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Animal Disease Pre-Event Preparedness versus Post-Event Response: When Is It Economic to Protect?

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We examine the economic tradeoff between the costs of pre-event preparedness and post-event response to the potential introduction of an infectious animal disease. In a simplified case study setting, we examine the conditions for optimality of an enhanced pre-event 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 postevent response actions. We show that the decision to invest in pre-event preparedness activities depends on such factors as probability of disease introduction, disease spread rate, relative costs, ancillary benefits, and effectiveness of mitigation strategies.

Key Words: animal disease, economic balance, mitigation strategies, preparedness, response

JEL Classifications: Q1, Q18, D81

Possible intentional or unintentional introductions of contagious animal diseases could result in substantial economic losses as seen during the U.K., U.S., and Canadian Bovine Spongiform Encephalopathy (BSE) (mad cow) events or the European Foot and Mouth Disease events (Henson and Mazzocchi 2002; Khan, Swerdlow, and Juranek 2001; Mangen and Burrell 2003; Thompson et al. 2001). Events with major consequences raise the specter of preventative and/or protective actions. Many appeals for such actions have been issued in the post-9/11 world. However the cost of following all of the protection and prevention actions that have been called for is far in excess of any practically available budget.

Many issues can be raised about animal disease management and the need for protection. One such issue involves the balance between pre-event investments in prevention, protection, and response capability versus the post-event costs of the event and associated disease management efforts. A key economic point in the context of this balance is the distinction between pre- and post-event costs. Pre-event actions impose costs regardless of event occurrence, while post-event costs are only incurred when an incident occurs and thus are multiplied by the probability of the event when computing expected annual costs. For example, the costs of setting up and operating a continuing animal health surveillance

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system are encountered whether or not an outbreak ever takes place. However, the costs of diseased animal slaughter, reduced market supply, disinfection, and event-enhanced detection arise only in the event of disease introduction.

This paper reports on an investigation of the above-mentioned balance problem; it addresses how disease event characteristics and mitigation options affect the desirability of pre-event investments versus post-event response. In carrying out this investigation, we first present and analyze a theoretical model of the balance problem. Subsequently, we conduct an empirical case study motivated by data representing Foot and Mouth Disease (FMD).

A Model of Pre- and Post-event Decision Making

Decisions in the context of an animal disease event can be categorized into six basic categories. These are:

- Anticipation actions—things undertaken to improve the forecast of event likelihood and consequences, such as intelligence gathering. These are largely pre-event actions.
- Prevention actions—things undertaken to avoid event introduction or mitigate event implications upon introduction, such as changes in sanitary or feeding practices along with the use of vaccinations. These are largely pre-event actions.
- Detection actions—things undertaken to screen for precursors to an outbreak that speed detection and allow rapid treatment, such as inspection for sick animals. These can be pre-event or post-event actions. In a post-event setting, they are reflective of enhanced detection to help avoid disease spread and or avoid entry of contaminated products into the food chain.
- Installation actions—facilities installed to allow more rapid or effective disease detection and management, for example, installation of sensors, construction of veterinary laboratories, training of first responders, or stocking of vaccines. These are largely pre-event actions.
- Response actions—disease management activities undertaken to halt the spread of the event, such as slaughter of infected animals, carcass disposal, vaccination of animals in proximity to an event, etc. These are post-event actions.
- Recovery actions—things undertaken to re-establish productive capacity and post-event market demand, such as decontamination of production and processing facilities or advertising to increase consumer confidence. These are post-event actions.

There are a number of important characteristics of decision making in this type of situation. These include:

- Irreversibility—when a pre-event action has not been undertaken; once an event has occurred, it is generally not possible or at least very expensive to put it in place.
- Conditional response—certain response options can be used only if certain pre-event actions have been undertaken. One cannot use detection equipment that has not been previously acquired and installed.
- Fixed cost versus probabilistic variable costs—in total cost accounting, the pre-event costs are always present; the post-event costs are only encountered when an event occurs.
- Large span of possible events—there is an enormous span of possible events that can never practically be enumerated. Thus, we will only deal with sample and abstract events herein. Furthermore these events differ in nature and severity.
- Probabilities—event probability is difficult to anticipate and in the case of deliberate actions is likely to be modified by pre-event actions.

