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The Benefits of Animal Traceability Systems on a Foot-and-Mouth Disease Outbreak in Utah

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THE BENEFITS OF ANIMAL TRACEABILITY SYSTEMS ON

A FOOT-AND-MOUTH DISEASE OUTBREAK IN UTAH

by

Christian Michael Ukkestad

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ABSTRACT

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Major Professor: Dr. DeeVon Bailey
Department: Applied Economics

This thesis estimates the impact of increased animal traceability on the immediate social welfare losses resulting from an outbreak of FMD in Utah to the cattle, pork and poultry industries in the state and the United States as a whole. An epidemiological model was used to simulate the spread of the disease throughout the livestock population of Utah and estimate a mean number of animals depopulated over 1000 iterations for low, medium and high levels of trace intensity. This number of animals depopulated was then used to create supply shocks in an equilibrium displacement model. This model revealed the welfare losses across four marketing levels for beef, three for pork and two for pork. The research contained in this thesis determined that the adoption of a high intensity trace system can prevent immediate welfare losses of between $131 and $190 million for the United States beef industry including $49 million to the Utah fed cattle, feeder cattle and market hog marketing levels.

(126 Pages)

PUBLIC ABSTRACT

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In recent decades, a number of foot-and-mouth disease (FMD) outbreaks have occurred in countries that had been FMD-free for many years. The last FMD outbreak in the United States occurred in 1929 and the country contains a naïve livestock population, meaning it is susceptible to an outbreak. In the event of an FMD outbreak in the United States, the speed at which the source and contacts between livestock can be identified impacts both the implementation and effectiveness of mitigation strategies. The purpose of this thesis was to analyze the impact of higher levels of animal traceability on the immediate welfare losses resulting from an FMD outbreak originating in Utah.

An epidemiological model was used to simulate the spread of the disease throughout the livestock population of Utah and estimate a mean number of animals depopulated over 1000 iterations for low, medium and high levels of trace intensity. This number of animals depopulated was then used to create supply shocks in an equilibrium displacement model. This model revealed the welfare losses across four marketing levels for beef, three for pork and two for pork. The research contained in this thesis determined that the adoption of a high intensity trace system can prevent immediate welfare losses of between $131 and $190 million for the United States beef industry, including $49 million to the Utah fed cattle, feeder cattle and market hog marketing levels.

(126 Pages)

DEDICATION

To the memory of my dad, Dennis Ukkestad (1946 – 2007),

and to my mom, Debora Ukkestad for their constant

love, support and encouragement.

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I would like to acknowledge everyone who has contributed to this thesis, both in terms of intellectual assistance and through moral encouragement. I am very grateful and indebted to my committee members for their patient guidance and helpful criticisms that improved the quality of my research. Particular thanks to Dr. Bailey who was constantly available to answer my questions and provide guidance which has been invaluable in this process. I am also grateful to Dr. Brester and Dr. Atwood of Montana State University who took the time to meet with me and patiently explain how to develop the model used in this thesis. Lastly, I would like to thank my family, friends, professors and fellow students for all the kind words and constant encouragement.

Michael Ukkestad

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CHAPTER 1

INTRODUCTION

Foot-and-Mouth Disease (FMD) is a highly contagious viral disease that affects cloven-hoofed animals such as cattle, swine, sheep and goats. The viral infection manifests with blisters around the mouth, hooves, teats and udder of an infected animal and can cause a loss of appetite and decreased mobility in its host. Despite a low mortality rate among infected adult animals and its harmlessness to humans, the disease causes decreased milk and meat yields which result in productivity losses. The disease can be transmitted directly through animal movement or indirectly through non-animal fomites or airborne transmission. An infected animal can be infected and transmit the virus before showing any clinical signs which makes immediate prevention problematic.

Due to the production losses that result from FMD and the economic consequences of culling exposed animals, the World Organization for Animal Health (OiE) has established a list of countries that are FMD-free. Countries that have this status have an incentive to not trade with countries where the disease is present due to the potential costs of an outbreak and the large premiums placed on FMD-free meat (Ekboir *et al*., 2002). The trade effects of livestock-borne diseases can be seen in the experience of the United States when a dairy cow was identified with Bovine Spongiform Encephalopathy (BSE) in 2003. Following detection, a number of the United States' major trading partners ceased trading and cattle-related exports dropped to nearly one fifth of their previous total. The losses of this incident amounted to between $3.2 and $4.7 billion (Coffrey *et al*., 2005).

As global food supply chains have become more interconnected, the risk of transmission has become a major concern for livestock exporters (Park *et al*., 2008).

The last FMD outbreak in the United States occurred in 1929 and originated among a group of hogs who consumed contaminated meat from Argentina. North America experienced its last outbreak in 1952 in Saskatchewan. Regardless of the duration of time that a country has been free of the Foot-and-Mouth Disease virus, all countries remain at risk of a recurrence. Following a 68-year period of maintaining FMD-free status, Taiwan experienced a crippling outbreak among swine that cost the country approximately $378.6 million (Yang *et al*., 1999). Indirect contact through imported straw that was contaminated with FMD led to an outbreak in South Korea after going eight years without an incident (Sugiura *et al*., 2001). Following the events of 11 September, 2001, the increased awareness that an intentional introduction of the virus by terrorists has also led to a reconsideration of biosecurity plans to avoid the consequences of such an attack (Waage *et al*., 2008; Farsang *et al*., 2013).

Livestock in Utah

Livestock comprises a major portion of the state agricultural economy of Utah. According to the USDA's 2012 Census of Agriculture, livestock and livestock products make up 68 percent of the market value of all agricultural products sold; a total of nearly $1.24 billion. Beef and dairy production make up the largest portion of livestock sales in Utah with $364.2 million and $326.4 million in sales in 2012, respectively. Hogs and pigs consist of $290.6 million while sheep, goats and other animals and animal products comprise the remainder.

While livestock production is a significant part of the state economy, Utah is only a moderately-ranked producer on a national scale, ranking 23rd in dairy production, 33rd in cattle, 14th in swine and 8th in sheep. While an FMD outbreak can be expected to have a significant impact on the state economy due to containment costs, loss of livestock, and movement controls, the entire country would also suffer from the trade restrictions that follow the loss of FMD-free status – even though this particular population is only a moderate segment of the national livestock population. Due to the small percentage of the United States' livestock population within Utah, the use of the state in this analysis not only allows for the examination of statewide effects but also allows the importance of animal identification for the nation as a whole given an outbreak even among a small population.

Objectives

Due to the delay in the presentation of clinical signs and the highly contagious nature of the FMD virus, immediate detection is crucial to disease-control efforts. Previous studies have addressed the reliance of mitigation strategies on early detection in to limit the size, duration and economic impact of an FMD outbreak (Keeling *et al.,* 2001; Pendell, 2006; Jones, 2010).

This thesis is designed to analyze the immediate economic welfare impacts of a hypothetical FMD outbreak among livestock in Utah under different levels of traceability. These levels of traceability will reflect improvements in animal identification that would allow for higher probabilities of a successful trace-back. Following Pendell (2006) and Jones (2010), an epidemiological model will be used to simulate an FMD outbreak among livestock in Utah to assess the impact of varying depths of traceability on the size and duration of the outbreak. A partial equilibrium framework known as an equilibrium displacement model (EDM) will be used determine the immediate welfare effects for both producers and consumers under each level of traceability for the duration of the outbreak. Using this epidemiological-economic framework, this thesis will attempt to demonstrate the impact of increased levels of animal identification for Utah in reducing the economic effects during the duration of an outbreak for the state and for the United States.

Organization of the Thesis

Chapter 2 provides an overview of the characteristics and economic impact of FMD, the previous modelling of FMD and the development of EDM for measuring welfare changes. Chapter 3 discusses the specification and assumptions of the North American Animal Disease Spread Model (NAADSM) that is used to simulate the spread of FMD among livestock in Utah. Chapter 4 explains the specification of the equilibrium displacement model utilized in this paper to demonstrate the welfare effects of the simulated outbreaks. Chapter 5 explains the source data used in the parameterization of both the epidemiological and economic models. Finally, Chapter 6 will present the results and implications of the research for animal identification systems for Utah and the United States.

CHAPTER 2

LITERATURE REVIEW

FMD is a highly contagious virus of the genus Aphthovirus that affects cloven-hoofed animals such as bovine, caprine, ovine, porcine and cervidaes. There are seven serotypes of the virus: O, A, C, South African Territories (SAT) 1, 2, 3 and Asia 1; and over 60 subtypes. These serotypes and strains vary across geographic region. Types O, A and Asia 1 are commonly found across Asia. Types O, A and C are present in Europe and parts of South America. A, O, Asia 1 and SAT 1 have been observed in the Middle East while strains 1, 2 and 3 of SAT have been identified in Africa. The intensity of viral prevalence also varies between geographic region with widespread FMD throughout Africa and Asia, sporadic disease presence in South America and several years of disease-free status in North America and Europe (USAHA, 2007). New Zealand remains the only country to have never had an FMD outbreak (Grubman and Baxt, 2004).

FMD presents with blisters around the mucosa of the mouth, the coronary band of the foot and on the teats or udder. It can also manifest with excess salivation, lameness, lethargy, fever, and anorexia. In adults, FMD has a high level of morbidity but low mortality while young animals have higher mortality due to necrosis of the heart muscle (Alexandersen *et al*., 2003). Typically, fewer than six percent of adult animals are killed by the disease (Mahul and Gohin, 1999) while mortality is about 80 percent in young animals (Rich *et al*., 2005).

The manifestation of clinical signs of FMD varies across species. In cattle, the infected animal develops a fever and lesions in and around the mouth while exhibiting a loss in weight and milk production (Mahul and Gohin, 1999). Pigs exhibit the most severe foot lesions and often present with lameness that progresses to muscle control problems and the shedding of claws (Yoon *et al*.,2012). Sheep develop the least severe clinical signs and have been frequently misdiagnosed (Ayers *et al*., 2001; Black *et al*., 2004).

All cloven-hoofed animals are susceptible to the FMD virus with naïve populations being particularly at risk (Barnett *et al*., 2002). The virus enters susceptible animals through the respiratory tract or through abrasions around the mouth, feet or teats (Sellers and Parker, 1969). The incubation period of the FMD virus is 2 to 14 days but varies according to strain, dose, species, transmission route and environment (Alexandersen *et al*., 2003). The virus can be detected from secretions for up to 5 days prior to the appearance of clinical signs, which can affect early detection of the virus (Sellers and Parker, 1969; Burrows *et al*., 1981).

The FMD virus can be transmitted through either direct or indirect contact. Direct contact consist of the movement of infected animals and is the most common and important method of disease transmission (Woolhouse *et al*., 2001; Kitching *et al*., 2005; Dube *et al*., 2009). According to the United States Animal Health Association’s Foreign Animal Diseases, over 68 percent of documented outbreaks from 1870 to 1963 were caused by the importation of infected animals or animal products (USAHA, 2007, p. 272). Indirect routes of transmission included non-animal fomites such as contaminated facilities, transportation, clothing, air and animal products such as meat, milk and semen (Ellis-Iversen *et al*., 2001; Fevre *et al*., 2006). While FMD is extremely rare in human beings, they may act as carriers with the virus remaining in their upper respiratory tract for up to 28 hours. Indirect contact through contaminated straw was the source of the

2000 FMD outbreak in the Republic of Korea (Sugiura *et al*., 2001). The aerosolized virus can be carried by the wind for up to 60 kilometers over land or 250 kilometers over water (Burrell and Mangen, 2001; Gloster *et al*., 2011). The threat of airborne transmission was observed in 1981 when the FMD virus was transmitted from swine in France to cattle on the Island of Jersey to the English coast (Donaldson *et al.*, 1982). Contact rates between species vary between regions due to production structures, management practices and movement patterns (Premashthira *et al*., 2011; McReynolds *et al*., 2014).

A significant degree of variance exists in the transmission of the FMD virus between infected animals due to differences in serotype, the timing of clinical signs and viral shedding among species (Kitching, 2005; Honhold *et al*., 2011). Swine exhale the largest amount of the virus and are considered amplifiers of airborne transmission (Sellers and Parker, 1969; Alexandersen *et al*., 2003). Swine, however, require significantly higher dosages of the virus for aerosolized infection (Kitching *et al*., 2005). Cattle and sheep, however, are highly susceptible to airborne infection by even a small dosage of the virus (Kitching, 2005). Cattle are generally the first animal to show signs of infection which makes them a good indicator of an FMD outbreak.

The Economic Impact of FMD Outbreaks

As mentioned above, despite the low mortality and non-zoonotic nature of FMD, an outbreak results in animal debilitation and substantial losses in both milk and meat production. Chronic FMD has been found to reduce milk yields by up to 80 percent (Bayissa *et al*., 2011) and can remain reduced by a third 60 days after an outbreak

(Ferrari *et al*., 2013). This has resulted in countries that are FMD-free ceasing trade with countries that have had outbreaks of the virus which results in severe economic losses for the impacted region (Knight-Jones and Rushton, 2013). FMD impacts every stage of cattle production through, breeding, feeding and marketing (Noguiera *et al*., 2011). As food supply chains have become increasingly globalized, the impact of a potential FMD outbreak on international trade has grown to be a major concern for livestock exporters (Park *et al*., 2008). Export countries have a vital interest in maintaining OiE FMD-free status to maintain trade relationships since FMD-free countries restrict the importation of meat and livestock from countries that are not designated as such (Burrell and Mangen, 2001; Rich *et al*., 2007).

FMD outbreaks have occurred in countries and regions that have previously been FMD-free. After an eight-year span, the Republic of Korea had an FMD outbreak that resulted in the culling of 151,425 cattle, 3,318,299 pigs, 8,071 goats and 2,728 deer (Park *et al*., 2013). After 68 years of FMD-free status, a 1997 outbreak among swine in Taiwan cost the country an estimated $378.6 million (Yang *et al.,* 1999). Following 34 years of being FMD-free, the United Kingdom experienced an outbreak that resulted in over eight million animals being culled (Sutmoller *et al*., 2003). The cost from the outbreak in the UK, both from loss of animals and from trade losses, is estimated to be between $3.6 and $11.6 billion (Noguiera *et al*., 2011). The 2001 U.K. outbreak spread via animal shipments to the Netherlands which resulted in 267,922 animals being culled there (Bouma *et al*., 2003).

North America has been FMD-free since the 1952 Canadian outbreak and has a naïve livestock population. FMD was first detected in the United States in 1870 and there were eight subsequent outbreaks with the last being in 1929. The largest outbreak in United States history began in Michigan in 1914 and spread as far south as Chicago by 1915. A 1924 outbreak in northern Calfornia spread from livestock to the local cervid population resulting in 109,000 cattle, sheep and swine being culled in addition to 22,000 deer (McCauley *et al*., 1979).

Epidemiological Modelling

Epidemiological modelling is a useful tool in the analysis of potential disease outbreaks under alternate control strategies. Simulations are particularly useful in countries where a particular disease is not present and therefore cannot be studied through observation (Mardones *et al*., 2010). Due to this constraint, contagion models have been crucial in estimating the impact of hypothetical FMD outbreaks in a United States context.

The mathematical modelling of disease outbreaks has its origins in the 1920s when a simple, iterative chain binomial model was put forth by Reed and Frost (Abbey, 1952). Eventually, stochastic elements began to be incorporated in the models to reflect variation and parameter uncertainty more accurately than deterministic models (Bartlett, 1953). Early epidemiological models were also non-spatial and assumed homogenous or random contact between units which led to inaccurate and underestimated transmission rates since contact probability is a function of the distance between operations (Carpenter *et al.*, 2011). Models with a spatial element including accurate estimations of farm locations, also allow for more accurately estimated transmission, depletion and mitigation rates (Tildesley *et al*., 2011).

The first epidemiological model to examine the impact of a hypothetical FMD outbreak was a state-transition model (Abbey, 1953). This model included the epidemiological states of susceptible, infected, immune and removed. The model demonstrated that a potential FMD outbreak in the United States would affect a minimum of 60 percent of the livestock population by week 30 and that 19 percent would be destroyed. This paper included no economic analysis.

Berensten *et al.* (1992) added an economic dimension to a state-transition model to calculate the direct and indirect costs to producers, consumers and the government of an FMD outbreak under different vaccination strategies. The paper determined that no annual vaccination strategy was preferable to annual vaccinations due to low control costs and the fact that vaccination had no impact on the entry of animals into FMD-free export markets.

Garner and Lack (1995) combined a stochastic, Markov-Chain state-transition epidemiological simulation with an input-output analysis to estimate the direct and indirect economic effects of an FMD outbreak under alternate control strategies in Australia. This paper determined that destroying infected and dangerous contact herds reduced the duration of the outbreak and the number of premises that became infected.

Ekboir (1999) also used a Markov-Chain state-transition model to assess the impact of an FMD outbreak in four Californian counties. The simulation included five disease states (susceptible, latent, infected, immune and depopulated) and the direct costs of destruction, disinfecting and quarantine. The epidemiological simulation was combined with input-output analysis using IMPLAN to determine the direct, indirect and induced losses for California. The paper determined that non-vaccination strategies were the least expensive and that immediate mitigation was vital to stemming an outbreak.

Keeling *et al*. (2001) developed a stochastic farm-based model of the 2001 FMD outbreak in the United Kingdom that included susceptible, incubating, infectious and slaughtered states. The authors found that the more quickly a disease control strategies can be implemented significantly reduced the impact of an outbreak. No economic analysis was included in the Keeling *et al*. (2001) study.

Following Garner and Lack (1995) and Disney *et al*. (2001), Schoenbaum and Disney (2003) used a stochastic, state-transition model to simulate an FMD outbreak in three circular regions in the United States. After running 72 scenarios, the paper determined that the best control strategy is highly dependent on herd demographics and regional contact rates.

Bates *et al.* (2003) performed a benefit-cost analysis of alternate control strategies a stochastic, spatial, state-transition simulation in three Californian counties. The paper utilized direct and indirect contact rates as well as travel distance form surveys and interviews to better parameterize the model. The authors determined that ring vaccination strategies were most effective but did not consider the economic effects of trade – a major factor in the economic impact of FMD outbreaks.

Rich (2004) utilized a dynamic, spatial simulation of FMD along with a mixed complementary programming model to analyze alternate mitigation strategies for Argentina, Uruguay, Paraguay and southern Brazil. The paper revealed that control methods should be continental and not regional due to the presence of externalities.

Le Menach *et al*. (2005) performed an FMD simulation and determined that pre-emptive culling and ring vaccination had the greatest impact on disease duration. The paper also examined the variation in the disease transmission due to the location, size and production type of the operation. This finding is supported by Dickey *et al*. (2008).

Zhao *et al.* (2006) used a deterministic, dynamic, state-transition epidemiological-economic framework to analyze the impact of an outbreak under alternate control strategies. The model included production, consumption and international trade elements. The paper demonstrated that increased levels of traceability was inversely related with the costs of an outbreak and the number of animals destroyed. Increased levels of traceability was also correlated with smaller welfare losses.

Looney (2009) used an epidemiological simulation called AusSpread to assess the impact of a traceability system on the direct costs of an outbreak. The paper used the number of days until dangerous contacts were found as a measure of traceability and included costs for slaughter, destruction, disposal, surveillance and disinfection to accurately depict various traceability scenarios. Contrary to Zhao *et al.* (2006), Pendell (2006) and Jones (2010), Looney (2009) found the number of days until dangerous contacts were found did not produce statistically significant results in the size of outbreaks.

This thesis will utilize the North American Animal Disease Spread Model (NAADSM) to estimate the economic impact of alternative traceability levels in the state of Utah. NAADSM is a stochastic, spatial, state-transition simulation model and is formally presented in Harvey *et al*. (2007). The epidemiological model and its assumptions are specified in Chapter 3.

Equilibrium Displacement Modelling

As briefly discussed in the previous section, many epidemiological models have been combined with different economic models. Rich *et al*. (2005) developed a typology of epidemiological-economic modelling based on the nature of the research question and unit of analysis being considered. The types of analysis identified are benefit-cost, linear programming, partial equilibrium, input-output and computable general equilibrium. This thesis is addressing a regional, state-level question concerning aggregate supply and demand functions for multiple markets and will use a form of partial equilibrium analysis known as an equilibrium displacement model.

Essentially, a linear elasticity model or equilibrium displacement model (EDM) is based around a set of comparative static results expressed in elasticity form. An EDM is a system of logarithmic differential equations that describe the movement from one equilibrium to another due to a change in at least one of the system parameters.

