: 2001 outbreak"* Internet site: http://www.defra.gov.uk/foodfarm/farmanimal/diseases/atoz/fmd/2001/index.htm (Accessed April 25th 2010).

Disney, W.T., J.W. Green, K.W. Forsythe, J.F. Wiemers, and S. Weber. "Benefit-Cost Analysis of Animal Identification for Disease Prevention and Control." *Revue Scientifique et Technique de l'Office International des Epizooties* 20(2001):385-405.

Dubé C., C. Ribble, D. Kelton, and B. McNab. “Comparing Network Analysis Measures to Determine Potential Epidemic Size of Highly Contagious Exotic Diseases in Fragmented Monthly Networks of Dairy Cattle Movements in Ontario, Canada.” *Transboundary and Emerging Diseases 55(2008):382-392.*

Dubé C., M.G. Garner, M.E. Teachman, J.W. Wilesmith, J. Griffin, A. van Haldered, M.A. Stevenson, R.L. Sanson, and N. Harvey. “The Animal Quadrilateral EpiTeam – an example of international collaboration for preparing and responding to animal health emergencies.” Paper presented at 11th Symposium of the International Society for Veternairy Epidemiology and Economic, Cairns, August 6-11, 2006.

Dubé, C., C. Ribble, D. Kelton, and B. McNab. “A Review of Network Analysis Terminology and its Application to Foot-and-Mouth Disease Modeling and Policy Development.” *Transboundry and Emerging Diseases* 56(2009):73-85.

Eblé, P.L., A. Bouma, K. Weerdmeester, J.A. Stegeman, and A. Dekker. “Serological and mucosal immune responses after vaccination and infection with FMDV in pigs.” *Vaccine* 25(2007):1043-1054.

Eblé, P.L., A. Bouma, M.G.M. de Bruin, F. van Hemert- Kluitenberg, J.T. van Oirschot, and A. Dekker. “Vaccination of pigs two weeks before infection significantly reduces transmission of foot-an-mouth disease virus.” *Vaccine* 22(2004):1372-1378.

Eblé, P.L., M.G.M. de Bruin, A. Bouma, F. van Hemert-Kluitenberg, and A. Dekker. “Comparison of immune responses after intra-typic heterologous and homologous vaccination against foot-and-mouth disease virus infection in pigs.” *Vaccine* 24(2006):1274-1281.

Ekboir, J., L.S. Jarvis, D.A. Sumner, J.E. Bervejillo, and W.R. Sutton. "Changes in Foot and Mouth Disease Status and Evolving World Beef Markets." *Agribusiness* 18(2002):213–29.

Ekboir, J.M. Potential Impact of Foot-and-Mouth Disease in California: The Role and Contribution of Animal Health Surveillance and Monitoring Services. Agricultural Issues Center, Division of Agriculture and Natural Resources, University of California, 1999.

Elbakidze, L., L. Highfield, M. Ward, B.A. McCarl, and B. Norby. “Economic Analysis of Mitigation Strategies for FMD Introduction in Highly Concentrated Animal Feeding Regions.” *Review of Agricultural Economics* 31(Dec. 2009):931-950.

Food and Agricultural Policy Research Institute (FAPRI) Website. *"FAPRI Elasticity Database"* Internet site: http://www.fapri.iastate.edu/tools/elasticity.aspx (Accessed May 4th 2010).

Ferguson, N., C. Donnelly and R. Anderson, "The foot-and-mouth epidemic in Great Britain: pattern of spread and impact of interventions." *Science* 292(2001):1155–1160.

Garabed, R.B., A.M. Perez, W.O. Johnson, and M.C. Thurmond. "Use of expert opinion for animal disease decisions: An example of foot-and-mouth disease status designation." *Preventative Veterinary Medicine* 92(2009):20-30.

Garner, M.G., and M.B. Lack. "An evaluation of alternative control strategies for foot-and-mouth disease in Australia: a regional approach." *Preventative Veterinary Medicine* 23(1995):9-32.

Gerbier, G. J. N. Bacrob, R. Pouillota, B. Duranda, F. Moutoua and J. Chadœufc. "A point pattern model of the spread of foot-and-mouth disease." *Preventive Veterinary Medicine* 56(2002):33-49.

