THESIS

ECONOMIC IMPACT OF FOOT-AND-MOUTH DISEASE MITIGATION STRATEGIES: A META-REGRESSION ANALYSIS

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ABSTRACT

ECONOMIC IMPACT OF FOOT-AND-MOUTH DISEASE MITIGATION STRATEGIES:

A META-REGRESSION ANALYSIS

A meta-regression analysis was conducted to more clearly identify the control strategies that influence the economic impacts due to a foot-and-mouth disease (FMD) outbreak in North America. Models were specified accounting for differences across control strategies (culling rate, vaccination, improving in traceability, and delayed detection) and epidemiological models that are used to simulate FMD outbreaks under different assumption. Results of the analysis show that applying vaccination-to-die policies increases the national loss but it might be a method to contain the disease when spreading widely. Delayed detection of infected animals is the most influential factor that impacts economic losses, however, by improving traceability system, the economic impacts can be reduces by localizing and depopulating latent or potentially infected animals before they allow disease to spread.

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DEDICATION

To my father,

who understands me, supports me, encourages me, and pushes me with all his love.

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Chapter 1. Introduction

Highly contagious animal diseases are a global concern drawing increasing attention among animal and human health officials. In 2015, the World Organization for Animal Health (OiE) listed 117 animal diseases, infections and infestations on the OiE list of notifiable terrestrial and aquatic diseases (OiE, 2015). Coupling the growing number of animal diseases with the 22.8% increase in international trade and 21.7% increase in international tourists between 2010 and 2014, the threat for spread of highly contagious animal disease continually increases (UN, 2015; UNWTO, 2015)

Equally concerning is the high percentage of infectious diseases of zoonotic origin, or those that are transmissible between animal and humans. Almost 60 percent of known human pathogens are of animal origin (Woolhouse and Gaunt, 2007). Between 1940 and 2004, Jones et al. (2008) found that 60 percent of emerging infectious diseases between 1940 and 2004 in the United States were zoonotic. According to King (2004), the trends suggest that the frequency of infectious diseases will continue to increase, especially with the growing interface between wildlife-domestic animals-humans.

Foot-and-mouth disease (FMD) is one of the most economically important animal diseases as it spreads rapidly and the losses to production and trade can be substantial. FMD is a highly contagious viral disease that occurs among cloven-hoofed animals such as swine, cattle, sheep and deer. The virus can spread via domestic and wild animals, people, aerosols and contact with contaminated fomites (such as clothing, feed, and equipment).

An FMD outbreak can have enormous effects on a country’s economic well-being. The negative impacts are a result of a potential reduction in domestic consumer demand, loss of export markets, depopulated animals, and costs to the government to control and eradicate the disease. The costs to the government include: indemnification payments, emergency vaccination, disposal and clean-up, surveillance, quarantine, and euthanasia costs. Agricultural producers and related industries suffer from losses within livestock and export markets, as well as possible reductions in domestic demand due to consumer fears (Paarlberg et al., 2002). Although there is no evidence that FMD can impact human health, it is typically assumed consumers will reduce their demand for meat and dairy products based on perceived threats to their well-being (Schroeder et al., 2015).

Both *ex post* (case studies) and *ex ante* (hypothetical or simulation) studies of FMD outbreaks and other animal diseases have examined the effectiveness of efforts and mitigation strategies. Typically, *ex post* studies have analyzed FMD outbreaks by discussing the government's response to the outbreak and summarize the economic impacts. *Ex ante* studies generally use an epidemiological model, such as the North American Animal Disease-Spread Model, to simulate an FMD outbreak and then analyze the economic impacts. The economic impacts can be estimated using a variety of economic modeling frameworks such as partial equilibrium models and input-output models.

Thompson et al. (2002) estimated the economic losses after an FMD outbreak in the United Kingdom in 2001. The economic losses to agriculture and the food chain were about $5 billion and agricultural producers' losses were estimated at approximately 20% of the estimated total income from farming. Overall, the total effect of the FMD outbreak was estimated to reduce the gross domestic product in the United Kingdom by less than 0.2% in 2001. Another severe FMD outbreak occurred in South Korea in 2010 and resulted in 3.37 million pigs, cows, goats and deer being culled and buried at a cost of nearly $2 billion in direct costs and compensation to the producers (OiE, 2012).

The United States has not had an outbreak of FMD since 1929 and is considered to be FMD free by their trading partners. However, FMD has broken out in a diverse set of regions including Africa, Asia, Europe, and South America in recent years. Because of the recent outbreaks as well as increases in international travel and trade among countries, there are increasing risks of FMD outbreaks in the United States.

From the moment that FMD is detected, the virus spreads rapidly and unpredictably. Additionally, the virus has up to a 14-day incubation period; thus, it has the opportunity to have been carried to multiple premises before being detected. Therefore, decision makers need analytical tools and decision criteria based on sound science including how geography, timing, and industry concentration may influence economic losses, as well as lessons learned from recent outbreaks (Hagerman et al., 2012). For example, the standard strategy for containing the 2010 FMD outbreak in Japan was stamping-out, along with movement control. However, the FMD outbreak occurred in one of the most densely populated areas of both cattle and pig farms in Japan. The disease spread rapidly and challenged efforts to promptly cull animals on these farms. About one month after the first detection in the affected area, emergency vaccination was implemented to supplement the insufficient mitigation strategies. Ultimately, a total of 292 farms were affected, and almost 290,000 animals, including both infected animals and vaccinated animals, were culled (Muroga et al., 2011).

The most common strategies used to mitigate and eradicate FMD during an outbreak are stamping-out infected animals, cleaning and disinfecting affected premises, animal movement restrictions, and quarantine. Stamping-out can be implemented alone or used in combination with other response and mitigation strategies such as vaccination, quarantine zone sizes, and depopulation alternatives for quick eradication before the disease spreads widely. Individually, most studies address only one or a rather limited array of policy options. Since all the control and mitigation strategies may affect the economic impacts of an FMD outbreak differently, this paper's goal is to combine all the results from previous studies and use a systematic analysis to examine the relationship between economic impacts and each control strategy.

