



**AgEcon** SEARCH  
RESEARCH IN AGRICULTURAL & APPLIED ECONOMICS

*The World's Largest Open Access Agricultural & Applied Economics Digital Library*

**This document is discoverable and free to researchers across the globe due to the work of AgEcon Search.**

**Help ensure our sustainability.**

Give to AgEcon Search

AgEcon Search

<http://ageconsearch.umn.edu>

[aesearch@umn.edu](mailto:aesearch@umn.edu)

*Papers downloaded from **AgEcon Search** may be used for non-commercial purposes and personal study only. No other use, including posting to another Internet site, is permitted without permission from the copyright owner (not AgEcon Search), or as allowed under the provisions of Fair Use, U.S. Copyright Act, Title 17 U.S.C.*

*No endorsement of AgEcon Search or its fundraising activities by the author(s) of the following work or their employer(s) is intended or implied.*

# Alternative Foot-and-Mouth Disease Eradication Strategies in a Large Feedlot Under Resource Limitations

Logan L. Britton, Amy D. Hagerman, Sarah R. Mielke,  
Columb P. Rigney, and Amy H. Delgado

Response to animal disease has importance for domestic supply and demand, trade implications, and other economic factors. Stamping out is effective at eradicating disease but requires resource investments that may be prohibitive in large-scale animal production systems. Alternative management strategies in a 50,000-head cattle feedlot are examined. Sample feedlot and epidemiological data are utilized for a discrete programming model. We analyze 14 scenarios across five management strategies under stochastic cattle prices and static disease management costs. Results show that targeted depopulation is a preferred method for the overall feedlot.

*Key words:* agricultural policy, animal health, disease response, livestock economics, simulation model, supply chain

## Introduction

Food and agriculture industries may face significant challenges in the coming decades as the world population is expected to reach over 9 billion by 2050 (Hemathilake and Gunathilake, 2022). Population increases lead to increases in food demand, including for animal protein. Agricultural productivity must increase to match this food demand, but industries face barriers to growth associated with climate change, food waste and inefficiencies, and depleting natural resources. In addition to these challenges, plant and animal diseases are a threat to the food system and financial viability of food producers and processors and ultimately consumers. The burden of animal and plant disease has economic and social dimensions, including food safety and security, consumer confidence in the food supply, animal welfare, damages and losses to animals and crops, international trade restrictions, and changes in food prices (Wilkinson et al., 2011; Espinosa, Tago, and Treich, 2020; Ristaino et al., 2021).

Foot-and-mouth disease (FMD) is a highly contagious viral disease that affects cloven-hoofed animals including cattle, swine, small ruminants, and wildlife ungulates.<sup>1</sup> The disease often causes high morbidity in susceptible livestock species, which results in respiratory problems and

Logan L. Britton (corresponding author, lbritton@ksu.edu) is an assistant professor in the Department of Agricultural Economics at Kansas State University. Amy D. Hagerman is an associate professor in the Department of Agricultural Economics at Oklahoma State University. Sarah R. Mielke is a biological scientist and Columb P. Rigney and Amy H. Delgado are veterinary epidemiologists in the USDA Animal and Plant Health Inspection Service (APHIS) Veterinary Services Center for Epidemiology and Animal Health.

This work was supported by US Department of Agriculture Animal and Plant Health Inspection Service under co-operative agreement number AP19-VSCEAH-00C022. The conclusions and opinions are those of the authors and do not necessarily represent the policies of the US Department of Agriculture.

This work is licensed under a Creative Commons Attribution-NonCommercial 4.0 International License. 

Review coordinated by Fabio G. Santeramo.

<sup>1</sup> FMD infections from livestock to humans are very rare and mild (US Department of Agriculture, 2014), so FMD is not considered a zoonotic disease. Further, it is sometimes confused with hand, foot, and-mouth disease in humans, but the two are not related (Weir, 2001).

other physiological issues. Mortality rates are generally low in adult animals (US Department of Agriculture, 2015b, 2020a), but clinical disease reduces productivity. Experiences in FMD-endemic regions have shown the difficulty of eradication in animal populations after the disease has spread widely in the environment or wild animal populations (US Department of Agriculture, 2015b, 2020a). FMD outbreaks have occurred throughout time, with the earliest probable description coming from Venice, Italy, in 1514 (Jamal and Belsham, 2013). Outbreaks have varied in frequency and scale geographically over the past 5 centuries (Jamal and Belsham, 2013). Recent instances of FMD outbreaks—such as the 2001 United Kingdom outbreak, the 2010 Japan outbreak, and the 2010–2011 South Korea outbreaks—have had significant economic impacts, including market closures and substantial losses to the livestock industry (Jamal and Belsham, 2013). The 2001 UK outbreak resulted in the depopulation of 750,000 cattle and \$4.7 billion in losses to the food and agriculture sector alone (Thompson et al., 2002). The Japan and South Korea outbreaks saw 290,000 and 3.47 million animals slaughtered, respectively. The last recorded FMD outbreak in the United States was in 1929 (McCauley et al., 1979).

Given these impacts, many countries have strong prevention measures in place, including in the form of border controls and sanitary trade restrictions, and support disease eradication efforts in FMD-endemic countries. When first detected in a previously FMD-free country, the economic impacts are often significant, including market closures with trading partners (Paarlberg, Lee, and Seitzinger, 2003; Junker, Ilicic-Komorowska, and van Tongeren, 2009; Tozer, Marsh, and Perevodchikov, 2015), losses associated with disease containment (Zhao, Wahl, and Marsh, 2006; Pendell et al., 2007), and loss of consumer confidence in the livestock sector (Saghaian, Maynard, and Reed, 2007; Schroeder et al., 2015).

The USDA has focused on policies related to full herd depopulation as a response to FMD to mitigate losses and eradicate disease before it can spread widely (McReynolds and Sanderson, 2014). Depopulating an infected herd prevents the continued spread of the disease; when combined with quarantine and movement restrictions (US Department of Agriculture, 2015c), it is commonly referred to as a “stamping-out” strategy. Countries with commercial livestock enterprises—like the United States—experience additional challenges to eradication. Commercial livestock enterprises may include large dairies, cattle feeding operations for beef and dairy cattle, and large swine operations. These operations may include a relatively dense population of individuals from multiple species, creating conditions suitable for rapid or airborne spread. In addition, stamping out of FMD would require depopulation of all directly exposed animals on the operation. Large commercial operations would require large amounts of labor and other resources to achieve stamping out in a reasonably short timeframe. Emergency response to contain FMD in large commercial operations could slow overall response due to labor and equipment resource constraints, disposal capacity for approved methods, and environmental management.

This paper focuses on the challenges posed by highly contagious disease eradication in confined feeding operations by examining FMD response in a large-scale cattle feedlot. In previous studies, the costs associated with FMD management have been estimated to range from \$150 million up to \$188 billion for various sizes of feedlots at regional levels, which includes the economic impacts for implementing disease-containing strategies (Elbakidze et al., 2009; Ward et al., 2009; McReynolds and Sanderson, 2014; Schroeder et al., 2015). Most of the few studies that have examined FMD management strategies in large feedlots examined stamping out alone as a disease control measure (DeOtte and DeOtte, 2010). One recent exception, Yadav et al. (2022), examined eradication via emergency vaccination-to-live and concluded that this strategy may have animal welfare and resource allocation benefits, particularly in outbreaks with a higher dairy density. Yet, their results were less conclusive in feedlot regions of the United States and trade losses were more significant for the beef industry than for the dairy industry. In addition, these logistic and welfare benefits came at the cost of longer-term trade consequences and market losses, which offset most of the cost benefits associated with stamping-out alternatives. In addition, Mielke et al. (2023), which this paper builds on, explored the consequences of within-feedlot spread following stamping-out alternatives. They

found significant disease spread reductions when resources were *not* diverted to highly concentrated animal operations and animals were allowed to recover instead before moving them to slaughter for either disposal or alternative protein use.

There is a need to investigate the economic aspects of strategies that achieve eradication while reducing costs associated with depopulation and disposal. The economic losses to producers and taxpayer dollars under a stamping-out strategy warrant exploration given the potential for benefits from stamping-out alternatives explored in Yadav et al. (2022) and Mielke et al. (2023). Globally, significant FMD outbreaks controlled through livestock depopulation have resulted in detrimental effects on livestock inventories and recovery time (e.g., the Japanese FMD outbreak described in Muroga et al., 2012). As a result, countries with large and valuable livestock industries are exploring whether alternatives (e.g., controlled slaughter or targeted depopulation) possible (McReynolds and Sanderson, 2014; Schroeder et al., 2015; Miller et al., 2019). Yet these studies have not examined the possibility of allowing cattle to recover from the disease as a strategy. Subsequently, there is limited information on the feasibility and potential impacts of such alternative management strategies related to spread and financial losses along the beef supply chain.

By exploring the economic impacts of implementing alternative FMD management strategies in a sample large feedlot of 50,000 head in the United States, this study will fill that gap for the beef feeding sector. In this analysis, the recoverable feedlot operator profits and government on-farm response costs are estimated under alternative control scenarios, including the indemnity payments transferred from the government to operators. The alternatives are then compared to traditional stamping-out methods. Multiple strategies for alternative eradication are examined: full depopulation, targeted depopulation, and controlled slaughter. We observe that (i) targeted depopulation yields higher recoverable profits over alternative management strategies; (ii) controlled slaughter of recovered livestock has value as an alternative method for cattle in a high-price environment, and (iii) for cattle in some larger weight classes, depopulation is the better management strategy under this simulation.

### **Food-and-Mouth Disease Response**

Within the United States, studies have focused on the origination and introduction of foreign animal disease, especially FMD. Some studies have estimated economic losses for simulated regional FMD outbreaks in California, Texas, Kansas, and the Midwest. These costs have been estimated to range from \$789.9 million to \$13.5 billion (Ekboir et al., 2002; Schoenbaum and Terry Disney, 2003). Other studies have focused on at-risk industries, including the high-value cattle feeding sector. Pendell et al. (2007) simulated an FMD outbreak in southwest Kansas and the surrounding region. Economic losses were estimated to be larger when starting in large feedlots rather than in smaller scale feedlots or cow–calf operations.

