Behavioral Incentives, Equilibrium Endemic Disease, and Health Management Policy for Farmed Animals

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Abstract

We develop a dynamic capital valuation model in which each farm can take an action with farm-varying cost to increase the probability of not contracting a disease. In the presence of infection externalities, circumstances are identified under which multiple equilibria exist and where the one involving the most extensive set of action takers is socially optimal. It is suggested that costly capital markets are one factor in determining the extent of endemic disease in a region. The introduction of frictions, such as dealing with a cumbersome veterinary public health bureaucracy, can enhance social welfare by encouraging precautionary biosecurity actions. Some technical innovations can reduce social welfare. The model is also extended to study a voluntary herd depopulation scheme. Moral hazard in the biosecurity action will dampen the scheme's welfare effect.

Keywords: biosecurity, continuous time, multiple equilibria, Nash behavior, reinfection.

JEL classification: D20, H4, Q1

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Endemic infectious animal diseases generate a variety of significant adverse economic consequences. Most directly, mortality, morbidity, barrenness, and miscarriage in production animals reduce technical efficiency. Costly treatments and altered management practices to ameliorate these losses also reduce profitability. Opportunities for trade within and between regions may be curtailed. In addition, some infectious animal diseases, such as bovine tuberculosis, brucellosis, avian influenza, and possibly Johne's disease, have adverse consequences for human health (Smith 1958; Myers and Steele 1969; National Academies 2003, 2005).

For these and other reasons, most countries invest in veterinary public health infrastructure. At the transnational level the United Nations, through its Food and Agricultural Organization and the World Health Organization units, seeks to facilitate better management of infectious animal diseases. The OIE, funded by countries but outside the United Nations structure, has more emphatic objectives in this regard. Many control policies, such as animal quarantine, human movement controls, border inspections, vaccinations, and mandatory testing schemes, also involve economic losses. In some cases, control places impositions on environmental benefits (Horan and Wolf 2005).

A large applied modeling literature has emerged at the interface of preventative veterinary medicine and economics (Perry, McDermott, and Randolph 2001; Chi *et al.* 2002; Bennett 2003; Mintiens *et al.* 2003). Some of this literature regards understanding and costing control and eradication strategies upon the event of an epidemic outbreak (Mahul and Gohin 1999). Some regards understanding and costing such strategies for endemic disease. Bicknell, Wilen, and Howitt (1999) include private incentives in their model of bovine tuberculosis control. Surprisingly, however, with the exception of the latter article and a pair of papers to be discussed

below, scholarship appears to have been silent on characterizing the economic nature of the equilibrium extent of endemic disease.[1]

That there is an economic dimension to endemic animal disease becomes apparent upon perusing any introductory animal/poultry production book, such as those by Ensminger (1992) or Gillespie (2002). Costly management strategies such as selective purchasing of feeder animals, implementing labor-consuming hygiene regimes, and timely equipment replacement are advocated. Beyond this, infection is an externality of a very public variety. A cursory assessment might suggest that developments in applied game theory should hold promise for better understanding the extent of endemic animal disease, and how to manage it. The intent of this article is to build a model to this end.

Hennessy (2005) has considered private actions to guard against spatial spread of a disease already in a region to conclude that the way in which farm actions behave as local substitutes can lead to peculiar spatial patterns in taking protective actions. That paper also considered the risk of disease entry into a region. Then efforts by producers are more likely to complement, so that policies to promote inter-farm communication should be beneficial.

The work most closely related to the content of the present article is in Hennessy, Roosen, and Jensen (2005). In it, two models are developed to address the strategy of internally supplying feeder animals for fattening. One looks at the externalities created by trading to take private advantage of feeder animal production cost differentials. The other looks at the internal organization of production to protect against the risk of disease entry into a farm. Both models are non-temporal in structure, viewing static farm decisions in which no distinction is made between farm disease statuses. This is an important limitation because in reality farms differ in the extent of disease. Farms transition between disease-free and diseased conditions over time, and this status heterogeneity drives much of public disease management policy. As a result, the

[1] Perhaps more surprisingly, the body of work on the economics of infectious human diseases is also very limited. Three examples are Kremer (1996), and Geoffard and Philipson (1996, 1997).

models are very limited in what they can say about the nature of incentives to protect against disease and the consequences of such control practices as testing, movement controls, and herd depopulation.

