An Optimal Surveillance Measure Against Foot-and-Mouth Disease in the United States

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Abstract: Surveillance programs on farms and in the local environment provide an essential protection against the importation and spread of exotic diseases. Combined with border quarantine measures, these programs protect both consumers and producers from major health concerns and disease incursions that can potentially destroy local agricultural production and supporting industries, as well as generate substantial losses in trade and tourism. However, surveillance programs also impose costs in the form of expenditures on the surveillance program itself, along with the costs of disease management and eradication should an incursion occur. Taking border quarantine expenditures as given, this paper develops a stochastic optimal control model (with a jump-diffusion process) to determine the optimal level of surveillance activity against a disease incursion by minimizing the present value of the major direct and indirect costs of the disease, as well as the cost of the surveillance and disease management and eradication programs. The model is applied to the case of a potential entry and spread of Foot-and-Mouth Disease in the United States. Results show that current surveillance expenditures are far less than optimal.

Keywords: Surveillance measures, border quarantine, disease incursion and spread, Foot-and-Mouth disease, stochastic optimal control.
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1.Introduction

The development of trade between regions and countries is an increasingly important characteristic of modern agriculture. Over the last two decades the gross value of agricultural trade has more than doubled, from $USD 234 billion in 1980 to $USD 522 billion in 2003 (FAO 2005a). With this increase in trade goes an increased likelihood of a disease or harmful pest incursion. In this regard, surveillance programs on farms and in the local environment provide an essential protection against the importation and spread of exotic diseases and pests. Combined with border quarantine and inspection services, these programs protect both consumers and producers from incursions that could potentially destroy local agricultural production and supporting industries, as well as generate substantial losses in trade and tourism. The key objective of surveillance activities is ‘early detection’, or becoming aware of the presence of an exotic disease before damages and management costs become too severe.

However, surveillance activities can be costly, depending on the severity of the surveillance measures in place and the target value for ‘early detection’ in the local environment. It is not hard to imagine that vast sums of money would be required to guarantee the detection of a specific exotic disease (much less all other possible diseases) in its first generation of growth or transmission, or over the smallest practical surface area of an outbreak. On the other hand, some pests and diseases can be so potentially damaging if an outbreak goes undetected for a sufficient period of time (or before it would be ‘naturally detected’ in the environment, say by local agricultural producers) that vast expenditures on early detection are justified.

This paper develops a practical model to determine an optimal surveillance measure against an exotic agricultural disease, with an application to the potential entry and spread of Foot-and-Mouth Disease (FMD) in the United States. Put simply, the idea is to minimize the total costs of a disease or FMD incursion, by minimizing the sum of the production losses that result from the disease and its transmission, the expenditures that go with the surveillance program itself, potential disease management and eradication costs, and the losses that result from trade bans and losses in tourism. The control variable is the potential target number of herds infected with FMD (which may not be zero, or even near zero), or the resulting cost of the surveillance program to generate this target. The trade off is simple. Early detection generally implies smaller potential production, trade and tourism losses following an FMD incursion, as well as lower management and eradication costs after a detection occurs. However, the earlier the detection of FMD the more expensive is the surveillance activity.

The application to FMD in the United States is an important case study. FMD is one of the most contagious diseases of mammals and has a great potential for causing severe economic loss in susceptible cloven-hoofed animals. In this regard, the livestock industry is the largest sector in the US agriculture, valued at more than $60 billion a year (USDA 2005), and is potentially at risk. An FMD outbreak could also severely affect related trade in agricultural products, valued at $50 billion annually (USDA 2005) and tourism. The annual value of livestock exports alone is roughly $USD 300 million (USDA 2005). A recent study estimated that the cost of an FMD outbreak in southern California alone could range between $USD 4.3 to $USD 13.5 billion (Ekboir 1999). The 2001 outbreak of FMD in the United Kingdom, with 2,030 confirmed cases of the disease and more than 6 million animals slaughtered (Hunter et al. 2003), resulted in an estimated $USD 5 billion direct loss in the food and agricultural sectors, as well as comparable losses in the tourism industry (GAO 2002, pp. 2, 20).

Section 2 of the paper briefly reviews previous studies of quarantine and surveillance measures. Numerical results are very rare even in basic deterministic models. They are virtually non-existent in properly defined stochastic models, in part because it is computationally demanding to solve stochastic optimal control problems in this setting, but also because required parameter values such as the probability of an incursion and the growth of transmission, not to mention potential measures of economic damages and surveillance costs, are difficult to obtain.

Second 3 provides the model. In general, protection against disease incursion and spread takes three forms: border quarantine and inspection, surveillance programs in the local environment and disease containment and/or eradication. In some cases, where the damages that result from a disease or pest are minimal, it pays to do none of these. In other cases, border quarantine measures may be sufficient, or these may be combined with reliance on a on a ‘natural detection point’, or the point at which the disease is identified in the environment by farmers or the public. Surveillance expenditures in this case are unnecessary, and only the cost of containment or eradication matters.

In this paper, current border quarantine measures are taken as given, and the focus instead is on optimal surveillance measures. The reason is simple. Given the extensive and elaborate Customs and border protection services in place in the US, it is difficult to determine what proportion of quarantine activities are directed specifically at FMD, making it hard to measure its relative effectiveness. WTO rules also prevent substantial and often needed flexibility in the terms of the severity of border quarantine measures, thus ruling out the possibility of a complete (or even a highly restrictive) barrier to FMD at the border. By their nature, local surveillance activities are much more flexible and are an important tool against FMD. Moreover, even where only limited livestock imports are permitted it would be impossible, given the many and various pathways, for border quarantine to prevent every incursion of FMD. Thus, given the severity of the disease, surveillance measures will most likely be needed against FMD in any case. That said, the model does allow for the possibility that the ‘natural detection point’ is optimal, or that surveillance expenditures are near zero. It also allows for the case that surveillance expenditures should be so large as to drive the optimal target number of infected herds to near zero. In all cases, given an outbreak of FMD it is assumed that eradication is the preferred outcome.