Gesinghaus, B. Personal Communication. Leader of the Canadian Food Inspection Agency's Humane Destruction Working Group, April 14th 2010.

Glostera, J., A. Jones, A. Redington, L. Burgin, J.H. Sørensenc, R. Turner, M. Dillon, P. Hullinger, M. Simpson, P. Astrup, G. Garner, P. Stewart, R. D'Amours, R. Sellers and D. Paton. "Airborne spread of foot-and-mouth disease – Model intercomparison." *The Veterinary Journal* 183(2010):278-286.

Golan, E., B. Krissoff, F. Kuchler, L. Calvin, K. Nelson, and G. Price. *Traceability in the US Food Supply: Economic Theory and Industry Studies*. Washington DC: U.S. Department of Agriculture – Economic Research Service, 2004.

Government of Alberta Website. *"Traceability."* Internet site: http://www1.agric.gov.ab.ca/$department/deptdocs.nsf/all/trace12895 (Accessed July 5th 2010)

Grant, Brenna. Personal Communication. Research analyst, Canfax Research Services, May 19th 2010.

Greathouse, B.D. "Vaccination Strategies for a Foot-and-Mouth Disease Outbreak in Southwest Kansas." Unpublished MS Thesis. Colorado State University, Fort Collins, CO, 2010.

Harvey, N. A. Reeves, M.A. Schoenbaum, F.J. Zagmutt-Vergara, C. Dubé, A.E. Hill, B.A. Corso, B. McNab, C.I. Cartwright, and M.D. Salman. "The *North American Animal Disease Spread Model*: A simulation model to assist decision making in evaluating animal disease incursions." *Preventative Veterinary Medicine* 82(2007):176-197.

Hicks, J.R. *The Theory of Wages*. (New York: Peter Smith, 1948), Appendix: 241-246.

Hobbs, J.E., M.T. Yeung, and W.A. Kerr. "Identification and Analysis of the Current and Potential Benefits of a National Livestock Traceability System in Canada." Agriculture and Agri-Food Canada, Ottawa, Ontario, 2007

Hu, R. "Market Reactions to Animal Disease: The Case of Bovine Spongiform Encephalopathy Discoveries in North America." PhD dissertation, Texas A&M University, College Stations, Texas, 2008.

Hugh-Jones, M. E. "A Simulation Spatial Model of the Spread of Foot-and-Mouth Disease through the Primary Movement of Milk." *The Journal of Hygiene* 77(1976):1-9.

Hunt, D. Personal Communication. Manitoba Agriculture, Food and Rural Initiatives - Agri-Food Traceability Coordinator, September 2009.

Keeling, M.J. "Models of foot-and-mouth disease." *Proceedings of the Royal Society B* 272(2005):1195-1202.

Kohls, L.R. and N.J. Uhl. *Marketing of Agricultural Products ninth edition*. New Jersey: Prentice Hall, 2002.

Koller-Jones, M.A.B. Personal Communication. Canadian Food Inspection Agency Senior Staff Veterinarian, July 2010.

Krystynak, R.H.E. and P.A. Charlebois. "The potential economic impact of an outbreak of foot-and-mouth disease in Canada." *Canadian Veterinary Journal* 28(1987):523-527.

Lane, W. Personal Communication. Director of the Dairy Farmers of Ontario, December 2009.

Leger, E. Personal Communication. Canadian Food Inspection Agency Chief Veterinarian, November 2009.

Livestock Marketing Information Center (LMIC) Website. *"Prices and Production."* Internet site: http://www.lmic.info/priprod/pandp.html (Accessed May 2nd 2010).

Looney, J, C. "Comparative Cost Analysis of Alternative Animal Tracing Strategies Directed Toward Foot and Mouth Disease Outbreaks in the Texas High Plains." M.Sc. thesis, Texas A&M University, College Stations, Texas, 2009.

Mahul, O. and B. Durand. “Simulated economic consequences of foot-and-mouth disease epidemics and their public control in France.” *Preventive Veterinary Medicine* 47(2000):23-38.

Marsh, J. M. "USDA Data Revisions of Choice Beef Prices: Implications for Estimating Demand Responses." *Journal of Agriculture and Resource Economics* 17(December 1992):323-334.

