Economics analysis of mitigation strategies for FMD introduction in highly concentrated animal feeding regions

Levan Elbakidze
University of Idaho
lelbakidze@uidaho.edu

Linda Highfield
Texas A&M University

Michael Ward
University of Sydney

Bruce A. McCarl
Texas A&M University

Bo Norby
Texas A&M University

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1 Introduction

Infectious livestock diseases present serious threats to the US agricultural economy as evidenced by the 2003 discovery of a US BSE infected cow and the consequent loss of export markets. Although foot and mouth disease (FMD) has not been observed in the US since 1929 (McCauley et al. 1979), a potential outbreak could lead to severe consequences for the agricultural industry as indicated by the 2001 outbreak in the UK. In that outbreak the losses to the agricultural industry were projected to be anywhere from $720 million to $2.304 billion with estimated tourism losses even higher (Mangen and Barrell, 2003).

Given the magnitude of potential damages a number of investigations of a possible US FMD outbreak and associated policies have been completed. For example, Pendell et al. (2007) studied the consequences of FMD outbreaks originating at a single cow-calf operation, a single medium size feedlot, and simultaneous introduction at five large feedlots in southwest Kansas. They found that economic damages would be substantially higher if an FMD outbreak started simultaneously at five large feedlots rather than at a single medium size feedlot or at a single cow-calf herd. Ekboir estimated that potential losses due to a hypothetical FMD outbreak in California would amount to $13.5 billion, which includes direct losses to livestock producers, disease control costs, including depopulation, and direct or imputed losses to businesses (Ekboir 1999, Pritchet et al. 2005). Schoenbaum and Disney (2003) estimated that net changes in consumers' and producers' surplus due to a hypothetical FMD outbreak in the United States would amount to $789.9 million annually.

Many studies have also investigated economic effectiveness of various strategies for infectious animal disease management. Vaccination and slaughter have been the most commonly studied responses. Ferguson et al. (2001) called for cost-benefit analysis of mass vaccination options versus slaughter based control of infrequent outbreaks. Schoenbaum and Disney (2003) investigated the effectiveness of four slaughter and three vaccination strategies under varying conditions of herd sizes and rates of disease spread in the U.S. The slaughter options included slaughtering only infected herds, slaughtering herds with direct contact with the infected herd in the 14 days prior to the detection of the infection, slaughtering herds within 3km distance of infected herd, and slaughtering herds with both direct and indirect contact with the infected herd. Vaccination options included no vaccination, vaccinating all herds within 10 kilometers of the infected herds after 2 herd infections were detected, and vaccinating all herds within 10 kilometers of the infected herds after 50 herd infections were detected. They found that the choice of the best mitigation strategy depended on herd demographics and on the rate of contact among herds. Generally, they found that ring slaughter (3 km) was more costly than other slaughter strategies. Ring vaccination was more costly than controlling with slaughter alone. However, early ring vaccination decreased the duration of outbreaks. Other studies have suggested that mitigation efforts need to be coordinated across the regions of the country involved in adverse events like infectious animal disease outbreaks. For example, Rich and Winter-Nelson (2007) argue that since some regions would gain more from vaccination than from stamping out, compensation mechanisms may be needed to make culling, which they found to be a preferred strategy in the long run, acceptable across the entire multiregional zone. Zhao et al. (2007) investigated the effects of traceability, depopulation, and vaccination strategies on prices, welfare changes, and cattle breeding stock under a hypothetical outbreak of FMD in the US.

Garner and Lack (1995) investigated the effectiveness of four control options for FMD, including a) "stamping out" of infected herdsonly, b)" stamping out of infected and dangerous contact herds, c) stamping out of infected herds plus early ring vaccination, and d) stamping of infected herds plus late ring vaccination. They found that if FMD is likely to spread rapidly then slaughter of dangerous contacts and infected herds reduced the economic impact of the FMD outbreak. Early ring vaccination turned out to reduce the size and duration of an outbreak, but was uneconomic when compared to stamping-out alone. Keiling, et al. (2001) found that both ring slaughtering and ring vaccination were effective if implemented rigorously, although ring slaughtering was more effective. A neighborhood cull option was found to be more effective than neighborhood vaccination. They also argue that spatial distribution, size, and species composition of farms all influence the pattern and regional variability of outbreaks.

Morris et al. (2001) found that delaying the slaughter of animals at the infected farms beyond 24 hours would have slightly increased the size of the FMD epidemic in Great Britain in 2001. Failure to carry out pre-emptive slaughter of animals at the susceptible farms would have substantially increased the size of the epidemic. Vaccination of up to three of the most outbreak dense areas, in addition to an adopted control policy, such as slaughter, would have slightly decrease the number of infected farms. However, relying solely on vaccination and disregarding other control policies would have significantly increase the size of an outbreak.

In this study we contribute to this literature by investigating the effectiveness of some previously unaddressed strategies including early detection, enhanced vaccine availability, and enhanced surveillance under various combinations of slaughter, surveillance, and vaccination options across four different disease introduction scenarios. The four scenarios for initial introduction of FMD are, introduction at a large feedlot (greater than 50,000 head), introduction at a backgrounder feedlot, introduction at a large grazing herd (greater than 100 head), and introduction at a backyard herd (less than 10 head) all done in the context of southern great plains beef feedlot operations.

We rely on an epidemiologic model to simulate the spread of disease across the region under various combinations of disease control options, and on the economic module to estimate monetary consequences for the regional cattle industry. The analysis is applied to a highly concentrated cattle feeding region of Texas, which is the largest cattle production state in the U.S., with more than 14 million cattle and calves produced annually (USDA, 2006). The predominant concentration of the feedlot industry in Texas is within the Panhandle region.

2 Modeling Approach

The modeling framework employed consists of two components. The epidemiologic module simulates the spread of FMD under various control policies and introduction scenarios. In turn, an economic module uses the epidemiologic output to calculate corresponding losses within local cattle industry and costs of employed disease control options.

