EX ANTE PREPAREDNESS VS. EX POST RESPONSE TO ANIMAL DISEASE INTRODUCTIONS: BETTER SAFE THAN SORRY?

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Abstract

This article examines a tradeoff between ex ante preparedness costs and ex post costs of response to a potential introduction of an infectious animal disease. In a simplified case study setting we examine the conditions for optimality of enhanced detection system considering various characteristics of a potential infectious cattle disease outbreak, costs of program implementation, severity of the disease outbreak, and relative effectiveness of ex ante preparedness and ex post response actions. We show that the decision to invest in ex ante preparedness activities depends on such factors as likelihood of disease introduction, disease spread rate, relative costs, ancillary benefits and effectiveness of mitigation strategies.

Ex Ante Preparedness vs. Ex Post response to Animal Disease Introductions: Better Safe than Sorry?

U.S. agriculture, which in 2002 accounted for $250 billion in gross domestic product and employed nearly 1.6 million people while feeding the US population (Bureau of Economic Analysis, 2004), represents a significant component of US economy. Possible intentional or unintentional disruptions in functionality of agricultural industry could result in substantial economic losses (Thompson *et al.,* 2003; Mangen and Barrell 2003; Henson and Mazzocchi 2002). Some have identified food and water contamination as a relatively easy way to initiate a possible bioterrorism attack (Khan *et al.* 2001). From an economic perspective, a major consequence of a possible intentional or unintentional agricultural contamination is that it would cause disruptions in agricultural commodity and related markets due to possible perceived human health implications (Henson and Mazzocchi, p. 371, 2002). In addition, potentially expensive and intrusive mitigation actions could also represent a significant portion of total costs. Agriculturally related contamination events could have large consequences for consumers, producers and international trade as seen during recent mad cow events as they influenced conditions in the US, Canada, UK, and Asia.

This possible disruption has raised many issues regarding protection of vulnerable components of the economy against potential events and regarding efficient response to possible attacks. One such issue involves the balance between ex ante and ex post efforts to rapidly respond to possible events and minimize the associated damages. The key point here is the distinction between costs of ex ante and ex post decision making. While costs of most ex ante actions are encountered regardless of event occurrence, ex post mitigation costs are present only when responding to materialized incident. For example, costs of initiating animal health surveillance system are encountered whether or not the outbreak of animal disease takes place. However, costs of slaughter and disinfection arise only in the event of disease introduction.

Agricultural security related decision making involves several economic issues. Economic welfare in the form of lost consumers' and producers' surpluses, plus the costs of ex ante and ex post mitigation actions are at the forefront of the economic issues. Here an investigation will be done on how the characteristics of outbreak events and characteristics of mitigation options influence the choice of economically optimal policy and management strategies addressing those events. Emphasis will be placed on the optimal balance between the use of ex ante pre-event alternatives versus ex post after event alternatives as influenced by potential event characteristics. For example, under what circumstances is it beneficial to invest in animal health surveillance program and thus intercept the disease spread in a timely manner, versus rely on response measure, which, unlike surveillance program, would be activated only if the outbreak occurs?

Our examination of this issue consists of two parts. First we will present a broad conceptual approach to the issue. We formalize a theoretical framework and conduct sensitivity analysis on the optimal use of ex ante actions. Subsequently we conduct an empirical case study in the context of Foot and Mouth Disease (FMD) and investigate optimality of using ex ante preparedness actions.

Analytical explorations of balance

The conceptual analysis is based on a two stage process. In stage the industry has the option to either invest in ex ante actions, such as surveillance and detection, or do nothing. In stage two there is a possibility of agricultural contamination such as introduction of infectious cattle disease. If an event takes place then decision makers can either initiate ex post response actions, or do nothing. As a response to infectious animal disease outbreak, various slaughter, vaccination, and quarantine strategies could allow reduction of economic losses by removing susceptible herds before infection. If there is no event then business continues as usual, although ex ante actions in the first stage will affect the profits.

In the case of possible introduction of infectious animal diseases, the severity of event, in part, will depend on the length of time that the disease is allowed to spread uninterrupted. Surveillance and detection systems, which could be established in the first stage, could allow timely recognition and intervention to stop the spread. However, the costs of such systems will be incurred whether or not the outbreak occurs. Therefore, perhaps a careful consideration of conditions for optimality of investing in ex ante animal health surveillance as a preparedness action is appropriate in light of possible intentional or unintentional introduction of infectious animal disease.

We adopt a cost minimization approach to investigate the relationship between ex ante preparedness and ex post response mechanisms. The goal is to minimize total costs associated with mitigation of a potential introduction of infectious cattle disease. Under the context considered in this work, mitigation costs are composed of investments made in ex ante preparedness actions (s), and ex post response actions (r). Monetary damages $L(\delta,r,s)$ are assumed to be a function of event severity (δ), and ex ante preparedness and ex post response actions. Denoting probability of event occurrence with P we can write a cost minimization problem as:

(1) $$C = P \cdot (L(\delta, r, s) + w_s \cdot s + w_r \cdot r) + (1 - P) w_s s$$

where $L(\delta,r,s)$ is monetary damages inflicted by agricultural contamination event such as intentional or unintentional introduction of infectious animal disease. These damages are formulated to be a function of severity of an event (δ), ex ante preparedness (s) and ex post response (r) actions. w_s and w_r are costs of ex ante preparedness and ex post response actions respectively. First order condition for the optimality of ex ante and ex post actions are as follows:

(2) $$PL_s(\delta, r, s) + w_s = 0$$

(3) $$L_r(\delta, r, s) + w_r = 0$$

Comparative static analysis could be used to examine the effects of disease severity (δ), mitigation costs $(w_s$ and $w_s)$, and probability of event occurrence. After total differentiation equations (2) and (3) could be written in the form of (4). By applying Cramer's rule we get equations (5) : (11), which could be analyzed for preliminary comparative static results.