Muth (1964) was the first to build on insights from Hicks (1946) to present the reduced form system of supply and demand equations along with exogenous supply and demand shifters that characterizes an EDM. Muth derived a system of differential equations to analyze the impact of exogenous shifts in supply and demand using the elasticities to reflect the relationships between changes in the exogenous variables. The Muth model assumed product homogeneity, identical production function, that production is independent of output and that the market is perfectly competitive.

Gardner (1975) applied the framework developed by Muth (1964) to develop the implications to shifts in industry supply and demand for price spreads for food between farm and retail levels. Sumner and Wohlgenant (1985) was the first to use the term "equilibrium displacement model" and extended the framework to include linkages with trade in the final and farm-level product. Lemieux and Wohlgenant (1989) used an EDM to evaluate welfare changes to analyze the effects of new technology.

Wohlgenant (1993) further expanded the model to multi-stage industries to include exogenous shifts in retail demand, farm supply and the marketing sector. Lusk and Anderson (2004) used a model with supply and demand shifters to evaluate country-of-origin labelling (COOL). Brester *et al.* (2004) also used an EDM to address the impact of COOL in the United States meat industry across multiple marketing levels for beef/cattle, pork and poultry. The model included cross-sector linkages to account for inter-sector effects and allowed production quantities to vary across marketing levels to allow for variable input proportions. Consumer substation was also incorporated through the use of cross-elasticities within the primary demand functions.

Pendell (2006) applied a methodology similar to this thesis by using NAADSM and an EDM to address the welfare consequences of an FMD outbreak in southwestern Kansas under three different depths of traceability (30, 60 and 90 percent chance of a successful trace). Similar to Brester *et al.* (2004), Pendell included four marketing chain levels for beef, three for pork and two for poultry. The model accounted for variable input proportions, welfare measures, consumer substitutability and trade impacts. Jones (2010) applied a similar framework to a potential outbreak in Ontario, Canada using 30, 60 and 95 percent likelihoods of a successful trace to estimate depths of surveillance. The findings of both of these papers demonstrated that higher degrees of surveillance increase the speed at which control strategies can be implemented and limit the impact of an FMD outbreak.

Pendell *et al*. (2010) used an EDM to analyze the economic impacts of adopting an animal identification system for cattle, swine, lamb, poultry and meat sectors in the United States. The model included exogenous shifts that represented the increased costs of the imposed surveillance system upon the farm level while vertical linkages were used to translate the effects of the shift to all other marketing levels. The paper concluded that a retail beef demand increase of just one percent would outweigh the costs of the surveillance system.

This thesis will seek to apply the epidemiological-economic framework used by Pendell (2006) and Jones (2010) to the case of a hypothetical FMD outbreak in the state of Utah. Due to the chief importance of livestock and agriculture to the economy of the state, the ability to address the immediate consequences of alternate surveillance strategies is important in the event an outbreak does occur. This thesis also addresses the national impact of a Utah-based FMD outbreak and the resulting trade consequences that might occur. The following two chapters describe the epidemiological and economic models that will be used to address these issues.

CHAPTER 3

EPIDEMIOLOGICAL MODEL

As discussed in the previous chapter, epidemiological simulation programs have been vital in measuring the effects of potential control methods in limiting the impact of hypothetical disease outbreaks. These models have been particularly beneficial in measuring the effects of unobservable disease outbreaks such as the impact of an FMD outbreak in the United States. This thesis will utilize the North American Animal Disease Spread Model (NAADSM) to simulate an outbreak of FMD among livestock in the state of Utah. This chapter will describe the methodological considerations and parameters included in this model.

North American Animal Disease Spread Model (NAADSM)

NAADSM was developed under the guidance of the United States Department of Agriculture's Animal and Plant Health Inspection Services (APHIS). The model has been used by Pendell (2006), Pendell *et al*. (2007), Jones (2010), McReynolds (2013) and others to simulate outbreaks of FMD in particular regions of the United States and Canada and to analyze the impacts of various control strategies. The model incorporates many elements of previous simulation models such as the SpreadModel of Schoenbaum and Disney (2003) and the state-transition model of Garner and Lack (1995). The methodology and parameterization of NAADSM have been formally presented by Harvey *et al*. (2007) from which many of the parameter definitions and descriptions in this chapter are drawn. The model is a stochastic, spatial, temporal, state-transition model. Each of these elements are briefly discussed below.

NAADSM is a stochastic model which allows for specific parameters to be defined as probability density functions (PDFs) to predict the characteristics of the disease in the presence of variability or uncertainty. Stochastic modelling also addresses issues related to variance in seasons, distance or uncommon events. A number of iterations of the simulation are performed until the means of the output values converge. These statistical properties are not utilized in the economic model but are valuable for assessing both the probability and the severity of the outbreak scenarios.

The model also contains spatial components which allow for more accurate estimations of transmission, depletion and mitigation rates than non-spatial models that assume homogenous or random contact between units (Tildesley *et al*. 2011). Because each of these epidemiological and control characteristics is a function of distance, geographic inputs and the distance between points can greatly improve the accuracy of the simulation. The primary unit of analysis used by NAADSM is the herd or "unit" (used interchangeably in this thesis) which consists of a number of animals of varying production types. The model requires the geographic coordinates of each of these herds within the region.

Temporality is a crucial aspect of epidemiological modelling since parameters such as the probability of observing clinical signs, the probability of reporting detection and imposing movement controls are all time-dependent. NAADSM uses a 24-hour time-step which leads to a new calculation of a discrete distribution of the livestock population after each day of the simulated outbreak as well as a calculation for the expected duration of the outbreak.

As mentioned above, NAADSM adopts the state-transition element of the Garner and Lack (1995) model. The disease state categories included in the model are: susceptible, latent, subclinically-infectious, clinically-infectious, immune and destroyed. The duration of each stage is determined stochastically through a PDF that is derived from clinical studies of individual animal characteristics. Susceptible herds are those which are vulnerable to infection by FMD. Latent herds are infected but do not exhibit any signs of infection. At this point, the disease can progress naturally through subclinically infectious (below the surface of clinical observation), clinically infectious (observable signs) and naturally immune states unless outside intervention is taken. It is important to remember that these categories refer to an entire herd and not individual animals – a characteristic discussed further below.

NAADSM involves six different categories of inputs: animal population, disease manifestation, disease transmission, disease detection and traceability, disease control and direct costs. This section discusses each of these inputs in turn. The input parameter definitions are listed in Tables 1, 2 and 3. The values and data sources are presented in Chapter 5.

Animal Population Inputs

As stated above, NAADSM simulates the spread of the disease at the level of the herd. The herd (or unit) is defined as a group of animals at a particular location. The first characteristic needed for a herd is the production type. This is grouping of herds that have similar characteristics such as rates of direct and indirect contact, airborne spread, probabilities of detection and within-herd transmission rates. In this thesis, the production types are cow-calf, feedlot, dairy, swine and sheep operations. The size or number of animals within a herd is also required for the model. The initial disease state of each herd is also specified. Finally, longitude and latitude for each individual herd are used to establish distance between units which is used in the calculation of a number of outputs from the model. Due to data unavailability regarding specific operation locations and sizes, a degree of estimation was required for these inputs. The estimation techniques used for these inputs are discussed in Chapter Five.

Disease Manifestation

NAADSM categorizes the natural disease states into susceptible, latent, subclinically infected, clinically infected and immune. The susceptible state, where the unit is vulnerable to infection, is the default state of all units in the simulation. If a unit becomes infected, it enters the latent state in which it does not exhibit any signs. At this point, assuming no intervention, the disease will naturally progress to the subclinically infectious, clinically infectious and immune states. If no action is taken, the herd returns to the susceptible state at the end of the cycle. The duration of each of these stages is specified as a PDF of the duration of each state (in days). The natural pattern can be disrupted through interventions such as vaccination or destruction.

Disease Transmission

The disease transmission elements of the simulation are divided into direct contact spread, indirect contact spread and airborne spread. Each form of contact rate is defined by the interaction between each of the five production types resulting in twentyfive production type combinations for each type of contact. Direct contact spread occurs through the direct interaction between herds. The first two direct contact parameters are Boolean variables (yes or no) concerning the ability of latent or subclinical units can spread the disease. The mean rate of movement, defined as recipient herds/herd/day or the number of herds of a specific production type that a herd of a specific production type comes into contact with per day, describes the frequency of direct contact between different production types per day. The model also uses a PDF to describe the distance (km) between the units that come in contact with one another. NAADSM also requires the specification of the probability of infection transfer to determine the likelihood that a herd will become infected after direct contact with an infected herd.

Indirect contact is the second mode through which a disease can be transmitted and includes transmission via human contact or through non-human fomites such as contaminated facilities, equipment or animal products. The variables specified for indirect contact spread are similar to those specified for direct contact spread but are independent of them. The notable exception is that latent herds cannot spread the disease indirectly so the related variable is not included.

Finally, the disease can spread through aerosol transmission or airborne spread. NAADSM contains three variables used in its simulation of airborne spread. First, the probability of infection at 1 km from the source is required and reflects the likelihood of a herd becoming infected by a herd located one kilometer away. Second, the simulation allows for wind direction to be specified as a range of degrees from 0 to 359 (with 0° being north). This parameter addresses the directionality of airborne disease spread. The model also requires a maximum distance of airborne spread to be specified.

Table 1
NAADSM Disease and Disease Spread Input Parameters

Parameter Description	Parameter Type
Disease Parameters	
Latent	Probability Density Function (Days)
Subclinically infectious	Probability Density Function (Days)
Clinically infectious	Probability Density Function (Days)
Naturally immune	Probability Density Function (Days)
Direct Contact Spread Parameters	
Mean rate of animal shipments	(Recipient units per source per day).
Movement distance	Probability Density Function (km)
Shipping delay	Probability Density Function (days)
Probability of infection of the recipient unit, given exposure to an infected unit	Probability, 0 to 1
Movement rate multiplier	Relational function: scalar value as a function of the number of days since first detection of the outbreak
Can latent units spread disease by Direct contact?	Yes/no
Can subclincally infectious units Spread disease by direct contact?	Yes/no
Indirect Contact Spread Parameters	
Mean rate of animal shipments	(Number of units receiving shipments from the source unit per day).
Movement distance	Probability Density Function (km)
Shipping delay	Probability Density Function (days)
Probability of infection of the recipient unit, given exposure (receipt of animal) from an infected unit	Probability, 0 to 1
Movement rate multiplier	Relational function: scalar value as a Function of the number of days since First detection of the outbreak
Can subclincally infectious units Spread disease by direct contact?	Yes/no
Airborne Transmission Parameters	
Probability of infection at 1 km	Probability, 0 to 1
Wind direction, given as a range north	Degrees (0 to 360) where 0 indicates
Maximum distance of spread	scalar value (km)
Airborne transport delay	Probability density function (days)

Disease Detection and Traceability

In the model, disease detection concerns the surveillance of the animal population by those involved directly in the production process. It refers to the likelihood that producers will observe and report an outbreak. In NAADSM, the model uses the probability of observing clinical signs given the number of days that the herd is infectious to describe the likelihood of detection over time. The model also requires the probability of reporting given the number of days since detection to describe the likelihood that an infected herd will be reported as time progresses.

NAADSM also allows for outside surveillance parameters to be specified. The relevant trace parameters for the purposes of this thesis concern trace-back. The model allows for both direct and indirect contacts to be discovered via trace-back. The number of days before detection since an animal came into direct or indirect contact with an infected herd is also specifiable. A trace delay, or the delay for carrying out a trace investigation, can also be specified to reflect any possible lags that may exist in the real world.

Of the available trace parameters provided in the model, the most relevant to the intents of this thesis is the probability of a successful trace. This thesis will follow Pendell (2006) and Jones (2010) in using three different probabilities – 30, 60 and 90 percent for this thesis – to reflect three different levels or depths of traceability for the cattle industry: low, medium and high levels of traceability intensity. These depths reflect different levels of adoption, functionality and accuracy of representative traceability systems and their associated success. A 30 percent probability of a successful trace back

Table 2
NAADSM Disease Detection and Control Parameters

Parameter Description	Parameter Type
Detection Parameters	
Probability of observing clinical signs in an infected unit.	Relational function
Probability of reporting units with observed clinical signs	Relational function
Parameters for Tracing Out	
Probability of a trace-out investigation succeeding when direct contact has occurred	Probability, 0 to 1
Period of interest for trace-out investigations of direct contacts	Fixed integer value (days)
Probability of a trace-out investigation succeeding when indirect contact has occurred	Probability, 0 to 1
Period of interest for trace-out investigations of indirect contacts	Fixed integer value (days)
Destruction Parameters	
Delay to begin a destruction program	Fixed integer value (days)
Destruction capacity	Relational function
Destruction priorities	Rank order of reasons for unit destruction
Does detection of an infected unit trigger a destruction ring?	Yes/no
Radius of destruction ring (if triggered)	Fixed value (km)
Will units be destroyed in a ring destruction program?	Yes/no
Will units identified by trace-out after direct contact be destroyed?	Yes/no
Will units identified by trace-out after indirect contact be destroyed?	Yes/no

is a level of success which adequately reflects the present level of trace intensity in the United States (Pendell, 2006). A 60 percent probability reflects a significantly adopted traceability system but one that might not be fully operational. Finally, a 90 percent success rate would reflect a nationally adopted, agile and accurate system of traceability.

Disease Control

NAADSM allows for the modelling of three different forms of disease control: vaccination, movement restriction and destruction. The role of vaccination in disease control strategies has been addressed elsewhere (Berensten *et al.*, 1992; Bates *et al.*, 2003; McReynolds, 2013) and will not be addressed in the current analysis. The movement restriction input is presented as a relational function of the number of days after detection that a restriction is imposed.

There are several destruction parameters included in the model. A delay (days) can be specified to reflect the time it would take for the appropriate authorities to begin destroying infected animals. A relational function reflecting destruction capacity can be used to specify the number of units per day that can be destroyed. The destruction priorities of the authorities can also be represented in the model. NAADSM divides these into two categories: primary and secondary priorities. There are three subcategories of primary priorities (reason for destruction, production type and days holding) and each subcategory contains four secondary priorities (detected, trace back of direct contact, ring and trace back of indirect contact).

Direct Costs

Finally, the model uses the direct costs of controlling an outbreak to estimate the total costs associated with control efforts. The costs included in this analysis are the cost of appraisal (dollar/herd). Cleaning and disinfection (dollar/herd), euthanasia (dollar/animal), indemnification (dollar/animal) and carcass disposal (dollar/animal).

These costs are estimated averages and are multiplied by the relevant number of herds or animals affected. The definitions of the direct cost variables are presented in Table 3.

Table 3 NAADSM
Direct Cost Parameters

Parameter Description	Parameter Type
Parameters Associated With Destruction	
Appraisal	Dollar amount per unit
Cleaning and disinfection	Dollar amount per unit
Euthanasia	Dollar amount per animal
Indemnification	Dollar amount per animal
Carcass Disposal	Dollar amount per animal

Output Parameters

The simulation in NAADSM provides specific output parameters that reflect the statistical means of the scenarios over all the iterations that are run. These outputs can be divided into two categories: epidemiological outputs and cost accounting outputs. These output parameters are defined in Tables 4 and 5. As mentioned above, although the statistical characteristics presented by these outputs are not used in the economic model, they do provide value in judging the probability and severity of the scenarios.

Assumptions and Limitations

There are several assumptions and limitations of the model which may lead to conservative estimations. There a number of spatial assumptions in NAADSM. As in most spatial epidemiological models, NAADSM assumes no entry or exit from the specified region and that the population remains constant (besides destroyed units) throughout the duration of the scenario. This relates to another assumption that there are no births, restocking, natural deaths or mortality from the disease within the simulated scenarios. This means the only depopulation that occurs in the model results from the destruction of animals that have been identified.

Table 4
NAADSM Epidemiological Output Parameters

Parameter	Definition
tscUSusc	Total number of herds that become susceptible over the iterations.
tscASusc	Total number of animals that become susceptible over the iterations.
tscULat	Total number of herds that become latent over the iterations.
tscALat	Total number of animals that become latent over the iterations.
tscUSubc	Total number of herds that become subclinical over the iterations.
tscASubc	Total number of animals that become subclinical over the iterations.
tscUClin	Total number of herds that become clinical over the iterations.
tscAClin	Total number of animals that become clinical over the iterations.
tscUNImm	Total number of herds that become naturally immune over the iterations.
tscANImm	Total number of animals that become naturally immune over the iterations
tscUVImm	Total number of herds that become vaccine immune over the iterations.
tscAVImm	Total number of animals that become vaccine immune over the iterations.
tscUDest	Total number of herds that become destroyed over the iterations.
tscADest	Total number of animals that become destroyed over the iterations.
infcUIni	Number of herds that are initially infected over the iterations.
infcAIni	Number of animals that are initially infected over the iterations.
infcUAir	Number of herds infected by airborne spread over the iterations.
infcAAir	Number of animals infected by airborne spread over the iterations.
infcUDir	Number of herds infected by direct contact over the iterations.
infcADir	Number of animals infected by direct contact over the iterations.
infcUInd	Number of herds infected by indirect contact over the iterations.
infcAInd	Number of animals infected by indirect contact over the iterations.
infcUTotal	Total number of herds infected over the iterations.
infcATotal	Total number of animals infected over the iterations.
expcUDir	Total number of herds directly exposed to an infected herd over the iterations.
expcADir	Total number of animals directly exposed to an infected herd over the iterations.
expcUInd	Total number of herds indirectly exposed to an infected herd over the iterations.

Table 4 (Continued)

NAADSM Epidemiological Output Parameters

Parameter	Definition
expcAInd	Total number of animals indirectly exposed to an infected herd over the iterations.
expcUTotal	Total number of herds exposed to any infected herd over the iterations.
expcATotal	Total number of animals exposed to any infected herd over the iterations.
trcUDirp	Total number of herds directly exposed and successfully traced over the iterations.
trcADirp	Total number of animals directly exposed and successfully traced over the iterations.
trcUIndp	Total number of herds indirectly exposed and successfully traced over the iterations.
trcAIndp	Total number of animals indirectly exposed and successfully traced over the iterations.
detcUClin	Total number of clinical herds detected over the iterations.
detcAClin	Total number of clinical animals detected over the iterations.
descUIni	Total number of herds destroyed prior to the start of an iteration.
descAIni	Total number of animals destroyed prior to the start of an iteration.
descUInd	Total number of herds destroyed because of indirect contact with an infected herd over the iterations.
descAInd	Total number of animals destroyed because of indirect contact with an infected herd over the iterations.
descUTotal	Total number of herds destroyed for any reason over the iterations.
descATotal iterations.	Total number of animals destroyed for any reason over the
vaccUIni	Total number of herds in the vaccine immune state at the start of an iteration.
vaccAIni	Total number of animals in the vaccine immune state at the start of an iteration.
vaccURing	Total number of herds vaccinated because they were within a vaccination ring over the iterations.
vaccARing	Total number of animals vaccinated because they were within a vaccination ring over the iterations.
firstDet	First day an infected herd of a specified production type is detected during an iteration.
firstVacc	First day a herd of a specified production type is vaccinated during an iteration.
firstDestr	First day a herd of a specified production type is destroyed during an iteration.
outbreakLen	Length of an outbreak during an iteration.

The estimation of exact herd sizes and locations (discussed in Chapter 5) also contributes to the conservative estimates provided by the model scenarios. The data provided for the size of operations provided the total number of operations and animals within particular size categories (1 – 9, 10 to 19, 20 to 49, etc.) for each of the 29 counties within the state of Utah. To estimate herd size, the number of animals in a specific size category for a particular county was divided by the total number of operations in that county. This results in a more uniform distribution of operation sizes than exists in reality for each category.

Due to the unavailability of geographic data stemming from privacy concerns, the specific location of many operations is not available. In order to overcome this, a spatial estimation technique detailed in Chapter 5 was utilized for these locations. As a result of this estimation technique, the point estimates of the operation locations are likely to be further apart than they are in reality, particularly in counties where livestock operations are more concentrated than in other counties. The size of the outbreak is likely to be a conservative estimate as a result of the increased distance between operations resulting from this technique.

In NAADSM, intra-herd movements and airborne spread contact rates are assumed to be uncorrelated with seasonality and herd size and are, therefore, assumed to be constant throughout the course of the scenario. This leads to further underestimation because herd size is positively correlated with the size of indirect contacts (Bates *et al*., 2001). NAADSM also has no way of incorporating the movement of migratory animals such as elk, boar or deer so these contacts are not included in the scenario.