Marsh, J. M. "Estimating Intertemporal Supply Response in the Fed Beef Market." *American Journal of Agricultural Economics* 76(Aug. 1994):444-453.

Miljkovic, D. “U.S. and Canadian Livestock Prices: Market Integration and Trade Dependence.” Paper presented at the American Agricultural Economics Association Annual Meeting, Long Beach, California, July 23-26, 2006.

Ministry of Agriculture and Forestry Website. “Review of Selected Cattle Identification and Tracing Systems Worldwide.” Internet site: http://www.maf.govt.nz/mafnet/review-cattleident-systems-worldwide.pdf (Accessed July 12th 2010).

Mitura, V., and L. Di Pietro. “Canada’s beef cattle sector and the impact of BSE on farm family income.” Working paper No. 69, Agriculture and Rural Working Paper Series, Agriculture Division, Statistics Canada, Ottawa, ON, 2004.

Muth, R. “The Derived Demand Curve for a Productive Factor and the Industry Supply Curve.” *Oxford Economics Papers* 16(1964):221-234.

Orsel, K., M.C.M. de Jong, A. Bouma, J.A. Stegeman, and A. Dekker. “Foot and mouth disease virus transmission among vaccinated pigs after exposed to virus shedding pigs.” *Vaccine* 25(2007):6381-6391.

Pendell, D.L., G.W. Grester, T.C. Schroeder, K.C. Dhuyvetter, and G.T. Tonsor. “Animal Identification and Tracing in the United States.” *American Journal of Agricultural Economics* 92(2010):in press.

Pendell, D.L., J. Leatherman, T.C. Schroeder, and G.S. Alward. “The Economic Impacts of a Foot-and-Mouth Disease Outbreak: A Regional Analysis.” *Journal of Agricultural and Applied Economics* 39(2007):19-33.

Pendell, D.L. “Value of Animal Traceability Systems in Managing a Foot-and-Mouth Disease Outbreak in Southwest Kansas.” PhD dissertation, Kansas State University, Manhattan, 2006.

Piggott, R.R., N.E. Piggott, and V.E. Wright. “Approximating Farm-Level Returns to Incremental Adverticing Expenditure: Methods and an Application to the Australian Meat Industry.” *American Journal of Agricultural Economics* 77(1995): 497-511.

Reeves, A. Personal Communication. NAADSM Development Team, Animal Population Health Institute, Colorado State University, January 2010.

Rich, K. M, A. Winter-Nelson, and G. Y. Miller. “Enhancing economic models for the analysis of animal disease.” *Review Scientifique et Technique (International Office of Epizootics)* 24(2005):847-856.

Rich, K. M., and A. Winter-Nelson. “An Integrated Epidemiological-Economic Analysis of Foot and Mouth Disease: Applications to the Southern Cone of South America.” *American Journal of Agricultural Economics* 89(August 2007):682-697.

Rich, K. M., G. Y. Miller, and A. Winter-Nelson. “A review of economic tools for the assessment of animal disease outbreaks.” *Review Scientifique et Technique (International Office of Epizootics)* 24(2005):833-845.

Rude, J., J. Carlberg, and S. Pellow. “Integration to Fragmentation: Post-BSE Canadian Cattle Markets, Processing Capacity, and Cattle Prices” *Canadian Journal of Agricultural Economics* 55(2007):197-216.

Saatkamp, H.W., A.A. Dijkhuizen, R. Geers, R.B.M. Huirne, J.P.T.M. Noordhuizen, and V. Goedseels. “Simulation studies on the epidemiological impact of national identification and recording systems on the control of classical swine fever in Belgium.” *Preventative Veterinary Medicine 26*(1996b):119-132.

Saatkamp, H.W., R. Geers, J.P.T.M. Noordhuizen, A.A. Dijkhuizen, R.B.M. Huirne, and V. Goedseels. “National identification and recording systems for contagious animal disease control.” *Livestock Production Science* 43(1995):253-264.

Saatkamp, H.W., R.B.M. Huirne, R. Geers, A.A. Dijkhuizen, J.P.T.M. Noordhuizen, and V. Goedseels. “State-Transition Modelling of Classical Swine Fever to Evaluate National Identification and Recording Systems – General Aspects and Model Discription.” *Agricultural Systems* 51(1996a):215-236.

