AGRICULTURAL FIRM RESILIENCE TO DISASTERS DOMESTICALLY AND ABROAD: APPLICATIONS IN ANIMAL HEALTH

By

TORI LEE MARSHALL

Bachelor of Science in Agriculture
Tennessee Tech University
Cookeville, TN
2017

Master of Science in Agricultural Economics
Mississippi State University
Starkville, MS
2019

Submitted to the Faculty of the
Graduate College of the
Oklahoma State University
in partial fulfillment of
the requirements for
the Degree of
DOCTOR OF PHILOSOPHY
December, 2022

AGRICULTURAL FIRM RESILIENCE TO DISASTERS DOMESTICALLY AND ABROAD: APPLICATIONS IN ANIMAL HEALTH

Dissertation Approved:

Dr. Amy Hagerman

Dissertation Adviser

Dr. Dayton Lambert

Dr. Derrell S. Peel

Dr. Shelly R. Legg

Dr. Rosslyn Biggs

.

ACKNOWLEDGEMENTS

The work in Chapter 3 of this dissertation is supported and funded by the U.S. Department of Agriculture-Animal and Plant Health Inspection Service by collaborative agreement USDA-APHIS AP19VSCEAH00C022.

Name: TORI LEE MARSHALL

Date of Degree: DECEMBER, 2022

Title of Study: AGRICULTURAL FIRM RESILIENCE TO DISASTERS DOMESTICALLY AND ABROAD: APPLICATIONS IN ANIMAL HEALTH

Major Field: AGRICULTURAL ECONOMICS

Abstract: Agricultural industries operate within a world of uncertainty, volatility, and risk. The degree to which an industry successfully responds to and recovers from exogenous events is dependent on industry resilience (Zolli and Healey, 2012). As a leader in world agricultural production, public and private initiatives are ongoing in the U.S. to maintain a resilient industry when faced with disruptive events both domestically and abroad. A resilient agricultural industry that can better cope with the uncertainty of production, markets, or trade consequently means a safe and abundant food supply domestically. This dissertation applies this idea of resiliency to the animal health spectrum. The first dissertation chapter examines the influence of media coverage during world events on the U.S. swine futures market. The second chapter in this dissertation expands a partial equilibrium framework to include the livestock sector allowing for a more rounded analysis of potential shocks (e.g. FMD outbreak, trade bans, etc.) occurring in the agricultural industry. Finally, the third chapter in this dissertation applies the model developed in Chapter 2 and explores the economic consequences of alternative marketing strategies amid a simulated foot-and-mouth disease outbreak.

TABLE OF CONTENTS

LIST OF TABLES

Table Page

LIST OF FIGURES

Figure Page

CHAPTER I

INFORMATION UNCERTAINTY IN A MEDIA-DRIVEN WORLD: THE INFLUENCE OF INFORMATION IN U.S. SWINE MARKETS

Introduction

The United States swine industry grappled with uncertainty on multiple fronts in 2018 and 2019. On April 2, 2018, China's Ministry of Commerce imposed a 25% retaliatory tariff on U.S. pork and pork products (Buckley, 2018). The tariff amplified trade tensions between the United States (U.S.), a global exporter of pork, and China, the world's largest producer and consumer of pork (USDA-FAS, 2020) in early 2018. Later that same year on August 3, 2018, China reported its first outbreak of African Swine Fever (ASF), a disease known to have high mortality rates in adult swine as well as high abortion rates in breeding herds. ASF resulted in large declines in the Chinese swine inventory, and as a consequence of China's relative size in terms of both production and trade, the outbreak had sizable consequences in world pork and swine product market dynamics. This outbreak also generated extensive media interest domestically and abroad. Both the contentious U.S.-China trade negotiations and China's ASF outbreak resulted in market disruptions globally in the near-term, and both have long-term implications for the U.S. domestic and international pork industry. Throughout 2018 and 2019, media platforms (e.g., newspapers, television, and social media) consistently documented the evolution of these events, occasionally focusing on their global impacts (Ivanova and Harris, 2018; Darrah, 2019; Lee, 2019).

Media dissemination of disturbing, disruptive, or controversial events quickly increases collective focus during and after crises (Bento et al., 2020). When markets are efficient, information on prices can be processed quickly and effectively. Applied to lean hog futures, prices should directly reflect relationships between the U.S. and its international trade partners concerning information received from or reported by media outlets. Futures prices proxy what traders believe the price will be in the future, subject to a set of information disseminated at some point in time in addition to an existing body of information (Leuthold, 1974).

The objective of this study is to explain the linkage between market expectations and unanticipated information conveyed by media coverage. The impact of anticipated reports on futures prices is well studied, but less work has focused on unexpected global events like ASF or trade negotiations between countries. After its announcement through media channels, ASF and the trade negotiations had consequential impacts on hog futures prices. Because these events have different implications for the swine industry in the short-term and long-term, the study also analyzes the influence of information on traders' expectations in nearby, medium-, and distant-horizon periods.

A previous study by Attavanich et al. (2011) analyzed the effect of media coverage influences from newspaper headlines from the 2009 H1N1 outbreak on lean hog futures prices. This study expands on Attavanich et al.'s (2011) work on unexpected information impacts on futures markets. In this study, we expand the type of media data used and apply a different econometric framework to account for a different type of disruption. The impact of ASF and trade war information from various media coverage formats on lean hog futures prices is analyzed using a state-space modeling approach. Also investigated are the influence of sentiments, discussed later on, attached to the information bytes circulated through media coverage.

Findings from this analysis will further understanding of the dynamic influences occurring in today's constant-contact media environment. The findings will be of interest to traders and policymakers as they seek to understand how media surrounding world events impacts futures markets both in the short- and long-term. When USDA information is unavailable (e.g. government shutdowns preventing releases of USDA reports) and even when it is available, consumers resort to other informational resources, whether quality information or not, to acquire news about current events and supply and demand conditions (Huffstutter and Polansek, 2019). Studies like this contribute toward a more precise understanding of how media affects market movements with implications for managing market risk.

Scope of the Issue

In 2018, the U.S. swine industry was operating at record production levels with an estimated 72.1 million head on March 1, 2018, and no indication of decline (NASS, 2018). The U.S. global share of exports for the pork industry have increased since events in 2018 and 2019. Most U.S.-produced pork is consumed domestically, but expectations of an expanding export market influence the domestic production decisions of swine integrators and domestic hog prices.

Trade tensions between the U.S. and China developed amid record hog and pork production.[1] Starting in April 2018, China placed retaliatory tariffs of up to 25% on U.S. pork and pork products, as well as other products, due to an ongoing trade war. China is the world's leading consumer of pork and pork products and was becoming an importer of growing importance for U.S. pork producers. As a result of the trade war, U.S. swine companies faced uncertainty in international markets, which affected demand for a record domestic supply of pork and pork products. Following the implementation of retaliatory tariffs, media outlets frequently published headlines, amplifying the gravity of the situation emerging in the hog industry. From April to October 2018, the U.S. experienced a $31 million decline in pork and pork product exports to China (GATS, 2020).

As the U.S. China-trade war lingered, a new dilemma emerged in the swine industry: outbreaks of ASF in several countries, including China. ASF is lethal to both domestic and wild

---

[1] In 2018, trade tensions developing over the previous two years between the U.S and China intensified as the Trump administration implemented tariffs and trade barriers on Chinese markets. The deterioration of trade relations between the U.S. and China became known as the "US-China trade war" and will otherwise be referred to here as this or simply "trade war."

swine with mortality rates as high as 100 percent in some herds. Currently, neither a cure nor an effective vaccine is available to mitigate the spread of the virus. China reported the first confirmed outbreak of ASF in August 2018[2].

From August 2018 through 2019, the ASF outbreak led to a large reduction of the Chinese hog inventory with sow inventories declining by approximately 41% and Chinese pork production declining by an estimated 10% (USDA-FAS, 2019). Before ASF, China had approximately half of the global hog herd and was the world's leading pork producer. The inventory losses of Chinese breeding sows associated with ASF were greater than the total U.S. hog inventory at that time (USDA-FAS, 2019). As a result, the opportunity arose for the U.S. and other pork exporting countries to increase shipments to meet China's shortfall and generate a domestic increase in prices. The extent to which the U.S. would be able to capitalize on these opportunities was moderated by retaliatory tariffs on pork, but as more world pork diverted to China, the U.S. also had an opportunity to form new trade relationships. Reports indicate exports to China from the U.S. still more than doubled in 2019 year over year. Given that each event has the potential to generate opposing effects on lean hog futures prices, this analysis measures the impact of each event on lean hog futures price movements as amplified through media.

Volatility in futures prices arises from supply and demand uncertainty (Anderson, 1986). Colling and Irwin (1990) found an unanticipated change in the Hogs and Pigs reports evokes a significant reaction in live hog futures prices. Mann and Down (1996) found an increase in trade volatility and volume in live hog and pork belly futures markets following published Hogs and Pigs reports. Isengildina-Massa et al. (2016) found the impact of USDA inventory reports on futures markets declined substantially, but "surprising" report estimates significantly influenced markets. Anticipation of reports can also affect markets given the uncertainty around what information will be

---

[2] At the time of this writing, no confirmed ASF cases are reported in the U.S.

released. A commonality between the aforementioned studies is they focus specifically on the influence of USDA reports and expected announcements on futures prices.

Event study methods are widely used to understand the impacts of public information on market trends (Colling and Irwin, 1990; Mann and Dowen, 1996; Attavanich et al., 2011; Isengildina-Massa et al., 2016). The concept of event studies is straightforward, as Campbell et al. (1997) suggested. If prices in efficient markets respond to informational announcements (i.e., an 'event') then the information reported has value to market participants. The U.S. hog industry has an opportunity to gain global market share when adverse events in other countries, such as ASF in China, deplete global supplies. However, the industry also faces challenges when adverse events occur domestically. One such event is the retaliatory tariffs on U.S. pork and pork products destined for China.

The current media environment is large and expansive, containing information originating from a variety of platforms that can vary in accuracy and quality. With consistent accuracy from various sources questionable, individual responses to an event may over- or under-estimate the future impact of current events. Media over-reporting of events may also increase the volatility of lean hog futures prices (Figure 1). Previous studies examined market movements subject to media reporting (Pudenz and Schulz, 2020). This research examines how media reports on U.S.-China trade negotiations and the ASF outbreak in China directly influenced price expectations of U.S. lean hog futures both in the short and long run.

<<Figure 1>>

Methods and Procedures

The influence of shocks on futures markets is a common theme in the time series literature, with considerable interest in modeling the impact of market reports on prices (Colling and Irwin, 1990; Lusk and Schroeder, 2002; Isengildina-Massa et al., 2016). A first glance at time series data usually entails conducting unit-root tests or tests for structural breaks. Unit-roots suggest the existence of a patterned break in data, whereas a structural break may create a singular and at times, an unpredictable break (Lumsdaine and Papell, 1997). The Phillips-Perron test is used to test for unit roots. If a unit root, or non-stationarity, exists, then the price series is often first-differenced to force stationarity (Phillips and Perron, 1988). The Supremum Wald statistic tests for the presence of structural breaks at unknown dates and is implemented in this case by regressing lean hog futures prices on continuous variables believed to affect price movement.

Many time-series models can be written as linear state-space models (StataCorp, 2021). State space modelling (SSM) was developed in the engineering field to analyze linear stochastic systems. SSMs produce estimates of observed, endogenous state variables, given their own past and the influence of other exogenous variables (Drukker and Gates, 2011). Figure 2 provides a visual representation of the SSM procedure used here. The SSM models the influence of structural breaks in the price data:

Equation 1) $$\mathbf{y}_t = \mathbf{A}_t + \mathbf{s}_t\mathbf{B} + \mathbf{x}_t\boldsymbol{\Gamma} + \boldsymbol{\varepsilon}_t\ , \quad \boldsymbol{\varepsilon}_t \sim N(\mathbf{0}, \boldsymbol{\Omega}_{(y)t})$$

Equation 2) $$\mathbf{s}_t = \mathbf{s}_{t-1}\boldsymbol{\beta} + \mathbf{w}_t\boldsymbol{\delta} + \boldsymbol{\upsilon}_t\ , \quad \boldsymbol{\upsilon}_t \sim N(\mathbf{0}, \boldsymbol{\Omega}_{(s)t})$$

where equations 1 and 2 are the observation and state equation, respectively. In the observation equation, $\mathbf{y}_t$ is a $p \times 1$ vector of observed prices in time t, $\mathbf{A}_t$ is a $p \times 1$ vector of intercepts in time t, $\mathbf{B}$ is a $q \times 1$ vector of estimated time-invariant coefficients, and $\mathbf{s}_t$ is a $p \times q$ matrix of latent state variables at time t which correspond with the number of ASF outbreaks and implemented tariffs.

<<Figure 2>>

The state equation consists of a vector of unobserved state variables where $\boldsymbol{\beta}$ is a $q \times q$ transition matrix. The public's expectations of the future may have significant influences, but these expectations are not observed directly (Hamilton, 1994). Matrix $\boldsymbol{\beta}$ therefore captures dynamic interactions between tariff levels and ASF outbreaks by permitting the lagged values of tariffs and outbreaks to influence current tariff levels and confirmed Chinese ASF outbreaks. Tariff levels and ASF outbreaks qualitatively represent the plurality of impacts that world events have on hogs and pork supply-demand expectations. Both $\mathbf{x}_t$ and $\mathbf{w}_t$ are vectors of exogenous variables. The stocastic terms $\boldsymbol{\varepsilon}_t$ are observation errors with a diagonal covariance matrix $\boldsymbol{\Omega}_{(y)t}$ (Gu and Yung, 2013).

The observed endogenous variables relate to the state variables through the observation equation. In this analysis, the state equation determines the likelihood of a price series transitioning from one state to another. The transition point signals a structural break. Exogenous variables included in state equations are ones hypothesized to cause a variable to occupy one state or another. For example, tariffs implemented during the US-China trade may cause breaks in futures prices, given a reduction in demand, which is driven by a tariff level variable appearing in the state equation.

State equations control for unobservable influences in the observation equation. State variables enter the observation equation where the endogenous variable is a price expectation series. State variables included in the observation equation control for factors that could generate structural breaks. The inclusion of such variables increases the precision of media impact estimates on futures prices. The current state is updated as new information enters the state equations (i.e., new tariff levels or confirmed ASF outbreaks). Variables known to directly influence futures prices, but do not necessarily lead to breaks in the time series, are included in the observation equation. One such variable is the lean hog index. Considerable research has been conducted on the convergence relationship between futures prices and cash prices (Schroeder and Mintert, 1999; Adjemian et al., 2013; Hoffman and Aulerich, 2013). Therefore, given this known relationship between the two commodity prices, it is important to account for this relationship in the observation equation but not in the state equation.

Two separate state equations are modeled to differentiate the influences of tariff levels and ASF outbreaks in the observation equation. The extended SSM for lean hog futures prices is:

Equation 3)

$$LHPrice_t = \mathrm{A}_t + \mathrm{B} \cdot ASFState_t + \mathrm{C} \cdot TariffState_t + \Gamma_{LHIndex} \cdot x_{LHIndex,t} + \Gamma_{SBPrice} \cdot x_{SBPrice,t} + \boldsymbol{ASFMedia}_t \boldsymbol{\Gamma}_{\boldsymbol{ASFMedia}} + \boldsymbol{TradeWarMedia}_t \boldsymbol{\Gamma}_{\boldsymbol{TradeWarMedia}} + \boldsymbol{Qtr}_t \, \boldsymbol{\Gamma}_{\boldsymbol{Qtr}} + \varepsilon_t , \quad \varepsilon_t \sim (0, \theta_t)$$

Equation 4) $$ASFState_t = \alpha_t + \beta \cdot ASFState_{t-1} + \delta_{ASFOccurence} \cdot w_{ASFOccurence,t} + \upsilon_t\ , \quad \upsilon_t \sim (0, \psi_t)$$

Equation 5) $$TariffState_t = \lambda_t + \phi \cdot TariffState_{t-1} + \vartheta_{TariffLevel} \cdot p_{TariffLevel,t} + \omega_t\ , \quad \omega_t \sim (0, \varphi_t).$$

In state equations 4 and 5, the current states, $ASFState_t$ and $TariffState_t$, are conditioned on previous states as well as tariff levels, $p_{TariffLevel,t}$, and ASF outbreak occurrences in time t, $w_{ASFOccurence,t}$. The observed endogenous variable, $LHPrice_t$, is conditioned on the current state but also on exogenous factors such as cash prices, $x_{LHIndex,t}$, soybean prices, $x_{SBPrice,t}$, matrices of media coverage variables (e.g., $\boldsymbol{ASFMedia_t}$) and seasonality which enters as quarterly dummy variables. The system's parameters are estimated with maximum likelihood.

Data

Daily lean hog futures prices and daily media information collected from Meltwater Software are used in this analysis. Variable descriptions and summary statistics are in Tables 1 and 2.

<<Table 1, 2>>

Futures Prices Data

The daily lean hog futures prices for all contract months, in U.S. dollars per hundred pounds, are used for the 2015 to 2020 period. Three different price series were collected: the nearby futures price, which are rolled over one week prior to expiration; a mid-horizon futures price; and a distant-horizon futures price. Similar to previous studies (Hudson, Koontz, and Purcell, 1984; Mann and Dowen, 1996), considering the impacts of media on the nearby time horizon as well as the distant horizon is required, given the long-term implications of both events on the swine industry. Examining both near and distant time horizons captures the immediate impacts on the market hog inventory and the long-term repercussions on the breeding hog inventory.

The price horizon definitions used here are similar to those used by Mann and Dowen (1996). The nearby futures price is the price of the next contract expiring. The mid-horizon futures price is the price of the lean hog contract expiring in 6 months. The distant-horizon futures price is the price of a contract expiring in the next 12 months. This characterization of contract prices allows for the inclusion of *price expectations*, given media influences. If media announcements play a role in influencing futures prices, then the method used here can determine if that influence is relatively stronger for nearby contracts or for contracts set to expire at a later date, given expectations arising from event reporting. In animal agriculture, lagged production cycles play a role in the expectations of futures prices (Anderson, 1974). The results provide inference on whether traders' recovery expectations for Chinese pork supply and global demand from market shocks affect nearby, mid-, and distant- price horizons. The nearby soybean futures contract, measured in U.S. cents per bushel for 2015 to 2020, is also used in the analysis, given the relationship between soybean prices, a feed cost to producers, and lean hog futures prices.

Media Influences Price Data

Meltwater Software is a global company that provides online media monitoring and conversation capturing. Meltwater tracks conversations containing keywords pertaining to specific topics monitored across various sources such as online and televised news platforms, social media, print, broadcasts, and podcasts. For this analysis, keywords used to measure the influences of both world events included "African Swine Fever" and "Trade War and Pork" and "Trade War and Soybeans." One of the above phrases was required to be present in the dialogue for a headline to be included in the data. The Meltwater analysis was obtained through a subscription by [XXXX] University.

Using the opportunity that Meltwater provided through its data collection of media information, this study analyzes how sentiments of headlines, and their numbers, influence futures prices presently and in the future. Meltwater provided every headline, broadcast, or conversation that included discussion around the above terms in the requested time period. The sources ranged from newspaper headlines, television reports, radio broadcasts, and social media conversations on the events. The analysis also contained information on the location of the headline and sentiment of the information. The location of the headline was further categorized as originating in the U.S. or the rest of the world (ROW). Questioning similar impacts of media coverage related to H1N1 (swine flu) on futures prices, Attavanich et al. (2011) concluded that media coverage negatively influenced domestic demand of pork and pork products, leading to negative influences on futures prices. Attavanich et al.'s analysis was limited to using only newspaper headlines to account for media coverage though. The information conveyed in the headlines was classified as either having a positive (Pos), neutral (Neut), or negative (Neg) tone, similar to this analysis. To understand the influence of media headlines, similar to Attavanich et al. (2011), the number of daily headlines pertaining to each topic was enumerated, as well as the number of headlines that were positive, neutral, or negative. Psychology literature finds that the distribution of negative information is more impactful on an individual's mindset than positive information (Baumeister et al., 2001; Rozin and Royzman, 2001).