The final assumptions in this model relate to the trace back feature of NAADSM. In the model, all trace backs occur within 24 hours of detection which is considerably less than the proposed period of time it would take to perform a trace back. This means there is less time for the disease to spread to more herds and affect larger numbers of animals. The final assumption is that the trace back in NAADSM only considers immediate contacts from detected units. In other words, tracing only occurs for one step forward. This means that fewer units would be detected and destroyed during the outbreak which also leads to more conservative estimates.

Table 5
NAADSM Cost Output Parameters

Parameter	Definition
destrAppraisal	Total cost associated with unit appraisal over the course of the iteration
destrCleaning	Total cost of cleaning and disinfection over the course of the iteration.
destrEuthenasia	Total cost of euthanasia over the course of the iteration.
destrIndemnification	Total cost of indemnification over the course of the iteration.
destrDisposal	Total cost of carcass disposal over the course of the iteration.

CHAPTER 4

EQUILIBRIUM DISPLACEMENT MODEL

The goal of this thesis is to analyze the impact of a hypothetical FMD outbreak in Utah's livestock population on the state's agricultural economy under three separate levels of traceability. To assess this impact, the output from the epidemiological simulation described in the previous chapter needs to be incorporated into an economic framework capable of demonstrating these effects. Based on the typology of epidemiological-economic modelling presented in Rich *et al*. (2005), this thesis uses a partial economic approach known as an equilibrium displacement model to measure the welfare effects for producers and consumers across different sectors and marketing chain levels for different outbreak scenarios. The methodology and approach to the equilibrium displacement model are explained in this chapter.

Equilibrium Displacement Model

An equilibrium displacement model consists of a system of linearly approximated supply and demand curves that are used to calculate welfare changes. To assess these effects, the equations are then totally differentiated to be converted into their elasticity forms. At this point, matrix algebra can be used to analyze the impact of the outbreak. Finally, the welfare effects of the outbreak are calculated through the use of annual baseline quantities.

To accurately investigate these economic consequences, vertical linkages between the levels in the marketing chain are needed in the model. These connections are integrated through the use of quantity transmission elasticities which improve the accuracy of the model (Brester, Marsh and Atwood 2004). These elasticities represent the percentage change in a quantity at one market level given a 1% change in another market level. To link the marketing levels, a homogenous output value needs to be created for the marketing chain. Following Pendell *et al*. (2010), this thesis will convert price into dollars per cwt and quantity values into live weight pounds. This involves an assumption about product homogeneity that is discussed in the final section of this chapter.

For each outbreak scenario, simultaneous demand and supply shifts will be utilized to assess the economic effects of an outbreak. The model incorporates two different sources for negative supply and demand shocks. The first group of supply shocks uses the projected number of animals destroyed and the associated costs of control which are included in the model as percentage shifts in supply. The second type of shock incorporated in the model is related to the loss of trade to the United States. The modelling strategy assumes that there is an immediate cessation of trade following the outbreak.

Before discussing the development of the equations that comprise the equilibrium displacement model, there needs to be a brief discussion of the short-run and long-run considerations in this thesis. The scope of an investigation of this sort is dependent on the availability of short-run or long-run elasticities. Due to the unavailability of long-run elasticities, Jones (2010) was unable to estimate the long-run impacts of a simulated FMD outbreak in Ontario, Canada. Both elasticities are, however, readily available for the United States so this thesis will follow Pendell (2006) in estimating both the short-run and long-run consequences of a simulated outbreak. Using long-run elasticities allows the long-term economic impacts of an outbreak in the state of Utah and the United States as a whole beyond the immediate localized effects of the disease.

Structural Model

The model developed here includes the marketing levels for three industries in the United States: beef, pork and poultry. Following Brester *et al.* (2004), four marketing levels are included for beef, three for pork and two for poultry based on the varying degrees of vertical integration for each industry. The beef market levels included are retail, wholesale, slaughter (fed cattle) and farm (feeder cattle). The pork marketing chain includes the level retail, wholesale and slaughter (market hog) levels. Finally, the poultry sector includes two levels: retail and wholesale levels. As described above, transmission elasticities are used to connect these equations.

The biggest economic losses resulting from an outbreak likely stem from the loss of trade. Countries have a large incentive to prevent the spread of the disease due to the premium placed on maintaining FMD-free status by the OiE and the trade benefits it affords. As a result, the model needs to incorporate international and domestic trade. In response to an outbreak, animal movement controls would be imposed to halt movement in and out of Utah. This is represented in the model by disaggregating Utah from the other states. To include all of these aspects, the following model has been adopted from Pendell (2006) and applied to Utah-based outbreak scenarios. The structural form of the model, equations (1) through (44), therefore contains the supply and demand equations for each marketing chain level for the beef, pork and poultry sectors for Utah, the other states and the United States as a whole.

$$Q_B^R = f_1(P_{BUS}^R, P_{PUS}^R, P_{YUS}^R, Z_{BUS}^R) \quad (1)$$

$$Q_B^R = f_2(P_{BUS}^R, Q_B^W, W_{BUS}^R) \quad (2)$$

$$Q_{BUS}^W = f_3(P_{BUS}^W, Q_{BUS}^R, Z_{BUS}^W) \quad (3)$$

$$Q_{BE}^W = f_4(P_{BE}^W, Z_{BE}^W) \quad (4)$$

$$Q_B^W = f_5(P_{BUS}^W, Q_B^S, W_{BUS}^W) \quad (5)$$

$$Q_{BI}^W = f_6(P_{BI}^W, W_{BI}^W) \quad (6)$$

$$Q_B^W = Q_{BUS}^{WD} + Q_{BE}^W \quad (7)$$

$$Q_B^W = Q_{BUS}^{WS} + Q_{BI}^W \quad (8)$$

$$Q_B^S = f_7(P_{BUS}^S, Q_B^W, Z_{BUS}^S) \quad (9)$$

$$Q_{BUT}^S = f_8(P_{BUT}^S, Q_B^W, W_{BUT}^S, N_B^S) \quad (10)$$

$$Q_{BO}^S = f_9(P_{BUS}^S, Q_B^F, W_{BO}^S) \quad (11)$$

$$Q_{BUS}^S = Q_{BUT}^S + Q_{BO}^S \quad (12)$$

$$Q_{BI}^S = f_{10}(P_{BI}^S, W_{BI}^S) \quad (13)$$

$$Q_B^S = Q_{BUS}^S + Q_{BI}^S \quad (14)$$

$$N_B^S = f_{11}(F_B^S) \quad (15)$$

$$Q_B^F = f_{12}(P_{BUS}^F, Q_B^S, Z_B^F) \quad (16)$$

$$Q_{BUT}^F = f_{13}(P_{BUT}^F, W_{BUT}^F, N_B^F) \quad (17)$$

$$Q_{BO}^F = f_{14}(P_{BUS}^F, W_{BO}^F) \quad (18)$$

$$Q_{BUS}^F = Q_{BUT}^F + Q_{BO}^F \quad (19)$$

$$Q_{BI}^F = f_{15}(P_{BI}^F, W_{BO}^F) \quad (20)$$

$$Q_B^F = Q_{BUT}^F + Q_{BO}^F \quad (21)$$

$$N_B^F = f_{16}(F_B^F) \quad (22)$$

$$P_{BUT}^S = P_{BO}^S + S_B^S \quad (23)$$

$$P_{BUT}^{F} = P_{BO}^{F} + S_{B}^{F} \tag{24}$$

$$Q_{P}^{R} = f_{17}(P_{BUS}^{R}, P_{PUS}^{R}, P_{YUS}^{R}, Z_{PUS}^{R}) \tag{25}$$

$$Q_{P}^{R} = f_{18}(P_{PUS}^{R}, Q_{P}^{W}, W_{PUS}^{R}) \tag{26}$$

$$Q_{PUS}^{WD} = f_{19}(P_{PUS}^{W}, Q_{PUS}^{R}, Z_{PUS}^{W}) \tag{27}$$

$$Q_{PE}^{W} = f_{20}(P_{PE}^{W}, Z_{PE}^{W}) \tag{28}$$

$$Q_{P}^{WS} = f_{21}(P_{PUS}^{W}, Q_{P}^{S}, W_{PUS}^{W}) \tag{29}$$

$$Q_{PI}^{W} = f_{22}(P_{PI}^{W}, W_{PI}^{W}) \tag{30}$$

$$Q_{P}^{W} = Q_{PUS}^{WD} + Q_{PE}^{W} \tag{31}$$

$$Q_{P}^{W} = Q_{PUS}^{WS} + Q_{PI}^{W} \tag{32}$$

$$Q_{P}^{S} = f_{23}(P_{PUS}^{S}, Q_{P}^{W}, Z_{PUS}^{S}) \tag{33}$$

$$Q_{PUT}^{S} = f_{24}(P_{PUT}^{S}, W_{PUT}^{S}) \tag{34}$$

$$Q_{PO}^{S} = f_{25}(P_{PUS}^{S}, W_{PO}^{S}, N_{P}^{S}) \tag{35}$$

$$Q_{PUS}^{S} = Q_{PUT}^{S} + Q_{PO}^{S} \tag{36}$$

$$Q_{P}^{S} = f_{26}(P_{PI}^{S}, W_{PI}^{S}) \tag{37}$$

$$Q_{P}^{S} = Q_{PUS}^{S} + Q_{PI}^{S} \tag{38}$$

$$N_{P}^{S} = f_{27}(F_{P}^{S}) \tag{39}$$

$$P_{PUT}^{S} = P_{PO}^{S} + S_{P}^{S} \tag{40}$$

$$Q_{Y}^{R} = f_{28}(P_{BUS}^{R}, P_{PUS}^{R}, P_{YUS}^{R}, Z_{YUS}^{R}) \tag{41}$$

$$Q_{Y}^{R} = f_{29}(P_{YUS}^{R}, Q_{Y}^{W}, W_{Y}^{R}) \tag{42}$$

$$Q_{Y}^{W} = f_{20}(P_{YUS}^{W}, Q_{Y}^{R}, Z_{YUS}^{W}) \tag{43}$$

$$Q_{Y}^{W} = f_{21}(P_{YUS}^{W}, Q_{Y}^{S}, W_{YUS}^{W}) \tag{44}$$

where P_{il}^{j} and Q_{il}^{j} represent for the price and quantity for commodity *i* at market level *j*.

The market level subscripts *b*, *p* and *y* represent beef, pork and poultry, respectively. The commodity superscripts *r, w, s* and *f* represents retail, wholesale, slaughter and farm levels, respectively. There are five locational subscripts (*l*) that represent the United States (*US*), Utah (*UT*), the other 49 states (*O*), imports (*I*) and exports (*E*). The variables z_i^j and w_i^j are the demand and supply shifters for the specific marketing levels of each commodity. These represent the exogenous shocks. The variable N_i^j stands for the inventories of slaughter cattle and hog inventories. These inventories are decreased by the proportion of animals destroyed out of the original number of the *i*th commodity for the *j*th market level (F_i^j). Finally, S_i^j denotes the transfer costs for shipping commodity *i* at market level *j*.

Before discussing the transformation of equations 1 – 44 into elasticity form, some clarification of the equations is necessary. Equations 7, 8, 14, 31, 32 and 38 are market clearing equations. Equations 23, 24 and 40 are included to account for the law of one price in relating the price of commodity *i* at market level *j* for Utah and the other states for fed cattle, feeder cattle and market hogs, respectively. As discussed in the previous chapter, the results of the epidemiological simulation can be divided into two categories: epidemiological outputs and cost accounting outputs. The epidemiological outputs (the percentage total of animals destroyed of each commodity at each marketing level) are used in equations 15, 22 and 39. The simulated cost information is incorporated in equations 5, 10, 11, 17, 18, 29, 34 and 35.

Totally differentiating equations 1 – 44, we get the elasticity form equations that comprise the equilibrium displacement model used in this analysis. Each of the following elasticity form equations (equations 45 – 88) correspond to the general form equations shown above. For example, equation 45 corresponds to equation 1, equation 46 corresponds to equation 2 and so on.

$$EQ_B^R = \eta_{BB}^R EP_{BUS}^R + \eta_{BP}^R EP_{PUS}^R + \eta_{BY}^R EP_{YUS}^R + Ez_{BUS}^R \tag{45}$$

$$EQ_B^R = \varepsilon_{BUS}^R EP_{BUS}^R + \tau_B^{RW} EQ_B^W \tag{46}$$

$$EQ_{BUS}^{WD} = \eta_{BUS}^W EP_{BUS}^W + \tau_B^{WR} EQ_B^R \tag{47}$$

$$EQ_{BE}^W = \eta_{BE}^W EP_{BE}^W \tag{48}$$

$$EQ_{BUS}^{WS} = \varepsilon_{BUS}^W EP_{BUS}^W + \tau_B^{WS} EQ_B^S + Ew_{BUS}^W \tag{49}$$

$$EQ_{BI}^W = \varepsilon_{BI}^W EP_{BI}^W \tag{50}$$

$$EQ_B^W = (Q_{BUS}^W/Q_B^W)EQ_{BUS}^{WD} + (Q_{BE}^W/Q_B^W)EQ_{BE}^W \tag{51}$$

$$EQ_B^W = (Q_{BUS}^W/Q_B^W)EQ_{BUS}^{WS} + (Q_{BI}^W/Q_B^W)EQ_{BI}^W \tag{52}$$

$$EQ_B^S = \eta_{BUS}^S EP_{BUS}^S + \tau_B^{SW} EQ_B^W \tag{53}$$

$$EQ_{BUT}^S = \varepsilon_{BUT}^S EP_{BUT}^S + \tau_B^{SF}(Q_{BUT}^F/Q_{BUS}^F)EQ_B^F + EN_B^S + Ew_{BUT}^s \tag{54}$$

$$EQ_{BO}^S = \varepsilon_{BUS}^S EP_{BUS}^S + \tau_B^{SF}(Q_{BO}^F/Q_{BUS}^F)EQ_B^F + Ew_{BO}^s \tag{55}$$

$$EQ_{BUS}^S = (Q_{BUT}^S/Q_{BUS}^S)EQ_{BUT}^S + (Q_{BO}^S/Q_{BUS}^S)EQ_{BO}^S \tag{56}$$

$$EQ_{BI}^S = \varepsilon_{BI}^S EP_{BI}^S \tag{57}$$

$$EQ_B^S = (Q_{BUS}^S/Q_B^S)EQ_{BUS}^S + (Q_{BI}^S/Q_B^S)EQ_{BI}^S \tag{58}$$

$$EN_B^S = EF_B^S \tag{59}$$

$$EQ_B^F = \eta_{BUS}^F EP_{BUS}^F + \tau_B^{FS} EQ_B^S \tag{60}$$

$$EQ_{BUT}^F = \varepsilon_{BUT}^F EP_{BUT}^F + EN_B^F + Ew_{BUT}^F \tag{61}$$

$$EQ_{BO}^F = \varepsilon_{BUS}^F EP_{BUS}^F + Ew_{BO}^F \tag{62}$$

$$EQ_{BUS}^F = (Q_{BUT}^F/Q_{BUS}^F)EQ_{BUT}^F + (Q_{BO}^F/Q_{BUS}^F)EQ_{BO}^F \tag{63}$$

$$EQ_{BI}^F = \varepsilon_{BI}^F EP_{BI}^F \tag{64}$$

$$EQ_B^F = (Q_{BUS}^F/Q_B^F)EQ_{BUS}^F + (Q_{BI}^F/Q_{BO}^F)EQ_{BI}^F \tag{65}$$

$$EN_B^F = EF_B^F \tag{66}$$

$$EP_{BUT}^S = (P_{BUS}^S / P_{BUT}^S) EP_{BUS}^S \tag{67}$$

$$EP_{BUT}^F = (P_{BUS}^F / P_{BUT}^F) EP_{BUS}^F \tag{68}$$

$$EQ_{Pork}^{Retail} = \eta_{PB}^R EP_{BUS}^R + \eta_{PP}^R EP_{PUS}^R + \eta_{PY}^R EP_{YUS}^R + Ez_{PUS}^R \tag{69}$$

$$EQ_{Pork}^{Retail} = \varepsilon_{PUS}^R EP_{PUS}^R + \tau_P^{RW} EQ_P^W \tag{70}$$

$$EQ_{PorkUS}^{WD} = \eta_{PUS}^W EP_{PUS}^W + \tau_P^{WR} EQ_P^R \tag{71}$$

$$EQ_{PorkE}^W = \eta_{PE}^W EP_{PE}^W \tag{72}$$

$$EQ_{PorkUS}^{WS} = \varepsilon_{PUS}^W EP_{PUS}^W + \tau_P^{WS} EQ_P^S + Ew_{PUS}^W \tag{73}$$

$$EQ_{PorkI}^W = \varepsilon_{PI}^W EP_{PI}^W \tag{74}$$

$$EQ_P^W = (Q_{PUS}^W / Q_P^W) EQ_{PUS}^{WD} + (Q_{PE}^W / Q_P^W) EQ_{PE}^W \tag{75}$$

$$EQ_P^W = (Q_{PUS}^W / Q_P^W) EQ_{PUS}^{WS} + (Q_{PI}^W / Q_P^W) EQ_{PI}^W \tag{76}$$

$$EQ_P^S = \eta_{PUS}^S EP_{PUS}^S + \tau_P^{SW} EQ_P^W \tag{77}$$

$$EQ_{PUT}^S = \varepsilon_{PUT}^S EP_{PUT}^S + EN_P^S + Ew_{PUT}^s \tag{78}$$

$$EQ_{PO}^S = \varepsilon_{PUS}^S EP_{PUS}^S + Ew_{PO}^s \tag{79}$$

$$EQ_{PUS}^S = (Q_{PUT}^S / Q_{PUS}^S) EQ_{PUT}^S + (Q_{PO}^S / Q_{PUS}^S) EQ_{PO}^S \tag{80}$$

$$EQ_{PI}^S = \varepsilon_{PI}^S EP_{PI}^S \tag{81}$$

$$EQ_P^S = (Q_{PUS}^S / Q_P^S) EQ_{PUS}^S + (Q_{PI}^S / Q_P^S) EQ_{PI}^S \tag{82}$$

$$EN_P^S = EF_P^S \tag{83}$$

$$EP_{PUT}^S = (P_{PUS}^S / P_{PUT}^S) EP_{PUS}^S \tag{84}$$

$$EQ_Y^{Retail} = \eta_{YB}^R EP_{BUS}^R + \eta_{YP}^R EP_{PUS}^R + \eta_{YY}^R EP_{YUS}^R + Ez_{YUS}^R \tag{85}$$

$$EQ_Y^{Retail} = \varepsilon_{YUS}^R EP_{YUS}^R + \tau_Y^{RW} EQ_Y^W \tag{86}$$

$$EQ_Y^W = \eta_{YUS}^W EP_{YUS}^W + \tau_Y^{WR} EQ_Y^R \tag{87}$$

$$EQ_Y^W = \varepsilon_{YUS}^W EP_{YUS}^W \tag{88}$$

The variables P_{il}^{j} and Q_{il}^{j} and the related superscripts and subscripts have been defined above. In the elasticity equations, the variable E denotes a relative change operator where $EQ = \frac{\partial Q}{Q} = \partial lnQ$. The variables η, ε, and τ denote the demand, supply and transfer elasticities, respectively. These are defined in Table 6.