(4) $$\begin{bmatrix} PL_{ss} & PL_{sr} \\ L_{rs} & L_{rr} \end{bmatrix} \begin{bmatrix} ds \\ dr \end{bmatrix} = \begin{bmatrix} -dw_s - L_s dP - PL_{s\delta} d\delta \\ -dw_r - L_{r\delta} d\delta \end{bmatrix}$$

(5) $$\frac{ds}{dw_s} = \frac{-L_{rr}}{P(L_{ss}L_{rr} - L_{sr}{}^2)}$$

(6) $$\frac{dr}{dw_s} = \frac{L_{rs}}{P(L_{ss}L_{rr} - L_{sr}{}^2)}$$

(7) $$\frac{ds}{dw_r} = \frac{L_{sr}}{(L_{ss}L_{rr} - L_{sr}{}^2)}$$

(8) $$\frac{dr}{dw_r} = \frac{-L_{ss}}{(L_{ss}L_{rr} - L_{sr}{}^2)}$$

(9) $$\frac{ds}{d\delta} = \frac{-L_{s\delta}L_{rr} + L_{sr}L_{r\delta}}{(L_{ss}L_{rr} - L_{sr}{}^2)}$$

(10) $$\frac{dr}{d\delta} = \frac{-L_{r\delta}L_{ss} + L_{rs}L_{s\delta}}{(L_{ss}L_{rr} - L_{sr}{}^2)}$$

$$(11) \qquad \frac{ds}{dp} = \frac{-L_s L_{rr}}{P(L_{ss}L_{rr} - L_{sr}{}^2)}$$

The above equations could be used to generate some insight on the sensitivity of ex ante investments to the likelihood and severity of the event, and costs of ex ante and ex post actions respectively. Assuming convexity of L with respect to s and r, the signs of equations 5 and 8 appear to be negative reflecting the fact that as the price of the activity increases the use of that activity decreases. The signs of equations (6) and (7) are determined by the sign of L_{rs} and L_{sr}. Negative L_{rs} and L_{sr} imply that ex ante preparedness and ex post response are complementary activities, while positive signs imply that the activities are employed as substitutes. The signs of equations (9) and (10) depend on the signs and relative magnitudes of L_{sr}, $L_{s\delta}$, and $L_{r\delta}$. Equation (11) is positive since L is decreasing in s and convex in r. This implies that increasing probability of event occurrence will increase use of ex ante preparedness actions.

Theoretical analysis of the sensitivity of ex ante preparedness and ex post response actions towards event severity, costs, and likelihood of event occurrence, presented above, provides a clear description of some of the relationships. However, other relationships remain ambiguous. Therefore, empirical investigation of those relationships is merited.

FMD case study

In this section we empirically investigate the optimal combination of ex ante preparedness and ex post response strategies under the scenario of possible introduction of FMD in a region such as the state of Texas, which in 2002 amounted to roughly 14 percent of the total U.S. cattle operations (NASS 2002). Although the US has been free of FMD since 1929 (McCauley *et al.* 1979), perhaps some mitigation options merit investigation of ways to minimize potential losses from possible future introductions of FMD which previously caused serious economic damages elsewhere. For example, Great Britain experienced an FMD outbreak in 2001 (Scudamore, 2002) where associated total losses are estimated to be £5.8-8.5 billion (Thompson *et al.* 2003 p. 25, Mangen and Barrell, 2003 p. 126).

Analysis of decision-making directed toward potential FMD outbreaks have been the topics of numerous studies (Bates *et al.* July 2003; Bates *et al.* September 2003; Bates *et al.* July 2001; Garner and Lack 1995, Schoenbaum and Disney, 2003; Berentsen *et al.*1992; McCauley *et al.* 1979; Ferguson *et al.* 2001). All of these studies mainly concentrate on decision-making once an outbreak has occurred largely addressing post outbreak vaccination and slaughter as FMD disease spread management policies. In such cases vaccination strategies are generally found to be economically inferior to slaughter strategies or a combination of slaughter and vaccination strategies (Berentsen *et al.* p. 239, Schoenbaum and Disney, p. 49, Bates *et al.* 2003 b p. 205, Keiling, *et al.* 2001 p. 815) largely due to the fact that once vaccinated the current state of the science is that one cannot differentiate between infected and vaccinated animals and thus must destroy the vaccinated animals. However, Bates et al. (July 2003) found that ring vaccination would be economically more effective than slaughter strategy if it was possible to differentiate vaccinated and FMD infected animals. In a similar study Bates et al. (February 2003 a, b) find that pre-emptive slaughter of high risk herds and vaccination of all animals within a specified distance of an infected herd decreases the duration and damages of an epidemic.

Less attention has been devoted to ex ante preparedness decision-making regarding in the form of surveillance and detection systems, which if present upon a disease outbreak, would allow for timelier and more effective response actions. Although some attention has been raised towards surveillance systems (Bates et al. September 2003; Akhtar and White 2003, Ekboir 1999), no empirical investigation has been performed, to the best of our knowledge, on the determinants of economic balance that might be drawn between ex ante preparedness and ex post response actions considering associated expenditures and damages.

Current US programs to detect and prevent FMD rely on the recognition and reporting of clinical signs by a producer, animal care taker, meat inspector or veterinarian (Bates *et al*. September 2003 p. 609). Reliance on such an approach has two major problems. First, detection based on visual observation of clinical signs implies that the disease could have been present and possibly spreading before the visual realization of its presence. Second, clinical signs of FMD are indistinguishable from the signs of some of the other diseases (Bates et al. September, 2003 p. 609). Therefore, more reliable methods for detection of such infectious diseases may be appropriate. One of the possible surveillance and detection systems could be a program requiring periodic health screening of animals. Regular testing of farm animals directed towards evaluating animal health could assist in preventing a possible spread of FMD or similar diseases. Latent period of FMD infected animal is around one to two weeks (Garner and Lack, 1995 p. 14; Carpenter *et al.* 2004 p 11), which means that frequent testing of animals could detect FMD carriers before the clinical signs of the disease appear. Earlier detection through periodic testing would allow for timelier implementation of response strategies such as slaughter, disposal, cleaning and disinfection. Hence, frequent animal testing could decrease the time of unobstructed spread of the disease. Therefore, periodic testing of animals could decrease the costs of response actions as well as the value of lost agricultural product. Moreover, screening and testing of animals could be conducted by either a regional veterinarian or employees of cattle operations provided adequate training in testing procedures.

A major decision in this setting is associated with ex ante investment in the animal health surveillance program. Specifically, under what circumstances is it beneficial to invest in periodic animal health testing program and thus intercept the disease spread in a timely manner, versus rely on response measure, which, unlike detection program, would be activated only if the outbreak occurs?

