Coordinating to Eradicate Animal Disease, and the Role of Insurance Markets

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Abstract

Farmed animal production has traditionally been a dispersed sector. Biosecurity actions relevant to eradicating infectious diseases are generally non-contractible, and might involve inordinately high transactions costs if they were contractible. If an endemic disease is to be eradicated within a region, synchronized actions need to be taken to reduce incidence below a critical mass so that spread can be contained. Using a global game model of coordination under public and private information concerning the critical mass required, this paper characterizes the success probability in an eradication campaign. As is standard in global games, heterogeneity in private signals can support a unique equilibrium. Partly because of strategic interactions, concentrated production is found to facilitate eradication whenever unit participation costs are decreasing. Policies to manipulate the critical mass have both a direct effect and a strategic coordination effect. Policies to manipulate information can have subtle and non-intuitive consequences. A program to keep disease out can be modeled similarly. It is shown, too, that coordination problems may lead to multiple equilibria in animal disease insurance markets, so that these markets may complicate a disease eradication program by creating opportunities for multiple inefficient equilibria. The presence of private insurance markets may facilitate coordination and, for good or ill, can seal the fate of a program.

Keywords: biosecurity, coordination failure, disease insurance, endemic disease, global games, market access, public information, veterinary public health.

JEL classification: D8, H4, Q1

Introduction

Bovine viral diarrhea virus (BVDV) is a disease that increases mortality and morbidity in calves, while decreasing weanling weight. Costs can be high. For example, Chi *et al.* (2002) have estimated the sum of costs from direct production losses and treatment at $2,422 (Canadian) per 50-cow dairy herd in Maritime Canada. The disease is generally accepted to have high prevalence in North America. National and transnational control and eradication campaigns are underway through much of Northern Europe (Houe, Lindberg, and Moennig 2006).

In 2006, the U.S. Academy of Veterinary Consultants resolved "that the beef and dairy industries adopt measures to control and target eventual eradication of BVDV from North America." In October 2007, the U.S. Animal Health Association Committee on Infectious Disease in Cattle, Bison and Camelids noted:[1]

> "The control and reduction of bovine viral diarrhea virus (BVDV) in the cattle population of the United States is a grass roots effort driven by the dairy and beef cattle industries. The National Cattleman's Beef Association, Academy of Veterinary Consultants, American Association of Bovine Practitioners and the United States Animal Health Association (USAHA) all have BVDV control committees or subcommittees, however, there is not a single entity acting as a coordinator for these activities."

With this in mind, the Committee passed Resolution 17 (U.S. AHA 2007), which reads as follows:

> "The U.S. Animal Health Association urges the U.S. Department of Agriculture to conduct an analysis to determine if the negative economic impact of BVDV infection in both beef and dairy cattle would warrant the development of an organized BVDV control and reduction program."

Coordination of private and public efforts ring large in these communiqués, and more broadly in the general medical literature on disease eradication (Arita, Wickett, and Nakone 2004).[2] The intent of this article is to provide a better understanding of coordination in the control and eradication of animal diseases.

The presence of infectious animal disease is a major impediment to productivity and market access for livestock products. For example, hoof and mouth disease (HMD), bovine spongiform

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[1] The U.S. AHA's stated mission is to protect animal and public health by (1) serving as a national forum for communication and coordination concerning: disease eradication, animal health, emergency preparedness, emergency response and recovery, emerging diseases, food safety, public health, animal welfare, and international trade; (2) serving as a clearinghouse for new information and methods for policy and programs development; and (3) developing solutions for animal health issues.

[2] Again concerning BVDV, Dr. Julia Ridpath at the U.S. National Animal Disease Center has stated, "Everybody is realizing that we all have to get in the same boat and row." See O'Rourke 2002.

encephalopathy, highly pathogenic avian influenza, and Newcastle disease are among many diseases that have placed practical limits in recent years on where and with whom the United States or its regions can trade. The need for some public involvement is not in question, as productivity losses and closed markets due to infection are negative externalities, and it is hard to conceive of a market solution in a sector with many small producers. A useful classification when considering public involvement is that of endemic, sporadic, and eradicated diseases. Authorities may seek to control a widespread, or endemic, disease so that outbreaks become sporadic and then to eradicate a sporadically recurring disease.

Most countries do not have the enviable animal health status levels attained in North America, Western Europe, and parts of off-shore Asia. For example, Kivaria (2003) presents the case of HMD in Tanzania. There, cattle trading, poor infrastructure, an inability to coordinate with war-torn neighbors, comparatively low productivity losses due to the production system in place, and a fatalistic attitude about the disease limit the potential for control. Commencing in the nineteenth century, the world's more prosperous and geographically isolated countries have had considerable success in eradicating such diseases as Texas cattle fever, bovine tuberculosis, brucellosis, bovine hypodermosis, pseudorabies, and HMD (Cousins and Roberts 2001; Boulard 2002; Leforban and Gerbier 2002; Ragan 2002; Müller *et al.* 2003; Sutmoller *et al.* 2003; Olmstead and Rhode 2004; Bowman 2006).[3]

But new concerns have emerged over time so that it is likely that all countries with a functioning animal health authority will continue to have ongoing eradication programs through the indefinite future. For example, in part because of concerns about transmissible spongiform encephalopathies, the United States and European Union member countries are presently involved in scrapie eradication. On-farm productivity losses as well as accumulating evidence on a link between Johne's disease in cattle and Crohn's disease in humans has motivated control programs in many countries (Greenstein and Collins 2004; Feller *et al.* 2007). A wide variety of infectious diseases causing high mortality and morbidity are endemic to most countries in the world, including rapidly developing countries that have strong trade interests. Disease-by-disease, they face the challenges of control and eradication.

Animal production is very much a decentralized endeavor, even in industrial format systems. Dispersed decision-making presents problems for disease eradication. Eradication provides a public good but involves the sorts of commitment by producers that would be difficult to monitor even if farms were to receive regular visits from public veterinary personnel (Wells 2000). Yet incentives to make these commitments are not entirely broken. Farmers do have the incentive to make the effort but only if they feel assured that others also have the incentive to do so. A critical mass of acting farms is necessary if the disease is to be eliminated; otherwise, public resources will be too stretched over residual disease pockets to prevent subsequent widespread re-infections.

