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

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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. Fourteen scenarios across five management strategies are analyzed 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 (Hemanthilake and Gunathilake, 2022). Population increases lead to increases in food demand, including 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 serve as 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. These include food safety and security, consumer confidence in the food supply, animal welfare, damages and losses to animals

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and crops, international trade restrictions, changes in food prices, among other topics (Wilkinson et al., 2011; Espinosa, Tago, and Treich, 2020; Ristaino et al., 2021).

Foot-and-mouth disease (FMD)[1] is a highly contagious viral disease that affects cloven-hoofed animals including cattle, swine, small ruminants, and wildlife ungulates. The disease often causes high morbidity in susceptible livestock species, which results in respiratory problems and other physiological issues. Mortality rates are generally low in adult animals (USDA, 2015b; USDA, 2020a), but clinical disease reduces productivity. Experiences in FMD-endemic regions have shown the difficulty of eradication in animal populations after the disease has widely spread in the environment or wild animal populations (USDA, 2015b; USDA, 2020a). FMD outbreaks have occurred throughout time with the earliest probable FMD description made in Venice, Italy in 1514 (Jamal and Belsham, 2013). Outbreaks have varied in frequency and scale geographically over the past three centuries (Jamal and Belsham, 2013). Recent instances of FMD outbreaks, such as the 2001 outbreak in the United Kingdom, the 2010 outbreak in Japan, and the 2010-2011 outbreaks in South Korea, have demonstrated significant economic imports, 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).

Therefore, strong prevention measures often take the form of border controls and sanitary trade restrictions, as well as supporting 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 a livestock sector (Saghaian, Maynard, and Reed, 2007; Schroeder et al., 2015).

The United States Department of Agriculture (USDA) has focused on policies related to full herd depopulation as a response to FMD (McReynolds and Sanderson, 2014) to mitigate losses and eradicate disease before it can spread widely. Depopulating an infected herd prevents the continued spread of the disease, and when combined with quarantine and movement restrictions (USDA, 2015c) is commonly referred to as a “stamping-out” strategy. In countries like the United States with commercial livestock enterprises additional challenges to eradication are introduced. 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 susceptible species, creating conditions suitable for rapid spread 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 a high amount 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 will focus 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 has been estimated to range from $150 million up to $188 billion for various sizes of feedlots at regional levels as well as the economic impacts for implementing disease-containing strategies (Elbakidze et al., 2009; Ward et al., 2009; McReynolds and Sanderson, 2014; Schroeder et al., 2015). Few studies have

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[1] FMD infections from livestock to humans are very rare and mild (USDA 2014), so FMD is not considered a zoonotic disease. Further it is sometimes confused with hand-foot-and-mouth disease in humans but is not related (Weir 2001).

examined FMD management strategies in large feedlots. Most studies that examined FMD in large feedlots examined stamping-out alone as a disease control measure (DeOtte and DeOtte, 2010). One recent exception examined eradication via emergency vaccination-to-live (Yadav et al., 2023). Yadav et al. (2023) concluded that vaccination-to-live may have animal welfare and resource allocation benefits, particularly in outbreaks with a higher dairy density. Yet, results were less conclusive in feedlot regions of the United States and trade losses were more significant for the beef industry versus 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 within-feedlot spread consequences of stamping-out alternatives and found significant disease spread reductions when resources are not diverted to highly concentrated animal operations, instead allowing the animals to recover before moving them to slaughter for either disposal or for 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 in under a stamping-out strategy warrant exploration given the potential for benefits from stamping-out alternatives explored in Yadav et al. (2023) and Mielke et al. (2023). Globally, significant FMD outbreaks controlled through livestock depopulation have resulted in detrimental effects on livestock inventories and recovery time (for example, the Japanese FMD outbreak described in Muroga et al. (2012)). As a result, countries with large and valuable livestock industries are exploring whether alternatives, such as controlled slaughter or targeted depopulation, are 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 the 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. It is observed that (1) targeted depopulation yields higher recoverable profits over alternative management strategies; (2) controlled slaughter of recovered livestock has value as an alternative method for cattle in a high-price environment, and (3) 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 regional FMD outbreaks, including several studies that have examined simulations of FMD in California, Texas, Kansas, and the Midwest. These costs have been estimated in the range of $789.9 million to $13.5 billion (Ekboir et al., 2002; Schoenbaum and 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 of an FMD outbreak were estimated to be larger when starting in large feedlots rather than 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; Itao 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 U.S. Department of Agriculture Animal and Plant Health Inspection Service (USDA 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. This creates an incentive 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, where there is 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 lasted around 50 days and about 100 herds would need to be depopulated to contain the disease (Ward et al., 2009). In the worst-case scenarios, the outbreak lasted 8-9 months and 230 herds were depopulation when the disease was initiated on site of large company feedlots. When outbreaks include large feedlots, the number of animals depopulated becomes very large due to the high density of livestock in a confined space. In a large 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). U.S. 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).