Results and Discussion

Unit roots, as well as structural breaks, were identified in the data series. To correct for non-stationarity, first differences were taken for lean hog futures contracts, soybean futures contracts, and the lean hog index (Table 3). Stationary processes were confirmed for the first-differenced variables. The test for structural breaks indicated the presence of structural breaks at unknown break points. The SSM can account for and attempt to control this unpredictability through the latent state variables and transition matrices (Kunst, 2007).

<<Table 3>>

State Equation Results

The two separate state equations for tariff levels and ASF occurrences facilitated the analysis of the opposing events through the observation equation. Results suggested that as confirmed ASF occurrences increased, the likelihood of a change of state (a structural break) was only evident for the distant-horizon contract. This may be a result of the greater effect of ASF on the Chinese breeding herd and the length of time required to rebuild that sector of the pork industry. Both of the magnitude of the outbreak and the expected timeframe of inventory recovery have consequences for the long-term impacts on global pork demand. When the gravity of the situation in China was reported by media outlets, market analysts may have been uncertain as to whether China would return to its previous hog population size, and thus, domestic production levels, even as pork demand remained strong among Chinese consumers.

Results also indicated that as tariff levels in time *t* increased, the likelihood of a structural break, or change of state, decreased in the mid- and distant-horizon contracts. In addition, the magnitude of the coefficient was smaller for the distant-horizon than in the mid-horizon. Knowledge of increased tariff levels influences markets tomorrow in the distant contract as suggested by the significance of lagged states. For the distant-horizon contract, lagged tariff level information increased the likelihood of a state change. These results may be driven by one or more considerations. First, as the trade war slowly developed and incremental retaliatory tariff increases were implemented, results suggest that the increases were less likely to lead to a break in the futures prices. The decreased likelihood of a structural break may also result from trader expectations of retaliatory tariffs being reduced or eliminated as negotiations continued, or that after negotiations were complete, tariff levels would revert to standard tariff levels on goods, and U.S. agricultural trade would be better off in the long run. Finally, while negotiations with China and retaliatory tariffs on pork exports destined for China may have dominated the media data there were also ongoing negotiations for what would eventually become the United States Mexico Canada Agreement. Successful conclusion of those negotiations may have generated positive expectations for a similarly successful conclusion of the U.S.-China trade negotiations.

Lean Hog Futures Price Regression Results

The null hypothesis that the state equations do not affect lean hog futures prices (observation equation) was rejected for multiple time horizons. The nearby- and distant-term contracts were related to the observation equation in the ASF state equation, suggesting that the latent components influenced futures contract prices.

As the likelihood of a state changing increased, there was a 12.70% increase in prices for the distant horizon contract and a 181.73% increase in the nearby contract, respectively. This increase in prices following ASF outbreaks was expected, as was the relatively strong effect on nearby contracts. Both the market hog inventory, as well as the breeding hog inventory in China, were depleted during the ASF outbreak. The impacts of the loss in the market hog inventory were felt immediately both in China and around the world as supplies diminished. Prices increased with the loss of hogs in China and in pork exporting countries as suppliers sought to meet pork demand. Although the loss of breeding hogs was still significant, a smaller price increase in the distant horizon was not unsurprising because trade and production practices shift to accommodate the consequences of ASF.

The state equation for tariff levels suggested that changes in tariff levels did not influence nearby lean hog futures prices. History and economic theory typically demonstrate that tariffs and trade wars lead to negative outcomes and expectations for a country’s economy. The findings indicate that, although traders believed the trade war and tariffs would negatively influence markets in the next six months (i.e., mid-horizon contract), traders’ price during the trade war resulted in a positive sign in the distant-horizon contract. Although this result differed from its hypothesized effect, the finding demonstrates the influence of two simultaneous world events.

This explanation is corroborated by expectations of producers in the Purdue Ag Economy Barometer (Purdue University, 2018-2019). Throughout 2018, the question of how agricultural producers viewed the trade war was posed multiple times. Although producers were concerned about the immediate impacts of higher tariffs on their net farm incomes from loss of exports during the trade war, overall, producers were still cautiously optimistic, with an average of 56% from April 2018 to January 2019 believing that agricultural exports would increase over the next 5 years (Purdue University, 2018-2019). In March 2019, 68% of producers were optimistic about the future of agricultural exports after the trade war.

Considering only the latest pork export levels, producers as well as traders had no reason to believe otherwise. The trade data shows increases in exports to China of pork and pork products doubling year over year in 2019 (Figure 4). There is no way to distinguish the true reason for such a large increase in exports, but several causes likely drive it. Increased exports could have been influenced by simultaneous world events, namely the rapid demand increase associated with ASF in China. Given the severity of the ASF outbreak, although excessive tariffs were in place on U.S. pork and pork products, China continued to purchase and import U.S. pork and pork products to provide for its domestic pork demand. Traders reacted to all available information when setting futures price expectations. A positive increase in trade led to a positive expectation in futures prices long term. Although it deviates from the expectations of this analysis, it aligns with typical trade behavior and expectations from the information received in the current markets.

<< Figure 4>>

The SSM analysis indicated that media information related to ASF and the retaliatory tariffs influence futures prices for all horizon contracts. Comparing across the three time horizons, the results suggest that media headlines hold a greater influence on expectations of contracts in the distant future. This relatively larger effect on the distant term contract may stem from the expectation of a lengthy recovery for the breeding hog inventory in China from the ASF outbreak and the long-term impacts of the trade war.

Futures prices also reflected the response to information disseminated outside the United States. Negative domestic ASF headlines were associated with a decrease in futures prices of 0.19%. Negative media attention pertaining to ASF in the rest of the world led to a decline in futures prices by approximately 0.15% for both the mid- and distant-horizon contracts. At the peak of the ASF outbreak, a large portion of ROW headlines included reports of new outbreaks globally not just in China. It is possible that this negative response to world headlines may stem disease risk concerns—as outbreaks increased globally, the concern of an outbreak occurring in the U.S. increased. Consequently, the expectation of potential gains from global pork shortfalls was more than outweighed by concerns about protecting domestic pork inventories.

There was an increase in lean hog futures prices as positive information about the trade war on pork in the U.S. circulated. However, U.S. information containing positive sentiments toward the trade war and soybeans were associated with a decline in lean hog futures prices across all three contracts. This result was expected based on economic theory as higher prices were potentially negotiated for soybeans, an input in hog production. For negative headlines in the ROW pertaining to the trade war and pork products, U.S. lean hog futures prices experienced a decline in the mid- and distant horizon contracts. When reviewing headlines for this classification, negative headlines typically discussed the increased tariff rate on U.S. pork products and seeking alternatives to U.S. pork products. When reading this information, this would lead to a negative expectation of lean hog futures prices given exports to China should decline in typical circumstances.

Results of the seasonality dummy variables were as expected with typical cycles for hog prices as shown in Table 3. The lean hog index is important. As expected, the lean hog index only influenced the nearby lean futures price contact. As futures and cash prices converge in days closer to contract closing, an increase in cash prices led to the lean hog futures price increasing by 60%. For nearby soybeans contracts though, the story is more complicated. Economic theory postulates lean hog prices should decline as soybean prices increase. However, in this analysis, the results indicate that as soybean prices increased, lean hog futures prices also increased. This may have stemmed from other market circumstances at the time, namely that demand was increasing strongly during the same period. The cumulative effect of a strong domestic economy in 2019 with robust pork demand and global pork market dynamics led to a significant increase in pork prices domestically. Some of the export demand resulted from opening new foreign markets for U.S. pork and some from increased year-over-year pork exports to China despite the retaliatory tariffs. Although soybean prices increased, lean hog futures prices were increasing to match the demand. It is evident though that as time from the expiration of the contract increased (i.e., distant-horizon), the impact of soybeans prices had less of an impact as markets would adjust farther out, but the demand would still be present.

Conclusions

Futures price expectations are established based on many types of information. While much of that information is based on fundamentals, unexpected disruptions are also incorporated into future price expectations. Media influences from news platforms and social media play important roles in influencing futures markets. Previous research was unable to discriminate between the effects of negative and positive media information on markets. This study analyzed the impacts of media on nearby (1-month), medium-term (6-month) and distant-term (12-month) futures contracts and the influences of media's coverage of uncertain events. This analysis uses state space modeling methods to determine the extent to which media coverage and digital conversations on ASF and the trade war in 2018-2019 influenced lean hog futures markets. Specific attention was given to both direct (retaliatory tariffs and the trade war) and indirect (global swine inventories and soybean export demand) influences on commodity futures.

Results suggest that two simultaneous events can, to some extent, be examined separately analytically. This is particularly useful when aggregate measures of total exports or lean hog futures prices digress from the expected movements based on price theory. Results indicate the idea that traders' price expectations of event impacts may differ depending on the expiration date of the selected contracts and the information received. Although economic theory predicts trade wars will generate negative expectations on futures prices due to the added cost of retaliatory tariffs, traders' price expectations during the U.S. China-trade war were found to be positive for futures contracts expiring 12 months later. This result may signal that observed export increases had the greater influence on future price expectations. This finding also solidifies the importance of accounting for latent influences on lean hog futures prices, which are recovered with SSM methods.

This study had a few limitations that could be addressed in future research. First, the study could not examine implications of the continued recovery of China's swine herd from ASF or the impact of ongoing pork tariffs and Phase I trade deal implementation that were still ongoing as of March, 2020 when this dataset was truncated. The addition of data after COVID-19, which disrupted many aspects of the U.S. economy, was felt to add noise to the analysis rather than clarity. Therefore, the full recovery period was not considered in this analysis but could be in future research. It is also acknowledged that additional analysis could consider policy interventions occurring as result of the trade war that impacted the financial viability of the wider U.S. agricultural sector, namely the Market Facilitation Program payments received by producers in 2018 and 2019. Additional analysis could also be conducted on the influence of media regarding soybean futures prices.

Agriculture is subject to the influence of unexpected occurrences, sometimes called “black swan” events. Aggregate economic measures can mask the complexities of market dynamics during simultaneous unexpected disruptions. In the future, multiple sources of information beyond fundamentals, including sentiment in media coverage, can be examined to explore the impacts of events on agricultural futures prices in the U.S.

REFERENCES

Adjemian, M.K., P. Garcia, S. Irwin, and A. Smith. 2013. "Non-convergence in Domestic Commodity Futures Markets: Causes, Consequences, and Remedies." *USDA-ERS Economic Information Bulletin* 1(115).

Anderson, K. 1974. "Distributed lags and barley acreage response analysis." *Australian Journal of Agricultural Economics* 18(2):119-132.

Anderson, R.W. 1986. "Some determinants of the volatility of futures prices." *The Journal of Futures Markets* (pre-1986) 5(3): 331.

Attavanich, W., B.A. McCarl, and D. Bessler. 2011. "The Effect of H1N1 (Swine Flu) Media Coverage on Agricultural Commodity Markets." *Applied Economic Perspectives and Policy* 33(2): 241-259.

Baumeister, R.F., E. B. Bratslavasky, C. Finkenauer, and K.D. Vohs. 2001. "Bad is stronger than good." *Review of general psychology,* 5(4): 323-370.

Bento, A. L., T. Nguyen, C. Wing, F. Lozano-Rojas, Y. Ahn, and K. Simon. 2020. "Evidence from internet search data shows information-seeking responses to news of local Covid-19 cases." *Proceedings of the National Academy of Sciences* 117(21):11220-11222.

Buckley, C. 2018. "China Slaps Tariffs on 128 U.S. Products, Including Wine, Pork, and Pipes." *New York Times.* Available online at: https://www.nytimes.com/2018/04/01/world/asia/china-tariffs-united-states.html (Accessed October 15, 2020).

Campbell, J.Y., A.W. Lo, and A.C. MacKinlay. 1997. *The Econometrics of Financial Markets.* Princeton, N.J.: Princeton University Press.

Colling, P.L., and S. Irwin. 1990. "The Reaction of Live Hog Futures Prices to USDA Hogs and Pigs Reports." *Journal of Agricultural Economics* 72(1): 84-94.

Darrah, N. 2019. "Millions of pigs in Asia culled as African swine fever spreads. *Fox News Channel.* Available online at: https://www.foxnews.com/world/african-swine-fever-asia-pigs-culled (Accessed October 16, 2020).

Drukker, D.M. and R.B. Gates. 2011. "State Space Methods in Stata." *Journal of Statistical Software* 41(10): 1-25.

Gu, F. and Y.F. Yung. 2013. "A SAS/IML program using the Kalman filter for estimating state space models." *Behavior research methods* 45(1):38-53.

Hamilton, J.D. 1994. State-space models. Vol. 4 of *Handbook of Econometrics*, Amsterdam, Elsevier, 3039-3080.

Hoffman, L.A. and N. Aulerich. 2013. “Recent Convergence Performance of Futures and Cash Prices for Corn, Soybeans, and Wheat.” *Economic Research Service/USDA*. FDS-13L-01.

Hudson, M.A., S.R. Koontz, and W.D. Purcell. 1984. “The Impact of Quarterly Hog and Pig Reports on Live Hog Futures Prices: An Event Study of Market Efficiency.” No. 2266-2019-3547.

Huffstutter, P.J., Polansek, T., 2019. “U.S. shutdown sends grain traders, farmers hunting for data.” Reuters Business News. Jan 11. https://www.reuters.com/article/ us-usa-shutdown-agriculture/u-s-shutdown-sends-grain-traders-farmers-hunting-for-data-idUSKCN1P51G3.

Isengildina, O., S.H. Irwin, and D.L. Good. 2006. “The value of USDA situation and outlook information in hog and cattle markets.” *Journal of Agricultural and Resource Economics* 1:262-282.

Isengildina-Massa, O., B. Karali, S.H. Irwin, M.K. Adjemian, and X. Cao. “The Value of USDA Information in a Big Data Era.” 2016. Paper presented at NCCC-134 Conference on Applied Commodity Price Analysis, Forecasting, and Market Risk Management, St. Louis, Missouri.

Ivanova, I. and L. Haris. 2018. “Trump tariffs on $50 billion in Chinese goods unveiled.” CBS News. Available online at https://www.cbsnews.com/news/trump-tariffs-on-50-billion-of-chinese-goods-unveiled/ (Accessed October 19, 2020).

Kalman, R.E. 1960. “A new approach to linear filtering and prediction problems.” *Transactions of the ASME-Journal of Basic Engineering* 82: 35-45.

Lee, H. 2019. “Kim Jong Un May Be Hiding a Hog Apocalypse From the World.” *Bloomberg News*. Available online at: www.bloomberg.com/news/articles/2019-10-12/kim-jong-un-may-be-hiding-a-hog-apocalypse-from-the-world (Accessed October 16, 2020).

Leuthold, R.M. 1974. “The Price Performance on the Futures Market of a Nonstorable Commodity: Live Beef Cattle.” *American Journal of Agricultural Economics* 56(2): 271-279.

Lumsdaine, R.L., and D. H. Papell. 1997. “Multiple Trend Breaks and Unit Root Hypothesis.” *The Review of Economics and Statistics* 79(2):212-218.

Lusk, J.L. and T.C. Schroeder. 2002. “Effects of meat recalls on futures market prices.” *Agricultural and Resource Economics Review* 31(1): 47-58.

Mann, T.L., and R. J. Down. 1996. “Are Hog and Pig Reports Informative?” *The Journal of Futures Markets* 47(1): 273-287.

National Agricultural Statistics Service (NASS). 2018. “Quarterly Hogs and Pigs.” Available online at: Quarterly Hogs and Pigs 09/27/2018 (cornell.edu) (Accessed October 20, 2020).

Kunst, R. 2007. "State Space Models and the Kalman Filter." Seminar paper prepared for 40461 Vektorautoregressive Methoden.

Phillips, P.C.B., and P. Perron. 1988. "Testing for a unit root in time series regression." *Biometrika* 75: 335 346.

Pudenz, C.C. and L. L. Schulz. 2020. "Quantifying the U.S. Market Response to African Swine Fever Outbreak in China." Paper prepared for Agricultural and Applied Economics Association Annual Meeting, Kansas City, Missouri.

Purdue University. 2018-2019. Ag Economy Barometer. https://ag.purdue.edu/commercialag/ageconomybarometer/category/report/page/4/

Rozin, P., and E.B. Royzman. 2001. "Negativity Bias, Negativity, Dominance, and Contagion." *Personality and Social Psychology Review*, 5(4): 296-320.

Schroeder, T.C. and J. Mintert. 1999. "Market Hog Price Discovery." Kansas State University, Swine Day: 5-8.

StataCorp. 2021. *Stata Statistical Software: Release 17.* College Station, TX: StataCorp LP.

United States Department of Agriculture: Foreign Agricultural Service (USDA-FAS). 2019. "Pork Production—Selected Countries Summary" Available online at: https://apps.fas.usda.gov/psdonline/circulars/livestock_poultry.pdf (Accessed October 9, 2020).

United States Department of Agriculture: Foreign Agricultural Service (USDA-FAS). 2020. "Global Agricultural Trade System (GATS)" Available online at: Standard Query (usda.gov) (Accessed October 5, 2020).

Tables

Table 1.1. Variable Definitions.

Variable	Description
Nearby Contract	Price of contract closest to expiring from time *t*
Mid-term Contract	Price of contract expiring in 6 months from time *t*
Distant-term Contract	Price of contract expiring in 12 months from time *t*
LeanHogIndex	Two-day weight average cash market price during time *t*
SBNearby/Mid/Distant	Price of soybean contract for near, mid-, or distant-term contract
ASFNegUS	African Swine Fever U.S. headlines with negative sentiment
ASFNeutUS	African Swine Fever U.S. headlines with neutral sentiment
ASFPosUS	African Swine Fever U.S. headlines with positive sentiment
ASFNegROW	African Swine Fever ROW headlines with negative sentiment
ASFNeutROW	African Swine Fever ROW headlines with neutral sentiment
ASFPosROW	African Swine Fever ROW headlines with positive sentiment
TWPorkNegUS	Trade war (pork emphasis) US headlines with negative sentiment
TWPorkNeutUS	Trade war (pork emphasis) US headlines with neutral sentiment
TWPorkPosUS	Trade war (pork emphasis) US headlines with positive sentiment
TWPorkNegROW	Trade war (pork emphasis) ROW headlines with negative sentiment
TWPorkNeutROW	Trade war (pork emphasis) ROW headlines with neutral sentiment
TWPorkPosROW	Trade war (pork emphasis) ROW headlines with positive sentiment
TWSBNegUS	Trade war (soybean emphasis) US headlines with negative sentiment
TWSBNeutUS	Trade war (soybean emphasis) US headlines with neutral sentiment
TWSBPosUS	Trade war (soybean emphasis) US headlines with negative sentiment
TWSBNegROW	Trade war (soybean emphasis) ROW headlines with negative sentiment
TWSBNeutROW	Trade war (soybean emphasis) ROW headlines with neutral sentiment
TWSBPosROW	Trade war (soybean emphasis) ROW headlines with positive sentiment
Contract Quarter	Quarter the contract is traded. 0 or 1 dummy variable for quarter *j* classes = Quarter Two, QuarterThree, QuarterFour; reference=QuarterOne

Table 1.2. Summary Statistics.