Schoenbaum, M.A., and W.T. Disney. “Modeling alternative mitigation strategies for a hypothetical outbreak of foot-and-mouth disease in the United States.” *Preventive Veterinary Medicine* 58(2003):25-52.

Sellers, R.F., and S.M. Daggupaty. “The Epidemic of Foot-and-Mouth Disease in Saskatchewan, Canada, 1951-1952.” *Canadian Journal of Veterinary Research* 54(1990):457-464.

Serecon Management Consulting. *Economic implications of BSE in Canada*. Prepared for: Canadian Animal Health Coalition, Edmonton, AB. November, 2003.

Serecon Management Consulting. *Potential Economic Impacts of a Foot and MouthDisease Outbreak in British Columbia*. Prepared for: Investment Agriculture Foundation of BC, Abbotsford, BC. Feburary, 2010.

Sparling, D. and B. Sterling. "Food Traceability: Understanding Business Value." RCM Technologies Canada, 2004.

Sparling, D., S. Henson, S. Dessureault, and D. Herath. "Costs and Benefits of Traceability in the Canadian Dairy-Processing Sector." *Journal of Food Distribution Research* 37(March 2006):154-160.

Statistics Canada Website. *"2006 Census of Agriculture"* Internet Site: http://www.statcan.gc.ca/ca-ra2006/index-eng.htm (Accessed September 11th 2010).

Stott, A.W., J. Lloyd, R.W. Humphry, and G.J. Gunn. "A linear programming approach to estimate the economic impact of bovine viral diarrhea (BVD) at the whole-farm level in Scotland." *Preventative Veterinary Medicine* 59(2003):51-66.

Sumner, D.A. Boxed In Conflicts between U.S. Farm Policies and WTO Obligations. Cato Institute, Center for Trade Policy Studies, Washington DC, 2005.

Sumner, D.A., and M.K. Wohlgenant. "Effects of an Increase in the Federal Excise Tax on Cigarettes." *American Journal of Agricultural Economics* 67(May 1985):235-242.

Thompson, D., P. Muriel, D. Russell, P. Osborne, A. Bromley, M. Rowland, S. Creigh-Tyte, and C. Brown. "Economic Costs of the Foot and Mouth Disease Outbreak in the United Kingdom in 2001." *Revue Scientifique et Technique de l'Office International des Epizooties* 21(2002):675-687.

United States Department of Agriculture (USDA) Website. *"Animal Disease Traceability."* Internet site: http://www.aphis.usda.gov/traceability (Accessed July 5th 2010).

Ward, M., L.D. Highfield, P. Vongseng, and M.G. Garner. "Simulation of foot-and-mouth disease spread within an integrated livestock system in Texas, USA." *Preventative Veterinary Medicine* 88(2009):286-297.

Wohlgenant, M.K. "Distribution of Gains from Research and Promotion in Multi-Stage Production Systems: The Case of the U.S. Beef and Pork Industries." *American Journal of Agricultural Economics* 75(1993):642-651.

World Organization for Animal Health (OIE) Website. *“Terrestrial Health Code”* Internet site: http://www.oie.int/eng/normes/mcode/en_sommaire.htm (Accessed June 16th 2009).

Young, L.M., and J. M. Marsh. “Integration and interdependence in the U.S. and Canadian live cattle and beef sectors.” *The American Review of Canadian Studies* 28(1998):335-354.

Zhao, Z., T.I. Wahl, and T.L. Marsh. “Invasive Species Management: Foot-and-Mouth Disease in the U.S. Beef Industry.” *Agricultural and Resource Economics Review* 35(April 2006):98-115.

Appendix

Figure A.1. Density of swine animals in Southern-Ontario

Note: Number of swine animals per hectare of farm land.
Source: 2006 Censes of Agriculture. Original figure produced by Remote Sensing and Geospatial Analysis, Agriculture Division, Statistics Canada, 2010.

Figure A.2. Density of swine animals in Canada

Note: Number of swine animals per hectare of farm land.
Source: 2006 Censes of Agriculture. Original figure produced by Remote Sensing and Geospatial Analysis, Agriculture Division, Statistics Canada, 2010.