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 Texas Panhandle, resulting in mean welfare losses ranging from $2.7 billion to $21.9 billion. These two studies show that vaccination programs were not cost effective as a disease control method (Elbakidze et al., 2009; Hagerman et al., 2012). Yet, Hagerman et al. (2012) 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. (2023) estimated the cost of disease response to range from $76 million to $230 million across vaccination-to-live scenarios, and welfare losses to range from $23 billion over 4 years 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 U.S. has 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 USDA APHIS FMD Response Plan (FMD RedBook[2]), three strategies are examined to potentially mitigate and manage the spread of disease and their effects on a sample feedlot's profits as an alternative to stamping-out.

- 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 RedBook), 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. This 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. There are movement restrictions and testing for operations in the control area as with stamping-out.
- 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. There are movement restrictions and testing for operations in the control area as with stamping-out. 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. There are movement restrictions and testing for operations in the control area as with stamping-out. 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 likely take several weeks in addition to yielding the highest government response costs at that site (DeOtte and DeOtte, 2010). All alternatives limit the resources that would have to be dedicated to a single operation, to some extent. 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 have the potential to enter the 'carrier' state—or the maintenance of detectable virus more than 28 days post-infection—up to 30 to 52 months. Yadav et al. (2023) found that the detectable virus in beef carrier animals would steadily decline over the two-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

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[2] https://www.aphis.usda.gov/animal_health/emergency_management/downloads/fmd_responseplan.pdf

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 FMDV strain-specific host dynamics (USDA, 2014; Sumption et al., 2020; Arzt et al., 2011a).

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 in which approved by an arbitrator. Under this strategy, it is assumed that only cattle that are susceptible (non-infected cattle as confirmed by diagnostic testing prior to movement) or recovered (known to have been infect but fully improved from clinical disease at the time of slaughter) are moved to the processing facility. These terminal cattle would be transported directly to slaughter without passing through sale barns or other feeding facilities to limit the potential impact of carrier animals.

Both controlled slaughter and managed outbreak would include moving recovered animals to processing, unlike stamping-out or targeted depopulation. 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, thereby reducing the transmission potential (Stenfeldt et al., 2016). Another possible outcome of vaccination use may be reduction in the incidence of extreme clinical illness, the preservation of valuable genetics, and reduced disruptions to supply chains (Stenfeldt et al., 2016, Yadav et al., 2023). Vaccines can be used to either 1) allow both recovered and non-infected vaccinates to go to controlled slaughter (vaccinate to live), or 2) depopulate all recovered and non-infected vaccinates to reduce spread (vaccinate to die). The disease spread and economic consequences of ‘vaccinate to live’ was explored for the targeted depopulation and controlled slaughter scenarios.

In addition, it would be expected that the economic outcomes would vary widely by the overall size of the outbreak and the occurrence 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. Three price distributions were developed based on 2020 market prices. These distributions are discussed 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 is coupled with simulated within-feedlot disease spread data provided by USDA APHIS to be incorporated into the analysis. The feedlot-level data is from a sample feedlot within the region with the exact location and feedlot owner remaining undisclosed due to 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 and 681 lbs., respectively, while sale weights are 1,360 and 1,227 lbs., respectively. The percentage change in the sale and placement weight, often referred to as shrink, is 3.37 percent for all cattle. This is consistent with the shrink observed in transporting cattle (Gill

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 – not applicable.