Variable	Mean	Std. Deviation	Min	Max
Nearby Lean Hog Contract[a]	$67.40	$9.73	$41.10	$92.38
Mid-term Lean Hog Contract[a]	$72.08	$8.77	$54.67	$94.57
Distant-term Lean Hog Contract[a]	$72.21	$7.57	$56.53	$92.25
NearbySoybeanContract[ab]	$9.42	$0.68	$8.14	$11.75
LeanHogIndex	$67.52	$10.27	$45.44	$92.84
ASFNegUS[b]	20.14	51.19	0	475
ASFNeutUS[b]	39.02	76.94	0	675
ASFPosUS[b]	6.77	17.95	0	228
ASFNegROW[b]	22.87	171.08	0	5765
ASFNeutROW[b]	31.99	54.85	0	533
ASFPosROW[b]	9.61	94.33	0	3244
TWPorkNegUS[b]	21.63	119.10	0	2271
TWPorkNeutUS[b]	46.09	206.71	0	3951
TWPorkPosUS[b]	3.33	19.57	0	567
TWPorkNegROW[b]	5.58	21.11	0	501
TWPorkNeutROW[b]	18.75	70.83	0	1073
TWPorkPosROW[b]	1.44	7.22	0	137
TWSBNegUS[b]	51.98	208.90	0	3764
TWSBNeutUS[b]	101.18	373.74	0	7964
TWSBPosUS[b]	6.53	32.43	0	785
TWSBNegROW[b]	12.32	41.38	0	794
TWSBNeutROW[b]	36.02	109.42	0	1937
TWSBPosROW[b]	1.75	6.42	0	91

[a] Nearby=Contract set to expire next; Mid-=Contract expiring in 6 months; Distant-= Contact expiring in 12 months.

[b] Sentiments of Headlines: **ASF**=African Swine Fever; **Pos**=Positive Sentiment, **Neut**=Neutral Sentiment, **Neg**=Negative Sentiment; **US**=United States, **ROW**=Rest of World (e.g. ASFNegUS=United States headlines pertaining to African Swine Fever with a negative sentiment).

Table 1.3. Lean Hog Futures Prices.

	Nearby[a]	Mid-term[a]	Distant-term[a]
State Equation (African Swine Fever)			
Lag (1)	0.0322	0.6547***	-0.0013
ASFOccurence	-0.0066	0.0502	0.4231***
State Equation (Tariff Level)			
Lag(1)	0.4356	-0.2230	0.4745**
TariffLevel	-15.3853	-1.322**	-0.8145***
Observation Equation			
StateEquation (African Swine Fever)	1.8173***	0.0447	0.1270***
StateEquation (Tariff Level)	0.0035	-0.0409**	0.0942***
LeanHogIndex	0.6025***	0.0371	0.0048
NearbySoybeanContract	2.794***	1.5617***	0.9712***
ASFNegUS[b]	0.0000	0.0007	0.0019**
ASFNeutUS[b]	-0.0026**	-0.0011	-0.0020**
ASFPosUS[b]	0.0045	-0.0068	-0.0008
ASFNegROW[b]	-0.0022	-0.0015*	-0.0015**
ASFNeutROW[b]	0.0025	0.0033*	0.0020
ASFPosROW[b]	0.0031	0.0020	0.0021*
TWPorkNegUS[b]	-0.0013	0.0002	0.0006
TWPorkNeutUS[b]	0.0000	-0.0001	-0.0005
TWPorkPosUS[b]	0.0122***	0.0086***	0.0067***
TWPorkNegROW[b]	-0.0039	-0.0073**	-0.0093***
TWPorkNeutROW[b]	0.0001	0.0007	0.0028*
TWPorkPosROW[b]	-0.0001	-0.0005	-0.0040
TWSBNegUS[b]	0.0009	-0.0000	-0.0001
TWSBNeutUS[b]	0.0007*	0.0002	0.0004*
TWSBPosUS[b]	-0.0060***	-0.0028*	-0.0023*
TWSBNegROW[b]	-0.0020	0.0024	0.0027
TWSBNeutROW[b]	-0.0016	-0.0014	-0.0017**
TWSBPosROW[b]	0.0180	0.0137	0.0104
QuarterTwo	0.1756	0.1023	0.1592**
QuarterThree	-0.0135	0.2851**	0.0393
QuarterFour	0.2180	0.3906***	-0.1284

[a] Nearby=Contract set to expire next; Mid-=Contract expiring in 6 months; Distant-= Contact expiring in 12 months.

[b] Sentiments of Headlines: **ASF**=African Swine Fever; **Pos**=Positive Sentiment, **Neut**=Neutral Sentiment, **Neg**=Negative Sentiment; **US**=United States, **ROW**=Rest of World (e.g. ASFNegUS=United States headlines pertaining to African Swine Fever with a negative sentiment).

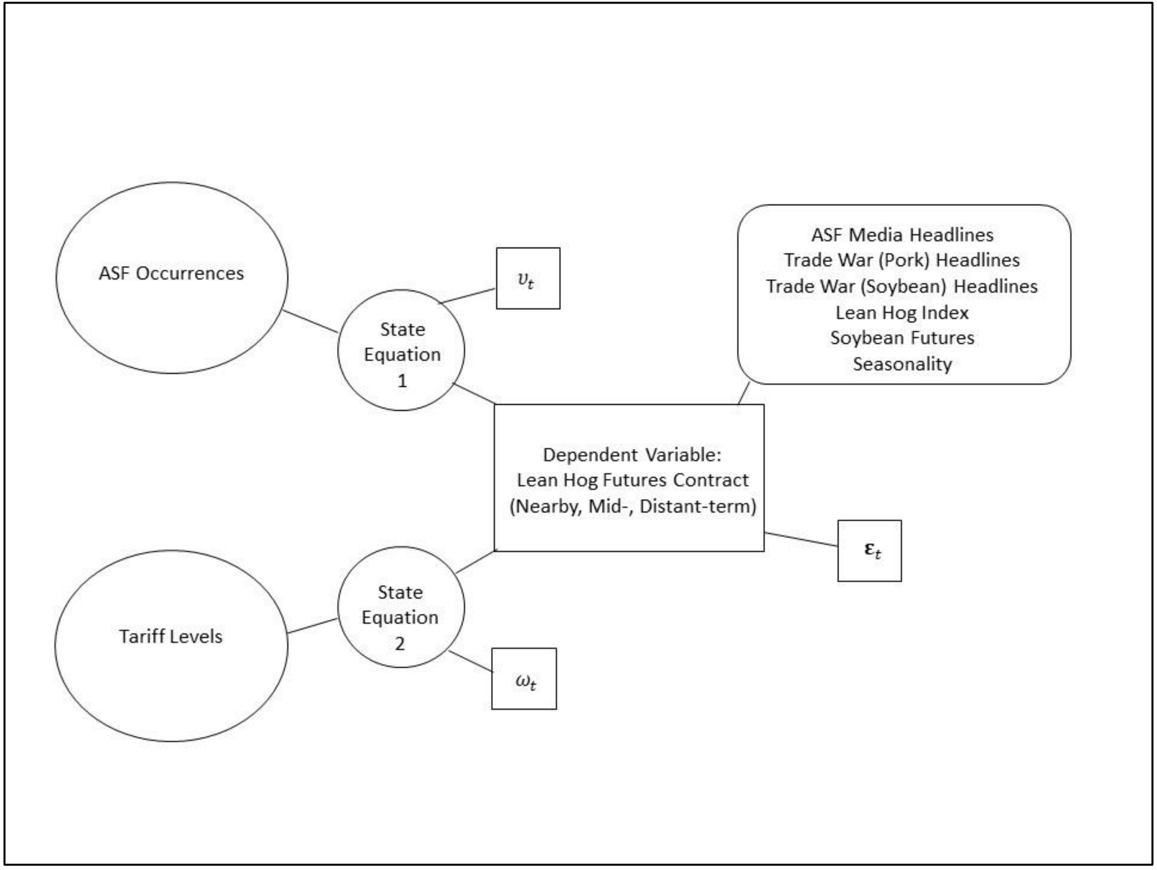
***Significantly different from zero at significance level $\alpha = 0.01$, ** at $\alpha = 0.05$, and * at $\alpha = 0.10$

Figures

Figure 1.1. Nearby Lean Hog DailyFutures Prices (January 1, 2017- March 31, 2020).

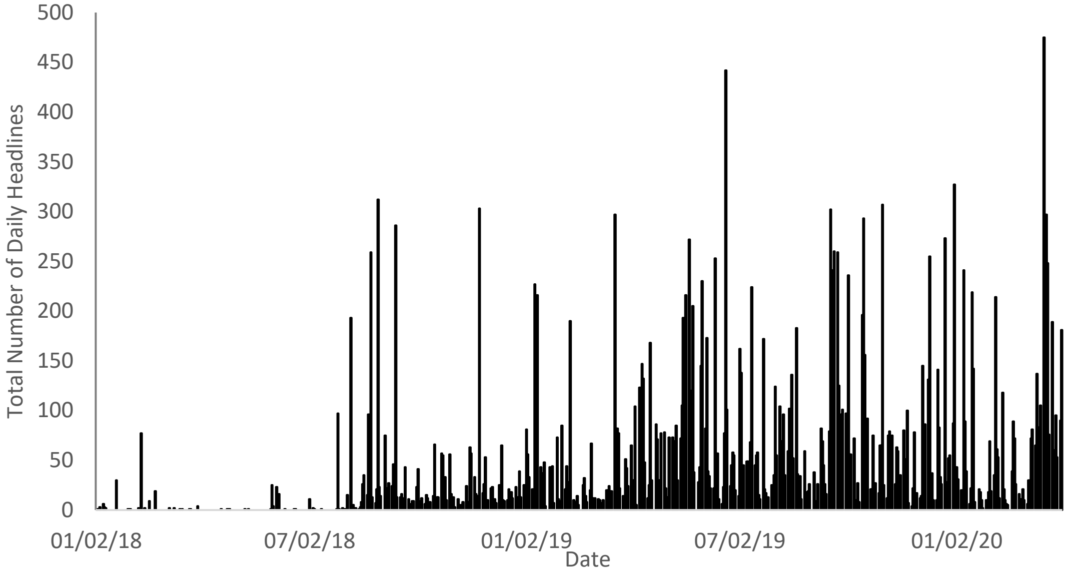
Source: Livestock Marketing Information Center (LMIC)

Figure 1.2. State-Space Model Representation.



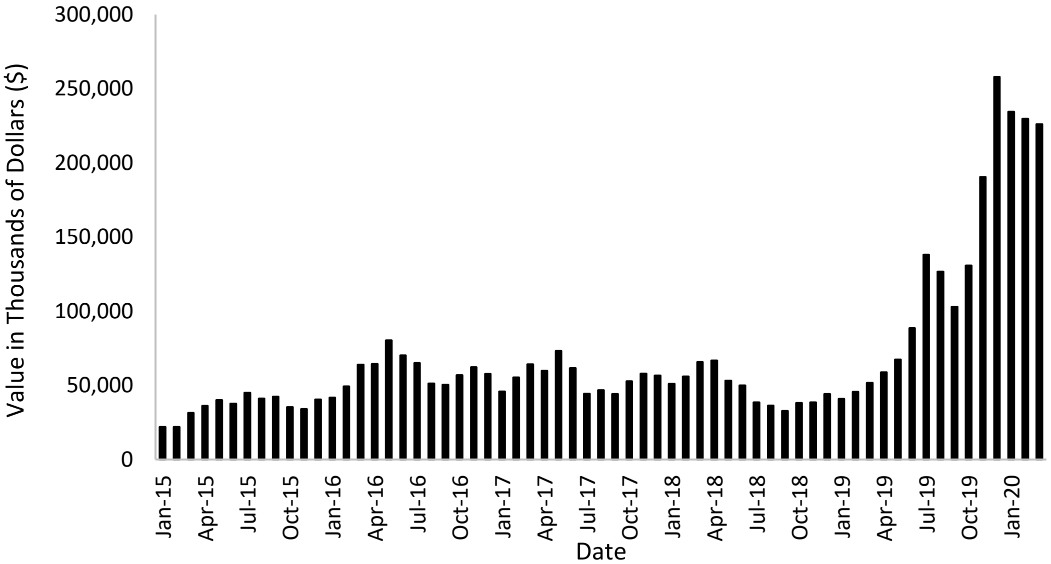
Note: ASF occurrences and tariff levels may lead to possible changes in state (i.e. structural breaks). Thus, two state equations are utilized to capture the unknown influences of the events on the dependent variable, lean hog futures contract, while additional exogenous variables are also included in the regression.

Figure 1.3. African Swine Fever U.S. Daily Negative Headlines.



Source: Meltwater Data

Figure 1.4. Export Value of U.S. Pork and Products to China.



Source: USDA Foreign Agricultural Service Global Agricultural Trade System (GATS)

CHAPTER II

EXPANDING A PARTIAL EQUILIBRIUM DISPLACEMENT MODEL TO ENCOMPASS THE AGRICULTURE SECTOR

Introduction

Equilibrium is a point of stable balance and markets are said to be in equilibrium when prevalent market prices cause the quantity supplied to equal quantity demanded. When shocks, positive or negative, are introduced to the market, the market will either (a) temporarily shift away from that equilibrium but eventually return to the same equilibriums or (b) arrive at a new equilibrium following a shock. Different types of models are appropriate for the evaluation of impacts to shocks of different breadth, depth, or length. For shocks that directly impact many sectors in a large geographic area simultaneously, for example the COVID-19 pandemic or a major hurricane, general equilibrium models are most relevant. In general equilibrium models, all sectors of the economy are incorporated into the analysis to find an equilibrium. Shocks that affect a limited number of sectors, particularly if those sectors do not make up a large portion of national Gross Domestic Product (GDP) can more effectively be evaluated using a partial equilibrium model (PEM). For example, an animal disease outbreak may have less significant impacts on industries in the overall economy, such as oil and gas. Therefore, including less responsive sectors to such an event can mask the impacts to the directly affected sector. Considering that agriculture, food, and related industries make up about 5% of the U.S. GDP, shocks affecting agriculture are generally evaluated in a PEM framework. Agricultural commodity analysis with local and regional focused scenarios have all effectively used PEM to understand effects from introduced shocks in sectors of the tightly linked agricultural industry (Hagerman et al., 2012; Thompson et al., 2015; Lusk, 2017).

When exogenous policy changes or production shocks are considered, such as production impacts for a foreign animal disease and control strategies to combat the animal disease outbreak, models can be used to create forward-looking projections of the economic effects in the agricultural sector. One benefit of applying PEM to the overall agricultural sector is that the direct impacts of occurrence of an event, or shock, occurring in one sector can be examined as well as the indirect impacts in other commodity sectors. For example, the impacts of depleted cattle supply from drought can be felt throughout the pork or poultry sector given that these commodities are substitutes for each other. Depleted livestock supplies can also influence the crop sector given the decline in livestock supply would lead to a decline in demand for feed grains. Understanding these influences across commodities and ripple effects on different agricultural markets from a singular shock is possible because PEM allows for the assessment of direct and indirect effects from the inclusion of elasticities, both own-price and cross-price.

With the worldwide occurrence of animal disease outbreaks becoming more prevalent, such as African Swine Fever, it is crucial to utilize a modelling approach which can account for ripple effects across the entire agricultural industry. A frequent tool used in agricultural analyses is the equilibrium displacement model (EDM), developed by Muth (1964). EDMs are a form of a PEM and have been extensively used to evaluate the impacts of exogenous shocks on endogenous variables. In an EDM, the base framework begins with a set of structural supply and demand equations, and the parameters linked with exogenous and endogenous variables represent elasticities. Common uses of the model include understanding exogenous shocks such as changes in government policies, subsidies, or tariffs. The economic impact of policy changes is determined by the difference, or the displacement, between the model’s predictions for market prices and quantities after the event and the baseline values of market prices and quantities before the event.

Several studies utilizing EDM applications are found in the agricultural sector due to the EDM's ability to provide detailed commodity-specific analytical results. EDMs are also relatively convenient for implementing various simulations with no need to estimate supply and demand functions with every iteration. EDMs only require behavioral parameters, which are the supply and demand elasticities for the chosen commodity, along with benchmark values for commodity flows.

A partial equilibrium displacement model (PEDM) framework was developed for the analysis of OECD agricultural policies specifically for the crops sector (OECD, 2001). Thomas Hertel and Roman Keeney from Purdue University in 2002 then adapted this model to GEMPACK to explore agricultural policy impacts on global trade. The original model, centered around the crop sector, includes the following crops: wheat, coarse grains, and oilseeds. This chapter focuses on expanding this PEDM to include the livestock sector and inputs associated with livestock production. The goal is to not only update behavioral parameters and commodity flows, but also develop a straightforward and manageable partial equilibrium model which estimates the ripple effects across the crop and livestock sectors from an exogenous shock.

Comparison of Economic Models

Before outlining the EDM structure, the conceptual description of other modeling structures will be discussed for comparison. Models considered in this review along with PEMs are computable general equilibrium (CGE) models and input-output (I-O) models. All models have their strengths when examining shocks to the agricultural industry and will be discussed in this review along with their weaknesses.

Computable General Equilibrium Model (CGE)

Over time, CGE models have been found to accurately reflect the economic impacts from man-made and natural disasters (Oladosu, Rose and Lee, 2013). When using CGE models, one of the ultimate goals of the modeler is to create an accurate representation and simulate a complete working economy. The United States Department of Agriculture (USDA) CGE was initially developed to analyze the impacts of domestic and international policies on trade (Robinson, Kilkenny, and Hanson, 1990). Given that CGE models are multi-market models, CGE modelling has been used to understand various agricultural policies, including the influences of very large animal disease outbreaks in the U.S. as well as foreign countries (Blake, Sinclair, Sugiyarto, 2003; Boisvert, Kay, Turvey, 2012; Oladosu, Rose and Lee, 2013). These studies held the stance that CGE was the most direct approach to studying economic impacts given the model's ability to capture the responses from both consumer and producer interaction (Blake, Sinclair, Sugiyarto, 2003; Oladosu, Rose and Lee, 2013). Although CGE analyses may provide a more thorough representation of the influences of shocks on an economy, there are drawbacks to this model. One is the intricacy of developing a model that requires a vast amount of moving parts, but the data necessities of such a model are typically what makes it less attractive than a PEM. Another is that agricultural sectors are often, necessarily, aggregated in the CGE model. For example, all red meat production might be aggregated into a single sector. This can make implementing a shock difficult unless the shock affects all subsectors (e.g. beef, pork, sheep, and goat) equally.

Input-Output Model

A common model to estimate a dollar value of economy-level impacts from shocks on an industry is the input-output model. I-O models are able to provide a detailed representation of an economy by providing a statistical representation of the flow of inputs and outputs throughout an economy. I-O models consist of budgets specifying the costs of inputs, outputs produced by each industry, and demands for those outputs. Impacts from shocks introduced as expenditure changes, and those estimates are used to estimate the direct and indirect consequences on an economy. Various studies have utilized I-O modelling to estimate the primary and secondary impacts of animal disease outbreak (Ekboir, 1999; Pendell et al., 2007; Lee et al., 2012). Two downfalls of I-O models are price changes and substitution effects. I-O models may imitate the foundation of an economy, but price-related adjustments when shocks are introduced are not possible in this modelling approach. The second limitation to this estimation approach is the lack of substitutability among inputs. Some studies have nested I-O multipliers for things like labor changes within an equilibrium model framework or paired analysis of a shock in both a PEM and an I-O model (e.g. Pendell et al., 2007).