An increasing number of studies are simulating hypothetical FMD outbreaks by using an epidemiological model and integrating the simulated results into an economic framework to estimate the impacts on producers, consumers, allied industries and/or the government under various mitigation strategies. The studies have investigated a number of disease management strategies that may reduce the duration of the outbreak. Such strategies include culling of infected animals, culling of animals that have had direct and/or indirect contact with an infected animal, culling of certain species, ring culling, emergency vaccination to die, ring vaccination, etc. Given the uncertainty surrounding the disease (e.g., spread, reactions by consumers, trading partners, etc.), developing a comprehensive mitigation strategy is not an easy task.

The main objective of this research is to analyze the published literature to establish a link between economic effects and the various mitigation and eradication management strategies that are used during hypothetical FMD outbreaks in North America. To address this objective, we employ a meta-regression analysis, which is, "a more formal and objective process of reviewing an empirical literature" (Stanley, 2001, pages 147-148). While numerous studies estimate epidemiological and economic impacts of hypothetical FMD outbreaks using certain mitigation strategies, the authors are not aware of any study that integrates the many disease management strategies that could be used during an outbreak. Thus, meta-regression analysis of the full range of studies may provide interesting insights to policy makers and researchers.

The diversity of control strategies stimulated our interests in examining the effectiveness of each control strategy. We believe the control strategies can decrease the economic impact from an FMD outbreak, but we also think that there are different levels of influence. By forming a meta-regression analysis, we seek to examine the effectiveness of each control strategy.

In the next chapter, a literature review is provided. Chapters 3 and 4 discuss the methods and data used in this study, respectively. Chapter 5 presents the results and discussion of the meta-regression analysis. Finally, we conclude by discussing the likely relationships between the economic impacts of the alternate disease mitigation and eradication strategies.

Chapter 2. Literature Review

This chapter contains a literature review that is sub-divided into two sections: meta-analysis methods and previous foot-and mouth disease (FMD) studies. The meta-analysis section describes the ways to conduct a meta-analysis and the issues that arise when forming a meta-analysis. The FMD discussion presents a literature review of economic analyses of FMD as well as a discussion surrounding FMD control strategies.

Meta-Analysis

Meta-analysis is a body of statistical methods for combining, reviewing and evaluating empirical research results (Stanley, 2001; Crombie and Davies, 2009). The first meta-analysis is attributed to Pearson (1904) who analyzed data from five studies on the correlation between the vaccination for enteritis fever and its mortality. Lewis et al. (2007) describes meta-analysis as a practice of gathering, combining, and analyzing the results of numerous studies. It is not only a systematic literature review, but also a way to recognize the impacts of different factors on a topic of interest. Meta-analysis involves collecting and selecting relevant studies with a research-based justification, conducting a meta-regression on the data collected from the studies, and discussing the problems that exist with the observed data.

Leandro (2005) indicates that a correct systematic review on a topic requires collection and analysis of all published data, and not only of those which are more interesting, relevant, or easily available. Two steps are important for the analysis: first, compiling a complete collection of the published literature; and second, the synthesis of the information acquired. Such synthesis can be done by an expert in the field as a traditional literature review, which may have a personal bias, or the synthesis can be made in a more structured and objective fashion using meta-regression analysis.

It is important to conduct a meta-analysis by gathering and combining all available, and deciding on criteria that will be used to filter and define the selected studies. Each study has intrinsic characteristics and the conclusions it provides may not be generalizable or comparable with those of other studies. Therefore, a researcher should pay adequate attention to how the information from each study was obtained to make sure it can be used appropriately within a meta-analysis. Also, a detailed description of reasons for including or excluding the selected studies in the meta-analysis should be provided.

Meta-analysis is commonly criticized for pooling of studies of varying quality, engaging in double counting and suffering from publication bias (Nelson and Kennedy, 2009). These problems, if any, should be addressed and treated properly by the researchers framing the meta-analysis. Dependence, publication bias, and heterogeneity are usually mentioned and addressed using different methods within each study. Nelson (2014) addressed the dependence issue by restricting the number of estimates per study, author-restricted samples, and author-specific variables.

Publication bias is another issue to consider when forming a meta-analysis. Publication bias may occur due to selective inclusion of studies written in a certain language, the public availability of the studies, bias toward the researcher's own disciplines, and the preferable outcome of the studies. Heterogeneity and selection bias are examined jointly in meta-regression containing moderator variables for econometric methodology, primary data and precision of the estimates. Stanley (2001) pointed out limitations of meta-regression analysis such as disagreement over the inclusion of important study characteristics, whether to weight the results of different studies differently, the risk that all studies contain the same misspecification errors, and the quality of selective inclusion of studies. Indeed, some limitations are unavoidable, and therefore, it is important to address the problems and attempt to correct them.

Economic Studies of Foot-and-Mouth Disease

Several studies have analyzed the economic impacts of a hypothetical FMD outbreak in the United States. Because the last FMD outbreak occurred in 1929 in the United States, most of these studies have employed an epidemiological model to simulate an FMD outbreak given today's industry structure. The output from the epidemiological model is then incorporated into an economic modeling framework.

The economic methods that are commonly used when estimating the impacts of an animal health event (e.g., FMD outbreak) include: benefit-cost analysis, linear and mathematical programming, partial equilibrium analysis, input-output (I-O) analysis social accounting matrix development, and computable general equilibrium modeling (Rich, Miller, and Winter-Nelson, 2005). As with any modeling framework, there are strengths and weakness with each method.

Schoenbaum and Disney (2003) used an epidemiological model to simulate FMD outbreaks in three representative animal populations of counties in the south-central, north-central, and western United States. They used cost-minimization techniques to compare alternative mitigation strategies in the various outbreak situations. The authors estimated government costs (which include depopulation, surveillance and vaccination), producer and consumer welfare estimates. Their results showed that the speed of FMD virus spread and the demographics of the susceptible population were the most influential factors that affected the costs of an FMD outbreak. The economic losses ranged from $231 million to $4,859 million.

Zhao, Wahl, and Marsh (2006) analyzed the economic impacts of hypothetical FMD outbreaks on the U.S. beef industry. They used a dynamic epidemiological-economic model of the U.S. beef industry, which included four major components: breeding decisions, feeding decisions, domestic and international markets, and invasive species dissemination. The authors found that as the depopulation rate increases, the welfare losses were smaller. Additionally, the welfare losses were smaller if no emergency vaccination was applied.