Table 2. Summary Statistics for Sample Feedlot

Feedlot Variables	Unit	All	Steers	Heifers
Average Purchase Weight	lbs.	732	756	681
Average Market Weight	lbs.	1,317	1,360	1,227
Average Shrink	%	3.31	3.19	3.56
Average Days on Feed	Days	169	168	171
Average Daily Gain	lbs./day	3.36	3.51	3.07
Average Feed to Gain	Dry Matter lbs.	6.21	6.10	6.43
Average Sick Head Days	%	0.91	0.83	1.09
Average Death Loss	%	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

et al., 1992). Average daily gain (ADG) for steers is marginally higher than for heifers, 3.51 and 3.08 lbs. per day, respectively. There are more than 690,000 cattle (62,768 average head per year) in the dataset with steers and heifers representing 70.7 and 29.3 percent of the 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 as lots hereby after. The lightest placement lot (L1) in the feedlot is 500 lbs. while the heaviest (L12) is 1,050 lbs. From the feedlot data, about 85 percent of the cattle are in the medium placement lots (L3 to L8 or 600 to 850 lbs.). About 71 percent of the total number of cattle on feed in the United States were within this weight range in January 2020 (USDA, 2020b).

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

	Steers		**Heifers**		**Mixed**	
Lot (Weight)	**Number of Head**	**Average Weight at Infection**	**Number of Head**	**Average Weight at Infection**	**Number of Head**	**Average Weight at Infection**
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

Note: N/A – not applicable. There are no heifer and mixed lots in the L11 and L12 placement groups.

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 U.S. dollars per hundredweight) are taken from monthly averages from 2009-2019 (USDA, 2020c). The final sale weights are divided by 100 to get in hundredweight terms.

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. A complete description of the disease spread model can be found in the publication by Mielke et al. (2023).

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

Table 4. Summary Statistics for Disease Spread Data

Disease Spread Variables		Percentile				
	Unit	**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

study is duration of disease. Disease duration is defined as the first detection of the disease to the last removal of an infected animal, and it is tracked at the pen level. While clinical signs of FMD may take several days to manifest, it is assumed that the feedlot is using 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 is detected by the state lab, a halt movement order would be placed on the feedlot while the sample is 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 (1) be identified through surveillance or clinical signs and will remain under strict movement bans and (2) 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 (USDA, 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 death loss for some other reason, are not eligible for indemnity and only contribute to cost of the outbreak for the producer. This aligns with the policies put in place during highly pathogenic avian influenza[3]. It is assumed that a herd management plan with an agreed upon indemnity value would be in place before disease response being for any animal to 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.

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[3] https://www.aphis.usda.gov/publications/animal_health/2016/hpai-indemnity.pdf

The number of cattle that are infected by pen in each of the 100 iterations are 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, both due to the disease and due to secondary infections. Bovine respiratory disease (BRD) commonly occurs in feedlots and has a similar morbidity rate to 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 infection for cattle already stressed from FMD infection. In this setting, it is assumed a FMD death loss would be 37.04 percent (Peel, 2020) for clinically FMD infected cattle. Further, cattle that do not perish from disease but experience severe clinical illness may require welfare euthanasia. It is assumed that about 10 percent 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 outbreak of FMD occurs in a herd, USDA APHIS will provide indemnity payments to recompense the value of eligible depopulated cattle (USDA, 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[4]. Furthermore, the USDA APHIS may provide compensation for producer time, equipment and supplies used in response activities on the operation in accordance with the herd management plan (USDA, 2024).

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

$$\max_{y} E(\pi) = [E(P) - E(r)]y \tag{1}$$

$$\text{subject to: } y \geq 0$$

$$y = N - z \tag{2}$$

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 in per head terms (Lardy, 2018). Feeding costs are in cents per lb. per head, which is taken by the average weekly pounds of feed per animal in the feedlot (personal communication, 2020). Disease management costs are used from Mielke et al. (2023). These costs relate to the detection, surveillance, cleaning and disinfecting, euthanasia, and disposal of animals.