2.1 *Epidemiologic component*

The epidemiologic model used (AusSpread) is a stochastic state transition model which operates within a geographic information system (GIS) framework (Garner and Beckett, 2005). The spread of the disease is based on a susceptible, latent, infectious, recovered state transition specification where herds fall into one of the four categories at any given time period (Garner and Beckett 2005). The probabilities of transition from susceptible to latent states depend on the rate of direct and indirect contacts between herds and the probability of infection given contact. Direct contacts between herds involve the movement of animals between herds. Indirect contacts arise as a result of people or equipment movement between herds. In addition to modeling contacts between herds, the model also incorporates disease spread due to sale barns, order buyers and windborne spread from large feedlots and swine facilities. AusSpread (Garner and Beckett, 2005) was calibrated (Ward et al., 2007) to fit the Texas High Plains cattle industry.

2.1.1 Data

The study area, in the High Plains of Texas, consisted of eight counties, which encompassed 20,500 square kilometers. In the 2002 National Agricultural Statistics Service (NASS) Census of Agriculture, there were 118 feedlots, 29 dairies, 88 swine farms, and 1,058 beef cattle premises in the study area (NASS, 2003). The Texas Commission on Environmental Quality, which keeps records of concentrated animal feeding operations (CAFOs) (e.g. feedlots and dairies), had records of 92 feedlots and 76 dairies in the study area. In total the model contains 10,675 farm premises of which 92 are feedlots. Premise boundary data was obtained from the U.S. Department of Agriculture, Agricultural Research Service (ARS).

Management practices and direct and indirect contact rates between different herd-types was estimated from face-to-face interviews with producers mentioned above, and used as input parameters in the epidemiological model. In total, 34 feedlot, 21 dairy, and 16 swine were interviewed. AusSpread simulates the spread of FMD across 13 herd types: feedlots (company-owned, stockholder, custom, backgrounder, yearling-pasture, and dairy calf-raiser), small (<100) and large grazing beef (>100), small (<1000) and large (>1000) dairy, backyard cattle, swine and small ruminant.

2.1.2 Detection

Two disease detection possibilities were considered in this study to evaluate the economic effectiveness of early detection. Specifically, early detection of FMD was assumed to occur on day 7, whereas late detection was assumed to occur on day 14 (Ward et al., 2007).

2.1.3 Slaughter

It was assumed that slaughter began 1 day post detection, day 8 or day 15 depending on early or late detection, and that only 1 herd (the index herd) would be slaughtered on the first day of discovering the epidemic (Ward et al., 2007). The number of herds that could be slaughtered per day was assumed to depend on resource availability, limited by the number of available slaughter teams (Ward et al., 2007). The estimated number of teams available was assumed to start at one and increased to a maximum of 10 on day 21 of the epidemic (Ward et al., 2007). Herds were prioritized for slaughter based on a an assigned risk category and based on elapsed time since scheduled for slaughter (Ward et al., 2007)

2.1.4 Vaccination

The effects of adequate and limited vaccine availability were compared in this study. For the adequate vaccine availability scenarios it was assumed that vaccine was available on the day of FMD detection. In the limited, or delayed, vaccine availability scenarios we assumed that vaccine was not available until one week after disease detection (day 14 or day 21 for early and late detection respectively) (Ward et al., 2007). It was also assumed that the employment of vaccination reduced the resources available for slaughter by 25%.

Two vaccination methods were modeled (Garner and Beckett, 2005; Ward et al., 2007): suppressive (or emergency) ring vaccination, and targeted protective vaccination. With the ring vaccination option, all farms within a certain radius of a newly identified infected farm were vaccinated. The targeted protective vaccination strategy involved selecting farms of particular types and vaccinating them before they were exposed to infection.

2.1.5 Surveillance

Surveillance visits were assumed to start one day after disease detection. Enhanced and regular surveillance options were compared (Ward et al., 2007). For regular surveillance, three herds were visited on the 1st day of surveillance and suspect herds were visited twice a week during a 30-day period. For enhanced surveillance six herds were visited on the 1st day and suspect herds were visited four times a week. Herds that had been vaccinated were not subject to surveillance visits. Surveillance also stopped if a contiguous slaughter policy was implemented (Ward et al., 2007).

2.1.6 AusSpread output

The model generates the status of each heard at the end of the outbreak. The output indicates for each herd whether or not it was infected, slaughtered, vaccinated, or under surveillance.

2.2 Economic component

The economic costing module calculates the costs associated with an animal disease outbreak based on the AUSPREAD output. Generally, components of total costs are grouped into two categories, losses incurred within the cattle industry as a result of the outbreak, and total costs of implementing the employed disease management strategies. Losses in cattle industry include gross lost value of animals, which includes lost sale value, and lost gross income due to temporary business inactivity of affected producers. Costs of implementing mitigation strategies include costs of slaughter, including costs of appraisal, euthanasia, carcass disposal, cleaning, and disinfection. In addition, the costs include costs of vaccination and costs of surveillance (see appendix).

AUSPREAD generates output by herd but not by animal type. In other words, the epidemiologic output reflects herd types but does not account for composition of herds by animal types. Thus the herd data was converted to the effect on types of animals so animal values could be applied. Herd compositions for the above 13 herd types were obtained from industry experts, primarily from Texas Cattle Feeders Association. The herds where characterized in terms of percentages of animals by type where the types used were:

- steers less then 600 lbs,
- heifers less then 600 lbs,
- steers between 600 and 800 lbs,
- heifers between 600 and 800 lbs,
- steers between 1000 and 1200 lbs,
- heifers between 1000 and 1200 lbs,
- steers between 1200 and 1400 lbs,
- heifers between 1200 and 1400 lbs,
- steers greater than 1400 lbs,
- heifers greater than 1400 lbs,
- dairy cows,
- ewes,
- rams,
- male lambs,
- female lambs,
- male yearling lambs
- female yearling lambs,
- sows,
- boars,
- male piglets, and
- female piglets.