Elbakidze et al. (2009) uses AusSpread to simulate an FMD outbreak under various introduction and control strategies in the Texas High Plains. A budgeting exercise is then used to summarize the total mitigation costs. The mitigation strategies used in Elbakidze et al. include detection, slaughter, vaccination, surveillance, and quarantine. They analyzed the economic impacts across four different FMD index herd[1] types: (a) large feedlot (greater than 50,000 head), (b) backgrounder feedlot, (c) large grazing herd (greater than 100 head), and (d) backyard herd (less than ten herds). In most of the scenarios, slaughter of infected and dangerous contact herds, combined with early detection and enhanced surveillance, was the preferred strategy. Early detection was found to be an effective method to reduce economic losses while vaccination costs and loss in the value of vaccinated animals led to vaccination not being a desirable strategy.

Pendell et al. (2007) conducted an epidemiological and economic analysis by using the North American Animal Disease-Spread Model (NAADSM) and both partial equilibrium and I-O models. The authors used NAADSM to simulate the spread of FMD in southwest Kansas. They evaluated the contagious animal disease spread for three different index herds: (1) a cow-calf herd, (2) a medium-sized feedlot, and (3) simultaneously in five large feedlots. The results suggested that if FMD begins in five large feedlots, economic losses are larger and the duration of the disease is longer relative to the other two smaller index herd scenarios. They concluded

[1] An index herd is the herd in which the first animal becomes infected. In the epidemiological model, an outbreak is simulated by spreading the disease from an index herd, which significantly affects the scale of the simulated outbreak by different types of species and herd sizes.

that the number of animals infected and length of disease outbreak were the two most important factors affecting the economic losses.

Hagerman et al. (2012) simulated FMD outbreaks in a three-county region in California using Davis Animal Disease Simulation model (DADS) and in an eight-county region in Texas High Plains using AusSpread model. The results indicated that a delay of detection has a significant impact in controlling the disease. As expected, if the detection delay is short, then the depopulation appears to limit economic losses. However, if the detection delay is long or if the outbreak is "extreme", then emergency vaccination may serve as an important mitigation strategy.

Schroeder et al. (2015) used NAADSM to simulated FMD outbreaks in the Midwestern U.S. under different emergency vaccination strategies and a partial equilibrium model to estimate the economic loss. The emergency vaccination strategies include: (1) vaccinate to live or die, (2) vaccination strategy, (3) vaccination capacity, (4) vaccination trigger, and (5) size of vaccination zone. The authors indicate that the possibility of spread of FMD once it breaks is high and introduction of emergency vaccination could significantly reduce economic losses.

In a recent article, Pendell et al. (2015) examined the impacts of a potential scenario with FMD virus escaping from the proposed National Bio and Agro Defense Facility in Manhattan, Kansas. The authors used an epidemiological (NAADSM) and economic modeling framework. The economic framework was comprised of a partial equilibrium model (producer and consumer impacts), I-O analysis (regional non-agricultural businesses impacts) and budget analysis (government costs). Regardless of the introduction scenario, the authors found the economic impacts are rather large. However, it was noted that looking at the distribution of impacts rather than a single point (e.g., mean) was warranted due to the stochastic nature of the disease spread.

The literature review provides a comprehensive knowledge of FMD control strategies and how researchers analyze economic impacts due to an FMD outbreak. This research summarizes the above literature and discusses the different FMD control strategies that were analyzed in each of the previous studies. The most applied economic measures from each study are producer and consumer welfare. The welfare measures will serve as the dependent variable in this thesis' meta-regression analysis and the various control strategies are the independent variables. By conducting a meta-regression analysis, we re-evaluate the effectiveness of each control strategy that was examined in the previous studies, discuss the factors that might the influence an FMD outbreak, and compare our findings with the previous studies.

Chapter 3. Methods and Model Specification

The focus of the meta-regression analysis (MRA) is to evaluate the diverse set of factors among FMD control strategies that might affect national losses in the U.S. agricultural sector. The regression focuses on the important disease mitigation strategies that have been used in past research. Additionally, this analysis assesses how certain factors influence magnitude of losses, which allows us to infer how effective each strategy might be.

When reviewing the literature for this meta-regression analysis, we found there is not much uniformity when considering control strategies being integrated into models or discussed across previous research. All the control strategies include the default strategy, stamping-out, and other disease management strategies (e.g., emergency vaccination, traceability, etc.).

The meta-regression model is given by equation 1:

$$l_i = \beta_0 + \Sigma\beta_k Z_{ik} + \varepsilon_i \ (i = 1, 2, \ldots, N). \tag{1}$$

l_i denotes national loss per animal for observation i, which is the total national loss measured by consumer welfare plus producer welfare divided by total animals. β_0 is the intercept term, β_k are the coefficients to be estimated, Z_{ik} is a binary variable for the various control strategies, k, (except for culling rate), and ε_i denotes an error term. Table 1 provides the descriptions for all variables used in this analysis.

Table 1. Meta-Regression Analysis Variables and Summary Descriptions

Variable	Definition	Mean	Standard Deviation
National Welfare Loss ($)	National welfare loss due to FMD outbreak ($ per head)	3,424	4,981
Culling Rate (%)	The ratio of animals culled to the total number of animals in the epidemic-economic model of original study	22	22
No Vaccination	Binary variable coded 1 if the scenario does not include vaccination, 0 otherwise	0.64	0.48
10 km Ring Vaccination	Binary variable coded 1 if the scenario includes vaccination and the vaccination zone is within 10 km, 0 otherwise	0.22	0.41
20 km Ring Vaccination	Binary variable coded 1 if the scenario includes vaccination and the vaccination zone is within 20 km, 0 otherwise	0.14	0.35
Low Traceability	Binary variable coded 1 if the scenario includes low traceability level, otherwise 0	0.68	0.47
High Traceability	Binary variable coded 1 if the scenario includes higher traceability level, otherwise 0	0.32	0.47
Delay Detection ≤ 2 Weeks	Binary variable coded 1 if the scenario includes delay detection less than or equal to 14 days, otherwise 0	0.84	0.37
Delay Detection > 2 Weeks	Binary variable coded 1 if the scenario includes delay detection more than 14 days, otherwise 0	0.16	0.37
United States	Binary variable coded 1 if the scenario is simulated in the United States, otherwise 0	0.68	0.47
Canada & Mexico	Binary variable coded 1 if the scenario is simulated in Canada or Mexico, otherwise 0	0.32	0.47
NAADSM	Binary variable coded 1 if the study used NAADSM, otherwise 0	0.24	0.43
AusSpread	Binary variable coded 1 if the study used the AusSpread model, otherwise 0	0.08	0.27
Dynamics	Binary variable coded 1 if the study used a dynamic disease spread model, otherwise 0	0.46	0.50
DADS	Binary variable coded 1 if the study used the DADS model, otherwise 0	0.22	0.42