Depopulation has been the preferred method of eradication by other countries that have had FMD outbreaks (Howard and Donnelly, 2000; Thompson et al., 2002; Jamal and Belsham, 2013; Knight-Jones and Rushton, 2013; Ito et al., 2019). It has also been the planned method of eradication for localized or regional outbreaks by the country's animal health authority, the USDA Animal and Plant Health Inspection Service (APHIS). Yet, all emergency response events begin with a state's animal health authority unless a national state of emergency is declared. This has led to collaborations between federal, state, and industry partners to develop an animal health responses policy that aims to eradicate FMD without causing excessive damage to the industry. Depending on the spread and severity of the disease in a geographical region, a stamping-out strategy along with movement restrictions may not be feasible given resource constraints. US animal health officials have considered vaccination as a disease management strategy if stamping out cannot contain the disease in a timely manner (Parent, Miller, and Hullinger, 2011). These factors create incentives for alternative responses to be considered and examined.

Regions that have dense large animal populations pose a challenge to stamping out. In the Texas Panhandle, with its high livestock population density, simulations of an FMD outbreak have been thoroughly studied. Given model assumptions and the study area, it was determined that an average outbreak lasting around 50 days and affecting about 100 herds would need to be depopulated to contain the disease (Ward et al., 2009). In the worst-case scenarios, the outbreak would last 8–9 months and require the depopulation of 230 herds when the disease was initiated on the site of large commercial feedlots. When outbreaks included large feedlots, the number of animals depopulated became very large due to the high density of livestock in a confined space. In a high-capacity setting, depopulation and disposal of more than 70,000 head of cattle in a feedlot would take an estimated 16 days (DeOtte and DeOtte, 2010).

Schroeder et al. (2015) investigated the value of vaccination strategies to manage an FMD outbreak in the Midwest using disease control simulations in a feedlot setting. Without an emergency vaccination program, government costs would total \$11 billion and consumer and producer welfare impacts would be nearly \$188 billion (Schroeder et al., 2015). Elbakidze et al. (2009) examined mitigation strategies (e.g., time of detection, slaughter of infected herds, and vaccination availability) of FMD in highly concentrated animal feed regions in the Texas Panhandle region and estimated total losses to the local cattle industry of around \$1 billion. Hagerman et al. (2012) focused on two varying hypothetical scenarios of an FMD outbreak in the central valley of California and the Texas Panhandle, resulting in mean welfare losses of between \$2.7 billion and \$21.9 billion. Elbakidze et al. and Hagerman et al. show that vaccination programs were not cost effective as a disease control method, yet Hagerman et al. did find that, as disease detection delays expanded, vaccination was a preferred strategy under high levels of risk aversion. While these focused on smaller-scale feedlot capacities, they showed value in timely response to a disease outbreak. Yadav et al. (2022) estimated that the cost of disease response ranged from \$76 million to \$230 million across vaccination-to-live scenarios, and welfare losses ranged from \$23 billion to \$2.1 trillion over 4 years, with no recovery in export markets during that time. It is important to note that livestock prices and export levels in the baseline varied over these studies. The size of livestock industries, value of animals, and share of production exported from the United States have grown over time. Further, the vulnerabilities (e.g., fewer cattle being rendered, limited processor operations and shutdowns, concerns about food security, Whitehead and Brad Kim, 2022) identified in protein supply chains during 2020 highlight the need to examine possible alternative control programs that can be deployed.

## Methods

### Scenarios

Based on the literature and procedures outlined in the APHIS FMD Response Plan (*FMD Red Book*, US Department of Agriculture, 2014), we examine four strategies to potentially mitigate and manage the spread of FMD and its effects on a sample feedlot's profits:

- Stamping out: quarantine of suspect feedlot premises, movement restrictions for operations within a control area (size of the control area varies based on epidemiological factors, as outlined in the *FMD Red Book*), and depopulation and disposal of animals on infected farms, followed by cleaning and disinfection of facilities before being released from quarantine.
- Targeted depopulation: quarantine of infect feedlot premises with extensive surveillance within the feedlot to quickly identify infected and adjacent pens for depopulation and disposal. Targeted depopulation would be used to create “fire breaks” around infected pens in the hope of limiting spread within the feedlot. Uninfected animals would eventually be marketed after the movement restrictions were lifted.

- **Controlled slaughter:** quarantine of infected feedlot premises with extensive movement controls to limit the virus spread from moving to nearby operations. After 28–30 days, controlled harvest would begin by moving recovered animals to an alternative processing stream. As with stamping out, movement is restricted and operations in the control area are tested. Further, cattle that were severely debilitated by the disease, particularly those with mobility issues, would be euthanized for welfare reasons.
- **Managed outbreak:** quarantine of infected feedlot premises with on-site response limited to treatment of sick animals and extensive movement controls to limit the virus from moving to nearby operations. After feedlot animals fully recovered, livestock would be sent to an alternative processing stream. As with stamping out, movement is restricted and operations in the control area are tested. Again, cattle that were severely debilitated by the disease, particularly those with mobility issues, would be euthanized for welfare reasons.

While stamping out the virus is practical when the number of cattle is relatively small, its feasibility and economic advisability dwindles as the size of feedlot capacity increases. Stamping out a large feedlot could take several weeks in addition to yielding the highest government response costs at that site (DeOtte and DeOtte, 2010). To some extent, all alternatives limit the resources that would have to be dedicated to a single operation. Targeted depopulation would still require intensive surveillance resources. The National Animal Health Laboratory Network is designed to handle testing surges by linking a network of state laboratories. However, the targeted depopulation strategy may still be a challenge to the laboratory capacity depending on the size of the overall FMD outbreak.

The controlled slaughter and management outbreak scenarios are similar from an animal treatment perspective but differ in the timing of a move to market. Recovered cattle can potentially be “carriers”—meaning virus is still detectable more than 28 days post-infection—for up to 30–52 months (Yadav et al., 2022). Yadav et al. found that detectable virus in beef carrier animals would steadily decline over the 2 years post-infection but is unlikely to be eliminated in either the controlled slaughter or managed outbreak scenarios. In both scenarios, cattle that experience limited mobility due to chronic hoof issues or face severe physical detriments because of clinical disease would be euthanized at the feedlot for animal welfare reasons. The number of cattle that would experience extreme clinical illness may vary widely by the FMD virus strain-specific host dynamics (Arzt et al., 2011a; US Department of Agriculture, 2014; Sumption et al., 2020).

The controlled slaughter scenario would move animals to slaughter more quickly rather than waiting for standard quarantine restrictions to lift. Controlled slaughter is defined as segmented processing of cattle that have recovered from FMD or are at high risk due to sharing a location with FMD-infected cattle as a separate packing facility approved by an arbitrator. Under this strategy, it is assumed that only cattle that are susceptible (noninfected cattle as confirmed by diagnostic testing prior to movement) or recovered (known to have been infected but fully improved from clinical disease at the time of slaughter) are moved to the processing facility. These cattle would be transported directly to slaughter without passing through sale barns or other feeding facilities to limit the potential impact of carrier animals.

Unlike stamping out or targeted depopulation, both controlled slaughter and managed outbreak would include moving recovered animals to processing. Meat products from FMD-recovered animals pose a minimal risk to disease spread, particularly when paired with extensive testing to identify and remove carrier animals. However, this does little to minimize the challenges associated with moving meat into the market or the acceptability of recovered cattle by processors due to concerns about their reputation.

The last two management strategies could be used in combination with vaccination programs. Vaccination should reduce the likelihood of infection in any given animal and reduce the clinical effects of disease and viral shedding if an animal should become infected, reducing its transmission potential (Stenfeldt et al., 2016). Other possible outcomes of vaccination use may be reduced

**Table 1. Summary of Foot-and-Mouth Disease Management Strategies**

| Management Strategy   | Vaccination Strategy | Price Level | Strategy Name    |
|-----------------------|----------------------|-------------|------------------|
| No disease outbreak   | No                   | High        | Baseline         |
| Managed outbreak      | No                   | Low         | MgO              |
| Controlled slaughter  | No                   | High        | CS_NV_highp      |
|                       | No                   | Medium      | CS_NV_midp       |
|                       | No                   | Low         | CS_NV_lowp       |
|                       | Yes                  | High        | CS_V_highp       |
|                       | Yes                  | Medium      | CS_V_midp        |
|                       | Yes                  | Low         | CS_V_lowp        |
| Targeted depopulation | No                   | High        | TD_NV_highp      |
|                       | No                   | Medium      | TD_NV_midp       |
|                       | No                   | Low         | TD_NV_lowp       |
|                       | Yes                  | High        | TD_V_highp       |
|                       | Yes                  | Medium      | TD_V_midp        |
|                       | Yes                  | Low         | TD_V_lowp        |
| Depopulation only     | N/A                  | N/A         | DepopulationOnly |

Notes: n/a indicates not applicable.

incidence of extreme clinical illness, the preservation of valuable genetics, and reduced disruptions to supply chains (Stenfeldt et al., 2016; Yadav et al., 2022). Vaccines can be used to either (i) allow both recovered and noninfected vaccinates to go to controlled slaughter (vaccinate to live) or (ii) depopulate all recovered and noninfected vaccinates to reduce spread (vaccinate to die). We explored the disease spread and economic consequences of “vaccinate to live” for the targeted depopulation and controlled slaughter scenarios.

In addition, economic outcomes are expected to vary widely by the overall size of the outbreak and the introduction of trade embargoes and potential consumer avoidance. The 2020 cattle market disruptions associated with the novel coronavirus (COVID-19) provided a recent example of the extent to which supply chain disruptions can impact market price movements. We developed three price distributions based on 2020 market prices, which we discuss in more detail in the economic model section. Altogether, 14 scenarios were examined with stochastic prices and static government costs for on-farm response. Table 1 shows the summary of disease response in terms of specific strategy, vaccination program, and price assumption.

### Data

Performance and cost data from a sample feedlot of more than 50,000 head are coupled with simulated within-feedlot disease spread data provided by APHIS to be incorporated into the analysis. The feedlot-level data are from a sample feedlot within the region with the exact location and feedlot owner remaining undisclosed for reasons of confidentiality. Expenses incurred by the feedlot include implementing disease management strategies, feeding, regular management costs, and routine vaccinations. Each scenario simulation was run for a total of 200 iterations for data analysis purposes.