Table A.1. NAADSM output statistics

Output Statistic	Description
tscUSusc	Number of units that become susceptible over an iteration
tscASusc	Number of animals that become susceptible over an iteration
tscULat	Number of units that become latent over an iteration
tscALat	Number of animals that become latent over an iteration
tscUSubc	Number of units that become subclinical over an iteration
tscASubc	Number of animals that become subclinical over an iteration
tscUClin	Number of units that become clinical over an iteration
tscAClin	Number of animals that become clinical over an iteration
tscUNImm	Number of units that become naturally immune over an iteration
tscANImm	Number of animals that become naturally immune over an iteration
tscUVImm	Number of units that become vaccine immune over an iteration
tscAVImm	Number of animals that become vaccine immune over an iteration
tscUDest	Number of units that are destroyed over an iteration
tscADest	Number of animals that are destroyed over an iteration
infcUIni	Number of units that are initially infected over an iteration
infcAIni	Number of animals that are initially infected over an iteration
infcUAir	Number of units that are infected by airborne spread over an iteration
infcAAir	Number of animals that are infected by airborne spread over an iteration
infcUDir	Number of units that are infected by direct contact over the course of an iteration
infcADir	Number of animals that are infected by direct contact over the course of an iteration
infcUInd	Number of units that are infected by indirect contact over the course of an iteration
infcAInd	Number of animals that are infected by indirect contact over the course of an iteration
infcUTotal	Total number of units that become infected over the course of an iteration
infcATotal	Total number of animals that become infected over the course of an iteration
expcUDir	Total number of units directly exposed to any infected unit during the course of an iteration
expcADir	Total number of animals directly exposed to any infected unit during the course of an iteration
expcUInd	Total number of units indirectly exposed to any infected unit during the course of an iteration
expcAInd	Total number of animals indirectly exposed to any infected unit during the course of an iteration
expcUTotal	Total number of units exposed to any infected unit during the course of an iteration
expcATotal	Total number of animals exposed to any infected unit during the course of an iteration
trcUDir	Number of units directly exposed and successfully traced over the course of an iteration
trcADir	Number of animals directly exposed and successfully traced over the course of an iteration
trcUInd	Number of units indirectly exposed and successfully traced over the course of an iteration

Note: The term unit refers to an individual herd.

Table A.1. NAADSM output statistics, continued

Output Statistic	Description
trcAInd	Number of animals indirectly exposed and successfully traced over the course of an iteration
trcUDirp	Number of units directly exposed could have been possibly traced over the course of an iteration
trcADirp	Number of animals directly exposed could have been possibly traced over the course of an iteration
trcUIndp	Number of units indirectly exposed could have been possibly traced over the course of an iteration
trcAIndp	Number of animals indirectly exposed could have been possibly traced over the course of an iteration
detcAClin	Number of animals detected by clinical signs over the course of an iteration
descUIni	Number of units destroyed prior to the start of the simulation
descAIni	Number of animals destroyed prior to the start of the simulation
descUDet	Number of units destroyed because they were detected positive over the course of an iteration
descADet	Number of animals destroyed because they were detected positive over the course of an iteration
descUDir	Number of units destroyed because they were direct traces over the course of an iteration
descADir	Number of animals destroyed because they were direct traces over the course of an iteration
descUInd	Number of units destroyed because they were indirect traces over the course of an iteration
descAInd	Number of animals destroyed because they were indirect traces over the course of an iteration
descURing	Number of units destroyed because they were in a destruction ring during the course of an iteration
descARing	Number of animals destroyed because they were in a destruction ring during the course of an iteration
descUTotal	Total number of units destroyed for any reason over the course of an iteration
descATotal	Total number of animals destroyed for any reason over the course of an iteration
vaccUIni	Total number of units that were vaccine immune prior to the start of the simulation
vaccAIni	Total number of animals that were vaccine immune prior to the start of the simulation
vaccURing	Total number of units vaccinated in rings around detected-infected units over the course of an iteration
vaccARing	Total number of animals vaccinated in rings around detected-infected animals over the course of an iteration
zoncFoci	Total number of new zone foci created around units of the indicated type over the course of an iteration
detOccurred	Number of iteration in which infected units were detected
firstDetection	Day of first detection of an infected unit in the specified iteration
vaccOccurred	Number of iterations in which vaccinations occurred
firstVaccination	Day of first vaccination of a infected unit in the specified iteration
destrOccurred	Number of iterations in which destruction occurred
firstDestruction	Day of first destruction of a infected unit in the specified iteration
diseaseEnded	Number of iterations in the active disease phase ended
diseaseDuration	Duration of the active disease phase in the specified iteration
outbreakEnded	Number of iterations in which the outbreak ended
outbreakDuration	Duration of the outbreak in the specified iteration

