

Title of the paper: Economics of Homeland Security: Carcass Disposal and the Design of Animal Disease Defense

Authors: Yanhong Jin, Wei Huang, and Bruce A. McCarl

Affiliation of the authors: Yanhong Jin is an assistant professor, Wei Huang is a graduate research assistant, and Bruce McCarl is a Regents Professor, in the Department of Agricultural Economics at Texas A&M University.

Name of conference: American Agricultural Economics Association, 2005

Copyright 2005 by Y. Jin, W. Huang and B. A. McCarl. All rights reserved. Readers may take verbatim copies of this document for non-commercial purposes by any means, provided that this copyright notice appears on all such copies.

Economics of Homeland Security: Carcass Disposal and the Design of Animal Disease Defense

Yanhong Jin, Wei Huang, and Bruce A. McCarl ¹

1 Introduction

New Yorkers, Washingtonians, Americans in general, and the whole world were shocked and terrified by September 11th, 2001 terrorist attack on the World Trade Center and the Pentagon. Americans did not subsequently feel as safe and at peace. Subsequently in an effort to bolster confidence and protect the nation the U.S. government through agencies like the Department of Homeland Security is identifying vulnerabilities and evolving strategies for protection. Agricultural food supply is one identified vulnerable area, and animal disease defense is one of the major concerns there under.

The Department of Homeland Security currently lists foot and mouth disease (FMD), Rift valley fever, avian influenza, and Brucella as priority threats to U.S. agriculture (Breeze 2004). Outbreaks of such diseases can have large economic implications as data on FMD outbreaks in the United Kingdom reveal. Namely,

- (a) The 1967/68 outbreak caused the slaughter of 434,000 animals, leading to a direct cost of £35 million borne by the Ministry of Agriculture, Fisheries and Food and an indirect cost of £150 million borne by the livestock industry (Doel and Pullen 1990).
- (b) The 2001 outbreak resulted in the slaughter of 6,612,038 animals (Scudamore et al. 2002) and a £3 billion cost to the UK government and a £5 billion cost to the private sector (NAO report 2002).

¹ Yanhong Jin is an assistant professor, Wei Huang is a graduate research assistant, and Bruce McCarl is a Regents Professor, in the Department of Agricultural Economics at Texas A&M University.

This research was supported by the Texas A&M based National Center for Foreign Animal and Zoonotic Disease Defense (FAZDD) that was established by the Department of Homeland Security. However, views expressed are those of the authors and do not necessarily represent those of the FAZDD. All remaining errors are the authors.

Should a major disease outbreak occur, it is crucial to have an effective strategy to control the disease spread and manage the resultant affected animals. From an economic sense such a strategy would be designed to minimize the costs arising from

- livestock losses;
- government, industry and consumer economic impacts;
- public health hazards; and
- environmental damages.

Disposal of slaughtered animals is part of this strategy.

Disease management strategies vary across the world. Vaccination has been widely used in some Asian, Africa and South American countries where diseases like FMD are endemic (Doel and Pullen 1990). However, in “disease-free” countries in North and Central American including the United States, the European Union, Australia and New Zealand, the basic disease control policy is slaughter of all infected animals along with those in contact (Breeze 2004). In the case of a large outbreak such an approach mandates the slaughter of a large number of animals. In turn this induces a large carcass disposal issue i.e. how, at a reasonable cost, do you dispose of 6 million carcasses without damaging air, water, and land quality. Such an issue may alter the optimal disease spread management system establishing a tradeoff between disease management costs and carcass disposal costs. This raises the economic issue addressed in this paper, namely, we investigate the way that the carcass disposal issue influences the design of the total disease management system.

2 Background - disease management and carcass disposal

There are various carcass disposal technologies that may be employed to address the carcass disposal problem. These include burial, incineration, composting, rendering, lactic acid fermentation, alkaline hydrolysis, and anaerobic digestion, as discussed in the recent carcass disposal review done by the National Agricultural Bio-security Center Consortium (2004).

These alternatives embody some pre outbreak activities. Namely, disposal facilities can be constructed and located before an outbreak occurs. However such facilities can be

expensive and typically have limited capacity. Pre outbreak actions may be difficult to justify given the infrequency of major outbreaks.

Carcass disposal concerns can also influence the type of disease spread management strategy employed. One can use strategies that reduce the rate of slaughter so that the needed rate of carcass disposal can be reduced which in turn reduces the immediate severity of the carcass disposal problem as well as the needed facilities to handle disposal. Vaccination of potentially infected animals is one of these strategies. Even though the emergency plan in some disease free countries such as the United Kingdom regards vaccination as a supporting strategy, vaccination is not considered as a main option due to disadvantages: (a) vaccinated animals cannot be distinguished from infected animals which have recovered although Breeze (2004) indicates in 1994 USDA scientists developed a test that can distinguish FMD vaccinated animals from infected animals and commercial tests are now available; (b) Vaccinated animals would need to be slaughtered anyhow given the current stamp out policy to maintain a countries "disease free" status; and (c) Some vaccinated and infected animals potentially still are contagious which reduces the disease management effectiveness relative to immediate slaughter (for further discussion see Doel, Williams, Barnett 1993, Elbakidze 2004, and APHIS 2002).

Carcass disposal in the case of a large outbreak can generate a tremendous operational concern and source of cost. For example in the 2001 UK outbreak a large scale incineration process was undertaken and in turn extensively publicized that caused substantial tourism losses (NAO report 2002). Vaccination in conjunction with later slaughter can buy time and lighten the carcass disposal requirement but poses tradeoffs between the costs of disease spread management and carcass disposal. Consider the following simplified problem statement: suppose we can dispose all carcasses within a day at an extremely high cost, or within a couple days at a much lower cost. Disease management policy should consider whether it is better to have a mechanism to delay slaughter/disposal to achieve the lower disposal cost while perhaps somewhat less effectively controlling disease spread.

This setting leads naturally to the following questions:

- Is it technically feasible and economically effective to slaughter all infected and other animals within a given proximity of the outbreak?
- If not, what are other choices could we have?

In this study, we examine vaccination as a supporting strategy to buy time in conjunction with later slaughter to reduce the carcass disposal load. Initially we develop a two period model to examine this question then later a multiple period model. In each setting, we minimize total cost by choosing the optimal amount of animals to be slaughtered or vaccinated by period, given

- the cost and capacity of carcass disposal,
- the cost of slaughter and vaccination,
- the initial size of event, i.e., the number of infected and contact animals,
- the disease spread caused by vaccinated and non-vaccinated animals, and
- the assumption that animals must eventually be slaughtered whether vaccinated or not

3 Model

Vaccination while being widely used in some Asian, African, and South American countries where FMD is endemic is not a recommended practice in the “disease-free” countries including the United Kingdom and the United States. Rather written policies in those countries regarding outbreaks employ strict movement controls and slaughter of all infected and contact animals. For example, if FMD virus were found in the United States, all animals in a radius of up to 3 kilometers around the infected farm, including the affected herd, cattle, sheep, goats, swine, and susceptible wildlife, whether they are infected or not, would be killed and disposed (Breeze, 2004).

However, the potential for large natural or deliberately caused terrorism induced outbreaks in multiple locations raises the possibility of mass slaughter and carcass disposal events. The following facts drawn from the UK experience under the 2001 FMD outbreak tell the possibilities of such events:

- (a) The 2001 FMD outbreak caused the slaughter of 6.6 million animals (Scudamore et al. 2002) and a mass backlog of slaughter and disposal. Figure 1 shows the weekly

amount of slaughter and carcass disposal over the course of FMD outbreak. The left panel shows that more than half of animals were awaiting slaughter and the right panel shows that more than 1/3 of animals were awaiting disposal of in the 6th week during the course of outbreak. The backlog of slaughtered animals awaiting disposal built up to a peak of over 200,000 carcasses in early April 2001. “At the height of the outbreak the daily weight of carcass moved was over half the weight of the ammunition the armed services supplies during the entire Gulf War” (NAO report 2002). This mass backlog suggests a potential value of vaccination as a supporting strategy in disease control and carcass disposal.