This leads us to a restatement of the balance problem as the establishment of the optimal tradeoff between the cost of pre-event actions and **occasional** post-event damages, including response and recovery costs. In such a setting, the best strategy would be a balance between many factors, including pre-event ac-

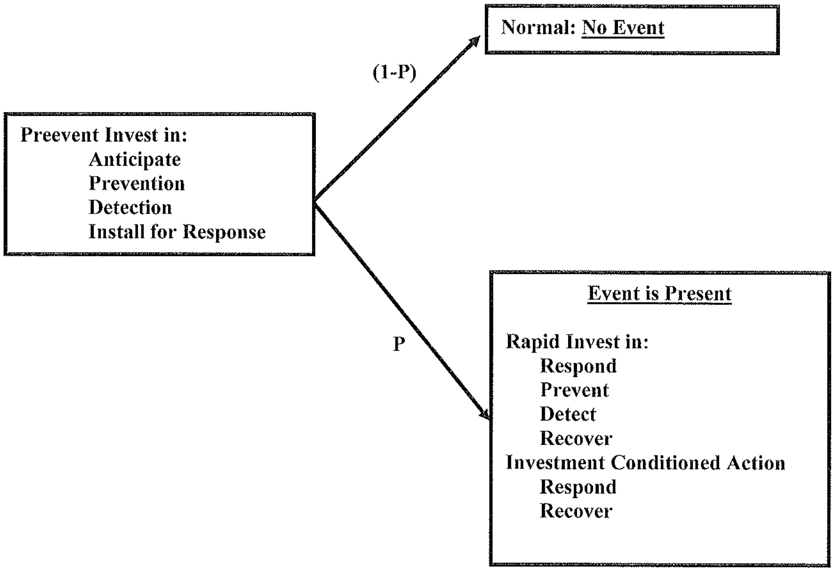

Figure 1. Event Space and Decisionmaking Stages

tion costs, disease management costs, potential damages, and event probability.

Formal Model Development

This problem can be addressed more formally. Consider the decision tree situation that depicts occurrence or nonoccurrence of a single event (Figure 1). Here we have a simple two-stage decision process. The first stage is pre-event, and the second stage post-event but allows for no event to have occurred (event occurrence probability is P, and no event $[1 - P]$). In stage one, decision makers have the option to invest in pre-event actions, such as anticipation, prevention, installation, and detection, as well as doing nothing. In stage two, there is a probabilistic possibility of an event—introduction of infectious cattle disease—or of no event. At the second stage, decision makers can either initiate post-event response actions with knowledge of an event taking place, or do nothing. The post-event response actions for animal disease management generally involve slaughter, vaccination, and quarantine strategies that are chosen so as to minimize disease-induced economic losses. If there is no event, then industry activities continue under normal conditions, although the costs of pre-event actions implemented in the first stage will be incurred.

Under the context considered in this work, mitigation costs are composed of the pre-event set of actions (s) with per unit cost w_s, and the post-event set of actions (r) with per unit cost w_r. Let us assume that the event damages $L(\delta, s, r)$ are a function of pre-event actions and postevent response actions along with an incident severity parameter (δ). Denoting probability of event occurrence as P, we can write average cost as:

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

Comparative Statics Analysis

We adopt an expected cost minimization approach to investigate the relationship between pre-event preparedness and post-event response mechanisms. Now suppose we study the optimal amount of pre- and post-event action and how it is influenced by

- the probability of the event,
- the costs of the pre-event and postevent actions, and

- the severity of the event.

First-order conditions for the optimality of pre- and postevent actions are as follows:

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

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

Comparative static analysis can be used to examine the balance between pre- and postevent actions with variations in disease severity (δ), pre- and postevent action costs (w_s and w_r), and probability of event occurrence (P). The total differential arising from Equations 2 and 3 is given in Equation 4. By applying Cramer's rule, we get Equations 5 through 11, which permit examination for comparative static results.