Table 2 presents summary statistics of cattle within the feedlot. Placement weights of steers and heifers are 756 lb and 681 lb, respectively, while sale weights are 1,360 lb and 1,227 lb, respectively. The percentage change in the sale and placement weight, often referred to as shrink, is 3.37% for all cattle. This is consistent with the shrink observed in transporting cattle (Gill et al., 1992). Average

**Table 2. Summary Statistics for Sample Feedlot**

| Feedlot Variables       | Unit           | All     | Steers  | Heifers |
|-------------------------|----------------|---------|---------|---------|
| Average purchase weight | lb             | 732     | 756     | 681     |
| Average market weight   | lb             | 1,317   | 1,360   | 1,227   |
| Average shrink          | Percentage (%) | 3.31    | 3.19    | 3.56    |
| Average days on feed    | Days           | 169     | 168     | 171     |
| Average daily gain      | lb/day         | 3.36    | 3.51    | 3.07    |
| Average feed to gain    | Dry matter lb  | 6.21    | 6.1     | 6.43    |
| Average sick head days  | Percentage (%) | 0.91    | 0.83    | 1.09    |
| Average death loss      | Percentage (%) | 2.38    | 2.29    | 2.57    |
| Total head              | Count          | 690,285 | 487,772 | 202,513 |
| Total pens              | Count          | 6,434   | 4,357   | 2,077   |
| Average pen size        | Head per pen   | 107     | 112     | 98      |

**Table 3. Summary of Cattle Numbers and Average Weight (lbs.) at FMD Infection by Lot and Gender**

| Lot (weight in lb) | Steers         |                                  | Heifers        |                                  | Mixed          |                                  |
|--------------------|----------------|----------------------------------|----------------|----------------------------------|----------------|----------------------------------|
|                    | Number of Head | Average Weight at Infection (lb) | Number of Head | Average Weight at Infection (lb) | Number of Head | Average Weight at Infection (lb) |
| 1 (500)            | 800            | 931                              | 1,200          | 918                              | 700            | 961                              |
| 2 (550)            | 1,600          | 989                              | 2,800          | 997                              | 1,000          | 1,015                            |
| 3 (600)            | 2,700          | 1,013                            | 2,930          | 1,023                            | 1,100          | 1,034                            |
| 4 (650)            | 3,830          | 1,064                            | 2,900          | 1,070                            | 1,000          | 1,015                            |
| 5 (700)            | 4,600          | 1,095                            | 2,400          | 1,122                            | 700            | 1,151                            |
| 6 (750)            | 4,800          | 1,115                            | 2,400          | 1,186                            | 400            | 1,169                            |
| 7 (800)            | 4,000          | 1,141                            | 1,400          | 1,188                            | 300            | 1,057                            |
| 8 (850)            | 3,080          | 1,198                            | 600            | 1,224                            | 300            | 1,161                            |
| 9 (900)            | 2,000          | 1,220                            | 200            | 1,300                            | 100            | 1,084                            |
| 10 (950)           | 700            | 1,236                            | 200            | 1,249                            | 100            | 1,087                            |
| 11 (1,000)         | 200            | 1,191                            | n/a            | n/a                              | n/a            | n/a                              |
| 12 (1,050)         | 100            | 1,276                            | n/a            | n/a                              | n/a            | n/a                              |

Notes: n/a indicates not applicable. There are no heifer and mixed lots in the L11 and L12 placement groups.

daily gain (ADG) for steers is marginally higher than for heifers, 3.51 lb and 3.08 lb per day, respectively. The dataset includes more than 690,000 cattle (62,768 average head per year), with steers and heifers representing 70.7% and 29.3% of total head, respectively.

Table 3 presents the summary of cattle and their placement weights. Cattle were placed in the feedlot by placement weight group in 50-lb increments, referred to hereafter as lots. The lightest placement lot (L1) in the feedlot is 500 lb, while the heaviest (L12) is 1,050 lb. From the feedlot data, about 85% of the cattle are in the medium placement lots (L3–L8 or 600–850 lb). About 71% of the total number of cattle on feed in the United States were within this weight range in January 2020 (US Department of Agriculture, 2020a).

Cattle gain weight from their initial placement in a lot; at the time of infection, average weights of those lots vary. ADG is taken from the feedlot data at the lot level and used to create a sale weight to the market in conjunction with the duration of the disease as the number of days on feed. It is assumed that while the feedlot is managing the disease, susceptible and recovered cattle might be moved to slaughter before a desired sale weight is reached. Recovered cattle likely experience suppressed growth, thus finish at a weight lighter than expected (Paarlberg et al., 2008). Price for steers and heifers (in US dollars per hundredweight) are taken from monthly averages from 2009

**Table 4. Summary Statistics for Disease Spread Data**

| Disease Spread Variables | Unit  | Percentile |        |        |        |        |
|--------------------------|-------|------------|--------|--------|--------|--------|
|                          |       | 0%         | 25%    | 50%    | 75%    | 100%   |
| Duration                 | Weeks | 25         | 31     | 34     | 38     | 99     |
| Morbidity                | Head  | 20,060     | 38,345 | 49,890 | 54,790 | 54,790 |
| Recovered                | Head  | 19,111     | 36,411 | 44,941 | 47,028 | 52,254 |
| Mortality                | Head  | 947        | 1,904  | 2,366  | 2,536  | 2,536  |

to 2019 (US Department of Agriculture, 2020b). Final sale weights are divided by 100 to create weights in terms of hundredweight (cwt).

### *Epidemiologic Model*

The epidemiological model was designed in InterSpread Plus (ISP) (Stevenson et al., 2013). The Feedlot Spread Model is a fully validated, spatially explicit, stochastic state transition model to evaluate disease response strategies for within-herd infectious spread at the feedlot level. Disease transmission and pathogenesis parameters are based on FMD serotype O, as used in the current national FMD ISP model (Sanson et al., 2011). The feedlot layout and movement within were based on industry data, subject matter expert (SME) input, and general management standards to test response strategies. Changes to response parameters—such as the number of pens that can be depopulated or the number of individual animals vaccinated per day—could affect the epidemiological output; current values for these response actions are based on SME input. Mielke et al. (2023) provide a complete description of the disease spread model.

The output from the epidemiological model is used in the economic analysis, specifically translating the disease spread extent and timing into economic shocks. The time element to this study is duration of disease. Disease duration, tracked at the pen level, is defined as the first detection of the disease to the last removal of an infected animal. While clinical signs of FMD may take several days to manifest, it is assumed that the feedlot uses a combination of passive surveillance and surveillance testing (based on response objectives) to look for disease after the first detection. Once a sample has been collected, it takes 24 hours to get results back from the state animal disease diagnostic laboratory. If FMD were to be detected by the state lab, a halt movement order would be placed on the feedlot while the sample was sent to the Foreign Animal Disease Diagnostic Laboratory for confirmatory testing. Table 4 reports summary statistics from variables in the disease spread model including outbreak duration and counts of cattle that are infected, recovered, and die from FMD. Table 3 also provides the average weight of cattle by lot and gender at infection across all scenarios.

### *Economic Model*

An empirical model is developed based on a feedlot operator's profit-maximizing problem. Based on the outcomes of the epidemiologic model, each animal in the feedlot will have one of three statuses at any given time in the hypothetical outbreak that would subsequently affect their value. Susceptible cattle are not infected but could become infected in future periods. Infected cattle are either subclinically or clinically infected and can shed the virus, thereby infecting other cattle. Recovered/removed cattle are further split into cattle that are recovered from FMD, cattle that are depopulated due to FMD infection, and cattle that die from disease (FMD or secondary infections) or conditions not uncommon in a feedlot setting.

The epidemiological model identifies infected cattle that are a subset of the entire population, but it is assumed that infected cattle will (i) be identified through surveillance or clinical signs and will remain under strict movement bans and (ii) eventually transition to the recovered/removed category. Thus, the only animals that contribute to recovered revenues are those that never became infected

(susceptible) and those that were recovered/removed. Among those that were removed, revenue may be recovered through either sending recovered cattle to be processed at a discounted price or through indemnity for cattle depopulated for disease control or welfare reasons (US Department of Agriculture, 2015a). In all scenarios, cattle that must be euthanized post-illness due to lameness or other welfare reasons (e.g., inability to eat) are indemnified. It is assumed that cattle dying either from complications associated with FMD or from some other reason, are not eligible for indemnity and only contribute to the cost of the outbreak for the producer. This aligns with the policies put in place during highly pathogenic avian influenza.<sup>2</sup> It is assumed that a herd management plan with an agreed-upon indemnity value would be in place before disease response begins, ensuring that any animal can be indemnified. Currently, indemnity values are established on an annual basis and held fixed. As a result, market prices will vary for recoverable profit, but the potential indemnity will remain constant. For the purposes of the economic model, costs and revenues associated with each lot of cattle in the feedlot will be associated with one of three mutually exclusive statuses: susceptible, recovered, or death/loss.

The number of cattle that are infected by pen in each of the 100 iterations is used to generate the number of infected, recovered, depopulated, and FMD death loss cattle in each week. In addition to the control strategies, FMD is expected to have an impact on death loss in the feedlot, due to both the disease and secondary infections. Bovine respiratory disease (BRD) commonly occurs in feedlots and has a morbidity rate similar to that of FMD (Snowder et al., 2006). We take the BRD death rate for “crash pens” in a feedlot setting from Peel (2020) and apply the percentage to FMD infected cattle, reflecting a high rate of secondary infections for cattle already stressed from FMD infection. In this setting, it is assumed that a FMD death loss would be 37.04% (Peel, 2020) for cattle clinically infected with FMD. Further, cattle that do not perish from disease but experience severe clinical illness may require welfare euthanasia. It is assumed that about 10% must be depopulated due to complications from the disease, while the remaining portion recover and are eligible for slaughter. Under a targeted depopulation strategy, cattle that have limited mobility and significant detriments will be euthanized.

When an FMD outbreak occurs in a herd, APHIS will provide indemnity payments to recompense the value of eligible depopulated cattle (US Department of Agriculture, 2024). Indemnity payments are calculated by multiplying the number of cattle depopulated by a fixed rate published annually. Indemnity rates for depopulated cattle were set in accordance with the 2021 USDA Commercial Values (US Department of Agriculture, 2024). Further, APHIS may provide compensation for producer time, equipment, and supplies used in response activities on the operation in accordance with the herd management plan (US Department of Agriculture, 2024).

Using the General Algebraic Modeling System (GAMS Development Corporation, 2019), we develop a model in which susceptible and recovered cattle are sold for revenue and any cattle depopulated from the feedlot result in an indemnity payment from the government. A feedlot’s recoverable profit for the duration of an FMD outbreak is calculated as

$$(1) \quad \max_y E(\pi) = [E(P) - E(r)]y, \\ \text{subject to } y \geq 0,$$

$$(2) \quad y = N - z,$$

where  $E(\pi)$  is expected profit,  $P$  is the price of cattle,  $r$  is management and disease costs, and  $y$  is the quantity of marketable cattle sold. Marketable cattle ( $y$ ) are calculated as the total inventory of the feedlot ( $N$ ) less the number of cattle that are depopulated or died from disease ( $z$ ).