Industry losses were calculated for number and type of culled animals, and number and type of vaccinated animals. The value of slaughtered herds was calculated according to herd status based on epidemiologic simulation coupled with information on herd size and herd composition in terms of animal types. Herds with the status of infected, dead, immune, or latent, were counted towards lost value. Losses by animal type were calculated by multiplying herd size by animal type distribution. This measure was summed for all slaughtered herds.

Vaccinated animals were assumed to lose 50% of their market value to reflect the fact that due to international regulations in the presence of FMD, even if trade was regionalized within the affected country, vaccinated animals were not eligible for trade. However, vaccinated animals might be eligible for some domestic uses such as dog food etc. The model was built with the capability to adjust the current assumption to allow vaccinated animals to retain their market value or to lose their market value completely.

Loss of animal sales revenues was calculated using estimates provided by industry experts at Texas Cattle Feeders Association. Forgone income was calculated according to herd type, animal type composition, and size assuming that producers whose cattle were culled were kept out of business for at least 60 days. In other words, after depopulation, infected premises were not allowed to repopulate the herds for at least 60 days, during which period they lost income which would have been generated if the herd was repopulated immediately after depopulation, cleaning and disinfection. In addition, loss of daily revenues was also calculated for quarantined farms depending on the length of quarantine. Costs associated with disinfection of feed trucks supplying feed to quarantined herds were also accounted for.

3 Study Design

Single site introductions of FMD at a large feedlot, backgrounder feedlot, large grazing operation, and backyard herd, were used to initiate the epidemic (Ward et al., 2007). Within each of these 4 introduction sites, 16 mitigation strategies were simulated, which included various combinations of early or late detection, ring or targeted vaccination, adequate or inadequate vaccination, and regular or enhanced surveillance. Each scenario was simulated one hundred times. A Complete Randomized Design (CRD) was used to conduct an ANOVA (Analysis of variance) analysis for comparison of early vs. late detection, adequate vs. delayed vaccine availability, and enhanced vs. regular surveillance.

4 Results

Simulations suggest that, on average, an epidemic might cost up to about $1 billion in local high-intensive cattle industry losses alone. Based on the assumptions and the results of epidemiologic disease spread simulations, the economic analysis indicated that generally early detection was the most economically effective control option of those considered in this study. The payoff for detecting an incursion earlier was substantial: in the case of an epidemic originating in a large feedlot, the cost saving on average was $150 million. Although the costs of early detection programs were not modeled in this study, the findings suggested that if an outbreak was to originate in a large feedlot an early detection program, which would cost up to $150 million would likely pass the benefit cost test. Adequate vaccine availability and enhanced surveillance were not economically effective in minimizing overall costs of disease outbreak, compared to delayed vaccine availability and the default surveillance strategy, respectively (Figure 1).

Using corresponding group medians as measures of the central values, we found that early detection (Table 2) resulted in lower median epidemic costs for all types of introduction scenarios. Early detection reduced the median epidemic costs by approximately $150 million (68%), $40 million (69%), $5 million (74%), and $3 million (97%) for Large Feedlot, Backgrounder Feedlot, Large Grazing, and Backyard introductions respectively.

Adequate vaccine availability and early application had a significant positive effect on the group medians for epidemic costs (Table 3) as compared to delayed vaccine availability and application. The epidemic costs increased significantly due to the costs of vaccination and due to the assumed 50% loss in the value of vaccinated animals. Depending on the introduction scenario, enhanced vaccination could increase median costs by 14 to 100 million due to costs of vaccination and losses the market values of vaccinated animals.

For enhanced vs. regular surveillance, the results suggested mixed effects on the medians of economic costs of the epidemic, depending on the introduction scenario (Table 4). The epidemic costs were increased by $53 million (45%) for the Large Feedlot introduction scenario. For backgrounder, feedlots, large grazing operations, and backyard incursion scenarios, enhanced surveillance decreased costs by $16 million (31%), $1 million (23%), and $1.6 million (77%).

The ANOVA comparison indicated that early detection had a statistically significant impact on the predicted economic costs of the epidemic for all introduction scenarios resulting in lower economic costs (Table 8). Enhanced vaccination also had a statistically significant effect on economic costs. However, the costs were increased due to enhanced vaccination. Enhanced surveillance did not have statistically significant effect on economic costs for backgrounder feedlot and large grazing farm introduction scenarios at the 99% level of confidence, but did have a statistically significant effect at the 95% confidence level, increasing costs.

Figures 2a :2d show cumulative distribution of loses under various combinations of mitigation strategies for the four introduction scenarios. Overall, the damages seem to be the greatest for large feedlot introduction scenarios where the costs could go up to 1 billion dollars, whereas in the other three introduction scenarios the losses go up to 600 to 800 million dollars. For each of the introduction scenarios cumulative density functions of some o the mitigation strategies cross while others do not. While for those that cross it is hard to assess stochastic dominance without prior information on risk preferences of decision makers (Meyer, 1977), for those that do not cross unambiguous statements can be made on relative superiority of respective mitigation strategies. For example, figure 2a shows that for large feedlot introduction, scenarios 57, 13, 9, 25, and 29 (Table 1), all of which have late detection, are stochastically inferior to the rest of the scenarios. While, for example, enhanced surveillance does not prove to be stochastically superior to regular surveillance under the context of slaughter of infected and dangerous contact herds, late detection, and targeted early vaccination (scenarios 25 vs 57), it is clear that ring vaccination with delayed vaccine availability (scenario 45) stochastically dominated target vaccination with early vaccine availability (scenario 57). Similarly, in Backgrounder feedlot introductions scenarios 10, 26, 58, 14, and 50 are stochastically inferior to other mitigation strategies (figure 2b). For the outbreaks originating in large grazing operations (figure 2c), mitigations strategies in scenarios 11, 27, and 59 appear to be stochastically inferior to the rest of the mitigation strategies. For backyard introductions (figure 2d), scenarios 12, 60, 28, 52, 16, and 32 are stochastically inferior to other scenarios. Overall these figures suggest that mitigation strategies with earlier disease detection are likely to be stochastically superior to those with delayed disease detection.