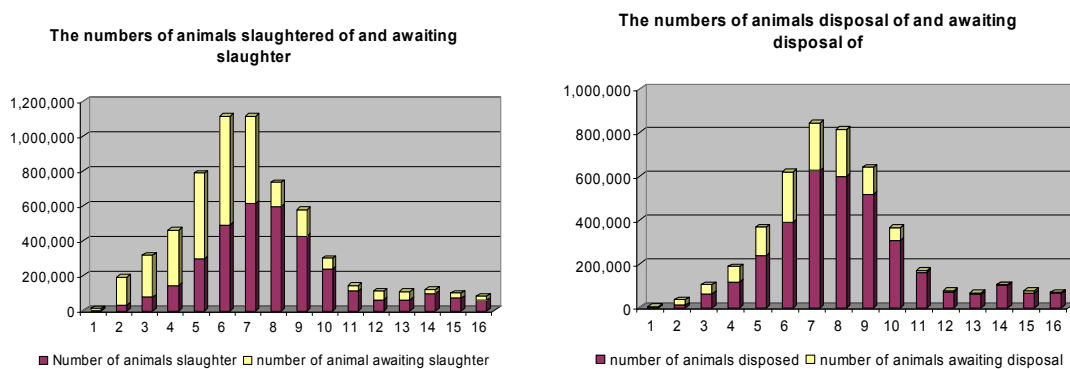


Figure 1: Slaughter and carcass disposal over time during the 2001 Britain FMD outbreak

Data Source: Scudamore et al (2002)

(b) All animals slaughtered were not necessarily infected or even in contact with infected animals. Figure 2 shows the number of animals slaughtered due to different reasons. The welfare slaughter category shows that 2,293,000 animals or approximately 36% of the total were just in the wrong place at the wrong time being killed because they could not be sent to the market given movement restrictions. Even among animals slaughtered for disease control purposes (those on infected premises, dangerous contact contiguous premises, and dangerous contact non-contiguous premises) a large proportion of animals were healthy at the time of slaughter. Vaccinating these classes of animals would slow the slaughter/disposal operation and might control disease spread while potentially easing slaughter/disposal burden and cost.

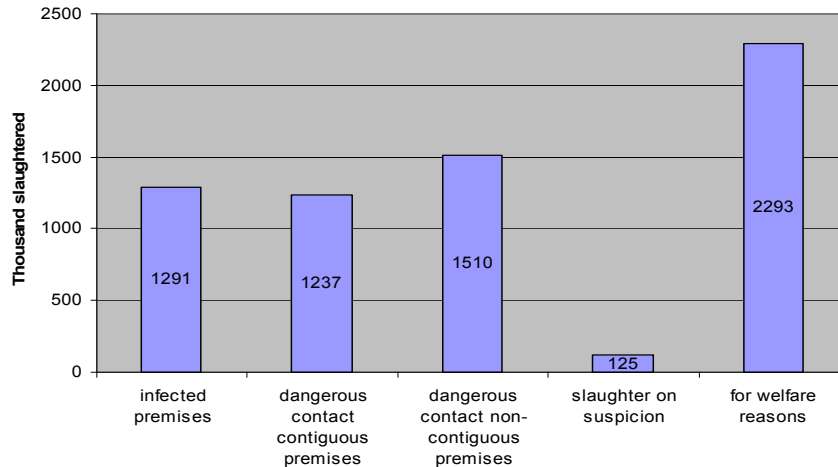


Figure 2: Animals slaughtered for FMD disease control and welfare purposes ²

Source: “The 2001 Outbreak of Foot and Mouth Disease”, report by the Comptroller and Auditor General, HC 939 Session 2001-2002: 21 June 2002.

- (c) The mass slaughter and disposal largely through incineration was the subject of extensive press and television coverage, which induced losses to the economy including a large reduction in tourism. The 2001 FMD outbreak resulted in an estimated cost of £4.5 to £5.4 billion for Media and Sport; and £2.7 to £3.2 billion to business directly affected by tourist and leisure (NAO report 2002). If instead vaccination was employed effectively, this might reduce the spectacular nature of the event and, thus may reduce the indirect damage to other sectors such as tourism.

3.1 Incorporating vaccination

The effectiveness of vaccination depends on various factors, including the

² The data compiling has the following considerations: (a) The totals for dangerous contact non-contiguous premises include the 3-kilometer cull; (b) The figures exclude approximately 4,000 other animals (mainly goats and deer) slaughtered for disease control purposes and approximately 3,000 other animals for livestock welfare purposes; (c) The figures exclude many slaughtered new born lambs and calves who were not counted in the database of the Department for Environment, Food and Rural Affairs and the Rural Payment Agency because their value, for compensation purpose, was included in the valuation assigned to their mothers.

- induced increase in the rate of disease spread,
- the scale of the initially infected and contact animals to be dealt with,
- the relationship of environmental damage and slaughter volume,
- the costs for slaughter
- the capacity for disposal, and
- the magnitude of vaccination costs

among other factors.

To model such a decision we use both a two-period setting and a multi-period setting. In setting up the model we make the following assumptions:

- The outbreak results in an initial total number of infected and contact animals to be slaughtered of \bar{Q} .
- The disease control authority decides the optimal number of animals to be slaughtered and vaccinated by period.
- That welfare slaughter is not required i.e. that there is sufficient feed and capacity to store the vaccinated animals.
- The parameters of the model will be based on the FMD literature. Mainly, there are two models for disease spread: exponential form (Anderson and May 1991) and Reed-Frost form (Thrushfield 1995, Carpenter et al. 2004). To capture the spatial patterns of FMD disease spread, some researchers, including Bates et al. (2001), and Schoenbaum and Disney (2003), distinguish disease contact and spread into three categories: (1) direct contact caused by movement of animals and other direct contact of animals within a herd and among herds; (2) indirect contact caused by movements of vehicles and people within a herd and among herds; and (3) airborne of contagious FMD virus.
- We assume that the total infected and susceptible infected animals in the next period (Q_{t+1}) include the remaining infected and contact animals from the previous period ($Q_t - s_t$) where s_t represents the amount of slaughter/disposal at time t , and the newly infected animals resulting from the disease spread $\alpha(Q_t - s_t)$:

$$Q_{t+1} = (1 + \alpha)(Q_t - s_t), \quad (1)$$

Here the value of α varies with and without vaccination because vaccinated animals are much less contagious (Breeze 2004),

$$\alpha = \begin{cases} \alpha_H & \text{if vaccination is not employed} \\ \alpha_L & \text{if vaccination is employed} \end{cases}. \quad (2)$$

To gain insight into the role of vaccination and carcass disposal considerations, we elaborate the two-period setting and multiple-period setting to solve the slaughter and carcass disposal problem dynamically. That is, policymakers have to make the following two decisions: (a) whether to employ vaccination as a supporting disease control and carcass management strategy; and (b) how many animals to be slaughtered/disposed and vaccinated in each period over the course of an FMD outbreak.

3.2 Two-period setting

In the two-period setting, we assume that policymakers have two options: (a) a slaughter of all infected and contact animals within a proximity of infected animals in the first period; and (b) vaccination of some animals in the first period to buy time to lessen the operational pressure and reduce the total disposal cost. But that all infected and contact animals will have to be slaughtered and disposed in the second period. The cost minimization problem in this setting is:

$$\min_{q_{s_1}, q_v} \underbrace{[SC(s_1) + VC(v_1) + EC(s_1)]}_{\text{Total cost in the first period}} + \frac{1}{1+r} \underbrace{[SC(s_2) + EC(s_2)]}_{\text{Total cost in the second period}}, \quad (3)$$

where

- $SC(s_1)$ and $SC(s_2)$ are the slaughter and carcass disposal cost in the first and second period, respectively. We assume that the disposal cost is a monotonic increasing and convex function of the total number of animal slaughtered and disposed of, i.e.

$$d SC(s)/ds > 0 \text{ and } d^2 SC(s)/d s^2 \geq 0.^3$$

³ The amount slaughter and disposal of animals should be at most equal to carcass disposal capacity. Otherwise, the total cost function should include the additional cost of building up new operation capacity.

- $VC(v)$ is the total cost of vaccinating v animals. We assume that $VC(v)$ is an increasing and convex function of the number of vaccinated animals such that $dVC(v)/dv > 0$ and $d^2VC(v)/dv^2 \geq 0$.
- $EC(s_1)$ and $EC(s_2)$ are the environmental damages corresponding to the number of animals slaughtered and disposed of in the first and second periods, respectively. We assume that $EC(\cdot)$ is an increasing, convex function.
- r denotes the time value of money, i.e. the value of delaying the slaughter and disposal of a head animal to the next period.