Now that the elasticity form equations have been derived, matrix algebra can be employed to solve for the effects of the exogenous shifts generated by NAADSM. In matrix form, the equilibrium displacement model is shown as:

$$M*Y = B*X \quad (89)$$

where M is a {44x44} matrix of the elasticity values contained in the equation, Y is a {44x1} vector of the endogenous variables (price and quantity), X is a {1x44} vector of percentage changes or shocks in the exogenous variables and B is a matrix of parameters associated with exogenous variables which is simply an identity matrix in this model so it is dropped. Restructuring the model, the solution matrix is:

$$Y=M^{-1}* X \quad (90)$$

Elasticities

While most of the elasticities mentioned above and listed in Table 6 are borrowed from previous literature, the analysis contained in this thesis requires that some of elasticities be estimated for certain commodities at particular marketing levels for the state of Utah. The elasticities that need to be estimated are the own-price elasticity for feeder cattle supply in Utah (ε_{BUT}^{F}) and the own-price elasticity for fed cattle supply in Utah (ε_{BUT}^{S}) which are not available in the literature. These elasticities allow for the

Table 6
Equilibrium Displacement Model Parameters and Definitions

Parameter	Definition
η_{BB}^{R}	Own-price retail beef demand elasticity
η_{BP}^{R}	Cross-price elasticity of retail beef demand w.r.t. pork price
η_{BY}^{R}	Cross-price elasticity of retail beef demand w.r.t. poultry price
η_{PB}^{R}	Cross-price elasticity of retail pork demand w.r.t. beef price
η_{PP}^{R}	Own-price elasticity of retail pork demand
η_{PY}^{R}	Cross-price elasticity of retail pork demand w.r.t. poultry price
η_{YB}^{R}	Cross-price elasticity of retail poultry demand w.r.t. beef price
η_{YP}^{R}	Cross-price elasticity of retail poultry demand w.r.t. pork price
η_{YY}^{R}	Own-price elasticity of retail poultry demand
η_{BUS}^{W}	Own-price elasticity of wholesale beef demand (Other States)
η_{BUS}^{S}	Own-price elasticity of slaughter cattle demand (Other States)
η_{BUS}^{F}	Own-price elasticity of feeder cattle demand (Other States)
η_{PUS}^{W}	Own-price elasticity of wholesale pork demand (Other States)
η_{PUS}^{S}	Own-price elasticity of slaughter hog demand (Other States)
η_{YUS}^{W}	Own-price elasticity of wholesale poultry demand (Other States)
ε_{BUS}^{R}	Own-price elasticity of retail beef supply (Other States)
ε_{BUS}^{W}	Own-price elasticity of wholesale beef supply (Other States)
ε_{BUS}^{S}	Own-price elasticity of slaughter cattle supply (Other States)
ε_{BUS}^{F}	Own-price elasticity of feeder cattle supply (Other States)
ε_{BUT}^{S}	Own-price elasticity of slaughter cattle supply (Utah)
ε_{BUT}^{F}	Own-price elasticity of feeder cattle supply (Utah)
ε_{PUS}^{W}	Own-price elasticity of wholesale pork supply (Other States)
ε_{PUS}^{S}	Own-price elasticity of slaughter hog supply (Other States)
ε_{PUT}^{S}	Own-price elasticity of slaughter hog supply (Utah)
ε_{YUS}^{R}	Own-price elasticity of retail poultry supply (Other States)
ε_{YUS}^{W}	Own-price elasticity of wholesale poultry supply (Other States)
ε_{BI}^{W}	Import supply elasticity of wholesale beef supply
ε_{BI}^{S}	Import supply elasticity of slaughter cattle supply
ε_{BI}^{F}	Import supply elasticity of feeder cattle supply
ε_{PI}^{W}	Import supply elasticity for wholesale pork supply
ε_{PI}^{S}	Import supply elasticity for slaughter hog supply
τ_{B}^{WR}	% change in wholesale beef quantity given a 1% change in retail beef quantity
τ_{B}^{SW}	% change in fed cattle quantity given a 1% change in wholesale beef quantity
τ_{B}^{FS}	% change in feeder cattle quantity given a 1% change in fed cattle quantity
τ_{P}^{WR}	% change in wholesale pork quantity given a 1% change in retail pork quantity
τ_{P}^{SW}	% change in slaughter hog quantity given a 1% change in wholesale pork quantity

Table 6 (Continued)
Equilibrium Displacement Model Parameters and Definitions

Parameter	Definition
τ_Y^{RW}	% change in wholesale poultry quantity given a 1% change in retail poultry quantity
τ_B^{RW}	% change in retail beef quantity given a 1% change in retail poultry quantity
τ_B^{WS}	% change in wholesale beef quantity given a 1% change in fed beef quantity
τ_B^{SF}	% change in fed cattle quantity given a 1% change in feeder cattle quantity
τ_P^{RW}	% change in retail pork quantity given a 1% change in wholesale pork quantity
τ_P^{WS}	% change in wholesale pork quantity given a 1% change in slaughter hog quantity
τ_Y^{RW}	% change in retail poultry quantity given a 1% change in wholesale quantity

effects of the economic shocks to be measured at these marketing levels for this commodity.

To estimate these elasticities, the following two systems of equations have been adopted from Marsh (2003). Equations 91 and 92 are the inverse slaughter cattle demand and slaughter cattle supply equations, respectively. Equations 94 and 95 are the inverse fed cattle demand and fed cattle supply equations, respectively. Equations 93 and 96 are market clearing equations for each system of equations.

$$P_S^D = \psi_1(Q_S^D, D_R, P_B, M, \mu_1) \tag{91}$$

$$Q_S^S = \psi_2(P_S^S, P_C, P_F, I, T_F, \mu_2) \tag{92}$$

$$Q_S^D = Q_S^S = Q_S;\ P_S^D = P_S^S = P_S \tag{93}$$

$$P_F^D = \psi_3(Q_F^D, P_S, P_C, I, T_F, \mu_3) \tag{94}$$

$$Q_F^S = \psi_4(P_F^S, P_W, P_H, T_C, \mu_4) \tag{95}$$

$$Q_F^D = Q_F^S = Q_F;\ P_F^D = P_F^S = P_F \tag{96}$$

Where Q_S^S and Q_S^D are the respective quantities demanded and supplied for slaughter cattle (number of head). Q_F^S and Q_F^D are the respective quantities demanded and supplied of feeder cattle (number of head). P_S^D and P_S^S are the demand and supply prices of slaughter steers. P_F^D and P_F^S are the demand and supply prices of feeder steers. P_W is the price of utility cows which represents the opportunity costs of breeding stock. P_C and P_H are the price of no. 2 yellow corn (dollar/bushel) and mixed grass-alfalfa hay (dollar/ton), respectively. P_B is the price of beef by-products, hide and offal (cents/lb.). D_R is the estimated retail beef demand index and captures the effects of shifts in retail beef demand on the buying behavior of beef packers. M is an index of food marketing costs and captures the effects of input costs and technological change on the demand for cattle inputs. I represents the prime interest rate. T_F and T_C are technology variables for cattle finishing and feeder cattle production. T_F is equal to the cattle marketings from feedlots of 32 thousand head divided by the total marketings of all fed cattle. This represents the scale economies and management organization (Marsh, 2003). T_C is the average live-weight of slaughter cattle (lbs.) which represents breeding genetics and the management practices of producers (Marsh, 2003).

There are a number of statistical issues that have been discussed by Marsh (2003) and Holzer (2005) that accompany this type of estimation including serial correlation, non-stationarity, simultaneity and contemporaneously correlated error terms. Non-stationarity means that there is “a linear combination of two series, each of which is integrated of order one, is integrated of order zero” (Wooldridge 2009, p. 836) or, in other words, that the underlying stochastic process of a particular variable may contain a random walk where the mean and variance are not time invariant (Pyndick and

Rubinfield, 1998). This results in inconsistent tests of significance and may contribute to a spurious regression (Holzer, 2005). In order to test for non-stationarity (or unit roots), an Augmented Dickey-Fuller test is used. If the null hypothesis of this test is rejected, then the data needs to be differenced before estimation.

Simultaneity (or joint dependency) is present when a model contains a diagonal covariance matrix of errors. If simultaneity exists, then the OLS estimator will be an inaccurate measure of the parameters. A Wu-Hausman specification test can be used to test for simultaneity. The null hypothesis for this test is that the dependent variables are uncorrelated with the error term. If the null hypothesis is rejected, then simultaneity exists and a difference estimator needs to be used (Greene, 2003). If simultaneity is present in a model, then cointegration problems are not normally considered and the model can be estimated in level form (Johnson and DiNardo, 1997).

Finally, another problem that is often present in the estimation of systems of time series data is the existence of contemporaneously correlated errors. This occurs due to the close relationship between the stochastic processes that underlie the market interactions in the system (Holzer, 2005). Further, misspecifications in the model can also result in a non-diagonal covariance error matrix (Wooldridge, 2009).

Due to the dynamics involved in cattle production, the fed and feeder cattle supply equations are modeled as autoregressive distributed lags (ADL) (Marsh, 1994, 2003). Following Marsh (2003), the slaughter supply equation is estimated with current period (*t*) and one-year (*t-1)* lags due to the adjustments that occur between the placement and finishing of feeder cattle. For the feeder cattle supply equation, one-year (*t-1*) and two-year (*t-2*) lags are used “to capture rigidities in inventory adjustments including cycles" (Marsh, 2003, p. 906). Due to the inability of economic theory to provide a guide for the length of the lag, the final lag structure is simplified through truncation (Marsh, 1994, 2003; Pendell, 2006). Through this process, the lagged parameters with the smallest t-values are dropped from the supply equations at a confidence level of five percent. The initial empirical models for the demand and supply (including the final lag structure) are shown in equations 97 - 100.

$$P_S^D = a(0) + a(1)lnQ_S^D + a(2)lnD_R + a(3)lnP_B + a(4)lnM \quad (97)$$

$$Q_S^S = b(0) + b(1)lnP_S^S + b(2)lnP_C + b(3)lnP_F + b(4)\ln I + b(5)lnT_F + b(6)lnQ_{S-1}^S \quad (98)$$

$$P_F^D = c(0) + a(1)lnQ_F^D + c(2)lnP_S + c(3)lnP_C + c(4)lnI + c(5)lnT_F \quad (99)$$

$$Q_F^S = d(0) + d(1)lnP_{F-2}^S + d(2)lnP_{W-2} + d(3)lnP_{H-1} + d(4)lnT_C + d(4)lnQ_{F-1}^S \quad (100)$$

Due to the presence of serial correlation, simultaneity and contemporaneously correlated error terms, an estimator needs to be used that will correct for these. A Two-Stage Least Squares (2SLS) estimator will correct for simultaneity but, as a limited information estimator, it will not correct for contemporaneously correlated errors. By using a full-information estimator, as suggested by Marsh (2003), Holzer (2005) and Pendell (2006), asymptotic efficiency and consistency is restored within the model. The Utah fed and feeder cattle supply elasticities in this thesis, therefore, will be estimated using a Three-Stage Least Squares (3SLS) estimator which combines 2SLS regression with a seemingly unrelated regressions (SUR) model. The empirical estimation of these systems is contained in Chapter 6.

Surplus Measures

To measure the economic impacts of each outbreak scenario, this thesis uses the concepts of consumer and producer surplus. Consumer surplus is defined as "the difference between the total use value and the actual expenditure" or the difference between what a consumer would have been willing to pay for a good and the amount they actually paid for it (Solberg, p. 135). Mathematically, this is equal to the area beneath the demand curve above the equilibrium price. Producer surplus, on the other hand, is "the net gain to sellers from receiving the market price for all units sold" (Solberg, p. 537). Mathematically, this is equal to the area beneath the supply curve and below the equilibrium price.

Since the equilibrium displacement model expresses shocks in terms of percentage changes that result in a new market equilibrium price, the welfare analysis contained in this thesis addresses relative changes in consumer and producer surplus. The equations for these surplus changes are shown below and are taken from Alston *et al.* (1998) who adopted them from Mullen *et al*. (1988). Equation 97 measures the change in consumer surplus for good *i* at the retail market level. Equation 98 measures the change in producer surplus in supplying factor *i* at market level *j*.

$$-P_i^R Q_i^R [E(P_i^R) - \alpha_i^R][1 + 0.5E(Q_i^R)] \tag{101}$$

$$P_i^j Q_i^j \left[E\left(P_i^j\right) + \alpha_i^j\right]\left[1 + 0.5E\left(Q_i^j\right)\right] \tag{102}$$

where P_i^j and Q_i^j are the price and quantity of commodity *i* at marketing level *j*, respectively and α_i^j is the exogenous shock to commodity *i* at marketing level *j*.

Sensitivity Analysis

Since the majority of the elasticities used in this model are borrowed from previous research, sensitivity analysis must be conducted to test their accuracy. This thesis follows the technique used by Jones (2010) in which four alternate elasticity scenarios are used to test the results of the EDM. First, the supply elasticities were increased by 50% while the demand elasticities remained unchanged. Second, the supply elasticities were decreased by 50% while the demand elasticities remained unchanged. Third, the demand elasticities were increased by 50% while the supply elasticities remained unchanged. Finally, the demand elasticities were decreased by 50% while the supply elasticities remained unchanged.

Assumptions

Equilibrium displacement models consist of a system of linear approximations of unknown supply and demand equations. As discussed by Wohlgenant (1993), this assumption implies that the level of accuracy of the economic surplus change measures is dependent on the level of non-linearity of the actual supply and demand curves. For these changes to be accurately reflected, exogenous shocks need to be relatively small since the further away the new equilibrium is from the initial equilibrium, the more reliant upon the accuracy of the elasticities it the model becomes (Piggott *et al*., 1995). Based on preliminary estimates of the size of the shocks, this limitation should not be a factor but the full extent of this phenomenon will be clarified by performing sensitivity analysis.

The model also assumes that all firms have identical production functions that are homogenous of degree one. This means the production functions of all firms are assumed to exhibit constant returns to scale (Muth, 1964). The markets are also assumed to be perfectly competitive with products that are perfectly homogenous across all marketing levels. This is employed in the model through the conversion of price into dollars per hundred weight (cwt.) and quantity values into live weight pounds as in Pendell *et al*. (2010).

Finally, there are assumptions implicit in the model used in this thesis about who shoulders the burden of the costs associated with a disease outbreak. This is due to uncertainty concerning the level of government assistance in helping producers shoulder the costs of controlling an outbreak (appraisal, disinfecting, euthanizing, indemnity payments and disposal). To include different levels of government compensation, this thesis runs alternative scenarios where producers bear the burden of different percentages of the cost. In the initial scenario, producers bear the entire costs while in a second scenario, the government and the producers split the direct costs of control equally.

CHAPTER 5

DATA AND SOURCES

This chapter discusses the values and data sources used in specifying the models contained in this thesis. The first section explains the data used to specify the epidemiological scenario in NAADSM. The second section describes the data used in estimating the Utah supply elasticities and the data used in developing the EDM.

North American Animal Spread Disease Model Data

As discussed in Chapter Three, there are six separate categories of inputs in the epidemiological simulation: animal population, disease manifestation, disease transmission, disease detection and traceability, disease control and direct costs. The values, derivations and sources of each of the inputs in these categories is described in the following section.

Animal Population Inputs

The animal population inputs required by NAADSM include the production type, the number of animals and the location of each individual herd in the area under study. The production types included in the simulations are cow-calf, large feedlots (>3000), small feedlots (<3000), dairy, large swine (>1000), small swine (<1000) and sheep operations. The division of feedlots and swine operations into separate groups based on size is due to the different rates of direct and indirect contact between larger and smaller operations. As such, the size distinction for these two operation types will only be mentioned when contact rates are being discussed.

The size data for each production type comes from the USDA National Agricultural Statistics Survey's 2012 Census of Agriculture. The Census contains data for each production type divided into size categories (1 to 9, 10 to 19, 20 to 49, and so on) for each of the 29 counties in Utah. Due to privacy concerns and other difficulties related to collecting data regarding herd size, an estimation technique was employed to find the average size for each operation in a particular size category for each county. For example, there were 14,132 cows spread over 3,412 beef operations in Utah County in 2012 in the category for cow-calf operations of 1 to 9 head. In order to produce an average for this category, the number of cows was divided by the number of operations to produce a rounded four head per herd in this category for this county. The aggregate summary statistics for each production type in the state of Utah are shown in Table 7.

Table 7
Summary Statistics for Herd Data

Species	Herd Count	Animals Mean	Minimum	Maximum
Cow-Calf	6815	54.41	4	1859
Feedlot	132	149.12	12	3994
Dairy	475	195.70	1	2751
Swine	665	313.54	1	65832
Sheep	1649	172.92	5	5457

Due to privacy issues, the exact locations of the operations are unavailable and also required estimation. This paper adapted the technique utilized by Jones (2010) which is described here. From the Census of Agriculture, the number of herds for each type of operation are known for each county. Using the geographic information systems package ArcGis®, a boundary file containing county distinctions was placed over a map of Utah. Using a random point generator contained in the software package, a number of random points equal to the number of operations were generated within the borders of each county. A rivers, streams and lakes layer was also included to prevent the placement of points in areas where operations would not normally exist. This method provides longitude and latitude coordinates within each of the counties' boundaries to put into NAADSM but does have the drawback that it is likely to place operations further apart than they are in the real world. The ramifications of this are discussed in the assumptions section of Chapter 3.

Disease Manifestation

The inputs for disease manifestation concern the characteristics of each production type and are divided into four disease states: latent, subclinically infectious, clinically infectious and immune. These are represented by PDFs for the duration of each disease state for a herd of each production type. The PDFs for latent, subclinical and clinical states for cow-calf, feedlot, dairy and swine operations have been adopted from a meta-analysis by Mardones *et al*. (2010). The latent, subclinical, clinical and immune PDFs for sheep are adopted from Premashthira *et al*. (2011). The remaining PDFs for the duration of the immune state for cow-calf, feedlot, dairy and swine operations are taken from empirical distributions used in Pendell (2006). These PDFs are shown in Table 8.

Disease Transmission

There are three categories of inputs for the disease transmission section in NAADSM: direct contact spread, indirect contact spread and airborne spread. Each form of contact rate is defined by the interaction between each of the seven production types resulting in forty-nine combinations for each type of contact. The values for direct and indirect contact rates for each production type are taken from a survey collected from operations in Colorado and Kansas by McReynolds (2013) who applied them in an FMD simulation for an area consisting of Colorado, Wyoming, South Dakota, Nebraska, Oklahoma, the Texas Panhandle and northern New Mexico. The values for direct and indirect contact are listed in Tables 9 and 10, respectively.