Section 4 of the paper briefly discusses FMD and section 5 outlines the livestock industry and current quarantine and surveillance activities in the United States. Section 6 details the risk assessment of the probability of an FMD incursion and key parameter values used to calibrate the model. Section 7, after a description of computational methods, provides final optimal results and sensitivity measures. Section 8 concludes.

2. Previous Studies

The fundamental relationship between surveillance expenditures and the target number of infected herds used in this paper is similar to that of McInerney et al. (1992) and McInerney (1996), which maps 'disease control' expenditures to production losses. An exact form of the surveillance expenditure function is contained in Kompas and Che (2003), which models border quarantine expenditures against a potential entry of Ovine Johne Disease to the sheep industry in Western Australia (WA). This model is similar in structure to the surveillance model used in this paper, but is it not an explicit stochastic optimal control model. Instead, it uses a genetic algorithm to directly minimize the cost of the disease and expenditures on the border quarantine program itself. Kompas et al. (2004) develops a related surveillance model for Papua fruit fly and its potential entry into Australia. The model has a probability of incursion but is also not an explicit stochastic control model. It is basically deterministic in structure, in a manner similar to a paper by Jensen (2002). Chi (2002) constructs an empirical model for the spread and control of infectious diseases on dairy farms and Zhao (2006) provides a dynamic disease model for FMD in the beef industry in the United Sates, nicely capturing producer response to a disease outbreak in a deterministic setting. The latter paper also details the tradeoffs associated with various disease management responses. A deterministic optimal control model of disease spread is constructed in Bicknell et al. (1999), focusing on private decisions on the level of diagnostic testing. Optimal quarantine and surveillance activities are not modeled, but it is argued that profit maximizing producers cannot be expected to eradicate a disease and that the current mix of policies to control bovine tuberculosis in New Zealand is achieving lower levels of prevalence than would occur in the absence of a national strategy.

Biological studies of the spread and management of exotic diseases, albeit with little or no explicit economic relationships, are numerous. Pech and Hone (1988) and Saphores and Shogren (2005) provide two good examples. Nunn (1997) provides a clear discussion of the structure of quarantine risk analysis, much of which is directly applicable to surveillance activities. A call for more extensive analyses of quarantine and related animal disease issues is nicely set out in James and Anderson (1998), and in terms of its impacts on international trade, in Mumford (2002).

3. Model Context

The model has five main components: (1) a biological model to describe both the growth and density growth of infected herds; (2) a surveillance expenditure function that maps the cost of surveillance to the spread of the disease and the point of detection; (3) a measure of production losses before detection occurs; (4) disease management costs, and trade and other losses that result during the disease management period, either in terms of disease containment or the time it takes for eradication; and (5) the stochastic process and objective function.

3.1 Growth and density growth of infected livestock

The unit of measurement is a 'herd', where the number of livestock in a herd will vary depending on whether it is dairy or beef cows, sheep or swine. Based on FMD development in a number of known cases in Europe, the Middle East and South America, the growth in the number of infected herds is assumed to follow a Verhulst-Pearl logistic function, so that

$$\frac{dN(t)}{dt} = gN(t)\left(1 - \frac{N(t)}{N_{\max}}\right) \tag{1}$$

for $N(t)$ the number of infected herds at time *t*, *g* the intrinsic or biological growth rate and $N_{\max}$ the maxmium number of infected herds, relative to the environmental 'carrying capacity'. In a similar fashion density growth is given by

$$\frac{dD(t)}{dt} = zD(t)\left(1 - \frac{D(t)}{D_{\max}}\right) \tag{2}$$

for *z* the density growth rate, *D(t)* the ratio of the number of infected herds to total herds and $D_{\max}$ the maximum density rate.

3.2 Surveillance expenditure function

A surveillance expenditure function maps surveillance expenditures to a point of early detection of a disease incursion, expressed in terms of the number of potentially infected animals in the population. Larger surveillance expenditures (e.g., blood and viral tests, screening, physical examination) generally result in points of 'earlier' detection and a smaller number of potentially infected livestock. Define R_m as the number of infected animals occurring at the 'natural detection point', or where the disease incursion is self-evident or recognized by farmers and/or the public, without any surveillance expenditures. Let E_m be the amount of surveillance expenditures that will ensure the earliest possible detection, or where the number of infected animals is either near zero, depending on the efficacy of border quarantine measures, or the incursion is detected before almost no spread of the disease. This amount can be finite, but it may also be infinite. The surveillance expenditure function is given by

$$E(X,\eta) = \frac{E_m(R_{\mathrm{m}} - X)}{R_{\mathrm{m}}(\eta X + 1)} \tag{3}$$

for X the target number of infected animals that potentially enter a population and η a surveillance effectiveness parameter. The higher the value of η the lower the expenditure on surveillance for a given number of infected livestock, or the more convex is the expenditure function. When $\eta = 0$ the expenditure function is linear; in all other cases, for $\eta > 0$, the marginal benefit of surveillance decreases with a decrease in the target value X .

3.3 Production loss

Once a potentially harmful disease is detected there are two management possibilities, eradication or containment. For FMD, eradication is the preferred option in most cases. FMD results in losses in animal weight and production that occur until the point of detection and the successful completion of an eradication campaign. This potential production cost before detection depends on the length of the time over which the disease has developed and the time to eradication. For the moment, assume that production loss at time *t* depends both on the number of herds and density and is given by

$$C_p(t) = c_p N(t) D(t) \tag{4}$$

for c_p average production loss per herd. For simplicity, it is assumed that any reduction in infected herds (through containment or eradication) implies that both density and infected herd numbers are reduced proportionately.