Stochastic programming is a widely accepted tool to address uncertainties related to objective function coefficients, input-output coefficients and right hand sides of the constraints (Dantzig 1955; Cocks 1968; Boisvert and McCarl 1990; Ziari 1991). Two major categories of stochastic programming are stochastic programming without recourse and stochastic programming with recourse. Stochastic programming without recourse assumes that the decision maker plans now and discovers the results of the decision later. These types of models do not provide adoptive solutions. In other words, solutions received from such models are based on unconditional expected values. On the other hand, stochastic programming with recourse allows some of the decisions to be modified at later stages of a process. In other words, some decisions are made ex ante, followed by a stochastically determined state of nature, after which the decision maker is allowed to adjust the previous decisions (depending on context) and/or make new decisions depending on the realized state of nature. Discrete stochastic programming with recourse considers sequential nature of resource endowments and allows for earlier decisions and their consequences to affect later decisions. A two stage discrete stochastic model with recourse (Dantzig 1955, Cocks 1968, Boisvert and McCarl 1990, Ziari 1991) will be used in this setting.

Total costs in this model include expenses on animal health surveillance, costs of response strategy, and economic damages from a potential outbreak. Surveillance and detection costs encompass fixed costs of installing testing facilities and variable costs of administering tests that are incurred regardless of outbreak occurrence. Response costs include costs associated with appraisal, slaughter, and disposal. Economic damages from potential outbreak include cattle inventory values lost due to infection and gross earnings lost per infected animal. This can be expressed mathematically as follows. Suppose an outbreak has probability P of occurrence, then total cost equals

$$C(N,R) = Y \times FTC + N \times VTC + P \times \left[V \times H(R) \times D(t(N)) + CR \times R \right] \tag{12}$$

where $C(N,R)$ is total costs and losses associated with prevention of, response to and occurrence of potential FMD outbreak. N is a number of annual tests performed on all herds in the region. R represents response activities under the state of nature where outbreak occurs. V is value of losses associated with each cattle herd infected with FMD. Y is a binary variable representing investment in surveillance system. Y=1 corresponds to the decision of investing in testing and screening facilities, while Y=0 corresponds to no investment in testing and screening system. Clearly, Y=0 implies that N=0. CR is the costs of response activity; FTC is fixed testing costs corresponding to investment in testing systems, while VTC is variable testing costs corresponding to one time health evaluation of all herds in the region. The response effectiveness function, *H(R)*, represents the proportion of herds, which would have been infected in case of an outbreak and only slaughter of infected herds as a response strategy, infected under various levels of response actions (*R*). *D(t)* is the disease spread function expressed in terms of number of herds infected on day *t.*

Empirical Specification

The response effectiveness function, *H(R),* is assumed to be convex implying that as we increase the level of response action, such as slaughtering of infected and contact herds, the damages from FMD outbreak will decrease. However, increasing the level of response action beyond certain point could increase the costs. Therefore, a convex quadratic form was assumed for the damage function.

$$H(R) = \left(a_1 + a_2 R + a_3 R^2\right) \tag{13}$$

where, *R* represents the level of response actions and *H(R)* is a proportion of herds lost as a function of response activity. For empirical analysis *H(R)* was normalized to1. In other words, this function is equal 1 when *R*=0 and is minimized at *R*=1. Schoenbaum and Disney estimate that the most effective response action against FMD outbreak in the US is slaughter of herds with clinical signs and herds in direct contact with the diagnosed herds. This strategy according to their study leads to 17% reduction in number of slaughtered animals as compared to the strategy of slaughtering only the diagnosed herds. Therefore, we assume that at *R*=1 the number of slaughtered animals is reduced by 17%. Therefore, at *R*=0 the proportion of lost animals is 1, corresponding to losses under slaughter of infected herds as the only response action, and at *R*=1 the proportion of lost herds is 0.83 of what would have bee under *R*=0. Consequently, the response effectiveness function used in this analysis was $H(R)=1-0.34R+0.17R^2$.

The disease spread function, $D(t)$, represents number of herds infected on any given day t after the initial infection in the region. Here, t is a function of number of animal screenings conducted in a region per year. This implies that $D(t(N))$ is a decreasing function of the number of screenings N. In other words, an increase in number of screenings per year will decrease the time period for the disease to spread unnoticed and uninterrupted and therefore will decrease the potential number of infected herds.

(14) $$\hat{D}_t = \left[TN - \sum_{t^*=0}^{t^*=t-1} \hat{D}_{t^*}\right]\left[1 - q^{CI}\right]$$

$\hat{D}_t$ is number of newly infected herds on day t and is assumed to have a Reed-Frost equation form[1] (Carpenter *et al.* 2004, p. 12). TN is total number of herds in the area, hence $\left[TN - \sum_{t^*=0}^{t^*=t-1} \hat{D}_{t^*}\right]$ is number of susceptible herds at time period t. q is the probability of avoiding the adequate contact, necessary to transmit the disease. Therefore, 1-q is the probability of making an adequate contact and is equal to $k/_{TN-1}$, where k is number of adequate contacts a herd makes per day. k was assumed to have slow, 0.2, and fast 0.4 rates based on contact rates used in previous investigations (Schoenbaum and Disney 2003; Garner and lack 1995; Bates, Thurmond and Carpenter 2001). CI is cumulative number of infectious herds in any time period during the outbreak. Number of infectious herds is calculated as $CI = \sum_{\mu}^{7} \hat{D}_{t-\mu}$ to reflect the fact that FMD spreads for at least 7 days before showing clinical signs of infection at which point the diseased herds are assumed to be diagnosed and destroyed. Since $\hat{D}_{t'}$ is number of newly infected herds in each of the time periods during the outbreak, therefore, the total number of infected herds at the time of screening (t^*) will be given by $D_t = \sum_{t=0}^{t} \hat{D}_t$.

This representation reflects the fact that in the early stages of FMD outbreak the disease will be spreading at an increasing rate. However, as the number of infected herds increases, number of susceptible herds will decrease. Therefore, at some point of FMD outbreak, number of infected herds will increase at a decreasing rate.