Partial Equilibrium Model

PEM provides an invaluable tool to model and study market movements in the event of an animal disease outbreak. With the use of own- and cross-price elasticities, a PEM can evaluate ripple effects across crop and livestock sectors. Numerous studies have utilized PEM to estimate the impact of animal disease outbreaks (Paarlberg, Lee, and Seitzinger, 2002; Pendell et al., 2007; Paarlberg et al., 2008; Carpenter et al, 2011; Hagerman et al., 2012). With supply and demand equations being the framework of PEM and the use of elasticities, various effects from animal disease outbreaks can be estimated in a single model. As previously mentioned, the PEM is an appropriate simplification when the industry is only a small share of the overall economy. The PEM in regards to an EDM will be discussed more extensively in the theoretical framework. Similar to CGE, the PEM restructured in this chapter allows for the examination of behavioral responses under the constraint of resources available to the producer.

Theoretical Framework

The theoretical framework for a partial equilibrium EDM starts with specific set of economic structural equations reflecting supply and demand constrained by benchmark values. This set of equations acknowledges the interdependent relationships between sector demands. For the specific EDM utilized in this analysis, supply and demand shifts, substitution effects, and changes in international trade are examined. Using Davis and Espinoza's (1998) example, the typical basis of an EDM framework denotes a market by three main equations:

Equation 1) $Q_d = D(P, \boldsymbol{Z})$

Equation 2) $Q_s = S(P, \boldsymbol{W})$

Equation 3) $Q_d = Q_s$

Equation 1 and 2 represent supply and demand equations where the demand function *D* is influenced by the price of good *P* and a vector of demand shifters **Z.** Supply is a function of *P* and supply shifters **W**. Starting with this framework, an EDM can include various equations to study various influences on markets and can become an elaborate model analyzing various components of a market such as international trade. For the model being amended in this chapter, supply and demand equations for inputs such as capital and labor are nested within the overall supply and demand equations for each commodity.

The EDM being modified for this chapter represents commodity supplies in terms of the value of aggregate production and linked factor, or input, demand and supply functions. The functional relationships in the model are approximated with equations linear in elasticities and percentage changes in quantities and prices. With constant elasticity of substitution, the demand for purchased inputs (e.g. fertilizer or feed) and owned-inputs (e.g. land) are nested into the total output nest to determine equilibrium values for parameters such as U.S. quantity supplied or U.S.

market prices. Conceptually, the model can be solved in two stages. The first stage involves solving for the optimal aggregate inputs, which are outputs for the inner nests of farm-owned inputs and purchased inputs. Once the aggregate inputs for each commodity are determined, the optimal prices and quantities can be solved for the outer nest. Figure 1 represents this relationship. It is assumed a constant elasticity of substitution within each nest.

When considering policy analysis, supply and demand relationships are combined with equilibrium requirements that demand must equal supply to simultaneously clear all output and factor markets. The EDM model originally created only analyzed the crop sector. When adding the livestock sector, five commodities were added: beef cattle, dairy cattle, hogs, small ruminants (i.e. sheep and goats), and poultry.

When developing this system of equations, the model is calibrated to replicate a specific market situation. This is the actual market prices and quantities observed in what is called a "base year" or the initial equilibrium. To analyze shocks, an exogenous parameter is introduced to calculate a new set of equilibrium values and estimate a change, or displacement, from the initial equilibrium. Various questions can be posed and multiple models can be constructed to reach the same conclusion. For this model development, simplicity is essential and the following assumptions, similar to Hertel (1989) are made:

1. Each commodity industry is treated as a single sector and exhibits competitive behavior and produces a single homogeneous product.
2. Shocks are modelled in the form of either ad valorem subsidy-equivalents or acreage restrictions
3. Any change, or shock, are introduced into an undistorted environment.

4. Non-land inputs are freely mobile and supply of land to each commodity industry is less than perfectly elastic. Constant elasticity of substitution among inputs are assumed.

Extended from the initial EDM framework, to account for resource constraints in the nested input models, eleven equations are utilized for the model:

Equation 4) $\hat{q}_k^{fown} = \widehat{qs}_k \times \sigma_k^{fown}[\widehat{ps}_k - \hat{p}_k^{fown}]$

Equation 5) $\hat{q}_k^{purchinput} = \widehat{qs}_k \times \sigma_k^{purch}[\widehat{ps}_k - \hat{p}_k^{purchinput}]$

Equation 6) $\widehat{ps}_{l,k} = \sum_l \theta_{l,k} \cdot \widehat{rd}_{l,k}$

Equation 7) $\widehat{pm}_k = \widehat{tm}_k + \widehat{pw}_k$

Equation 8) $\widehat{ps}_k = \widehat{ts}_k + \widehat{pm}_k$

Equation 9) $\widehat{rs}_{l,j} = \widehat{ti}_{l,j} + \widehat{rd}_{l,j}$

Equation 10) $\widehat{qd}_k = \sum_{k'} \varepsilon_{k,k'} \cdot \widehat{pm}_{k'}$

Equation 11) $\widehat{qd}_k^{ROW} = \sum_{k'} \varepsilon_{k,k'}^{ED} \cdot \widehat{pw}_{k'}$

Equation 12) $\widehat{qs}_k^{ROW} = \sum_{k'} \varepsilon_{k,k'}^{ES} \cdot \widehat{pw}_{k'}$

Equation 13) $VOW_k \cdot \widehat{qs}_k = VDW_k \cdot \widehat{qd}_k + VDWROW_k \cdot \widehat{qd}_k^{ROW} - VOWROW_k \cdot \widehat{qs}_k^{ROW}$

Equation 14) $\widehat{xd}_{l,k} = \widehat{xs}_{l,k}$

Equation 4 estimates the demands of each commodity *k* for farm-owned inputs: land and labor. Commodity demands for purchased inputs including machinery, feed, and fertilizer are estimated in equation 5. The third equation in this grouping, equation 6, creates a pure profit condition where the supply price of each input *l* for each commodity ($ps_{l,k}$) equals the demand price for each input ($rd_{l,k}$). Equations 7, 8, and 9 link prices and allow for policy changes, or shocks, to be introduced. Supply and demand equations are equations 10, 11, and 12. Equation 10 represents the domestic demands for each commodity where quantity demanded domestically, qd_k, equals the sum of world prices for each commodity given their own-price and cross-price elasticities. The rest-of-the-world (ROW) demand for commodities is represented in equation 11 and the elasticity, $\varepsilon_{k,k'}^{ED}$, represents the ROW excess demand. Equation 12 estimates the ROW supply of each commodity, qs_k^{ROW}, and the elasticity takes into account the ROW excess supply. Equation 13 and 14 are the market clearing conditions for agricultural commodities and inputs. To assure the markets clear for agricultural commodities, equation 13 assures that the domestic supply of commodity k at world prices, VOW_k, multiplied by the quantity produced or supplied, qs_k, equals the value of domestic purchases at world prices, VDW_k, multiplied by the domestic market demand, qd_k, plus the multiple of the ROW demand for each commodity valued at world prices, $VDWROW_k$, and the ROW quantity demanded of each agricultural commodity, qd_k^{ROW}, less the value of the ROW supply, $VOWROW_k$, multiplied by ROW production of each commodity, qs_k^{ROW}. A detailed appendix is included to document the entire estimation procedure and was amended from its original format by Lambert (2020).

Data Collection and Estimation

To update the existing EDM for the crop sector and implement a new portion considering the livestock sector, data was collected and updated to reflect average values. Below provides a detailed description of all data for the model.

Behavioral Parameters

Behavioral parameters are considered stand-alone data and help determine responses in supply and demand when shocks are introduced. Behavioral parameters include three sets of elasticities:

1. Uncompensated cross-price elasticities of domestic demand between crop and livestock commodities
2. Rest of the world (ROW) excess demand cross-price elasticities for crop and livestock commodities
3. ROW excess supply cross-price elasticities for crop and livestock commodities

For elasticity calculations, it is assumed a simple logarithmic equation is suitable for estimation. For uncompensated cross-price elasticities of domestic demand, elasticities from Brorsen (2022) were utilized. It is necessary to note that the equations to estimate domestic demand elasticities use real prices to impose homogeneity of degree zero, but parameter constraints, including adding up, could not be imposed for this diverse group of commodities. For ROW excess demand elasticities, general rule of thumb in global trade analysis is the division of domestic demand elasticities by two to estimate excess demand elasticities (Hertel and Mensbrugghe, 2019). The final elasticity, ROW excess supply elasticities, is estimated by the following equation:

- *ROW Net Exports (for commodity k)* as a function of current prices for commodity k and substitutes k', and one-year lagged prices

Econometrically, the equation can be approximately represented as,

Equation 15) $$\ln\left(Q_{k,t}\right) = \alpha_1 \ln(p_{k,t}) + \alpha_2 \ln(p_{k,t-1}) + \sum_{k'=1}^{4} \alpha_{k'} \ln(p_{k',t})$$

where *k* is the set of commodities coarse grains, oilseeds, wheat, beef, pork, poultry, small ruminants, and dairy. For own-price elasticities, the current-period price and lagged price coefficients are summed to estimate long-run price elasticities. For estimation, market prices, total supply, and exports for crop commodities were collected from the World Agricultural Supply and Demand Estimates (WASDE) for the years 2000-2020. For livestock commodities, U.S. net export totals were collected from the USDA-Foreign Agricultural Services and the Global Agricultural Trade System. For ROW livestock exports and production numbers, the Food and Agriculture Organization (FAO) of the United Nations data system was utilized. It is noted that upon estimation, some signs (i.e. positive or negative) may differ from what one would expect, but elasticities are consistent with other published studies using a similar estimation process to the one currently used. However, it is strongly believed the current elasticities can be improved with a deeper investigation later on to impose homogeneity as well as other constraints in the estimation process.

Baseline Commodity Flows

Commodity flows in the model provide baseline resource constraints for inputs as well as quantities supplied. Baseline estimates for commodity flows include the following:

- Supply of commodity *k* valued at world prices (VOW_k)
- Supply of commodity *k* valued at market prices (VOM_k)
- Supply of commodity *k* valued at agent prices (VOA_k)
- Domestic purchases of commodity *k* valued at market prices (VDW_k)
- ROW supply of commodity *k* valued at world prices ($ROWVOW_k$)
- ROW demand of commodity *k* valued at world prices ($ROWVDW_k$)
- Supply of input *l* to commodity values at market prices (VFM_l)
- Demand for input *l* valued at producer prices (VFA_l)

All baseline estimates are in terms of millions of dollar value. To avoid redundancy, data and estimations that go into each parameter will be discussed. After each new data information or estimation, parameters utilizing this data will be listed. Tables 1 through 17 report estimations for all parameters below.

Average estimates are used to reflect an accurate representation of supplies. In regard to prices, for market prices, the USDA-WASDE from 2000-2020 was used to gain an average estimate. Market prices were utilized in the following parameters:

- Supply of commodities (VOM_k)
- Domestic purchases of commodity (VDW_k)
- Supply of input to commodity (VFM_l)

The world price for crop commodities was calculated by taking the US quantity of exports to the world in million metric tons, converting this into millions of bushels and then taking the total value of world exports dividing it by total bushels to get world crop prices in bushels. World prices were used to calculate the following parameters:

- Supply of commodity (VOW_k)
- ROW supply of commodity ($ROWVOW_k$)
- ROW demand for commodity ($ROWVDW_k$)

For livestock, the total supply of each commodity was calculated by using the total supply of, for example, beef and backing it out to an "on-hoof" supply basis. Dressing percentage for cattle is normally 62% of their live weight (Back and Lalman, 2013), using this assumption and adding back the 62% to the pounds of beef supply in the U.S., we found a live weight for the supply of beef. With world prices, we take the value of U.S. beef exports to the world and divide by the total quantity of U.S. beef exports to the world to capture the world price. To calculate supply for all livestock commodities, dressing percentages for each livestock commodity were as follows (Rentfrow, 2020):

- Beef Cattle: 62%
- Hogs:70%
- Small Ruminants: 52%
- Poultry: 70%

For the crop sector, to estimate total supply for the U.S. and ROW, WASDE estimates were used to estimate an average supply from 2000 to 2020.

Conclusion

This chapter highlights the use of partial equilibrium models, specifically an EDM, as well as other potential economic frameworks that could be used to estimate the impacts of shocks to U.S. agriculture markets, such as an animal disease outbreak. The EDM originally designed by OECD (2001) to assess agricultural policy changes and also adapted by Hertel and Keeney (2001) was updated to include a livestock sector. By updating an easily accessible and useable model, there are opportunities to explore the impacts of various policy changes or shocks to the agriculture industry and the ripple effects into various agricultural markets.

REFERENCES

Beck, P. and D. Lalman. 2021. “Finishing Beef Cattle on the Farm.” *Oklahoma State University Extension Publication.* Publication: AFS-3303.

Blake, A., M.T. Sinclair and G. Sugiyarto. 2003. "Quantifying the Impact of Foot and Mouth Disease on Tourism and the UK Economy." *Tourism Economics* 9:449-465.

Boisvert R.N., D. Kay, and C.G. Turvey. 2012. “Macroeconomic costs to large scale disruptions of food production: The case of foot-and-mouth disease in the United States.” *Economic Modeling*. 29: 1921-1930.

Carpenter T.E., J.M. O’Brien, A.D. Hagerman, and B.A. McCarl. 2011.“Epidemic and economic impacts of delayed detection of foot-and-mouth disease: a case study of a simulated outbreak in California.” *Journal of Veterinary Diagnostic Investigation*. 23: 26–33.

Davis, G.C. and M.C. Espinoza. 1998. “A unified approach to sensitivity analysis in equilibrium displacement models.” *American Journal of Agricultural Economics*, *80*(4):868-879.

Ekboir, JM. 1999. “Potential Impact of Foot-and-Mouth Disease in California.” *Agricultural Issues Center, Division of Agriculture and Natural Resources, University of California.*

Food and Agriculture Organization (FAO) of the United Nations. 2022. “FAOStat Data System.” Available online at: https://www.fao.org/faostat/en/#data/QCL. (Accessed September 26, 2022).

Hagerman A.D., B.A. McCarl, T.E. Carpenter, M.P. Ward, and J. O’Brien. 2012. “Emergency vaccination to control foot-and-mouth disease: Implications of its inclusion as a U.S. policy option.” *Applied Economic Perspectives and Policy*. 34(1): 119–146.

Hertel, T.W. 1989. “Negotiating reductions in agricultural support: Implications of technology and factor mobility.” *American Journal of Agricultural Economics*, 71(3):559-573.

Hertel, T., and D. van der Mensbrugghe. 2019. “Behavioral Parameters.” In GTAP 9 Database Documentation. Available at https://www.gtap.agecon.purdue.edu/databases/v9/v9_doco.asp.

Lambert, DM. 2020. “Partial equilibrium model of agricultural sector with constant elasticity of substitution.” AREC 6103 Notes. Dept. of Agricultural Economics. Oklahoma State University.

Lee B, J. Park, P. Gordon, J.E. Moore, and H.W. Richardson. 2012. "Estimating the state-by-state impacts of a foot- and-mouth disease attack." *International Regional Science Review*. 35:26-47.

Lusk, J.L. 2017. "Distributional Effects of Crop Insurance Subsidies." *Applied Economic Perspectives and Policy.* 39(1):1-15.

Muth, R.F. 1964. "The Derived Demand Curve for a Productive Factor and the Industry Supply Curve." *Oxford Economic Papers.* 16(2):221-234.

OECD (Organisation for Economic Co-operation and Development). 2001. *Market Effects of Crop Support Measures.* Paris: OECD.

Oladosu G., A. Rose, and B. Lee. 2013. "Economic Impacts of Potential Foot and Mouth Disease Agroterrorism: A General Equilibrium Analysis." *Bioterrorism and Biodefense.* S12: 001.

Paarlberg PL, J.G. Lee, and A.H. Seitzinger. 2002. "Potential revenue impact of an outbreak of foot-and- mouth disease in the United States." *Journal of American Veterinary Medical Assoc*. 220(7): 988–992.

Paarlberg P.L., A.H. Seitzinger, J.G. Lee, and K.H. Mathews. 2008. "Economic Impacts of Foreign Animal Disease." *Economic Research Report Number 57.*

Pendell DL, J. Leatherman, T.C. Schroeder, and G.S. Alward. 2007. "The Economic Impacts of a Foot-and-Mouth Disease Outbreak: A Regional Analysis." *Journal of Agricultural and Applied Economics.* 39:19–33.

Rentfrow, G. 2020. "How Much Meat to Expect from a Carcass a Consumer's Guide to Purchasing Freezer Meats." *University of Kentucky College of Agriculture Cooperative Extension Service.* Publication: ASC-179.

Robinson, S., M. Kilkenny, and K. Hanson. "The USDA/ERS Computable General Equilibrium Model of the United States." Agriculture and Rural Economy Division, Economic Research Service, USDA. Staff Report No. AGES 9049.

Thompson, J., D. Pendell, T. Weaver, K. Patyk, and S. Malladi. 2015. "Potential Economic Impacts of a Highly Pathogenic Avian Influenza Outbreak on Upper Midwestern United States Table-Egg Laying Operations." *In 2015 AAEA and WAEA Joint Annual Meeting, July 26-28, San Francisco, California* (No. 205119). Agricultural and Applied Economics Association.

United States Department of Agriculture: Agricultural Marketing Service (USDA-AMS). 2022. "World Agricultural Supply and Demand Estimates (WASDE)" Available online at https://www.usda.gov/oce/commodity/wasde (Accessed September 8, 2022).

United States Department of Agriculture: Foreign Agricultural Service (USDA-FAS). 2022. "Global Agricultural Trade System (GATS)" Available online at: Standard Query (usda.gov) (Accessed June 12, 2022).

Tables

Table 2.1 Uncompensated Cross-Price Elasticity of Domestic Demand[a].

	Wheat	Coarse Grains	Oilseeds	Beef	Dairy	Hog	Sheep	Poultry
Wheat	-0.444	0.087	0.350					
Coarse Grains	0.104	-0.599	0.665					
Oilseeds	-0.200	0.079	-0.246					
Beef				-0.54	-0.002	0.05	0.070	0.030
Dairy				-0.002	-0.006	-0.063	0.021	0.050
Hog				0.05	0.124	-0.800	0.040	0.070
Sheep				0.03	0.004	0.070	-0.370	0.070
Poultry				0.07	0.021	0.040	0.070	-0.970

[a] In estimating elasticities, real prices are used to impose homogeneity of degree zero, but parameter constraints, including adding up, could not be imposed for this diverse group of commodities.

Table 2.2 Excess Demand Elasticity.

	Wheat	Coarse Grains	Oilseeds	Beef	Dairy	Hog	Sheep	Poultry
Wheat	-0.222	0.044	0.175					
Coarse Grains	0.052	-0.300	0.3325					
Oilseeds	-0.100	0.040	-0.123					
Beef				-0.270	-0.001	0.025	0.015	0.035
Dairy				-0.001	-0.003	-0.031	0.025	0.011
Hog				0.025	0.062	-0.400	0.035	0.020
Sheep				0.015	0.002	0.035	-0.485	0.035
Poultry				0.035	0.011	0.020	0.035	-0.185

Table 2.3 Excess Supply Elasticity.

	Wheat	Coarse Grains	Oilseeds	Beef	Dairy	Hog	Sheep	Poultry
Wheat	0.085	-0.035	0.150					
Coarse Grains	-0.521	0.247	-0.142					
Oilseeds	0.050	-0.060	0.003					
Beef				-0.055	0.097	-0.128	0.204	0.172
Dairy				0.052	0.187	-0.314	0.247	0.264
Hog				0.113	-0.190	0.042	0.311	0.119
Sheep				0.058	0.258	-0.601	0.782	0.449
Poultry				-0.036	0.212	-0.317	0.144	0.259

Table 2.4 Supply of Input Valued at Market Prices.