Animal health and management costs are assumed to be per head (Lardy, 2018). Feeding costs are in cents per pound per head, which is calculated by taking the average weekly pounds of feed per

<sup>2</sup> [https://www.aphis.usda.gov/publications/animal\\_health/2016/hpai-indemnity.pdf](https://www.aphis.usda.gov/publications/animal_health/2016/hpai-indemnity.pdf)

**Table 5. Summary of Production Cost, Disease Management and Response, and Market Values**

| Variable                              | Unit               | Value         |
|---------------------------------------|--------------------|---------------|
| Production costs                      |                    |               |
| Labor wage                            | \$/hour            | 12.96         |
| Management                            | \$/hour            | 57.43         |
| Animal health costs                   | \$/head            | 12            |
| Feed costs                            | \$/lb              | 0.075         |
| Disease management and response costs |                    |               |
| Vaccination costs                     | \$/head            | 7.01          |
| Virus detection costs                 | \$/head            | 68.87         |
| Virus elimination costs               | \$/head            | 63.9          |
| Appraisal costs                       | \$/head            | 89            |
| Disposal costs                        | \$/head            | 70.12         |
| Equipment costs                       | \$/week            | 125           |
| Truck costs                           | \$/mile            | 4             |
| Indemnity                             |                    |               |
| Indemnity                             | \$/head            | 1,268.80      |
| Market prices <sup>a</sup>            |                    |               |
| Low price range                       |                    |               |
| Heifers                               | \$/cwt             | 88.00/106.99  |
| Steers                                | \$/cwt             | 95.20/114.39  |
| Medium price range                    |                    |               |
| Heifers                               | \$/cwt             | 104.64/127.92 |
| Steers                                | \$/cwt             | 108.70/134.98 |
| High price range                      |                    |               |
| Heifers                               | \$/cwt             | 121.00/139.43 |
| Steers                                | \$/cwt             | 123.2/148.16  |
| Price standard deviation <sup>b</sup> |                    |               |
| Heifers                               | Standard deviation | 8.56/10.18    |
| Steers                                | Standard deviation | 7.10/11/09    |
| Discount mean (std. dev.)             | Percentage decline | 20 (10)       |

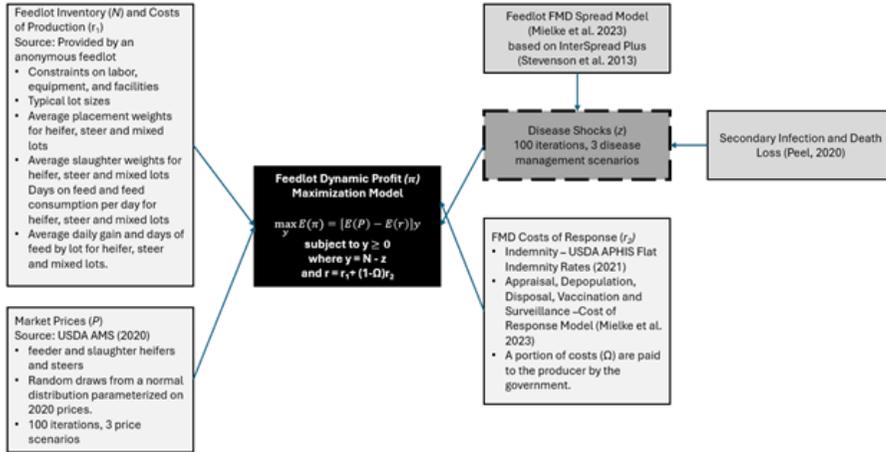
Notes: <sup>a</sup>Price ranges reflect the varying prices per hundredweight (cwt) for cattle of different weights at the time of slaughter. In these scenarios, some cattle are marketed at weights lighter than or heavier than the optimal slaughter weight.

<sup>b</sup>The range of standard deviations varies for different weights of cattle and does not necessarily correspond to the same weight class of cattle in each price range or sex.

animal in the feedlot (personal communication, 2020). Disease management costs—relating to the detection, surveillance, cleaning and disinfecting, euthanasia, and disposal of animals—are taken from Mielke et al. (2023).

Because of the international trade issues an FMD outbreak would have on world prices, price shocks are estimated using prices from 2020. Severe supply chain disruptions due to the COVID-19 pandemic created a wide range of prices, with the lowest prices reflecting severe supply chain disruptions and the highest prices reflecting recovery as shutdowns lifted. This year was used to reflect potential market-wide disruptions in the absence of simulated market-wide shocks. While the fundamental reasons for the price swings are different, the general trend of a sharp price reduction followed by a sharp price increase aligns with the patterns of price changes reported in the simulated FMD market impact studies mentioned in the background section.

This simulated feedlot outbreak could occur at any point in a wider FMD outbreak, and using varying price levels reflects the wider dynamics identified by Paarlberg et al. (2008), among others. Market prices from 2020 were broken into an early-year period (normal or mid-level prices), an



**Figure 1. Graphical Representation of the Feedlot Dynamic Profit Maximization Model**

initial shock period (low prices), and a recovery period (high prices). In each of these periods, the mean and standard deviation of observed market prices were used to create daily prices to represent volatile market conditions in various phases of the outbreak and recovery. Table 5 includes a summary of production costs, management expenses, and market values.

Perhaps the greatest economic uncertainty in moving away from depopulation to any alternative management strategy is the acceptability of recovered cattle for controlled processing. To assess the results’ sensitivity to a processor discount, results were assessed for stochastic price discounts using 50 draws from a normal distribution with a mean of 20% discount and a standard deviation of 10%. This was paired with the stochastic daily market prices associated described above. Figure 1 displays the data inputs into the feedlot profit model.

**Results and Discussion**

Tables 6 and 7 show the average recoverable feedlot profits and governmental expenditures from the stochastic model by management strategy and lot. Beginning with the highest price scenario, which is measured by the baseline scenario, average profit for the entire feedlot is over \$48 million, assuming prices do not decline significantly due to the disease. Recoverable profits average around \$37 million. If total depopulation were employed, profits would decrease by around \$5 million, with an additional \$51 million in government expenditure. When vaccination is incorporated into a controlled slaughter management strategy, recoverable profits are lower, reflecting the costs of vaccination and movement restrictions of lots within the feedlot. Yet when targeted depopulation occurs with vaccination, recoverable profits are higher under vaccination procedures. Under targeted depopulation, cattle in adjacent pens of infected animals are euthanized to mitigate disease spread, increasing the indemnity payments received by the feedlot. Among the management strategies, targeted depopulation with vaccination would be preferred in the absence of significant price declines. When prices are closer to the 2020 low or average, which is likely dependent on the severity of the outbreak, targeted depopulation without vaccination would produce higher recoverable profits. In the instance of controlled slaughter and targeted depopulation, the government would prefer vaccination only in targeted depopulation due to the costs.

The depopulation of the entire feedlot would result in an average recoverable profit of \$43 million. This is a larger profit compared to alternative scenarios, namely in low- to medium-price environments, where indemnity payment may not offset the losses incurred by the feedlot or discounted prices of marketable cattle. The government could pursue alternative indemnities,

**Table 6. Average Recoverable Profit by Weight Grouping and Management Strategy (\$ millions)**

| Strategy Name    | Weight Grouping |              |       |              |              |       |       |       |       |       |              | Total |        |
|------------------|-----------------|--------------|-------|--------------|--------------|-------|-------|-------|-------|-------|--------------|-------|--------|
|                  | L1              | L2           | L3    | L4           | L5           | L6    | L7    | L8    | L9    | L10   | L11          |       | L12    |
| Baseline         | 4,284           | 5,095        | 3,826 | 3,574        | <b>5,098</b> | 3,617 | 2,996 | 3,779 | 3,878 | 4,494 | 4,859        | 2,566 | 48,067 |
| MgO              | 3,443           | <b>3,889</b> | 2,898 | 2,601        | 3,866        | 2,872 | 2,444 | 2,926 | 3,046 | 3,545 | 3,749        | 1,832 | 37,112 |
| CS_NV_highp      | 3,927           | 4,629        | 3,719 | 3,271        | <b>4,917</b> | 3,580 | 2,973 | 3,503 | 3,618 | 4,175 | 4,371        | 2,136 | 44,82  |
| CS_NV_midp       | 3,633           | 4,238        | 3,276 | 2,991        | <b>4,293</b> | 2,996 | 2,559 | 3,036 | 3,243 | 3,655 | 3,879        | 1,925 | 39,723 |
| CS_NV_lowp       | 3,077           | <b>3,594</b> | 2,638 | 2,344        | 3,491        | 2,492 | 2,120 | 2,628 | 2,775 | 3,200 | 3,274        | 1,677 | 33,31  |
| CS_V_highp       | 3,921           | 4,634        | 3,717 | 3,274        | <b>4,921</b> | 3,564 | 3,001 | 3,321 | 3,588 | 4,089 | 4,289        | 2,165 | 44,483 |
| CS_V_midp        | 3,642           | 4,238        | 3,253 | 2,929        | <b>4,280</b> | 3,054 | 2,482 | 3,072 | 3,238 | 3,624 | 3,853        | 1,920 | 39,586 |
| CS_V_lowp        | 3,060           | <b>3,492</b> | 2,659 | 2,361        | 3,408        | 2,483 | 2,154 | 2,654 | 2,727 | 3,189 | 3,443        | 1,625 | 33,254 |
| TD_NV_highp      | 4,575           | 5,348        | 4,229 | 3,769        | <b>5,625</b> | 3,867 | 3,445 | 3,916 | 4,087 | 4,695 | 4,952        | 2,552 | 51,059 |
| TD_NV_midp       | 4,053           | <b>4,920</b> | 3,772 | 3,354        | 4,859        | 3,329 | 2,810 | 3,518 | 3,654 | 4,094 | 4,327        | 2,151 | 44,841 |
| TD_NV_lowp       | 3,457           | <b>4,042</b> | 2,970 | 2,607        | 3,774        | 2,853 | 2,463 | 2,934 | 3,095 | 3,565 | 3,796        | 1,900 | 37,458 |
| TD_V_highp       | 4,560           | 5,452        | 4,258 | 3,785        | <b>5,688</b> | 3,997 | 3,436 | 3,904 | 4,054 | 4,768 | 4,927        | 2,451 | 51,279 |
| TD_V_midp        | 4,166           | <b>4,973</b> | 3,775 | 3,397        | 4,884        | 3,316 | 2,764 | 3,461 | 3,643 | 4,116 | 4,336        | 2,232 | 45,063 |
| TD_V_lowp        | 3,371           | <b>4,033</b> | 2,953 | 2,612        | 3,780        | 2,806 | 2,398 | 3,006 | 3,104 | 3,695 | 3,801        | 1,877 | 37,436 |
| DepopulationOnly | 3,282           | 3,797        | 2,807 | <b>2,481</b> | 3,711        | 4,041 | 3,363 | 3,932 | 3,959 | 4,264 | <b>4,814</b> | 2,562 | 43,013 |

Notes: An *italicized* figure signifies the worst lot outcome in a strategy whereas a **boldface** figure signifies the best.