The problem is largely one of coordination. If a grower is confident that others are committed to disease eradication, he will have sufficient confidence to make the effort. However, if the grower forecasts that few others will act, he may foresee private costs but no gain, as the disease will

[3] See Boulard (2002) in particular for comments on the need for synchronized actions.

remain endemic, international markets will remain curtailed, and the farm is likely to remain infected in the long run from contact with neighbors. And there is agreement that control often needs to occur at a transnational level (Sutmoller *et al.* 2003). The specific motive for founding the OIE (World Organization for Animal Health) was the control of Rinderpest in Europe. Seeing pseudorabies as an impediment to trade, the European Union has been involved in its control since 1964 (Müller *et al.* 2003). Correa *et al.* (2002) point to the need for coordinated, region-wide efforts at HMD control in South America.

The possibility of multiple equilibria is not difficult to envision. The problems of bank runs, speculator attacks on a currency regime, coordination on a technology standard, and plebeian revolt against an unpopular government present related phenomena. Consider the case of a bank run. A bank takes in deposits that can be removed at short notice. Believing that only a small fraction will withdraw in the near-term, the bank makes mainly far-term investments that are difficult to liquidate in the near-term but have high expected returns. So the bank provides a near-term liquidity service to depositors. If something, real or otherwise, spooks some depositors then they may withdraw. If enough do so, then the bank's viability comes into question, as it must liquidate far-term investments at a loss. Now depositors have more substantial worries, and continued withdrawals may cause the bank to fail.

Diamond and Dybvig (1983) and others have pointed to the possibility of expectation-induced multiple equilibria in such settings, whereas that of the bank run is clearly Pareto dominated. As with disease eradication, what others think, what you think others think, and so on, all matter. Yet their story is not entirely satisfactory because it sees little role for information on noisiness in "fundamentals" that should be influential in determining equilibrium. In our case, this might be imperfect and heterogeneous information concerning disease prevalence that is available to growers.

Carlsson and van Damme (1993) provide a framework for studying games in which the payoff is random and players are incompletely informed on the true payoff. Frankel, Morris, and Pauzner (2003), Morris and Shin (1998), Hellwig (2002), Angeletos and Pavan (2004), Angeletos and Werning (2006), Angeletos, Hellwig, and Pavan (2006, 2007) and others have developed this literature on what are now called global games. One of the main points to emerge is that noise in the signals may create a unique equilibrium, one in which private and public signals on fundamental information can matter in subtle ways. The literature has provided a clearer specification of how coordination can occur, and especially how information structures influence the equilibrium settled upon.

This article will use a global games model to extract insights concerning strategic dimensions to the management of animal disease eradication programs. Given the levels of resources devoted to coordination of veterinary health programs at the more practical level, at least some effort should be expended on asking what these efforts do for private incentives. We will adapt a standard model, as presented in Morris and Shin (2004). Several inferences emerge. One is that there may be strategic merit to concentrated animal production in that growers think it will be easier to coordinate toward eradicating a disease, and that may be half the battle when growers have strategic complementarities. The self-fulfilling positive beliefs are due to the larger potential gains that bigger enterprises can accrue from market access or enhanced productivity.

Another is that efforts to improve fundamentals should provide both direct *and* strategic motives to encourage grower biosecurity actions and so should enhance the probability of disease eradication. Such efforts to improve fundamentals might include strengthening public sector institutions through timely protocols based on prudent and informed use of scientific knowledge, through intolerance of corruption among public officials, through public control of disease in wildlife reservoirs, or through intensive monitoring on a fraction of farms.

We also point to the coordinating role an insurance market against an adverse disease outcome can have. As with other financial prices, the premium price is presumably determined in part by demands originating in private signals. So the premium is a noisy aggregation of private signals on the probability of an infectious disease outcome, be it eradication of or entry of a disease.[4] Just as commodity futures prices help guide crop-planting decisions, policy premium quotes should guide biosecurity decisions. If the premium is high, due to mainly bearish private signals or for other reasons, then growers may conclude that the disease control program is ill-starred and that they can save on biosecurity costs, thus reinforcing the likelihood of program failure.

Model

The model concerns a region with a fixed stock of animals sold per year, which we will label as $\bar{Q}$. This level of stock does not change with disease eradication, but profit per animal does. The model has three components. The payoffs for participating, or not, in a program are such that the probability of program success is endogenously determined by the actions of all players. The information structure relates information on fundamental issues (the fundamentals) that contribute to the success of a program, on the signals growers receive about these fundamentals, and on the information a grower has about the signals other growers receive. These, in addition to rational information processing, imply equilibrium actions the modeling of which is the model's third component. Equilibrium actions depend on both the actual signals received for any given level of fundamentals and on what growers project other growers to have done given the relationship between the signal received and the signals others likely have received.

Payoffs

A disease eradication program has been devised for a region, and risk-neutral farm operators must decide whether to participate. All farms are considered to be identical in all ways except for a noisy signal received, to be explained later. Participation in the program at time point $t = 0$ would cost $W(q)$, q the level of farm output. If the program succeeds then the disease remains only in pockets among non-participating farms at time $t = 1$, to be cleaned up later, so that non-participating farms should not expect to acquire all the benefits of success. To eliminate further complications, it is assumed by all that the disease will certainly be eradicated across the region in any case at $t = 2$.[5] So our model concerns the timing of eradication, and not whether it occurs

[4] Quite apart from insurance contract markets, online and offline betting businesses provide quotes on such wagers as whether bird flu will be confirmed in the United States by date x.

[5] The insights obtained from the model are robust to alternative assumptions on what happens if the program fails, e.g., the region remains diseased thereafter without ever trying to eradicate again, or a further attempt is made to eradicate thereafter. However, the analysis becomes more involved, as assumptions need to be made on learning, and so on. Clearly, reality is better

at all. Four possibilities exist. The grower may or may not participate and the program may or may not succeed at the period's end.