	Wheat	Coarse Grains	Oilseeds	Beef	Dairy	Hog	Sheep	Poultry
Land	6751.569	12024.850	10706.344	680.552	206.418	172.72	973.458	8.548
Labor	1265.826	2484.69	1425.762	466.351	4023.495	272.289	202.597	17.382
PurchInputs[a]	3413.345	11973.113	1642.107	107.823	46.0852	124.086	136.686	2.703
Machinery	7077.945	12606.162	11223.916	1181.01	1547.583	131.767	216.051	3.084

[a] Purchased Inputs for crops represents fertilizer where purchased inputs represents feed for livestock.

Table 2.5 Value of supply at world prices.

Commodity	Value ($ Millions)
Wheat	22398.26523
Coarse Grains	90616.33336
Oilseeds	74239.45237
Beef	36835.8
Dairy	249004.622
Hog	154617.7971
Poultry	9936.1395
Sheep	120.369888

Table 2.6 Supply of Commodity valued at market prices

Commodity	Value ($ Millions)
Wheat	17268.66599
Coarse Grains	66666.6842
Oilseeds	48331.18063
Beef	15390.3
Dairy	38390.31
Hog	6591.5
Poultry	16184.6
Sheep	274.25

Table 2.7 Supply of Commodity valued at agent prices.

Commodity	Value ($ Millions)
Wheat	17268.66599
Coarse Grains	66666.6842
Oilseeds	48331.18063
Beef	15390.3
Dairy	38390.31
Hog	6591.5
Poultry	16184.6
Sheep	274.25

Table 2.8 Domestic purchases at world prices.

Commodity	Value ($ Millions)
Wheat	707.56
Coarse Grains	647.99
Oilseeds	283.07
Beef	846.802
Dairy	141.02
Hogs	132.341
Poultry	27.20
Sheep	79.811

Table 2.9 ROW supply at world prices.

Commodity	Value ($ Millions)
Wheat	234166.739
Coarse Grains	254620.770
Oilseeds	302761.728
Beef	253495.827
Dairy	244652
Hog	214328.3
Poultry	315281
Sheep	40113.43

Table 2.10 ROW demand valued at world prices.

Commodity	Value ($ Millions)
Wheat	255647.271
Coarse Grains	344356.351
Oilseeds	376566.366
Beef	288304.855
Dairy	492741.948
Hog	365841.744
Poultry	325200.440
Sheep	40198.771

Table 2.11 Value of domestic purchases at world prices.

Commodity	Value ($ Millions)
Wheat	917.733
Coarse Grains	880.779
Oilseeds	434.815
Beef	2026.772
Dairy	914.674
Hogs	3104.353
Poultry	16.699
Sheep	35.029

Table 2.12 Power of market price support.

Commodity	Value ($ Millions)
Wheat	0.771
Coarse Grains	0.736
Oilseeds	0.651
Beef	0.418
Dairy	0.154
Hog	0.043
Poultry	1.629
Sheep	2.278

Table 2.13 Power of output price support.

Commodity	Value ($ Millions)
Wheat	1
Coarse Grains	1
Oilseeds	1
Beef	1
Dairy	1
Hog	1
Poultry	1
Sheep	1

Table 2.14 Power of Input Subsidies.

	Wheat	Coarse Grains	Oilseeds	Beef	Dairy	Hog	Sheep	Poultry
Land	1	1	1	1	1	1	1	1
Labor	1	1	1	1	1	1	1	1
PurchInputs[a]	1	1	1	1	1	1	1	1
Machinery	1	1	1	1	1	1	1	1

[a] Purchased Inputs for crops represents fertilizer where purchased inputs represents feed for livestock.

Table 2.15 Elasticity of substitution among inputs.

Commodity	Elasticity
Wheat	0.9
Coarse Grains	0.9
Oilseeds	0.9
Beef	0.9
Dairy	0.9
Hog	0.9
Poultry	0.9
Sheep	0.9

Table 2.16 Elasticity of substitution among owned-inputs.

Commodity	Elasticity
Wheat	0.77
Coarse Grains	0.77
Oilseeds	0.77
Beef	0.77
Dairy	0.77
Hog	0.77
Poultry	0.77
Sheep	0.77

Table 2.17 Elasticity of substitution among purchased inputs.

Commodity	Elasticity
Wheat	0.60
Coarse Grains	0.60
Oilseeds	0.60
Beef	0.60
Dairy	0.60
Hog	0.60
Poultry	0.60
Sheep	0.60

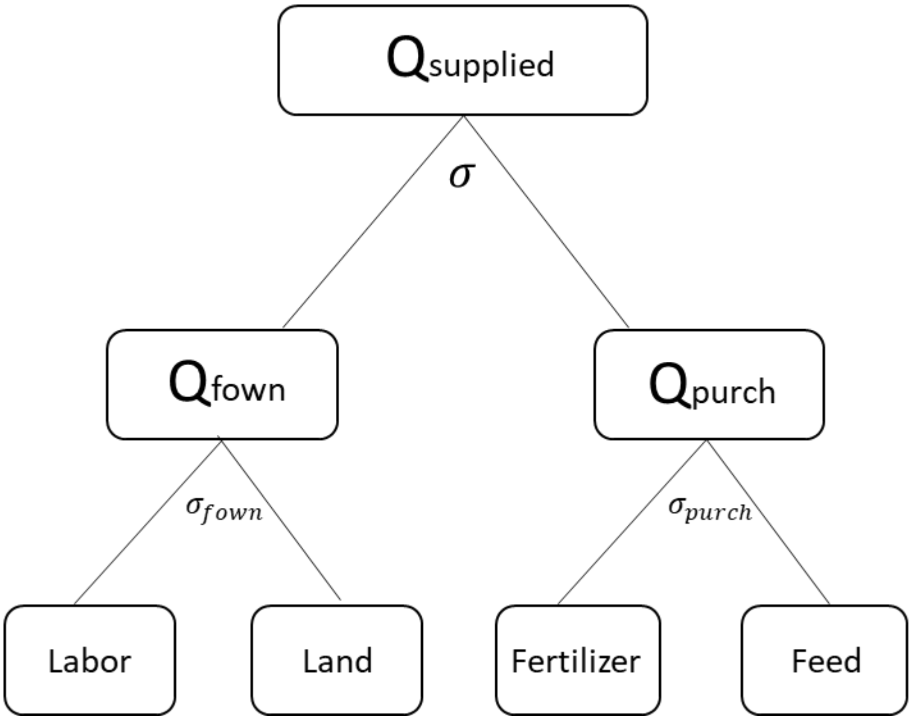
Table 2.18 Elasticity of transformation for input supplies.

Commodity	Elasticity
Land	-0.25
Labor	-0.5
Machinery	-2.5
Purchased Inputs[s]	-2.5

[a] Purchased Inputs for crops represents fertilizer where purchased inputs represents feed for livestock.

Figures

Figure 2.1 CES Nested Production Function and Factor Markets



Appendix: Partial Equilibrium Model for Full Agricultural Sector with Constant Elasticity of Substitution[3]

All commodities **(ALL_COM):**

i = wheat, coarse grains, oilseeds, beef, dairy, hogs, poultry, sheep, other agriculture and non-agriculture

Agricultural commodities **(AG_COMM):**

k(i) = wheat, coarse grains, oilseeds, beef, dairy, hogs, poultry sheep

Crop commodities **(CROP_COMM):**

j(k) = wheat, coarse grains, oilseeds

Livestock commodities **(LVSTK_COMM)**

m(k) = beef, dairy, hogs, poultry, sheep

alias for crop and livestock commodities are j' and m'

Input commodities demanded by agricultural producers **(DEM_COMM)**

l = land, labor, fertilizer, machinery, and other purchased inputs

Other purchased inputs- for crops, this represents fertilizer; for livestock this represents feed

Alias for demanded input commodity l is l'

Endowments **(ENDW_COMM)**

d = land and labor

Purchased commodities **(PURCH_COMM)**

r = Machinery and Other Purchased Inputs

Behavioral Parameters:

Uncompensated cross-price elasticities of domestic demand between crop commodities (8x8 matrix):

$$E^{D} = \varepsilon^{D}_{k,k'}$$

Rest-of-world (ROW) excess demand cross-elasticities for crop commodities (8x8 matrix**):**

$$ED^{ROW} = \varepsilon^{ED}_{k,k'}$$

Rest-of-world (ROW) excess supply cross-elasticities for crop commodities (8x8 matrix):

$$ES^{ROW} = \varepsilon^{ES}_{k,k'}$$

---

[3] Amendment of D. Lambert's AGEC 6103 Notes (Advanced Mathematical Programming)

Baseline commodity flow ($ Value of Terms):

Supply of commodity k valued at world prices: VOW_k

Supply of commodity k valued at market prices: VOM_k

Supply of commodity k valued at producer (agent) prices: VOA_k

Domestic purchases of commodity k valued at market prices: VDM_k

ROW supply of commodity k valued at world prices: $VOWROW_k$

ROW demand of commodity k valued at world prices: $VDWROW_k$

Value of domestic purchases for commodity k at world prices: VDW_k

Power of market price support for commodity k: TM_k

Power of output price support for commodity k: TS_k

Power of market and output price support for commodity k: TW_k

Supply of input l to commodities values at market prices: $VFM_{l,i}$

Demand for input l valued at producer (agent) prices: $VFA_{l,i}$

***Pre-processing Parameters*:**

$$TM_k = \frac{VOM_k}{VOW_k}$$

$$TS_k = \frac{VOA_k}{VOM_k}$$

$$TW_k = \frac{VOA_k}{VOW_k}$$

$$VDW_k = \frac{VDM_k}{TM_k}$$

$$VDWROW_k = VOW_k + VOWROW_k - VDW_k$$

Power of input subsidies of all types:

$$TI_{l,k} = \frac{VFM_{l,k}}{VFA_{l,k}}$$

$$TI_{l,k} = \frac{VFM_{l,k}}{VFA_{l,k}}$$

Variables

Percent Changes… (“^”) → Estimated by model

Quantity of agricultural commodity *k* produced: $\widehat{qs}_k$

Domestic market demand for agricultural commodity *k*: $\widehat{qd}_k$

World price of agricultural commodity *k*: $\widehat{pw}_k$

Domestic market price of agricultural commodity *k*: $\widehat{pm}_k$

Supply price of agricultural commodity *k*: $\widehat{ps}_k$

Quantity of agricultural commodity *k* produced in ROW: $\widehat{qs}_k^{ROW}$

Quantity of agricultural commodity *k* demanded in ROW: $\widehat{qd}_k^{ROW}$

Supply price of input *l* used in production of commodity *i*: $\hat{r}s_{l,i}$

Quantity of input *l* supplied to production of commodity *i*: $\widehat{xs}_{l,i}$

Demand price of input *l* used in production of commodity *k*: $\widehat{rd}_{l,k}$

Quantity of input *l* used in production of agricultural commodity *k*: $\widehat{xd}_{l,k}$

Setting Benchmark Values

Update Supply of commodity *k* valued at world prices:

$$\widehat{pw}_k \times \widehat{qs}_k \leq VOW_k$$

Update supply of commodity *k* valued at market prices:

$$\widehat{pm}_k \times \widehat{qs}_k \leq VOM_k$$

Update supply of commodity *k* valued at producer (agent) prices:

$$\widehat{ps}_k \times \widehat{qs}_k \leq VOA_k$$

Update domestic purchases of *k* at market prices:

$$\widehat{pm}_k \times \widehat{qd}_k \leq VDM_k$$

Update ROW supply of commodity *k* valued at world prices:

$$\widehat{pw}_k \times \widehat{qs}_k^{ROW} \leq VOWROW_k$$

Equations

Update supply of *l* valued at market prices for commodity *i*:

$$\widehat{rs}_{l,i} \times \widehat{xs}_{l,i} \leq VFM_{l,i}$$

Update demand for input *l* valued at producer's (agent) prices:

$$\widehat{rd}_{l,k} \times \widehat{xd}_{l,k} \leq VFA_{l,k}$$

Total Output Nest

Elasticity of substitution among commodity crops: σ_k

Variable

Demand for the composite farm-owned input: $\hat{q}_k^{fown}$

Demand for the composite input: $\hat{q}_k^{purch}$

Percentage change in firms' price of composite purchased input: $\widehat{pc}_k^{purch}$

Percentage change in firms' price of composite farm-owned input: $\widehat{pc}_k^{fown}$

Equations

Sector demands for the composite farm-owned input for each commodity *k*:

$$\hat{q}_k^{fown} = \widehat{qs}_k \times \sigma_k[\widehat{ps}_k - \widehat{pc}_k^{fown}]$$

Sector demands for the composite purchased input:

$$\hat{q}_k^{purch} = \widehat{qs}_k \times \sigma_k[\widehat{ps}_k - \widehat{pc}_k^{purch}]$$

Composite Farm-Owned Input Nest

Elasticity of substitution among composite inputs for production: σ_k^{fown}

Share of land in as a total cost index:

$$\theta_k^{land} = \frac{VFA_{land,k}}{\sum_d VFA_{d,k}}$$

Share of labor in total cost index:

$$\theta_k^{labor} = \frac{VFA_{labor,k}}{\sum_d VFA_{d,k}}$$

Share of total farm-owned inputs in total cost:

$$\theta_k^{fown} = \frac{\sum_d VFA_{d,k}}{\sum_l VFA_{l,k}}$$

Equations

Composite price for farm owned input in commodity *k*:

$$\hat{p}_k^{fown} = \theta_k^{land} \cdot \widehat{rd}_{land,k} + \theta_k^{fown} \cdot \widehat{rd}_{labor,k}$$

Commodity *k* demands farm owned inputs:

$$\widehat{xd}_{d,k} = \hat{q}_k^{fown} + \sigma_k^{fown} \cdot [\hat{p}_k^{fown} - \widehat{rd}_{d,k}]$$

Composite Purchased Input Nest

Elasticity of substitution among purchased inputs for production: σ_k^{purch}

Share of purchased inputs (i in total purchased input cost:

$$\theta_k^{otherpurch} = \frac{VFA_{otherpurch,k}}{\sum_r VFA_{r,k}}$$

Share of machinery in total purchased input cost:

$$\theta_k^{machinery} = \frac{VFA_{machinery,k}}{\sum_r VFA_{r,k}}$$

Equations

Composite price for purchased input for commodity *k*:

$$\hat{p}_k^{purch} = \theta_k^{machinery} \cdot \widehat{rd}_{machinery,k} + \theta_k^{otherpurch} \cdot \widehat{rd}_{otherpurch,k}$$

Commodity *k* demands for purchased inputs:

$$\widehat{xd}_{r,k} = \hat{q}_k^{purch} + \sigma_k^{purch} \cdot [\hat{p}_k^{purch} - \widehat{rd}_{r,k}]$$

Zero Profits

Cost of share of input *l* in total costs of commodity *k* (note *l'* aliases *l*):

$$\theta_{l,k} = \frac{VFA_{l,k}}{\sum_{l'} VFA_{l',k}}$$

Commodity *k*'s zero ("pure") profit condition:

$$\widehat{ps}_k = \sum\nolimits_l \theta_{l,k} \cdot \widehat{rd}_{l,k}$$

Policy Variables and Equations

Variables

Percentage change in power of market support: $\widehat{tm}_k$

Percentage change in power of output subsidy: $\widehat{ts}_k$

Percentage change in power of input subsidy: $\widehat{ti}_{l,k}$

Equations

Equation links world and domestic market prices:

$$\widehat{pm}_k = \widehat{tm}_k + \widehat{pw}_k$$

Equation links market and supply prices:

$$\widehat{ps}_k = \widehat{ts}_k + \widehat{pm}_k$$

Equation links farm and market supply prices for each input:

$$\widehat{rs}_{l,j} = \widehat{ti}_{l,j} + \widehat{rd}_{l,j}$$

Revenue Shares from all commodities (note, *i'* aliases *i)*

$$\theta_{l,i}^{rev} = \frac{VFM_{l,i}}{\sum_{i\prime} VFM_{l,i\prime}}$$

Constant elasticity of transformation (CET) for input supplies (non-positive by definition):

$$\sigma_l^{trans}$$

Variable

Percent change in the composite price for inputs: $\hat{r}$

Equations

Equation generates the composite price for input supplies:

$$\hat{r}_l = \sum_i \theta_{l,i}^{rev} \cdot \widehat{rs}_{l,i}$$

Equation distributes the inputs across sectors:

ROW Excess Supply and Demand Conditions for Commodities

Equations

Domestic demands for commodities:

$$\widehat{qd}_k = \sum_{k\prime} \varepsilon_{k,k\prime} \cdot \widehat{pm}_{k\prime}$$

Rest-of-World demands for commodities:

$$\widehat{qd}_k^{ROW} = \sum_{k\prime} \varepsilon_{k,k\prime}^{ED} \cdot \widehat{pw}_{k\prime}$$

Rest-of-world supply of commodities:

$$\widehat{qs}_k^{ROW} = \sum_{k\prime} \varepsilon_{k,k\prime}^{ES} \cdot \widehat{pw}_{k\prime}$$

Equilibrium Conditions

Equations

Equation assures market clearing for agricultural commodities:

$$VOW_k \cdot \widehat{qs}_k = VDW_k \cdot \widehat{qd}_k + ROWVDW_k \cdot \widehat{qd}_k^{ROW} - ROWVOW_k \cdot \widehat{qs}_k^{ROW}$$

Equations assures market clearing for inputs:

$$\widehat{xd}_{l,k} = \widehat{xs}_{l,k}$$

Closure: Exogenous Shocks

$$\widehat{ti}_{l,j}$$

$$\widehat{ts}_k$$

$$\widehat{tm}_k$$

Objective

$$\max Z = 0$$

Subject to all equations.

CHAPTER III

MARKET IMPACTS OF ALTERNATIVE ERADICATION STRATEGIES DURING A FOOT AND MOUTH DISEASE OUTBREAK

Introduction

The United States (U.S.) has a highly productive and thriving livestock industry, and a highly contagious animal disease outbreak could lead to devastating losses in production, international trade, and domestic markets. The introduction of a disease such as foot and mouth disease (FMD) can be considered one of the most dangerous animal disease threats to the U.S. agriculture industry (Breeze, 2004). FMD is a viral disease with the potential to infect cattle, sheep, swine, goats, deer, and all other cloven-hoofed animals. As the disease is contained and eradicated, the ripple effects of an FMD outbreak are felt throughout the entire agriculture supply chain. In addition to the loss of animals and production resulting from the clinical disease, control strategies to achieve eradication such as depopulation of infected animals, movement restrictions, and surveillance can be costly and disruptive to the supply chain. Response from international trading partners in the form of sanitary trade bans and the potential for U.S. consumer avoidance further threatens economic damages. Although the loss of animal lives or productivity may be extensive in a large outbreak, historically, the danger of FMD has not come from excessively high mortality rates but instead stems from the economic consequences that have followed an outbreak (Graves, 1979; Carpenter et al., 2007). Because of the economic implications an outbreak can bring, FMD could be considered an “economic disease.”

Policies implemented during an outbreak not only impact the short-term outcomes but also the long-term success and resiliency of an agriculture industry. The U.S. has not experienced an FMD outbreak since 1929 and is currently considered FMD free. Given the last outbreaks in Texas and California occurred in 1929, institutional knowledge of how to respond and the impacts of a response in a real outbreak is limited, thus making the U.S. livestock industry extremely vulnerable to such a disease (Ward et al., 2009). Because the industry is susceptible to such an outbreak, investments in animal health, biosecurity, and response plans are vital for the U.S. to respond quickly and efficiently. For many countries, stamping-out (SO) is one of the key response strategies to eradicate the disease in a timely manner and minimize the duration of trade restrictions (McReynolds and Sanderson, 2014). SO is the immediate depopulation, or euthanasia, of all clinically infected and susceptible animals on premises with confirmed infections of the disease, combined with quarantines and movement restrictions in control zones (Junker, 2008). Although SO is designed to eradicate the disease in a timely manner, the utilization of SO incurs significant financial costs as the method is laborious and requires extensive logistical planning. Even with the potential of significant costs accrual, SO of infected herds, movement controls, and quarantines are currently expected to be the primary means of disease eradication for the U.S. (McReynolds and Sanderson, 2014). Ultimately, countries must assess if the financial burden of an eradication strategy, such as SO, outweighs the economic costs of alternative eradication strategies that could postpone possible recovery of the agriculture industry.