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

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

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

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

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

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

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

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

Assume the L function is convex in r, s, and δ. In turn, the above equations reveal information on the sensitivity of the optimal balance between pre- and post-event actions relative to the other model parameters. Namely,

- Equation 5 can be signed as negative indicating downward sloping demand for pre-event actions, i.e., the higher the per-unit cost of pre-event action, the less of that activity is used.
- Equation 8 similarly indicates downward sloping demand for post-event actions.
- Equation 11 can be signed to be positive, since L is decreasing in s and convex in r, indicating that pre-event actions increase with increasing probability of event occurrence.
- The signs of the terms within Equations 6 and 7 are determined by the sign of L_{rs} and L_{sr}, and when negative, indicate complementarity between pre-event preparedness and postevent response, while positive signs imply they are substitutes.
- Equations 9 and 10 are not readily signed, because they are dependent on the signs and relative magnitudes of L_{sr}, $L_{s\delta}$, and $L_{r\delta}$ and thus remain ambiguous.

Empirical Investigation Using FMD Motivated Data

Our ability to sign some but not all of the terms combined with the somewhat abstract nature of the pre- and post-event actions make it desirable to do a case study. Thus, we empirically investigate the optimal combination of pre-event preparedness and postevent response strategies in an empirical setting using data drawn from the FMD literature in the context of possible introduction into Texas.

Case Study Background

Although the United States has been free of Foot and Mouth Disease (FMD) since 1929 (McCauley et al. 1979), disease introduction has been shown to have substantial implications elsewhere. For example, Great Britain experienced an FMD outbreak in 2001 where associated total losses were estimated to be £5.8–8.5 billion (Mangen and Burrell, 2003, p. 126; Thompson et al., 2003 p. 25). Given such large risks, FMD is a priority area of concern within the United States Department of Agriculture (USDA) and the Department of Homeland Security (DHS).

Analysis of FMD-related decision making

has been the topic of numerous studies (e.g., Bates, Thurmond, and Carpenter 2001; Bates, Thurmond, and Carpenter 2003 a,b,c; Bates et al. 2003; Berentsen, Dijkuizen, and Oskam 1992; Ferguson, Donnelly, and Anderson 2001; Garner and Lack 1995; Keiling et al. 2001; McCauley et al. 1979; Schoenbaum and Disney 2003). These studies mainly concentrate on decision making once an outbreak has occurred and largely address postoutbreak disease spread management with vaccination and slaughter.

Less attention has been devoted to pre-event decision making. Issues have been raised regarding surveillance systems (Akhtar and White 2003; Ekboir 1999; Bates et al. 2003), but we cannot find empirical investigations that address the economic balance that might be drawn between pre-event preparedness and post-event response actions. We address this issue in a limited setting focusing on the installation and operation of surveillance and detection systems versus post-event slaughter actions. In particular, we examine the balance between initiation and operation of a farm-level periodic animal testing program versus slaughter.

A major decision in this setting involves the level of pre-event investment in the animal testing program. We examine the reliance within an optimal cost minimizing plan on pre-event periodic animal health testing, versus sole reliance on post-event response measures.

Empirical Model Setup

Modeling of this situation requires a modeling formulation that depicts the two-stage decision making process in Figure 1. Namely, decision making has to be represented in multiple stages with decisions to install and operate the pre-event animal inspection procedure at the first stage and second stage, and the decisions must be conditional on both whether or not an outbreak occurs and whether or not the animal testing was in place. Stochastic programming with recourse (SPR), also known as discrete stochastic programming, provides such a modeling approach (for discussion see Apland and Hauer 1993; Boisvert and McCarl 1990; Chen and McCarl 2000; Cocks 1968; Dantzig 1955; Ziari, McCarl, and Stockle 1995). In setting up the SPR formulation, the decisions and cost factors are:

- whether to do animal testing (Y) incurring the fixed costs of installing the capability (FTC),
- the frequency with which to do testing (N) and the costs per test (VTC), and
- the level of response action (R) in the form of animal slaughter.