We used Generalized Stochastic Dominance methodology (McCarl 1990) to make inferences on the scenarios for which the cumulative distribution functions crossed. We found that for large feedlot introduction scenarios of all 16 considered mitigation strategies, the strategy of slaughter of infected, slaughter of dangerous contacts combined with regular surveillance and early detection was dominant if risk aversion coefficient (RAC) is below 0.01 or above 0.099, while for RAC between those values the strategy of slaughtering infected and dangerous contact herds combined with early detection and enhanced surveillance was dominant. For backgrounder feedlot introduction scenarios, if RAC is lower than -0.099 then slaughtering infected and dangerous contact herds combined with early detection and enhanced surveillance is dominant. If RAC is greater then -0.099 than the strategy with slaughtering infected and dangerous contact herd combined with early detection and regular surveillance is dominant. For large grazing herd introduction scenarios, if RAC is below 0.13 then the dominant strategy is to slaughter infected and dangerous contact herds combined with regular surveillance and early detection. Otherwise dominant strategy is slaughter of infected and dangerous contact herds combined with early detection and enhanced surveillance. For backyard herd introduction scenarios the strategy of slaughtering infected and dangerous contact herds combined with enhanced surveillance and early detection is dominant at all values of RAC.

Overall, early detection of FMD had the largest impact on reducing the epidemic costs. Vaccine availability did not reduce economic costs while intensity of disease surveillance only affected results in some specific epidemic scenarios. These results indicate that programs for early detection of the disease may be desirable. For the sake of comparison we assumed that early detection occurred seven days prior to late detection. Such a difference could be achieved via education of livestock managers to recognize the early signs of FMD. Technological advances may also assist in detection of an outbreak early. There is an opportunity to optimize surveillance systems, particularly in the form of the application of syndromic surveillance.

In general, enhanced vaccine and enhanced surveillance mitigation options were not cost effective. In the scenarios in which the index case was a large feedlot, these mitigation options could increase the median total cost by $50 to $100 million. However, in the scenarios in which the index case was a backgrounder feedlot, large grazing herd, or backyard herd, the cost was reduced with enhanced surveillance.

5 Conclusions

In this study we used a linked epidemiologic-economic modeling framework to investigate the effectiveness of several options to control Foot-and-Mouth disease under four scenarios of introduction within a highly concentrated cattle feeding region. The AusSpread epidemiologic model (Garner and Beckett, 2005) was calibrated to fit the cattle industry characteristics of Texas High Plains and used to simulate disease outbreak and control option cases (Ward et al., 2007). The economic component reflected the costs of disease outbreak for the local livestock industry in terms of lost animal values and lost gross revenues due to the outbreak. In addition, the economic component included the costs of some of the disease management strategies. Specifically, management costs included costs of euthanasia, carcass disposal, cleaning and disinfection, vaccination, and periodic surveillance.

The results suggest that, of the strategies considered in this study, the most effective for reducing the economic impact of an incursion of FMD in the study area is to detect the incursion as early as possible. In some situations, putting response efforts into enhanced surveillance as a management tool during the outbreak might also produce a benefit. The cost of having more vaccine available earlier during an epidemic does not appear to be effective in reducing the overall costs.

6 APPENDIX

Total costs are given by:

$$TC_{s,i} = TDC_{s,i} + TER_{s,i}$$

Where,

$TC_{s,i}$ is the total cost of outbreak under mitigation strategy *s* under introduction scenario *i*. For notational convenience subscript i is dropped in the remainder of this notation;
$TDC_{s,i}$ is the total direct cost which includes market value of lost animals and lost income
$TER_{s.i}$ is the summation of all extra expenditures to mitigate the disease, such as, surveillance implementation, slaughter costs, quarantine implementation, and vaccination costs.

The total direct cost (TDC) of the outbreak under mitigation strategy *s* is equal to:

$$TDC_s = TMVL_s + TFI_s$$

where,

$TMVL_s$ is the market value of lost animals,
TFI_s is the foregone income of farms,

$$TMVL_s = \sum_{id}\sum_{ht}\sum_{at}\sum_{status} NA_{id} AHT_{id,ht} LH_{id,status,s} Comp_{ht,at} V_{at}$$

where:

NA_{id} is the number of animals in the herd *id*
$AHT_{id,ht}$ is 0 if herd *id* is not of a type *ht*, and 1 if herd *id* is of a type *ht*
$LH_{id,status,s}$ 1 if herd *id* is latent, infected, immune, dead under strategy s
0 if susceptible
$Comp_{ht,\,at}$ is proportion of animals of type *at* in herd type *ht*
V_{at} is value per animal of type *at*

$$TFI_s = \sum_{id}\sum_{ht}\sum_{hs}\sum_{status} NA_{id} LH_{id,status,s} AHT_{id,ht} Comp_{ht,at} Income_{at} * time_{id}$$

where,

$LH_{id,status,s}$ status of the herd *id*, 1 indicates the status is latent, infected, dead and immune according to strategy s, 0 if susceptible
$AHT_{id,ht}$ is 1 if herd *id* is of a type *ht*, 0 otherwise
$Comp_{ht,\,at}$ is Proportion of animal of type *at* in herd type *ht*
$Income_{at}$ is loss per day per animal type *at*
$Time_{id,s}$ is number of days that the farm *id* was inactive; from the day that animals were slaughtered to the day that production is reinitiated.

$$TER_s = TCC_s + TSURC_s + TVC_s + QC_s$$

where,

TCC_s is the total culling costs,
$TSURC_s$ represents the total surveillance costs
TVC_s is the vaccination costs.