The financial and economic losses from an FMD outbreak create a need for strategic response plans before such an outbreak occurs in the United States. In the event of an FMD outbreak, the goal of any response effort is to stop the spread of the virus. However, the strategy implemented depends on various factors. Response plans considered when controlling an FMD outbreak should not only consider the time it takes to eradicate the disease but also minimize financial impacts for an economy (Hagerman et al., 2010).

Utilizing SO as a response to FMD in a feedlot can potentially slow down the overall eradication effort given high resources needs for SO in a large feedlot would tie up limited resources in equipment, labor, and disposal capacity. These resource limitations, and the effect of those limitations on the ability to quickly eradicate the disease, have given rise to interest in better understanding the offsetting costs of alternatives to SO. Given that FMD has no effect on humans through consumption, one option that could be examined is “controlled marketing” of FMD recovered cattle from feedlots. “Controlled marketing” as used in this context would include the care of animals through a recovery period on the feedlot, followed by the movement of recovered cattle to a harvest facility in the same FMD-infected geographic area. This would, in theory, prevent the excessive loss of animal protein loss due to depopulation, allow limited resources to be allocated to other critical activities to slow disease spread, and potentially reduce the potential for a negative public reaction to large scale depopulation on a single operation. However, moving cattle previously destined to be culled into the domestic meat supply chain is not without tradeoffs. SO responses have been found to contribute to a faster recovery of international export markets based on FMD outbreaks in other countries (Cabezas et al., 2022). Therefore, the movement of recovered cattle may lead to a variety of economic consequences associated with oversupply of meat domestically in the face of trade bans, consumer confidence responses to the control strategy, or packer willingness to accept recovered cattle. This study will provide preliminary information to quantify the tradeoffs of the U.S. utilizing a controlled marketing strategy in the midst of an FMD outbreak that includes large feedlots. Quantifying the impacts of each eradication strategy and understanding the resiliency, or response to shocks (Martin and Sunley, 2015), of U.S. markets during any animal health disease outbreak is vital and necessary in improving the U.S. preparedness for animal disease outbreaks.

The objective of this study is to aid disease response planning by providing policy makers and animal health response agencies with market consequence estimates of alternative controlled marketing strategies in feedlots, as compared to a SO strategy. This is accomplished by combining a series of hypothetical FMD outbreaks in a feedlot dense region with an economic impact analysis of the range of disease outcomes. Given the ripple effects that will occur in other agricultural markets, there is need to examine both the crop sector and the livestock sector. Therefore, a partial equilibrium displacement model (PEDM) is needed for the analysis to understand the direct and indirect effects of an FMD outbreak. This model returns the response to shocks in supply and trade over the entire agricultural sector specified.

Background

A review of FMD is conducted and the history of FMD outbreaks, both domestic and international, are initially discussed. Second, a review of control strategies and how other countries have responded to said outbreaks and the financial consequences of such actions are analyzed. Lastly, studies conducted to estimate the implications of an FMD outbreak using various eradication strategies in the U.S. are reviewed. This provides context in which to understand the motivation for examining the economic tradeoffs associated with controlled marketing at this juncture.

FMD Description and History of Outbreaks

FMD is an extremely contagious viral disease that can spread through a secretions or excretions from an infected animal as well as through fomites (i.e., trucks, clothes, equipment, etc.). Animals that are incubating the virus but not exhibiting symptoms have the ability to spread the disease before clinical signs are recognized. Clinical signs are characterized by fever and vesicles or ulcers appearing around the feet or in the mouth. However, severity can vary among species but is generally more severe in cattle and swine. Severity can further vary with the serotype of FMD (Musser, 2004). With low mortality rates but morbidity rates of approximately

100% in adult animals (Musser, 2004), the disease's negative impact on production of meat and milk products is of great concern to producers.

The U.S. has experienced a total of nine FMD outbreaks since 1870 with the last occurring in California in 1929. The most severe outbreak experienced in the U.S. occurred in 1914 and impacted 22 states. Although outbreaks in the U.S. have not recently occurred, FMD in other parts of the world has been identified with some regularity and FMD is considered endemic in many countries (Thornton et al., 2002; Knight-Jones and Rushton, 2013). In the last 25 years, FMD outbreaks have occurred in Taiwan (1997), Netherlands (2001), Japan (2009), and the United Kingdom (2001; 2007; 2017). Taiwan was FMD free for nearly 70 years, similar to the U.S., until the 1997 epidemic (Huang et al., 2000). Since March of 2000, 52 other countries have experienced outbreaks of FMD. One of the hardest hit countries was the United Kingdom in 2001. While eradication via SO was utilized in Taiwan, Netherlands, Japan and the United Kingdom, the control strategies utilized and consequences for the domestic industries varied as discussed below.

Control Strategies and the Consequences for FMD Outbreaks

When an outbreak of FMD occurs, countries can respond in a multitude of ways. However, each control strategy has different financial consequences. Eradication strategies, as outlined in (Junker, 2008), currently include:

- Stamping out: the immediate depopulation, or euthanasia, of all clinically infected and susceptible animals on premises with confirmed infections;
- Stamping-out plus vaccinate-to-kill: the slaughter of clinically infected and susceptible animals on premises with confirmed infections, as well as vaccination followed by slaughter of at-risk animals (i.e. vaccinate-to-kill);

- Stamping-out plus vaccinate-to-live: the slaughter of all clinically and susceptible animals on premises with confirmed infections, as well as vaccination of at-risk animals who are then allowed to remain in production (i.e. vaccinate-to-live); and
- Systematic vaccination without stamping-out: vaccination with no slaughter of infected or susceptible animals.

A key response to eradicate the disease in a timely manner is immediate depopulation of all infected and susceptible animals on the same premises as the infected animals (McReynolds and Sanderson, 2014). With the United Kingdom's 2001 outbreak, SO was the country's main response strategy and approximately 6.1 million head of livestock were slaughtered (Thompson et al., 2002). The same approach was later utilized in 2007 (Knight-Jones and Rushton, 2013). Losses to the agriculture and food industries were estimated at £3.1 billion (U.S. $3.8 billion) in 2001 and £147 million (U.S. $300 million) in 2007. Paarlberg et al. (2002) found that a similar outbreak occurring in the U.S. could result in the nation suffering farm income losses of approximately $14 billion.

SO results in the removal of all susceptible animals on an infected premises. Expanding that out to a regional or national outbreak, the removal of such significant numbers of animals not only depletes available supplies from an industry, but previous studies have identified that depopulation incurs significant costs and significant logistical planning challenges (McReynolds and Sanderson, 2014). One example of this financial burden is the 1997 epidemic in Taiwan. Approximately 4 million pigs were depopulated leaving behind a financial cost of $379 million, not including the economic loss of at least $1.6 billion to the country (Yang et al., 1999). The concerns with employing SO in a U.S. geographic region where large herds are concentrated (e.g. feedlots) is this could present a colossal and possibly infeasible undertaking if resources for eradication (trained people, specialized equipment, and supplies) are limited. In Pendell et al.

(2007), when simulating an FMD outbreak in a 40,000+ feedlot located in Kansas, results showed that greater than 1.2 million out of the 2 million cloven-hoofed animals in the surrounding 14-county geographic area from the infected herd would be culled.

One solution or additional strategy to helping slow the spread of FMD is vaccination. Emergency vaccination of animals has been considered a viable alternative when the risk of disease spread is high (Schroeder et al., 2015). However, vaccination comes with resource and logistical challenges as well. In addition, vaccination may result in additional trade losses as industries determine how to handle long lived vaccinates, regardless of their subsequent infection status. In regard to trade, research has found that a substantial share of the economic losses from an FMD outbreak may stem from the impacts on international trade.

For current FMD-free countries, there is significant concern of FMD entering the country from the importation of infected livestock or contaminated feeds. If FMD introduction were to occur, strict trade regulations would be immediately implemented to halt trade from an infected country. Studies have shown that large domestic economic losses associated with simulated FMD outbreaks in the U.S. are expected to be caused by the loss of international trade due to trade bans (Ekboir, 1999; Paarlberg et al., 2002). Ekboir (1999) found an FMD outbreak beginning in California could lead to losses between $8.5 million and $13.5 billion with a substantial share of those losses being credited to U.S. meat export restrictions. The U.S. is well aware of the notable repercussions that trade restrictions can have on the economy. The U.S. beef industry lost $3.2 to $4.7 billion because of trade embargoes due to three reported cases of bovine spongiform encephalopathy (BSE) in 2004 (Coffey et al., 2005). As a result, studies examining hypothetical FMD outbreaks in the U.S. tend to examine a wide range of possible trade outcomes. Although a country is likely to endure trade bans when an outbreak of FMD is confirmed, the length of those trade restrictions can vary based on the eradication strategy utilized and the bilateral agreements that may be in place between two trading partners.

Any strategy implemented by a country during an FMD outbreak may ultimately affect the duration of an outbreak, where duration is measured as the day the last case is depopulated minus the day the first case was identified. It is only when the disease has been eradicated that the process of proving disease freedom can begin. Thus, the time a country is placed under trade bans is potentially linked to the duration of an outbreak. Other factors will contribute to the length of trade bans as well, such as the control strategy selected and the thoroughness of the disease freedom surveillance process to provide sufficient proof for trade partners to lift embargoes, country income and veterinary services capacity, and whether the country borders another FMD infected country (Cabezas et al., 2022). The World Animal Health Organization (WOAH) offers guidelines to countries placing trade bans on a trading partner that experiences a highly contagious foreign animal disease. A country utilizing SO plus vaccinate-to-kill are recommended, under WOAH guidelines, to be placed under a minimum waiting period of three months from the time of the last confirmed case before trade restrictions are lifted. However, a country utilizing SO vaccinate-to-live can slow the process of reinstatement of the country's FMD-free status as there is hesitation given the difficulty to differentiate between FMD-recovered animals and vaccinated animals. Therefore, it is recommended that a country using a vaccinate-to-live approach be placed under trade restrictions from importing countries for at least six months from the last confirmed case (Musser, 2004; Junker, 2008).

Repercussions from an extended trade ban of livestock products can be detrimental to the agriculture industry. In terms of tradeoffs, the primary concerns for the use of vaccination or controlled marketing are consumer acceptance – in this case, international consumer demand is measured by the magnitude and length of trade bans, but it could also include the acceptance of domestic consumers to FMD vaccinated or FMD recovered animals. Consumer acceptance repercussions could outweigh any losses from increased financial and logistical burden of immediate of SO for countries that are net exporters of livestock, meat and associated animal products.

When an FMD outbreak occurs, countries can use a combination of response strategies to control and eradicate the disease. Countries such as the United Kingdom solely used SO methods and controlling movements of livestock in 2001 and 2007. Taiwan, however, implemented both SO and vaccination responses to the outbreak in 1997 as did Brazil in 2001 and 2005. Regardless of the strategy utilized, substantial costs were and will be accumulated with an FMD outbreak. Therefore, the need has been demonstrated to consider alternative response options that may minimize not only the disease spread but the financial and economic costs as well while allowing animals to reach their intended purpose.

Measuring Impacts of Alternative Response Strategies

Possible economic losses of alternative response strategies will be estimated utilizing an integrated epidemic-economic model. The use of an integrated model combines an epidemiological model simulating the spread of FMD in the United States with an expanded PEDM based on an OECD policy model of the crop sector (OECD, 2001). To understand the quantitative impacts of an FMD outbreak, it is believed necessary to qualitatively discuss outbreak consequences on domestic demand and supply and international markets as well as the modelling methods.

Epidemic Modelling (Hypothetical FMD Outbreaks – U.S. Standard FMD Spread Model)

Before FMD impacts of alternative control strategies can be quantified, it is necessary to calibrate the epidemic model. Given an FMD outbreak has not recently occurred in the U.S., it is difficult to hypothesize how an actual outbreak would unfold in the present-day industry. Therefore, the goal of the epidemic model is to simulate the spread of a hypothetical disease outbreak under alternative control strategies as accurately as possible. Dynamics contributing to the spread of a highly contagious, viral disease are complex and vary based on the density of susceptible species (farms and farm types), the direct and indirect (animal movements, fomites, and biosecurity) contacts between susceptible farms, and the weather (aerosol spread). The U.S. Standard FMD Model, managed by epidemiologists at USDA Animal and Plant Health Inspection Service Center for Epidemiology and Animal Health is based on the dynamic, stochastic disease spread model InterSpread Plus (Stevenson et al., 2013). The disease spread model includes a full, spatially located population of 1.8 million farms across the U.S. and the probabilities of contacts (direct and indirect) between those farms. The model is a daily model that estimates the probability that any given farm on any given day can become infected given a hypothetical start location. The estimation of this probability is based on the USDA National Animal Health Monitoring System and literature-based parameters. The model examines a large number of iterations – in this case, 150 iterations – for every disease spread and control scenario. In each iteration, the model begins the simulated spread from the same ‘seeded’ infection points, in this case 3 large (200+ head) cow-calf operations, 1 medium-sized (6,000-35,000 head) feedlot, and 2 large (35,000+ head) feedlots in Kansas. It is important to note that these are not associated with any actual farm businesses, rather these are approximations based on known operation numbers and sizes from USDA Census of Agriculture data. The model also does not consider FMD-susceptible wildlife (e.g. deer) travelling across farms or the surrounding area. After each simulation period (day), farms are classified as either infected or uninfected. A detailed framework of this epidemic model can be found in Stevenson et al. (2013).

The outputs of the U.S. National Standard FMD Model include the farm types (e.g. cow-calf, dairy, feedlot, etc.), sizes, states, the day infected farms become infected, detected, and depopulated, and the surveillance across all farms in surveillance zones. The disease spread model has other outputs, but these are the most critical ones used for the economic impact analysis. These outcomes are linked to the economic analysis through supply shocks and demand (trade ban) shocks.

For this analysis, four scenarios comparing alternative control strategies are conducted. The scenarios are as follows:

1. Stamping out with no vaccination (SO_NOVX)
2. Stamping out with vaccination (SO_VX)
3. Controlled slaughter with no vaccination (CS_NOVX)
4. Controlled slaughter with vaccination (CS_VX)

Specific procedures are conducted under each scenario. For baseline scenarios, or SO procedures, all infected premises are depopulated. When vaccination is implemented, all cattle on non-infected premises within a 10-kilometer (6.2 miles) radius of infected premises are vaccinated. For controlled slaughter strategies, depopulation is still utilized except for cattle feedlots which contain greater than 35,000 head of cattle.

Economic Modelling (PEDM)

The goal of a PEDM is to analyze all ripple effects, both direct and indirect, that an FMD outbreak can have on the agriculture industry. This model, linking supply of U.S. and foreign agricultural commodities, allows the losses of an FMD outbreak on affected livestock markets as well indirect effects (e.g. feed grain markets) across the entire agriculture sector to be quantified in percentage changes. Once the epidemic model and its parameters are selected to accurately measure the scope of the question being asked, the epidemic model’s results are integrated into PEDM to assess the impacts of each control strategy.

The PEDM uses the interactions between supply and demand to define relationships between all agriculture markets in the sector (e.g. livestock markets and feed grain markets) and identify optimal control strategies. Originally developed by Muth (1964), the base framework of an EDM utilizes the framework provided by supply and demand equations and elasticities for commodities. Within each agricultural sector, the model incorporates variable input distributions among livestock and crops. By utilizing input proportions, the substitution of inputs among commodities in response to shocks is possible. Prices and quantities are endogenously determined by the associations between supply and demand in the model. The goal of an EDM is to estimate displacement from the initial equilibrium after a shock is introduced into the model.

The PEDM framework used for the analysis was originally designed to evaluate OECD agricultural policy changes for the crops wheat, coarse grains, and oilseeds (OECD, 2001). The original model was adapted to GEMPACK by Thomas Hertel and Roman Keeney from Purdue University in 2002. This analysis has extended the model to include the livestock sector for the following commodities: beef cattle, dairy cattle, hogs, poultry, and small ruminants. To use this model, all behavioral parameters, including elasticities, and commodity flow values were re-estimated. A detailed discussion can be found in Chapter 2 concerning the revision of this model.

Integrated Epi-Econ Model

To integrate the two models, results from the epidemic model must be adapted to accurately reflect shifts in supply and demand in the economic model and provide accurate estimates. The PEDM for this analysis represents commodity supplies in terms of the value of aggregate output. Two shocks are introduced into the PEDM that will influence the supply of the commodity output and the demand of the output from the ROW: a supply shock and a trade shock.

Supply Shock

One of the most direct impacts would be the impact of a reduced livestock inventory and associated animal product supplies, which would be felt throughout the U.S. supply chain as quantities of products available declines. This decline comes from either SO and removal of animals from the supply chain to contain the disease or from the decline in productivity of recovered animals (e.g. lower milking rates in a recovered dairy herd). Livestock herds and numbers cannot quickly acclimate to changing markets in the midst of an outbreak given the necessary time for reproduction and fattening cattle. Therefore, this inability to adjust makes the supply of livestock markets and herds inelastic. Initial impacts of lower supply would lead to an increase in market prices for livestock, but this is without accounting for domestic avoidance, as well as trade bans. This impact on supply is reflected in the supply shock.

For the supply shock, initial estimates provided from the epidemic model reflect the percentage of supply depopulated. This initial estimate is categorized by type of livestock (e.g. beef cows in feedlots, beef cows in third trimester, backgrounded lambs, etc.). Given the PEDM represents the value of aggregate output "on-hoof," the supply shock had to represent the production loss in value from mortality as well as morbidity. Using beef as the example, the production shock is transformed to represent the percent of value lost in depopulated beef animals plus the reduced productivity of recovered beef cattle in some scenarios. For dairy cattle, the shock is converted to represent the percent of value lost from the depopulation of dairy cows plus the lost value of milk production. There is no morbidity loss considered for dairy cattle as this is accounted for in the foregone milk production.

Both shocks, in percentage forms, are introduced into the economic model in the form of a wedge between domestic, world, and input prices. The supply shock is introduced in the equation linking the farm's supply price for each input used in production of commodity *k* and the demand price of each input. This equation is represented in equation 1.

Eq 1) $$P_{k,i}^{Supply} = P_{k,i}^{Demand} + ti_k$$

The supply price for each input *i* is represented by $P_{k,i}^{Supply}$ and the demand price is represented by $P_{k,i}^{Demand}$. As the outbreak spreads, the supply declines from mortality and morbidity. Therefore, the cost of input per animal unit increases by the percent of supply lost, which is represented by ti_k. This shock forces the supply price of input *i* for each commodity *k* higher. With these shocks implemented, equilibrium prices and quantities change to respond to the loss of supply in U.S. markets and demand of U.S. products in foreign markets.

Trade Shock

The second shock introduced into the economic model is a trade shock. When a country verifies that an outbreak has occurred, the movement of products to other countries via exports are stopped temporarily via a trade ban. Subsequently, trading partners, particularly those that are FMD-free will place national, state, or control zone trade bans preventing any products from those restricted areas being shipped to the partner country. A reduction of imports from the infected country is almost immediate.