The model solution optimally allocates all initially infected and contact animals within a given proximity of the infected animals for slaughter or vaccination, which is shown in equations (4-a). All vaccinated animals in the first period along with newly infected due to disease spread by the vaccinated animals and associated contact animals will be slaughtered and disposed of in the second period, as given by equation (4-b).

$$s_1 + v_1 = \bar{Q} \quad \text{in the first period,} \quad (4-a)$$

$$s_2 = (1 + \alpha_L)v_1 \quad \text{in the second period.} \quad (4-b)$$

Minimizing equation (3) subject to equations (4-a) and (4-b) yields the optimality condition below:

$$\frac{dSC(s_1)}{ds_1} + \frac{dEC(s_1)}{ds_1} = \frac{dVC(v_1)}{dv_1} + \frac{1 + \alpha_L}{1 + r} \left(\frac{dSC(s_2)}{ds_2} + \frac{dEC(s_2)}{ds_2} \right). \quad (5)$$

The two terms on the left side of equation (5) represent the first period present value of the marginal slaughter/disposal cost plus the marginal environmental damage. The three terms on the right side consist of: (a) the present value of the first period marginal vaccination cost; and (b) the discounted marginal cost of the slaughter/disposal and (c) the discounted marginal environmental damage in the second period. The optimal number of animal slaughter/disposed in the first period (s_1^*) is achieved when the sum of the marginal slaughter/disposal cost and the marginal environmental damage equals the total marginal cost of postponing slaughter via vaccination on one animal to the next period to dispose.

Assuming, the optimal number of animals vaccinated in the first period is $v_1^* = \bar{Q} - s_1^*$ then when $s_1^* < \bar{Q}$ or $v_1^* > 0$, it is optimal to employ vaccination.

In the absence of vaccination all the subject animals \bar{Q} have to be disposed in the first period. Thus, the total slaughter and disposal is \bar{Q} at the cost of $SC(\bar{Q}) + EC(\bar{Q})$. With the second option, some animals are slaughtered and the remaining animals are vaccinated in the first period, and then disease is stamped out in the second period. Therefore, the total slaughter and disposal is $s_1^* + s_2^*$ and the corresponding cost is the net present value of slaughter and disposal, vaccination, and environmental costs in two periods. Let Δ_q denote the difference in total number of animals slaughtered and disposed of and Δ_c denote the cost difference between the two options. Δ_c measures the cost reduction should vaccination could be used to buy time to control disease and manage carcass disposal. Hence, Δ_c represents the value of vaccination. Algebraically, Δ_q and Δ_c are written below:

$$\Delta_q = (s_1^* + s_2^*) - \bar{Q} = [s_1^* + (1 + \alpha_l)(\bar{Q} - s_1^*)] - \bar{Q} = \alpha(\bar{Q} - s_1^*), \quad (6-a)$$

$$\Delta_c = \underbrace{[SC(\bar{Q}) + EC(\bar{Q})]}_{\text{Total cost without vaccination}} - \left(\underbrace{[SC(s_1^*) + VC(v_1^*) + EC(s_1^*)]}_{\text{Total cost in the first period}} + \frac{1}{1+r} \underbrace{[SC(s_2^*) + EC(s_2^*)]}_{\text{Total cost in the second period}} \right). \quad (6-b)$$

The magnitudes of these Δ measures depend upon the rate of disease spread, the time value, current capacity of slaughter and carcass disposal, etc.

Proposition 1: In the two-period setting,

- the total number of animals slaughtered and subsequently disposed of increases with an increase in (a) the rate of disease spread from vaccinated animals, (b) the event size – the number of initially infected and contact animals, and/or (c) the time value of money $\left(\frac{d \Delta_q}{d \alpha_l} > 0, \frac{d \Delta_q}{d \bar{Q}} > 0 \text{ and } \frac{d \Delta_q}{dr} > 0 \right)$.
- the number of vaccinated animals becomes smaller (conversely the larger the first period slaughter becomes) when we have (a) increases in the disease spread rate from vaccinated animals, (b) increases in event size, and/or (c) decreases in the

time value of money

$$\left(\frac{d v_1^*}{d \alpha_L} < 0, \frac{d v_1^*}{d Q} > 0, \frac{d v_1^*}{d r} > 0, \text{ and } \frac{d s_1^*}{d \alpha_L} > 0, \frac{d s_1^*}{d Q} < 0, \frac{d s_1^*}{d r} < 0 \right).$$

- the value of vaccination is greater when we have (a) an decrease in the rate of disease spread from vaccinated animals; (b) an increase in the event size; and/or (c) an increase in the time value of money $\left(\frac{d \Delta_c}{d \alpha_L} < 0, \frac{d \Delta_c}{d Q} > 0 \text{ and } \frac{d \Delta_c}{d r} > 0 \right)$

Proof: See Appendix A.

Proposition 1 suggests the following results:

- When the disease strain is more contagious and spread faster, employing vaccination could induce a greater slaughter and disposal, which would result in a lower cost saving, thereafter a lower value of vaccination. Vaccination is more valuable when vaccinated animals spread disease slower, especially when the so-like “Britain-on-fire” imagines induce public concerns and enormous damage to the economy.
- When the even size is greater in terms of the number of initially infected and contact animals, the number of slaughter/disposal goes up and the total cost will increase in either options. However, employing vaccination could decrease cost more.
- The higher discount rate, the more valuable becomes vaccination even though the total slaughter and disposal increases. Vaccination gains time to consider multiple alternate courses of action. It is more likely to employ more cost effectively dispose of carcasses. Because of the environmental regulations and public health concerns, on-farm burial was generally not used in the 2001 outbreak. Instead, seven mass burial pits were built in England (5), Scotland (1) and Wales (1) at a construction cost of £79 million; and the cost of restoration and management in the future are estimated at £35 million during the course of the 2001 FMD outbreak (NAO report 2002). We speculate that UK could have constructed the disposal capacity at a lower cost if the great time pressure did not exist.

3.3 Multiple-period setting

Should an FMD outbreak occur in the United States, movement ban and slaughter are the main strategies and vaccination is not an officially favored option. However, as discussed in the previous section, vaccination could be beneficial as a supporting strategy conjunction allowing more time for slaughter of animals.

Let i denote two options of multiple periods: (a) $i=nv$ when vaccination is excluded from disease control and carcass disposal management; and (b) $i=v$ when vaccination is used as a supporting strategy. We assume that an infected animal is either killed and disposed or vaccinated in the second option, i.e. no animal is carried on to the next period if it is not vaccinated. Comparison of the total costs between these two options quantifies the value of vaccination. Let Q_t^i denote the total infected and contact animals, and s_t^i be the amount of slaughter and disposal, at time t given an option i . $Q_t^{nv} - s_t^{nv}$ represents the total amount of infected and contact animals carried on to the next period, and $Q_t^v - s_t^v$ is the total vaccinated animals at time t . The change in the number of infected and contact animals is

$$\dot{Q}_t^i = -s_t^i + \alpha(Q_t^i - s_t^i), \quad (7)$$

where α is the rate of disease spread as defined in equation (2). Equation (7) decomposes the change of the total infected and contact animals into two components: (a) a decrease because of the current slaughter s_t^i and (b) an increase resulting from the disease spread ($\alpha(Q_t^i - s_t^i)$). Because of economic costs including the loss in tourism industry and trade, environmental damage, the authority aims to control disease and manage carcass disposal in a timely manner. We assume that the FMD virus has to be stamped-out within a time period T . Now let us analytically investigate the cases.

3.3.1 Option 1 -- vaccination is not allowed

The first option assumes that vaccination is excluded from the strategy set. Given that the disease has to be stamped out by the time period T , the authority has to decide the optimal number of slaughter and disposal at each period. Hence, the cost minimization problem is written below:

$$\min_{q_{st}, q_{st} \text{ at } t=0} \int_0^T e^{-rt} [SC(s_t^{nv}) + EC(s_t^{nv})] dt \quad (8-a)$$

$$\text{s.t. } \dot{Q}_t^{nv} = -s_t^{nv} + \alpha_H(Q_t^{nv} - s_t^{nv}), \quad (8-b)$$

where s_t^{nv} is the amount of slaughter and disposal under this no vaccination option at time t . Based on equation (8-a) and (8-b), the Hamiltonian equation thus is

$$H = [SC(s_t^{nv}) + EC(s_t^{nv})] + \lambda(-s_t^{nv} + \alpha_H(Q_t^{nv} - s_t^{nv})). \quad (9)$$

The first order necessary conditions for an internal solution are

$$\partial H / \partial s_t^{nv} = (SC' + EC') - (1 + \alpha_H)\lambda = 0, \quad (10-a)$$

$$\partial H / \partial Q_t^{nv} = \lambda \alpha_H = r\lambda - \dot{\lambda}, \quad (10-b)$$

$$\partial H / \partial \lambda = \alpha_H Q_t^{nv} - (1 + \alpha_H)s_t^{nv} = \dot{Q}_t^{nv}. \quad (10-c)$$

Equation (10-a) suggests that the optimal slaughter is achieved when the marginal cost ($SC' + EC'$) equals the gain $(1 + \alpha_H)\lambda$ because the current slaughter will slow down the disease spread. Based on equations (10-a), (10-b), and (10-c), we can derive the optimal dynamic solution for the number of slaughtered at time t , the number of total infected and contact animals at time t , and λ :

$$s_t^{nv} = \frac{(r - \alpha_H)(SC' + EC')}{SC'' + EC''}, \quad (11-a)$$

$$\dot{Q}_t^{nv} = \alpha_H Q_t^{nv} - (1 + \alpha_H)s_t^{nv} \quad (11-b)$$

$$\dot{\lambda} = \frac{(r - \alpha_H)(SC' + EC')}{(1 + \alpha_H)}, \quad (11-c)$$

Equation (11-a) implies that the change in the number of slaughtered animals increases (decreases) over time if the time value is greater (smaller) than the speed of disease spread. This suggests that more animals will be slaughtered in the later periods if the time value of money increases.