Table 8
Disease Parameters in NAADSM

Disease State	Production Type	PDF
Latent	Cow-Calf	Weibull (α=1.782, β=3.974)
Latent	Feedlot	Weibull (α=1.782, β=3.974)
Latent	Dairy	Weibull (α=1.782, β=3.974)
Latent	Swine	Gamma (α=1.617, β=1.914)
Latent	Sheep	Pert (*m*=3.963, *a*=0, *b*=13.983)
Subclinical	Cow-Calf	Gamma (α=1.222, β=1.672)
Subclinical	Feedlot	Gamma (α=1.222, β=1.672)
Subclinical	Dairy	Gamma (α=1.222, β=1.672)
Subclinical	Swine	Inverse Gaussian (μ=2.3, λ=3.045)
Subclinical	Sheep	Gamma (α=2.4, β=0.898)
Clinical	Cow-Calf	Gamma (α=3.969, β=1.107)
Clinical	Feedlot	Gamma (α=3.969, β=1.107)
Clinical	Dairy	Gamma (α=3.969, β=1.107)
Clinical	Swine	Log Logistic (γ=0, β =5.39, α=5.474)
Clinical	Sheep	Pearson V (α=6.188, β=17.192)
Immune	Cow-Calf	Piecewise (Empirical)
Immune	Feedlot	Piecewise (Empirical)
Immune	Dairy	Piecewise (Empirical)
Immune	Swine	Piecewise (Empirical)
Immune	Sheep	Triangular (100, 300, 500)

NAADSM also allows for the disease to be transmitted via airborne spread. The values for these specifications are also taken from McReynolds (2013). The probability of spread per day, at 1 km, for an average size operation was set 0.5 for all operation

Table 9
Direct Contact Spread Parameters in NAADSM

Source to Recipient	DCR	Distance Distribution (km)	Transfer Prob.
Cow Calf to Cow Calf	0.027	Triangular (0,30,100)	0.90
Cow Calf to Large Feedlot	0.002	Triangular (0,75,190)	0.90
Cow Calf to Small Feedlot	0.002	Triangular (0,75,190)	0.90
Cow Calf to Dairy	0.000	Triangular (0,30,100)	0.90
Cow Calf to Large Swine	0.000	0.000	0.90
Cow Calf to Small Swine	0.000	0.000	0.90
Cow Calf to Sheep	0.000	Triangular (1,20,500)	0.90
Large Feedlot to Cow Calf	0.000	Triangular (0,75,190)	0.90
Large Feedlot to Large Feedlot	0.005	Triangular (0,30,190)	0.90
Large Feedlot to Small Feedlot	0.000	Triangular (0,30,190)	0.90
Large Feedlot to Dairy	0.000	Triangular (0,75,190)	0.90
Large Feedlot to Large Swine	0.000	0.0	0.90
Large Feedlot to Small Swine	0.000	0.0	0.90
Large Feedlot to Sheep	0.000	Triangular (1,50,100)	0.90
Small Feedlot to Cow Calf	0.000	Triangular (0,75,190)	0.90
Small Feedlot to Large Feedlot	0.019	Triangular (0,30,190)	0.90
Small Feedlot to Small Feedlot	0.017	Triangular (0,30,190)	0.90
Small Feedlot to Dairy	0.000	Triangular (0,75,190)	0.90
Small Feedlot to Large Swine	0.000	0.0	0.90
Small Feedlot to Small Swine	0.000	0.0	0.90
Small Feedlot to Sheep	0.000	Triangular (1,50,100)	0.90
Dairy to Cow Calf	0.000	Triangular (0,30,100)	0.90
Dairy to Large Feedlot	0.000	Triangular (0,30,190)	0.90
Dairy to Small Feedlot	0.000	Triangular (0,30,190)	0.90
Dairy to Dairy	0.065	Triangular (0,30,190)	0.90
Dairy to Large Swine	0.000	0.0	0.90
Dairy to Small Swine	0.000	0.0	0.90
Dairy to Sheep	0.000	0.0	0.90
Large Swine to Cow Calf	0.000	0.0	0.90
Large Swine to Large Feedlot	0.000	0.0	0.90
Large Swine to Small Feedlot	0.000	0.0	0.90
Large Swine to Dairy	0.000	0.0	0.90
Large Swine to Large Swine	0.186	Triangular (0,20,181)	0.90
Large Swine to Small Swine	0.000	Triangular (0,20,181)	0.90
Large Swine to Sheep	0.000	0.0	0.90
Small Swine to Cow Calf	0.000	0.0	0.90
Small Swine to Large Feedlot	0.000	0.0	0.90
Small Swine to Small Feedlot	0.000	0.0	0.90
Small Swine to Dairy	0.000	0.0	0.90
Small Swine to Large Swine	0.000	Triangular (0,20,181)	0.90
Small Swine to Small Swine	0.013	Triangular (0,20,181)	0.90
Small Swine to Sheep	0.000	0.0	0.90
Sheep to Cow Calf	0.000	Triangular (1,20,500)	0.90

Table 9 (Continued)
Direct Contact Spread Parameters in NAADSM

Source to Recipient	DCR	Distance Distribution (km)	Transfer Prob.
Sheep to Large Feedlot	0.000	Triangular (1,500,1000)	0.90
Sheep to Small Feedlot	0.000	Triangular (1,500,1000)	0.90
Sheep to Dairy	0.000	Triangular (0,30,100)	0.90
Sheep to Large Swine	0.000	0.0	0.90
Sheep to Small Swine	0.000	0.0	0.90
Sheep to Sheep	0.024	Triangular (1,25,100)	0.90

types. The maximum distance spread (under these conditions) is 3 km. The wind directionality, or area of risk of exposure around an infectious unit located at the center of a circle, is 359°. This means that the wind is directionless or that the disease can be spread via aerosol transmission in all directions.

Disease Detection and Traceability

Disease detection in NAADSM is specified by two relational functions. The first relational function relates the probability of observing clinical signs and the number of days that a unit has been clinically infectious. The second function relates the probability of reporting an observed clinical unit and the number of days since it was first detected. The values for these functions are taken from Premashthira *et al*. (2011) and are listed in Tables 11 and 12, respectively.

The trace parameters in NAADSM include the ability to conduct trace back investigations to search for both direct and indirect contacts where the unit that was reported was the recipient of contact. Based on Pendell (2006), a critical period of 14 days before detection is specified for all production types. For all non-cattle production types, the probability of a successful trace is held at 0.75 for direct and indirect contacts.

For cow-calf, feedlot and dairy operations, a value of 0.3, 0.6 or 0.9 is used for each scenario.

Table 10
Indirect Contact Spread Parameters in NAADSM

Source to Recipient	ICR	Distance Distribution (km)	Transfer Prob.
Cow Calf to Cow Calf	0.133	Triangular (0,39,190)	0.20
Cow Calf to Large Feedlot	1.711	Triangular (0,39,190)	0.20
Cow Calf to Small Feedlot	0.141	Triangular (0,39,190)	0.20
Cow Calf to Dairy	0.623	Triangular (0,39,190)	0.20
Cow Calf to Large Swine	0.044	0.0	0.20
Cow Calf to Small Swine	0.020	0.0	0.20
Cow Calf to Sheep	0.052	Triangular 1,25,100)	0.20
Large Feedlot to Cow Calf	0.123	Triangular (0,39,190)	0.20
Large Feedlot to Large Feedlot	1.589	Triangular (0,39,190)	0.20
Large Feedlot to Small Feedlot	0.131	Triangular (0,39,190)	0.20
Large Feedlot to Dairy	0.578	Triangular (0,39,190)	0.20
Large Feedlot to Large Swine	0.041	0.0	0.20
Large Feedlot to Small Swine	0.019	0.0	0.20
Large Feedlot to Sheep	0.048	Triangular (1,25,100)	0.20
Small Feedlot to Cow Calf	0.090	Triangular (0,39,190)	0.20
Small Feedlot to Large Feedlot	1.155	Triangular (0,39,190)	0.20
Small Feedlot to Small Feedlot	0.095	Triangular (0,39,190)	0.20
Small Feedlot to Dairy	0.420	Triangular (0,39,190)	0.20
Small Feedlot to Large Swine	0.030	0.0	0.20
Small Feedlot to Small Swine	0.014	0.0	0.20
Small Feedlot to Sheep	0.035	Triangular (1,25,100)	0.20
Dairy to Cow Calf	0.181	Triangular (0,39,190)	0.20
Dairy to Large Feedlot	2.326	Triangular (0,39,190)	0.20
Dairy to Small Feedlot	0.191	Triangular (0,39,190)	0.20
Dairy to Dairy	0.026	Triangular (0,39,190)	0.20
Dairy to Large Swine	0.015	0.0	0.20
Dairy to Small Swine	0.030	0.0	0.20
Dairy to Sheep	0.078	Triangular (1,25,100)	0.20
Large Swine to Cow Calf	0.026	Triangular (0,39,190)	0.20
Large Swine to Large Feedlot	0.337	Triangular (0,39,190)	0.20
Large Swine to Small Feedlot	0.028	Triangular (0,39,190)	0.20
Large Swine to Dairy	0.136	Triangular (0,39,190)	0.20
Large Swine to Large Swine	0.086	Triangular (0,30,90)	0.30
Large Swine to Small Swine	0.014	Triangular (0,30,90)	0.30
Large Swine to Sheep	0.008	Triangular (1,25,100)	0.20
Small Swine to Cow Calf	0.005	Triangular (0,39,190)	0.20
Small Swine to Large Feedlot	0.063	Triangular (0,39,190)	0.20
Small Swine to Small Feedlot	0.005	Triangular (0,39,190)	0.20
Small Swine to Dairy	0.026	Triangular (0,39,190)	0.20

Table 10 (Continued)
Indirect Contact Spread Parameters in NAADSM

Source to Recipient	ICR	Distance Distribution (km)	Transfer Prob.
Small Swine to Large Swine	0.015	Triangular (0,30,90)	0.30
Small Swine to Small Swine	0.003	Triangular (0,30,90)	0.30
Small Swine to Sheep	0.002	Triangular (1,25,100)	0.20
Sheep to Cow Calf	0.018	Triangular (0,39,190)	0.20
Sheep to Large Feedlot	0.229	Triangular (0,39,190)	0.20
Sheep to Small Feedlot	0.019	Triangular (0,39,190)	0.20
Sheep to Dairy	0.093	Triangular (0,39,190)	0.20
Sheep to Large Swine	0.015	0.0	0.20
Sheep to Small Swine	0.003	0.0	0.20
Sheep to Sheep	0.070	Triangular (1,25,100)	0.20

Two forms of disease control are used in the scenarios contained in this thesis: movement restrictions and destruction. Based on McReynolds (2013), the direct contact rates for all production types are restricted to 15 percent by the seventh day after detection. Due to the lower level of control for indirect contact rates, these are reduced to 30 percent by the seventh day following detection.

A delay of 2 days exists before a destruction program is implemented. By Day 10, the destruction capacity is eight herds per day. From Day 30 until the end of the outbreak, destruction capacity is held at 16 herds per day. If a unit of any production type is detected via trace-back of direct or indirect contact, it is destroyed. This requires a set of destruction priorities which, in rank order, are: detected units, trace-back of direct contact, units within a destruction ring and trace-back of indirect contact. The diameter of the destruction ring is specified at 2.42 km around a detected herd.

Direct Costs

The final set of NAADSM inputs are the cost estimates for appraisal, cleaning and disinfection, indemnification, euthanasia and disposal. These are taken from unpublished estimates by APHIS that were used by Pendell (2006). Cost estimates for sheep could not be found so they are left out of these calculations (which does not affect the economic analysis that this thesis is concerned with). The cost values are listed in Table 13.

Table 11
Probability of Observing

Operation Type	Clinical Days	Percent
Cow-Calf, Feedlot and Sheep	0	0
	1	30
	2	53
	3	30
	4	33
	5	17
	6	15
	7	13
Dairy	0	0
	1	30
	2	50
	3	30
	4	23
	6	17
Swine	0	0
	2	50
	3	30
	4	27
	6	25

Table 12
Probability of Reporting

Operation Type	Clinical Days	Percent
	0	70
	1	75
	2	81
	3	87
	4	93
	5	100

Table 13
Direct Costs

Operation Type	Types of Cost	Costs
Cow Calf	Cost of Appraisal (per herd)	$84.00
Cow Calf	Cost of Cleaning and Disinfecting (per herd)	$1565.00
Cow Calf	Indemnification (per animal)	$766.0
Cow Calf	Euthanasia (per animal)	$24.59
Cow Calf	Carcass disposal (per animal)	$13.19
Feedlot	Cost of Appraisal (per herd)	$210.00
Feedlot	Cost of Cleaning and Disinfecting (per herd)	$9844.00
Feedlot	Indemnification (per animal)	$766.00
Feedlot	Euthanasia (per animal)	$5.10
Feedlot	Carcass disposal (per animal)	$1.83
Dairy	Cost of Appraisal (per herd)	$84.00
Dairy	Cost of Cleaning and Disinfecting (per herd)	$3315.00
Dairy	Indemnification (per animal)	$1583.00
Dairy	Euthanasia (per animal)	$5.02
Dairy	Carcass disposal (per animal)	$1.97
Swine	Cost of Appraisal (per herd)	$84.00
Swine	Cost of Cleaning and Disinfecting (per herd)	$1127.50
Swine	Indemnification (per animal)	$92.00
Swine	Euthanasia (per animal)	$3.61
Swine	Carcass disposal (per animal)	$2.55
Sheep	Cost of Appraisal (per herd)	$0.0
Sheep	Cost of Cleaning and Disinfecting (per herd)	$0.0
Sheep	Indemnification (per animal)	$0.0
Sheep	Euthanasia (per animal)	$0.0
Sheep	Carcass disposal (per animal)	$0.0

Equilibrium Displacement Model

The economic information used to complete this analysis include the data used in estimating the elasticities for Utah cattle supplies, the elasticities adopted from previous research for use in the EDM and the baseline quantities and prices used in the calculation of welfare changes. The data used in determining the Utah cattle supply elasticities and baseline values are discussed in this section. The values and sources for the elasticities taken from previous literature are listed in Table 14.

Utah Cattle Supply Elasticities

The estimation of slaughter and farm-level supply elasticities for the state of Utah requires the use of annual data for the years 1990 – 2013. The quantity of fed cattle (in thousands) was taken from information provided by the Livestock Marketings Information Center (LMIC). The quantity of feeder cattle (in thousands) is derived from the Utah Agricultural Statistics cow-calf lagged one year with the number of beef heifer and dairy replacements subtracted. This is also taken from the LMIC. The prices for Utah fed cattle are those for slaughter steers ($/cwt) and are from the USDA's Agricultural Marketing Service (AMS). Utah feeder cattle prices also come from the AMS and are for 500 – 600 lbs. feeder steers. The prices of utility grade slaughter cows and beef by-products are taken from the LMIC. The prices of corn ($/bu.) and hay ($/ton) come from the LMIC and the USDA's Economic Research Service. The marketing cost index was developed from data in the USDA's *Agricultural Outlook* series. The United States' prime interest rate and the CPI were taken from the *Federal Reserve Economic Data*. Per capita beef consumption (lbs.) and retail beef prices ($/lb.) were taken from the USDA

Table 14
Summary Statistics for Data Used in Estimated Cattle Supply Elasticities

Variables	Mean	Standard Deviation	Minimum	Maximum
Q_S^S, Q_S^D	38.13	11.32	25	60
Q_F^S, Q_F^D	263.63	15.50	224	285
P_S^S, P_S^D	81.61	17.83	61.15	123.85
P_F^S, P_F^D	101.02	23.78	59.12	155.81
P_Y	9.03	1.98	7.00	14.22
P_U	49.45	12.35	33.11	80.01
P_C	3.08	1.44	1.86	6.67
P_H	112.73	37.58	75.45	206.58
D	101.73	3.83	94.48	112.26
M	150.96	37.09	77.59	214.37
I	6.59	2.24	3.25	10.01
T_S	1230.29	50.79	1140	1314
T_F	0.40	0.05	0.31	0.48

Economic Research Service. Finally, fed cattle marketings by feedlot size and the average live weight of fed cattle (lbs.) were obtained from the LMIC.

Baseline Quantities and Prices

The equilibrium prices and quantities for each marketing chain level are needed in order to calculate the consumer and producer welfare from the EDM. The quantity and price data discussed here are from 2013 and the values used are shown in Table 14. The retail quantities for beef, pork and poultry in the United States are taken from the ERS. These values are the product of the per capita consumption of each good and the total population of the United States. The retail prices for each of these commodities are the annual averages and are taken from the Bureau of Labor Statistics (BLS). The wholesale quantities for beef and pork are taken from the LMIC and are equal to total disappearance less imports (which are accounted for separately). The wholesale quantity of poultry is simply total disappearance because imports are not considered separately for this

Table 15
Equilibrium Displacement Model Parameters, Values and Sources

Parameter	Short-run Value	Source
η_{BB}^{R}	-0.56	Brester (1996)
η_{BP}^{R}	0.10	Brester (1996)
η_{BY}^{R}	0.05	Brester (1996)
η_{PB}^{R}	0.23	Brester (1996)
η_{PP}^{R}	-0.69	Brester (1996)
η_{PY}^{R}	0.04	Brester (1996)
η_{YB}^{R}	0.21	Brester (1996)
η_{YP}^{R}	0.07	Brester (1996)
η_{YY}^{R}	-0.33	Brester (1996)
η_{BUS}^{W}	-0.57	Marsh (1992)
η_{BUS}^{S}	-0.66	Marsh (1992)
η_{BUS}^{F}	-0.62	Marsh (2001)
η_{PUS}^{W}	-0.71	Brester *et al.* (2004)
η_{PUS}^{S}	-0.51	Wohlgenant (1989)
η_{YUS}^{W}	-0.22	Brester *et al.* (2004)
ε_{BUS}^{R}	0.36	Brester *et al.* (2004)
ε_{BUS}^{W}	0.28	Brester *et al.* (2004)
ε_{BUS}^{S}	0.26	Brester *et al.* (2004)
ε_{BUS}^{F}	0.22	Brester *et al.* (2004)
ε_{BUT}^{S}	0.83	Estimated
ε_{BUT}^{F}	0.27	Estimated
ε_{P}^{R}	0.73	Brester *et al.* (2004)
ε_{PUS}^{W}	0.44	Brester *et al.* (2004)
ε_{PUS}^{S}	0.41	Lemieux and Wohlgenant (1989)
ε_{PUT}^{S}	0.325	Meekhof (2007)
ε_{YUS}^{R}	0.18	Brester *et al.* (2004)
ε_{YUS}^{W}	0.14	Brester *et al.* (2004)
ε_{BI}^{W}	1.83	Pendell (2006)
ε_{BI}^{S}	7.38	Pendell (2006)
ε_{BI}^{F}	4.40	Pendell (2006)
ε_{PI}^{W}	1.41	Pendell (2006)
ε_{PI}^{S}	1.60	Pendell (2006)
τ_{B}^{WR}	1.03	Brester *et al.* (2004)
τ_{B}^{SW}	1.02	Brester *et al.* (2004)
τ_{B}^{FS}	0.78	Brester *et al.* (2004)
τ_{P}^{WR}	1.01	Brester *et al.* (2004)

Table 15 (Cont.)
Equilibrium Displacement Model Parameters, Values and Sources

Parameter	Short-run Value	Source
τ_P^{SW}	1.00	Brester *et al.* (2004)
τ_Y^{RW}	0.98	Brester *et al.* (2004)
τ_B^{RW}	1.02	Pendell (2006)
τ_B^{WS}	0.94	Pendell (2006)
τ_B^{SF}	0.97	Pendell (2006)
τ_P^{RW}	0.99	Pendell (2006)
τ_P^{WS}	0.92	Pendell (2006)
τ_Y^{RW}	0.93	Pendell (2006)

commodity in this analysis. The wholesale prices for these goods are taken from the LMIC. The wholesale price for beef is the average price of boxed beef Choice 600-900 and Select 600-900. The wholesale price of pork is the carcass cut-out value (51-52% lean). The price of wholesale poultry is for broilers (12 City price). The wholesale import and export quantities for beef and pork are collected from the LMIC. The import and export prices at the wholesale level are assumed to be equal to the national price for the respective commodities.

Fed cattle quantities for Utah and Other States (U.S. quantities less Utah quantity) are taken from USDA, NASS. The price of Utah fed cattle is the average price of Wyoming steers and heifers Choice 2-3 and Select 2-3 for 1100-1300 lbs. The price for Other States fed cattle is the national average for 2013 and is taken from the LMIC. The quantities and prices of market hogs in Utah and Other States are taken from the LMIC. The Other States price for market hogs is the average of barrows and gilts for the Eastern Corn Belt and Western Corn Belt. The quantity data for imported beef and pork data were collected from the LMIC. These data, however, are only available in number of head. To convert these quantities into pounds, the number of head for each was multiplied by the average weight (taken from the USDA). As with wholesale import prices, the import prices for the slaughter level are assumed to be the same as the national price. The quantities (head) for Utah, Other States and imported feeder cattle are taken from NASS and similarly converted to pounds by multiplying the number of head by the average weight of feeder cattle (collected from the USDA). The price of Utah feeder cattle is assumed to be equal to the price of feeder cattle in Colorado and is taken from the LMIC. The Other States price of feeder cattle is also taken from the LMIC.

Table 16
Baseline Prices and Quantities

	Quantities (million lbs.)	Prices ($/lb.)
Retail Beef US	17,830.8	$4.94
Retail Pork US	14,511.42	$3.64
Retail Poultry US	25,958.30	$1.48
Wholesale Beef US	23,263.00	$2.99
Wholesale Pork US	18,221.10	$0.64
Wholesale Poultry US	30,184.10	$1.00
Import Beef	2,249.62	$2.99
Export Beef	2,590	$2.99
Import Pork	880	$0.64
Export Pork	4,992	$0.64
Slaughter Beef UT	313.66	$1.24
Slaughter Beef OS	55,221.55	$1.17
Slaughter Hog UT	291.78	$0.67
Slaughter Hog OS	33,071.37	$0.67
Import Beef	809.45	$1.17
Import Pork	1,168.50	$0.67
Farm Beef UT	322.08	$1.52
Farm Beef OS	20,035.92	$1.74
Import Beef	159.48	$1.74

CHAPTER 6

RESULTS

The results of the epidemiological simulations and the economic model are presented and discussed in this chapter. In the first section, the output of each of the three simulated scenarios (30, 60 and 90 percent trace-back success) are examined. This section discusses estimation of the Utah supply elasticities for fed and feeder cattle, the EDM output for each outbreak scenario and the sensitivity analysis performed. As described in Chapter 2, the 30 percent scenario is reflective of the current state of animal surveillance in the United States. The 60 percent scenario reflects a widely adopted statewide traceability system that may not be fully operational. Finally, the 90 percent scenario reflects a universally adopted, flexible national system such as the proposed Animal Disease Traceability rule (Golan *et al*., 2004; Pendell, 2006).