(12) minimize

$$C(N, R) = Y + FTC + N \times VTC + P \times \{V \times H(R) \times D[t(N)] + CR \times R\},$$
$$\text{S.T.} - 99999Y + N \leq 0,$$

where

- $C(N, R)$ is the expected cost;
- Y is a binary decision variable representing investment in surveillance systems ($Y = 1$ corresponds to the decision of investing in testing and screening facilities, while $Y = 0$ corresponds to no investment in testing and screening system);
- FTC is fixed testing costs corresponding to investment in testing systems;
- N is an integer decision variable giving the number of tests performed during a year on all herds in the region, where $Y = 0$ implies that $N = 0$;
- VTC is variable testing costs corresponding to one-time testing of all herds in the region;
- R is the level of response activity represented by slaughter under the state of nature where outbreak occurs;
- V is the value of loss arising when a cattle herd is infected with FMD;
- $H(R)$ is the proportion of herds that would be infected in case of an outbreak when R effort is applied to animal slaughter;
- $D(t(N))$ is the disease spread function in terms of number of herds infected when the disease is undetected for t days after initiation, which in turn is influenced by the number of tests done per year (N); and

- CR is the per-unit costs of the response activity.

Total costs in this model include expenses on the event-independent animal health surveillance, plus the event-dependent costs of slaughtering and outbreak damages. Surveillance and detection costs encompass fixed costs of installing testing facilities and variable costs of administering tests. Slaughter costs include costs associated with appraisal, slaughter, and disposal. Outbreak damages include the value of the slaughtered animals.

Empirical Specification

Response effectiveness. Schoenbaum and Disney found that the most effective FMD response action was slaughter of herds with clinical signs and herds in direct contact. In their study, this led to a 17% reduction in the number of slaughtered animals as compared to the strategy of slaughtering only the diagnosed herds. We represent this with a quadratic convex function.

$$H(R) = (a_1 + a_2R + a_3R^2) \tag{13}$$

where R represents the level of response actions and $H(R)$ is a proportion of herds lost as a function of response activity. To parameterize this function, we set $H(R) = 1$ when $R = 0$, indicating that without response, all of the herds that could naturally be infected would be lost, and then we set the function up so it reaches a minimum at $R = 1$. Furthermore, following Schoenbaum and Disney's results, we assumed that at $R = 1$, the number of slaughtered animals is reduced by 17%, so $H(R)$ equals 0.83. Solving Equation 13, we get

$$H(R) = 1 - 0.34\mathrm{R} + 0.17R^2.$$

Disease spread. FMD spreads for at least seven days before showing clinical signs of infection, at which point the diseased herds are assumed to be diagnosed and destroyed. The disease spread function, $D(t(N))$, represents number of infected herds as a function of the time from initiation when the outbreak is discovered. However, t is a function of the number of animal screenings, and $D(t(N))$ is a decreasing function of the number of screenings N. In other words, an increase in number of screenings per year will decrease the expected time period for the disease to spread unnoticed and uninterrupted.

To parameterize $D(t(N))$, we assume $\hat{D}_t$ is number of newly infected herds on day t (total infected herds$_t$ − total infected herds$_{t-1}$), which arises from an underlying Reed-Frost equation form[1] (Carpenter, Thurmond and Bates 2004, p. 12)

$$\hat{D}_t = \left(TN - \sum_{t^*=0}^{t^*=t-1} \hat{D}_{t^*}\right)(1 - q^{CI_t}). \tag{14}$$

- where TN is the total number of herds in the area;

$$\left(TN - \sum_{t^*=0}^{t^*=t-1} \hat{D}_{t^*}\right)$$

is number of susceptible herds at time period t.

- q is the probability of avoiding disease transmission, and thus $1 - q$ is the probability of transmission, which under the Reed-Frost equation is equal to $k/(TN - 1)$, where k is number of contacts a herd makes per day;
- CI_t is cumulative number of infectious herds at time t during the outbreak calculated as $\Sigma_{\mu}^{7} \hat{D}_{t-\mu}$ to reflect the fact that FMD spreads for at least seven days before showing clinical signs of infection at which point the diseased herds are assumed to be diagnosed and destroyed and;
- the total number of infected herds will be given by $D(t) = \Sigma_{t=0}^{t} \hat{D}_t$. 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, the number of susceptible herds will decrease. Therefore, at some point of FMD outbreak, num-

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[1] Exponential spread was also considered where $D(t) = e^{\beta t} = e^{\beta[365/(N+1)]}$ (Anderson and May, 1991).

ber of infected herds will increase at a decreasing rate.