**Table 7. Average Government Expenditure by Weight Grouping and Management Strategy (\$ millions)**

| Strategy Name    | Weight Grouping |              |       |       |       |       |       |       |       |       |       | Total        |        |
|------------------|-----------------|--------------|-------|-------|-------|-------|-------|-------|-------|-------|-------|--------------|--------|
|                  | L1              | L2           | L3    | L4    | L5    | L6    | L7    | L8    | L9    | L10   | L11   |              | L12    |
| Baseline         | 0.383           | <i>0.445</i> | 0.328 | 0.287 | 0.413 | 0.284 | 0.234 | 0.276 | 0.276 | 0.303 | 0.350 | <b>0.197</b> | 3.777  |
| MgO              | 0.347           | <i>0.403</i> | 0.297 | 0.259 | 0.374 | 0.256 | 0.211 | 0.249 | 0.249 | 0.274 | 0.316 | <b>0.180</b> | 3.417  |
| CS_NV_highp      | 0.347           | <i>0.403</i> | 0.297 | 0.259 | 0.374 | 0.256 | 0.211 | 0.249 | 0.249 | 0.274 | 0.316 | <b>0.180</b> | 3.417  |
| CS_NV_midp       | 0.347           | <i>0.403</i> | 0.297 | 0.259 | 0.374 | 0.256 | 0.211 | 0.249 | 0.249 | 0.274 | 0.316 | <b>0.180</b> | 3.417  |
| CS_NV_lowp       | 0.347           | <i>0.403</i> | 0.297 | 0.259 | 0.374 | 0.256 | 0.211 | 0.249 | 0.249 | 0.274 | 0.316 | <b>0.180</b> | 3.417  |
| CS_V_highp       | 0.347           | <i>0.403</i> | 0.297 | 0.259 | 0.374 | 0.256 | 0.211 | 0.249 | 0.249 | 0.274 | 0.316 | <b>0.180</b> | 3.417  |
| CS_V_midp        | 0.347           | <i>0.403</i> | 0.297 | 0.259 | 0.374 | 0.256 | 0.211 | 0.249 | 0.249 | 0.274 | 0.316 | <b>0.180</b> | 3.417  |
| CS_V_lowp        | 0.383           | <i>0.445</i> | 0.328 | 0.287 | 0.413 | 0.284 | 0.234 | 0.276 | 0.276 | 0.303 | 0.349 | <b>0.197</b> | 3.776  |
| TD_NV_highp      | 0.383           | <i>0.445</i> | 0.328 | 0.287 | 0.413 | 0.284 | 0.234 | 0.276 | 0.276 | 0.303 | 0.349 | <b>0.197</b> | 3.776  |
| TD_NV_midp       | 0.383           | <i>0.445</i> | 0.328 | 0.287 | 0.413 | 0.284 | 0.234 | 0.276 | 0.276 | 0.303 | 0.349 | <b>0.197</b> | 3.776  |
| TD_NV_lowp       | 0.383           | <i>0.445</i> | 0.328 | 0.287 | 0.413 | 0.284 | 0.234 | 0.276 | 0.276 | 0.303 | 0.349 | <b>0.197</b> | 3.776  |
| TD_V_highp       | 0.383           | <i>0.445</i> | 0.328 | 0.287 | 0.413 | 0.284 | 0.234 | 0.276 | 0.276 | 0.303 | 0.349 | <b>0.197</b> | 3.776  |
| TD_V_midp        | 0.383           | <i>0.445</i> | 0.328 | 0.287 | 0.413 | 0.284 | 0.234 | 0.276 | 0.276 | 0.303 | 0.349 | <b>0.197</b> | 3.776  |
| TD_V_lowp        | 0.383           | <i>0.445</i> | 0.328 | 0.287 | 0.413 | 0.284 | 0.234 | 0.276 | 0.276 | 0.303 | 0.349 | <b>0.197</b> | 3.776  |
| DepopulationOnly | 4.130           | 4.782        | 3.533 | 3.116 | 4.627 | 4.670 | 3.882 | 4.542 | 4.569 | 4.934 | 5.586 | <b>2.995</b> | 51.366 |

Notes: An *italicized* figure signifies the worst lot outcome in a strategy whereas a **boldface** figure signifies the best.

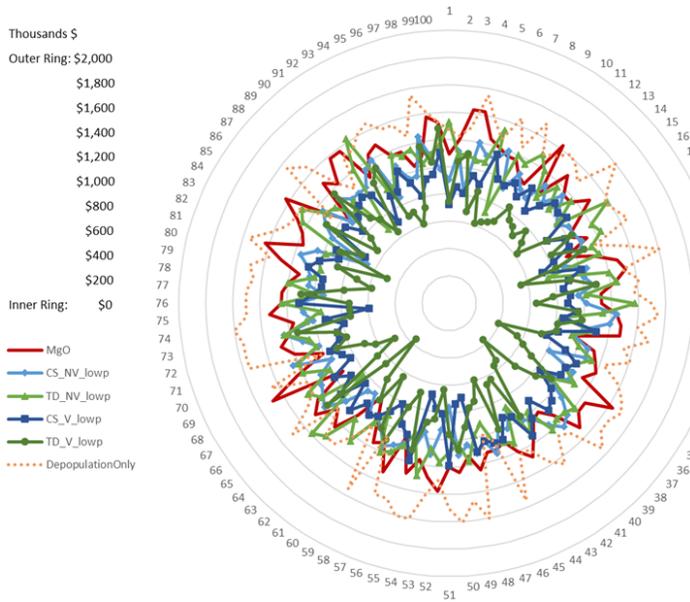
such as tiered payments, to incentivize targeted depopulation or controlled slaughter management strategies over depopulation to reduce their expenditure while bolstering recoverable profit for feedlot operators.

When examining the lot or weight grouping by recoverable profit, the preferred management strategy changes. In most weight groupings, targeted depopulation without vaccination would be preferred over controlled slaughter. When prices are low and a controlled slaughter response may be enforced by the government, total depopulation would be preferred because it yields a higher recoverable profit due to fixed indemnities. In a low- or medium-price environment, controlled slaughter would be least desired. Yet for the weight groupings L6, L8, and L12, total depopulation would be preferred in all instances. For these weight groupings, it is not beneficial to sell at a discounted market; therefore, an indemnity payment would be preferred. For light- to mediumweight cattle, a feedlot operator would least prefer total depopulation, while the reverse is true for medium- to heavyweight cattle. As movement restrictions are enforced in a managed outbreak, the cost of feeding those medium- to heavyweight animals grows substantially each day.

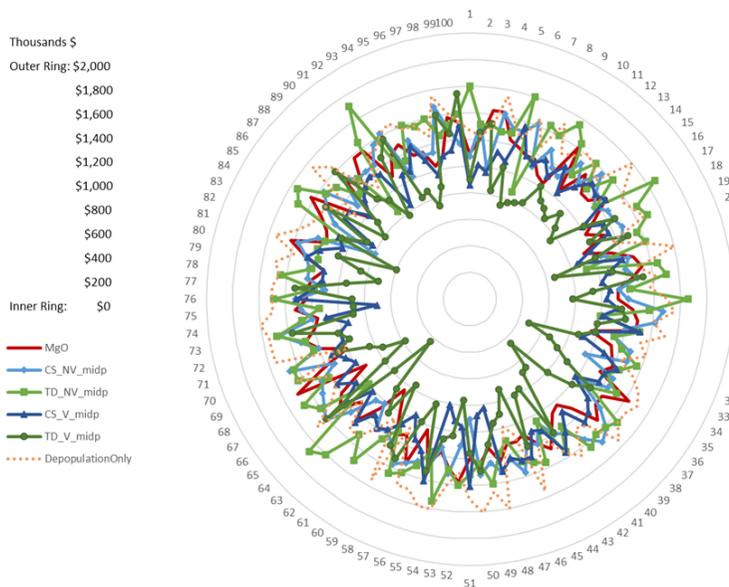
Depopulation is the least preferred strategy across all weight groupings when considering government response costs. Controlled slaughter is preferred over targeted depopulation for each weight category. Regardless of the price level or vaccination programming, the cost of the management strategy will be the same. It is important to note that private feedlot owners and the government have conflicting objectives: Feedlot owners and governmental agencies often have opposing goals when it comes to managing FMD outbreaks. For feedlot owners, the primary economic objective is to maximize profit. This involves selecting a management strategy that minimizes financial losses and allows for business continuity. Controlled slaughter and targeted depopulation are attractive strategies to owners because they enable recovered animals to be sold, even if at a lower price to manage risk, ensuring some revenue generation. Controlled slaughter reduces the immediate financial impact on feedlot operations by allowing healthy and recovered cattle to be processed and sold, maintaining a flow of income and mitigating business disruption. On the other hand, the government's primary concern is to control the outbreak swiftly and efficiently to protect public health, ensure food security, and minimize overall economic disruption. Full depopulation mitigates the spread of disease, preventing further outbreaks and longer-term economic impacts, justifying the high costs associated with the strategy. It is important that policies geared toward FMD management are flexible based on the severity of the outbreak, resources available, and conditions within the region to balance the needs of both feedlot owners and the government.

When comparing strategies in terms of government expenditures and recoverable profits, some strategies are statistically different from others. Supplement Table S1 presents the  $p$ -values from pairwise comparison tests of the 14 strategies as well as the baseline scenario for recoverable profits. In terms of recoverable profits, a controlled slaughter strategy, both with and without vaccination, is not statistically different from the other three scenarios in a high-price environment. The strategies of targeted depopulation with and without vaccination are also not statistically different at all three price levels. In terms of government expenditure, a managed outbreak is no different from any of the targeted depopulation strategies. Furthermore, targeted depopulation and controlled slaughter are no different from their vaccination or price counterparts. Regardless of market prices, response costs will be nearly identical for those strategies.