$$TCC_s = \sum_{id}\sum_{ht}\sum_{at}\sum_{status} NA_{id} AHT_{id,ht} Comp_{ht,at} LH_{id,status,s}(eut + CD) + \sum_{id}\sum_{hs}\sum_{status}(APC_{hs} + CCD_{hs}) LH_{id,status,s}$$

Where,

NA_{id} is the number of animals in herd *id*
$AHT_{id,ht}$ is 0 if herd *id* is not of a type *ht*, 1 if herd *id* is of a type *ht*
$Comp_{ht,at}$ is Proportion of animal of type *at* in herd type *ht*
$LH_{id,status,s}$ status of the herd *id*, 1 indicates the status is latent, infected, dead and immune according to strategy s, 0 otherwise
eut per animal cost of euthanasia
CD per animal cost of carcass disposal
APC_{hs} appraisal cost per herd based on herd size
CCD_{hs} costs of cleaning and disinfection based on herd size

$$TSURC_s = \sum_{id}\sum_{hs} HS_{id,hs} NV_{id} \cdot CT_{hs} + CV_{hs} \cdot SD_{id} \cdot HS_{id,hs}$$

$HS_{id,hs}$ is 1 if herd *id* is of herd size *hs*; i.e. small, medium, large 0 otherwise
NV_{id} is number of visits per herd
CT_{hs} is cost of testing the whole herd once
CV_{hs} is fixed cost of being under surveillance
SD_{id} is a dummy variable which is 0 if NV_{id}=0, and is 1 if NV_{id}>0

$$TVC_s = \sum_{id} NA_{id} V_{id,s} CV + \sum_{id}\sum_{hs} V_{id,s} HS_{id,hs} FCV_{hs}$$

$V_{id,s}$ is 0 if herd *id* is not vaccinated, 1 if herd *id* is vaccinated under strategy *s*
CV is cost of vaccination per animal
$HS_{id,hs}$ is 1 if herd *id* is of herd size *hs*; i.e. small, medium, large 0 otherwise
FCV_{hs} is fixed cost of vaccinating per herd size *hs*

$$QC_s = \sum_{id}\sum_{ht}\sum_{at} NA_{id} Q_{id,s}(DESCOST + Income_{at}) \cdot Time_{id,s}$$

NA_{id} is the number of animals in herd (id)
$AHT_{id,ht}$ is 0 if herd (id) is not of a type *ht*, 1 if herd (id) is of a type *ht*
$Q_{id,s}$ is 0 the herd (id) is not quarantined, 1 herd (id) is quarantined
$Comp_{ht,at}$ is Proportion of animal of type (*at*) in herd type (*ht*)
V_{at} is Value per animals of type (*at*)

DESCOST is daily disinfection costs per animal
$Income_{at}$ is loss per day per animal type *at*
$Time_{id,s}$ is number of days that the herd (id) was cut in transit under quarantine restrictions under strategy s

7 References

Bates, W. T., T. E. Carpenter, M. C. Thurmond (2003) 'Benefit-Cost Analysis of Vaccination and Preemptive Slaughter as a Means or Eradicating Foot-and-mouth Disease', *American Journal of Veterinary Research*, Vol. 64, No. 7, pp. 805-12.

Berentsen, P.B.M., A.A Dijkuizen, and A.J. Oskam. "A Dynamic Model for Cost-Benefit Analysis of Foot-and Mouth Disease Control Strategies." *Preventive Veterinary Medicine.* 12 (March, 1992):229-243.

Department for Environment Food and Rural Affairs (DEFRA), "Foot and Mouth Disease: Veterinary Risk Assessment" October 19, 2007, available on line at http://www.defra.gov.uk/footandmouth/ Last accessed, Nov, 2, 2007

Ekboir, J. M. (1999) Potential Impact of Foot-and-Mouth Disease in California, Agricultural Issues Center, Division of Agricultural and Natural Resources, University of California Davis, California.

Ferguson N. M., C.A. Donnelly, and R. M. Anderson (2001) 'The Foot-and-Mouth Epidemic in Great Britain: Pattern of Spread and Impact of Interventions', *Science*, Vol. 292, No. 5519, pp.1155-1160.

Garner, M. G. and S. D. Beckett, "Modeling the spread of foot-and-mouth disease in Australia." *Australian Veterinary Journal* 2005, 83: 758-766.

Garner M. G., and M. B. Lack., "An Evaluation of Alternative Control Strategies for Foot-and-Mouth Disease in Australia: A Regional Approach." *Preventative Veterinary Medicine*. 23(May, 1995):9-23.

Jalvingh A.W., M. Nielen, H. Maurice, A. J. Stegeman, A. R.W. Elbers, and A.A. Dijkhuizen (1999) 'Spatial and Stochastic Simulation to Evaluate the Impact of Events and Control Measures on the 1997-1998 Classical Swine Fever Epidemic in The Netherlands', *Preventative Veterinary Medicine*, Vol. 42, No. 3/4, pp.271-295.

Keiling M. J., M. E. J. Woolhouse, D. J. Shaw, L. Mattews, M. Chase-Topping, D. T. Haydon, S. J. Cornell, J. Kappey, J. Wilesmith, and B. T. Grenfell, "Dynamics of the 2001 UK Foot and Mouth Epidemic: Stochastic Dispersal in Heterogeneous Landscape." *Science.* 294 (October, 2001):813-817.

Mangen, M-J. J., and A.M. Burrell, "Who Gains, Who Losses? Welfare Effects of Classical Swine Fever Epidemics in The Netherlands." *European Review of Agricultural Economics*, 30(June, 2003):125-154.

Meyer, Jack. "Choice Among Distributions." *Journal of Economic Theory*. 14(1977):326-336.

McCauley E.H., A.A. Nasser, J.C. New, W.B. Sundquist, and W.M. Miller. *A Study of Potential Economic Impact of Foot and Mouth Disease in the United States*. Pp.242. University of Minnesota, St. Paul Minnesota, 55108. May 1979.