The U.S. is a net-exporter of two key fresh and frozen proteins, beef and pork. The combined effects of supply and demand impacts from FMD have the ability to be transmitted through the international market as well as the domestic market. First, restricted supply of animal products from non-infected animals that was destined for international export markets floods the domestic market. This leads to a reduced domestic price, which may create a temporary windfall for U.S. consumers in the form of lower grocery store prices and result in a higher quantity consumed due to affordability. Other consumers may avoid consumption of beef and pork temporarily out of concern about the virus, although FMD is not a risk to humans from meat and animal product consumption. These two responses can create the potential for offsetting impacts on markets. The volume of U.S. exports for beef and pork creates the possibility that domestic supply increase will cause a price decline, causing revenue to be lost as domestic prices drop.

When the United States is placed under trade bans of agricultural products, world markets also feel the repercussions. When the demand in other countries stays constant, importing countries must look either towards increased domestic protein market production or other foreign protein producers. Consider a more specific product, such as fresh or frozen fed beef, and the significance of international trade loss for the U.S. economy is more obvious. Given the U.S. is a net exporter of fed beef, trade losses could be detrimental under even a reasonably short, regionalized trade bans. Larger levels of depopulation or longer trade bans can actually result in a permanent contraction of the industry. This was seen through Taiwan which never regained its export markets after the 1997 FMD outbreak (Hayes et al., 2011) or fully rebuilt its swine inventory (FAS, 2011).

To implement a trade shock capturing these potential impacts, the assumption is for regionalized trade bans that are not lifted by the end of the outbreak year. To estimate the shock, a geographically weighted export loss per state is estimated and then aggregated across all states with at least one herd involved in the outbreak. The epidemic model provides the day each state had a confirmed FMD case in the outbreak. Given the outbreak begins in Kansas for each simulation, Kansas is infected on day one. For each scenario and iteration, the day each state is infected varies. For example, Texas was infected in one simulation on day 7 but for another simulation infection occurred on day 53 of the outbreak. It is known that repercussions for both supply and demand can extend past one year. However, for this analysis, the impacts of sanitary trade bans are measured for only the initial year that the outbreak occurred (i.e., the first 365 days). To estimate the impacts for one year, the percentage of days out of one year a state was infected and a trade ban was enacted was calculated. For example, trade from Kansas was restricted 99% of the entire year. For Texas, if the confirmed case was found on day 98, trade from Texas was restricted for approximately 73% of the year. With state exports being restricted for a percentage of the year, annual individual state exports were then multiplied by the percent of trade restriction and then divided by the U.S. exports to calculate the percentage of each state’s impact on total trade restrictions. For example, for one iteration of SO without vaccination, Kansas resulted in a decline of 11% in overall trade for the U.S., and the overall U.S. trade loss for that same iteration was approximately 30%.

The trade shock places the wedge between the world price and the domestic market price. From the General Agreement on Tariffs and Trade (GATT), nations are allowed to enact trade bans to protect the country from animal and plant health risks. As a substitute for the rest of the world banning imports from the U.S., countries are able to implement a discriminatory tariff (Paarlberg and Lee, 1998). As an outbreak spreads among multiple states in the U.S., importers are less willing to receive commodities from infected states and can enact a discriminatory tariff on infected states. This *ad valorem* barrier is introduced into the model equation linking the market price and the world price.

Eq 2) $$P_k^D = P_k^W - t_k$$

P_k^D is the domestic market price for commodity k and P_k^W is the world price for each commodity. The variable t_k, which is the percentage of exports lost, creates a tariff-like wedge on the U.S. commodities exported and forces domestic (U.S.) prices lower. Crop exports are not impacted by any trade restrictions; therefore, t_k is zero for crop commodities.

Results

Results from the epidemic model can be found in Table 1 and Table 2. For scenarios that did not implement a vaccination protocol, both the number of infected states and duration of outbreak were greater or equal compared to the two scenarios with vaccination. This aligns with previous studies that show the potential of emergency vaccination to slow the rate of infection and potentially prevent or decrease the spread outside of the vaccination zone. Across the 150 iterations, the average duration of the outbreak was smallest for CS with vaccination. However, CS had some of the largest iterations in the tails indicating the potential for a slower eradication timeframe, and consequently a longer period before animal health agencies can begin postoutbreak surveillance for disease freedom status. For the maximum duration of any outbreak, CS with vaccination had at least one iteration with a 264-day outbreak while SO with vaccination had a maximum outbreak duration of 201 days. Disease spread simulation results indicated that including an emergency vaccination protocol in the overall response may decrease the duration of the outbreak or reduce the risk of spread to other states. However, the disease response costs and trade implications associated with implementing a vaccination strategy may offset some of the benefits associated with reduced disease spread.

Table 3 through Table 10 presents the results from the integrated model. It is important to recollect that for displacements in equilibrium, the changes in quantities represent percentage losses in the total value of commodity output. Although loss values discussed below will seem similar to previous research, comparisons to previous literature should be done thoughtfully since most of those results are loss in total welfare.

SO vs. CS Without Vaccination

Results discussed first compare the strategies SO without vaccination and CS without vaccination. Every simulated scenario resulted in a decline in the market price for beef, ranging from an 8.095% decline to a 40.895% decline as shown in Table 3. For beef cattle, the average reduction in market price for SO without vaccination (-18.425%) could result in an approximately $2.795 billion loss in the value of beef supply. Using the average beef price loss under the CS without vaccination (-18.954%), results in a potential $2.889 billion loss in value from a decline in market prices. This reflects a $94.297 million beef industry value loss difference between the two scenarios with the greater loss stemming from the CS without vaccination strategy. When comparing the impact from loss of market price for hogs between scenarios, there is a difference of $40.013 million between SO and CS strategies without vaccination, with the economic costs favoring the SO without vaccination again. These results indicate that, in these simulations, the supply shocks were more than outweighed by the trade bans, increasing domestic supply and pushing down prices. In these simulations, saving viable protein may well have exacerbated the oversupply of protein on the domestic market associated with a reduction in exports and pushed prices lower. It is important to consider though the overall burden of the outbreak to society and that lower economic losses in implementing a SO strategy may be negated by the response costs of executing SO in large feedlots.

Comparing the same scenarios, SO without vaccination and CS without vaccination, the effect of potential trade bans can be further examined with the results associated with changes in the U.S. quantity supplied. The value of U.S. quantity supplied declined for beef cattle, dairy cattle, hogs, and sheep. With a CS strategy, the longevity of trade bans could be lengthened as the allowance of the disease to burn through feedlots of greater than 35,000 head may create an additional burden proving disease freedom among exporters or they may expand regionalized trade bans to national ones – a scenario that was not explored in detail in this study. The average value of U.S. beef cattle supply declines by 13.563% for SO without vaccination, a $2.09 billion loss of value for the beef cattle industry. CS without vaccination results in a potential $2.16 billion loss of U.S. beef cattle supply value, a $70 million difference between the two strategies.

While susceptible species such as cattle, hogs, and sheep saw declines in value of U.S. quantity supplied, poultry, as a substitute protein, increased by an average 1.800% for SO without vaccination and 1.876% for CS without vaccination. Under CS without vaccination, this change could result in a $303.62 million dollar increase in the value of all U.S. poultry at market prices. This model does not capture a change in consumer’s preferences for the protein substitute (i.e. demand), but instead may capture that either a greater quantity demanded is desired or the market price for poultry increases.

Continuing the comparison between SO and CS without vaccination but shifting the discussion to the crop sector, as the supply of animals decline, the demand for feed declines as well. This results in the decline of market prices witnessed across all scenarios for coarse grains and oilseeds. This loss in value can also be reflected in the total value of supply for coarse grains. Using coarse grains for discussion, for SO and CS strategies, the loss in animal supply results in close to a potential $1 billion loss in the value of total coarse grain supply.

SO vs. CS with Vaccination

Similar comparisons can be made between other scenarios including vaccination scenarios for both SO and CS. As previously mentioned, both scenarios resulted in a decline in the market price. For SO with vaccination, the market price declined by an average of 18.171% out of 150 iterations. This equates to a $2.87 billion loss in the value of beef supply from a loss of market price. The CS with vaccination strategy results in a $2.75 billion loss in the value of beef supply. Similar to strategies without vaccination, CS with vaccination results in a $115 million greater loss than SO with vaccination. However, there is still considerable question as to if this reduction in loss of value would be negated by depopulation and vaccination response costs.

Comparing the same scenarios, similar results were found when examining potential impacts from the trade bans on the value of quantity supplied. Implementing CS with vaccination results in a potential loss of $94.958 million more in the value of U.S. beef supply compared to SO with vaccination. It is important to note that this analysis examines the impacts of only the first 365 days of the FMD outbreak. With a CS with vaccination strategy implemented, it is likely that the longevity of trade bans may extend past this 365-day mark, resulting in a larger difference between CS and SO than mentioned above. Although the strategy of SO may produce logistical and resource concerns, it is necessary to consider the possibility of larger economic losses by loss of trade on top of those resource burdens with implementing vaccination.

SO Without vaccination vs. CS With Vaccination

Comparing SO without vaccination to CS with vaccination is necessary as these two strategies demonstrate two potential objectives of strategy response. Although both strategies' goal is to effectively eradicate the disease in a timely manner, SO without vaccination may provide the strategy that provides the U.S. with the fastest return to international trade markets while CS with vaccination provides the U.S. a conservative approach to handling an outbreak under resource constraints. Both strategies have tradeoffs that must be taken into consideration.

When discussing the value of quantity supplied for beef cattle, CS with vaccination results in a 14.010% loss in the value of beef cattle. This loss is $68.795 million more compared to SO without vaccination. When comparing the loss in value from a decline of market prices for beef, CS with vaccination leads to a loss of $141 million more than SO without vaccination. Although for each comparison CS has led to greater initial economic losses in value, regardless of the strategies compared, it is important to consider and account for the costs necessary to properly execute SO or vaccination which may negate the difference between any two arguing strategies.

Limitations and Further Extensions

Two limiting factors are not considered for the analysis of CS. For CS strategies, a fairly large assumption is made that there are processors in an FMD-infected geographic area willing to accept FMD-recovered cattle. The second discussion or potential not considered in this analysis is the possibility that with a CS strategy, the government may have to purchase meat from recovered cattle or pay to ensure the safe processing of CS meat. Although both are essential factors, it is not possible to know the exact repercussions of such an outbreak in a hypothetical event. Uncertainties, such as the two mentioned above, give clear reasoning for having several possible response strategies in place before the occurrence of a real outbreak.

Another limitation of this study is regarding the longevity of FMD economic impacts. For the livestock industry, especially the beef industry, it could take multiple years to completely adjust to the shock of an animal disease outbreak. Impacts on the production cycle, as well as, extended trade bans can easily flow into a second year of adjustments. This model only estimates the FMD outbreak’s impact in the first year, or 365 days, after the initial confirmed case. With this said, it is acknowledged that this model would serve of greater benefit to the interested audience if dynamics were included. Therefore, it is determined a dynamic component will be added to the PEDM at a later date to include additional year impacts of an FMD outbreak.

Conclusion

The U.S. had been FMD since 1929 and livestock are highly susceptible to an outbreak. It is imperative that strategic response plans are in place before the confirmation of an outbreak occurs. Various policies are considered when determining the best control strategy to eradicate an outbreak of such an infectious disease. The key response strategy is currently SO to eradicate the disease in a timely manner and as quickly as possible regain trade access. However, SO can significant financial costs as the method is laborious and requires significant logistical planning. Under constrained resources for eradication, infected large scale animal feeding operations can slow response. One option for response is controlled slaughter which allows FMD recovered livestock to reenter the supply chain. However, the economic consequences of this strategy include additional trade bans and potential consumer avoidance. When determining a strategic response plan, the U.S. must decide if the financial burden of an eradication strategy, such as SO, outweighs the economic costs of alternative eradication strategies that could postpone possible recovery of the agriculture industry on the world market.

A PEDM can provide a thorough economic framework which accounts for the interactions and dependencies of commodities across various agricultural industries when exogenous shocks are introduced into the economy. This model's goal is to simulate the effects of an animal disease outbreak, specifically FMD, on the U.S. agricultural industry in terms of supply and trade shocks. The goal of this analysis is to estimate the short-run changes in equilibrium prices and quantities for the livestock and crop sector, which are a result from loss of supply due to disease eradication and assumed trade bans placed on the U.S. upon identification of FMD. This PEDM incorporates supply shocks and trade shocks as the percentages lost in the value of supply and exports and accounts for the relationships between inputs and commodities, and the substitutability among meat demands.

As previous research has concluded, regardless of control strategy, an outbreak of FMD in the U.S. can have disastrous economic implications with widespread economic consequences stemming largely from the effects of trade bans. Typical control strategies involve the immediate depopulation of infected premises, and allowance for controlled slaughter strategies could result in upwards of $4 billion loss in value of beef cattle supply. Although the logistical concerns of implementing a completing stamping-out strategy create extensive costs and feasibility problems, the economic costs of implementing a controlled marketing may need to be considered given the loss of value in supply when animals are kept alive that can no longer be exported or are demanded.

REFERENCES

Breeze, R. 2004. “Agroterrorism: betting far more than the farm.” *Biosecurity and Bioterrorism: biodefense strategy, practice, and science.* 2:251–264.

Carpenter, T.E., L.E. Christiansen, B.F. Dickey, C. Thunes, and P.J. Hullinger. 2007. “Potential impact of an introduction of foot-and-mouth disease into the California State Fair.” *Journal of American Veterinary Medical Association* 231(8):1231-1235.

Cabezas, A.H., N.J. Mapitse, P. Tizzani, M.J. Sanchez-Vazquez, M. Stone, and M.K. Park. 2022. “Analysis of suspensions and recoveries of official foot and mouth disease free status of WOAH Members between 1996 and 2020. *Frontiers in Veterinary Science, 9.*

Coffey, B., Mintert, J., Fox, J.A., Schroeder, T.C. and Valentin, L., 2005. “The economic impact of BSE on the US beef industry: product value losses, regulatory costs, and consumer reactions.”

Ekboir, JM. 1999. “Potential Impact of Foot-and-Mouth Disease in California.” *Agricultural Issues Center, Division of Agriculture and Natural Resources, University of California.*

Federation of American Scientists (FAS). 2011. “Economic Impact of FMD Outbreaks.” Available online at: https://biosecurity.fas.org/education/dualuse-agriculture/1.-agroterrorism-and-foodsafety/economic-impact-of-fmd-outbreaks.html (Accessed November 15, 2022).

Graves, JH. 1979. “Foot-and-mouth disease: a constant threat to US livestock.” *Journal of American Veterinary Medical Association.* 174:174-176.

Hagerman, A.D., B.A. McCarl, and J. Mu. 2010. “Economic Impact of a Livestock Attack.” *Wiley Handbook of Science and Technology for Homeland Security*. pp. 1-11.

Hayes, D.J., J.F. Fabiosa, A. Elobeid, and M. Carriquiry. 2011. “Economy Wide Impacts of a Foreign Animal Disease in the United States (No. 11-wp525)”. Center for Agricultural and Rural Development (CARD) at Iowa State University.

Hertel, T.W. 1989. “Negotiating reductions in agricultural support: Implications of technology and factor mobility.” *American Journal of Agricultural Economics*, 71(3):559-573.

Huang, C.C., M.H. Jong, and S.Y. Lin. 2000. “Characteristics of foot and mouth disease virus in Taiwan. *Journal of Veterinary Medical Science.* 62(7):677-679.

Junker, F., J. Komorowska, and F. van Tongeren. 2009. “Impact of Animal Disease Outbreaks and Alternative Control Practices on Agricultural Markets and Trade: The case of FMD”, *OECD Food, Agriculture and Fisheries Working Papers,* No. 19, OECD

Knight-Jones, T.J. and J. Rushton. 2013. “The Economic Impacts of Foot and Mouth Disease – What are they, how big are they and where do they occur?” *Preventive Veterinary Medicine.* 112(3-4):161-173.

Martin, R. and P. Sunley. 2015. “On the notion of regional economic resilience: conceptualization and explanation.” *Journal of economic geography*. 15(1):1-42.

McReynolds, S.W., and M.W. Sanderson. 2014. “Feasibility of depopulation of a large feedlot during a foot-and-mouth disease outbreak.” *Journal of the American Veterinary Medical Association.* 244(3): 291-298.

Musser, J.M.B. 2004. “A practitioner’s primer on foot-and-mouth disease.” *Journal of the American Veterinary Medical Association.* 224(8): 1261-1268.

Muth, R.F. 1964. “The Derived Demand Curve for a Productive Factor and the Industry Supply Curve.” *Oxford Economic Papers.* 16(2):221-234.

OECD (Organisation for Economic Co-operation and Development). 2001. *Market Effects of Crop Support Measures.* Paris: OECD.

Paarlberg PL, J.G. Lee, and A.H. Seitzinger. 2002. “Potential revenue impact of an outbreak of foot-and- mouth disease in the United States.” *Journal of American Veterinary Medical Assoc*. 220(7): 988–992.

Pendell, D.L., J. Leatherman, T.C. Schroeder, and G.S. Alward. 2007. “The economic impacts of a foot-and-mouth disease outbreak: a regional analysis.” *Journal of Agricultural and Applied Economics*. 39(1):19-33.

Rault, A., and S. Krebs. 2011. “Livestock epidemics and catastrophic risk management. State of the art and prospects on economic dynamics. In 13. *EAAE Congress*.” *Change and Uncertainty Challenges for Agriculture, Food and Natural Resources.* pp. 12.

Schroeder, T.C., D.L. Pendell, M.W. Sanderson, and S. Mcreynolds. 2015. “Economic impact of alternative FMD emergency vaccination strategies in the midwestern United States.” *Journal of Agricultural and Applied Economics*, 47(1): 47-76.

Stevenson, M.A., R.I.Sanson, M.W. Stern, B.D. O’Leary, M. Sujau, N. Moles-Benfell, and R.S. Morris. 2013. “InterSpread Plus: a spatial and stochastic simulation model of disease in animal populations.” *Preventive Veterinary Medicine* 109: 10-24.

Thompson, D., P. Muriel, D. Russell, P. Osborne, A. Bromley, M. Rowland, S. Creigh-Tyte, and C. Brown. 2002. "Economic costs of the foot and mouth disease outbreak in the United Kingdom in 2001." *Revue scientifique et technique (International Office of Epizootics)* 21(3): 675-687.

Thornton, P.K., R.I. Kruska, N. Henninger, P.M. Kristjanson, R.S. Reid, F. Atieno, A. Odero, and T. Ndegwa. 2002. “Mapping Poverty and Livestock in the Developing World. International Livestock Research Institute. Nairobi, Kenya. Pp 124.

Ward, M.P., L.D. Highfield, P. Vongseng, and M.G. Garner. 2009. Simulation of foot-and-mouth disease spread within an integrated livestock system in Texas, USA. *Preventive veterinary medicine*. *88*(4): 286-297.

Yang, P.C., R.M. Chu, W.B. Chung, and H.T. Sung. 1999. “Epidemiological characteristics and financial costs of the 1997 foot-and-mouth disease epidemic in Taiwan.” *Veterinary Record*, 145(25):731-734.

Tables

Table 3.1 Number of Infected States by Scenario[a].

	Average	Minimum	Maximum
Baseline_NOVX[b]	4	1	20
Baseline_VX[b]	4	1	14
CS_NOVX[b]	4	1	16
CS_VX[b]	4	1	16

[a] Results estimated after 150 iterations of each scenario.
[b] Baseline_NOVX=Depopulation with no vaccination; Baseline_VX=Depopulation with vaccination; CS_NOVX=Controlled slaughter with no vaccination; CS_VX=controlled slaughter with vaccination.

Table 3.2 Duration of Outbreak (Days)[a].