The nature of the data varies greatly across the studies. Most of the studies focus on one particular control strategy and change the scale or the level of the control strategy under certain conditions. The characteristics include: vaccination (apply or not), the size of vaccination zone if vaccination is applied, the length of delay detection, and the degree of traceability (high or low level).

The meta-regression analysis model is estimated using three different models – a linear model, a double-log model (using the log of national loss and culling rate), and a two-step GLS model – to obtain a better model of robustness. All of the independent variables are dummy variables {1,0} indicating whether or not the study had the particular data or estimation characteristic. We test for heteroskedasticity using both Breusch-Pagan test and White's test. The null hypothesis for Breusch-Pagan test is constant variance. The result of Breusch-Pagan test is $\chi^2 = 47.82$ and the df = 9, so we reject the null hypothesis. The null hypothesis for White's test is homoscedasticity. The result of White's test is $\chi^2 = 48.85$ and the df = 30, so we reject the null hypothesis as well. Both the test results indicated that heteroskedasticity exists. In all of the MRA models, White's heteroskedasticity-consistent standard errors are used.

A potential estimation complication for the model is the non-independence of error across observations given that, in some instances, we employed multiple estimates from the same study. There is no clear consensus on how clustering should be treated in unbalanced data sets used in MRA. Some studies employ Weighted Least Squares (WLS) with cluster-corrected standard errors while others employ fixed effects (FE) or random effects (RE) panel data estimators. Two-Step Generalized Least Squares (two-step GLS) is used in this paper to estimate the model due to differences in the variances of the dependent variable estimates across studies. Although the inverse variance of each observation has been shown to result in optimal weights, variances from the selected studies were not available. Therefore, a two-step GLS is used instead of WLS.

The key response goal of an FMD outbreak is to detect, control, and eradicate the disease as quickly as possible. In addition to the default control strategies of stamping-out and animal movement restrictions, others such as surveillance, traceability, and emergency vaccination are also used as control strategies. Time is a critical factor that influences the outcome of the disease spread. Studies conclude that shortening the duration of an FMD outbreak could minimize economic losses. Controlling the disease as soon as possible will not only prevent the disease from spreading, and possibly resulting in more depopulated animals, but will also result in a country being able to resume international trade faster. Therefore, delay of detection is included in the model. However, the duration of the disease is not included in the model because not all studies include these data for us to consider.

Chapter 4. Data

This meta-regression analysis follows the guidelines established by Stanley et al. (2013). To obtain studies for this research, databases searched include various Internet search engines such as Google Scholar, EconLit, Jstor, and Wiley online library. To identify pertinent studies, a combination of keywords was queried including: foot-and-mouth disease, FMD, North America, United States, Canada, Mexico, surplus, welfare and economics. The database searches were conducted during the Spring of 2015.

In total, 18 separate peer reviewed studies, government reports, and working papers that simulate FMD outcomes using an epidemiological-economic modeling framework are collected. However, only seven studies are included in this MRA because the others (excluded from this analysis) did not report producer and consumer welfare or total national welfare (Table 2). Also, studies that did not include the control strategies of interest are excluded. This research only includes studies conducted in North America because animal agriculture is vastly different in other parts of the world. The publication dates of the studies ranged from 2006 to 2015. A summary of the studies included in this MRA is presented in Table 2.

Table 2. Studies Included in the Meta-Regression Analysis

No.	Reference	Publication Year	Control Measure	Usable Scenarios	Epidemiological model	Economic Model	Region
1	Schroeder et al.	2015	Stamping-out Vaccination	9	North American Animal Disease-Spread Model (NAADSM)	Quarterly Multi-Market Partial Equilibrium	Midwestern U.S.
2	Tozer, Marsh, and Perevodchikov	2014	Stamping-out Culling Capacity	6	Dynamic Disease and Economic Optimization Model	Dynamic Disease and Economic Optimization Model	Canada
3	Hagerman et al.	2012	Stamping-out Delay detection Vaccination	10	Davis Animal Disease Simulation Model and AusSpread Model	Agricultural Sector Model	California and Texas
4	Carpenter et al.	2011	Stamping-out Delay detection	5	Davis Animal Disease Model	Agricultural Sector Model	California
5	Jones, Carlberg, and Pendell	2011	Stamping-out Traceability	3	North American Animal Disease-Spread Model (NAADSM)	Equilibrium Displacement Model (EDM)	Ontario, Canada
6	Nogueira et al.	2011	Stamping-out Culling Capacity	7	Dynamic Disease and Economic Optimization Model	Dynamic Disease and Economic Optimization Model	Mexico
7	Zhao, Wahl, and Marsh	2006	Stamping-out Culling Capacity	10	Dynamic Disease and Economic Optimization Model	Dynamic Disease and Economic Optimization Model	U.S.

All economic welfares values are presented as social welfare change per head of animal to normalize the measure of economic impacts because of the diversity across the studies. The economic loss per head of animal ranges from $95 to $6,750 dollars, here ignoring the five extreme large numbers (Figure 1). The mean welfare loss is $3,424 dollars with a standard deviation of $4,981 per head (Table 1). The wide range of the economic loss per animal is due various different factors including year of study, industry of focus, international trade and domestic consumer demand. For example, if an FMD breaks out in a heavily populated livestock area (like the Schroeder et al. (2015) study), the impacts could be more substantial when compared to a study that has a small scale FMD outbreak that ultimately results in an increase in consumer welfare (Zhao, Wahl, and Marsh, 2006).