The product of disease spread *D(t)* and response effectiveness function *H(R)* is multiplied by the average loss value per infected herd *(V)*. This value was calculated as follows:

$$V = CS \times NH + \left(MV + \frac{GI}{TN} \right) \times NH \tag{15}$$

where, CS is costs of slaughter, disposal, cleaning and disinfection and was assumed to be $69 per head (Bates et al., February 2003 a, p. 807). NH is average number of cattle heads per herd in Texas, which was found to be around 50 (Ernie Davis, Personal Communication, August 2004). MV is an average market value per cattle head assumed to be $610.00. GI is gross income for Texas cattle and calves operations reported to be $7,890,683,000 in 2003 (Texas Department of Agriculture 2003). TN is number of cattle heads in Texas reported to be approximately 14,000,000 in 2003. Thus, the value used for V was $62,000, which reflected annual gross income and value of inventory.

The costs of testing include fixed costs of surveillance per herd and costs of surveillance per visit corresponding to variable costs. Fixed testing costs (FTC) are estimated to be $22,650,000, which was calculated by multiplying per herd testing costs ($150) for operations of less than 100 animal heads (Schoenbaum and Disney, p. 36) and the number of cattle operations in TX (151,000). The investment made in form of fixed costs is independent of the number of screenings employed. Variable testing costs (VTC) are calculated assuming a $50 per visit per herd (Schoenbaum and Disney, p.36), under the scenario where an outside expertise is required to conduct the screenings at each farm. VTC represent variable costs that correspond to single testing of all the farms in the whole region. Hence, for Texas the costs per visit would be 50*151,000=$7,550,000.

Cost of response (CR) associated with slaughter of contact herds with no clinical signs, correspond expenses for appraisal ($300 per herd), euthanasia ($5.5 per head), and carcass disposal ($12 per head) (Schoenbaum and Disney, p. 36). Thus, costs of response were calculated to be $1,175 per herd. Optimal number of herds slaughtered under response strategy in Schoenbaum and Disney (2003) was 37 herds. Therefore, costs of response strategy corresponding to R=1 are assumed to be 37*1175=$43,475. CR could also include costs of vaccination, the estimates of which range from $6 to $8.61 per head (McCuley et al. p. 4, Bates et al. February 2003 a p. 806, Schoenbaum and Disney p. 36). However, we rely on Schoenbaum and Disney's results, which show that the most effective response strategy did not involve vaccination. We exclude vaccination from response measures and assume that loss minimizing response activity corresponds to slaughter of infected herds and herds with direct contacts with the diagnosed infected animals. This analysis essentially corresponds to the scenario under which vaccinated animals are ultimately slaughtered to facilitate fulfillment of requirements for restoring participation in international trade. However, this may not be necessary after development of a vaccine which could be differentiated from FMD infection. The model presented here could be adapted to such scenario.

It was decided to approximate the disease spread using a logistic functional form (16) because of difficulties in getting numerical solutions using the Reed-Frost formulation directly. Reed-Frost formulation was used to simulate daily spread of FMD spread under slow and fast rates of spread. In other words, daily numbers of infected herds were simulated using equation (14). TN was 151,000, k was 0.15 and 0.4 for slow and fast spreads respectively.

(16) $$D(t) = \frac{TN}{1 + \beta_1 e^{\beta_2 t}}$$

For fast disease spread, the logistic function gave an almost perfect fit to the Reed-Frost formulation with an R^2 equal to 0.99, β_1= 381140, β_2=-0.348. For slow disease spread β_1= 102000, β_2=-0.144, R^2=0.97. Letting t=(365/N+1) and plugging (16) into (12) the optimal values for N were derived under various scenarios for Reed-Frost disease spread approximated by logistic function.

Model experimentation and results

The model was used to examine the optimality of investing in ex ante animal health surveillance to minimize expected costs of possible FMD introduction. Specifically, the model is used to evaluate the effects of likelihood and severity of an outbreak, along with effectiveness and costs of considered mitigation options on the decision to invest in ex ante preparedness in the form of animal health surveillance and disease detection system. Total of 9 scenarios were considered for each of the two disease spread rates (Table 1). Outbreak likelihood and disease spread rate were varied to evaluate the effects of threat characteristics. Probability of FMD introduction was varied from 0.001 to 1 and two disease spread rates, in the form of low (0.2) and high (0.4) daily inter herd contact rates, were considered. The effect of mitigation costs were analyzed by decreasing the variable per herd testing costs by tenfold and hundredfold consecutively from the base scenario of $50 per herd per test, and increasing response costs hundred fold from $1175/per herd. The response strategy effectiveness was analyzed by considering two levels of response effectiveness. One implied a 17 percent decrease in animal losses due to response actions compared to no response actions (Schoenbaum and Disney, p. 49). The other implied a 30 percent decrease in animal losses due to more effective response actions. The possibility that detection activities could provide ancillary benefits by identifying for example other animal health problems was also considered. Specifically, per herd fixed costs associated with instituting the surveillance systems were decreased by half from $150 to $75 per herd. The motivation behind this decrease is that investments made in detection systems could bring other benefits that are not related to FMD detection. Therefore, those benefits could be used to offset some of the fixed investment costs. Also, possible implications economies of scale were investigated by increasing average herd size from 50 to 400 animals.

First we investigated the effect of potential outbreak likelihood and disease spread rate. The hypothesis is that the higher the disease introduction likelihood and spread rate the more the optimal strategy would rely on ex ante preparedness actions. The results show (Figure 2) that number of annual rests performed on all herds in the region becomes considerably more advantageous for fast spreading disease than for slow spreading disease. At the lowest considered likelihood of disease introduction no investment is made under either fast or slow spreading diseases. However, as likelihood of disease introduction increases the investment in surveillance system becomes increasingly more advantageous under fast spreading disease than under slow spreading disease. This also implies that optimal mix of mitigation activities also depends on the probability of an event. Overall, increasing the probability of an outbreak increased the optimal use of surveillance systems. Figure 2 also shows the effects of changing the variable costs of surveillance and detection. It can easily be observed that decreasing variable costs of testing animal health increases the worth of investing in such systems. If variable testing costs were decreased hundredfold, then under outbreak of a fast spreading disease (p=1) the number of annual tests goes from 17 to 34 (Figure 2). The results are similar for outbreak of a slow spreading disease. When variable costs are decreased hundredfold, corresponding to the scenario where testing is cheaply performed by farm employees, the number of annual tests increases from 9 to 22.