3.4 Disease management and trade and tourism losses

An outbreak of FMD immediately generates disease management costs. Generally, all livestock in an infected heard are destroyed, including feedstuff and milk, and additional costs are incurred through disinfection and cleaning activities. Within the designated buffer zone, ϕ, or the area that defines the FMD eradication zone, vaccination costs are also imposed for all animals entering the area for at least two years after a successful eradication campaign. Assuming that all costs are proportional to the target number of potentially infected herds X gives

$$C_{me} = c_{me} X \qquad C_{mv} = c_{mv} \phi X \tag{5}$$

for C_{me} eradication costs and C_{mv} vaccination costs, with average cost parameters c_{me} and c_{mv}.

An FMD outbreak also generates an immediate trade ban for exported livestock products to disease free areas. The cost here can be considerable. In addition, the tourism industry also suffers losses due to travel restrictions and quarantine provisions. The loss in tourism revenue in the recent UK FMD outbreak, for example, was estimated to be well over a billion dollars (GAO 2002, pp. 2, 20). Trade and tourism losses depend on the length of time length for disease management, or until a FMD free status is declared. In general, the larger the number of infected herds the longer the disease management period, with a minimum of 24 weeks in all known cases. Let the length of time for disease management (T_m) be given by

$$T_m = \alpha_0 + \beta X \tag{6}$$

where α_0 is the minimum time for disease management and β is a given parameter. Trade and tourism losses (C_{tt}) are thus

$$C_{tt} = \left(\alpha_1 Y_{tr} + \alpha_2 Y_{tou}\right) T_m \tag{7}$$

where Y_{tr} and Y_{tou} is the gross value of livestock trade and relevant tourism respectively, and α_1 and α_2 are parameters.

3.5 Stochastic process and objective function

The basic idea is to construct a stochastic optimal control problem, with a jump-diffusion process. Assume that both a disease incursion Q_i and a disease detection Q_d are Poisson processes, with an incursion arrival rate $\lambda_i = 0.03$ and a detection arrival rate that depends on the number of infected herds and target number of infected herds *X*, or

$$\lambda_d = \theta \frac{N(t)/X}{N(t)/X + \delta} \tag{8}$$

where θ and δ are positive coefficients. The functional form of λ_d ensures that the rate of detection will be maximised when the number of infected herds reaches the target value *X*, and be zero when $N(t) = 0$. Assume as well that that any infected herds and density growth are affected by (non-correlated) Brownian processes W_N and W_D with standard deviations $\sigma_N = 0.05N(t)$ and $\sigma_D = 0.05D(t)$. Using this and equation (1) and (2), equations of motion for the number of infected herds and density are given by

$$dN(t) = gN(t)\left(1 - \frac{N(t)}{N_{\max}}\right)dt + \sigma_n N(t) dW_n + N_0 dQ_i - N_e dQ_e \tag{9}$$

and

$$dD(t) = zD(t)\left(1 - \frac{D(t)}{D_{\max}}\right)dt + \sigma_d D(t) dW_d + D_0 dQ_i - D_e dQ_e \tag{10}$$

where detection is immediately followed by a process of eradication, which decreases the number of infected herds and their density, where N_e and D_e take on positive values if eradication is unsuccessful or zero if it is successful.

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The problem now is to minimize the discounted value over time of total costs (ρ is the discount rate) associated with the FMD, including surveillance expenditures, production losses, disease management costs and trade and tourism losses. Using equations (3) to (7) the problem at any moment in time is to minimize

$$TC(X)=\min_X E\left\{\int_0^\infty\left[\frac{E_m(R_m-X)}{R_m(\eta X+1)}+c_pN(t)D(t)\right]e^{\rho t}dt+\int_0^\infty c_pN_0D_0e^{\rho t}dQ_i\right.$$
$$\left.+\int_0^\infty\left[(c_m+c_{mc}\phi)X+(\alpha_1Y_{TR}+\alpha_2Y_{TOU})T_M\right]e^{\rho t}dQ_e\right\} \tag{11}$$

subject to motion equations (9) and (10), where the control variable is the target number of potentially infected herds *X* and *E* is the usual expectations operator. The third term on the right-hand side of equation (11) is the production loss or cost of an initial incursion (at time 0) integrated over the number of potential incursions. The functional equation for (11) is

$$C(N(t),D(t))=\max_X E\left\{\left[\frac{E_m(R_m-X)}{R_m(\eta X+1)}+c_pN(t)D(t)\right]dt+c_pN_0D_0dQ_i\right.$$
$$\left.+\left[(c_m+c_{mc}\phi)X+(\alpha_1Y_{TR}+\alpha_2Y_{TOU})T_M\right]dQ_e+e^{-\rho dt}C(N(t)+dN(t),D(t)+dD(t))\right\} \tag{12}$$

with a solution, applying Ito’s lemma, given by

$$\rho C(N(t),D(t))=\max_X\left\{\frac{E_m(R_m-X)}{R_m(\eta X+1)}+\lambda_ic_pN_0D_0+c_pN(t)D(t)+\lambda_d(c_{me}+c_{mc}\phi)X\right.$$
$$+\lambda_d(\alpha_1Y_{tr}+\alpha_2Y_{tou})T_m+C_NgN(t)\left(1-\frac{N(t)}{N_{\max}}\right)$$
$$+C_dzD(t)\left(1-\frac{D(t)}{D_{\max}}\right)+0.5C_{nn}\sigma_n^2N(t)^2+0.5C_{dd}\sigma_d^2D(t)^2$$
$$\left.+\lambda_i\left[C(N(t)+N_0,D(t)+D_0)-C(N(t),D(t))\right]+\lambda_e\left[C(N_e,D_e)-C(N(t),D(t))\right]\right\} \tag{13}$$

using equations of motion and relevant first and second order variations on $C(N(t),D(t))$, with respect to *N* and *D*.