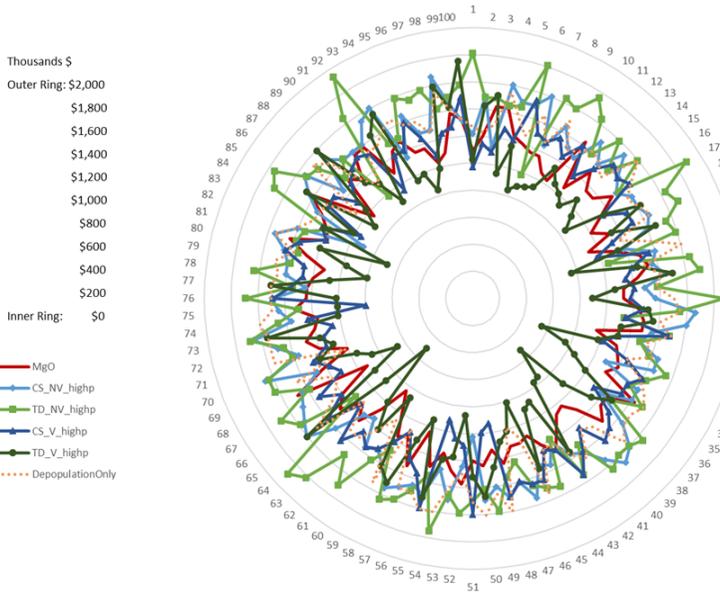
The preference among strategies is further highlighted in Figures 2–4 for the low, mid, and high 2020 price distributions, respectively. Across all simulated disease spread outcomes, targeted depopulation is more likely to provide feedlot operators with the highest recoverable profits when there are no significant price declines. This is unlikely to be the case for a foreign animal disease outbreak like FMD, even if it was limited to a single state for this feedlot. Under all iterations of the low- and mid-price distributions, a managed outbreak or depopulation is more likely to result in higher recoverable profits under many of the simulated outbreaks. Since indemnity values are set across a year, producers may find it financially preferable to manage the outbreak and utilize a stamping-out strategy.



**Figure 2. Recoverable Profit by Disease Spread Iteration and Scenario Under Low 2020 Cattle Prices (thousands of 2020 dollars)**



**Figure 3. Recoverable Profit by Disease Spread Iteration and Scenario Under Mid-2020 Cattle Prices (thousands of 2020 dollars)**

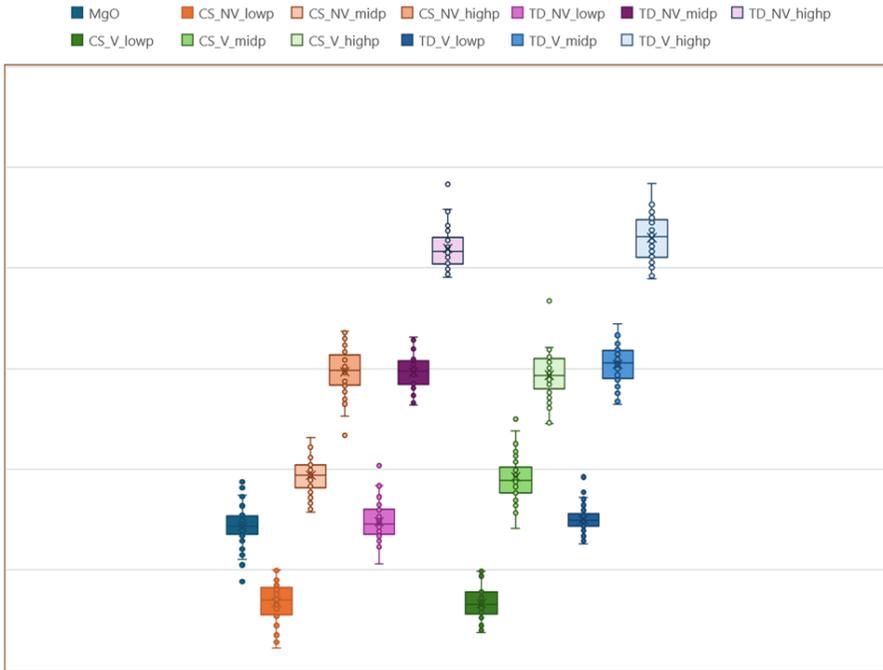


**Figure 4. Recoverable Profit by Disease Spread Iteration and Scenario Under Peak 2020 Cattle Prices (thousands of 2020 dollars)**

Many factors would contribute to the feasibility of stamping out versus a controlled slaughter response on a feedlot operation, and the decision would likely depend on individual feedlot characteristics, location, nearby processor capacity, market conditions, and resources available (Elbakidze et al., 2009; DeOtte and DeOtte, 2010; McReynolds and Sanderson, 2014; Schroeder et al., 2015). Some of these considerations—like varying price environments, finite labor and disease response resources, and availability of nearby processing facilities—are included in the calculations of recoverable profits and governmental expenditures. This approach allows us to model real-world complexities and trade-offs involved in choosing between stamping-out and controlled slaughter strategies.

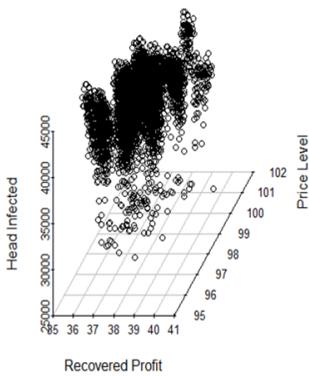
Key parameters of the model’s results include outbreak size and duration as derived from the InterSpread Plus (ISP) framework, alongside market prices and disease management costs. As illustrated in Figures 5 and 6, fluctuations in market prices have a direct relationship with recoverable profits, particularly under larger outbreak scenarios. Figure 5 shows the range of recoverable profits under the varying price discounts for low, mid-level, and high prices. The three price levels (Table 5) have a notable influence on both controlled slaughter and targeted depopulation strategies. However, since targeted depopulation is more dependent on the value that can be recovered from the market than on price received for cattle, the results have a greater sensitivity to the discounts applied to recovered cattle.

Figure 6 expresses the simultaneous effect of price discounts and head infected for the targeted depopulation strategy. Because the number of head infected is typically the entire feedlot for managed outbreak and controlled slaughter, only the targeted depopulation strategy is examined in three dimensions. In the low-price setting, recovered profits cluster more tightly at lower levels under lower prices, as would be expected in a profit-maximization framework. Recoverable profits continue to be low in most iterations of increasing outbreak duration and size; consequently, greater numbers of cattle are subject to a steep price decline. The effect of the number of head infected is somewhat similar for mid- and high-price levels. Yet processors’ potential to recover profit is consistently greatest under less steep discount conditions. It is important to note that longer,

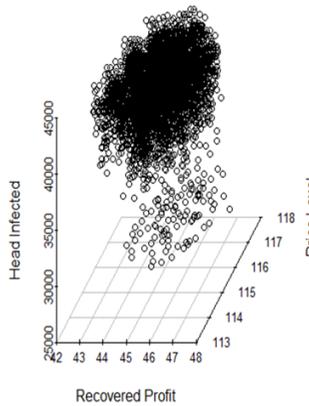


**Figure 5. Comparison of Recoverable Profits by Management Strategy with Varying Market Prices**  
*Notes:* For each scenario, each dot represents one of the price levels with stochastic discounts. The box represents the 25th to 75th percentile of recoverable profits across varying market prices. The horizontal line in the box is the median recoverable profit. The vertical line represents the minimum to the maximum recoverable profits across varying market prices.

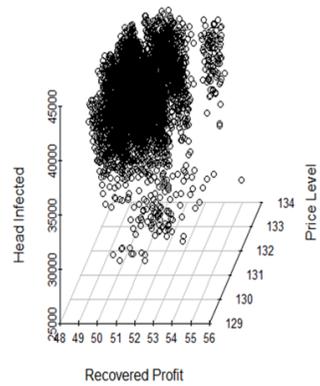
(a) Under Low Price Levels



(b) Under Mid Price Levels



(c) Under High Price Levels



**Figure 6. Comparison of Targeted Depopulation in Targeted Depopulation Management Strategies, Based on Recoverable Profit, Price Level, and Head Infected**

more severe outbreaks under low market prices lead to the lowest potential to recover profit losses (x-axis). Longer durations influence cattle size and the ability to maintain a desirable carcass to market, leading to reductions in revenue generated from the sale of these cattle. Thus, recoverable profits are sensitive in these scenarios because recovered cattle are worth less. Additionally, outbreaks of longer duration also contribute to higher production and disease response costs. Yet when market prices are high, the likelihood of achieving positive recoverable profits increases.

### Conclusions

An outbreak of FMD in a highly concentrated, large-capacity livestock facility such as a feedlot could have major implications for an individual feedlot operator while also leading to greater social and economic welfare losses, supply chain disruptions, and food security issues. This study provides insight on the trade-offs among alternative management strategies to mitigate disease spread and allow business operations to resume in a large feedlot setting. Data from a single feedlot and a simulated disease spread model are used to calculate recoverable profits and governmental expenditures based on fixed disease response expenses and variable livestock prices through a discrete programming model. While procedures are implemented to prevent and control the spread of disease among livestock in a highly concentrated area, certain variables may be out of our control (e.g., vaccine costs, labor, and trucking availability). When disease management strategies are incorporated in an outbreak event, social economic welfare loss can be mitigated. The key findings indicate that disease management strategies can effectively reduce animal losses and welfare impacts, though variability in feedlot characteristics warrants context-specific decisions, often involving a combination of management strategies. The results of this study may help feedlot owners and decision makers when selecting a response from the list outlined in the *FMD Red Book* to ensure minimal animal and welfare losses to businesses in the United States.

While this study investigated response to FMD in a single feedlot, it should be recognized that such an outbreak would likely cause rippling effects down the supply chain, depending on its scope and severity. Estimating sector or larger economic impacts due to an FMD outbreak in a large feedlot would be valuable knowledge to the agriculture and food industry. These results can be complemented by analyses of wider implications on trade, other sectors of the beef industry (primarily the processing sector), and consumers.

One limitation of this study is that we did not explore how beef from controlled slaughter can be used or where to market that beef. The acceptability of FMD-vaccinated beef or beef from FMD-recovered animals could be a topic of future research. In addition, this study is based on a single feedlot, but feedlots come in many sizes and layouts as well as feed out different cattle types. Therefore, the complexity of decisions may be highly dependent on the individual feedlot. Further, it is possible for a feedlot to use a combination of the three management strategies used in this study. For example, due to delays in movement, some cattle may be too big for the processing line. It may be necessary to depopulate some larger lots while continuing to move cattle of optimal slaughter weight to processing.

Animal disease response has social components that feedlot operators should consider. While disposing of many carcasses presents logistical issues for producers, these events will likely be picked up by news and media outlets due to the economic impact and societal concerns about animal welfare. Disposal methods such as burials and incineration may be viewed negatively by the public and end consumers of meat products. From a scientific perspective, meat from recovered animals is safe to eat (Arzt et al., 2011b; US Department of Agriculture, 2014). Although alternative management strategies attempt to conserve resources and move healthy and/or recovered livestock into further processing, these responses may not be feasible if consumers do not perceive the end products to be safe for consumption.