3.3.2 Option II -- vaccination is use as a supporting strategy

The net present value of the total event cost flow is minimized by choosing the optimal number of animals to be slaughtered s_t^v and to be vaccinated v_t^v at each time period t . The cost minimization problem is given below:

$$\min_{q_{st}^v, q_{vt}^v} \int e^{-rt} [SC(s_t^v) + VC(v_t^v) + EC(s_t^v)] dt, \quad (12-a)$$

$$\text{s.t. } \dot{Q}_t^v = -s_t^v + (1 - \alpha_L)(Q_t^v - s_t^v). \quad (12-b)$$

where $SC(\cdot)$, $VC(\cdot)$, and $EC(\cdot)$ are increasing, convex, cost functions. Again, r is the time value of money, i.e. the value of postponing the slaughter and disposal of one head animal to the next period. We treat the number of infected and susceptibly infected animals at time period t as a state variable Q_t . Given equations (12-a) and (12-b) we can write the Hamiltonian equation as:

$$H = [SC(s_t^v) + VC(Q_t^v - v_t^v) + EC(s_t^v)] + \lambda(-s_t^v - (1 - \alpha_L)(Q_t^v - s_t^v)). \quad (13)$$

The first order necessary conditions for an internal solution are

$$\partial H / \partial s_t^v = (SC' - VC' + EC') - (1 + \alpha_L)\lambda = 0, \quad (14-a)$$

$$\partial H / \partial Q_t^v = VC' + \lambda\alpha_L = -\dot{\lambda} + r\lambda, \quad (14-b)$$

$$\partial H / \partial \lambda = \alpha Q_t^v - (1 + \alpha_L)s_t^v = \dot{Q}_t^v. \quad (14-c)$$

Based on equations (14-a), (14-b), and (14-c), we derive the following dynamics:

$$\dot{s}_t^v = \frac{V''\dot{Q}_t^v - (1+r)VC' + (r - \alpha_L)(SC' + EC')}{SC'' + VC'' + EC''}, \quad (15-a)$$

$$\dot{v}_t^v = \frac{(SC'' + EC'')\dot{Q}_t^v + (1+r)VC' - (r - \alpha_L)(SC' + EC')}{SC'' + VC'' + EC''}, \quad (15-b)$$

$$\dot{Q}_t^v = \alpha_L Q_t^v - (1 + \alpha_L)s_t^v, \quad (15-c)$$

$$\dot{\lambda} = \frac{1}{1 + \alpha_L} [VC' + \alpha_L(SC' + EC')]. \quad (15-d)$$

As show in equation (15-a), when the dynamics of the amount of slaughter and disposal achieves its stability if there is any, the discounted marginal gain of postpone the slaughter and disposal of one head of animal $\left(\frac{VC''\dot{Q}_t^v + (r - \alpha)(SC' + EC'')}{SC'' + VC'' + EC''} \right)$ equals to the discounted marginal cost of vaccination $\left(\frac{(1 + r)VC''}{SC'' + VC'' + EC''} \right)$.

3.3.3 Comparison between two options in the multiple-period setting

To compare these two options and quantify the value of vaccination, we make following additional assumptions: (a) a constant variable cost vc of vaccination and a zero fixed cost, which leads to $VC' = vc$ and $VC'' = 0$; (b) a zero environmental cost that cause us to underestimate the value of vaccinations; and (c) a quadratic cost of slaughter $S(q_{st}) = a - b s_t + c s_t^2$ such that both b and c are positive.⁴ Figure 3 illustrates the dynamics of two options. The vertical axis represents the total number of infected and contact animals (Q_t^i), and the horizontal axis shows the number of slaughter and disposal (s_t^i). Curve OE is an isoline along which $\dot{Q}_t^i = 0$, curves BG is an isoline along which $\dot{s}_t^{nv} = 0$ and $s_t^{m\Delta} = b/2c$ for the option I; and Curve AF is an isoline along which $\dot{s}_t^v = 0$ and $s_t^{v\Delta} = \frac{b}{2c} + \frac{(1+r)vc}{2(r-\alpha_L)c}$ for the option II. All L-shaped directional arrows suggest the trajectories of the number of slaughter and the number of infected and contact animals: The first option when vaccination is not allowed has dashed arrows; and the second option when vaccination could be used has solid arrows.

Proposition 2: Disease may become endemic from a cost perspective if the time value is less than the disease spread. However, to stamp out the disease, it is necessary to slaughter and dispose at least $\alpha_L/(1 + \alpha_L)$ of currently infected and contact animals in each period when vaccination is used, and $\alpha_H/(1 + \alpha_H)$ when vaccination is not allowed.

⁴ We assume that c is positive to ensure $SC'' > 0$. However, b is assumed to negative to ensure the optimal slaughter is positive.

Proof: See the phase diagram in Figure 3.

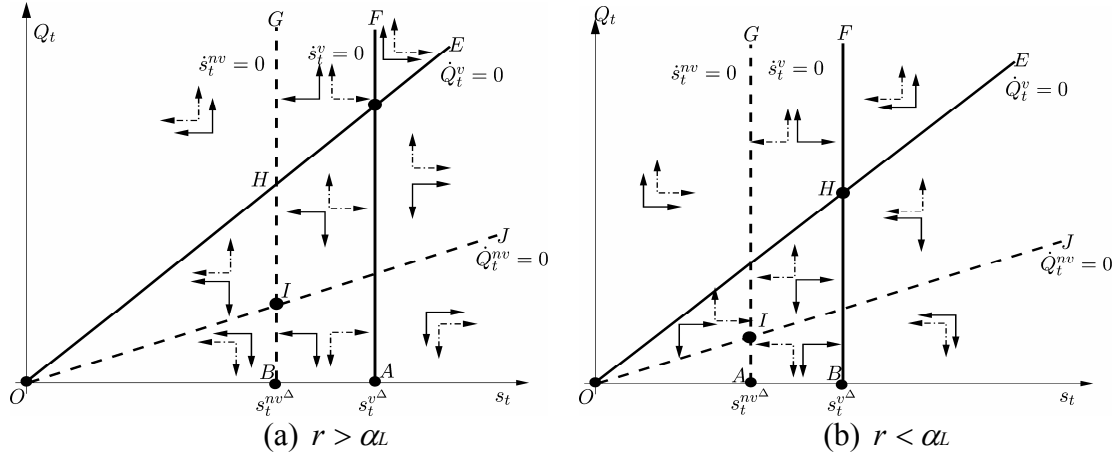


Figure 3: The phase diagrams of two options when vaccination is used or not as a supporting strategy conjunction with later slaughter of animals

Based on Figure 3 Proposition 2 implies the following result: In order to bring disease under control, a higher percentage of currently infected and contact animals are likely to be killed and disposed under the first option when vaccination is not allowed

($\frac{\alpha_L}{1 + \alpha_L} < \frac{\alpha_H}{1 + \alpha_H}$). If in case, $\alpha_L/(1 + \alpha_L)$ percentage of currently infected and contact

animals already exceeds the operation capacity, it is less likely to bring disease under control. However, there are two possible outcomes: (1) the disease becomes endemic when the time value is smaller than the disease spread rate (see Points *I* when vaccination is not allowed and *H* when vaccination is used in the right panel); or (2) build up new slaughter capacity to kill more animals as fast as it could to bring the disease under control.

As a supporting strategy in conjunction with later slaughter of animals in a total disease control management, our analytical results show that vaccination has the following potential advantages:

- (a) *It permits slowing down the flow of carcasses for disposal while controlling disease spread.* Many animals killed and disposed are likely not infected at all. In the 2001 FMD outbreak in the United Kingdom, less than 1% disposed animals were known to be infected (NAO report, Scudamore et al. 2002). Vaccination of these animals

(b) *It gains time allowing cost reductions for carcass disposal.* Vaccination could lessen pressure on the expensive facility construction. This extra time may permit use of cheaper and more environmental friendly options.