4. Foot and Mouth Disease

Foot and Mouth disease (FMD) is a highly contagious disease of susceptible cloven-hoofed animals. The potential economic losses from a disease incursion can be enormous. As mentioned, the 2001 outbreak of FMD in the United Kingdom resulted in over $5 billion in losses in the food and agricultural sectors alone, as well as comparable losses to its tourism industry (GAO, 2002, pp. 2, 20). FMD hosts are typically cattle, sheep and swine, but the disease can also occur in domestic and water buffalos, goats, yaks and zebras. Animals become infected through inhalation, ingestion and by venereal transmission. The primary mechanism of spread within herds is by direct contact, through inhalation of virus aerosols. Under the right conditions long distance spread of FMD by wind-borne virus can occur over a number of kilometers. However, contact between and movement of infected animals is the most common pathways for the spread of the disease between herds. Other sources of infection include contaminated vehicles, equipment, people and farm products. The FMD virus can also survive for long periods in meat as well as in frozen lymph nodes, bone marrow, salted and cured meats and non-pasteurized dairy products. It has also been shown experimentally that FMD can be transmitted through artificial insemination where semen from infected animals is used.

There are seven serotypes of the FMD virus. Infection with one serotype does not confer immunity against another. At present FMD is endemic in parts of Asia, Africa, the Middle East and South America. The incubation period is short but varies and the clinical signs of the disease are usually mild and may be masked by other conventional conditions, allowing the disease to go unidentified for some period of time. Typical cases of FMD are characterized by a vesicular condition of the feet, mucosa and the mammary glands in females. Diagnosis is obtained through examination of vesicles or vesicular fluid, and where this is not possible from blood samples or throat swabs (in pigs). The mortality rate for non-adult animals infected with FMD varies and depends on the species and strain of the virus. In most cases adult animals usually recover once the disease has run its course. However, because the disease leaves them severely debilitated, meat-producing animals do not normally regain their lost weight for many months, if at all, and dairy cows seldom produce milk at their former rate, causing severe losses in the production of meat and milk (GAO, 2002, p. 12).

5. The Livestock Industry and Quarantine and Surveillance Activities in the USA

There is about 2.1 million livestock in the US, including almost 1 million major dairy and beef farms, 73,800 sheep and lamb farms, 20,300 pig farms and more than a million small cattle farms. For over four decades, the live cattle industry has been the largest sector in agriculture contributing on average $US 62.4 billion gross value of production a year or almost 30 per cent of the major agricultural output (NASS 2005). Production occurs throughout the country but is concentrated in the Midwest States, Texas, California and the Northeast. Beef cows in particular accounted for 78.6 per cent of the total cow inventory in 2005, with a relatively large number of operators, or 774,630 farms. Large farms of 100 head or more account for only 10 per cent of total farms but more than half of the total beef cow inventory.

The US has been declared disease free of FMD since 1929. Between 1870 and 1929 FMD incursions occurred 8 times, with the most devastating in 1914 resulting in the loss of more than 100,000 livestock. The potential impact of FMD on the livestock industry depends on the distribution of cattle and their susceptibility from state to state. Susceptibility depends on livestock concentration and a host of natural conditions, generating different risk assessments. The standard measure used is that by Miller (1979), who developed a model of an FMD epidemic, dividing the country into three risk zones. Zone 3 is designated as the zone with the highest risk of incursion and spread of FMD. Table 1 indicates the number of farms by state, their risk level and the number of what are termed Foreign Animal Disease (FAD) inspections, or field investigations and diagnostic laboratory surveillance, for FMD in 2005. Of the total number of farms (2,113,470) in 2005, 1,822,360 were classified in zone 3, with 75 per cent of these (1,366,788) designated as highly susceptible.

Preventing the incursion and spread of FMD involves both border inspections and border quarantine and field surveillance measures. Again, there are a number of key pathways through which FMD could potentially enter the United States: live animal imports, imports of animal and other products, international passengers and their luggage, garbage from international carriers, international mail, and military personnel and equipment returning from overseas. For each of these pathways, the United States Department of Agriculture (USDA) has developed and implemented specific preventive measures (GAO 2002, pp. 38-43). For example, the USDA allows imports of livestock only from countries deemed to be free of FMD and other diseases of concern, through designated ports of entry. Livestock brought to the US must have an import permit and a health certificate from an official government veterinarian in the country of origin. The health certificate states that the animals have been in the exporting country for at least 60 days prior to shipment and are free of any diseases of concern. Food and non-food (hay, grass and farm equipment) imports are allowed from FMD infected countries under strict conditions. In cooperation among Customs, the USDA and the Animal and Plant Health Inspection Service (APHIS), all animals, food and non-food products are subject to inspection at the border and potential quarantine to determine their FMD or other disease status. Customs is authorized to either release shipments into commerce or hold them for USDA inspection and the USDA provides Customs with a list of products to be flagged for inspection by APHIS.