Morris R.S., J.W. Wilesmith, M.W. Stern, R.L. Sanson, and M.A. Stevenson. "Predictive Spatial Modeling of Alternative Control Strategies for the Foot-and Mouth Disease Epidemic in Great Britain, 2001." *The Veterinary Record.* 149(August, 2001):137-144

NASS 2003. NASS 2002 Census of Agriculture (Washington, DC, United States Department of Agriculture). (electronic reference)

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

Pritchet, J., D. Thilmany and K. Johnson (2005) 'Animal Disease Economic Impacts: A survey of Literature and Typology of Research Approaches', *International Food and Agribusiness Management Review*, Vol. 8, No. 1, pp.23-39.

Rich, K. M., and A. Winter-Nelson, (2007) 'An Integrated Epiemiological-Economic Analysis of Foot-and-Mouth Disease: Application to the Southern Cone of South America', *American Journal of Agricultural and Applied Economics*, Vol. 89. No. 3, pp. 682-697.

Schoenbaum M. A. and W. T. Disney (2003) ‘Modeling Alternative Mitigation Strategies for a Hypothetical Outbreak of Foot-and-Mouth Disease in the United States’, *Preventative Veterinary Medicine*, Vol. 58, No. 1-2, pp.25-52.

U.S. Department of Agriculture: National Agricultural Statistics Service, "Texas State Agriculture Overview, 2004", 3 January 2006, <http://www.nass.usda.gov/Statistics_by_State/Ag_Overview/AgOverview_TX.pdf> (12 January 2006)

Ward, M.P., Highfield, L.D., and Garner, M.G., Potential impact of foot-and-mouth disease incursions in the High Plains region of Texas. In RP Ellis (editor) *Proceedings of the 88th Annual Meeting of the Conference of Research Workers in Animal Diseases,* Chicago, 2-4 December 2007. Iowa State University Press, Ames IA, abstract number 23.

Zhao, Z., T. I. Wahl, and T. L. Marsh, “Invasive Species Management: Foot-and-Mouth Disease ine the U.S. Beef industry”, *Agricultural and Resource Economics Review* 35(1)(April 2006):98-115

Table 1. Median economic losses under early and late detection in ($) millions

Herd Type	Early Detection	Late Detection	Difference	Percent Difference
Large Feedlot	71.0	221.0	150.0	68%
Backgrounder Feedlot	17.8	57.7	39.8	69%
Large Beef	1.74	6.64	4.90	74%
Backyard	0.10	3.22	3.12	97%

Table 2. Median economic losses under early and delayed vaccine availability in ($) millions.

Herd Type	Early Vac.	Delayed Vac.	Difference	Percent Difference
Large Feedlot	307.0	205.0	-102.0	-50%
Backgrounder Feedlot	112.0	34.1	-77.8	-228%
Large Beef	15.9	1.90	-14.0	-736%
Backyard	74.0	0.92	-73.1	-7968%

Table 3. Median economic losses under enhanced and regular surveillance in ($) millions.

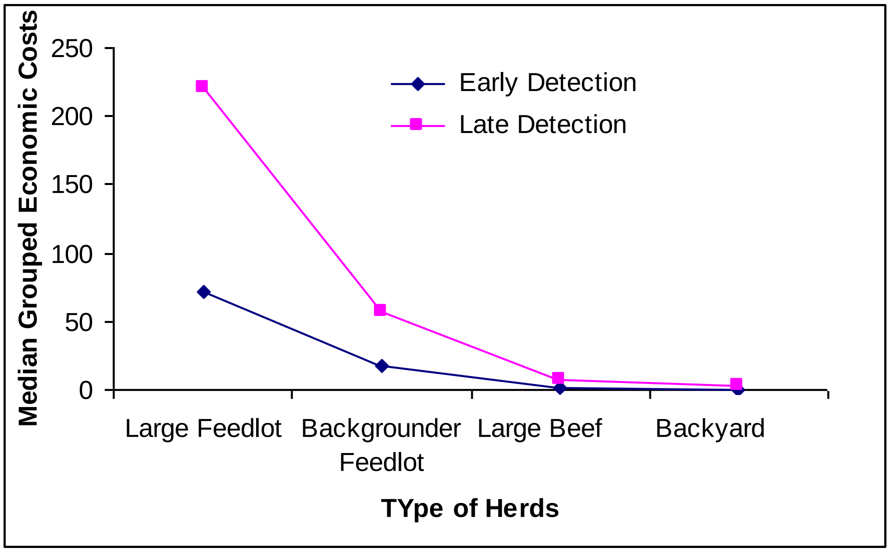
Herd Type	Enhanced Surveillance	Regular Surveillance	Difference	Percent Difference
Feedlot Type 1	172.5	119.1	-53.4	-45%
Feedlot Type 4	34.4	50.1	15.8	31%
Large Beef	3.32	4.29	0.97	23%
Backyard	0.49	2.10	1.61	77%

Table 4. ANOVA results for economic costs for mitigation strategies by introduction scenario