Next we investigated the effects of costs and effectiveness of response actions on level of ex ante preparedness. Figure 3 shows that, as discussed earlier, the level of ex ante preparedness is affected by severity of expected event. However, the effect of response effectiveness and costs has small effect on the level of ex ante preparedness under considered scenarios. In fact, under certainty of slow spreading disease outbreak number of annual tests does not change as a response to increase in response effectiveness from 0.17 to 0.3 and in response to increasing response costs from $1175/herd to $117,500/herd. This is mainly explained by high fixed costs of animal testing system and higher marginal productivity/marginal cost ratio of testing system relative to that of response system. Hence, cross price effect of ex post response on the use of ex ante preparedness indicates that the two options are neither complements nor substitutes. However, under some scenarios ex ante preparedness and ex post response actions seem to act as substitutes. For example, under the scenarios with decreased variable testing costs to $0.5 per test per herd and increased response costs to $117,500 per herd, level of ex ante preparedness increases as level of response actions decreases in response to increase in outbreak likelihood (Figure 4). This substitution could be explained by relative costs of preparedness and response strategies and by the fact that as more animal testing is performed the latent period of infected animals is reduced. Therefore, fewer herds are infected by sick herds. This means that fewer herds will have to be slaughtered due to direct contacts with infected herds. On the other hand, at lower probabilities of event occurrence, surveillance investment costs are higher than expected costs of FMD outbreak under optimal response strategy. Therefore, as testing frequency decreases at lower probabilities of an outbreak, the level of responsive measures increases in case of an outbreak.

Investing in surveillance systems for detection of FMD could have ancillary benefits in terms of facilitating other animal health and management activities. Testing could facilitate keeping inventory of farm animals in the region, which could be of benefit to researchers and policy makers. To examine this possibility we analyzed scenarios with decreased per herd fixed costs of testing. It was found that ancillary benefits did not have significant effect on ex ante preparedness levels. Under high contact rates scenario decreasing fixed per herd testing costs by a half (from $150 to $75 per herd) had no effect on number of annual tests performed on all herds in TX.

Optimal number of annual animal health tests was found to be affected by the average herd size. After changing the current average herd size of 50 to 400, surveillance and detection systems become more advantageous than with smaller herd sizes. For example, with a fast spreading disease and minimal variable testing costs the optimal number of animal tests reached 50 per year. This result was expected due to the effect of fixed costs of detection systems per herd.

Economic costs of potential agricultural sabotage, in the form of FMD outbreak, and various mitigation strategies were calculated in terms of expected monetary losses in the cattle industry. Specifically, losses consisted of two parts, cattle values per head and average revenue per head. The results are depicted in Figure 5. Expected losses varied from around \$6.5 million to around \$175 million depending on outbreak likelihood, spread rate, and mitigation strategy. Under high contact rate scenarios, the economic losses are significantly higher than under low contact rate. In thus analysis the losses mainly varied according to costs of surveillance and detection programs. Three levels of variable costs were considered in this work. Hence, three main patterns of monetary losses stand out. Increasing effectiveness of response activities had a minor effect on decreasing the losses.

Figure 6 shows expected losses as a percentage of total monetary worth of Texas cattle industry under the possibility of FMD outbreak with animal health surveillance system in place. The value of cattle industry was supposed to consist of monetary values of live animals and annual gross revenues generated by those animals. Hence, losses calculated in this work provide a lower bound of potential losses from a possible FMD outbreak since they do not include losses in trade or consumer surplus. Under such calculations, losses from a potential FMD outbreak reached almost 1.2% of total cattle industry's economic worth under high probabilities of outbreak when surveillance and detection systems were adopted. The losses with active surveillance and detection system are considerably lower than losses under no surveillance and detection system. Up to 70% of Texas cattle industry value could be lost if preparedness actions such as the periodic animal health testing are not exercised and response actions, consisting of slaughtering only infected and contact herds, were used as mitigation policy.

Conclusions

The goal of this work was to evaluate the optimality of adopting ex ante preparedness and ex post response actions to fight possible intentional or unintentional introduction of infectious foreign animal disease. Aspects such as event likelihood and severity, along with costs and effectiveness of mitigation options were considered as they influence optimal combination of ex ante preparedness and ex post response actions. We formulated a framework where we minimized total costs associated with damages from possible agricultural contamination and costs associated with mitigation activities. Theoretical analysis showed that under convexity of damage function with respect to ex ante actions, the use of ex ante preparedness actions increases with event severity and likelihood, and with reduction in costs of ex ante actions. However, theoretical results were ambiguous as far as substitutability/complementarity of ex ante preparedness and ex post response actions.

The empirical model is based on minimizing probabilistic weighted costs of potential FMD outbreak and associated ex ante preparedness and ex post response measures. We investigated periodic cattle health screening as an ex ante preparedness action and slaughter of infected and direct contact herds as ex post response action in light of potential FMD outbreak in a region such as Texas. Periodic testing and screening of cattle allows detection of potential infection before the appearance of clinical signs and thus increases level of preparedness in case of infectious disease outbreak. This strategy is adopted prior to a realization of an outbreak and thus introduces costs that are incurred regardless of whether or not an outbreak occurs. Slaughter of infected and direct contact herds, corresponding to Schoenbaum and Disney (2003), was considered as an ex post measure, which is activated only in case of disease introduction. A cost minimizing model was developed that traded off ex ante fixed costs of animal health surveillance system and ex-post response costs considering stochastic event frequency where outbreaks only occur with a given probability. Considered damages included loss of cattle values and loss of gross income. The tradeoff was examined by varying the probability of event occurrence, disease spread rates, costs of ex ante and ex post actions, effectiveness of response activities, ancillary benefits of surveillance and detection activities, and average herd size.

The results suggest that the optimal combination of preparedness and responsive strategies depends on such factors as disease spread rate, strategy effectiveness, likelihood of disease introduction, and costs of mitigation strategies. It was found that investment in ex ante surveillance increases with increased likelihood of disease introduction, reduced costs of testing, increased disease spread rate, decreased response effectiveness, and increased average herd size. In some scenarios use of ex ante preparedness increased while response level decreased as a result of increasing probability of FMD outbreak. However, it was found that use of ex ante actions was inelastic with respect to response action costs.