It is impossible to guarantee that the FMD virus will be stopped at the border in every case. Border quarantine is supplemented with surveillance on farms and in the local environment. In the United States the National Animal Health Surveillance System (NAHSS) is responsible for this activity, including field investigations and diagnostic laboratory surveillance. These FAD investigations are conducted by specially trained Federal, State and privately accredited veterinarians, along with trained farmers who check for suspicious clinical signs. From 1997 to 2004, the number of FAD investigations per year in the 50 states and Puerto Rico ranged from a low of 254 in 1997 to a high of 1,013 in 2004. There were 689 vesicular complaints, of which 511 were in horses, donkeys, and mules and 178 in other species (e.g., ruminants and swine). Generally, vesicular conditions in species other than equines are considered suggestive of FMD (NAHSS 2005). The most FAD investigations in 2005 were conducted in California, Louisiana, Texas, Illinois, Tennessee and Wisconsin (see table 1).

Along with field investigations, the recognition of the suspicious clinical signs for FMD depends very much on the general public awareness, and educational campaigns to heighten that awareness. However it is difficult to recognize FMD, and distinguish it from other similar diseases, which are much less harmful, such as vesicular stomatitis, bovine viral diarrhea and foot rot. Two foreign swine diseases (swine vesicular disease and vesicular exanthema of swine) are also clinically identical to FMD. Therefore, the only way to distinguish between FMD and these other diseases is through laboratory analyses of fluid and tissue samples (GAO 2002).

Currently diagnostic testing for FMD is restricted to the Foreign Animal Disease Diagnostic Laboratory located at Plum Island, which routinely performs diagnostic tests for FMD as a part of FAD investigation (Bates et al. 2003b). This single lab would be quickly overwhelmed in the event of an FMD outbreak. For example, the 2001 FMD outbreak in the UK required 15,000 sample tests as part of its eradication program and more than a million tests to establish a disease-free confirmation (GAO, 2002). Recently, the USDA has initiated improvements to its diagnostic and research facilities in Ames, Iowa and Plum Island, and more than $USDA 15.3 million was allocated to the Agricultural Research Service to improve 'rapid detection technology' for FMD as well as other animal diseases (GAO 2002).

6. Risk Assessment and Key Parameter Values

Calibration of the model requires both a risk assessment on a probable disease incursion and key parameter values. The key parameter set includes: (1) incursion and biological parameters; (2) parameters in the surveillance expenditure function; and (3) production cost, disease management and trade tourism parameters.

6.1 Incursion and biological parameters

Key incursion and biological parameters are drawn from the GAO (2002) and Bates et al. (2001, 2003a, 2003b). The probability of a FMD incursion is the most difficult parameter to determine. The probability is thought to be increasing over time with increases in international trade and the growing prevalence of the disease in various of the world, but its precise measure for the United States is unclear. With current quarantine restrictions in place, a possibility of an outbreak once in every 30 years is commonly discussed. Subject to sensitivity analysis, the annual probability of an incursion λ_i is thus roughly taken as 0.03. The transmission or growth rate of the disease is more easily known, with studies drawn from the recent UK experience (GAO 2002) and Uruguay (Chowell et al. 2005 and FVO 2002). The value *g* is taken as 0.45 per cent per week and density growth *z* is 0.2 per cent per week. According to USDA estimates (GAO 2002), the potential number of initial infected herds N_0 is 15 and maximum number of infected herds $N_{\max}$ is 81,000. The initial density D_0 is taken as 5 per cent of a given herd, maximum density $D_{\max}$ is 75 per cent and the eradication zone is typically (in practice) set at a radius 9 times the radius of the original area in which infected livestock were found. In order to determine the detection rate, values of $\theta = 52*1.1$ and $\delta = 0.1$ are assumed.

6.2 Surveillance expenditure function parameters

Parameter values for equation (3), the surveillance expenditure function, are based on Bates, (2003a, 2003b). Current surveillance expenditures against FMD in the United States are roughly $USD 8.29 million. This is based on FAD operating expenses of $USD 24 million and associated capital (laboratories and equipment) of more than $USD140 million. The cost of surveillance on FMD, given the 834 FAD investigations (table 1), for a number of different diseases, is thought to be about 25 per cent of the total operating budget and roughly 35 per cent of the value of all labs and equipment. A 5 per cent interest rate is used to account for capital costs. Detecting FMD in the first week of outbreak is estimated to require at least 2,000 individual FAD inspections for FMD alone, compared to 200 in 2005. The 'natural detection point' or R_m is calculated to be 4,000 herds and E_m is 10 times current expenditures or $USD 82.9 million. The value of η, or the surveillance effectiveness parameter, is thus approximated by $\eta = .0021$. Based on equation (3) the target number of infected herds under the current surveillance program is 2000 herds.

6.3 Production cost, disease management and trade tourism parameters

Herd size varies across different livestock, as does the cost of production losses associated with an FMD outbreak. In this paper it is assumed that the cost of the disease in terms of production loss occurs only at the farm level (directly, for example, affecting milk and meat production), and not to the indirect farm sector (such as transportation, retail and supporting industries). It is also assumed that only beef, dairy, sheep and pig industries are potentially subjected to FMD. Average cost or production losses are drawn from a USDA study (USDA 2005) with a value of $c_p = 0.224$ in equation (4), and are comparable to average production losses in the 2001 UK outbreak (GAO 2002).

Average indemnity cost is estimated to be roughly $USD 224,000 per herd. This value is estimated from the average market value of livestock (Bates et al. 2003a), average herd sizes and the proportional share of dairy, beef, pig and sheep farms in susceptible areas (USDA 2005). The market value per head for dairy heifer, heifer calves, sheep and pigs is $1,200, $602, $231 and $120 per head respectively in USD (Bates et al. 2003a). The average cost of cleaning and disinfection is $USD 18,062 per herd and vaccination costs are $USD 2,960 per herd (Bates et al. 2003a). The vaccination zone, once again, is taken as 8 times the size of the radius of the initial infestation, as simulated in the study of a hypothetical outbreak of FMD in California (Bates et al. 2001). In equations (5), ϕ is thus 8 and the calculated average disease management costs, or c_{me} and c_{mv}, are 0.018 and 0.00296 respectively.