Note: The term unit refers to an individual herd.

Table A.2. Miscellaneous parameters used in the epidemiological model

Parameter Description	Parameter Value
Shipping delay for direct and indirect contacts	24 hours
Ability of latent units to cause infection by direct contact	Yes
Probability of infection through airborne spread	0.01*
Wind Direction	360 degrees
Distribution used to represent airborne spread	exponential
Airborne spread transport delay	24 hours
Destruction program delay	24 hours

Note: Higher of the two estimates that were provided by the source.
Source: Personal Communication with Dr. Emery Leger of the CFIA.

Table A.3. Parameterization for reduced movement restriction scenario

Movement restriction	Number of days following zone creation	Percentage of movements still permitted
Direct contacts in disease free and security zones	0	100%
	1	50%
	5	10%
Indirect contacts in disease free and security zones	0	100%
	1	100%
	5	60%
Direct contacts in infected zone	0	10%
	1	6%
	2	1%
Indirect contacts in infected zone	0	20%
	1	10%
	2	6%
Direct contacts in restricted zone	0	100%
	1	26%
	5	6%
Indirect contacts in restricted zone	0	100%
	1	60%
	5	30%

Note: Relation functions of the effectiveness of movement restrictions.

Table A.4. Epidemiological results without preemptive destruction of direct contacts

	Traceability Scenario		
Output Statistic	Low	Medium	High
Outbreak duration (days)	86.53	86.59	86.46
Standard deviation of outbreak duration	37.14	37.33	33.79
Number of infected zones	90.31	87.50	88.59
Number of farms directly exposed and successfully traced	2.67	4.84	7.32
Number of farms infected by direct contact	8.08	8.47	7.78
Number of farms infected by indirect contact	10.36	9.91	10.00
Number of farms infected by airborne transmission	70.68	68.68	69.99
Beef cattle destroyed (head)	5,444	5,267	5,304
Dairy cattle destroyed (head)	2,499	2,418	2,449
Swine destroyed (head)	13,039	12,440	12,876
Total animals destroyed (head)	20,983	20,127	20,630
Standard deviation of total animals destroyed	15,559	13,731	14,363

Notes: Results display the mean output values of 1000 iterations of the disease spread. High contact rate scenario.

Table A.5. Epidemiological results of the feedlot introduction scenario

	Traceability Scenario		
Output Statistic	Low	Medium	High
Outbreak duration (days)	28.56	28.18	27.85
Standard deviation of outbreak duration	20.51	21.28	19.94
Number of infected zones	5.94	5.69	5.69
Number of farms directly exposed and successfully traced	0.06	0.10	0.17
Number of farms infected by direct contact	0.20	0.19	0.18
Number of farms infected by indirect contact	0.88	0.84	0.82
Number of farms infected by airborne transmission	3.90	3.74	3.80
Beef cattle destroyed (head)	737	736	733
Dairy cattle destroyed (head)	109	107	107
Swine destroyed (head)	1,285	1,138	1,147
Total animals destroyed (head)	2,132	1,980	1,986
Standard deviation of total animals destroyed	3,627	3,417	3,712

Notes: Results display the mean output values of 1000 iterations of the disease spread. High contact rate scenario.