Due to 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 COVID-19 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 simulated FMD market impact studies 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 authors such as Paarlberg et al. (2008). Market prices from 2020 were broken into an early year period (normal or mid-level

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[4] Available online at: https://www.fsa.usda.gov/programs-and-services/conservation-programs/reports-and-statistics/conservation-reserve-program-statistics/index

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

Variable	Unit	Value
Production Costs		
Labor Wage	Dollar Per Hour	12.96
Management	Dollar Per Hour	57.43
Animal Health Costs	Dollar Per Head	12.00
Feed Costs	Dollar Per Pound	0.075
Disease Management and Response Costs		
Vaccination Costs	Dollar Per Head	7.01
Virus Detection Costs	Dollar Per Head	68.87
Virus Elimination Costs	Dollar Per Head	63.90
Appraisal Costs	Dollar Per Head	89.00
Disposal Costs	Dollar Per Head	70.12
Equipment Costs	Dollar Per Week	125.00
Truck Costs	Dollar Per Mile	4.00
Indemnity		
Indemnity	Dollar Per Head	1,268.80
Market Prices		
Low Price Range[1]		
heifers	Dollar Per CWT	88.00/106.99
steers	Dollar Per CWT	95.20/114.39
Medium Price Range[1]		
heifers	Dollar Per CWT	104.64/127.92
steers	Dollar Per CWT	108.70/134.98
High Price Range[1]		
heifers	Dollar Per CWT	121.00/139.43
steers	Dollar Per CWT	123.2/148.16
Price Standard Deviation[2]		
heifers	Standard Deviation	8.56/10.18
steers	Standard Deviation	7.10/11/09
Discount Mean (Standard Deviation)	Percent Decline	20% (10%)

Notes: 1/Price ranges reflect the varying price per hundred weight (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.
2/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.

prices), an 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. A summary of production costs, management expenses, and market values has been included in **Table 5**.

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.

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 was 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. This would increase 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, 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 of 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 is possibly enforced by the government, total depopulation would be preferred as 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 in all instances would be preferred. For these weight groupings, it is not beneficial to sell at a discounted market, therefore an indemnity payment would be preferred. For light- to medium-weight cattle, a feedlot operator, while the reverse is true for medium- to heavy-weight cattle. As movement restrictions are enforced in a managed outbreak, the cost of feeding those medium- to heavy-weight animals grows substantially each day.

Depopulation is the least preferred across all weight groupings when examining 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 the conflicting objectives between private feedlot owners and the government. Feedlot owners and governmental agencies often have opposing goals when it comes to managing an FMD outbreak. For feedlot owners, the primary economic objective is to maximize profit. This involves selecting a management strategy that minimizes

Table 6. Average Recoverable Profit by Weight Grouping and Management Strategy (in Million U.S. Dollars)

	Weight Grouping												
Strategy Name	**L1**	**L2**	**L3**	**L4**	**L5**	**L6**	**L7**	**L8**	**L9**	**L10**	**L11**	**L12**	**Total**
Baseline	4.284	5.095	3.826	3.574	5.098	3.617	2.996	3.779	3.878	4.494	4.859	2.566	48.067
MgO	3.443	3.889	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	4.917	3.580	2.973	3.503	3.618	4.175	4.371	2.136	44.820
CS_NV_midp	3.633	4.238	3.276	2.991	4.293	2.996	2.559	3.036	3.243	3.655	3.879	1.925	39.723
CS_NV_lowp	3.077	3.594	2.638	2.344	3.491	2.492	2.120	2.628	2.775	3.200	3.274	1.677	33.310
CS_V_highp	3.921	4.634	3.717	3.274	4.921	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	4.280	3.054	2.482	3.072	3.238	3.624	3.853	1.920	39.586
CS_V_lowp	3.060	3.492	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	5.625	3.867	3.445	3.916	4.087	4.695	4.952	2.552	51.059
TD_NV_midp	4.053	4.920	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	4.042	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	5.688	3.997	3.436	3.904	4.054	4.768	4.927	2.451	51.279
TD_V_midp	4.166	4.973	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	4.033	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	2.481	3.711	4.041	3.363	3.932	3.959	4.264	4.814	2.562	43.013

Note: An underlined figure signifies the worst lot outcome in a strategy whereas a bold figure signifies the best.