In setting up this equation empirically, we choose to examine two cases: $k = 0.2$ for slow disease spread, and $k = 0.4$ for fast spread (based on contact rates used by Bates, Thurmond, and Carpenter 2001; Garner and Lack 1995; Schoenbaum and Disney 2003). In addition, we found a need to approximate the Reed-Frost disease spread using a logistic functional form (Equation 15) fit to the Reed-Frost function.

$$(15) \quad D[t(N)] = \frac{TN}{1 + \beta_1 e^{\beta_2 t}}.$$

For fast disease spread, the logistic function gives an almost perfect fit (R^2 equal to 0.99) to the Reed-Frost formulation using $\beta_1 = 381{,}140$ and $\beta_2 = -0.348$. For slow disease spread, we found $\beta_1 = 102{,}000$, and $\beta_2 = -0.144$, with $R^2 = 0.97$. We also set $t = 365/(N + 1)$.

Total costing. The average loss value per infected herd (V) was calculated as follows:

$$(16) \quad V = CS \times NH + \left(MV + \frac{GI}{TN}\right) \times NH,$$

where CS is costs of slaughter, disposal, cleaning, and disinfection, which was assumed to be \$69 per head (Bates, Thurmond, and Carpenter 2003a, p. 807); NH is average number of head in a herd, which was assumed to be 50 based on extensive observations (Davis 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); and TN is number of heads in Texas, which was approximately 14,000,000 in 2003. Thus, the value used for V was \$62,000, which reflected annual gross income and value of inventory.

Surveillance costs. The surveillance costs consisted of fixed and variable cost terms. The fixed costs (FTC) were estimated to be \$22,650,000, which was calculated by multiplying Schoenbaum and Disney's estimate (p. 36) of per herd testing costs (\$150) for operations of less than 100 head times the number of cattle operations in Texas (151,000). Variable testing costs (VTC) were calculated assuming \$50 per visit per herd (Schoenbaum and Disney, p.36), assuming outside expertise would be required, or \$7,550,000 for the whole Texas herd.

Slaughter costs. Cost of slaughter (CR) associated with slaughter of contact herds was based on Schoenbaum and Disney's (p. 36) estimates of appraisal (\$300 per herd), euthanasia (\$5.50 per head), and carcass disposal (\$12 per head) or, for a 50 head herd, a total of \$1,175. The optimal number of herds slaughtered in Schoenbaum and Disney was 37. Therefore, costs of response strategy corresponding to $R = 1$ were assumed to be $37 \times 1{,}175 = \$43{,}475$.

Model Experimentation and Results

Following parameterization, the model was used to examine the sensitivity of pre-event investment to changes in the probability and severity of an outbreak, along with effectiveness and costs of considered mitigation options. We also report on the cost and livestock slaughter implications of pre-event investment.

Investment Sensitivity Analysis

In a sensitivity context, the model was used to examine the optimal level of investment in pre-event animal health surveillance given changes in:

- Probability of FMD introduction varying from 0.00001 to 0.1;
- disease spread rates at low (0.2) and high (0.4) levels;
- variable per herd testing costs;
- response costs;
- response strategy effectiveness; and
- the possibility that detection activities could provide ancillary benefits by finding other herd problems when an outbreak did not occur.

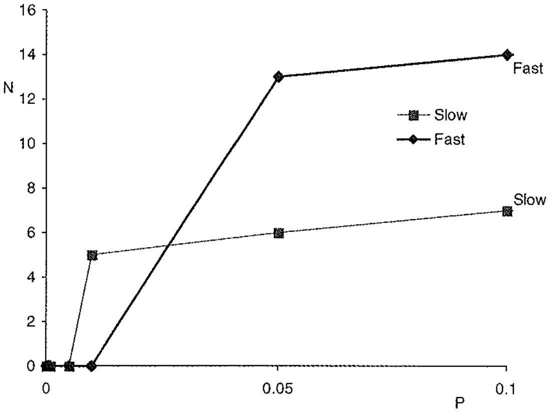

Figure 2. Number of Annual Tests under Slow- and Fast-Spreading Scenarios

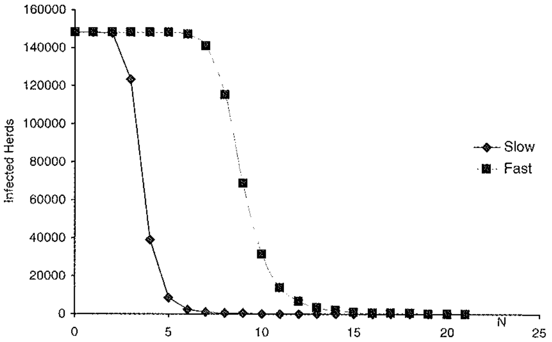

Figure 3. Number of Infected Herds for Slow- and Fast-Spreading Scenarios under Various Levels of Animal Testing