Table A.6. Epidemiological results when increasing the number of iterations in the high contact rate scenario

	Traceability Scenario		
Output Statistic	Low	Medium	High
Outbreak duration (days)	86.37	86.09	85.68
Standard deviation of outbreak duration	36.45	36.38	35.97
Number of infected zones	89.36	86.67	84.65
Number of farms directly exposed and successfully traced	2.65	4.85	7.32
Number of farms infected by direct contact	8.54	8.29	8.08
Number of farms infected by indirect contact	10.07	9.71	9.47
Number of farms infected by airborne transmission	70.90	69.49	68.56
Beef cattle destroyed (head)	5,427	5,324	5,245
Dairy cattle destroyed (head)	2,500	2,441	2,392
Swine destroyed (head)	12,929	12,804	12,522
Total animals destroyed (head)	20,857	20,569	20,158
Standard deviation of total animals destroyed	16,333	16,350	15,515

Note: Results display the mean output values of 10,000 iterations of the disease spread.

Table A.7. Direct disease outbreak costs for the feedlot introduction scenario

Disease Outbreak Cost	Operation Type	Traceability Scenario Low	Medium	High
Surveillance	All	15,910,290	15,227,151	15,215,416
Indemnity	Beef	700,492	699,286	695,951
	Dairy	218,220	213,200	214,000
	Swine	188,913	167,213	168,552
	Total	1,107,625	1,079,698	1,078,503
Euthanasia	Beef	73,736	73,609	73,258
	Dairy	10,911	10,660	10,700
	Swine	25,702	22,750	22,932
	Total	110,349	107,019	106,890
Cleaning and Disinfection	Beef	147,472	147,218	146,516
	Dairy	21,822	21,320	21,400
	Swine	32,128	28,438	28,665
	Total	201,422	196,976	196,581
Disposal	Beef	294,944	294,436	293,032
	Dairy	43,644	42,640	42,800
	Swine	51,405	45,500	45,864
	Total	389,993	382,576	381,696
	Total direct outbreak cost	$17,719,678.84	$16,993,419.75	$16,979,086.15

Notes: Results displayed are calculated from the mean values of 1000 iterations of the disease spread. High contact rate scenario.

Table A.8. Welfare changes generated by the feedlot introduction scenario

	Traceability Scenario		
	Low	Medium	High
Change in consumer welfare	440,184,746	438,867,938	437,594,458
Change in producer welfare			
Retail	-1,698,496,416	-1,692,949,193	-1,688,263,708
Wholesale beef	-600,419,916	-598,455,658	-596,800,684
Fed cattle	-835,244,513	-832,396,388	-830,146,733
Feeder cattle	-279,220,885	-278,408,674	-277,585,121
	-3,413,381,731	-3,402,209,914	-3,392,796,245
Total change in welfare	-$2,973,196,984	-$2,963,341,977	-$2,955,201,786

Notes: Results displayed are calculated from the mean output values of 1000 iterations of the disease spread. Direct disease control costs are bared by the producer. High contact rate scenario.

Table A.9. Welfare changes generated when costs split 50-50

	Traceability Scenario		
	Low	Medium	High
Change in consumer welfare	673,439,608	668,062,454	662,631,506
Change in producer welfare			
Retail	-2,504,744,951	-2,487,486,726	-2,469,790,717
Wholesale beef	-884,354,112	-878,296,127	-872,078,679
Fed cattle	-1,200,735,408	-1,193,451,171	-1,185,840,877
Feeder cattle	-424,925,076	-421,651,199	-418,302,129
	-5,014,759,548	-4,980,885,223	-4,946,012,402
Total change in welfare	-$4,341,319,940	-$4,312,822,769	-$4,283,380,896

Notes: Results displayed are calculated from the mean output values of 1000 iterations of the disease spread. High contact rate scenario.

Table A.10. Welfare changes generated when government bears all outbreak costs

	Traceability Scenario		
	Low	Medium	High
Change in consumer welfare	657,303,500	652,461,239	647,521,899
Change in producer welfare			
Retail	-2,539,931,455	-2,521,368,688	-2,502,553,973
Wholesale beef	-897,906,760	-891,346,765	-884,698,815
Fed cattle	-1,250,178,679	-1,241,099,576	-1,231,932,085
Feeder cattle	-416,973,589	-413,913,863	-410,790,352
	-5,104,990,483	-5,067,728,892	-5,029,975,225
Total change in welfare	-$4,447,686,983	-$4,415,267,653	-$4,382,453,326

Notes: Results displayed are calculated from the mean output values of 1000 iterations of the disease spread. High contact rate scenario.