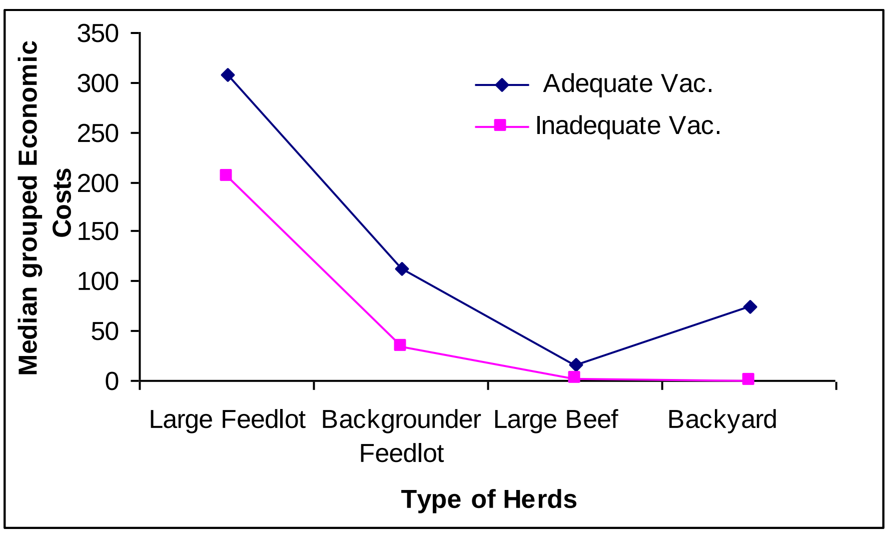
Comparison	Significantly Different?	Result	P-Value
Large Feedlot Introduction			
Early vs. late detection	Yes	Lower economic costs	<0.0001
Early vs. delayed vaccine	Yes	Higher Economic costs	=0.0001
Enhanced vs. regular surveillance	Yes	Higher Economic costs	<0.0001
Backgrounder Feedlot Introduction			
Early vs. late detection	Yes	Lower Economic Costs	<0.0001
Early vs. delayed vaccine	Yes	Higher Economic Costs	<0.0001
Enhanced vs. regular surveillance	No	Higher Economics Costs	0.19
Large beef herd introduction			
Early vs. late detection	Yes	Lower Economic Costs	<0.0001
Early vs. delayed vaccine	Yes	Higher Economic Costs	<0.0001
Enhanced vs. regular surveillance	No	Higher Economic Costs	0.0137
Backyard herd introduction			
Early vs. late detection	Yes	Lower Economic Costs	<0.0001
Early vs. delayed vaccine	Yes	Higher Economic Costs	<0.0001
Enhanced vs. regular surveillance	No	Higher Economic Costs	0.028

Figure 1. Profile plot of epidemic costs by strategy in million ($).

a) Median economic costs for early and late detection strategies



b) Median economics costs for adequate vs. delayed vaccination



c) Median economic costs for enhanced vs. regular surveillance

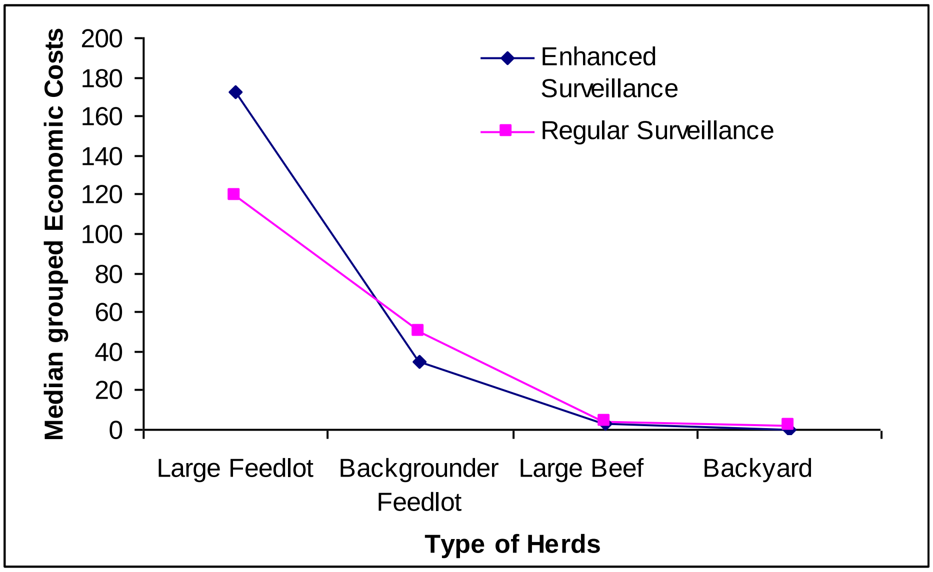
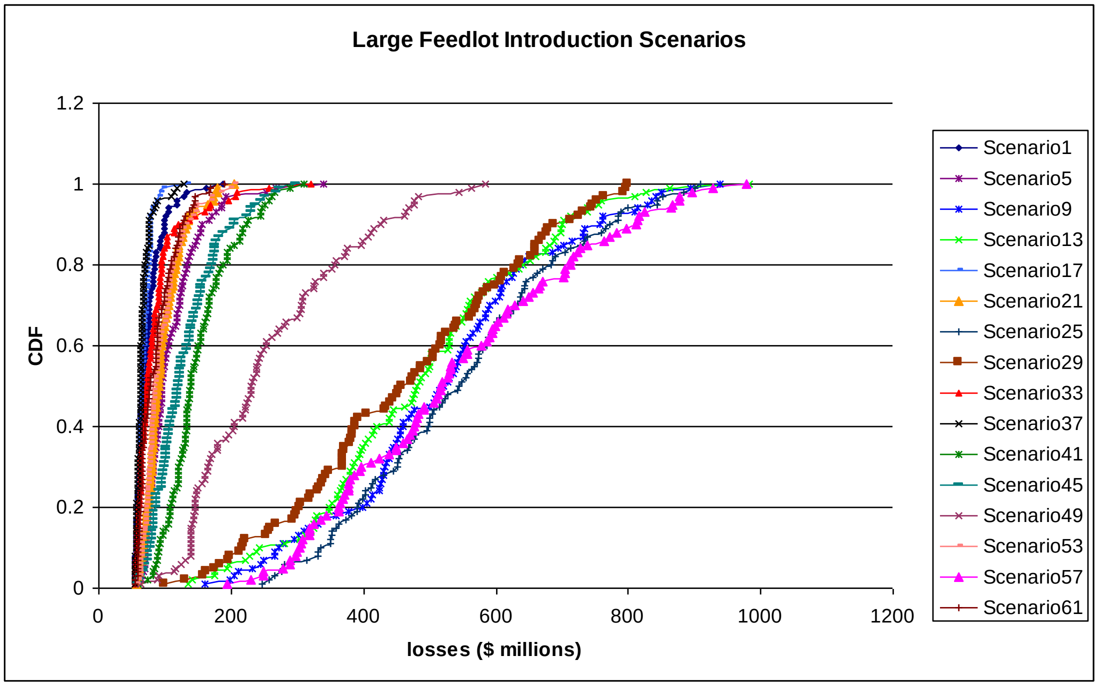
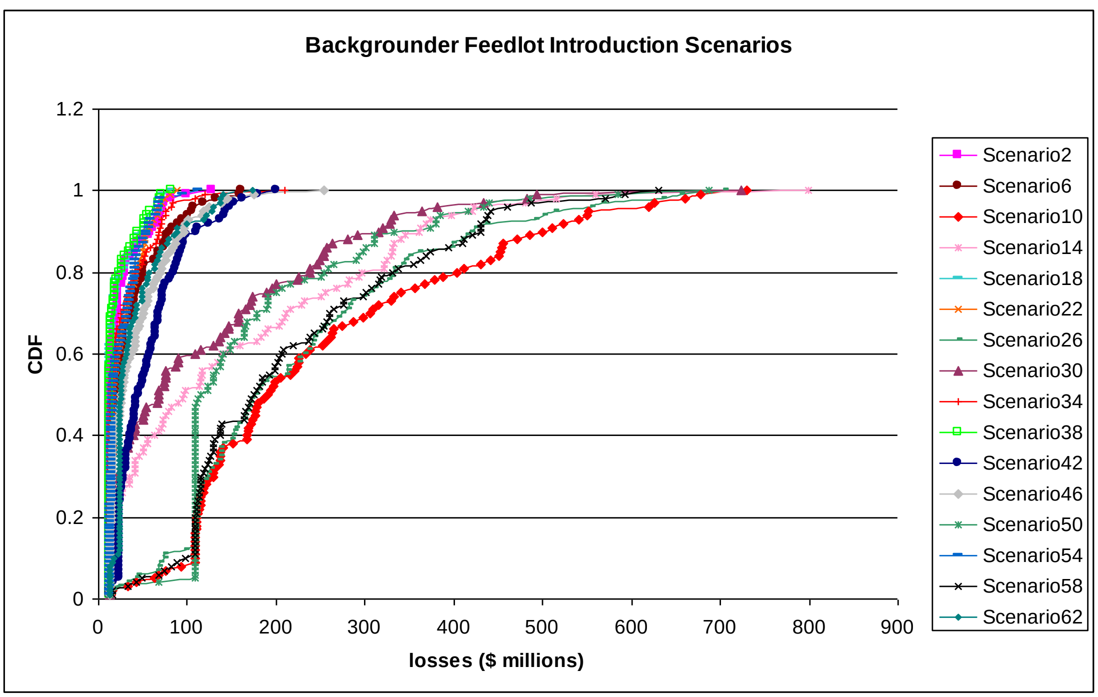