4 Empirical Simulation

The analytical results show that the desirability and value of vaccination depends on the time value of money, the vaccination costs, the rate of disease spread from vaccinated animals or non-vaccinated animals, and the number of initially infected and contact animals. However, the impacts of one particular parameter on the total number of slaughter and disposal and the total cost depend on the value of other factors. We conduct empirical simulations varying one parameter a time while controlling for other factors to quantify its impacts. In doing this we make additional assumptions: (a) The slaughter and carcass disposal cost is quadratic, $SC(s_t) = 10 - 2s_t + s_t^2$, which ensures that $SC' > 0$ for any $s_t > 1$ and $SC'' > 0$; (b) the disease has to be stamped out within two weeks; and (c) the environmental cost resulting from mass slaughter and disposal was set to zero due to the limited information and knowledge of the environmental damage (Hence, the value of vaccination as a supporting strategy could be underestimated).

We assume the following parameters for the base case: (a) a constant vaccination cost of \$1.2 per head; (b) the disease spreads at a per period rate of 20% from infected and contact animals that are not slaughtered or vaccinated and 10% from vaccinated animals, i.e. $\alpha_H = 0.2$ and $\alpha_L = 0.1$; (c) the number of initially infected and contact animals equals 100 ($\bar{Q} = 100$); and (d) the time value of money is $r=20\%$. Figure 4 provides a graphic illustration on the number of slaughter/disposal and the total infected and contact animals with and without vaccination use. The horizontal and vertical axes represent time and the number of animals, respectively. Under the second option when vaccination is used, the dashed lines traces the number of infected and contact animals (Q_t^v) and the solid line reveals the amount of slaughter and disposal (s_t^v), respectively. The difference between these two lines (dashed and solid) represents the number of animals vaccinated and, thus, the area between these two lines shows the total vaccination. In turn the dotted and dash-dotted lines represent the dynamic outcomes (s_t^m and Q_t^m) when vaccination is not allowed.

The gap between these two lines (dotted and dash-dotted) is the number of infected and contact animals carried on to the next period. The area under the solid (dash-dotted) line indicates the total slaughter and disposal of the outbreak when vaccination is (isn't) used. This basic case shows that vaccination decreases the total slaughter and disposal of animals. One possible reason could be vaccinated animals shed fewer virus and, thus, it curbs disease spread and, thus decreases the total slaughter and disposal of animals.

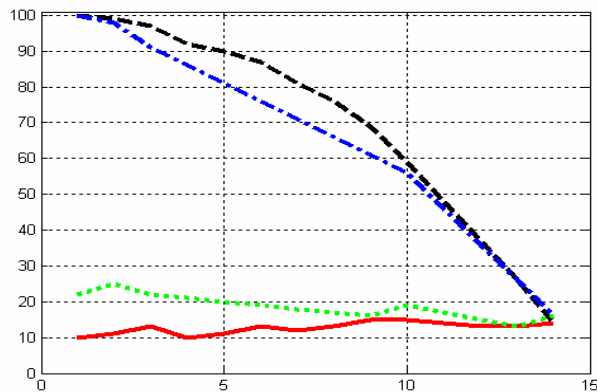


Figure 4: Dynamics of the number of slaughter and the total infected and contact animals during the course of an FMD outbreak (base case)

We conduct four sets of simulation varying only one parameter at a time and present the dynamic outcome of each set in figures 5-9. The legend of Figures 5-9 is the same as that in Figure 3. Later, to quantify the value of vaccination, we provide a summary of all simulations in terms of the total slaughter/disposal and the total cost.

4.1 Effects of the time value

To quantify the effects of the time value of money r , we vary the value of r ranging 0 to 1 with an increment of 0.1 and, thus, the discount rate changes from 1 to 0.5 correspondingly. Figure 5 provides a graphical illustration of several simulations with different time value of money. Our results suggest the following: Delaying slaughter could facilitate disease spread, but vaccination could curtail the spread because vaccinated animals shed less. These two conflicting effects on disease spread will affect the total amount of disease spread of an outbreak. Figure 4 shows that as the time value of money increases, the total slaughter and disposal of animals (the area under the solid line), the

amount of vaccination, and the difference in the total slaughter and disposal of animals with and without vaccination (the areas between dotted and solid lines) increase.

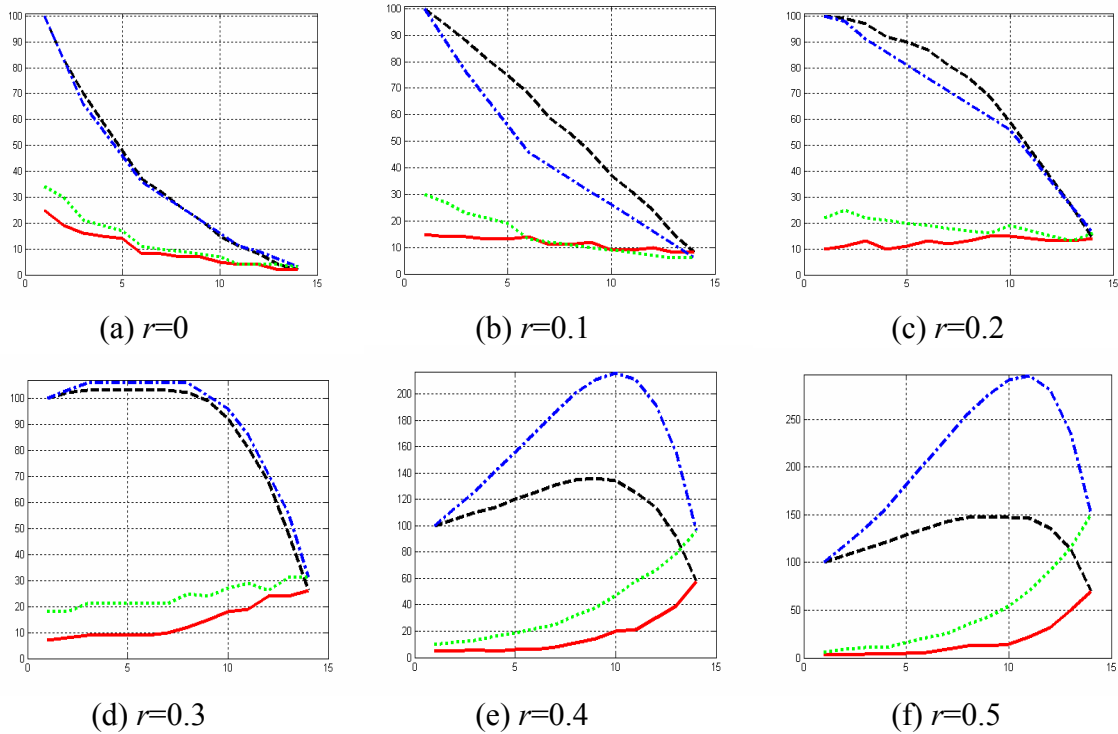


Figure 5: Sensitivity analysis on the time value of money

4.2 Effects of vaccination costs

The vaccination costs consist of the cost of vaccines and the cost of administering vaccinations in the field. In the United States, the North American Vaccine Bank (NAVVB) stores viral antigens for FMD and other diseases and the Foreign Animal Disease Diagnostic Laboratory at Plum Island, New York identifies the viral subtype. If vaccinations for the viral subtype are not available at NAVVB or a similar international vaccine bank, then the viral antigen has to be manufactured, which will lead to a higher vaccination cost. The vaccination administration cost depends on various factors such as transportation costs, institutional efficiency of delivering appropriate vaccines and operate vaccinations, etc. Our analytical results suggest that a high vaccination cost will decrease the value of vaccination (see Proposition 1).

The literature suggests the following vaccination cost per head of animals: (a) Breeze (2004) assumes that the United States will incur \$1.2 per head when using the

current 15 FMD virus types; (b) Schoenbaum and Disney (2003) assume that vaccination cost per head is \$6. To examine sensitivity to different cost levels we ran 10 simulations varying the marginal vaccination cost from zero, \$0.5, \$1.0, \$1.2, \$1.4, \$1.6, \$1.8, \$2, \$4 to \$6. All the other parameters have the same value as that in the base case, i.e. $r=0.2$; $\alpha_H = 0.2$ and $\alpha_L = 0.1$, and $\bar{Q} = 100$. Figure 5 traces the dynamics of s_t^{nv} (dotted line) and Q_t^{nv} (dash-dotted line) when vaccination is not allowed and s_t^v (solid line) and Q_t^v (dashed line) when vaccination is used. Obviously, the change of the marginal vaccination cost only affects the dynamics of s_t^v and Q_t^v but not s_t^{nv} and Q_t^{nv} because vaccination does not take place in the first option.