## References

- Arzt, J., B. Baxt, M. J. Grubman, T. Jackson, N. Juleff, J. Rhyan, E. Rieder, R. Waters, and L. L. Rodriguez. 2011a. "The Pathogenesis of Foot-and-Mouth Disease II: Viral Pathways in Swine, Small Ruminants, and Wildlife; Myotropism, Chronic Syndromes, and Molecular Virus-Host Interactions: Foot-and-Mouth Disease Pathogenesis: Atypical Syndromes." *Transboundary and Emerging Diseases* 58(4):305–326. doi: 10.1111/j.1865-1682.2011.01236.x.
- Arzt, J., N. Juleff, Z. Zhang, and L. L. Rodriguez. 2011b. "The Pathogenesis of Foot-and-Mouth Disease I: Viral Pathways in Cattle: Foot-and-Mouth Disease Pathogenesis in Cattle." *Transboundary and Emerging Diseases* 58(4):291–304. doi: 10.1111/j.1865-1682.2011.01204.x.
- DeOtte, R. E. J., and R. E. I. DeOtte. 2010. "Considerations for Management of Livestock During an Infectious Animal Disease Incident as an Alternative to Massive Carcass Disposal Using Foot-and-Mouth Disease in Beef Cattle Feedlots as an Example." Paper presented at the International Symposium on Air Quality and Manure Management for Agriculture Conference Proceedings, Dallas, Texas, September 13–16. doi: 10.13031/2013.32701.
- Ekboir, J., L. S. Jarvis, D. A. Sumner, J. E. Bervejillo, and W. R. Sutton. 2002. "Changes in Foot and Mouth Disease Status and Evolving World Beef Markets." *Agribusiness* 18(2):213–229. doi: 10.1002/agr.10014.
- Elbakidze, L., L. Highfield, M. Ward, B. A. McCarl, and B. Norby. 2009. "Economics Analysis of Mitigation Strategies for FMD Introduction in Highly Concentrated Animal Feeding Regions." *Review of Agricultural Economics* 31(4):931–950. doi: 10.1111/j.1467-9353.2009.01477.x.
- Espinosa, R., D. Tago, and N. Treich. 2020. "Infectious Diseases and Meat Production." *Environmental and Resource Economics* 76(4):1019–1044. doi: 10.1007/s10640-020-00484-3.
- GAMS Development Corporation. 2019. "General Algebraic Modeling System (GAMS) Release 27.1.0."
- Gill, D., K. Barnes, K. Lusby, and D. S. Peel. 1992. *Ranchers' Guide to Custom Cattle Feeding*. Beef Cattle Handbook BCH-8040. Extension Beef Cattle Resource Committee. Available online at <http://www.iowabeefcenter.org/bch/RanchCustomFeeding.pdf>.
- 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. doi: 10.1093/aep/ppr039.
- Hemathilake, D. M. K. S., and D. M. C. C. Gunathilake. 2022. "Agricultural Productivity and Food Supply to Meet Increased Demands." In R. Bhat, ed., *Future Foods: Global Trends, Opportunities, and Sustainability Challenges*, Academic Press, 539–553. doi: 10.1016/B978-0-323-91001-9.00016-5.
- Howard, S. C., and C. A. Donnelly. 2000. "The Importance of Immediate Destruction in Epidemics of Foot and Mouth Disease." *Research in Veterinary Science* 69(2):189–196. doi: 10.1053/rvsc.2000.0415.
- Itao, K., F. Omata, Y. Nishikawa, T. Oda, T. Sasaki, C. Zhang, J. Solomon Maninang, and T. Yamaguchi. 2019. "Threshold Phenomena with Respect to the Initiation of Depopulation in a Simple Model of Foot-and-Mouth Disease." *Mathematical Biosciences and Engineering* 16(5): 5931–5946. doi: 10.3934/mbe.2019297.
- Jamal, S. M., and G. J. Belsham. 2013. "Foot-and-Mouth Disease: Past, Present and Future." *Veterinary Research* 44(1):116. doi: 10.1186/1297-9716-44-116.
- Junker, F., J. Ilicic-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 Papers 19. OECD Publishing. doi: 10.1787/221275827814.
- Knight-Jones, T. J. D., 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. doi: 10.1016/j.prevetmed.2013.07.013.

- Lardy, G. 2018. *A Cow-Calf Producer's Guide to Custom Feeding*. Extension Publication AS-1162. North Dakota State University Extension Service. Available online at <https://www.ag.ndsu.edu/publications/livestock/a-cow-calf-producers-guide-to-custom-feeding/as1162.pdf>.
- McCauley, E. H., N. A. Aulaji, J. C. J. New, W. B. Sundquist, and W. M. Miller. 1979. *A Study of the Potential Economic Impact of Food-and-Mouth Disease in the United States*. Technical Bulletin TB-1597. USDA Animal and Plant Health Inspection Service. doi: 10.22004/ag.econ.157744.
- 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. doi: 10.2460/javma.244.3.291.
- Mielke, S. R., C. Rigney, A. D. Hagerman, T. C. Boyer, A. H. Delgado, J. Arzt, and L. K. Holmstrom. 2023. "Assessment of a Reconfiguration of the Interspread Plus US National FMD Model as a Potential Tool to Analyze a Foot-and-Mouth Disease Outbreak on a Single Large Cattle Feedlot in the United States." *Frontiers in Veterinary Science* 10:1205485. doi: 10.3389/fvets.2023.1205485.
- Miller, M., L. Liu, S. Shwiff, and S. Shwiff. 2019. "Macroeconomic Impact of Foot-and-Mouth Disease Vaccination Strategies for an Outbreak in the Midwestern United States: A Computable General Equilibrium." *Transboundary and Emerging Diseases* 66(1):156–165. doi: 10.1111/tbed.12995.
- Muroga, N., Y. Hayama, T. Yamamoto, A. Kurogi, T. Tsuda, and T. Tsutsui. 2012. "The 2010 Foot-and-Mouth Disease Epidemic in Japan." *Journal of Veterinary Medical Science* 74(4):399–404. doi: 10.1292/jvms.11-0271.
- Paarlberg, P. L., J. G. Lee, and A. H. Seitzinger. 2003. "Measuring Welfare Effects of an FMD Outbreak in the United States." *Journal of Agricultural and Applied Economics* 35(1):53–65. doi: 10.1017/S1074070800005939.
- Paarlberg, P. L., A. H. Seitzinger, J. G. Lee, and K. H. Mathews, Jr. 2008. *Economic Impacts of Foreign Animal Disease*. Economic Research Report ERR-57. USDA Economic Research Service. Available online at [https://www.ers.usda.gov/webdocs/publications/45980/12171\\_err57\\_1\\_.pdf](https://www.ers.usda.gov/webdocs/publications/45980/12171_err57_1_.pdf).
- Parent, K. B., G. Y. Miller, and P. J. Hullinger. 2011. "Triggers for Foot and Mouth Disease Vaccination in the United States." *Revue Scientifique et Technique de l'OIE* 30(3):789–796. doi: 10.20506/rst.30.3.2078.
- Peel, D. S. 2020. "The Effect of Market Forces on Bovine Respiratory Disease." *Veterinary Clinics of North America: Food Animal Practice* 36(2):497–508. doi: 10.1016/j.cvfa.2020.03.008.
- 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(s1):19–33. doi: 10.1017/S1074070800028911.
- Ristaino, J. B., P. K. Anderson, D. P. Bebber, K. A. Brauman, N. J. Cunniffe, N. V. Fedoroff, C. Finegold, K. A. Garrett, C. A. Gilligan, C. M. Jones, M. D. Martin, G. K. MacDonald, P. Neenan, A. Records, D. G. Schmale, L. Tateosian, and Q. Wei. 2021. "The Persistent Threat of Emerging Plant Disease Pandemics to Global Food Security." *Proceedings of the National Academy of Sciences* 118(23):e2022239118. doi: 10.1073/pnas.2022239118.
- Saghaian, S. H., L. J. Maynard, and M. R. Reed. 2007. "The Effects of *E. coli* O157:H7, FMD and BSE on Japanese Retail Beef Prices: A Historical Decomposition." *Agribusiness* 23(1):131–147. doi: 10.1002/agr.20106.
- Sanson, R. L., N. Harvey, M. G. Garner, M. A. Stevenson, T. M. Davies, M. L. Hazelton, J. O'Connor, C. Dube, K. Forde-Folle, and K. Owen. 2011. "Foot and Mouth Disease Model Verification and 'Relative Validation' Through a Formal Model Comparison." *Revue Scientifique et Technique de l'OIE* 30(2):527–540. doi: 10.20506/rst.30.2.2051.
- Schoenbaum, M. A., and W. Terry Disney. 2003. "Modeling Alternative Mitigation Strategies for a Hypothetical Outbreak of Foot-and-Mouth Disease in the United States." *Preventive Veterinary*