The probability that a farm goes out of business is assumed to depend on the program's success, where other businesses enter to take its place. Business quit rates matter because the discounted present value of gains from eradication that are expected to accrue to farmers making the investment will decline if the quit rate is high. If the program succeeds at $t = 0$ then fraction e^{-h^s} of businesses operating in that period are still in business at $t = 1$. Prior to eradication, farms survive at the rate e^{-h^f} where $h^f > h^s$. We denote the difference in these fractions as hazard differential $z_1 = e^{-h^s} - e^{-h^f}$.

Farm output per period is set at q and cost per unit output is c, where both are independent of the program's success. If the eradication program succeeds then access to international markets increases price per unit output from P to $P + \delta$, $\delta > 0$. With $z_2 = P - c$ as the net margin under disease, eradication changes the net margin from z_2 to $z_2 + \delta$. The continuous time discount rate is constant at r, so that the discount factor is e^{-r} per period.

We need to establish the value of the enterprise if the program succeeds by $t = 1$ and the value of the enterprise if the program fails, where V^s and V^f are the respective values under success and failure. Bearing in mind that no price premium is achieved in the year eradication occurs, the value under success is

(1) $$V^s = z_2 q + q e^{-(h^s + r)} (z_2 + \delta) \sum_{i=0}^{\infty} e^{-(h^s + r)i} = z_2 q + \frac{e^{-(h^s + r)} (z_2 + \delta) q}{1 - e^{-(h^s + r)}}.$$

The value under failure at $t = 1$ is $z_2 q$ for the first year plus the discounted expected value of the firm given that the eradication program did not succeed, or

(2) $$V^f = z_2 q + e^{-(h^f + r)} V^s = \left[1 + e^{-(h^f + r)}\right] z_2 q + \frac{e^{-(h^f + h^s + 2r)} (z_2 + \delta) q}{1 - e^{-(h^s + r)}}.$$

Some algebra confirms

(3) $$J(r, \delta, z_1, z_2, q) \equiv V^s - V^f = \left(\left[1 - e^{-(h^f + r)}\right] e^{-h^s} \delta + z_1 z_2\right) \frac{e^{-r} q}{1 - e^{-(h^s + r)}}.$$

The term involving z_2 reflects the gain from a lower farm failure rate. The term involving δ reflects the gain from market access. Clearly, marginal effects satisfy $J_\delta \geq 0$, $J_{z_1} \geq 0$, and $J_{z_2} \geq 0$, but J_r has an indeterminate sign. Note in particular that

(4) $$J_q(r, \delta, z_1, z_2, q) = \frac{J(r, \delta, z_1, z_2, q)}{q} \geq 0;$$

the marginal value of success is in proportion to production.

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represented by allowing for dynamic interactions. Dynamic global games have been studied in Angeletos, Hellwig, and Pavan 2007. Though the details are enriched, the equilibrium features of interest to our analysis continue to apply.

If the program succeeds, then net value to the participating farm is $V^s - W(q)$, whereas if the program fails, net value to the participating farm is $V^f - W(q)$. A successful program is assumed to have net value $\rho V^s + (1-\rho)V^f$, $\rho \in (0,1)$, to the non-participating farm so that there is a cost to non-participation in the event the program succeeds. Here, ρ may be read as the success-sharing parameter. Non-participating farms then have access to international markets, and while they may have the disease, they will have an easier time in managing their own residual disease problems. The value to them of not participating is V^f if the program fails.

What follows is an adaptation of the model in Morris and Shin (2004), and also the interpretation by Metz (2002), to our purposes. In order to succeed, the program must have participation of fraction a of farms where $a \geq \theta$, θ an unknown threshold. Here, a is the fraction of all farms in the region. Threshold θ represents fundamentals concerning disease eradication. If it is low, then a comparatively small fraction of farmers need to act in order to succeed. So θ will be determined by efforts to control disease in wildlife refuges, clean up livestock markets, or strengthen the capabilities and integrity of animal public health institutions, among other factors (Leonard 2000; Kivaria 2003; Corner 2006).

When specifying $a \geq \theta$ as the criterion (or hurdle) for success, note that the number of farms does not enter grower considerations about the likelihood of success in coordination. It would seem reasonable to reduce the threshold fraction of participating growers required for success when the number of farms in the region is lower.[6] But we will find that this is not necessary in motivating the argument that a more concentrated industry should promote the prospects for success in disease eradication.

Summarizing the above, a participating farm, denoted by "act," and a non-participating farm, denoted by "na" for not act, have state and action-contingent payoffs:

$$U(\text{act}) = \begin{cases} V^s - W(q) & \text{if} \quad a \geq \theta; \\ V^f - W(q) & \text{if} \quad a < \theta; \end{cases}$$
$$U(\text{na}) = \begin{cases} \rho V^s + (1-\rho)V^f & \text{if} \quad a \geq \theta; \\ V^f & \text{if} \quad a < \theta. \end{cases} \tag{5}$$

Growers have to choose between acting or not, and they also have to form opinions on the likelihood that the eradication program will succeed. These decisions are linked: both depend on the information available to the grower and also the grower's knowledge of information available to other growers.

Information Environment

Turning to information on the determining mass parameter θ, its value is uncertain ex ante. Farmers receive a noisy signal on this θ where the signal received is given by

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[6] Criterion $a \geq \theta$ assumes uniform spatial mixing of non-participating farmers. When a region is large and heterogeneous, some sub-regions may not attain sufficient participation to eradicate the disease there so that the disease re-emerges later.

(6) $x_i = \theta + \eta_i$.

Here θ has normal distribution $N(y(\nu), \alpha^{-1})$, where the first argument is the mean and α^{-1} is the variance. Mean $y(\nu): \mathbb{R} \times ... \times \mathbb{R} \to \mathbb{R}$ is a function of factors influencing fundamentals, such as those outlined previously. The inverse of variance, in this case α, is referred to as the random variable's precision. The i^{th} farm idiosyncratic component of the information, η_i, is independent of θ, independent of other farm idiosyncratic components, and follows $N(0, \beta^{-1})$.