The results illustrated in Figure 6 show the following results as the marginal vaccination cost goes up: (a) more animals will be killed and disposed in early periods to control disease spread; and (b) both the total slaughter and disposal of animals (the area under the solid line for s_t^{nv}) and total vaccinated animals decreases (the area between the dashed and solid lines) decrease.

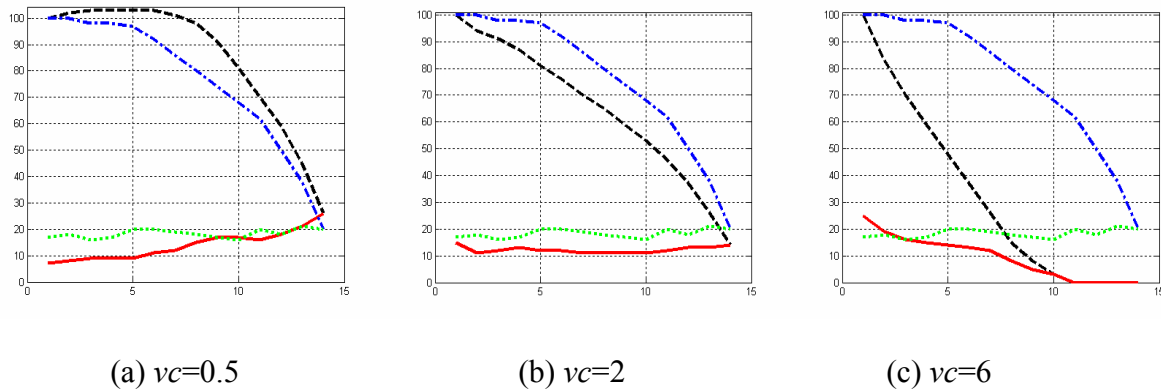


Figure 6: Sensitivity analysis of constant marginal vaccination cost

4.3 Effects of FMD disease spread

The model assumes that the disease spread mainly depends on the total number of initial animals and a constant per head spread rate. Here we examine the effects of alternative disease spread parameters investigating two factors:

- (a) *The rate at which disease spreads from vaccinated animals:* Vaccinated animals shed the virus at a lower rate and, thus, the disease spreads more slowly from vaccinated

herds. We ran six simulations varying spread rates from vaccinated herds such that α_L ranges from 2% to 20% with an incremental increase of 2%. $\alpha_L = 2\%$ implies that vaccination is substantially effective in controlling disease spread while disease spread rate among non-vaccinated animals is 20%. Hypothetically, vaccinated and non-vaccinated animals have the same disease spread rate when $\alpha_L = 20\%$. Figure 7 shows that the higher the disease spread speed rate among vaccinated animals, the less vaccination is taken place, and the more animals will be slaughtered and disposed during the course of FMD outbreak.

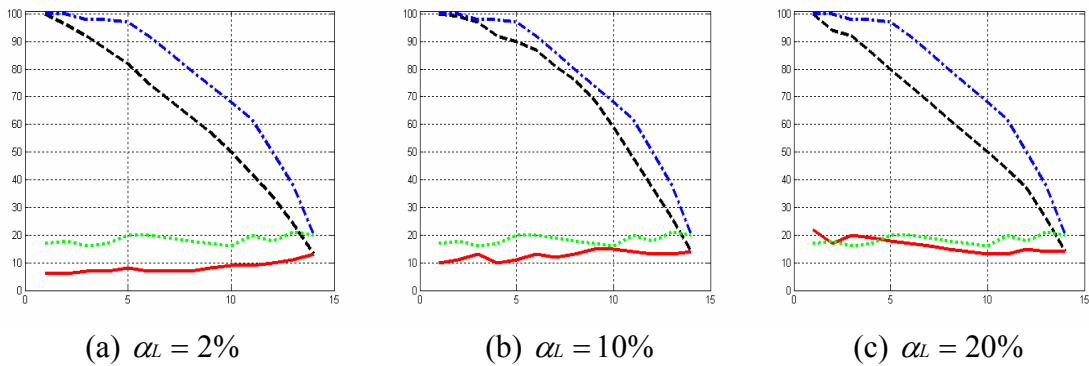
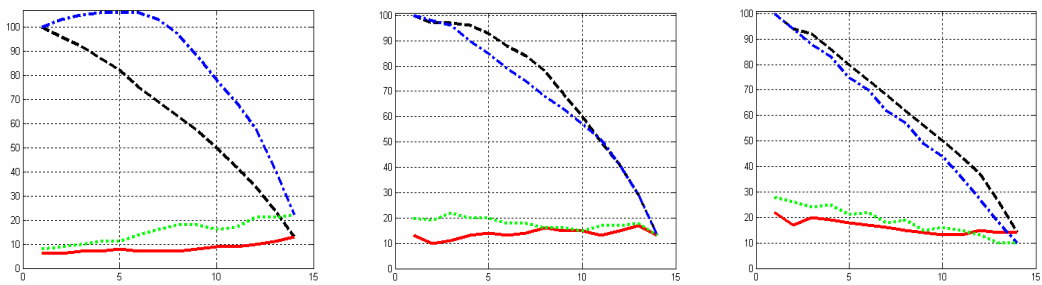


Figure 7: Effectiveness of vaccination in controlling disease spread

(b) *Varying overall disease spread rate:* We also simulated results assuming a constant difference in spread rates (10%) between herds that are vaccinated and those that are not. That is, α_H ranges from 12% to 30% and α_L changes from 2% to 20% accordingly with an incremental increase of 2% for both α_H and α_L . Three panels of Figure 7 suggest that the total slaughter and disposal of animals increase as the spread rate increases and total vaccinated animals decreases.



(a) $\alpha_H = 12\% \ \& \ \alpha_L = 2\%$ (b) $\alpha_H = 20\% \ \& \ \alpha_L = 10\%$ (c) $\alpha_H = 30\% \ \& \ \alpha_L = 20\%$

Figure 8: Sensitivity analysis of FMD disease spread

4.4 Effects of the number of initial infected animals

FMD virus is 20 times more infectious than human smallpox (Breeze, 2004). Infected animals shed enormous amounts of virus, and they can easily infect other animals in the same herd and among herds by direct or indirect contact. FMD virus could also infect animals within a large premise by contamination of water, soil, etc. We conduct seven simulations with various $\bar{Q} = 20, 40, 60, 80, 100, 150, 200, 250, 300,$ and 400 animals. It is obvious that both the total slaughter and disposal will increase if the even size goes up regardless whether vaccination is allowed or not. Figure 9 suggests that the difference in the total slaughter and disposal of animals between two options increases as the even size goes up.

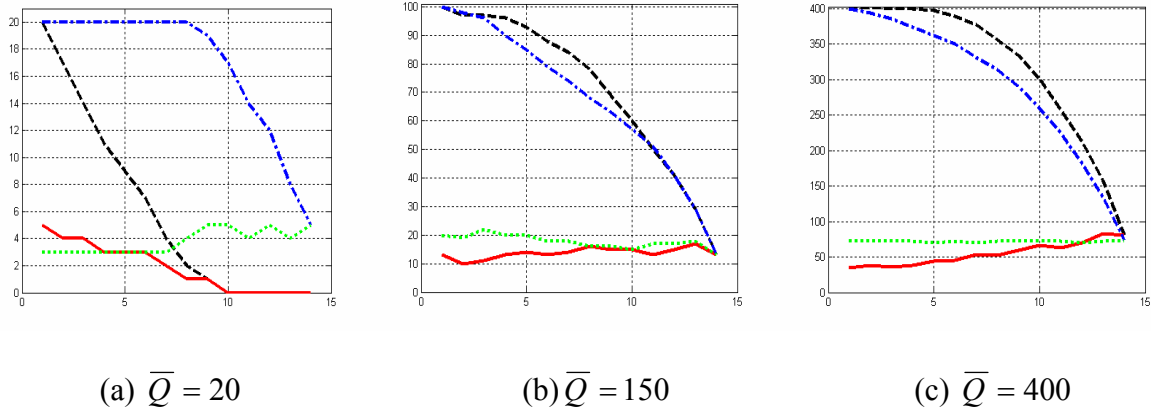


Figure 9: Sensitivity analysis of total initially infected and contact animals

4.5 Comparative results across simulated alternatives

Now suppose we compare across the simulations. We separate the simulations into five blocks: (a) the first block 1 consists of 11 simulations with different time value of money r from zero to 1; (b) the second block includes 10 cases with alternative vaccination cost from zero to \$6; (c) the third block has 10 simulations in which the disease spread rate from the vaccinated herd changes from 2% to 20%; (d) the fourth block includes the overall disease spread alternatives; and (e) simulations in the last block have different initial infection size (31 to 38). We summarize simulation results in terms of the total

number of slaughter and disposal of animals and the cost ratio between two options (with and without vaccination) below.