The empirical results of this work need to be interpreted with care as numerical outcomes depend on the functional formulation of the disease spread and on the parameters assumed in the model. Although exponential diseases spread was also investigated in this work and the results were compatible with those of RF spread, true spread mechanics could be different from those considered in this study. Moreover, since the exact rate of disease spread is not known, the model was analyzed under low and high daily inter herd contact rates based on previous studies (Schoenbaum and Disney (p. 28) and Bates et al., 2001 p. 1121) It is possible that the actual rate of the disease spread is substantially different from those assumed in this study. In such case the numerical results will differ but general conclusion regarding the relationship between ex ante preparedness and ex post response activities will stay the same.

The damages considered in this investigation include lost value of infected and slaughtered cattle and associated lost gross income. Losses from trade bans, decreased tourism, consumer scare and other consequences of FMD outbreak are not considered in this study. Hence, losses considered here are likely to be lower than actual losses. Therefore, ex ante preparedness strategies may be even more advantageous than reported in this study. Even though the results of empirical investigation reported in this article are contingent on the assumptions made regarding the disease spread and the simplifications made regarding the damages of outbreak and benefits of mitigation strategies, the results shed some light on broad disease management approaches. Effectiveness of ex ante preparedness actions seem to depend on various context attributes such as likelihood and severity of potential agricultural terrorism event, costs and effectiveness of ex ante and ex post strategies, and ancillary benefit of those strategies.

Footnotes

[1] Exponential spread was also considered where $D(t) = e^{\beta t} = e^{\beta \frac{365}{N+1}}$ (Anderson and May).

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Table1. Experiment scenarios for fast and slow spreading outbreaks

Scenarios Fast/ Slow	Scenario Description
1	Response effectiveness=0.17; Response costs= $1,175/herd; Variable testing cost=$50/herd; Fixed testing costs=$150/herd; Herd size=50
2	Response effectiveness=0.3; Response costs= $1,175/herd; Variable testing cost=$50/herd; Fixed testing costs=$150/herd; Herd size=50
3	Response effectiveness=0.17; Response costs= $1,175/herd; Variable testing cost=$5/herd; Fixed testing costs=$150/herd; Herd size=50
4	Response effectiveness=0.3; Response costs= $1,175/herd; Variable testing cost=$5/herd; Fixed testing costs=$150/herd; Herd size=50
5	Response effectiveness=0.17; Response costs= $1,175/herd; Variable testing cost=$0.5/herd; Fixed testing costs=$150/herd; Herd size=50
6	Response effectiveness=0.3; Response costs= $1,175/herd; Variable testing cost=$0.5/herd; Fixed testing costs=$150/herd; Herd size=50
7	Response effectiveness=0.17; Response costs= $117,500/herd; Variable testing cost=$50/herd; Fixed testing costs=$150/herd; Herd size=50
8	Response effectiveness=0.17; Response costs= $1,175/herd; Variable testing cost=$50/herd; Fixed testing costs=$75/herd; Herd size=50
9	Response effectiveness=0.17; Response costs= $1,175/herd; Variable testing cost=$50/herd; Fixed testing costs=$150/herd; Herd size=400

STAGE 2

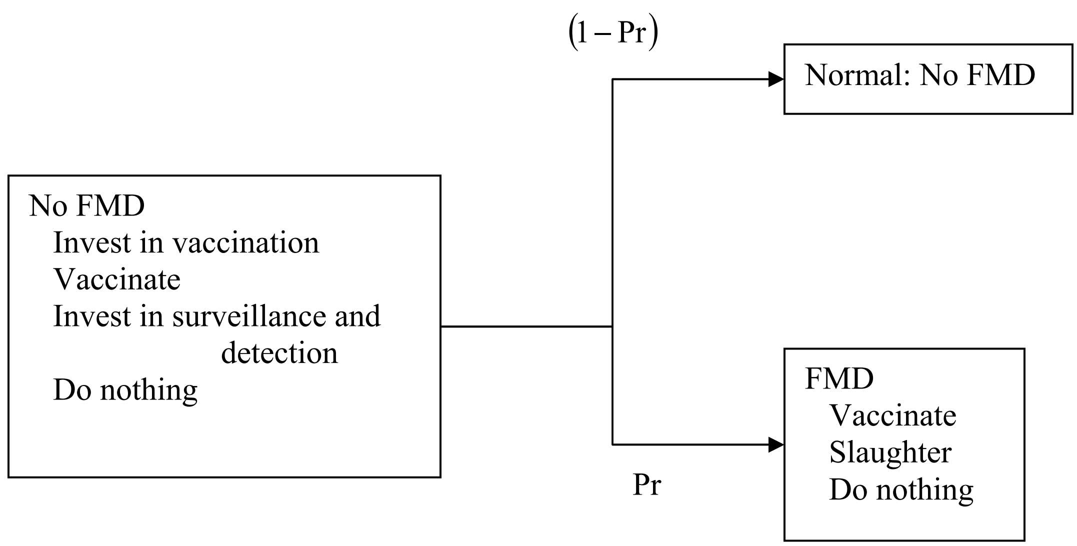
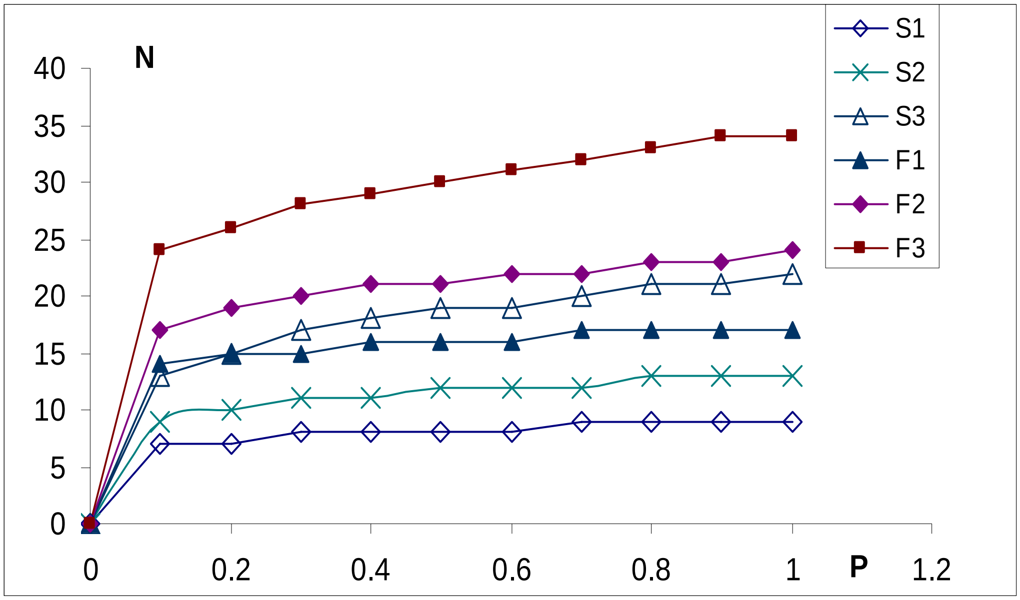
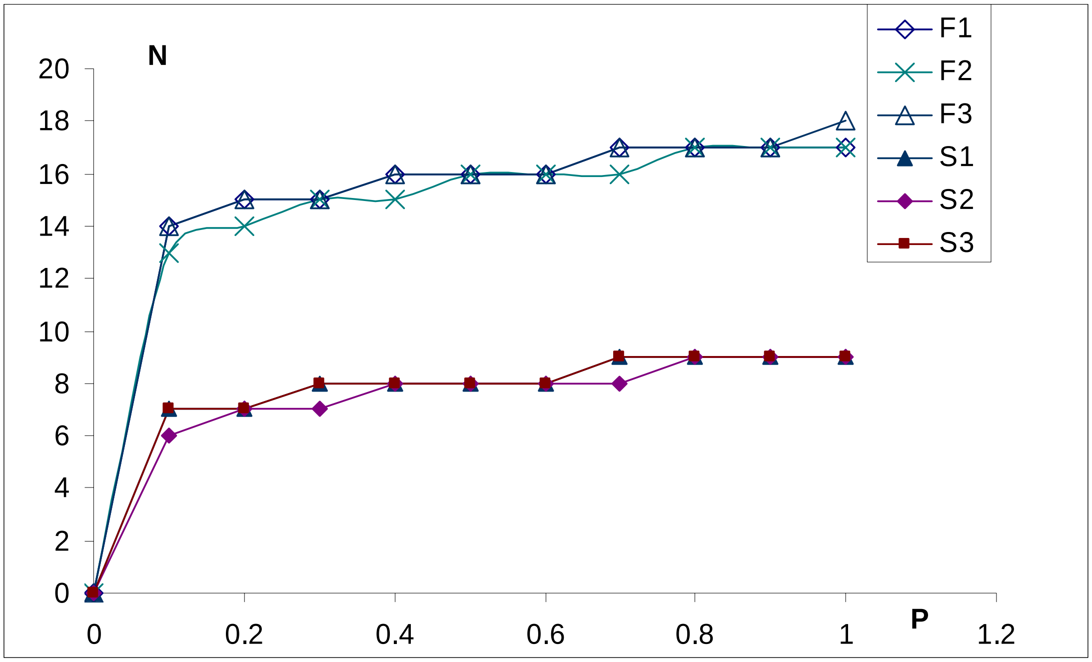