Figure 2. Cumulative Distribution of losses by introduction scenario

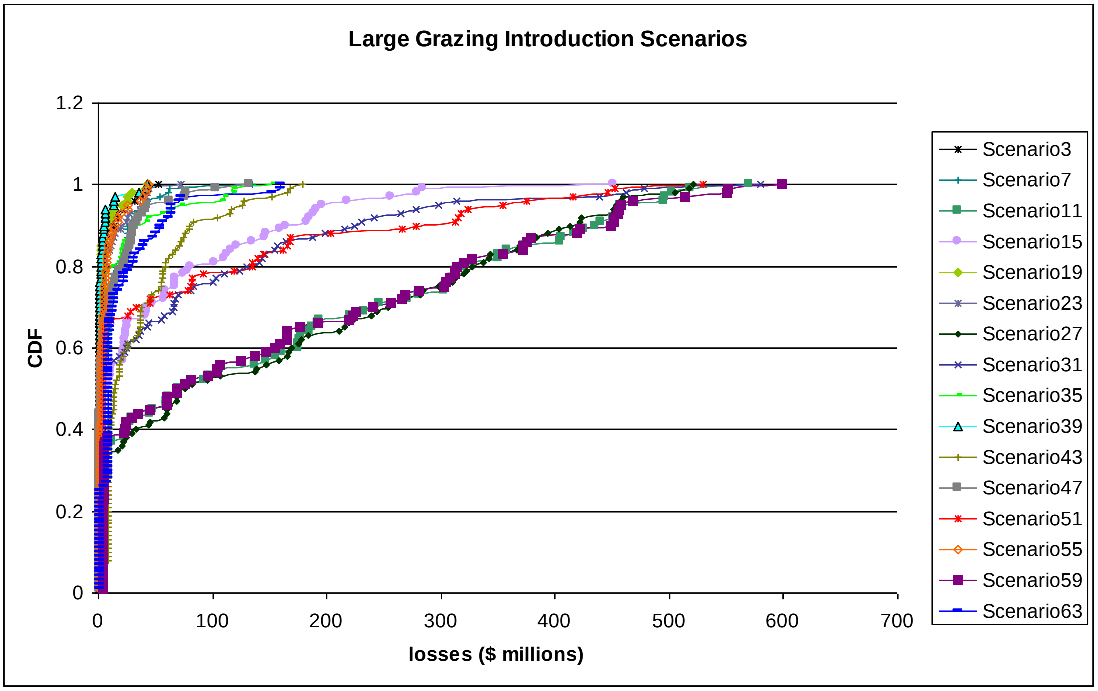
a) Cumulative Distribution of losses for large feedlot introduction scenarios



b) Cumulative Distribution of losses for backgrounder feedlot introduction scenarios



c) Cumulative Distribution of losses for large grazing operation introduction scenarios



d) Cumulative Distribution of losses for backyard herd introduction scenarios