	Average	Minimum	Maximum
SO_NOVX[b]	110	69	348
SO_VX[b]	104	69	201
CS_NOVX[b]	102	57	458
CS_VX[b]	96	55	264

[a] Results estimated after 150 iterations of each scenario.
[b] SO_NOVX=Depopulation with no vaccination; SO_VX=Depopulation with vaccination; CS_NOVX=Controlled slaughter with no vaccination; CS_VX=controlled slaughter with vaccination.

Table 3.3 Scenario Results for Beef Cattle Sector.

	SO_NoVX[a]					
	MktPrice[b]	ROWPrice[b]	USQD[c]	USQS[c]	ROWQD[c]	ROWQS[c]
Beef Cattle						
Average	-18.425%	-07.715%	+09.154%	-13.563%	-02.016%	+00.179%
Max	-40.895%	+15.097%	+17.692%	-28.591%	-03.697%	+00.305%
Min	-08.112%	+03.572%	+04.241%	-05.963%	-00.565%	-00.565%
	SO_VX[a]					
	MktPrice[b]	ROWPrice[b]	USQD[c]	USQS[c]	ROWQD[c]	ROWQS[c]
Beef Cattle						
Average	-18.171%	+07.606%	+09.044%	-13.393%	-01.994%	+00.179%
Max	-32.308%	+12.005%	+15.190%	-23.228%	-03.114%	+00.305%
Min	-08.112%	+03.572%	+04.241%	-05.962%	-00.941%	-00.112%
	CS_NoVX[a]					
	MktPrice[b]	ROWPrice[b]	USQD[c]	USQS[c]	ROWQD[c]	ROWQS[c]
Beef Cattle						
Average	-18.954%	+07.946%	+09.379%	-14.020%	-02.061%	+00.170%
Max	-34.854%	+12.101%	+15.575%	-24.822%	-03.025%	+00.323%
Min	-08.095%	+03.624%	+04.069%	-06.052%	-00.878%	-00.206%
	CS_VX[a]					
	MktPrice[b]	ROWPrice[b]	USQD[c]	USQS[c]	ROWQD[c]	ROWQS[c]
Beef Cattle						
Average	-18.918%	+07.943%	+09.382%	-14.010%	-02.073%	+00.178%
Max	-40.524%	+16.447%	+19.600%	-29.574%	-04.086%	+00.419%
Min	-08.095%	+03.625%	+04.098%	-06.053%	-00.878%	-00.192%

[a] SO_NOVX=Depopulation with no vaccination; SO_VX=Depopulation with vaccination; CS_NOVX=Controlled slaughter with no vaccination; CS_VX=controlled slaughter with vaccination.

[b] MktPrice=Market Price; ROWPrice=World Price.

[c] USQD=U.S. Quantity Demanded; USQS=U.S. Quantity Supplied; ROWQD=World Quantity Demanded; ROWQS=World Quantity Supplied.

Table 3.4 Scenario Results for Dairy Cattle Sector.

	SO_NoVX					
	MktPrice[b]	ROWPrice[b]	USQD[c]	USQS[c]	ROWQD[c]	ROWQS[c]
Dairy						
Average	-06.106%	+02.419%	+00.286%	-00.739%	-00.057%	+00.640%
Max	-17.622%	+35.974%	+01.684%	-00.216%	+00.006%	+01.640%
Min	-02.429%	-01.514%	-00.229%	-02.954%	-00.838%	+00.183%
	SO_VX					
	MktPrice[b]	ROWPrice[b]	USQD[c]	USQS[c]	ROWQD[c]	ROWQS[c]
Dairy						
Average	-06.030%	+02.441%	+00.270%	-00.736%	-00.054%	+00.641%
Max	-12.742%	+25.074%	+00.847%	-00.216%	00.006%	+01.667%
Min	-02.430%	-01.514%	-00.410%	-02.346%	-00.403%	+00.233%
	CS_NoVX					
	MktPrice[b]	ROWPrice[b]	USQD[c]	USQS[c]	ROWQD[c]	ROWQS[c]
Dairy						
Average	-06.373%	+02.940%	+00.321%	-00.782%	-00.070%	+00.657%
Max	-14.295%	+26.181%	+01.774%	-00.216%	+00.006%	+01.698%
Min	-02.440%	-02.017%	-00.150%	-02.553%	-00.462%	+00.139%
	CS_VX					
	MktPrice[b]	ROWPrice[b]	USQD[c]	USQS[c]	ROWQD[c]	ROWQS[c]
Dairy						
Average	-06.339%	+02.780%	+00.297%	-00.778%	-00.063%	+00.668%
Max	-14.284%	+21.143%	+00.957%	-00.216%	+00.006%	+01.574%
Min	-02.440%	-01.524%	-00.172%	-02.082%	-00.377%	+00.139%

[a] SO_NOVX=Depopulation with no vaccination; SO_VX=Depopulation with vaccination; CS_NOVX=Controlled slaughter with no vaccination; CS_VX=controlled slaughter with vaccination.

[b] MktPrice=Market Price; ROWPrice=World Price.

[c] USQD=U.S. Quantity Demanded; USQS=U.S. Quantity Supplied; ROWQD=World Quantity Demanded; ROWQS=World Quantity Supplied.

Table 3.5 Scenario Results for Hog Sector.

	SO_NoVX					
	MktPrice[b]	ROWPrice[b]	USQD[c]	USQS[c]	ROWQD[c]	ROWQS[c]
Hogs						
Average	-06.116%	+01.317%	+02.899%	-00.987%	-00.177%	+00.451%
Max	-34.077%	+28.073%	+21.690%	-+16.569%	00.450%	+01.661%
Min	-01.848%	-00.419%	-01.409%	+03.515%	-08.376%	-04.243%
	SO_VX					
	MktPrice[b]	ROWPrice[b]	USQD[c]	USQS[c]	ROWQD[c]	ROWQS[c]
Hogs						
Average	-05.827%	+01.188%	+02.696%	-00.818%	-00.130%	+00.407%
Max	-15.982%	+11.774%	+09.449%	-06.495%	-00.450%	+01.354%
Min	-01.848%	-00.419%	-01.604%	+03.419%	-03.119%	-04.237%
	CS_NoVX					
	MktPrice[b]	ROWPrice[b]	USQD[c]	USQS[c]	ROWQD[c]	ROWQS[c]
Hogs						
Average	-06.718%	+01.785%	+03.308%	-01.299%	-00.321%	+00.438%
Max	-26.913%	+15.724%	+18.971%	-14.838%	-00.461%	+03.196%
Min	-01.773%	-00.421%	-00.576%	+02.896%	-05.205%	-03.245%
	CS_VX					
	MktPrice[b]	ROWPrice[b]	USQD[c]	USQS[c]	ROWQD[c]	ROWQS[c]
Hogs						
Average	-06.374%	+01.507%	+03.038%	-01.053%	-00.224%	+00.421%
Max	-18.966%	+09.974%	+10.602%	-06.490%	-02.618%	+01.695%
Min	-01.773%	-00.421%	-00.331%	+02.680%	+00.461%	-02.883%

[a] SO_NOVX=Depopulation with no vaccination; SO_VX=Depopulation with vaccination; CS_NOVX=Controlled slaughter with no vaccination; CS_VX=controlled slaughter with vaccination.

[b] MktPrice=Market Price; ROWPrice=World Price.

[c] USQD=U.S. Quantity Demanded; USQS=U.S. Quantity Supplied; ROWQD=World Quantity Demanded; ROWQS=World Quantity Supplied.

Table 3.6 Scenario Results for Sheep Sector.

	SO_NoVX					
	MktPrice[b]	ROWPrice[b]	USQD[c]	USQS[c]	ROWQD[c]	ROWQS[c]
Sheep						
Average	-06.944%	+01.272%	+00.869%	-01.023%	+00.068%	+00.072%
Max	+00.426%	+06.393%	+10.730%	+02.026%	+01.547%	+01.583%
Min	-40.652%	-04.759%	-01.269%	-15.231%	-00.364%	-00.361%
	SO_VX					
	MktPrice[b]	ROWPrice[b]	USQD[c]	USQS[c]	ROWQD[c]	ROWQS[c]
Sheep						
Average	-06.744%	+01.152%	+00.824%	-00.958%	+00.083%	+00.087%
Max	+00.426%	+04.643%	+10.123%	+02.026%	+01.540%	+01.595%
Min	-33.456%	-04.656%	-01.269%	-14.349%	-00.302%	-00.294%
	CS_NoVX					
	MktPrice[b]	ROWPrice[b]	USQD[c]	USQS[c]	ROWQD[c]	ROWQS[c]
Sheep						
Average	-07.412%	+01.411%	+00.981%	-01.171%	+00.067%	+00.072%
Max	+00.430%	+09.993%	+11.220%	+02.739%	+01.228%	+01.268%
Min	-39.055%	-003.322%	-01.644%	-15.909%	-01.061%	-01.066%
	CS_VX					
	MktPrice[b]	ROWPrice[b]	USQD[c]	USQS[c]	ROWQD[c]	ROWQS[c]
Sheep						
Average	-07.312%	+01.288%	+00.956%	-01.134%	+00.081%	+00.086%
Max	+00.430%	+04.476%	+08.822%	+02.047%	+01.194%	+01.232%
Min	-32.221%	-03.072%	-01.274%	-12.746%	-00.398%	-00.402%

[a] SO_NOVX=Depopulation with no vaccination; SO_VX=Depopulation with vaccination; CS_NOVX=Controlled slaughter with no vaccination; CS_VX=controlled slaughter with vaccination.

[b] MktPrice=Market Price; ROWPrice=World Price.

[c] USQD=U.S. Quantity Demanded; USQS=U.S. Quantity Supplied; ROWQD=World Quantity Demanded; ROWQS=World Quantity Supplied.

Table 3.7 Scenario Results for Poultry Sector.

	SO_NoVX[a]					
	MktPrice[b]	ROWPrice[b]	USQD[c]	USQS[c]	ROWQD[c]	ROWQS[c]
Poultry						
Average	-00.537%	-00.537%	-00.971%	+01.800%	+00.471%	+00.429%
Max	+04.066%	+04.066%	-00.107%	+07.188%	+00.730%	+00.662%
Min	-01.073%	-01.073%	-10.472%	+00.712%	-00.482%	-00.724%
	SO_VX[a]					
	MktPrice[b]	ROWPrice[b]	USQD[c]	USQS[c]	ROWQD[c]	ROWQS[c]
Poultry						
Average	-00.562%	-00.562%	-00.904%	+01.759%	+00.473%	+00.433%
Max	+00.839%	+00.839%	-00.107%	+04.289%	+00.723%	+00.662%
Min	-01.073%	-01.073%	-04.664%	00.712%	+00.111%	+00.047%
	CS_NoVX[a]					
	MktPrice[b]	ROWPrice[b]	USQD[c]	USQS[c]	ROWQD[c]	ROWQS[c]
Poultry						
Average	-00.463%	-00.463%	-01.134%	+01.918%	+00.462%	+00.416%
Max	+02.831%	+02.831%	-00.104%	+04.499%	+00.714%	+00.658%
Min	-01.083%	-01.083%	-05.648%	+00.716%	-00.383%	-00.525%
	CS_VX[a]					
	MktPrice[b]	ROWPrice[b]	USQD[c]	USQS[c]	ROWQD[c]	ROWQS[c]
Poultry						
Average	-00.529%	-00.529%	-01.038%	+01.876%	+00.478%	+00.436%
Max	+00.817%	+00.817%	-00.104%	+04.735%	+00.942%	+00.873%
Min	-01.200%	-01.200%	-04.664%	+00.716%	-00.030%	-0.081%

[a] SO_NOVX=Depopulation with no vaccination; SO_VX=Depopulation with vaccination; CS_NOVX=Controlled slaughter with no vaccination; CS_VX=controlled slaughter with vaccination.

[b] MktPrice=Market Price; ROWPrice=World Price.

[c] USQD=U.S. Quantity Demanded; USQS=U.S. Quantity Supplied; ROWQD=World Quantity Demanded; ROWQS=World Quantity Supplied.

Table 3.8 Scenario Results for Coarse Grains Sector.

	SO_NoVX[a]					
	MktPrice[b]	ROWPrice[b]	USQD[c]	USQS[c]	ROWQD[c]	ROWQS[c]
Coarse Grains						
Average	-05.519%	-05.519%	01.728%	-01.259%	-00.427%	-00.124%
Max	-13.658%	-13.658%	04.279%	-03.081%	-01.052%	-00.311%
Min	-02.353%	-02.353%	00.737%	-00.539%	-00.182%	-00.052%
	SO_VX[a]					
	MktPrice[b]	ROWPrice[b]	USQD[c]	USQS[c]	ROWQD[c]	ROWQS[c]
Coarse Grains						
Average	-05.443%	-05.443%	01.704%	-01.242%	-00.421%	-00.122%
Max	-10.270%	-10.270%	03.217%	-02.334%	-00.793%	-00.231%
Min	-02.353%	-02.353%	00.737%	-00.539%	-00.182%	-00.052%
	CS_NoVX[a]					
	MktPrice[b]	ROWPrice[b]	USQD[c]	USQS[c]	ROWQD[c]	ROWQS[c]
Coarse Grains						
Average	-05.735%	-05.735%	01.796%	-01.306%	-00.443%	-00.129%
Max	-11.034%	-11.034%	03.455%	-02.520%	-00.854%	-00.247%
Min	-02.381%	-02.381%	00.746%	-00.543%	-00.184%	-00.053%
	CS_VX[a]					
	MktPrice[b]	ROWPrice[b]	USQD[c]	USQS[c]	ROWQD[c]	ROWQS[c]
Coarse Grains						
Average	-05.711%	-05.711%	01.788%	-01.301%	-00.442%	-00.128%
Max	-12.483%	-12.483%	03.909%	-02.838%	-00.965%	-00.281%
Min	-02.381%	-02.381%	00.746%	-00.543%	-00.184%	-00.053%

[a] SO_NOVX=Depopulation with no vaccination; SO_VX=Depopulation with vaccination; CS_NOVX=Controlled slaughter with no vaccination; CS_VX=controlled slaughter with vaccination.

[b] MktPrice=Market Price; ROWPrice=World Price.

[c] USQD=U.S. Quantity Demanded; USQS=U.S. Quantity Supplied; ROWQD=World Quantity Demanded; ROWQS=World Quantity Supplied.

Table 3.9 Scenario Results for Oilseeds Sector.

	SO_NoVX[a]					
	MktPrice[b]	ROWPrice[b]	USQD[c]	USQS[c]	ROWQD[c]	ROWQS[c]
Oilseeds						
Average	-02.090%	-02.090%	00.440%	01.650%	00.513%	00.234%
Max	-05.169%	-05.169%	01.086%	04.040%	01.262%	00.581%
Min	-00.891%	-00.891%	00.188%	00.706%	00.219%	00.100%
	SO_VX[a]					
	MktPrice[b]	ROWPrice[b]	USQD[c]	USQS[c]	ROWQD[c]	ROWQS[c]
Oilseeds						
Average	-02.061%	-02.061%	00.434%	01.627%	00.506%	00.231%
Max	-03.888%	-03.888%	00.818%	03.058%	00.953%	00.436%
Min	-00.891%	-00.891%	00.188%	00.706%	00.219%	00.100%
	CS_NoVX[a]					
	MktPrice[b]	ROWPrice[b]	USQD[c]	USQS[c]	ROWQD[c]	ROWQS[c]
Oilseeds						
Average	-02.171%	-02.171%	00.457%	01.711%	00.533%	00.244%
Max	-04.177%	-04.177%	00.880%	03.301%	01.026%	00.469%
Min	-00.902%	-00.902%	00.190%	00.711%	00.221%	00.101%
	CS_VX[a]					
	MktPrice[b]	ROWPrice[b]	USQD[c]	USQS[c]	ROWQD[c]	ROWQS[c]
Oilseeds						
Average	-02.162%	-10.872%	00.455%	01.705%	00.533%	00.243%
Max	-04.726%	-04.726%	00.995%	03.719%	01.158%	00.530%
Min	-00.902%	-00.902%	00.190%	00.711%	00.221%	00.101%

[a] SO_NOVX=Depopulation with no vaccination; SO_VX=Depopulation with vaccination; CS_NOVX=Controlled slaughter with no vaccination; CS_VX=controlled slaughter with vaccination.

[b] MktPrice=Market Price; ROWPrice=World Price.

[c] USQD=U.S. Quantity Demanded; USQS=U.S. Quantity Supplied; ROWQD=World Quantity Demanded; ROWQS=World Quantity Supplied.

Table 3.10 Scenario Results for Wheat Sector.

	SO_NoVX[a]					
	MktPrice[b]	ROWPrice[b]	USQD[c]	USQS[c]	ROWQD[c]	ROWQS[c]
Wheat						
Average	-01.810%	-01.810%	-00.408%	02.339%	-00.045%	-00.274%
Max	-04.469%	-04.469%	-01.013%	05.802%	-00.109%	-00.678%
Min	-00.772%	-00.772%	-00.174%	00.997%	-00.019%	-00.117%
	SO_VX[a]					
	MktPrice[b]	ROWPrice[b]	USQD[c]	USQS[c]	ROWQD[c]	ROWQS[c]
Wheat						
Average	-01.785%	-01.785%	-00.402%	02.307%	-00.044%	-00.271%
Max	-03.365%	-03.365%	-00.760%	04.359%	-00.083%	-00.510%
Min	-00.772%	-00.772%	-00.174%	00.997%	-00.019%	-00.117%
	CS_NoVX[a]					
	MktPrice[b]	ROWPrice[b]	USQD[c]	USQS[c]	ROWQD[c]	ROWQS[c]
Wheat						
Average	-01.880%	-01.880%	-00.424%	02.431%	-00.047%	-00.285%
Max	-03.619%	-03.619%	-00.815%	04.683%	-00.089%	-00.549%
Min	-00.781%	-00.781%	-00.176%	01.009%	-00.019%	-00.118%
	CS_VX[a]					
	MktPrice[b]	ROWPrice[b]	USQD[c]	USQS[c]	ROWQD[c]	ROWQS[c]
Wheat						
Average	-01.872%	-01.872%	-00.422%	02.421%	-0.046%	-0.284%
Max	-04.091%	-04.091%	-00.924%	05.294%	-0.101%	-0.621%
Min	-00.781%	-00.781%	-00.176%	01.009%	-0.019%	-0.118%

[a] SO_NOVX=Depopulation with no vaccination; SO_VX=Depopulation with vaccination; CS_NOVX=Controlled slaughter with no vaccination; CS_VX=controlled slaughter with vaccination.

[b] MktPrice=Market Price; ROWPrice=World Price.

[c] USQD=U.S. Quantity Demanded; USQS=U.S. Quantity Supplied; ROWQD=World Quantity Demanded; ROWQS=World Quantity Supplied.

VITA

Tori Lee Marshall

Candidate for the Degree of

Doctor of Philosophy

Dissertation: AGRICULTURAL FIRM RESILIENCE TO DISASTERS DOMESTICALLY AND ABROAD: APPLICATIONS IN ANIMAL HEALTH

Major Field: AGRICULTURAL ECONOMICS

Biographical:

Education:

Completed the requirements for the Doctor of Philosophy in Agricultural Economics at Oklahoma State University, Stillwater, Oklahoma in December, 2022.

Completed the requirements for the Master of Science in Agricultural Economics at Mississippi State University, Starkville, Mississippi in 2019.

Completed the requirements for the Bachelor of Science in Agriculture at Tennessee Tech University, Cookeville, Tennessee in 2017.

Experience: Farm Management Specialist-University of Tennessee

Professional Memberships: Agricultural and Applied Economics Association (AAEA); Southern Agricultural Economics Association (SAEA)