Figure 1. Stages of decision support tool



S1 – Slow Spread, Variable Testing Costs=$50/herd
S2 – Slow Spread, Variable Testing Costs = $5/perd
S3 – Slow Spread, Variable Testing Costs = $0.5/herd
F1 – Fast Spread, Variable Testing Costs=$50/herd
F2 – Fast Spread, Variable Testing Costs = $5/herd
F3 – Fast Spread, Variable Testing Costs = $0.5/herd

Figure 2. Number of annual tests under slow and fast spreads with various testing costs.



S1 – Slow Spread, Response effectiveness 0.17, Response Costs $1,175/herd, Testing costs $50/herd

S2 – Slow Spread, Response effectiveness 0.3, Response Costs $1,175/herd, Testing costs $50/herd

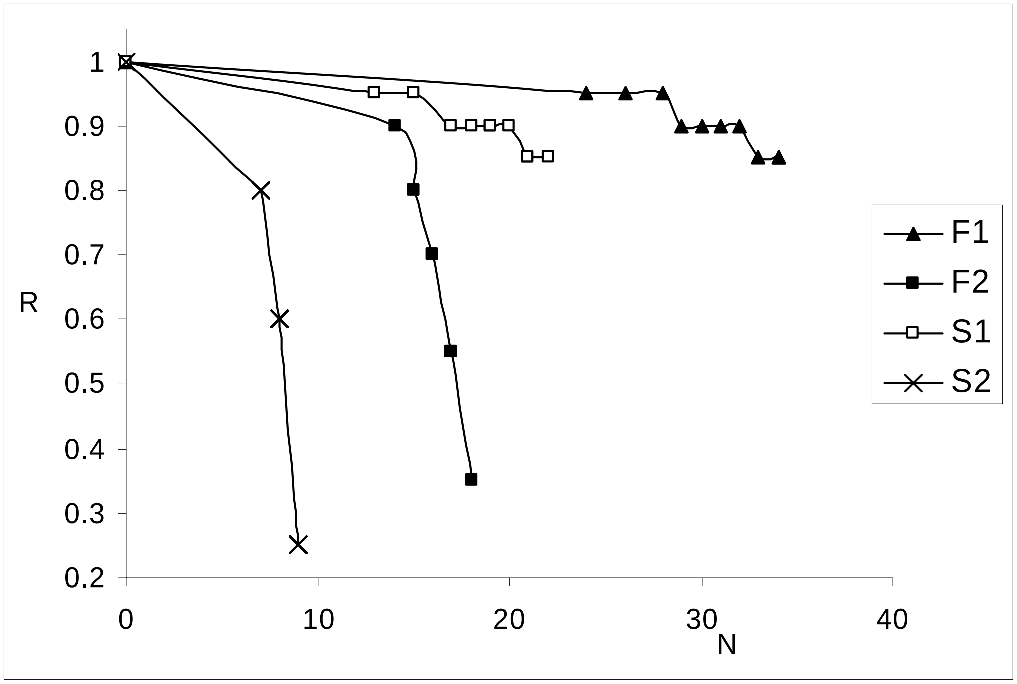
S3 – Slow Spread, Response effectiveness 0.17, Response Costs $117,500/herd, Testing costs $50/herd

F1 – Fast Spread, Response effectiveness 0.17, Response Costs $1,175/herd, Testing costs $50/herd

F2 – Fast Spread, Response effectiveness 0.3, Response Costs $1,175/herd, Testing costs $50/herd