In light of Bayes' rule, its observation of x_i, and conjugacy properties of the normal distribution (Berger 1985), the i^{th} farm's posterior distribution on θ follows

(7) $$\xi_i \sim N\left(\frac{\alpha y(\nu) + \beta x_i}{\alpha + \beta}, \frac{1}{\alpha + \beta}\right).$$

Grower decisions can only be based on the posterior.

Equilibrium Beliefs and Decisions

Specify as $\hat{\theta}$ any critical realization of fundamentals for which the program is at the boundary between success and failure. Since $\theta \sim N(y(\nu), \alpha^{-1})$, it follows that the unconditional probability of eradication is

(8) $$\Pr(\text{erad}) = \Phi\left[(\hat{\theta} - y(\nu))\sqrt{\alpha}\right],$$

the cumulative standard normal with density function $\phi(\cdot)$. In the appendix it is shown that these values must satisfy

(9) $$\hat{\theta} = \Phi\left(\frac{\alpha}{\sqrt{\beta}}\left[\hat{\theta} - y(\nu) - \frac{\sqrt{\alpha + \beta}}{\alpha}\Phi^{-1}\left(B(\cdot)\right)\right]\right);$$
$$B(\rho, r, \delta, z_1, z_2, q) = \frac{W(q)}{(1-\rho)J(r, \delta, z_1, z_2, q)};$$

where $\Phi^{-1}(\cdot)$ is the inverse of the cumulative standard normal distribution.

Together, (8) and (9) relate the equilibrium unconditional probability of eradication.[7] Notice that on-farm parameters are captured entirely by the cost-to-benefit ratio $B(\cdot)$. There is a natural interpretation to this ratio. In the appendix, it is shown that the signal-conditioned probability of eradication is

(10) $$\Pr(\text{erad} \mid \hat{x}) = \frac{W(q)}{(1-\rho)J(r, \delta, z_1, z_2, q)},$$

where $\hat{x}$ is a farm's signal realization that equates the net benefits of participating with those of not doing so.

[7] There are technical issues to be dealt with. The strategy of choosing to participate if and only if the private expectation of the threshold is high enough could conceivably be dominated by some other strategy. As explained in Heinemann and Illing (2002, p. 434) and in Theorem 1 of Morris and Shin (2004), it is not.

Overall, (8)-(9) may be viewed as providing the program's equilibrium failure rate consistent with beliefs used when making participation decisions. It cannot be a Pareto-efficient equilibrium. Suppose that θ is certain. From (5), if $B(\cdot) \in (0,1)$ then social welfare is a discontinuous function of the participation rate, as laid out in Figure 1. For any certain $\theta \in (0,1)$, it is Pareto optimal for all to participate.

Policy Issues

Together, (8) and (9) provide a system that can reveal much about policies with intent to increase the eradication probability. A concern is whether any equilibrium is unique. If it is not then the effects of a policy modification are not as clear to discern, a central point in the global games literature.[8]

Point 1: A sufficient condition for a unique equilibrium is $\alpha \le \sqrt{2\pi\beta}$.

Differentiate the right-hand side of the fixed-point equation in (9) with respect to $\hat{\theta}$ to obtain

$$(11) \qquad \frac{\alpha}{\sqrt{\beta}}\phi\left(\frac{\alpha}{\sqrt{\beta}}\left[\hat{\theta} - y(\nu) - \frac{\sqrt{\alpha+\beta}}{\alpha}\Phi^{-1}\left(B(\cdot)\right)\right]\right).$$

The density function's maximum value over its entire range is $1/\sqrt{2\pi}$, which it attains at just one point. The derivative of the left-hand side in (9) is 1. As the right-hand side in (9) never has larger slope than the left-hand side whenever $\alpha \le \sqrt{2\pi\beta}$, this condition suffices to ensure that any solution to (9) is unique.[9] The right-hand side in (9) has range $[0,1]$ and is continuous while the left-hand side covers the range. So a solution must exist, and it is stable to perturbations. In fact, the normal information framework for θ and the η_i allow for at most two solutions that are stable to local perturbations. Strict inequality $\alpha < \sqrt{2\pi\beta}$ is not necessary to ensure a unique equilibrium, but there exist $y(\nu)$ values that support multiple equilibria whenever $\alpha > \sqrt{2\pi\beta}$.

The sufficiency condition suggests that multiple equilibria for the eradication probability are more likely to arise when precision concerning the fundamentals, or α, is high. Bear in mind that multiple equilibria arise in the model of Diamond and Dybvig (1983) and other coordination game models when θ is known with certainty. It is the lack of precision on fundamentals that admits a unique equilibrium. But (11) also suggests that more precision on the noisy private information makes uniqueness more likely. The reason why an increase in β such that θ is certain at the limit (see [7]) should make uniqueness more likely whereas an increase in α makes it less likely has to do with uncertainty concerning the participation decisions of others. This has been explored in Morris and Shin (2003).

[8] The parallel result in Morris and Shin (2004) is on page 139.

[9] If $\Phi = 0.5$ at a solution to (9), then $\phi = 1$ at that solution and the values of ϕ are smaller at either side so there can be no other solution.

Point 2: At the limit with almost no fundamental uncertainty and almost no noise in private signals, a unique inefficient equilibrium can sometimes be supported.

As in equation (16) of Morris and Shin (2004), let $\alpha \to \infty$ and $\beta \to \infty$ but require $\alpha\beta^{-0.5} \equiv \vartheta \leq (2\pi)^{0.5}$. Then (9) becomes

(12) $$\hat{\theta} = \Phi\left[(\hat{\theta} - y(\nu))\vartheta - \Phi^{-1}\left(B(\cdot)\right)\right],$$

and there is a unique equilibrium. Now from (8) and (12), when $(\alpha,\beta) \to (\infty,\infty)$ along the curve $\alpha\beta^{-0.5} = \vartheta$ then