The value of α_0 in equation (6) is 24 weeks, the usual minimum time requirement for FMD free status assuming the disease can be detected and eradicated in the first week of incursion. For time periods longer than this, $\beta = 0.008$, based on the UK experience (DEFRA 2002). Losses from trade bans and falls in tourism depend on the time length of disease management. The average weekly gross value of exported livestock is $USD 5.7

million (USDA 2005) and the average weekly value of all tourist activities is estimated to be 0.7 billion (USCB 2005). Clearly only a small part of contractions in tourist revenue will be due to an FMD outbreak. The values of α_1 and α_2 in equation (7) are taken as 0.1 and 0.005, roughly (again) the same proportions as in the recent UK experience (GAO 2002 and DAFRD 2002).

7. Computation, Results and Sensitivity Measures

A solution to equation (13) is obtained through a finite difference method (see Judd1999) for a given *X*, and then *X* is varied to find the target value of *X* that minimizes total costs in (13). The finite difference method maps a total cost function defined across a domain $(N_0...N_{\max}, D_0...D_{\max})$ in a grid pattern where the distance between the closet node in dimension *N* is *h* and in dimension *D* it is *k*. In total there will be $H*K$ nodes, where $H=(N_{\max}-N_0)/h+1$ and $K=(D_{\max}-D_0)/k+1$. At an arbitrary node (i,j), denote $C_{ij}=C(i,j)$ and approximate the partial derivatives of the cost function $C(N,D)$ by

$$C_N = (C_{i+1,j} - C_{ij})/h \tag{14}$$

$$C_{NN} = (C_{i+1,j} - 2C_{ij} + C_{i-1,j})/h^2 \tag{15}$$

$$C_D = (C_{i+1,j} - C_{ij})/k \tag{16}$$

and the variation

$$C_{DD} = (C_{i,j+1} - 2C_{ij} + C_{i,j-1})/k^2 \tag{17}$$

Substituting (14)-(17) into equation (13) and thus approximating C_{ij} defines the cost function and a system of $(H+N_0/h)*(K+D_0/K)$ unknowns in $H*K$ to solve for each C_{ij}. When $N=D=0$, $C_{i,-1}$ and $C_{-1,j}$ will vanish, and closure is provided by two boundary conditions specifying that the cost function becomes 'flat' at levels of *N* and *D* that exceed $N_{\max}$ and $D_{\max}$. In other words, once maximum carrying capacity is reached, in both the number of infected herds and density, it is assumed that there are no additional economic costs to a disease incursion.

With this method, solving (13) is now equivalent to solving a basic linear system. However, as the grid for the finite difference method defining the cost function gets finer, or with more defined nodes, computational time increases rapidly. Even with a modest grid size of dimension 200 by 200, the relevant matrix will have a dimension of 40,000-squared, and with 8 bytes per element requires approximately 12 gigabytes of RAM to store the matrix. To reduce computational time both a sparse matrix and iteration method are used. Sparse matrix methods keep only non-zero elements of the relevant matrix and the iteration method helps to reduce computation time in comparison with traditional matrix inversion method. We also employ a Richardson extrapolation method (see Marchuk & Shaidurov, 1983) to refine the solution with relatively smaller number of nodes. To further accelerate convergence of the iterative methods the BiCGSTAB (or biconjugate gradient stabilized) routine, first introduced by Vorst (1992), and the PETSC library package (see Balay et al. 2004, 2001,1997) are used. The model is coded in the *C* programming language.

An example of a mapped total cost function is given in figure 1, with a grid size of 800 by 800. This function is mapped over the entire range of costs in million USD defined over density and the number of infected herds. The increasing wave-like pattern is due to a new incursion stepping beyond, at some point, a given eradication zone. A disease incursion, in other words, thus results in an immediate jump in costs, which increase given the properties of equations (4) to (7), until a new incursion is realized past the given or current eradication zone.

Using the risk assessment and all key parameter values from section 6, the minimum value cost function obtained by varying the number of potentially infected herds *X* is given in figure 2. All growth and density rates and potential damages are translated into yearly measures. The optimal value of *X* is 405 herds at a potential disease incursion cost of $USD 4,320.23 million or roughly 4.3 billion US dollars. Using equation (3), optimal surveillance expenditures against an FMD incursion amount to roughly $USD 40.3 million per year. Current annual surveillance expenditures are approximately $USD 8.29 million, and thus far below optimal values. Current expenditures, assuming that current policy was consistently applied with equation (3) operating, in fact act as if the target was 2,000 potentially infected herds, rather than 405.

Sensitivity across key parameter values varies considerably. For example, a change in the growth rate of disease transmission is relatively insensitive: an increase in the growth rate of more than 16 times results in only a 0.7 per cent change in total incursion costs and a negligible variation in the target value of *X*. A change in the density growth rate has even less of an effect, with virtually no change in the target number of infected herds over a wide rang of parameter values. (Tables indicating all results for changes in growth and density rates across a range of parameter values are available from the authors on request.) The reason for these outcomes is straightforward. Although a higher growth rate for disease transmission causes more damages, it is also more likely to be detected earlier, and hence controlled and eradicated. In terms of density growth, higher density growth rates do create more production losses initially, but an outbreak of FMD immediately creates an eradication zone in which all animals are destroyed regardless of their density growth.