- (a) Figure 10 shows the total numbers of animals slaughtered in the vertical axis and the case number in the horizontal axis. It shows that vaccination uniformly decreases the total number of animals slaughtered and disposed of. This slaughter differential falls when (1) the time value of money is smaller; (2) the disease spread rate from vaccinated herds is smaller; (3) the disease spread rate in general is lower; and/or (4) the initially infection size is smaller.

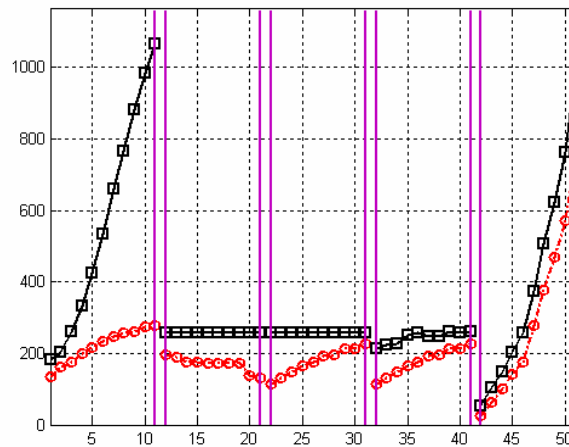


Figure 10: Amount of slaughter and disposal under two cases

(Solid line with diamonds: vaccination is not allowed; dashed line with circles: vaccination is used)

- (b) Figure 11 presents the cost ratio $\mu = \frac{TC_{nv} - TC_v}{TC_{nv}} 100\%$ where TC_{nv} and TC_v

represent the net present value of total cost of slaughter/disposal without and with vaccination. When this ratio is positive (negative) vaccination could reduce (increase) total cost. The results in Figure 10 indicate

- Vaccination conjunction with later slaughter of animals can be a cost saving option. Some of the simulation cases (4 and 12) result in at least a 50% reduction in total cost.
- Vaccination becomes more valuable if the time value of money decreases, vaccination is less costly, vaccinated animals spread disease much less than

others, the disease is more contagious, and/or there is a larger scale of initially infected and contact animals.

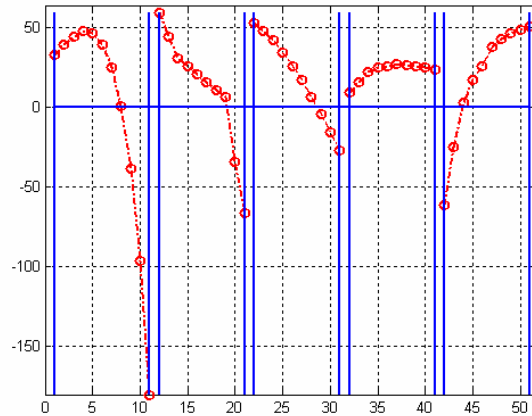


Figure 11: The cost ratio when vaccination is not allowed and vaccination is used

The result that vaccination becomes less valuable as the time value of money increases counters our intuition. Based on the cost function without vaccination in equation (8-a) and with vaccination in equation (12-a), we could identify two conflicting effects of vaccination on the total cost: (a) vaccination reduces cost because the total amount of slaughter/disposal of animals is smaller when vaccination is used. Thus, it gains a saving of slaughter cost adjusted by the time value of money; and (b) vaccination add another cost component, the cost of vaccine and operating vaccination. The time value of money, the marginal vaccination cost, the difference in the current slaughtered and disposed animals, and the amount of vaccination affect the relative magnitudes of these two effects. Given values of all parameters we chosen, we showed that when the time value is small, saving of slaughter and disposal cost dominates and, thus, vaccination is a valuable option.

5 Concluding Remarks and Policy Implications

In this study, we argue that vaccination could be a supporting strategy in FMD outbreak emergency. Mainly, while controlling disease spread since vaccinated animals shed less, vaccination could gain time to slow down the flow of slaughter, thereafter the disposal operation of animal carcasses. Thus, employing vaccination may allow policy makers to seek a set of lower cost and environmental friendly strategies to control disease and manage carcass disposal. The potential supporting role of vaccinations in a large scale

disease outbreak has been recognized since the 1967/68 UK FMD outbreak.⁵ This paper investigates the question economically showing case where vaccinations could play an important role in reducing the total costs.⁶ The main cases where value is attained are summarized below:

- (a) Even though the total slaughter and disposal of animals is greater if we only use vaccination to buy one period (see Proposition 1), vaccination generally decreases the total number of slaughter and disposal of animals in the multiple-period setting. Especially, fewer animals are killed and disposed of when the time value is greater time value and/or vaccination is less costly.
- (b) Vaccination becomes more valuable in reducing total cost when the costs of vaccinating fall, the disease outbreak becomes larger, the vaccines are more effective in controlling disease spread, and/or the disease in general spreads faster.

Vaccination would be even more valuable if we overcame two limitations in our model: (a) we included nonzero environmental damages as we feel environmental costs fall if time pressures were removed; and (b) We did not incorporate the loss of cattle in our model. If indeed the total amount of slaughter and disposal of animals decreases with vaccination, the reduction in the loss of cattle would increase the value of vaccination. Nevertheless, our study shows that vaccination could be a valuable strategy of FMD disease control and carcass disposal management.

⁵ The Northumberland Committee was established to review the outbreak and its control and eradication responses of the 1968/69 FMD outbreak in England. The committee recommended vaccination as a supporting mechanism for FMD outbreak control. Ever since then, European Union law permits the use of emergency vaccination as part of a stamping out policy where appropriate (NAO report 2002).

⁶ We admit that we did not include several components of cost, including environmental cost and cost of lost animals. The exclusion of environmental cost may lead to underestimate of the value of vaccination; and the ignorance of the animal loss there are some limitations that may lead to the underestimate of the value of vaccination as a supporting strategy with slaughter policy.

Should the authority agree on the value of vaccination as a supporting strategy conjunction with the later slaughter of animals, there are several remaining feasibility questions:

- *Could rules be relaxed to diminish the trade disadvantage?* The International Office of Epizootics (OIE), is the WTO named agency that sets standards to prevent international spread of livestock diseases. International rules strongly favor “disease free” countries and are restrictive toward animal exports of countries where FMD is endemic. Therefore, countries like UK and US mainly rely on movement ban and slaughter policy to maintain their disease free status to take the trade advantages. The trade disadvantage of vaccination was the main reason that the UK Farmers’ Unions opposed to vaccination during the 2001 FMD outbreak (NAO report). However, the relevant rules about FMD penalizing vaccination and encouraging mass slaughter do not reflect technology advances and economic rationale. First of all, scientists associated with the USDA have developed a test that can distinguish vaccinated animals from infected ones (Breeze 2004), which will lessen the worry of disease spread through trade. Secondly, our results show that vaccination is an effective supporting tool to buy time to reduce the cost of carcass disposal. To reflect the model technology and economic considerations, it may be of OIE’s interest to relax international trade regulations related to FMD diseases and allow disease-free but vaccinated animal into the world trade.
- *Can an adequate supply of vaccines in a timely manner?* When an FMD outbreak occurs, the feasibility of vaccination as a supporting strategy requires the availability of vaccines. There are two types of vaccine reserves (Doel and Fullen 1990): (1) conventional commercial FMD vaccine that has a 12-month shelf life; and (2) concentrated inactivated vaccines with a 15-year predicted shelf life. The latter one are held and managed by a consortium of three countries including Canada, Mexico and the United States at the North American Vaccine Bank, NAVB (Breeze 2004), and a consortium of seven countries including Australia, Eire, New Zealand, Norway, Sweden and the United Kingdom at the Pairbright Laboratory of the AFRC Institute for Animal Health (Doel and Fullen 1990). The

threat of bioterrorism imposes some pressure on vaccine reserves and, thus these FMD vaccine banks may need to take another look on their reserves.

- *Could the Authority deliver vaccines into infected and contact regions in a timely manner?* Even if there is enough vaccine matching the virus strings identified in infected animals, it will take time to move the vaccines to the needed points for use. Breeze (2004) argues it will take 1-2 days for transportation for a specimen and preliminary diagnosis at the Plum Island Foreign Animal Disease Diagnostic Laboratory; 2 days to determine the virus subtype; 4 days to produce the vaccine and deliver it to the outbreak location; and at least 1 day to administer the vaccine within the initial area designated for vaccination. Therefore, we need a minimum of 8 or 9 days to employ vaccination even if virus subtypes are available in NAVB. NAVB may need to design and establish a faster response procedure.