(13) $$\begin{aligned}\frac{d\,\Pr(\text{erad})}{d\alpha} &= \left.\frac{d\Phi\left((\hat{\theta} - y(\nu))\sqrt{\alpha}\right)}{d\alpha}\right|_{\alpha\beta^{-0.5}\equiv\vartheta} \\ &= \phi\left((\hat{\theta} - y(\nu))\sqrt{\alpha}\right)\sqrt{\alpha}\overbrace{\left.\frac{d\hat{\theta}}{d\alpha}\right|_{\alpha\beta^{-0.5}\equiv\vartheta}}^{=0} + \frac{\phi\left((\hat{\theta} - y(\nu))\sqrt{\alpha}\right)}{2\sqrt{\alpha}}(\hat{\theta} - y(\nu)) \overset{sign}{=} \hat{\theta} - y(\nu).\end{aligned}$$

So if $\hat{\theta} \leq y(\nu)$ then the eradication probability decreases with an increase in α (and increases with an increase in β) along the curve $\alpha\beta^{-0.5} \equiv \vartheta$. Put differently, if the eradication probability is less than 0.5 then a tailored increase in precision on the fundamentals decreases the probability of eradication. On the other hand, if the eradication probability is larger than 0.5 then more precision on the fundamentals along this specific curve increases the eradication probability. Overall elimination of uncertainty in the direction $\alpha \to \infty$, $\beta \to \infty$, $\alpha\beta^{-0.5} \equiv \vartheta$, is good for social welfare if the odds are already in favor of eradication. But when the odds for eradication are low then, perhaps paradoxically, a lack of transparency may be all to the better, as it muddies the waters.

Point 3: In unique equilibrium, the eradication probability increases with an increase in production scale whenever the private participation unit cost $W(q)/q$ is decreasing.

Differentiate the fixed-point condition in (9) with respect to q to obtain

(14) $$\frac{d\hat{\theta}}{dq} = -\frac{\dfrac{\sqrt{\alpha+\beta}}{\sqrt{\beta}}\dfrac{\phi\left(\dfrac{\alpha}{\sqrt{\beta}}\left[\hat{\theta} - y(\nu) - \dfrac{\sqrt{\alpha+\beta}}{\alpha}\Phi^{-1}\left(B(\cdot)\right)\right]\right)}{\phi\left(B(\cdot)\right)}B_q(\cdot)}{1 - \dfrac{\alpha}{\sqrt{\beta}}\phi\left(\dfrac{\alpha}{\sqrt{\beta}}\left[\hat{\theta} - y(\nu) - \dfrac{\sqrt{\alpha+\beta}}{\alpha}\Phi^{-1}\left(B(\cdot)\right)\right]\right)}.$$

Now $B_q(\cdot) \leq 0$, from $W(q)/q$ decreasing. The denominator in (14) is positive in unique equilibrium; see point 1. Eradication probability equation (8) then implies

(15) $$\frac{d\,\Pr(\text{erad})}{dq} = \alpha^{0.5}\phi\left[(\hat{\theta} - y(\nu))\sqrt{\alpha}\right]\frac{d\hat{\theta}}{dq} \geq 0.$$

To the extent that an increase in scale increases a farm’s gains from participation, it increases the incentive to participate. Farms with more to protect are more likely to participate for any given signal. So a larger set of realizations of fundamentals parameter θ supports signal distributions that lead to eradication.

Two distinct effects can be identified in (14). By itself, the numerator in the right-hand expression can be viewed as the direct effect. At farm level, when there are scale economies in the biosecurity action then the cost-benefit ratio increasingly favors action as herd size increases. The second effect concerns the denominator, is indirect, and may be viewed as strategic. Since the denominator is bounded in $(0,1)$, it acts to multiply the direct effect. Growers recognize that when other herds are larger, the threshold private signal that elicits action is smaller so that other farms are more likely to act. Possessed with more confidence that the program will succeed, a grower's own threshold private signal for action also decreases. Perhaps more important than the sign in (15) is the magnification effect. Because of the strategic effect just outlined, a small change in farm output could shift the farm-level cost-benefit ratio enough to dramatically alter participation incentives and thus the eradication probability.

Point 4: In unique equilibrium, an increase in the mean of fundamentals decreases the probability of eradication.

Differentiate the threshold in (8) with respect to y and apply $d\hat{\theta}/dy$ from (9) to obtain

$$(16) \qquad \frac{d\,\Pr(\text{erad})}{dy} = -\frac{\phi\left[(\hat{\theta} - y(\nu))\sqrt{\alpha}\,\right]\sqrt{\alpha}}{1 - \frac{\alpha}{\sqrt{\beta}}\phi\left(\frac{\alpha}{\sqrt{\beta}}\left[\hat{\theta} - y(\nu) - \frac{\sqrt{\alpha+\beta}}{\alpha}\Phi^{-1}\left(B(\cdot)\right)\right]\right)} < 0.$$

Consider an institutional innovation represented by a change in some ν argument of $y(\nu)$ that increases the mean of the fundamental's hurdle that the mass of participating growers must exceed. From (16), any such institutional innovation will reduce the eradication probability. The impact here is largely strategic. When y is large, then each farm's posterior distribution on θ has a larger mean and each farm conjectures that other farms receive high signals, even if the farm itself receives a low signal. Again, one may view the numerator as the direct effect and the denominator as strategic, to do with how some institutional parameter in ν affects what growers think about the signals other growers receive.

Note that the effect of y on the eradication probability is low when y is low and *also* when it is high, for in each case the value of $\phi[(\hat{\theta} - y(\nu))\alpha^{0.5}]$ is low. The effect will tend to be largest when y has a value close to the (endogenous) $\hat{\theta}$, for then the farm reckons that other farms also receive signals that put them on the cusp of changing their minds about participation. There can be a form of cascade in which a small shift in the underlying fundamentals can have a large impact on the equilibrium eradication probability because growers factor in the responses of others.

Point 5: In unique equilibrium, an increase in either participation cost $W(q)$ (for a given q) or sharing parameter ρ decreases the eradication probability. An increase in any of market access premium δ, hazard differential $z_1 = e^{-h^s} - e^{-h^f}$, or surplus $z_2 = P - c$ increases the eradication probability.