In terms of sensitivity results, differences in the probability of an FMD incursion do matter, and considerably. Table 2 shows the total costs of a disease incursion in million USD with different probabilities (*p)* of a disease incursion and the optimal target number of infected herds (*X*). The benchmark case is $p = 0.03$ and $X = 405$. An increase in the probability of an incursion to 0.036 results in the optimal target for *X* falling to 330; a fall in the probability of an incursion to 0.024 increases *X* to 510. It is important to note that even at a very low incursion rate and target of $X = 510$ optimal surveillance expenditures are still $USD 34.9 million dollars, or more than four times more than current surveillance expenditures in the United States. In table 3 an increase in the average production losses clearly decreases the optimal target *X*. The benchmark case is

$c_p = 0.22$. An increase in c_p to 0.31, for example, decreases *X* to 370, with an annual surveillance expenditure of roughly $USD 42 million. Table 4 shows some limited sensitivity between the size of the eradication zone and the optimal target number of infected herds *X*. The benchmark is 8. The larger the eradication zone the larger the resulting damages in production and disease management costs, and thus the smaller the target number of infected herds.

8. Concluding Remarks

Surveillance activates provide an important means of protection against the importation and spread of exotic diseases, especially those that can do enormous harm to local agricultural production. However, surveillance programs also impose costs in the form of expenditures on the surveillance program itself, along with the costs of disease management and eradication should an incursion occur. Taking border quarantine expenditures as given, this paper develops a model to determine the optimal level of surveillance activity against a disease incursion and spread by minimizing the present value of the major direct and indirect costs of the disease, as well as the costs of the surveillance and disease management and eradication programs. The model is applied to surveillance activities against a potential entry of FMD in the United States.

The model allows for both zero surveillance expenditures, or reliance simply on a ‘natural detection point’, as well as the possibility that surveillance expenditures should be sufficiently large to drive the optimal number of potentially infected herds close to zero, with detection and eradicated at the earliest possible moment. Final results generate an intermediate case, showing a target number of 405 infected herds with $USD 40.3 million in annual surveillance expenditures, or almost five times larger than the current $USD 8.29 annual surveillance expenditure program in the United States. These results were obtained assuming no indirect costs of an FMD incursion on retail and transportation sectors, or any other farm-related activities, and by assuming that the probability of an incursion is only once in every 30 years. Assuming that this rate falls to once in every 40 years still generates at annual expenditure of roughly $USD 35 million, well above current values.

An essential aspect of homeland security is to protect the United States against costly and potentially devastating disease incursions and spread. Surveillance activities offer an effective and flexible means of protecting against such events. With regard to FMD, the United States is clearly under-investing in its surveillance program.

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Table 1: Number of livestock farms by state, FMD risk and FAD surveillance

State	No of farms	Risk Zone	No of FAD investigations
Alabama	45,000	3	7
Alaska	610	3	30
Arizona	10,300	2	17
Arkansas	47,500	3	12
California	78,500	1	159
Colorado	31,400	2	16
Connecticut	4,200	3	1
Delaware	2,300	3	0
Florida	44,000	3	14
Georgia	49,300	3	36
Hawai	5,500	3	0
Idaho	25,000	2	26
Illinois	73,000	3	55
Indiana	59,500	3	4
Iowa	90,000	3	27
Kansas	64,500	3	12
Kentucky	87,000	3	6
Louisiana	27,200	3	66
Maine	7,200	3	1
Maryland	12,100	3	3
Massachusetts	6,100	3	7
Michigan	53,300	3	10
Minnesota	80,000	3	3
Mississippi	42,800	3	4
Missouri	106,000	3	2
Montana	28,000	2	4
Nebraska	48,500	3	16
Nevada	3,000	2	0
New Hampshire	3,400	3	2
New Jersey	9,900	3	5
New Mexico	17,500	2	16
New York	37,000	3	6
North Carolina	53,500	3	13
North Dakota	30,300	3	10
Ohio	77,600	3	9
Oklahoma	83,500	3	8
Oregon	40,000	1	9
Pennsylvania	58,200	3	12
Rhode Island	850	3	5
South Carolina	24,400	3	10
South Dakota	31,600	3	3
Tennessee	87,000	3	44
Texas	229,000	3	62
Utah	15,300	2	9
Vermont	6,500	3	3
Virginia	47,500	3	17
Washington	35,500	1	11
West Virginia	20,800	3	0
Wisconsin	76,500	3	38
Wyoming	9,200	2	4
Total	2,113,470		834

Sources: *United States Department of Agriculture (USDA), 2005; Miller, 1979; and the National Animal Health Surveillance System (*NAHSS). (2005).

Figure 1: An example total cost function mapped over density and the number of infected herds