NAADSM Results

For the purposes of this analysis, there are three specific sections of epidemiological output that will be discussed: the duration of each outbreak scenario, the summary statistics for the number of livestock destroyed and the summary statistics for the associated costs of destruction. Overall, an inverse relationship between the total number of animals depopulated across production types and the probability of a successful trace was found. This is consistent with the findings of previous research such as Zhao *et al.* (2001) and Pendell (2006). The summary statistics for the disease outbreak and number of animals depopulated by production type are presented in Table 17. Table 18 presents the cost estimates for each production type for each trace scenario.

The epidemiological outputs for the production types used in the EDM (cow-calf, feedlot and swine) and the differences in outbreak duration are consistent with the findings of Griffiths and Zhao (2000) and Pendell (2006) both in magnitude and response to increased levels of surveillance. The percentage of fed cattle and slaughter hogs depopulated in Utah for all scenarios are larger than either of these studies. This is a reflection of the small number of feedlot and slaughter hog operations in the state and the concentration of a large number of animals in a few feedlots. The percentage of operations infected is consistent with previous simulated outbreaks in other regions of the United States.

In the scenario involving a low level of trace success (reflective of the current state of animal identification), the simulated outbreak results in a 36.595% decrease in Utah's fed cattle population. This percentage is reduced to 31.354% under the medium level of trace success and 27.710 under the highest level. The large size of these mean effects is the result of three of Utah's 132 feedlot operations possessing nearly half of the state's fed cattle population so that once FMD is detected in the NAADSM simulation, the depopulation of any of these three feedlot operations has a disproportionate effect on the overall fed cattle population. The number of feeder cattle destroyed under the 30, 60 and 90 percent trace success scenarios are 4.790%, 3.011% and 2.172%, respectively.

Similarly to feedlots in Utah, a small number of swine operations in Utah contain a disproportionate number of slaughter hogs which resulted in larger relative depopulation compared to other studies. Under the lowest level of trace success, 13.676% of slaughter hogs are depopulated. Under the medium and high trace success scenarios, 12.241 and 12.087 percent of slaughter hogs are depopulated, respectively. This reflects the indirect benefits of higher levels of cattle traceability which limits the indirect spread of the disease to other animal types by allowing for quicker response times to an FMD outbreak in the cattle industry. A similar pattern is present among sheep, which are not included in the EDM used in this thesis, between trace scenarios.

Table 17
Outbreak Summary Statistics

Output Statistic	Low	Medium	High
Outbreak Duration (Days)	160	154	150
Std. Dev of Outbreak Duration	63	59	55
Fed Cattle Depopulated (Head)	8,730	7,480	6,611
Feeder Cattle Depopulated (Head)	17,702	11,132	8,029
Dairy Cows Depopulated (Head)	21,315	18,324	17,231
Swine Depopulated (Head)	100,059	89,564	88,433
Sheep Depopulated (Head)	15,148	14,303	13,273
Total Animals Depopulated (Head)	*162,956*	*140,518*	*135,477*
Std. Dev of Total Animals Depopulated	92,987	103,843	96,507

As discussed in Chapter 3, NAADSM also provides direct cost estimates for control and depopulation including appraisal, euthanasia, indemnification, carcass disposal and disinfection. The direct cost outputs produced by NAADSM are shown in Table 18 for each production type (with the exception of sheep for which cost estimates were not provided). Since the cost estimates are based directly on the depopulation figures described above, the same inverse relationship between the probability of a successful trace back and the costs of an outbreak exists. Under the lowest level of trace success, direct costs are estimated to be $66.1 million in response to an outbreak. Under the medium level of trace success, these costs are estimated to decrease by over $12 million to $53.8 million. If the most effective trace system were to be adopted, direct costs decrease by a further $5 million to $48.6 million.

In addition to the supply shocks for slaughter hogs, fed cattle and feeder cattle presented above, two additional shocks – one for the wholesale supplies of both beef and pork – have been calculated to account for the closure of processing plants and the disposal of a day's worth of meat and by-product. The following calculations are adapted from Pendell (2006). The plants used to calculate these wholesale shocks for beef and pork are JBS and Circle Four Farms. The cost of plant closure for beef is equal to product of the total capacity of the plant, the fixed cost per head and the number of days the operation is closed. The capacity (2,500 head) was gathered from personal communication with JBS. The fixed cost is adapted from Duewer and Nelson (1991) and assumed to be $65 per head. Following Pendell (2006), a plant closure of 10 days is assumed. The costs of disposed meat and by-products is the sum of the product of the number of head, the average dressed weight of steers and heifers, the average boxed-beef price for choice 6-9 and select 6-9 and the product of the beef by-product price, the average liveweight for cattle and the number of head. All this information was collected from the LMIC. The estimated total cost for the beef industry resulting from wholesale closure and disposal is $8,154,544.70 which, by dividing by the wholesale value of the beef industry (price multiplied by quantity) of $59.56 billion, is equivalent to 0.0117%.

Table 18
Comparison of Direct Costs

Production Type	30 Percent Scenario	60 Percent Scenario	90 Percent Scenario
Cow-Calf	$7,000,824	$6,043,872	$5,393,153
Feedlot	$14,995,154	$9,429,859	$6,799,944
Dairy	$34,258,246	$29,462,621	$27,704,180
Swine	$9,866,921	$8,842,201	$8,720,741
Total	*$66,121,146*	*$53,778,554*	*$48,618,020*

The cost of closure and disposal are similarly calculated for wholesale pork. The number of head is 21,000 and was gathered from personal communication. A fixed cost of $6 per head is taken from Hayenga (1998). Finally, as with beef, a closure of 10 days is assumed for pork processing plants. The costs of meat disposal here is equal to the product of the capacity, the average dressed weight for market hogs, and the cut-out value (51-52% lean). The costs of by-product disposal are equivalent to the pork by-product price multiplied by the average liveweight for market hogs and the number of head. All of the price and weight data is taken from the LMIC. The total cost of plant closure and a single days processed pork and by-products is estimated to be $6,332,324.60. Dividing by a wholesale pork value of $11,661,504,000, this yields a percentage cost shift of 0.054%. All of the percentage shocks used in the EDM are presented in Table 19.

Table 19
Percentage Shocks in EDM

	30 Percent Scenario		60 Percent Scenario		90 Percent Scenario	
Beef	Quantity	Cost	Quantity	Cost	Quantity	Cost
Retail	0.00	0.00	0.00	0.00	0.00	0.00
Wholesale	0.00	0.012	0.00	0.012	0.00	0.012
Fed (O)	0.00	0.005	0.00	0.005	0.00	0.004
Fed (UT)	-36.6	0.011	-31.4	0.009	-27.7	0.008
Feeder (O)	0.00	0.021	0.00	0.013	0.00	0.010
Feeder (UT)	-4.79	0.042	-3.01	0.027	-2.17	0.020
Pork						
Retail	0.00	0.00	0.00	0.00	0.00	0.00
Wholesale	0.00	0.05	0.00	0.05	0.00	0.05
Market (O)	0.00	0.02	0.00	0.02	0.00	0.02
Market (UT)	-13.68	0.04	-12.24	0.04	-12.09	0.04
Poultry						
Retail	0.00	0.00	0.00	0.00	0.00	0.00
Wholesale	0.00	0.00	0.00	0.00	0.00	0.00

Utah Supply Elasticities

As mentioned in Chapter 4, there are a number of statistical problems that are often present when estimating time series systems such as serial correlation, non-stationarity and simultaneity. In addition to these problems, a non-diagonal covariance matrix of errors was detected when examining the residual correlation matrix. As discussed above, while a Two-Stage Least Squares estimation would correct for simultaneity, it would not resolve the problem of contemporaneously correlated error terms. In order to correct for these, a Three-Stage Least Squares (3SLS) estimator is used in Stata. The results of the estimations for the fed and feeder cattle supply and demand equations are presented in Tables 20 and 21, respectively.

Table 20
Regression Results for Utah Slaughter Cattle

Fed Cattle Demand:

$$lnP_S = 6.9125 - .7822lnQ_S - .0748lnD + .4183lnP_Y - .1162lnM$$

(3.63) (-5.65) (0.841) (3.95) (-3.63)

R^2=0.9023

Fed Cattle Supply:

$$lnQ_S = 3.3873 + .8270lnP_S + 0.2236lnI - .2270lnP_C - .9513lnP_F + 0.4026lnT_F$$

(2.00) (2.56) (0.52) (-3.29) (-4.69) (1.88)

$$-.5547lnQ_{S-1}$$

(3.00)

R^2=0.8896

All of the estimated coefficients in the fed cattle supply and demand equations were statistically significant at the 0.05 level except for the demand index (D) in the demand equation and the prime interest rate (I) which were statistically insignificant. In the slaughter demand equation, the coefficient for the quantity of cattle slaughtered was -0.7822 which is consistent with economic theory. The magnitude of this value is also consistent with previous studies that estimated the U.S. demand elasticity for slaughter cattle to be -0.61 and -.0688 (Buhr and Kim, 1997; Marsh, 2003). The price of beef by-products is positively related to fed cattle price and the coefficient is similar to the 0.382 estimated by Marsh (2003).

The short-run supply elasticity for slaughter cattle was estimated to be 0.8270 which is consistent with the economic theory that an increase in the price of slaughter cattle is associated with an increase in the number of slaughter cattle supplied. The coefficient for the quantity supplied in the previous year is also positive as expected. The price of corn and price of feeder cattle are both negative as expected. The long-run supply elasticity is calculated by dividing the coefficient of the fed cattle quantity variable by the difference of the coefficient of the quantity from the previous period subtracted from one.

Table 21
Regression Results for Utah Slaughter Cattle

Feeder Cattle Demand:

$$lnP_F = 4.6686 - .6633lnQ_F + 1.0515lnP_S -.2358lnP_C + 0.0169lnI +.8540lnT_F$$

(1.52) (-1.76) (4.76) (-4.14) (0.33) (2.57)

R^2=0.9395

Feeder Cattle Supply:

$$lnQ_F = 5.3991 + .2743lnP_{F-2} +.0276lnP_{H-1} - .4127P_{W-2} - .1992lnT_C + .2170lnQ_{F-1}$$

(1.49) (1.67) (0.38) (-2.78) (-0.28) (1.01)

R^2=0.5154

All of the variables in the feeder cattle demand equation are statistically significant at the 0.10 level with the exception of the prime interest rate which was found to be statistically insignificant. The price of feeder cattle and the quantity demanded are negatively related as predicted by economic theory. The value of the coefficient (-0.6633) is similar to the value of the feeder cattle demand elasticity of -0.62 estimated by Marsh (2001). The slaughter price transmission coefficient is positive and similar to the value of

1.1999 estimated by Marsh (2003). The corn price coefficient is negatively related to feeder price and similar in size to previous estimates (Hinckley, 1985; Buccola, 1980; Pendell, 2006).

In the feeder cattle supply equation, only the lagged feeder price and lagged price of slaughter grade utility cows were found to be statistically significant. The feeder cattle supply elasticity estimated here (0.2742) is similar to the previous estimate of 0.220 by Marsh (2003).

EDM Results

As explained in Chapter 4, the percentage shocks resulting from the depopulation of fed cattle, feeder cattle and market hogs are used on equations 15, 22 and 39, respectively. The cost estimations provided by NAADSM are applied to equations 10, 11, 17, 18, 34 and 35. The wholesale beef and pork industry effects calculated above are applied to equations 5 and 29. Finally, demand shocks (where included) are used on equations 1, 25 and 41. The EDM is solved by multiplying the inverse matrix of endogenous variables ($\mathbf{M}^{-1}$) by the matrix of exogenous shocks ($\mathbf{X}$).

The output from the epidemiological simulation of each trace scenario has been used as input for the EDM under four alternate sets of assumptions. The first set assumes that there are no changes in demand in response to an outbreak and that the producers assume the full burden of the costs. The second scenario assumes that the demand for beef and pork will decrease by 2 percent while the demand for poultry will increase by 1 percent in response to an outbreak and that the producer bears the total cost. The third and fourth scenarios contain the same demand assumptions as scenarios one and two, respectively, but assume that the government subsidizes 50% of direct costs to producers.

These results indicate an inverse relationship between the depth of animal identification and the percentage change in the price and quantity resulting from an FMD outbreak in Utah. This is reflective of the lower number of animals being destroyed and the associated costs of containment resulting from the ability of producers to quickly identify and control an outbreak. As would be expected, the size of the percentage changes are larger in the scenarios involving demand changes compared to those which held demand constant. In the scenarios where producers only bare 50% of the total costs, the percentage changes in price and quantity are smaller than in their full cost counterparts. The differences in price and quantity changes across marketing levels in the pork industry are less consistent, particularly in the scenarios involving demand shifts. This is consistent with findings in previous EDM analyses (Brester *et al.* 2004; Pendell, 2006) and is discussed further in the sensitivity analysis section of this chapter.

The consumer and producer surplus changes in each scenario for all marketing levels across all three industries are presented in Tables 6.10 – 6.14. In the first scenario where producers bare all costs and there is no change in demand, the loss in producer surplus for the entire beef industry is estimated to be $570.75 million under the lowest level of trace success. Under the medium level, the producer surplus losses to the beef industry are reduced to $456.33 million and under the highest level, these losses are reduced further to $387.14 million. The fed and feeder cattle industries in Utah experience notable benefits between the highest and lowest levels of trace success with $20.76 million and $23.48 million fewer losses in producer surplus, respectively. The market hog industry in Utah similarly benefits from increased animal identification in the cattle industry with $4.76 million fewer losses in the high trace success scenario compared to the low scenario. Overall, the 90% trace scenario prevents $130.77 million in producer surplus losses across all marketing levels for all commodities compared to the 30% trace scenario.

Table 22
Changes in Producer and Consumer Surplus for Scenario I

Scenario	30 Percent Scenario	60 Percent Scenario	90 Percent Scenario
Producer Surplus:			
Retail Beef:	-200.66	-165.66	-138.72
Wholesale Beef:	-135.19	-109.35	-93.17
Fed Cattle (Other States):	-47.45	-35.87	-29.58
Fed Cattle (Utah):	-85.45	-73.21	-64.69
Feeder Cattle (Other States):	-59.24	-48.45	-41.70
Feeder Cattle (Utah):	-42.76	-26.80	-19.28
Total ΔPS for Beef:	*-570.75*	*-456.33*	*-387.14*
Retail Pork:	17.42	14.75	12.82
Wholesale Pork:	5.85	6.46	6.19
Market Hog (Other States):	14.93	13.94	13.64
Market Hog (Utah):	-40.99	-36.69	-36.23
Total ΔPS for Pork:	*-2.78*	*-1.54*	*-3.57*
Retail Poultry:	94.41	74.58	62.84
Wholesale Poultry:	61.23	48.37	40.75
Total ΔPS for Poultry:	*115.64*	*122.95*	*103.59*
Total ΔPS for All Meat:	-417.89	-334.92	-287.12
Consumer Surplus:			
Retail Beef:	-175.84	-141.53	-120.31
Retail Pork:			
Retail Poultry:	-26.58	-20.99	-17.69
Total ΔCS for Retail:			

If demand is assumed to decrease for beef and pork as a result of an FMD outbreak, the losses to producer and consumer surplus are considerably larger. In the lowest trace success scenario, losses in producer surplus to the beef industry are $1.23

billion compared to $570.75 when no change in demand existed. This relative size increase in consistent with the effects found in Pendell (2006) and Brester *et al.* (2004) concerning the addition of a demand shock. The relative benefit of the high scenario compared to the low for the beef industry under these assumptions is $214.98 million in producer surplus. This is larger than the $183.61 million benefit produced when no demand shift was assumed. Assuming a demand shock, the relative benefit of the most effective trace scenario is somewhat less for Utah fed cattle ($17.55 million) and the same for Utah feeder cattle and slaughter hogs from when no demand change was assumed. Overall, the relative benefit of the high trace back scenario over the low is $190.02 million for all meat producers and $70.46 million in consumer surplus losses.

When only 50 percent of the costs are borne by producers and no demand shift occurs, the losses in producer surplus are only somewhat smaller than when producers bare the full-cost. For the low trace scenario under the full-cost assumption, the beef industry is estimated to lose $570.75 million in producer surplus compared to $520.21 million when half the costs are borne by producers. The relative benefits of the highest level of animal identification compared to the lowest are comparable to the full-cost scenario with $183.61 in prevented losses to producer surplus for the beef industry. The 50 percent cost scenario with changes in demand exhibits a similar relationship when compared to its full-cost counterpart with only a small reduction in surplus losses.

Sensitivity Analysis

As discussed in Chapter 4, this thesis follows Jones (2010) in performing sensitivity analysis by adjusting the supply and demand elasticities under four different scenarios. First, the supply elasticities were increased by 50% while the demand elasticities remained unchanged. Second, the supply elasticities were decreased by 50% while the demand elasticities remained unchanged. Third, the demand elasticities were increased by 50% while the supply elasticities remained unchanged. Finally, the demand elasticities were decreased by 50% while the supply elasticities remained unchanged. The results of each of the four elasticity scenarios for each of the depths of animal identification under each set of cost and demand assumptions are presented in the Appendix

Table 23
Changes in Producer and Consumer Surplus for Scenario II

	30 Percent Scenario	60 Percent Scenario	90 Percent Scenario
Producer Surplus:			
Retail Beef:	-705.43	-667.46	-643.55
Wholesale Beef:	-227.34	-201.48	-185.28
Fed Cattle (Other States):	-82.83	-50.88	-33.53
Fed Cattle (Utah):	-86.32	-74.11	-65.61
Feeder Cattle (Other States):	-94.05	-83.25	-76.50
Feeder Cattle (Utah):	-42.53	-26.57	-19.04
Total ΔPS for Beef:	*-1238.50*	*-1103.75*	*-1023.52*
Retail Pork:	-366.04	-368.70	-370.62
Wholesale Pork:	-73.22	-72.61	-72.89
Market Hog (Other States):	-27.82	-28.82	-29.12
Market Hog (Utah):	-41.04	-36.73	-36.26
Total ΔPS for Pork:	*-508.12*	*-506.86*	*-508.89*
Retail Poultry:	444.31	433.64	427.31
Wholesale Poultry:	188.18	183.66	180.98
Total ΔPS for Poultry:	*632.49*	*617.30*	*608.30*
Total ΔPS for All Meat:	-1114.13	-993.31	-924.11
Consumer Surplus:			
Retail Beef:	-429.43	-395.25	-374.11
Retail Pork:	-342.66	-337.72	-336.41
Retail Poultry:	-40.38	-34.80	-31.49
Total ΔCS for Retail:	*-812.47*	*-767.77*	*-742.01*

Table 24
Changes in Producer and Consumer Surplus for Scenario III

Scenario	30 Percent Scenario	60 Percent Scenario	90 Percent Scenario
Producer Surplus:			
Retail Beef:	-167.12	-134.61	-113.40
Wholesale Beef:	-112.54	-90.41	-76.07
Fed Cattle (Other States):	-36.51	-28.50	-23.99
Fed Cattle (Utah):	-85.41	-73.16	-64.65
Feeder Cattle (Other States):	-76.26	-58.31	-48.22
Feeder Cattle (Utah):	-42.37	-26.56	-19.11
Total ΔPS for Beef:	*-520.21*	*-411.55*	*-345.45*
Retail Pork:	14.66	12.44	10.74
Wholesale Pork:	5.28	5.99	5.76
Market Hog (Other States):	14.63	13.68	13.41
Market Hog (Utah):	-40.99	-36.69	-36.23
Total ΔPS for Pork:	*-6.42*	*-4.58*	*-6.32*
Retail Poultry:	78.16	60.99	50.57
Wholesale Poultry:	50.69	39.56	32.80
Total ΔPS for Poultry:	*128.85*	*100.55*	*83.38*
Total ΔPS for All Meat:	-397.77	-315.59	-345.45
Consumer Surplus:			
Retail Beef:	-149.16	-119.64	-100.83
Retail Pork:	-23.32	-18.19	-16.94
Retail Poultry:	-24.40	-19.53	-16.59
Total ΔCS for Retail:	*-196.87*	*-157.36*	*-134.36*

Across all elasticity scenarios and all cost and demand assumptions, the general relationship between higher levels of animal identification and decreased welfare losses both for the beef industry and for all meat producers in aggregate is maintained. Consistent with Jones (2010), a more inelastic supply is associated with larger producer surplus changes while more elastic supply is associated with lower producer surplus

Table 25
Changes in Producer and Consumer Surplus for Scenario I

Scenario	30 Percent Scenario	60 Percent Scenario	90 Percent Scenario
Producer Surplus:			
Retail Beef:	-676.68	-644.12	-622.92
Wholesale Beef:	-205.54	-183.37	-169.02
Fed Cattle (Other States):	-52.17	-30.09	-17.65
Fed Cattle (Utah):	-86.29	-74.07	-65.58
Feeder Cattle (Other States):	-111.40	-93.45	-83.35
Feeder Cattle (Utah):	-42.14	-26.33	-18.87
Total ΔPS for Beef:	*-1174.23*	*-1051.42*	*-977.39*
Retail Pork:	-362.08	-364.40	-366.10
Wholesale Pork:	-56.58	-56.16	-56.42
Market Hog (Other States):	-15.30	-16.86	-17.21
Market Hog (Utah):	-40.90	-36.60	-36.14
Total ΔPS for Pork:	*-474.85*	*-474.02*	*-475.87*
Retail Poultry:	426.39	417.29	411.70
Wholesale Poultry:	180.59	176.74	174.37
Total ΔPS for Poultry:	*606.98*	*594.04*	*586.08*
Total ΔPS for All Meat:	-1042.10	-931.40	-867.18
Consumer Surplus:			
Retail Beef:	-394.04	-364.79	-346.07
Retail Pork:	-294.83	-290.88	-289.77
Retail Poultry:	-31.00	-26.25	-23.32
Total ΔCS for Retail:	*-719.88*	*-681.92*	*-659.16*

changes. Similarly, more elastic demand tends to increase welfare losses for retail and wholesale producers while decreasing the size of the losses for fed and feeder cattle producers. The relative size of the changes between elasticity scenarios for beef industry producers surplus in the scenarios involving no change in demand are consistent in relative magnitude with those presented in Jones (2010). The range of changes in welfare loss between elasticity scenarios when demand shifts are also included is wider than those scenarios with only supply shifts which is also consistent with previous research. The widest ranging changes occur in the pork industry which is consistent with Brester *et al.* (2004) and Pendell (2006) which found frequent statistical insignificance for welfare changes for marketing levels in the pork industry.