Using (9), differentiate (8):

$$(17) \qquad \frac{d\,\Pr(\text{erad})}{dB} = -\frac{\sqrt{\dfrac{\alpha^2+\alpha\beta}{\beta}}\;\dfrac{\phi\left[(\hat{\theta}-y(\nu))\alpha^{0.5}\right]\phi\left(\dfrac{\alpha}{\sqrt{\beta}}\left[\hat{\theta}-y(\nu)-\dfrac{\sqrt{\alpha+\beta}}{\alpha}\Phi^{-1}(B)\right]\right)}{\phi(B)}}{1-\dfrac{\alpha}{\sqrt{\beta}}\phi\left(\dfrac{\alpha}{\sqrt{\beta}}\left[\hat{\theta}-y(\nu)-\dfrac{\sqrt{\alpha+\beta}}{\alpha}\Phi^{-1}(B)\right]\right)} \le 0.$$

The rest follows from the properties of $B(\cdot)$. Thus, a subsidy on the cost of participation will indeed increase the eradication probability, and the effect may be large due to strategic responses.

Coordinating to Prevent Entry

Turning the problem around, suppose that growers need to act collectively to ensure that a disease does not take hold in a region. Rather than (5), let the payoff structure for biosecuring be

$$(18) \qquad \begin{aligned} U(\text{act}) &= \begin{cases} -W(q) & \text{if} \quad a \ge \theta; \\ -L - W(q) & \text{if} \quad a < \theta; \end{cases} \\ U(\text{na}) &= \begin{cases} 0 & \text{if} \quad a \ge \theta; \\ -L - M & \text{if} \quad a < \theta. \end{cases} \end{aligned}$$

Here, L may be considered to be the loss due to closed export markets if the disease takes hold, while M is an expected additional loss because the farm of a non-acting grower is more likely to be afflicted by the disease. It is readily established that the analog to (9) is

$$(19) \qquad \hat{\theta} = \Phi\left(\frac{\alpha}{\sqrt{\beta}}\left[\hat{\theta} - y(\nu) - \frac{\sqrt{\alpha+\beta}}{\alpha}\Phi^{-1}\left(\frac{W(q)}{M}\right)\right]\right).$$

The probability of entry, $\Pr(\text{entry})$, can then be studied in the manner of system (8)-(9).

Insurance Market Coordination, For Better or Worse

Market-based solutions are attractive in large part because prices signal information, and this transparency can often guide decisions toward a more efficient outcome. For example, insurance product prices should inform those not presently in a market about risks one would face were one to enter. To this point the analysis has assumed that public information is exogenous. A market to insure against the failure of an eradication program, or alternatively against failure to keep a foreign disease out, amounts to an endogenous public signal. This is because some of the information that determines the insurance product's price will reflect participation in the market by individuals using private information on the event.

The main potential social benefit of a private insurance market is the discipline it may bring in internalizing the cost of the disease risks to which a producer is exposed. The extent to which this would occur in a free market will be tempered by the difficulties involved in protecting one's farm against a disease once it emerges in a neighborhood. We state this because it is not clear to us that a well-functioning private insurance market would improve incentives for biosecurity decisions. Whether it does or not, we will point out in this section that animal disease insurance markets are likely to be complicated by other issues that have not, to the best of our knowledge, been pointed out before. Private insurance against animal disease epidemics is available in much of the world but is not widely available (OIE 2007). In some cases, such as HMD in France, producers have run their own mutual insurance scheme (Cassagne 2002).

It is easy to identify reasons why private insurers might shy away from these markets. Ekboir (1999) and Harvey (2001) summarize many of these concerns.[10] Rate-making is facilitated by historical data on risks, but data on the event of and size of losses are largely absent for epidemic disease events. Furthermore, globalized travel and trade, major restructuring and new technologies in the livestock sector, as well as newer agroterrorism concerns leave insurers very uncertain about the relevance of the data they do have. Other successfully marketed insurance products face similar rate-making problems, so these may not be insurmountable. A further concern is that epidemic risks are systemic by nature. So insurers will need to rely on re-insurance markets to diversify.

There is also the issue of loss assessment. An event will lead to a variety of losses, including direct production losses, marketing losses for farms where movement controls are in place, and price-related losses due to foreclosed markets. In addition, governments are likely to be heavily involved in compensation to encourage reporting, because healthy animals are condemned as a precaution, and to promote recovery. Apart from mitigating losses, the prospect of government compensation is likely to reduce the extent of interest in these insurance products.

In light of the above, it is clear that private insurance markets for livestock disease will likely have more than the usual set of incentives problems. In what follows we point to one further problem, to do with coordination in control of sporadic outbreaks of a disease or preventing entry. It is an issue that should be much more problematic for infectious animal disease insurance than for crop insurance markets because it has to do with biosecurity incentives and there is usually little farmers can do to prevent the spread of infectious plant disease.

In their 2006 study of financial crises, Angeletos and Werning, henceforth A&W, have extended the standard coordination game model in two relevant ways. In the first, they introduce a market on the fundamentals, in our case, the unknown critical mass parameter θ. In this scenario, one might view the situation as a producer taking out a futures position on exogenous θ as a form of insurance. For crop growers, this is more like taking out a weather futures contract than taking out crop insurance. A more likely scenario is one in which insurance is on the event of failure to eradicate or the event of entry, and not on the underlying exogenous fundamentals. Here, it is not only the fundamentals that matter but also the decisions taken based on reading the fundamentals and inferring what biosecurity actions others will take given one's reading of the fundamentals. We will work through summary versions of both settings.

[10] In OIE (2007), insurance company representatives are surveyed. Their comments cover most of those mentioned by Ekboir (1999) and Harvey (2001), and various others besides.

Contract on Fundamentals

Applying the classical Grossman and Stiglitz (1976, 1980) model on trading price in a market as an information aggregator, A&W let the total payoff for an asset be $R=\theta$ where the asset price is the, yet to be determined, price p. The model has two stages, wherein the first involves trading in an asset and the second involves making the biosecuring decisions that influence the disease program's success. In the first stage of the model, a position is taken in the asset market to the level k_i for the i^{th} participant.