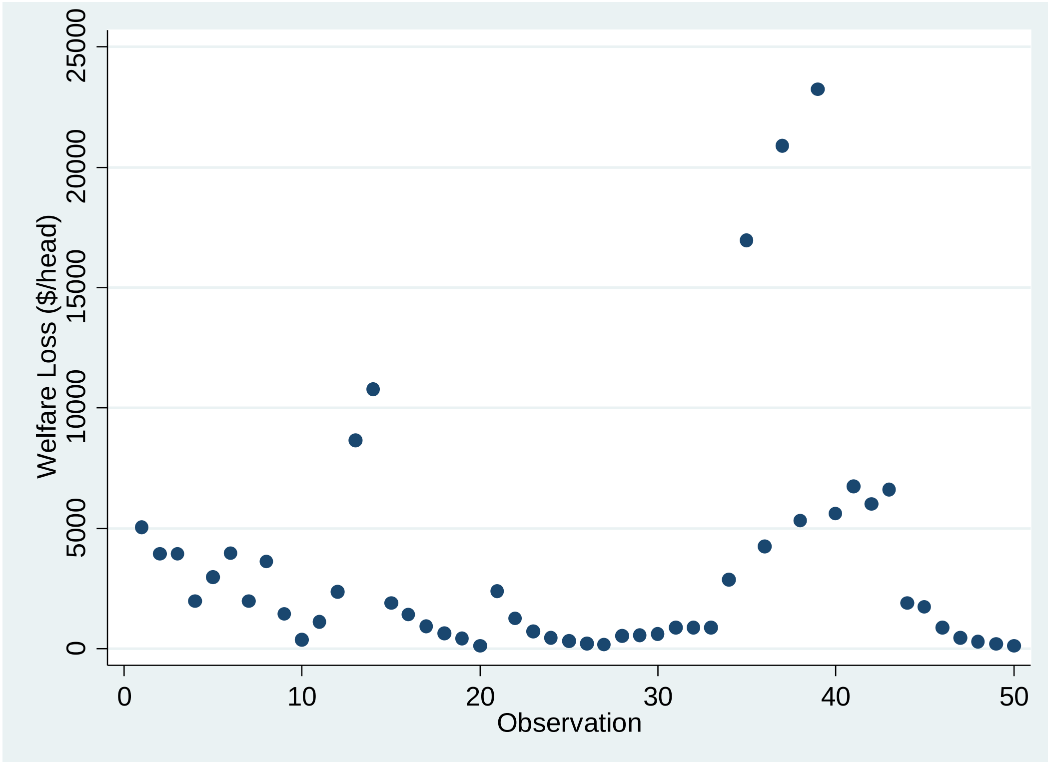

Figure 1. Data Scatter Plot of Welfare Loss Estimates ($/head)

As described above, the dependent variable is the national welfare loss ($ per head). The independent variables contain: (i) FMD control strategies such as vaccination and levels of traceability, (ii) the assumptions under different scenarios simulated in the epidemiological model such as culling rate and delay detection of disease, (iii) geographic study region, and (iv) the epidemiological model used in each study.

National welfare loss is measured by combining consumer and producer welfare measures and mitigation costs. This is calculated as the national welfare loss divided by percentage of animals culled in the study region. The economic welfare measures differ across studies due to the region of interest (i.e., both size and type of livestock production). Therefore, we use the marginal economic impact of an animal as the effect measure to normalize the dependent variable.

Culling rate is the number of animals culled divided by the total number of animals in the study region. The percentage is included to account for the variance of animal populations among different study regions.

Historically, stamping-out is the main control strategy to contain FMD; however, today many studies are focusing on alternate disease mitigation strategies including emergency vaccination. Vaccination can be applied in several ways including mass vaccination or vaccination ring. Several studies that have investigated a vaccination ring (or a certain km ring around the infected premises) have found this can significantly lower the economic impacts of an FMD outbreak. The types of vaccination strategies included in this study are no vaccination, a 10 km radius vaccination ring, and a 20 km ring vaccination.

Traceability can play an important role in assuring food safety and in animal disease control by being able to monitor animals' movement. Once an FMD-infected animal is detected, the animal's movement history can easily be traced, resulting in culling of infected or suspected animals. Several studies such as Jones, Carlberg, and Pendell (2011), Nogueira et al. (2011), and Zhao, Wahl, and Marsh (2006) examined the economic impact of FMD outbreaks in different levels of traceability. Jones, Carlberg, and Pendell evaluated low, medium, and high levels of traceability, while Nogueira et al. and Zhao, Wahl and Marsh presented the level of traceability system by setting different depopulation levels. Depopulation level is the percentage of the animals that are being able to trace as having contacts with the infected animal and are also destroyed. That is to say, as the depopulation level is higher, the traceability system is better.

Detection delay can have a significant effect on the spread of the disease because the longer the detection delay, the higher the probability animate and inanimate vectors come in contact with susceptible animals. Reducing detection delay can reduce the number of direct and indirect animals thus avoid significant losses to livestock. Detection delay is an issue that should not be ignored as we can see that all the five extreme large numbers in Figure 1 share a same characteristic, which is that the detection delay is more than two weeks.

Table 3 presents the average national welfare loss categorized by model characteristic. The mean of total national loss is $3,424 per animal, while when focusing on the characteristics of control strategies, high level of traceability has the smallest average welfare loss at $427 per animal, and detection delay of more than two weeks has the highest average welfare loss at $11,843 per animal. Both control strategies, improving traceability and reducing detection delay, are two methods to contain the spread of disease. The function of these two methods responds to the key goal of controlling an FMD outbreak – to contain the disease as soon as possible.