CHAPTER 7

CONCLUSION

The research in this thesis has analyzed the potential economic impacts from the duration of an FMD outbreak originating in Utah. Using the North American Animal Disease Spread Model, empirical livestock data was used to generate estimates of the average number of animals depopulated as the result of an outbreak under three different levels of livestock traceability. These quantities and their associated costs were then used to apply supply shocks in an equilibrium displacement model to generate percentage changes to the prices and quantities of all marketing levels for beef, pork and poultry. This made it possible to estimate the producer and consumer surplus changes that would result from an outbreak.

Given the history of FMD outbreak occurring in countries after decades of being free of the disease such as in South Korea (8 years), Taiwan (68 years) and the United Kingdom (34 years), the ability to quickly identify and implement control strategies is crucial given the potential for an outbreak to occur even in the United States which has been FMD-free since 1929. Previous research has engaged with a hypothetical FMD outbreak that originated in specific geographical areas such as southwestern Kansas where a large portion of the cattle marketings in the United States. This thesis has demonstrated the value of a fully functioning nationwide animal identification system in stemming outbreaks in even states with relatively small livestock populations such as Utah. Further, this thesis has also estimated the welfare losses to fed cattle, feeder cattle and slaughter hog producers in Utah resulting from a local FMD outbreak under different levels of traceability.

As of 2013, Utah is only the 14th largest producer of swine and 33rd largest producer of cattle in the United States. Despite Utah's relatively small size, this simulation of a Utah-based FMD outbreak still produces producer surplus losses to the beef industry of between $570.75 million and $1.24 billion, depending on whether demand shocks occur simultaneously or not. By adapting a national, fully functional animal identification system such as the ADT – represented by a 90 percent successful trace-back – producer surplus losses of between $130.77 million and $190.02 million could potentially be prevented.

While livestock in Utah constitutes only a small portion of the nation's livestock economy, livestock comprise a major part of the state's overall agricultural economy. In 2012, livestock and livestock products made up 68 percent of the market value of all agricultural products sold in the state totaling nearly $1.24 billion. The ability to quickly identify and implement control strategies in response to an outbreak is important to the economy of Utah. By adapting a fully functional ADT-style traceability system, the producer surplus losses to Utah's fed cattle, feeder cattle and market hogs of $49 million can be prevented compared to the current standard of limited or no traceability.

The findings of this thesis are consistent with previous research such as Zhao *et al.* (2006), Disney *et al*. (2001) and Pendell (2006) who found that increased animal identification and surveillance reduces the welfare losses to both consumers and producers in the United States even when the costs of implementation are included. If a high-level system of animal identification is adopted, not only is the duration of an FMD outbreak decreased but the number of animals depopulated is decreased as a result of the ability to quickly identify, quarantine and control the spread of the disease. The reduction in producer surplus losses in the event of an FMD outbreak are in additional benefit to the increase in consumer demand resulting from increased consumer confidence that occurs as a result of the ability of producers to trace meat products back to their source, as discussed by Dickinson *et al*. (2003).

Limitations and Future Research

The research conducted in this thesis provides an application of an epidemiological-economic framework adapted from Pendell (2006) and Jones (2010) to analyze the economic impacts of an FMD outbreak in the state of Utah. One of the basic drawbacks of the trace-back function in NAADSM is that it is only capable of tracing backwards one step which prevents tracing back to the source.

The unavailability of previously published elasticities for marketing levels in the sheep industry prevented the incorporation of this industry in the EDM. Given the relative size of the sheep industry in Utah, the 8^{th} largest in the United States, future research should seek to include this into the economic framework. In addition, including the livestock populations of surrounding states in the epidemiological framework would produce more accurate estimates of the national effects of an FMD outbreak based in Utah. Future research for the state of Utah should also seek to include stochastic inputs in the EDM to generate distributions of price, quantity and welfare changes to better demonstrate their accuracy. Finally, future research may wish to incorporate the cost effects of adopting higher levels of animal identification to more accurately portray the economic effects discussed in this thesis.

Overall, the research contained in this thesis reveals the importance and benefit of higher levels of animal identification and surveillance for the state of Utah and the United States as a whole. It reveals the importance of better traceability systems in reducing negative economic welfare effects even when an outbreak is centered in a relatively small livestock population such as Utah.

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APPENDIX

Table 26
Percentage Changes of Endogenous Variables for Outbreak Scenarios with 100% Costs Borne by the Produce and No Change in Demand

Endogenous Variables	Percentage Changes		
	30 Percent	60 Percent	90 Percent
Retail Beef Price	0.200	0.161	0.137
Retail Beef Quantity	-0.108	-0.088	-0.075
Wholesale Beef Price	0.099	0.079	0.067
Wholesale Beef Quantity	-0.177	-0.143	-0.122
Wholesale Import Beef Price	0.099	0.079	0.067
Wholesale Import Beef Quantity	0.181	0.145	0.123
Fed Cattle Price (Other States)	0.099	0.083	0.074
Fed Cattle Quantity (Other States)	-0.058	-0.040	-0.030
Fed Cattle Price (Utah)	0.094	0.079	0.070
Fed Cattle Quantity (Utah)	-36.508	-31.354	-27.645
Fed Cattle Price (Import)	0.099	0.083	0.074
Fed Cattle Quantity (Import)	0.732	0.616	0.545
Feeder Cattle Price (Other States)	-0.158	-0.141	-0.127
Feeder Cattle Quantity (Other States)	-0.013	-0.018	-0.018
Feeder Cattle Price (Utah)	-0.180	-0.161	-0.145
Feeder Cattle Quantity (Utah)	-4.795	-3.028	-2.192
Feeder Cattle Price (Import)	-0.158	-0.141	-0.127
Feeder Cattle Quantity (Import)	-0.693	-0.619	-0.557
Retail Pork Price	0.002	-0.007	-0.009
Retail Pork Quantity	0.047	0.044	0.040
Wholesale Pork Price	0.013	0.007	0.004
Wholesale Pork Quantity	0.046	0.050	0.047
Wholesale Import Pork Price	0.013	0.007	0.004
Wholesale Import Pork Quantity	0.019	0.009	0.006
Market Hog Price (Other States)	0.144	0.138	0.135
Market Hog Quantity (Other States)	-0.028	-0.021	-0.022
Market Hog Price (Utah)	0.144	0.138	0.135
Market Hog Quantity (Utah)	-13.584	-12.157	-12.004
Market Hog Price (Import)	0.144	0.138	0.135
Market Hog Quantity (Import)	0.231	0.221	0.216
Retail Poultry Price	0.069	0.055	0.046
Retail Poultry Quantity	0.019	0.015	0.013
Wholesale Poultry Price	0.050	0.039	0.033
Wholesale Poultry Quantity	0.007	0.006	0.005

Table 27
Percentage Changes of Endogenous Variables for Outbreak Scenarios with 100% Costs Borne by the Produce and Changes in Demand

Endogenous Variables	Percentage Changes		
	30 Percent	60 Percent	90 Percent
Retail Beef Price	-0.511	-0.480	-0.574
Retail Beef Quantity	-0.719	-0.717	-0.686
Wholesale Beef Price	-0.353	-0.336	-0.384
Wholesale Beef Quantity	-0.524	-0.534	-0.470
Wholesale Import Beef Price	-0.353	-0.336	-0.384
Wholesale Import Beef Quantity	-0.646	-0.615	-0.703
Fed Cattle Price (Other States)	-0.219	-0.244	-0.244
Fed Cattle Quantity (Other States)	-0.171	-0.191	-0.144
Fed Cattle Price (Utah)	-0.206	-0.230	-0.230
Fed Cattle Quantity (Utah)	-36.757	-31.556	-27.894
Fed Cattle Price (Import)	-0.219	-0.244	-0.244
Fed Cattle Quantity (Import)	-1.613	-1.798	-1801
Feeder Cattle Price (Other States)	-0.287	-0.273	-0.256
Feeder Cattle Quantity (Other States)	-0.042	-0.073	-0.047
Feeder Cattle Price (Utah)	-0.328	-0.312	-0.293
Feeder Cattle Quantity (Utah)	-4.835	-3.122	-2.232
Feeder Cattle Price (Import)	-0.287	-0.273	-0.256
Feeder Cattle Quantity (Import)	-1.263	-1.201	-1.126
Retail Pork Price	-0.349	-0.179	-0.360
Retail Pork Quantity	-0.853	-0.961	-0.860
Wholesale Pork Price	-0.435	-0.355	-0.444
Wholesale Pork Quantity	-0.604	-0.839	-0.603
Wholesale Import Pork Price	-0.435	-0.355	-0.444
Wholesale Import Pork Quantity	-0.613	-0.501	-0.626
Market Hog Price (Other States)	-0.543	-0.761	-0.552
Market Hog Quantity (Other States)	-0.328	-0.450	-0.321
Market Hog Price (Utah)	-0.543	-0.761	-0.552
Market Hog Quantity (Utah)	-13.808	-12.528	-12.227
Market Hog Price (Import)	-0.543	-0.761	-0.552
Market Hog Quantity (Import)	-0.868	-1.218	-0.884
Retail Poultry Price	0.605	0.635	0.582
Retail Poultry Quantity	0.169	0.177	0.162
Wholesale Poultry Price	0.436	0.457	0.419
Wholesale Poultry Quantity	0.061	0.064	0.059

Table 28
Percentage Changes of Endogenous Variables for Outbreak Scenarios with 50% Costs Borne by the Produce and No Change in Demand

Endogenous Variables	Percentage Changes		
	30 Percent	60 Percent	90 Percent
Retail Beef Price	0.169	0.136	0.115
Retail Beef Quantity	-0.087	-0.070	-0.059
Wholesale Beef Price	0.084	0.068	0.057
Wholesale Beef Quantity	-0.145	-0.117	-0.098
Wholesale Import Beef Price	0.084	0.068	0.057
Wholesale Import Beef Quantity	0.154	0.124	0.104
Fed Cattle Price (Other States)	0.106	0.093	0.084
Fed Cattle Quantity (Other States)	-0.030	-0.019	-0.013
Fed Cattle Price (Utah)	0.100	0.087	0.079
Fed Cattle Quantity (Utah)	-36.491	-31.264	-27.629
Fed Cattle Price (Import)	0.106	0.093	0.084
Fed Cattle Quantity (Import)	0.783	0.683	0.619
Feeder Cattle Price (Other States)	-0.158	-0.137	-0.122
Feeder Cattle Quantity (Other States)	-0.008	-0.004	-0.008
Feeder Cattle Price (Utah)	-0.181	-0.157	-0.139
Feeder Cattle Quantity (Utah)	-4.753	-3.000	-2.171
Feeder Cattle Price (Import)	-0.158	-0.137	-0.122
Feeder Cattle Quantity (Import)	-0.694	-0.605	-0.536
Retail Pork Price	0.044	0.034	0.032
Retail Pork Quantity	0.011	0.010	0.006
Wholesale Pork Price	0.031	0.024	0.022
Wholesale Pork Quantity	0.021	0.016	0.018
Wholesale Import Pork Price	0.031	0.024	0.022
Wholesale Import Pork Quantity	0.043	0.034	0.031
Market Hog Price (Other States)	0.084	0.079	0.076
Market Hog Quantity (Other States)	-0.064	-0.056	-0.056
Market Hog Price (Utah)	0.084	0.079	0.076
Market Hog Quantity (Utah)	-13.626	-12.196	-12.042
Market Hog Price (Import)	0.084	0.079	0.076
Market Hog Quantity (Import)	0.135	0.127	0.121
Retail Poultry Price	0.064	0.051	0.043
Retail Poultry Quantity	0.018	0.014	0.012
Wholesale Poultry Price	0.046	0.037	0.031
Wholesale Poultry Quantity	0.006	0.005	0.004

Table 29
Percentage Changes of Endogenous Variables for Outbreak Scenarios with 50% Costs Borne by the Produce and Changes in Demand

Endogenous Variables	Percentage Changes		
	30 Percent	60 Percent	90 Percent
Retail Beef Price	-0.551	-0.584	-0.606
Retail Beef Quantity	-0.706	-0.689	-0.678
Wholesale Beef Price	-0.374	-0.390	-0.401
Wholesale Beef Quantity	-0.498	-0.469	-0.451
Wholesale Import Beef Price	-0.374	-0.390	-0.401
Wholesale Import Beef Quantity	-0.684	-0.714	-0.734
Fed Cattle Price (Other States)	-0.216	-0.230	-0.238
Fed Cattle Quantity (Other States)	-0.146	-0.134	-0.128
Fed Cattle Price (Utah)	-0.204	-0.217	-0.225
Fed Cattle Quantity (Utah)	-36.744	-31.517	-27.881
Fed Cattle Price (Import)	-0.216	-0.230	-0.238
Fed Cattle Quantity (Import)	-1.596	-1.695	-1.758
Feeder Cattle Price (Other States)	-0.289	-0.269	-0.253
Feeder Cattle Quantity (Other States)	-0.021	-0.032	-0.036
Feeder Cattle Price (Utah)	-0.331	-0.307	-0.290
Feeder Cattle Quantity (Utah)	-4.793	-3.041	-2.212
Feeder Cattle Price (Import)	-0.289	-0.269	-0.253
Feeder Cattle Quantity (Import)	-1.271	-1.182	-1.113
Retail Pork Price	-0.440	-0.447	-0.449
Retail Pork Quantity	-0.800	-0.803	-0.807
Wholesale Pork Price	-0.479	-0.485	-0.487
Wholesale Pork Quantity	-0.484	-0.482	-0.484
Wholesale Import Pork Price	-0.479	-0.485	-0.487
Wholesale Import Pork Quantity	-0.675	-0.683	-0.686
Market Hog Price (Other States)	-0.438	-0.443	-0.446
Market Hog Quantity (Other States)	-0.261	-0.256	-0.256
Market Hog Price (Utah)	-0.438	-0.443	-0.446
Market Hog Quantity (Utah)	-13.729	-12.306	-12.153
Market Hog Price (Import)	-0.438	-0.443	-0.446
Market Hog Quantity (Import)	-0.700	-0.708	-0.714
Retail Poultry Price	0.581	0.568	0.561
Retail Poultry Quantity	0.162	0.158	0.156
Wholesale Poultry Price	0.418	0.409	0.404
Wholesale Poultry Quantity	0.059	0.057	0.057

Table 30
Sensitivity Analysis for All Industries in Full Cost, No Demand Shift Scenario

Scenario	30 Percent	60 Percent	90 Percent
50% More Elastic Supply			
ΔPS for Beef Industry	-432.51	-341.86	-288.03
ΔPS for Pork Industry	-12.97	-13.29	-14.75
ΔPS for Poultry Industry	103.19	86.78	75.51
ΔPS for All Meat	-342.29	-268.37	-227.27
50% Less Elastic Supply			
ΔPS for Beef Industry	-718.46	-575.07	-488.53
ΔPS for Pork Industry	-12.12	-11.19	-13.41
ΔPS for Poultry Industry	267.83	213.96	181.74
ΔPS for All Meat	-462.76	-372.30	-287.12
50% More Elastic Demand			
ΔPS for Beef Industry	-443.97	-355.14	-301.15
ΔPS for Pork Industry	-13.86	-12.59	-13.49
ΔPS for Poultry Industry	108.44	93.27	82.39
ΔPS for All Meat	-349.39	-274.47	-232.24
50% Less Elastic Demand			
ΔPS for Beef Industry	-591.98	-472.82	-400.63
ΔPS for Pork Industry	-40.97	-23.75	-20.64
ΔPS for Poultry Industry	202.29	149.43	123.45
ΔPS for All Meat	-430.67	-347.14	-297.81

Table 31
Sensitivity Analysis for Beef Industry in Full Cost, No Demand Shift Scenario

Scenario	30 Percent	60 Percent	90 Percent
50% More Elastic Supply			
ΔPS for Retail	-119.14	-95.47	-80.80
ΔPS for Wholesale	-103.50	-83.51	-70.97
ΔPS for Fed (O)	-44.19	-33.50	-27.61
ΔPS for Fed (UT)	-85.25	-73.04	-64.54
ΔPS for Feeder (O)	-37.45	-29.33	-24.64
ΔPS for Feeder (UT)	-42.99	-27.01	-19.47
ΔPS for Beef Industry	-432.51	-341.86	-288.03
50% Less Elastic Supply			
ΔPS for Retail	-310.44	-250.05	-212.78
ΔPS for Wholesale	-153.04	-123.25	-104.87
ΔPS for Fed (O)	-39.86	-29.30	-23.84
ΔPS for Fed (UT)	-85.62	-73.35	-64.82
ΔPS for Feeder (O)	-87.10	-72.62	-63.21
ΔPS for Feeder (UT)	-42.41	-26.50	-19.01
ΔPS for Beef Industry	-718.46	-575.07	-488.53
50% More Elastic Demand			
ΔPS for Retail	-96.14	-76.67	-64.54
ΔPS for Wholesale	-96.74	-78.01	-66.17
ΔPS for Fed (O)	-64.70	-51.08	-43.19
ΔPS for Fed (UT)	-84.96	-72.79	-64.32
ΔPS for Feeder (O)	-58.68	-49.80	-43.66
ΔPS for Feeder (UT)	-42.76	-26.79	-19.27
ΔPS for Beef Industry	-443.97	-355.14	-301.15
50% Less Elastic Demand			
ΔPS for Retail	-233.37	-190.04	-162.28
ΔPS for Wholesale	-141.56	-114.40	-97.45
ΔPS for Fed (O)	-38.75	-28.27	-22.81
ΔPS for Fed (UT)	-85.58	-73.33	-64.80
ΔPS for Feeder (O)	-49.90	-39.92	-33.96
ΔPS for Feeder (UT)	-42.82	-26.86	-19.33
ΔPS for Beef Industry	-591.98	-472.82	-400.63

Table 32
Sensitivity Analysis for Pork Industry in Full Cost, No Demand Shift Scenario