Table 7. Average Government Expenditure by Weight Grouping and Management Strategy (in Million U.S. Dollars)

	Weight Grouping												
Strategy Name	**L1**	**L2**	**L3**	**L4**	**L5**	**L6**	**L7**	**L8**	**L9**	**L10**	**L11**	**L12**	**Total**
Baseline	0.383	0.445	0.328	0.287	0.413	0.284	0.234	0.276	0.276	0.303	0.350	0.197	3.777
MgO	0.347	0.403	0.297	0.259	0.374	0.256	0.211	0.249	0.249	0.274	0.316	0.180	3.417
CS_NV_highp	0.347	0.403	0.297	0.259	0.374	0.256	0.211	0.249	0.249	0.274	0.316	0.180	3.417
CS_NV_midp	0.347	0.403	0.297	0.259	0.374	0.256	0.211	0.249	0.249	0.274	0.316	0.180	3.417
CS_NV_lowp	0.347	0.403	0.297	0.259	0.374	0.256	0.211	0.249	0.249	0.274	0.316	0.180	3.417
CS_V_highp	0.347	0.403	0.297	0.259	0.374	0.256	0.211	0.249	0.249	0.274	0.316	0.180	3.417
CS_V_midp	0.347	0.403	0.297	0.259	0.374	0.256	0.211	0.249	0.249	0.274	0.316	0.180	3.417
CS_V_lowp	0.383	0.445	0.328	0.287	0.413	0.284	0.234	0.276	0.276	0.303	0.349	0.197	3.776
TD_NV_highp	0.383	0.445	0.328	0.287	0.413	0.284	0.234	0.276	0.276	0.303	0.349	0.197	3.776
TD_NV_midp	0.383	0.445	0.328	0.287	0.413	0.284	0.234	0.276	0.276	0.303	0.349	0.197	3.776
TD_NV_lowp	0.383	0.445	0.328	0.287	0.413	0.284	0.234	0.276	0.276	0.303	0.349	0.197	3.776
TD_V_highp	0.383	0.445	0.328	0.287	0.413	0.284	0.234	0.276	0.276	0.303	0.349	0.197	3.776
TD_V_midp	0.383	0.445	0.328	0.287	0.413	0.284	0.234	0.276	0.276	0.303	0.349	0.197	3.776
TD_V_lowp	0.383	0.445	0.328	0.287	0.413	0.284	0.234	0.276	0.276	0.303	0.349	0.197	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	2.995	51.366

financial losses and allows for business continuity. Controlled slaughter and target depopulation are attractive strategies to owners as they enable for the sale of recovered animals, even if at a lower price to manage risk. These sales ensure 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. A 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, it is noted that some strategies are statistically different from others. Appendix **Table A1** 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, both controlled slaughter under high prices strategies, with and without vaccination, are not statistically different from the three other scenarios. As well, the strategies of targeted depopulation with no vaccination are not statistically different from the equivalent with vaccination at all three price levels, respectively. 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 respective strategies.

This is further highlighted in **Figures 2**, **3**, and **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 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 foot-and-mouth disease, 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 are 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 is financially better to manage the outbreak and utilize a stamping-out strategy.

Many factors would contribute to the feasibility of stamping-out on a feedlot operation versus a controlled slaughter response, and the decision would likely be dependent on individual feedlot characteristics, location, nearby processor capacity, market conditions, and resources available (McReynolds and Sanderson, 2014; Schroeder et al., 2015; DeOtte and DeOtte, 2010; Elbakidze et al., 2009). Some of these considerations are included in the calculations of recoverable profits and governmental expenditures. Considerations include varying price environments, finite labor and disease response resources, and availability of nearby processing facilities. This approach allows for real-world complexities and tradeoffs 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 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 prices, mid-level prices, and high prices. The three price levels (**Table 5**) have a notable influence in both controlled slaughter and targeted depopulation strategies. Yet, since targeted depopulation is more dependent on the value that can be recovered from the market, 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 head infected is typically the entire feedlot for managed outbreak and controlled slaughter, only the targeted depopulation strategy is examined in three