With initial wealth s_0, the individual's realized final wealth is $s_i = s_0 + (R-p)k_i$. For CARA expected utility and risk-aversion parameter λ, the utility of final wealth is $-e^{-[s_0+(R-p)k_i]\lambda}$. This characterizes the preferences for holding the asset. Stage 1 asset choices will be made given private signal x_i and public signal p. Supply of the asset is exogenous, but random, at $K^s(\varepsilon) \equiv \mu_\varepsilon + \sigma_\varepsilon \varepsilon \equiv \mu_\varepsilon + \varepsilon/\gamma^{0.5}$ where ε is standard normal. Here, the supply location parameter is μ_ε, the risk scale parameter is σ_ε, and precision is $\gamma \equiv 1/\sigma_\varepsilon^2$.

Since supply of asset positions is random, the equilibrium price for the contract will contain information available to agents on $R=\theta$ but will also reflect supply-side randomness. Solving this rational expectations model in the standard manner, individual demand for information is given as

(20) $$k_i^*(x_i,p) = \arg\max_{k_i\in\mathbb{R}} E\left[e^{-[s_0+(R-p)k_i]\lambda} \mid x_i, p\right] = \frac{(x_i-p)\beta}{\lambda},$$

where $E[\cdot \mid x_i, p]$ is a conditional expectation.

Upon aggregating, demand is $(\theta-p)\beta/\lambda$, supply is $\mu_\varepsilon + \sigma_\varepsilon\varepsilon$, while equilibrium price given θ and ε is

(21) $$p \equiv P(\theta,\varepsilon) = \theta - \left(\mu_\varepsilon + \frac{\varepsilon}{\gamma^{0.5}}\right)\frac{\lambda}{\beta}.$$

The error on price as a signal for θ is $-\varepsilon\lambda/(\gamma^{0.5}\beta)$, giving precision in the public signal as $\gamma\beta^2/\lambda^2$. In stage 2, concerning coordination in biosecurity actions, public signal precision $\gamma\beta^2/\lambda^2$ replaces α so that Point 1 above modifies to

(22) $$\gamma\beta^{1.5} \le \lambda^2\sqrt{2\pi};$$

see Proposition 3 in A&W. If this does not hold then multiple equilibria are possible, and conditions exist under which the model will certainly support two locally stable equilibria. Any public effort at stabilizing the supply of futures positions (increasing γ) may only give rise to a less certain market outcome by increasing the risk of coordination on a bad equilibrium.

In Point 1 above, more precision in private information made a unique equilibrium more likely, as precision in this public information is fixed. In relation (22), by contrast, private information also alters the precision of public information through trading to determine the publicly available price. The net effect of this dual role for public information in this linear model is that more precise private information can always support multiple equilibria. In our case, an actively traded futures market on the fundamentals determining the threshold critical mass may generate a public signal that supports multiple equilibria. A&W go on to show that if either the private information becomes very precise or the exogenous component of public information becomes very precise (high γ) then one of the equilibria involves action by a mass of agents below the critical mass while another involves action by a sufficient mass for the program to succeed. In our case, an equilibrium involving eradication may result, as may one involving a failure of the eradication program.

Contract on Program Outcome
A second scenario is one in which insurance is on the event, be it eradication or disease outbreak, and not on the underlying fundamentals. A&W also adapt their model for pricing an asset whose payoff depends on success or failure of their regime. Again, they find that multiple equilibria will exist whenever the private information becomes very precise or the exogenous component of public information becomes very precise. Again, one equilibrium involves the regime standing while another involves the regime falling.

In our context, the event-conditioned payoff may be viewed as an insurance policy over the event of failure of a disease eradication program, or to prevent entry, or to prevent a sporadic outbreak. The equilibrium price plays several roles. One is that people use it to decide their insurance positions. Another is that the price provides a rational expectation on the probability the disease management program will work; it is a signal. Finally, farmers use this signal to divine what others do and so to decide on whether to biosecure. In other words, for good or for ill, the price is part of the coordination game and contributes to determining the payoff in an internally consistent manner.

As far as policy for infectious animal disease is concerned, the point is that any market that conveys significant information on disease outcomes may not be just a sideshow. If other forms of public information are limited, then the market's price may signal the program's fate. The program's prospects may depend on strong supply of the financial instrument, the price of which provides the public signal for coordination.

Conclusion
The utility of the model presented above is not so much in its practical application but rather in facilitating thinking on how to go about designing successful control, eradication, and prevention programs for infectious animal diseases. Eradication programs can be very expensive, as livestock culling may be involved. They often fail, with little goodwill from many of those they are intended to benefit. The burden of an eradication program may be particularly onerous for less developed countries with large animal agriculture sectors and pastoral production systems involving commonage.

Our analysis confirms the possibility of multiple equilibrium outcomes to an eradication program while also characterizing some aspects of the involved roles that public and private information can play in determining the probability of success. This suggests that progression and regression in a disease eradication program may not always be attributed to variable weather and other technical factors that affect spread. Financial markets, human communications, and adjusting beliefs may be just as important. The physical and biological epidemiology will also interact with human decisions, the information these decisions generate, and the beliefs the information support.

The model suggests that control and eradication will be more problematic when herd size is small. It also shows how the strength and probity of veterinary public health institutions affect prospects for disease control. Not only does integrity in these institutions firm up direct incentives to biosecure by each producer but these actions also spill over to re-enforce incentives among all growers. On the flip side, concerns have been raised in Leonard (2000), Le Brun (2004), Cheneau, El Idrissi, and Ward (2004), and elsewhere about how public and private sector provision of animal health services adapt to the trend of privatization and decentralization in developing countries. If public veterinary health infrastructure does not strengthen as a result, the private sector may be indifferent toward any program mooted by central authorities. Apathy may become, or remain, endemic.

A further lesson is that patient effort spent on seeking to elicit coordination throughout an animal production sector matters. There is an economic incentives foundation to the coordination missions of such institutions as the OIE, the U.S. AHA, and the many animal health activities that producer groups engage in. When the message is abroad that others are likely to move toward control, then sentiment can snowball toward a critical mass that, with luck, can clean out a chronically debilitating scourge.