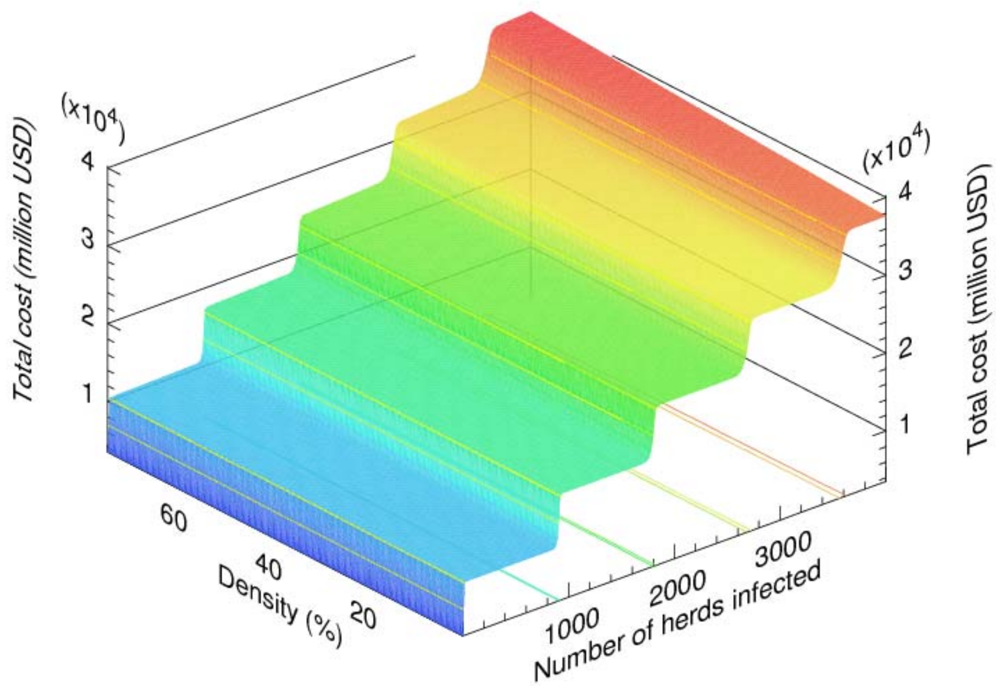

Figure 2: Optimal target value of infected herds *X* and costs from a disease incursion

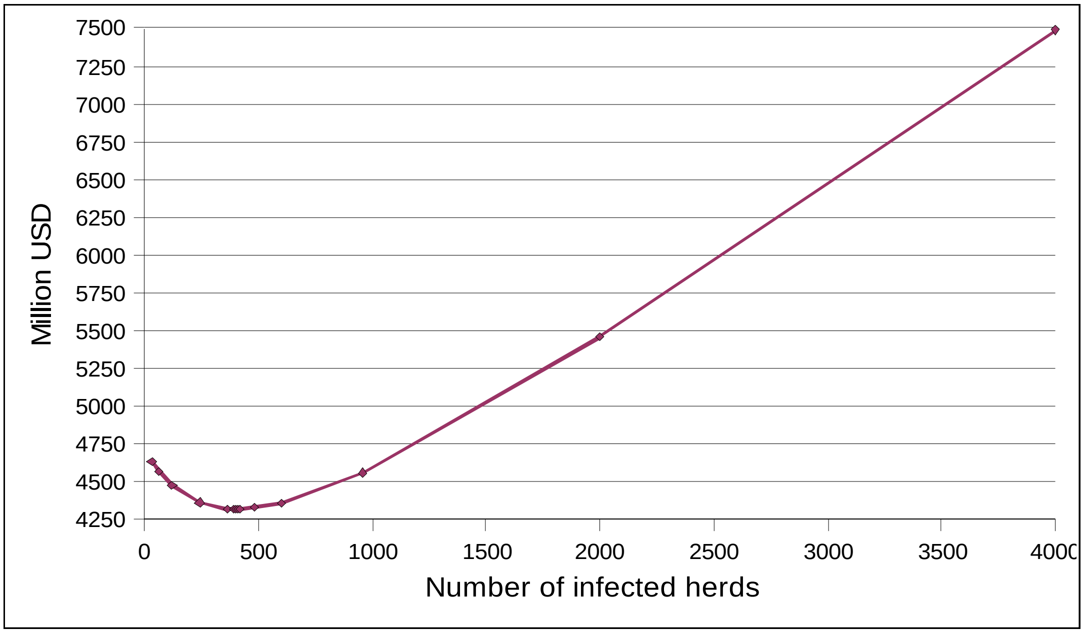

Table 2: The total costs of a FMD incursion in million USD with different probabilities (*p*) of disease incursion and the optimal target number of infected herds (*X*)

p	*X*									
	310	330	350	370	405	430	450	490	510	530
0.024	3652.85	3643.23	3634.95	3627.92	3618.36	3613.49	3610.66	3607.59	**3607.25**	3607.64
0.027	3993.15	3985.78	3979.76	3974.98	3969.37	3967.31	**3966.73**	3968.16	3970.07	3972.71
0.030	4333.32	4328.21	4324.44	4321.91	**4320.23**	4320.98	4322.65	4328.57	4332.72	4337.6
0.033	4673.39	4670.52	4668.99	**4668.71**	4670.96	4674.51	4678.41	4688.81	4695.19	4702.31
0.036	5013.34	**5012.71**	5013.43	5015.38	5021.54	5027.88	5034.02	5048.88	5057.5	5066.84

Table 3: The total costs of a FMD incursion in million USD with variations in average production losses (c_p) and the optimal target number of infected herds (*X*)

c_p	*X*							
	350	370	390	405	410	430	450	470
0.13	4301.67	4298.07	4295.64	4294.53	4294.29	**4293.94**	4294.54	4296.02
0.18	4313.05	4309.99	4308.09	4307.38	**4307.27**	4307.46	4308.59	4310.61
0.22	4324.44	4321.91	4320.55	**4320.23**	4320.26	4320.98	4322.65	4325.19
0.27	4335.82	4333.83	**4333.00**	4333.09	4333.24	4334.5	4336.7	4339.78
0.31	4347.21	**4345.45**	4345.75	4345.94	4346.23	4348.02	4350.75	4354.36

Table 4: The total costs of a FMD incursion in million USD with variations in the size of the eradication zone (ϕ) and the optimal target number of infected herds (*X*)

ϕ	*X*					
	395	400	405	410	415	420
1.6	4315.91	4315.75	4315.65	**4315.62**	4315.66	4315.75
4.8	4318.14	4318.01	4317.94	**4317.94**	4318.00	4318.12
8.0	4320.38	4320.27	**4320.23**	4320.26	4320.35	4320.5
11.2	4322.61	4322.53	**4322.52**	4322.58	4322.69	4322.87
14.4	4324.84	**4324.79**	4324.81	4324.89	4325.04	4325.25