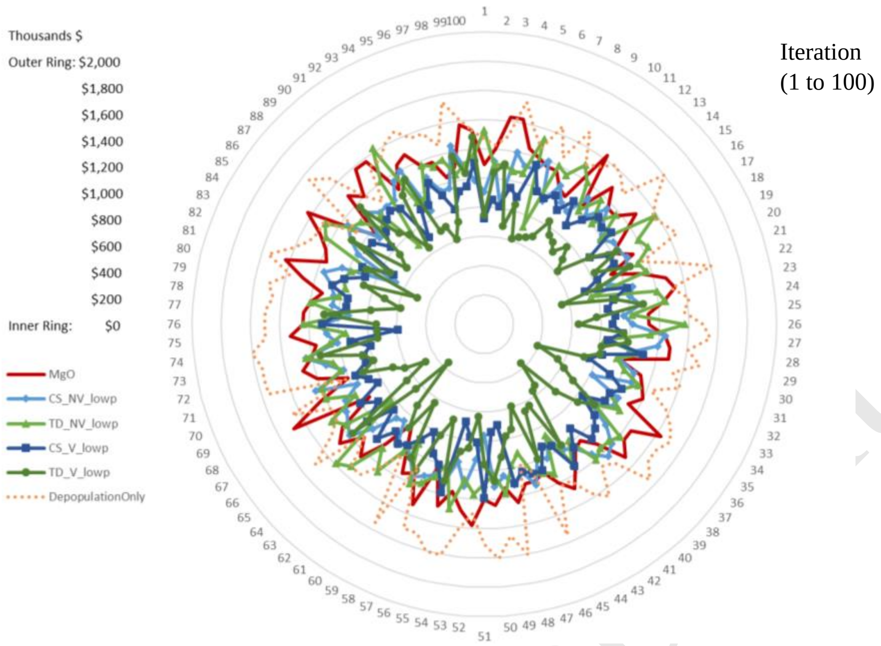


Figure 2. Recoverable Profit by Disease Spread Iteration and Scenario Low 2020 Cattle Prices (thousands of 2020 dollars)

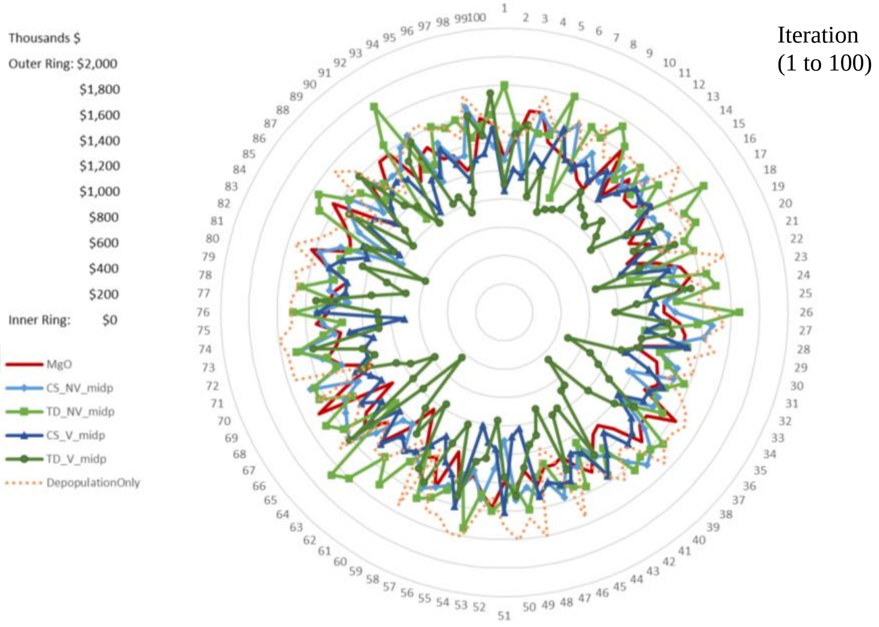


Figure 3. Recoverable Profit by Disease Spread and Scenario Under Mid 2020 Cattle Prices (thousands of 2020 dollars)