Table 3. Average National Loss of FMD Categorized by Model Characteristic

Independent Variable	Number of Observations	Mean National Welfare Loss ($/head)
Culling Rate	50	$3,424
No Vaccination	32	$2,482
10 km Ring Vaccination	11	$5,157
20 km Ring Vaccination	7	$5,005
Low Traceability	34	$4,834
High Traceability	16	$427
Delay Detection ≤ 2 Weeks	42	$1,820
Delay Detection > 2 Weeks	8	$11,843
United States	34	$4,638
Canada and Mexico	16	$844
Epidemiological Model:		
NAADSM	12	$2,618
AusSpread	4	$6,238
Dynamic	23	$786
DADS	11	$8,797
Total	50	$3,424

* The dependent variable is National Welfare Loss ($/head).

All the studies include stamping-out as default control strategy combined with other supplemental control strategies. The studies that are included share the following common features:

- Each study uses an epidemiological model that simulated an FMD outbreak.
- Each study analyzes the economic impacts based on the simulated epidemiological output.

Studies report the economic impacts as consumer welfare, producer welfare, government costs and/or total welfare. Therefore, we carefully examined the economic measurement and use national economic loss as dependent variable.

All the studies presented in Table 2 use one of four epidemiological disease spread models. The North American Animal Disease-Spread Model (NAADSM) has been used in several FMD economic analyses including Pendell et al. (2015), Schroeder et al. (2015), Jones, Carlberg, and Pendell (2011), Paarlberg et al. (2008), Pendell et al. (2007), and Disney et al. (2001). NAADSM was developed by USDA's Animal and Plant Health Inspection Service (APHIS). NAADSM is a stochastic simulation model that simulates an outbreak of foot-and-mouth disease, which integrates specific disease parameters, animal movement information, a disease control strategy, and herd demographic data (Jones, Carlberg, and Pendell, 2011). It is a flexible tool allowing for simulation of varying temporal and spatial spread scenarios for FMD at the herd level (Harvey et al., 2007).

A second set of economic studies use the AusSpread model to simulate disease spread (Hagerman et al., 2012; Hagerman et al., 2010; Elbakidze et al., 2009). The AusSpread model is a stochastic state transition model that operates within a geographic information system (GIS) framework (Ward et al., 2009). AusSpread uses point location data to represent a farm, the epidemiological unit of interest. The model is unique in that it has been developed within a geographic information system (GIS) environment. This provides access to sophisticated spatial functions and mapping capabilities, and allows for easy incorporation of spatial data layers, such as roadways, waterways, urban centers and elevation.

The third type of disease-spread model is a dynamic disease spread model. The model maximizes profit of breeding, feeding, and marketing while incorporating the disease spread process and capturing the dynamic nature of livestock inventories. Zhao, Wahl, and Marsh (2006), Nogueira et al. (2011) and Tozer et al. (2014) all used this model in their studies.

The final epidemiological model, the Davis Animal Disease (DADS) model, is used by Carpenter et al. (2011) and Hagerman et al. (2012). DADS is a spatial, stochastic, individual-animal-based simulation model. The model simulates the animal disease outbreak in different premises type and direct/indirect contacts among all herd types.

Another issue to be noted is the geographic region of interest. Most of the studies simulate the FMD outbreaks in California, Texas, or Kansas, where the livestock industry is relatively large or dense. As previously noted, the geographic scale of an outbreak tremendously affects the economic losses. Hagerman et al. (2012) focused on three counties in California while Schroeder et al. (2015) was interested in studying feedlots in an eight state region in the Midwestern U.S. To address this issue, the dependent variable was normalized by size of region studied.

Most of the economic analyses used a partial equilibrium model to estimate the economic impacts. In these studies, producer and consumer welfare or total national welfare are reported, except for Pendell et al. (2007), Paarlberg et al. (2008), and Elbakidze et al. (2009). Pendell et al. (2007) only reports the producer welfare and I-O results. Paarlberg et al. (2008) only reports meat price fluctuations and the returns to capital and management for each kind of livestock producer. Elbakidze uses a budget analysis and reports the costs to the government and to producers. Although these studies did not report the results that meet our requirements, they provided helpful ideas on establishing economic analysis and different aspects that influence economic impacts of FMD outbreaks.

In this chapter, we introduce the variables included in the MRA that are selected from seven studies. The above discussion gives us a comprehensive knowledge about the factors that influence the scale of an FMD outbreak. Particularly, we can see that delay detection has a tremendous effect on welfare loss while by improving traceability system, welfare loss can be greatly reduced.

Chapter 5. Results and Discussion

Table 4 presents the results of the meta-regression analysis of economic loss per head of animal due to an FMD outbreak. The base model in this study is a scenario that does not apply vaccination, has low traceability with the delay in detection being less than or equal to two weeks. It also simulates FMD outbreaks in Canada or Mexico using a dynamic disease and economic optimization model. The base model's data represents several scenarios in Nogueira et al. (2011), which also references several other studies.

Among all three models, the double-log model is superior to the other two in that it provides more precise estimates (lower standard error and more statistically significant estimates) and overall model fit (adjusted R-squared is the highest). Also, we used the coefficient of variance for root mean squared error (CVRMSE) to test for a better model fit. CVRMSE is defined as the ratio of the root mean squared error to the mean of the dependent variable. The lower the CVRMSE, the smaller the residual relative to the predict value. We found that the double-log model has the smallest CVRMSE.

As expected, all three models indicate that increasing the culling rate will increase the estimated national loss. For the double-log model, an increase in 1% of culling rate will increase the estimated national loss from about 0.5% to 38%. If you take the average culling rate of 22% reported in Table 1, a 1% increase in culling rate will exacerbate the national welfare loss by 2%[2]. For the linear and the GLS models, an increase of 1% in the culling rate will increase loss

[2] Since the culling rate is already a ratio, we cannot directly calculate the percent change in the double-log model. If we take a 22% culling rate for example, increasing the culling rate by 1% leads to a 23%, then the percent change of national loss is calculated as: $\ln(Loss_2/Loss_1) = \beta * \ln(\text{Culling Rate}_2/\text{Culling Rate}_1)$, so $(Loss_2/Loss_1) = (\text{Culling Rate}_2/\text{Culling Rate}_1)^\wedge\beta = (23/22)^\wedge 0.4680 = 1.0210$. Therefore, a one-percent increase in the base 22% culling rate

to $26 and $36 per head of animal, respectively. The potential reason is that the culling rate implicitly reflects the degree of an outbreak. However, the marginal loss of increasing the culling rate by one percent is surprisingly small since the cost of culling an animal includes all the other mitigation costs as well. The potential reason for the result is that the culling rate is related to culling capacity. Culling capacity refers to the number of animals that could be destroyed per day. The higher the culling capacity, which may result in a high culling rate, the shorter period of time an outbreak needs to be controlled. Since an increase in culling rate increases mitigation costs, the economic loss could be alleviated by a fast stamping-out strategy.