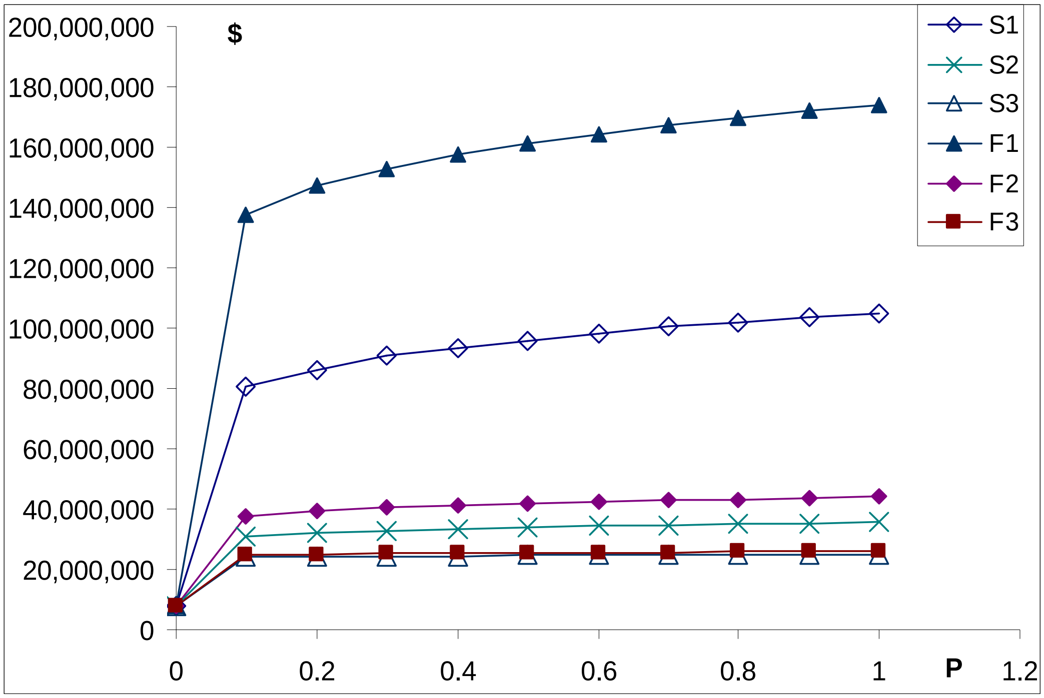
F3 – Fast Spread, Response effectiveness 0.17, Response Costs $117,500/herd, Testing costs $50/herd

Figure 3. Number of annual tests under slow and fast spreads with various response costs and effectiveness



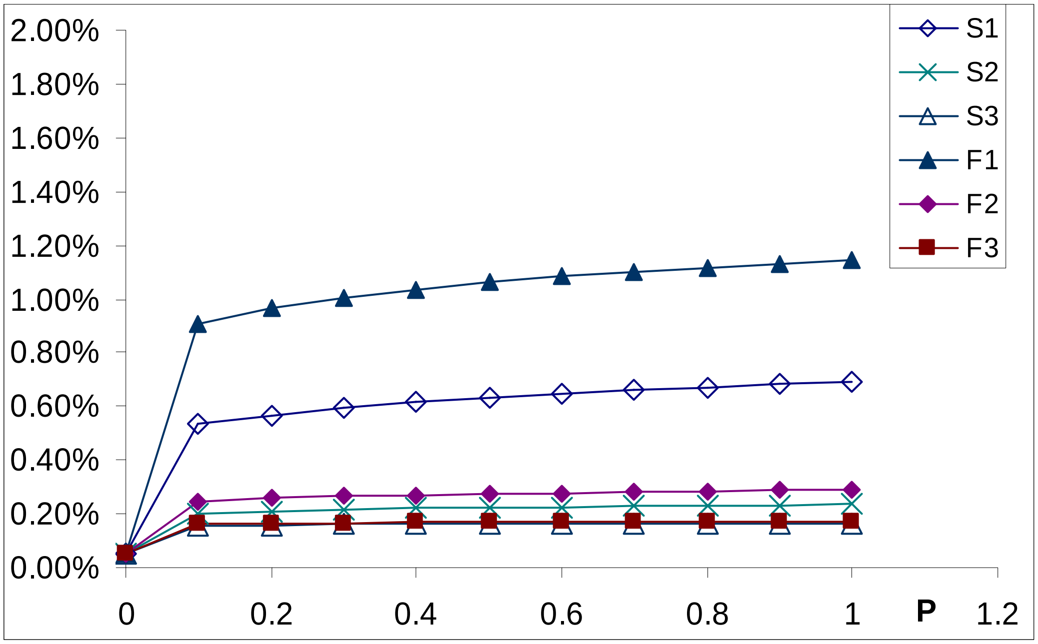
S1 – Slow Spread, Response effectiveness 0.17, Testing Costs \$0.5/herd, Response Costs \$1,175/herd
S2 – Slow Spread, Response effectiveness 0.17, Testing Costs \$50/herds, Response Costs \$117,500/herd
F1 – Fast Spread, Response effectiveness 0.17, Testing Costs \$0.5/herd, Response Costs \$1,175/herd
F3 – Fast Spread, Response effectiveness 0.17, Testing costs \$50/herd, Response Costs \$117,500/herd

Figure 4. Ex post slaughter vs. ex ante animal health testing



S1 – Slow Spread, Variable Testing Costs=$50/herd
S2 – Slow Spread, Variable Testing Costs =$5/herd
S3 – Slow Spread, Variable Testing Costs = $0.5/herd
F1 – Fast Spread, Variable Testing Costs=$50/herd
F2 – Fast Spread, Variable Testing Costs = $5/herd
F3 – Fast Spread, Variable Testing Costs = $0.5/herd

Figure 5. Economic losses under slow and fast spread



S1 – Slow Spread, Variable Testing Costs =$50/herd
S2 – Slow Spread, Variable Testing Costs = $5/herd
S3 – Slow Spread, Variable Testing Costs = $0.5/herd
F1 – Fast Spread, Variable Testing Costs=$50/herd
F2 – Fast Spread, Variable Testing Costs = $5/herd
F3 – Fast Spread, Variable Testing Costs = $0.5/herd

Figure 6. Proportion of cattle industry's monetary value lost under slow and fast spread with surveillance and detection