We envision several extension of this study on carcass disposal and disease management: (a) Should an FMD outbreak occur, we may face a shortage of slaughter and disposal facilities. Policy makers have two options: either to build up slaughter and disposal facilities ex ante that will not be used if there is no outbreak; or to build up slaughter and carcass facility ex post that could be substantially costly. It is important to determine the optimal investment in disposal facilities ex ante; (b) Welfare slaughter accounts for a substantial percentage in the total slaughter and disposal of animals. Animals killed due to the welfare purpose are not infected at all, and they are in the wrong place at the wrong time because of movement ban. If we could have a differentiate meat market coming from uninfected animals or use these carcasses for other purpose such as doggie food, vaccination may be more valuable, and the total cost of event could be lower. However, policy makers shall take consideration of trade disadvantage if carcasses of uninfected animals have certain salvage values.

Reference:

APHIS (2002). Foot-and-Mouth Disease Vaccine at

http://www.aphis.usda.gov/lpa/pubs/fsheet_faq_notice/fs_ahfmdvac.html.

Veterinary Services, United States department of Agriculture. Last access on May 3rd, 2005.

- Anderson, R.M and R.M. May (1991). *Infectious diseases of humans: dynamics and control*. Oxford, UK: Oxford University Press. p 412-28.
- Breeze, R. (2004). "Agroterrorism: Betting Far More than the Farm". *Biosecurity and Bioterrorism: Biodefence Strategy, Practice, and Science*. 2(4): 251-264.
- Bates. T.W., M.C. Thurmond, and T.E. Carpenter (2001). "Direct and Indirect Contact Rates among Beef, Dairy, Goat, Sheep, and Swine Herds in Three California Counties, with Reference to Control of Potential Food-and-Mouth Disease Transmission". *American Journal of Veterinary Research*. 62(7):1121-1129.
- Carpenter, T.E., M.C. Thurmond, and T.W. Bates (2004). "A Simulation Model of Intraherd Transmission of Foot and Mouth Disease with Reference to Disease Spread Before and After Clinic Signs". *Journal of Veterinary Diagnostic Investigation*. 16(1): 11-16.
- Doel, T.R. and L. Pullen (1990). "International Bank for Foot-and-Mouth Disease Vaccine: Stability Studies with Virus Concentrates and Vaccines Prepared from Them". *Vaccine*, 8(5): 473-478.
- Doel, T.R., L Williams and P. V. Barnett (1994). "Emergency vaccination against foot-and-mouth disease. The rate of development of immunity and its implications for the carrier state". *Vaccine*, 12(7), 592-600.
- Elbakidze L. (2004). *Agricultural Bio-Security as an Economic Problem: An Investigation for the Case of Foot and Mouth Disease*. Unpublished PhD Thesis, Department of Agricultural Economics, Texas A&M University, 2004.
- NAO report (2002). The 2001 Outbreak of Foot and Mouth Disease, report by the Comptroller and Auditor General, HC 939 Session 2001-2002: 21 June 2002.
- National Agricultural Bio-security Center Consortium, *Carcass Disposal: A Comprehensive Review*. Prepared by the National Agricultural Bio-security Center Consortium at Kansas State University, Carcass Disposal Working Group for the USDA Animal & Plant Health Inspection Service per Cooperative Agreement 02-

1001-0355-CA, 2004. The entire report is available at <http://fss.k-state.edu/research/books/carcassdispfiles/Carcass%20Disposal.html>.

Schoenbaum, M.A. and W.T. Disney (2003). "Modeling alternative mitigation strategies for a hypothetical outbreak of food-and-mouth disease in the United States". *Preventive Veterinary Medicine*, 58: 25-32.

Scudamore, J.M., G.M. Trevelyan, M.V. Tas, E.M. Varley, and G.A.W. Hickman (2002). "Carcass disposal: lessons from Great Britain following the foot and mouth disease outbreaks of 2001". *Rev. Sci. Tech. Off. Int. Epiz.*, 21(3): 775-787.

Thrushfield, M.V. (1995). *Veterinary Epidemiology*, 2nd ed. Blackwell Science, Oxford, UK.

United Kingdom Comptroller and Auditor General, "The 2001 Outbreak of Foot and Mouth Disease" report to HC 939 Session 2001-2002: 21 June 2002.

6 Appendix A: Proof of Proposition 1

The comparative static analysis of equation (4) yields the following inequalities:

$$\frac{d s_1^*}{d \alpha} = \frac{1}{(1+r)SOC} \left(\frac{dSC(s_2)}{d s_2} + \frac{dEC(s_2)}{d s_2} + (1+\alpha_L)(\bar{Q} - s_1) \left(\frac{d^2 SC(s_2)}{d s_2^2} + \frac{d^2 EC(s_2)}{d s_2^2} \right) \right) > 0; \quad (\text{A-1})$$

$$\frac{d s_1^*}{d \bar{Q}} = \frac{1}{SOC} \left[\frac{dVC(s_2)}{d s_2} + \frac{(1+\alpha_L)^2}{1+r} \left(\frac{dSC(s_2)}{d s_2} + \frac{dEC(s_2)}{d s_2} \right) \right] > 0; \quad (\text{A-2})$$

$$\frac{d s_1^*}{dr} = -\frac{1+\alpha_L}{(1+r)^2 SOC} \left[\frac{dSC(s_2)}{d s_2} + \frac{dEC(s_2)}{d s_2} \right] < 0, \quad (\text{A-3})$$

where $SOC > 0$ is the second order condition of the cost minimization problem.

Taking the total derivative of Δ_c yields the following inequalities:

$$\frac{d \Delta_c}{d \alpha_L} = -\frac{\bar{Q} - s_1^*}{1+r} \left(\frac{\partial SC}{\partial s_2}(s_2^*) + \frac{\partial EC}{\partial s_2}(s_2^*) \right) < 0, \quad (\text{A-4})$$

$$\begin{aligned} \frac{d \Delta_c}{d \bar{Q}} &= \left(\frac{dSC}{d s_1}(\bar{Q}) + \frac{dEC}{d s_1}(\bar{Q}) \right) + \left(\frac{dVC}{d v_1}(v_1^*) + \frac{1+\alpha_L}{1+r} \left(\frac{dSC}{d s_2}(s_2^*) + \frac{dEC}{d s_1}(s_2^*) \right) \right) \\ &= \left(\frac{\partial SC}{\partial s_1}(\bar{Q}) - \frac{\partial SC}{\partial s_1}(s_1^*) \right) + \left(\frac{\partial EC}{\partial s_1}(\bar{Q}) - \frac{\partial EC}{\partial s_1}(s_1^*) \right) > 0 \end{aligned} \quad (\text{A-5})$$

$$\frac{d \Delta_c}{dr} = \frac{1}{(1+r)^2} (SC(s_2^*) + EC(s_2^*)) > 0. \quad (\text{A-6})$$

Differentiate equation (6-a) with respect to r yields the inequality below:

$$\frac{d \Delta q}{dr} = -\alpha_L \frac{d s_1}{dr} > 0 \quad (\text{since } \frac{d s_1^*}{dr} < 0) \quad (\text{A-7})$$

Differentiate equation (6-a) with respect to \bar{Q} yields and the following equation:

$$\frac{d \Delta q}{d \bar{Q}} = -\alpha_L \left(1 - \frac{d s_1}{d \bar{Q}} \right). \quad (\text{A-8})$$

Substituting equation (A-2) and SOC into (A-8)

$$\frac{d\Delta q}{d\bar{Q}} = \frac{\alpha_L}{SOC} \left(\frac{d^2 SC(s_1, c)}{d s_1^2} + \frac{d^2 EC(s_1)}{d s_1^2} \right) > 0. \quad (\text{A-9})$$

Similarly, we obtain another two inequalities below:

$$\begin{aligned} \frac{d\Delta q}{d\alpha_L} &= -\alpha_L \frac{d s_1}{d\bar{Q}} + (\bar{Q} - s_1) \\ &= \frac{1}{SOC} \left(\frac{d^2 SC(s_1)}{d s_1^2} + \frac{d^2 EC(s_1)}{d s_1^2} + \frac{d^2 VC(v_1)}{d v_1^2} + \frac{1 + \alpha_L}{1 + r} \left(\frac{d^2 SC(s_2)}{d s_2^2} + \frac{d^2 EC(s_2)}{d s_2^2} \right) \right) > 0 \end{aligned} \quad (\text{A-10})$$

We summarize inequalities in equations (A-1)-(A-5), (A-7), (A-9) and (A-10) below:

Table 1: Comparative Static Analysis for the two-period setting

	Disease spread	Initially infected and contact animals	Time value
Amount of slaughter and disposal in period 1	+	+	-
Difference in total slaughter and disposal with vaccination	+	+	+
Value of vaccination	-	+	+

■