Vaccination has been a controversial issue as a potential mitigation strategy because vaccinated animals are not distinguishable from infected animals. Ekboir et al. (2002) found that countries with the FMD-free without vaccination status could result in premiums for meat exports in the range of 50-60%. Additionally, vaccinations represent extra mitigation expenses that will be borne by the government. The results suggest that 10 km rings for vaccination interventions increase the estimated national loss. Although it has positive coefficient, the increase is very small and is not statistically significant in both the double-log and the GLS models; however, in the linear model, applying a 10 km vaccination ring will increase economic losses by about $2,600 per animal. For the 20 km ring vaccination strategy, the economic impact is rather large in the linear and the double-log models. The estimated economic loss will increase about $2,700 in the linear model and increase by about 40%[3] of the loss in the double-log model. The result in the GLS model is statistically insignificant and is a negative number, counter to our expectation.

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will increase the national loss by 2.1%. As the culling rate increases, the percentage of increase in national loss will decrease due to one-percent increase in culling rate.

[3] $\ln(Loss_2/Loss_1) = \beta*(Vaccine=1)$, so $(Loss_2/Loss_1) = e^{(0.3409)} = 1.4062$.

The results indicate that, when applying vaccination in a smaller ring zone, the economic loss may not be significant while expanding the vaccination ring zone will increase economic loss significantly, which reinforces the conclusions of several other studies that analyze vaccination as a control strategy and conclude it may not be optimal for minimizing economic loss. However, there are many aspects of applying vaccinations besides ring vaccination. Schroeder et al. (2015) analyzed the economic impacts of FMD outbreaks emphasizing alternative FMD vaccination strategies. Different from other studies that use short-run localized impacts of FMD outbreaks, their model contained all or parts of eight states located in the Midwestern United States. All reported results of different scenarios, regarding vaccinated to live or die, vaccination capacity, and vaccination trigger, indicated that applying vaccinations has smaller economic impacts than non-vaccine scenario. Their study points out an issue related to the size of an outbreak. It is widely believed that vaccination has relatively more merit for controlling FMD outbreaks when it spreads widely among several counties or states.

Traceability has been studied as an important tool to mitigate losses and impacts to the industry when an animal disease occurs. The results show that improvements in traceability systems notably reduces the estimated economic loss. Improvements in traceability reduce the economic loss by about $1,900 per head in the linear model, and about a 60%[4] reduction in the double-log model. Although improvements in traceability are not free of costs, it helps to detect and locate the latent animals and/or potentially infected animals more efficiently and in a shorter period of time. On average, the latent period of FMD is about two weeks. During this period, infected animals showing no signs of infection continue to move and spread the disease. A herd, on average, makes 3.5 direct contacts with other herds per week, and 80 percent of them are

[4] $\ln(Loss_2/Loss_1) = \beta^*(Traceability=1)$, so $(Loss_2/Loss_1) = e^{(-0.8951)} = 0.4085$.

effective in transmitting the disease (Zhao, Wahl, and Marsh, 2006). Therefore, improvements in traceability systems can help locate the potentially infected animals and can destroy them sooner to prevent them from infecting other animals.

Delayed detection has always been a big concern in controlling an FMD outbreak. Because the latent period of FMD is about 14 days, historically, the delay in detection is about 14.4 days on average. The result shows that delayed detection has a tremendous effect on the national welfare loss estimate. The national loss due to delayed detection of more than 2 weeks in the double-log model is estimated as almost 2.6 times[5] of the loss when compared to a less than 2 weeks delay detection window. The results in the linear and the GLS models also show huge economic losses due to delayed detection of more than 2 weeks, which is about $8,000 to $9,000 per animal of loss. As expected, the estimation implies that the faster the disease is detected, the smaller the losses would be. It is straightforward to think that the earlier the control strategies are applied, the fewer the animals that will be infected, and ultimately depopulated. This corresponds to one of the key goals of controlling an FMD outbreak, which is to control the disease as soon as possible.

The national loss of an FMD outbreak in the United States is less than that in Canada and Mexico. The result might be driven by the larger livestock industry in the United States when compared to Canada and Mexico. But, it may also be true that, as the industry is larger, it has a better ability to absorb the economic loss. Another potential reason for the lesser national loss in Canada and Mexico is because the FMD outbreaks are all locally simulated, which means that the simulated outbreak was narrowed within a certain region and was not set to influence the country more broadly.

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[5] $\ln(Loss_2/Loss_1) = \beta*(Delay=1)$, so $(Loss_2/Loss_1) = e^{(0.9546)} = 2.5976$.

The epidemiological model variables have quite similar results. All three models – NAADSM, AusSpread, and DADS models – that are regressed in the MRA have much larger estimated national losses than the base, dynamic optimization model. The potential reason for the result may due to the original settings of the models from the studies. For example, NAADSM, AusSpread, and DADS models allow researchers to simulate the outbreaks and predict the spread by entering different parameters such as animal movements, herd types, and contact rate, and then analyze economic impacts based on the simulated outbreaks, while the Dynamic Disease and Economic Optimization model focuses on building a dynamic livestock production model and utilizing the partial equilibrium model, and then analyzes the economic impacts with the introduction of FMD.

As mentioned in chapter 3, we use the Breusch-Pagan test and White's test to test for heteroskedasticity and some problems exist. We conducted linear, double-log, and 2-step GLS models to find a best-fit model. The double-log model is identified as superior to the other two models either from comparing the statistics (adjusted R^2 and CVRMSE) or the coefficients. We found that increase in the culling rate will somewhat increase economic loss since stamping-out is the most direct way to contain the spread of the disease. We also found that delayed detection will devastate the economy the most. Meanwhile, improving the traceability system allows potentially infected or latent animals to be located and quickly destroyed, and thus reduces economic loss. We conclude that time plays a crucial role in controlling the disease because the goal of all the influential factors, including culling rate, improvement in traceability, and delayed detection, is to shorten the time of achieving containment of the disease.