- Medicine* 58(1-2):25–52. doi: 10.1016/S0167-5877(03)00004-7.
- 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. doi: 10.1017/aae.2014.5.
- Snowder, G. D., L. D. Van Vleck, L. V. Cundiff, and G. L. Bennett. 2006. “Bovine Respiratory Disease in Feedlot Cattle: Environmental, Genetic, and Economic Factors.” *Journal of Animal Science* 84(8):1999–2008. doi: 10.2527/jas.2006-046.
- Stenfeldt, C., M. Eschbaumer, S. I. Rekant, J. M. Pacheco, G. R. Smoliga, E. J. Hartwig, L. L. Rodriguez, and J. Arzt. 2016. “The Foot-and-Mouth Disease Carrier State Divergence in Cattle.” *Journal of Virology* 90(14):6344–6364. doi: 10.1128/JVI.00388-16.
- Stevenson, M. A., R. L. 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(1-2):10–24. doi: 10.1016/j.prevetmed.2012.08.015.
- Sumption, K., T. J. D. Knight-Jones, M. McLaws, and D. J. Paton. 2020. “Parallels, Differences and Lessons: A Comparison of the Management of Foot-and-Mouth Disease and COVID-19 Using UK 2001/2020 as Points of Reference.” *Proceedings of the Royal Society B: Biological Sciences* 287(1938):20200906. doi: 10.1098/rspb.2020.0906.
- Thompson, D. K., 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 de l’OIE* 21(3):675–687. doi: 10.20506/rst.21.3.1353.
- Tozer, P. R., T. L. Marsh, and E. V. Perevodchikov. 2015. “Economic Welfare Impacts of Foot-and-Mouth Disease in the Canadian Beef Cattle Sector.” *Canadian Journal of Agricultural Economics* 63(2):163–184. doi: 10.1111/cjag.12041.
- US Department of Agriculture. 2014. *Foot-and-Mouth Disease Response Plan: The Red Book*. Foreign Animal Disease Preparedness & Response Plan. USDA Animal and Plant Health Inspection Service. Available online at [https://www.aphis.usda.gov/animal\\_health/emergency\\_management/downloads/fmd\\_responseplan.pdf](https://www.aphis.usda.gov/animal_health/emergency_management/downloads/fmd_responseplan.pdf) [Accessed June 5, 2020].
- . 2015a. *Emergency Response Procedures—Appraisal and Indemnity*. Producer information sheet. USDA Animal and Plant Health Inspection Service. Available online at <https://www.aphis.usda.gov/sites/default/files/ER-Appraisal-Indemnity.pdf>.
- . 2015b. *Overview of FMD Freedom and Vaccination*. FMD Response: Ready Reference Guide. USDA Animal and Plant Health Inspection Service. Available online at [https://www.aphis.usda.gov/animal\\_health/emergency\\_management/downloads/fmd\\_rrg\\_freedom\\_and\\_vaccination.pdf](https://www.aphis.usda.gov/animal_health/emergency_management/downloads/fmd_rrg_freedom_and_vaccination.pdf).
- . 2015c. *Quarantine, Movement Control, and Continuity of Business*. FMD Response: Ready Reference Guide. USDA Animal and Plant Health Inspection Service. Available online at [https://www.aphis.usda.gov/animal\\_health/emergency\\_management/downloads/fmd\\_rrg\\_freedom\\_and\\_vaccination.pdf](https://www.aphis.usda.gov/animal_health/emergency_management/downloads/fmd_rrg_freedom_and_vaccination.pdf).
- . 2020a. *Cattle on Feed*. 1948-9080. USDA National Agricultural Statistics Service. Available online at [https://www.nass.usda.gov/Publications/Todays\\_Reports/reports/cofd0220.pdf](https://www.nass.usda.gov/Publications/Todays_Reports/reports/cofd0220.pdf).
- . 2020b. “QuickStats.” USDA National Agricultural Statistics Service. Available online at <https://data.nal.usda.gov/dataset/nass-quick-stats> [Accessed June 5, 2020].
- . 2020a. *Etiology and Ecology*. FMD Response: Ready Reference Guide. USDA Animal and Plant Health Inspection Service. Available online at [https://www.aphis.usda.gov/animal\\_health/emergency\\_management/downloads/fmd\\_plan\\_rrg\\_ee.pdf](https://www.aphis.usda.gov/animal_health/emergency_management/downloads/fmd_plan_rrg_ee.pdf).
- . 2024. *Conservation Reserve Program (CRP) Statistics*. USDA Farm Service Agency. Available online at <https://www.fsa.usda.gov/resources/programs/conservation-reserve-program/statistics>.

- Ward, M. P., L. D. Highfield, P. Vongseng, and M. Graeme Garner. 2009. "Simulation of Foot-and-Mouth Disease Spread Within an Integrated Livestock System in Texas, USA." *Preventive Veterinary Medicine* 88(4):286–297. doi: 10.1016/j.prevetmed.2008.12.006.
- Weir, E. 2001. "Foot-and-Mouth Disease in Animals and Humans." *CMAJ: Canadian Medical Association Journal* 164(9):1338.
- Whitehead, D., and Y. H. Brad Kim. 2022. "The Impact of COVID 19 on the Meat Supply Chain in the USA: A Review." *Food Science of Animal Resources* 42(5):762–774. doi: 10.5851/kosfa.2022.e39.
- Wilkinson, K., W. P. Grant, L. E. Green, S. Hunter, M. J. Jeger, P. Lowe, G. F. Medley, P. Mills, J. Phillipson, G. M. Poppy, and J. Waage. 2011. "Infectious Diseases of Animals and Plants: An Interdisciplinary Approach." *Philosophical Transactions of the Royal Society B: Biological Sciences* 366(1573):1933–1942. doi: 10.1098/rstb.2010.0415.
- Yadav, S., A. H. Delgado, A. D. Hagerman, M. R. Bertram, K. I. Moreno-Torres, C. Stenfeldt, L. Holmstrom, and J. Arzt. 2022. "Epidemiologic and Economic Considerations Regarding Persistently Infected Cattle During Vaccinate-to-Live Strategies for Control of Foot-and-Mouth FMD in FMD-Free Regions." *Frontiers in Veterinary Science* 9:1026592. doi: 10.3389/fvets.2022.1026592.
- Zhao, Z., T. I. Wahl, and T. L. Marsh. 2006. "Invasive Species Management: Foot-and-Mouth Disease in the U.S. Beef Industry." *Agricultural and Resource Economic Review* 35(1):98–115. doi: 10.22004/ag.econ.10174.

# Online Supplement: Alternative Foot-and-Mouth Disease Eradication Strategies in a Large Feedlot Under Resource Limitations

Logan L. Britton, Amy D. Hagerman, Sarah R. Mielke,  
 Columb P. Rigney, and Amy H. Delgado

**Table S1. Pairwise Comparison Test Results for Recoverable Profits and Government Expenditures**

| Strategy         | Recoverable Profits |             |            |            |            |           |           |             |            |            |            |           |           |
|------------------|---------------------|-------------|------------|------------|------------|-----------|-----------|-------------|------------|------------|------------|-----------|-----------|
|                  | MgO                 | CS_NV_highp | CS_NV_midp | CS_NV_lowp | CS_V_highp | CS_V_midp | CS_V_lowp | TD_NV_highp | TD_NV_midp | TD_NV_lowp | TD_V_highp | TD_V_midp | TD_V_lowp |
| CS_NV_highp      | <0.01               |             |            |            |            |           |           |             |            |            |            |           |           |
| CS_NV_midp       | <0.01               | 1.00        |            |            |            |           |           |             |            |            |            |           |           |
| CS_NV_lowp       | <0.01               | 1.00        | 1.00       |            |            |           |           |             |            |            |            |           |           |
| CS_V_highp       | <0.01               | 1.00        | 1.00       | 1.00       |            |           |           |             |            |            |            |           |           |
| CS_V_midp        | <0.01               | 1.00        | 1.00       | 1.00       | 1.00       |           |           |             |            |            |            |           |           |
| CS_V_lowp        | <0.01               | 1.00        | 1.00       | 1.00       | 1.00       | 1.00      |           |             |            |            |            |           |           |
| TD_NV_highp      | 0.99                | <0.01       | <0.01      | <0.01      | <0.01      | <0.01     | <0.01     |             |            |            |            |           |           |
| TD_NV_midp       | 0.99                | <0.01       | <0.01      | <0.01      | <0.01      | <0.01     | <0.01     | 1.00        |            |            |            |           |           |
| TD_NV_lowp       | 0.99                | <0.01       | <0.01      | <0.01      | <0.01      | <0.01     | <0.01     | 1.00        | 1.00       |            |            |           |           |
| TD_V_highp       | 0.99                | <0.01       | <0.01      | <0.01      | <0.01      | <0.01     | <0.01     | 1.00        | 1.00       | 1.00       |            |           |           |
| TD_V_midp        | 0.99                | <0.01       | <0.01      | <0.01      | <0.01      | <0.01     | <0.01     | 1.00        | 1.00       | 1.00       | 1.00       |           |           |
| TD_V_lowp        | 0.99                | <0.01       | <0.01      | <0.01      | <0.01      | <0.01     | <0.01     | 1.00        | 1.00       | 1.00       | 1.00       | 1.00      |           |
| DepopulationOnly | <0.01               | <0.01       | <0.01      | <0.01      | <0.01      | <0.01     | <0.01     | <0.01       | <0.01      | <0.01      | <0.01      | <0.01     | <0.01     |

| Strategy         | Recoverable Profits |             |            |            |            |           |           |             |            |            |            |           |           |
|------------------|---------------------|-------------|------------|------------|------------|-----------|-----------|-------------|------------|------------|------------|-----------|-----------|
|                  | MgO                 | CS_NV_highp | CS_NV_midp | CS_NV_lowp | CS_V_highp | CS_V_midp | CS_V_lowp | TD_NV_highp | TD_NV_midp | TD_NV_lowp | TD_V_highp | TD_V_midp | TD_V_lowp |
| MgO              | <0.01               |             |            |            |            |           |           |             |            |            |            |           |           |
| CS_NV_highp      | <0.01               |             |            |            |            |           |           |             |            |            |            |           |           |
| CS_NV_midp       | 0.01                | <0.01       |            |            |            |           |           |             |            |            |            |           |           |
| CS_NV_lowp       | <0.01               | <0.01       | <0.01      |            |            |           |           |             |            |            |            |           |           |
| CS_V_highp       | <0.01               | 0.75        | <0.01      | <0.01      |            |           |           |             |            |            |            |           |           |
| CS_V_midp        | 0.02                | <0.01       | 0.90       | <0.01      | <0.01      |           |           |             |            |            |            |           |           |
| CS_V_lowp        | <0.01               | <0.01       | <0.01      | 0.96       | <0.01      | <0.01     |           |             |            |            |            |           |           |
| TD_NV_highp      | <0.01               | <0.01       | <0.01      | <0.01      | <0.01      | <0.01     | <0.01     |             |            |            |            |           |           |
| TD_NV_midp       | <0.01               | 0.98        | <0.01      | <0.01      | 0.73       | <0.01     | <0.01     | <0.01       |            |            |            |           |           |
| TD_NV_lowp       | <0.01               | 0.74        | <0.01      | <0.01      | <0.01      | <0.01     | <0.01     | <0.01       | <0.01      |            |            |           |           |
| TD_V_highp       | <0.01               | <0.01       | <0.01      | <0.01      | <0.01      | <0.01     | 0.83      | <0.01       | <0.01      | <0.01      |            |           |           |
| TD_V_midp        | <0.01               | 0.82        | <0.01      | <0.01      | 0.58       | <0.01     | <0.01     | <0.01       | <0.01      | <0.01      | <0.01      |           |           |
| TD_V_lowp        | 0.76                | <0.01       | 0.03       | <0.01      | <0.01      | 0.04      | <0.01     | <0.01       | <0.01      | <0.01      | <0.01      | <0.01     |           |
| DepopulationOnly | <0.01               | 0.09        | <0.01      | <0.01      | 0.16       | <0.01     | <0.01     | <0.01       | 0.08       | <0.01      | <0.01      | 0.05      | <0.01     |