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Appendix

Demonstration of equation (9): Given their posterior distribution, a belief the grower will need to form is the probability the program will succeed. Write this as $\Pr(\text{erad} \mid x)$ for a farm's x signal. Given this, the grower will compare expected profits when it acts with expected profit when it does not act. They are equal when $[V^s - W(q)]\Pr(\text{erad} \mid x) + [V^f - W(q)][1 - \Pr(\text{erad} \mid x)] =$ $[\rho V^s + (1-\rho)V^f]\Pr(\text{erad} \mid x) + V^f[1 - \Pr(\text{erad} \mid x)]$ or

(A1) $$\Pr(\text{erad} \mid x) = \frac{W(q)}{(1-\rho)J(r,\delta,z_1,z_2,q)}.$$

Clearly the effect of a farm's x on the eradication probability is key to understanding this condition. But $\Pr(\text{erad} \mid x) = \Pr(\theta \le \hat{\theta} \mid x)$ for some critical $\hat{\theta}$ that has yet to be determined. This is the realization of θ such that the signals resulting ensure the program's success is at a knife-edge, or $a = \theta$. We may use (7) to develop an expression for $\Pr(\text{erad} \mid x)$, namely,

(A2) $$\Pr(\theta \le \hat{\theta} \mid x) = \Phi\left[\left(\hat{\theta} - \frac{\alpha y(\nu) + \beta x}{\alpha + \beta}\right)\sqrt{\alpha + \beta}\right].$$

From (A1), it follows that growers are indifferent between the participation choices whenever

(A3) $$\Phi\left[\left(\hat{\theta} - \frac{\alpha y(\nu) + \beta x}{\alpha + \beta}\right)\sqrt{\alpha + \beta}\right] = \frac{W(q)}{(1-\rho)J(r,\delta,z_1,z_2,q)}.$$

How $\hat{\theta}$ is determined has yet to be established. The fraction of growers who participate is determined by the fraction receiving a signal that is sufficiently low. In particular, for a given realization of θ, the fraction should be lower than some value $\hat{x}$ that we must also determine. So the θ-conditioned fraction of participating farms, $a(\theta)$, is

(A4) $$a(\theta) = \Pr(x \le \hat{x} \mid \theta).$$

Since $x - \theta \equiv \eta \sim N(0, \beta^{-1})$, from (6), it follows that

(A5) $$\Pr(x \le \hat{x} \mid \theta) = \Phi\left[(\hat{x} - \theta)\sqrt{\beta}\right],$$

and threshold condition $a(\hat{\theta}) = \hat{\theta}$ is the same as

(A6) $$\Phi\left[(\hat{x} - \hat{\theta})\sqrt{\beta}\right] = \hat{\theta}.$$

Furthermore, from the definition of $\hat{x}$ as the critical signal value below which participation occurs, the participation indifference relation (A1) may be fixed as

(A7) $$\Phi\left[\left(\hat{\theta} - \frac{\alpha y(\nu) + \beta \hat{x}}{\alpha + \beta}\right)\sqrt{\alpha + \beta}\right] = \frac{W(q)}{(1-\rho)J(r,\delta,z_1,z_2,q)}.$$

Together, (A6) and (A7) provide a system from which to solve for the pair $(\hat{\theta}, \hat{x})$.

To solve, write

(A8) $$\begin{aligned} \hat{x} - \hat{\theta} &= \frac{1}{\sqrt{\beta}}\Phi^{-1}(\hat{\theta}); \\ \hat{x} - \hat{\theta} &= \left(\hat{\theta} - y(\nu)\right)\frac{\alpha}{\beta} - \frac{\sqrt{\alpha + \beta}}{\beta}\Phi^{-1}\left(\frac{W(q)}{(1-\rho)J(r,\delta,z_1,z_2,q)}\right). \end{aligned}$$

Equate both sides to obtain:

(A9) $$\hat{\theta} = \Phi\left(\frac{\alpha}{\sqrt{\beta}}\left[\hat{\theta} - y(\nu) - \frac{\sqrt{\alpha+\beta}}{\alpha}\Phi^{-1}\left(\frac{W(q)}{(1-\rho)J(r,\delta,z_1,z_2,q)}\right)\right]\right).$$

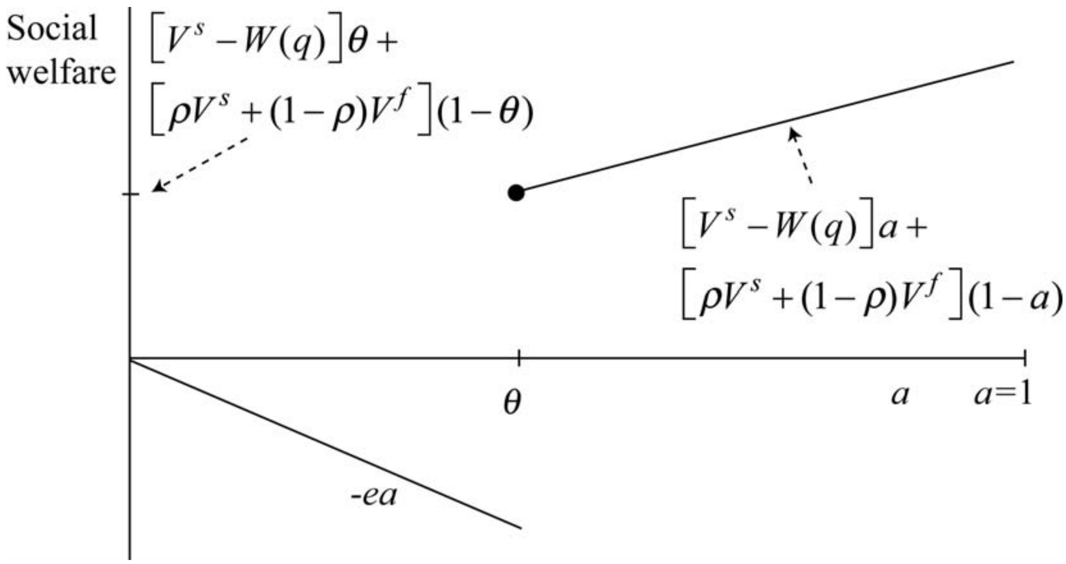

Figure 1. Social welfare as participation rate changes, with threshold θ certain