Table 4. Meta-Regression Analysis of National Welfare Loss due to Simulated FMD Outbreaks

	Linear		Double-Log		Two-step GLS	
Independent Variable	Coefficient	Standard Error	Coefficient	Standard Error	Coefficient	Standard Error
Culling Rate	25.73	27.23			36.18**	9.09
Ln (Culling Rate)			0.4680**	0.0861		
Vaccination 10 km	2,631.08*	1,425.69	0.0699	0.2191	820.39	581.16
Vaccination 20 km	2,725.74	1,806.88	0.3409**	0.1687	-107.70	497.44
High Traceability	-1,874.74	1,667.06	-0.8951**	0.2239	-18.93	552.50
Delay Detection > 2 Weeks	8,360.21**	2,239.43	0.9546**	0.2698	9,089.55**	3,148.40
U.S.	99.45	761.11	-0.2512	0.1692	345.74	248.72
NAADSM	-764.10	2,393.14	1.5334**	0.3348	2,334.80**	797.80
AusSpread	-94.90	3,349.23	2.2328**	0.5330	3,725.58*	1,913.52
DADS	3,258.21	2,237.25	2.4968**	0.5334	3,818.19**	997.37
Constant	564.16	1,858.32	7.5468**	0.1362	-830.79	636.55
Adjusted R^2	0.6840		0.8938		0.7454	
Coefficient of Variation	81.78		6.01		26.02	

Note: N = 50, from 7 studies. The dependent variable is national welfare loss ($/head). Single (*) and double asterisks (**) denote significance at the 10% and 5% levels, respectively.

Chapter 6. Conclusions

Animal disease spread can be widespread and cause serious economic impacts. Animal health officials and policy makers play a critical role in developing policies that will control and eradicate contagious animal diseases. To make sound decisions, they need sufficient empirical and analytical studies that will serve as references in establishing policies surrounding disease control strategies.

Foot-and-mouth disease is highly contagious and easily breaks out again after claims it is eliminated. For example, FMD broke out in South Korea in April 2010, after a reported outbreak in May 2002. Meanwhile, in November 2010, seven months after the last outbreak, FMD broke out again at a larger scale and lasted through April 2011 (Park et al., 2013). FMD has continuously existed in various regions of the world. For example, during 2014, fifteen countries reported FMD outbreaks by OiE, and all the countries were in Asia and Africa (OiE, WAHID).

After an FMD outbreak in the UK in 2001, research about effectively controlling the disease and its economic impacts has received more attention. Schoenbaum and Disney (2003), Zhao, Wahl, and Marsh (2006), Ward et al. (2009), Hagerman et al. (2012), Schroeder et al. (2015), and Pendell et al. (2015) analyze how different vaccination strategies such as vaccination time frame, size of vaccination zone, and vaccination capacity influence the economic impacts. Zhao, Wahl, and Marsh (2006), Hagerman et al. (2010), Jones, Carlberg, and Pendell (2011), Nogueira et al. (2011), and Tozer, Marsh, and Perevodchikov (2014) discuss how different levels of traceability systems affect the economic loss. Ward et al. (2009), Elbakidze et al. (2009), Carpenter et al. (2011), and Hagerman et al. (2012) examine the impacts of different lengths of delayed detection to the economy. Therefore, to better understand the impacts of the various FMD control strategies, this research uses a novel meta-regression analysis to systematically analyze the economic impacts resulting from different mitigation strategies used in hypothetical FMD outbreak simulations.

The meta-regression analysis (MRA) applied follows the guidelines from Stanley et al. (2013) and is refined using the details and steps from other published papers. The estimate is standardized by using national welfare loss divided by total animals in the industry. MRA provides a quantity method to examine the FMD control strategies include culling rate, vaccination, traceability, and disease detection that affect the estimates. The estimation results from the double-log model indicate that, under average culling conditions, increasing 1% of culling rate will increase economic loss by 2%. Applying vaccinations within 20 km ring zone will increase economic loss by 40%, compared to the non-vaccination scenario. Delay in disease detection devastates the economy the most. The result shows that a more than 2 weeks delayed detection will increase economic losses by 2.6 times. On the other hand, improvement in traceability can greatly reduce economic losses, by up to 60%. In conclusion, shortening the delay in disease detection and improvement in traceability greatly reduce economic loss, which implies the time length of an outbreak tremendously affects the impacts of an outbreak.

The value of this research lies in its ability to quantify the economic impacts regarding different FMD control strategies. We examine the level of influence of a control strategy to economic impacts from an FMD outbreak. Our purpose is not to find the best model that presents the best scenario of control strategies but to create a comprehensive set of knowledge about how FMD control strategies are likely to affect the economy. Through our paper, decision makers and researchers can easily approximate the amount of economic loss under different control strategies, and thus, can establish a desirable (or context-driven) scenario regarding their concerns to control the disease.

The meta-regression analysis presented has several limitations. Although the number of studies investigating FMD control strategies conducted is growing, linking an epidemiological disease spread model to an economic framework is fairly new over the past 10-15 years. The number of studies that combine a disease spread model to an economic model with welfare measures is limited. Also, due to wide diversity of FMD response policies in different countries and the differences in animal agriculture, all the studies in the MRA are those that have analyzed FMD outbreaks in just the regions of North America (the United States, Canada, and Mexico). While it is beyond the scope of this study, it would be interesting for future researchers to compare the FMD response strategies in different countries. Another interesting idea would be to investigate other highly contagious animal diseases to see how disease mitigation impacts vary across diseases.

Overall, the research reported here increases our understanding related to the level of economic impacts under different control strategies. The meta-regression analysis was used to quantify these effects. Findings show that delayed detection and improvement in traceability are the two most influential factors in controlling an FMD outbreak. Although there are some limitations, this MRA provides a good indication of the impacts of different FMD control strategies. Further, its potential in looking at other contagious animal disease outbreaks makes it attractive.

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