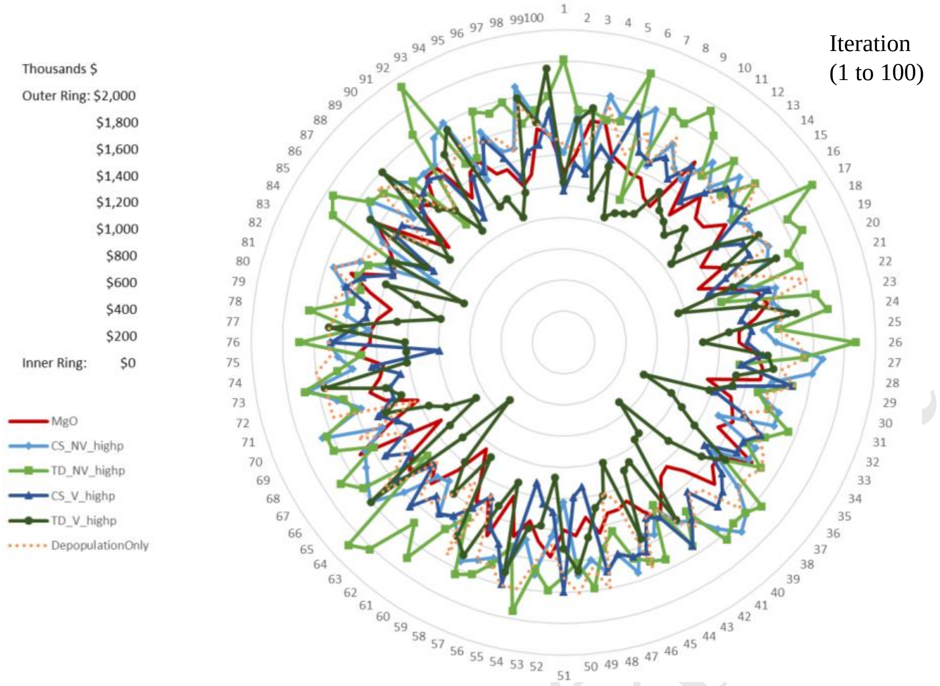


Figure 4. Recoverable Profit by Disease Spread Iteration and Scenario Under Peak 2020 Cattle Prices (thousands of 2020 dollars)

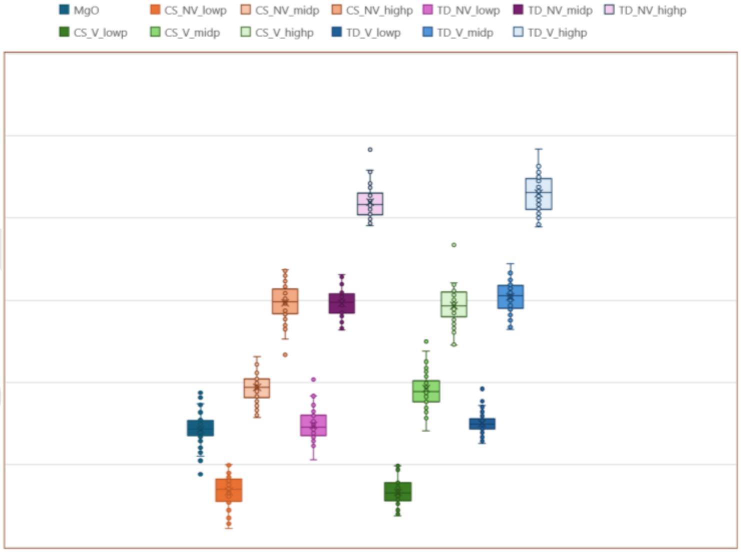
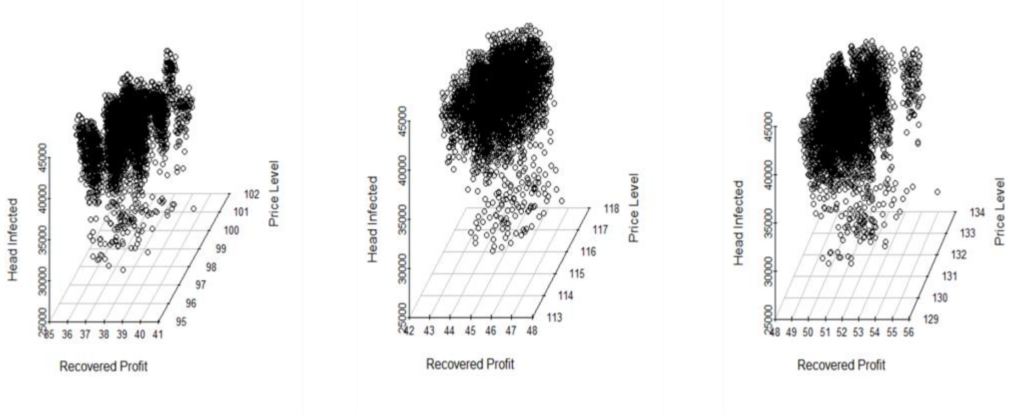