Scenario	30 Percent	60 Percent	90 Percent
50% More Elastic Supply			
ΔPS for Retail	7.48	5.16	3.95
ΔPS for Wholesale	3.17	2.81	2.51
ΔPS for Market Hog (O)	17.37	15.43	15.02
ΔPS for Market Hog (UT)	-40.99	-36.69	-36.23
ΔPS for Pork Industry	-12.97	-13.29	-14.75
50% Less Elastic Supply			
ΔPS for Retail	22.04	18.09	15.45
ΔPS for Wholesale	0.00	1.22	1.26
ΔPS for Market Hog (O)	6.83	6.19	6.11
ΔPS for Market Hog (UT)	-40.99	-36.69	-36.23
ΔPS for Pork Industry	-12.12	-11.19	-13.41
50% More Elastic Demand			
ΔPS for Retail	9.72	8.94	8.20
ΔPS for Wholesale	2.25	1.84	1.58
ΔPS for Market Hog (O)	15.23	13.38	13.02
ΔPS for Market Hog (UT)	-41.06	-36.75	-36.29
ΔPS for Pork Industry	-13.86	-12.59	-13.49
50% Less Elastic Demand			
ΔPS for Retail	-3.97	3.96	5.32
ΔPS for Wholesale	-4.65	-0.34	0.64
ΔPS for Market Hog (O)	8.62	9.30	9.60
ΔPS for Market Hog (UT)	-40.97	-36.66	-36.20
ΔPS for Pork Industry	-40.97	-23.75	-20.64

Table 33
Sensitivity Analysis for Poultry Industry in Full Cost, No Demand Shift Scenario

Scenario	30 Percent	60 Percent	90 Percent
50% More Elastic Supply			
ΔPS for Retail	55.32	46.53	40.48
ΔPS for Wholesale	47.87	40.26	35.03
ΔPS for Poultry Industry	103.19	86.78	75.51
50% Less Elastic Supply			
ΔPS for Retail	197.15	157.49	133.78
ΔPS for Wholesale	70.68	56.47	47.96
ΔPS for Poultry Industry	267.83	213.96	181.74
50% More Elastic Demand			
ΔPS for Retail	50.40	43.35	38.30
ΔPS for Wholesale	58.04	49.92	44.10
ΔPS for Poultry Industry	108.44	93.27	82.39
50% Less Elastic Demand			
ΔPS for Retail	139.38	102.95	85.06
ΔPS for Wholesale	62.91	46.47	38.40
ΔPS for Poultry Industry	202.29	149.43	123.45

Table 34
Sensitivity Analysis for All Industries in Full Cost, Demand Shift Scenario

Scenario	30 Percent	60 Percent	90 Percent
50% More Elastic Supply			
ΔPS for Beef Industry	-1708.54	-1599.16	-1535.04
ΔPS for Pork Industry	-536.02	-536.34	-537.80
ΔPS for Poultry Industry	892.66	883.00	876.36
ΔPS for All Meat	-1351.90	-1252.50	-1196.48
50% Less Elastic Supply			
ΔPS for Beef Industry	-697.88	-535.84	-439.63
ΔPS for Pork Industry	-386.99	-386.04	-388.25
ΔPS for Poultry Industry	233.70	216.24	205.80
ΔPS for All Meat	-851.18	-705.64	-622.09
50% More Elastic Demand			
ΔPS for Beef Industry	-1113.96	-976.36	-894.55
ΔPS for Pork Industry	185.52	202.31	205.29
ΔPS for Poultry Industry	-25.44	-49.60	-61.47
ΔPS for All Meat	-953.89	-823.65	-750.73
50% Less Elastic Demand			
ΔPS for Beef Industry	-1893.46	-1780.87	-1713.15
ΔPS for Pork Industry	-615.89	-614.63	-615.53
ΔPS for Poultry Industry	1320.66	1313.41	1308.21
ΔPS for All Meat	-1188.69	-1082.10	-1020.48

Table 35
Sensitivity Analysis for Beef Industry in Full Cost, Demand Shift Scenario

Scenario	30 Percent	60 Percent	90 Percent
50% More Elastic Supply			
ΔPS for Retail	-963.00	-939.37	-924.74
ΔPS for Wholesale	-349.93	-329.94	-317.40
ΔPS for Fed (O)	-184.36	-154.88	-138.65
ΔPS for Fed (UT)	-86.79	-74.61	-66.14
ΔPS for Feeder (O)	-81.56	-73.44	-68.75
ΔPS for Feeder (UT)	-42.91	-26.91	-19.36
ΔPS for Beef Industry	-1708.54	-1599.16	-1535.04
50% Less Elastic Supply			
ΔPS for Retail	-300.85	-240.40	-203.08
ΔPS for Wholesale	-118.86	-89.03	-70.63
ΔPS for Fed (O)	-51.84	-22.73	-7.67
ΔPS for Fed (UT)	-85.88	-73.63	-65.11
ΔPS for Feeder (O)	-98.14	-83.66	-74.25
ΔPS for Feeder (UT)	-42.31	-26.40	-18.91
ΔPS for Beef Industry	-697.88	-535.84	-439.63
50% More Elastic Demand			
ΔPS for Retail	-654.91	-611.59	-583.83
ΔPS for Wholesale	-194.67	-167.48	-150.51
ΔPS for Fed (O)	-71.48	-42.57	-27.51
ΔPS for Fed (UT)	-86.10	-73.86	-65.34
ΔPS for Feeder (O)	-64.07	-54.10	-48.13
ΔPS for Feeder (UT)	-42.72	-26.76	-19.24
ΔPS for Beef Industry	-1113.96	-976.36	-894.55
50% Less Elastic Demand			
ΔPS for Retail	-1031.57	-1012.17	-1000.09
ΔPS for Wholesale	-371.84	-353.14	-341.31
ΔPS for Fed (O)	-134.52	-97.04	-75.34
ΔPS for Fed (UT)	-87.30	-75.19	-66.7
ΔPS for Feeder (O)	-226.56	-217.67	-211.53
ΔPS for Feeder (UT)	-41.68	-25.66	-18.11
ΔPS for Beef Industry	-1893.46	-1780.87	-1713.15

Table 36
Sensitivity Analysis for Pork Industry in Full Cost, Demand Shift Scenario

Scenario	30 Percent	60 Percent	90 Percent
50% More Elastic Supply			
ΔPS for Retail	-345.99	-348.31	-349.52
ΔPS for Wholesale	-91.25	-91.61	-91.91
ΔPS for Market Hog (O)	-57.75	-59.69	-60.11
ΔPS for Market Hog (UT)	-41.04	-36.73	-36.26
ΔPS for Pork Industry	-536.02	-536.34	-537.80
50% Less Elastic Supply			
ΔPS for Retail	-336.12	-340.05	-342.68
ΔPS for Wholesale	-15.30	-14.09	-14.05
ΔPS for Market Hog (O)	5.43	4.80	4.72
ΔPS for Market Hog (UT)	-41.00	-36.70	-36.24
ΔPS for Pork Industry	-386.99	-386.04	-388.25
50% More Elastic Demand			
ΔPS for Retail	85.33	92.84	94.08
ΔPS for Wholesale	90.73	95.03	96.01
ΔPS for Market Hog (O)	50.06	50.74	51.03
ΔPS for Market Hog (UT)	-40.60	-36.30	-35.84
ΔPS for Pork Industry	185.52	202.31	205.29
50% Less Elastic Demand			
ΔPS for Retail	-370.66	-371.46	-372.20
ΔPS for Wholesale	-127.37	-127.78	-128.05
ΔPS for Market Hog (O)	-77.42	-79.78	-79.64
ΔPS for Market Hog (UT)	-40.44	-36.11	-35.64
ΔPS for Pork Industry	-615.89	-614.63	-615.53

Table 37
Sensitivity Analysis for Poultry Industry in Full Cost, Demand Shift Scenario

Scenario	30 Percent	60 Percent	90 Percent
50% More Elastic Supply			
ΔPS for Retail	583.83	577.50	573.16
ΔPS for Wholesale	308.84	305.49	303.20
ΔPS for Poultry Industry	892.66	883.00	876.36
50% Less Elastic Supply			
ΔPS for Retail	185.64	171.77	163.48
ΔPS for Wholesale	48.06	44.47	42.32
ΔPS for Poultry Industry	233.70	216.24	205.80
50% More Elastic Demand			
ΔPS for Retail	-19.36	-37.74	-46.78
ΔPS for Wholesale	-6.08	-11.85	-14.69
ΔPS for Poultry Industry	-25.44	-49.60	-61.47
50% Less Elastic Demand			
ΔPS for Retail	799.93	795.54	792.39
ΔPS for Wholesale	520.73	517.87	515.82
ΔPS for Poultry Industry	1320.66	1313.41	1308.21

Table 38
Sensitivity Analysis for All Industries in Half Cost, No Demand Shift Scenario

Scenario	30 Percent	60 Percent	90 Percent
50% More Elastic Supply			
ΔPS for Beef Industry	-404.21	-315.53	-262.94
ΔPS for Pork Industry	-14.98	-14.77	-16.03
ΔPS for Poultry Industry	72.20	58.39	48.35
ΔPS for All Meat	-346.99	-271.91	-230.63
50% Less Elastic Supply			
ΔPS for Beef Industry	-650.79	-518.09	-437.05
ΔPS for Pork Industry	-29.23	-27.07	-28.88
ΔPS for Poultry Industry	235.84	189.84	161.60
ΔPS for All Meat	-444.19	-355.32	-304.33
50% More Elastic Demand			
ΔPS for Beef Industry	-421.48	-332.15	-278.25
ΔPS for Pork Industry	-21.60	-19.83	-20.57
ΔPS for Poultry Industry	69.28	56.53	46.78
ΔPS for All Meat	-373.80	-295.45	-252.05
50% Less Elastic Demand			
ΔPS for Beef Industry	-524.73	-413.73	-345.69
ΔPS for Pork Industry	-110.00	-91.54	-88.43
ΔPS for Poultry Industry	247.34	198.99	175.82
ΔPS for All Meat	-387.38	-306.28	-258.30

Table 39
Sensitivity Analysis for Beef Industry in Half Cost, No Demand Shift Scenario

Scenario	30 Percent	60 Percent	90 Percent
50% More Elastic Supply			
ΔPS for Retail	-101.86	-81.19	-68.05
ΔPS for Wholesale	-86.25	-68.87	-57.65
ΔPS for Fed (O)	-33.23	-25.72	-21.43
ΔPS for Fed (UT)	-85.23	-73.01	-64.52
ΔPS for Feeder (O)	-55.03	-39.96	-32.00
ΔPS for Feeder (UT)	-42.61	-26.77	-19.30
ΔPS for Beef Industry	-404.21	-315.53	-262.94
50% Less Elastic Supply			
ΔPS for Retail	-260.34	-209.37	-176.76
ΔPS for Wholesale	-128.42	-103.28	-87.20
ΔPS for Fed (O)	-30.45	-23.63	-20.02
ΔPS for Fed (UT)	-85.57	-73.30	-64.77
ΔPS for Feeder (O)	-103.98	-82.25	-69.46
ΔPS for Feeder (UT)	-42.02	-26.26	-18.85
ΔPS for Beef Industry	-650.79	-518.09	-437.05
50% More Elastic Demand			
ΔPS for Retail	-81.98	-64.80	-53.84
ΔPS for Wholesale	-79.55	-63.10	-52.41
ΔPS for Fed (O)	-53.51	-43.23	-37.02
ΔPS for Fed (UT)	-84.96	-72.78	-64.31
ΔPS for Feeder (O)	-79.12	-61.70	-51.57
ΔPS for Feeder (UT)	-42.35	-26.62	-19.09
ΔPS for Beef Industry	-421.48	-332.15	-278.25
50% Less Elastic Demand			
ΔPS for Retail	-185.00	-148.69	-124.34
ΔPS for Wholesale	-117.17	-94.19	-79.30
ΔPS for Fed (O)	-28.19	-21.31	-17.63
ΔPS for Fed (UT)	-85.53	-73.27	-64.74
ΔPS for Feeder (O)	-66.41	-49.66	-40.51
ΔPS for Feeder (UT)	-42.43	-26.62	-19.17
ΔPS for Beef Industry	-524.73	-413.73	-278.25

Table 40
Sensitivity Analysis for Pork Industry in Half Cost, No Demand Shift Scenario

Scenario	30 Percent	60 Percent	90 Percent
50% More Elastic Supply			
ΔPS for Retail	9.65	7.52	6.42
ΔPS for Wholesale	1.66	1.38	1.12
ΔPS for Market Hog (O)	14.76	13.08	12.72
ΔPS for Market Hog (UT)	-41.06	-36.75	-36.29
ΔPS for Pork Industry	-14.98	-14.77	-16.03
50% Less Elastic Supply			
ΔPS for Retail	16.29	13.06	10.76
ΔPS for Wholesale	-7.88	-6.47	-6.41
ΔPS for Market Hog (O)	3.42	3.10	3.05
ΔPS for Market Hog (UT)	-41.06	-36.75	-36.29
ΔPS for Pork Industry	-29.23	-27.07	-28.88
50% More Elastic Demand			
ΔPS for Retail	4.24	3.66	3.01
ΔPS for Wholesale	1.77	1.41	1.17
ΔPS for Market Hog (O)	13.52	11.92	11.60
ΔPS for Market Hog (UT)	-41.14	-36.82	-36.36
ΔPS for Pork Industry	-21.60	-19.83	-20.57
50% Less Elastic Demand			
ΔPS for Retail	-44.12	-35.54	-34.15
ΔPS for Wholesale	-23.29	-18.77	-17.82
ΔPS for Market Hog (O)	-1.48	-0.46	-0.15
ΔPS for Market Hog (UT)	-41.10	-36.78	-36.32
ΔPS for Pork Industry	-110.00	-91.54	-88.43

Table 41
Sensitivity Analysis for Poultry Industry in Half Cost, No Demand Shift Scenario

Scenario	30 Percent	60 Percent	90 Percent
50% More Elastic Supply			
ΔPS for Retail	38.71	31.30	25.92
ΔPS for Wholesale	33.49	27.08	22.43
ΔPS for Poultry Industry	72.20	58.39	48.35
50% Less Elastic Supply			
ΔPS for Retail	173.60	139.74	118.95
ΔPS for Wholesale	62.24	50.10	42.65
ΔPS for Poultry Industry	235.84	189.84	161.60
50% More Elastic Demand			
ΔPS for Retail	32.20	26.27	21.74
ΔPS for Wholesale	37.08	30.26	25.04
ΔPS for Poultry Industry	69.28	56.53	46.78
50% Less Elastic Demand			
ΔPS for Retail	170.42	137.11	121.14
ΔPS for Wholesale	76.92	61.89	54.68
ΔPS for Poultry Industry	247.34	198.99	175.82

Table 42
Sensitivity Analysis for All Industries in Half Cost, Demand Shift Scenario

Scenario	30 Percent	60 Percent	90 Percent
50% More Elastic Supply			
ΔPS for Beef Industry	-1545.05	-1456.67	-1404.15
ΔPS for Pork Industry	-539.72	-540.02	-541.34
ΔPS for Poultry Industry	1530.47	1516.04	1505.90
ΔPS for All Meat	-554.30	-480.65	-439.59
50% Less Elastic Supply			
ΔPS for Beef Industry	-596.59	-463.82	-382.72
ΔPS for Pork Industry	-364.11	-363.49	-365.48
ΔPS for Poultry Industry	656.08	610.74	582.57
ΔPS for All Meat	-304.63	-216.57	-165.63
50% More Elastic Demand			
ΔPS for Beef Industry	-1036.50	-924.82	-856.68
ΔPS for Pork Industry	326.10	339.39	341.81
ΔPS for Poultry Industry	-245.98	-289.82	-312.44
ΔPS for All Meat	-956.37	-875.24	-827.31
50% Less Elastic Demand			
ΔPS for Beef Industry	-1764.20	-1675.23	-1621.45
ΔPS for Pork Industry	-606.62	-605.65	-606.49
ΔPS for Poultry Industry	2798.23	2784.66	2774.78
ΔPS for All Meat	427.41	503.78	546.84

Table 43
Sensitivity Analysis for Beef Industry in Half Cost, Demand Shift Scenario

Scenario	30 Percent	60 Percent	90 Percent
50% More Elastic Supply			
ΔPS for Retail	-932.83	-912.38	-899.29
ΔPS for Wholesale	-328.90	-311.58	-300.36
ΔPS for Fed (O)	-55.56	-48.06	-43.77
ΔPS for Fed (UT)	-86.75	-74.56	-66.09
ΔPS for Feeder (O)	-98.49	-83.42	-75.46
ΔPS for Feeder (UT)	-42.52	-26.67	-19.19
ΔPS for Beef Industry	-1545.05	-1456.67	-1404.15
50% Less Elastic Supply			
ΔPS for Retail	-250.61	-199.59	-166.94
ΔPS for Wholesale	-93.90	-68.72	-52.62
ΔPS for Fed (O)	-9.20	-2.38	1.24
ΔPS for Fed (UT)	-85.84	-73.58	-65.06
ΔPS for Feeder (O)	-115.12	-93.39	-80.60
ΔPS for Feeder (UT)	-41.93	-26.16	-18.74
ΔPS for Beef Industry	-596.59	-463.82	-382.72
50% More Elastic Demand			
ΔPS for Retail	-637.84	-600.95	-576.52
ΔPS for Wholesale	-174.20	-151.11	-136.19
ΔPS for Fed (O)	-14.41	-7.54	-3.87
ΔPS for Fed (UT)	-86.08	-73.84	-65.32
ΔPS for Feeder (O)	-81.64	-64.86	-55.2
ΔPS for Feeder (UT)	-42.33	-26.52	-19.06
ΔPS for Beef Industry	-1036.50	-924.82	-856.68
50% Less Elastic Demand			
ΔPS for Retail	-1002.97	-986.02	-975.13
ΔPS for Wholesale	-350.40	-334.03	-323.36
ΔPS for Fed (O)	-37.83	-27.57	-21.38
ΔPS for Fed (UT)	-87.27	-75.15	-66.72
ΔPS for Feeder (O)	-244.45	-227.03	-216.90
ΔPS for Feeder (UT)	-41.28	-25.42	-17.95
ΔPS for Beef Industry	-1764.20	-1675.23	-1621.45

Table 44
Sensitivity Analysis for Pork Industry in Half Cost, Demand Shift Scenario

Scenario	30 Percent	60 Percent	90 Percent
50% More Elastic Supply			
ΔPS for Retail	-355.57	-357.54	-358.61
ΔPS for Wholesale	-89.62	-89.95	-90.22
ΔPS for Market Hog (O)	-53.62	-55.92	-56.36
ΔPS for Market Hog (UT)	-40.90	-36.61	-36.15
ΔPS for Pork Industry	-539.72	-540.02	-541.34
50% Less Elastic Supply			
ΔPS for Retail	-335.47	-338.82	-341.12
ΔPS for Wholesale	0.00	0.93	0.94
ΔPS for Market Hog (O)	12.21	10.96	10.81
ΔPS for Market Hog (UT)	-40.86	-36.58	-36.11
ΔPS for Pork Industry	-364.11	-363.49	-365.48
50% More Elastic Demand			
ΔPS for Retail	164.60	170.40	171.38
ΔPS for Wholesale	130.54	133.95	134.76
ΔPS for Market Hog (O)	71.30	71.10	71.26
ΔPS for Market Hog (UT)	-40.34	-36.06	-35.59
ΔPS for Pork Industry	326.10	339.39	341.81
50% Less Elastic Demand			
ΔPS for Retail	-363.73	-364.48	-365.15
ΔPS for Wholesale	-127.68	-128.05	-128.29
ΔPS for Market Hog (O)	-74.92	-77.16	-77.55
ΔPS for Market Hog (UT)	-40.28	-35.97	-35.50
ΔPS for Pork Industry	-606.62	-605.65	-606.49

Table 45
Sensitivity Analysis for Poultry Industry in Half Cost, Demand Shift Scenario

Scenario	30 Percent	60 Percent	90 Percent
50% More Elastic Supply			
ΔPS for Retail	820.80	813.05	807.61
ΔPS for Wholesale	709.67	702.98	698.29
ΔPS for Poultry Industry	1530.47	1516.04	1505.90
50% Less Elastic Supply			
ΔPS for Retail	482.96	449.58	428.84
ΔPS for Wholesale	173.12	161.16	153.73
ΔPS for Poultry Industry	656.08	610.74	582.57
50% More Elastic Demand			
ΔPS for Retail	-169.46	-199.66	-215.25
ΔPS for Wholesale	-76.52	-90.16	-97.20
ΔPS for Poultry Industry	-245.98	-289.82	-312.44
50% Less Elastic Demand			
ΔPS for Retail	1301.20	1294.88	1290.28
ΔPS for Wholesale	1497.04	1489.78	1484.49
ΔPS for Poultry Industry	2798.23	2784.66	2774.78