Table A.11. Welfare changes generated by a 50% more-inelastic supply

	Traceability Scenario		
	Low	Medium	High
Change in consumer welfare	545,517,428	540,335,333	535,202,689
Change in producer welfare			
Retail	-5,350,636,883	-5,316,172,963	-5,280,328,663
Wholesale beef	-1,062,080,220	-1,055,316,251	-1,048,265,885
Fed cattle	-955,106,253	-950,883,755	-946,145,262
Feeder cattle	-324,267,849	-321,390,275	-318,465,286
	-7,692,091,205	-7,643,763,244	-7,593,205,097
Total change in welfare	-$7,146,573,777	-$7,103,427,910	-$7,058,002,407

Notes: Supply elasticities were multiplied by 0.5. Results displayed are calculated from the mean output values of 1000 iterations of the disease spread. High contact rate and producers bear direct outbreak costs.

Table A.12. Welfare changes generated by a 50% more-elastic supply

	Traceability Scenario		
	Low	Medium	High
Change in consumer welfare	804,522,840	798,010,759	791,442,485
Change in producer welfare			
Retail	-1,300,975,587	-1,292,560,312	-1,283,820,931
Wholesale beef	-647,754,979	-643,608,967	-639,294,738
Fed cattle	-1,127,304,103	-1,121,885,591	-1,115,925,723
Feeder cattle	-513,750,236	-509,827,876	-505,787,973
	-3,589,784,905	-3,567,882,746	-3,544,829,365
Total change in welfare	-$2,785,262,064	-$2,769,871,988	-$2,753,386,880

Notes: Supply elasticities were multiplied by 1.5. Results displayed are calculated from the mean output values of 1000 iterations of the disease spread. High contact rate and producers bear direct outbreak costs.

Table A.13. Welfare changes generated by a 50% more-inelastic demand

	Traceability Scenario		
	Low	Medium	High
Change in consumer welfare	1,745,356,512	1,731,678,442	1,717,827,542
Change in producer welfare			
Retail	-1,512,571,438	-1,502,782,053	-1,492,619,281
Wholesale beef	-965,193,638	-959,000,659	-952,561,148
Fed cattle	-2,086,147,785	-2,074,966,062	-2,062,940,010
Feeder cattle	-1,120,758,149	-1,112,243,466	-1,103,528,838
	-5,684,671,009	-5,648,992,240	-5,611,649,277
Total change in welfare	-$3,939,314,496	-$3,917,313,798	-$3,893,821,735

Notes: Demand elasticities were multiplied by 0.5. Results displayed are calculated from the mean output values of 1000 iterations of the disease spread. High contact rate and producers bear direct outbreak costs.

Table A.14. Welfare changes generated by a 50% more-elastic demand

	Traceability Scenario		
	Low	Medium	High
Change in consumer welfare	395,172,895	391,566,910	387,979,767
Change in producer welfare			
Retail	-2,708,628,711	-2,691,157,199	-2,672,993,315
Wholesale beef	-679,840,581	-675,508,088	-670,993,384
Fed cattle	-686,309,711	-683,643,181	-680,558,884
Feeder cattle	-239,050,515	-237,081,617	-235,046,494
	-4,313,829,517	-4,287,390,086	-4,259,592,076
Total change in welfare	-$3,918,656,622	-$3,895,823,176	-$3,871,612,309

Notes: Demand elasticities were multiplied by 1.5. Results displayed are calculated from the mean output values of 1000 iterations of the disease spread. High contact rate and producers bear direct outbreak costs.

Table A.15. Change in welfare losses in billions of dollars generated by the elasticity sensitivity analysis

	Supply Elasticities		Demand Elasticities	
	50%-more Inelastic	50%-more Elastic	50%-more Inelastic	50%-more Elastic
Marketing Level				
Retail	-5.5	-3.6	-4.7	-3.9
Wholesale beef	-4.9	-3.8	-4.1	-4.3
Fed cattle	-4.8	-3.8	-4.4	-4.2
Feeder cattle	-4.3	-4.1	-3.8	-4.4

Note: Elasticity parameters for each marketing level are changed individually.