Variations in Outbreak Probability and Disease Spread Rate

We investigated the effect of potential outbreak probability and disease spread rate. Our theoretical results indicate that the higher the disease introduction probability, the higher the pre-event investment; this is reflected in the empirical results (Figure 2). We also found that faster disease spread rates increase reliance on pre-event preparedness. The Figure 2 results show that the optimal number of annual tests is generally larger for fast-spreading disease than for slow-spreading disease. At the lowest considered probabilities of disease introduction, no investment is made for either fast- or slow-spreading diseases. However, as the probability of disease introduction increases, the investment in surveillance systems becomes increasingly more advantageous. Notice that for slow-spreading diseases, the probability at which testing becomes desirable is lower than at a corresponding probability for fast-spreading diseases. The reason is that effectiveness of testing decreases as the spread rate increases (Figure 3). In other words, relatively more frequent tests are need for fast-spreading diseases than for slow-spreading diseases in order to significantly decrease the number of infected herds. Therefore, it is uneconomical to invest in surveillance systems for fast-spreading disease and conduct relatively infrequent tests. However, more frequent tests could significantly slow down the spread of the disease and therefore be economically justified at higher probabilities, where fixed investment costs are offset by losses prevented by a surveillance system. On the other hand, a slow-spreading disease could be controlled by relatively fewer annual tests, thus requiring smaller investment in the form of variable testing costs.

Variation in Costs of Surveillance

We also examined the effects of reducing the variable costs of surveillance and detection; we find that the amount of testing increases. Namely under a fast-spreading disease, the number of annual tests for an outbreak probability of 1 goes from 17 to 34 when variable testing costs are decreased by one hundredfold. The results are similar for the outbreak of a slow-spreading disease, where the number of annual tests increases from 9 to 22.

Effects of Changes in Costs and Effectiveness of Response Actions

Empirically we find that increases in response effectiveness from 17% to 30% or decreases in response costs by 90% or 99% had a small effect on the level of pre-event investment.

Effects of Ancillary Benefits

Investing in a surveillance system for detection of FMD could have ancillary benefits in terms of herd health in the face of other diseases. To examine this possibility, we analyzed scenarios with the per herd fixed costs of testing reduced by 50%. It was found that ancillary benefits do not have a significant effect on pre-event preparedness levels. Under the fast-spread scenario, the effect of decreasing fixed per herd testing costs by a half (from \$150 to \$75 per herd) had no effect on the number of annual tests performed on all herds in Texas. However, decreases in the variable costs did have an effect, as discussed already.

Effects of Pre-Event Investment

The economic costs of an event are affected by pre-event investment. Using these data, up to 70% of Texas cattle industry value was lost when preparedness actions, such as periodic animal health testing, were not used. However when surveillance was used, losses from a potential FMD outbreak fell to about 1.2% of total cattle industry's economic worth. In terms of total number of herds slaughtered, the optimal choice of surveillance tests decreased the number of slaughtered herds to less than 1% of what would have been lost without pre-event testing. This indicates desirability of such pre-event preparedness under the fast-spreading FMD scenario.

Conclusions

We developed a model of the balance between pre-event preparedness and postevent response in addressing introductions of infectious foreign animal disease. We found that pre-event investment would increase with event probability and severity, along with costs and effectiveness of response options. Specifically, theoretical and empirical investigations suggest that the optimal level of investment in pre-event preparedness increases as:

- disease spread rate gets larger,
- response strategy is less effective or more costly,
- the probability of disease introduction increases,
- the costs of the pre-event activity fall, and
- the ancillary benefits of the strategy outside of an event increase.

We would caution that the empirical results of this work need to be interpreted with care, as numerical outcomes depend critically on the functional forms and parameters, which, while suggestive of FMD disease, are just that.

We also believe this model could be used in a number of other settings in order to address preparedness for infrequent events like floods, hurricanes, droughts, etc.

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