Figure 5. Comparison of Recoverable Profits by Management Strategy with Varying Market Prices.

Note: 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) Targeteed Depopulation Low Price Levels (a)

(b) Targeteed Depopulation Mid-Price Levels (b)

(c) Targeteed Depopulation High Price Levels (c)

Figure 6. Comparison of Targeted Depopulation under low prices (6a), mid-prices (6b) and high prices (6c) in Targeted Depopulation Management Strategies, Based on Recoverable Profit, Price Level and Head Infected

dimensions. In the low-price range setting, recovered profits cluster more tightly at lower levels under lower prices, as would be expected in a profit-maximization framework. Recoverable profits continued to be low in most iterations of increasing outbreak duration and size — and consequently greater numbers of cattle subject to a steep price decline. The effect of head infected is somewhat similar for mid-price and high-price levels. Yet, the potential to recover profit is consistently greatest under less steep discounts by processors. It is important to note that larger outbreaks in severity and duration 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 as recovered cattle are worth less. Additionally, outbreaks of longer duration also contributed 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 but greater social and economic welfare losses, supply chain, and food security. This study provides insight on the tradeoffs of alternative management strategies in a large feedlot setting to mitigate disease spread and allow business operations to resume. 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, such as vaccine, 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 result of this study may help feedlot owners and decision makers when selecting a response from the list outlined in the FMD RedBook to ensure minimal animal losses 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.

Exploring how beef from controlled slaughter can be used or where to market the beef were not evaluated and is a limitation of this study. 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, layouts, and 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 still moving cattle in the 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; USDA, 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 as safe for consumption.

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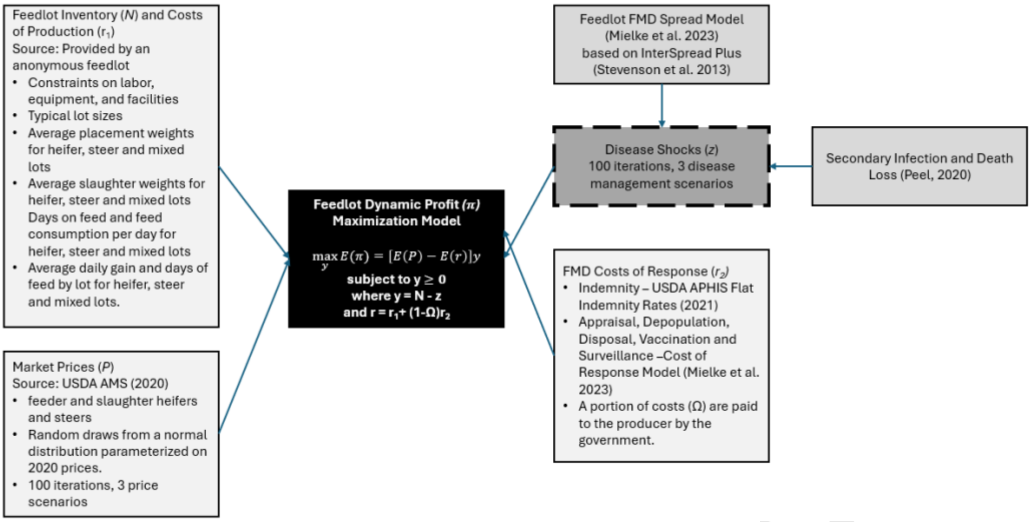

Figure 1. Graphical Representation of the Feedlot Dynamic Profit Maximization Model

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