In this paper we will develop a continuous-time dynamic model of farm-level capital values in which disease status is influenced by farm actions but is still stochastic. The approach is to use a stochastic model of transitions between two disease states in order to value firms in either state, and so to characterize incentives to change the state transition probabilities. Similar models have been used elsewhere in economics, where the best-known application is perhaps that of efficiency wage and involuntary unemployment by Shapiro and Stiglitz (1984).[2] We will lean quite heavily on parts of their model, although the interesting economics differ fundamentally. In our case the public goods externality of infectious disease is of interest whereas in their case it is the resource inefficiency effects of a moral hazard problem with no non-market externalities that is of interest.

The efficiency wage argument is that the incentive for an employee to apply productive effort that is incompletely monitored depends in part on the monitoring technology and in part on the reward differential. If the expected net present value of becoming unemployed as a result of shirking is not too low, the workers will logically shirk unless wages are raised. But then the labor market may not clear because the wage rate exceeds the marginal value product at full employment. While monitoring and involuntarily idle resources are of no concern to us, a parallel between our model and the efficiency wage model is the role of differential incentives in encouraging an action.[3]

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[2] Moretti and Perloff (2002) provide some empirical support for the efficiency wage theory in agricultural labor markets.

[3] This is not to suggest that public disease management policies would never involve attempts to monitor farm actions. We choose not to consider farm-level monitoring issues because attempts to monitor such actions are rare for infectious animal disease. This is in contrast with food safety actions at processing, distribution, and restaurant operations, and some farm-level production practices that might harm the environment (e.g., nitrogen application near streams). One class of exceptions is the dipping mandate. An example is the sheep scab (psoroptic mange) dipping

Our analysis points to the possibility of a multiplicity of equilibrium disease levels. It also suggests, in resonance with the efficiency wage model, that ostensibly wasteful public disease management programs could conceivably improve social welfare. This could occur by encouraging farmers to protect against becoming entangled in the bureaucracy of acquiring disease-free status. We show it is also possible that one class of disease management innovations could reduce social welfare. This class is comprised of innovations that increase the probability of transition from diseased status to disease-free status. The anomalous effect is due to a reduction in the loss expected from becoming diseased when externalities ensure that the level of protection against disease is socially inadequate. We also apply our model to better understanding the effects of a voluntary depopulation (buyout) scheme for infected herds. Interestingly, some farms may both act to guard against infection and take a herd buyout payment upon becoming infected. The extent of social benefit from a buyout scheme will be constrained by moral hazard. A brief discussion concludes.

Framework

There are N animal-husbanding farms in a region where N is a large number, and all farms face the same incentives. Farm decision-makers are risk-neutral and are possessed of identical technological opportunities, with the exception of the cost of taking a biosecurity action against a disease. Even if this cost is common, however, it is not necessarily true that farms are identical because we will show that some may be infected with an endemic disease while some are not. Infection is endogenous to our model, and we need to first develop the incentive structures facing farm decision-makers.

The model is in continuous time, and farms can be in one of the two states "disease-free" and "diseased" at any time. A disease-free farm earns profit flow R gross of any biosecurity action. A diseased farm earns profit flow $R-\delta$ gross of any biosecurity action, where $\delta \in [0,R]$. A

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mandate that was in place in the United Kingdom between 1972 and 1992.

farm's disease status is held to be readily ascertainable at no cost.[4] There are no human health externalities.[5] A biosecurity action designed to maintain disease-free status costs e to a farm where e has continuously differentiable mass distribution $F(e):[0,\overline{e}]\rightarrow[0,N]$ with point density $f(e)$; i.e., we treat farms as a continuum.[6]

If a disease-free farm takes the action then there is probability $b(\cdot)\in[0,1]$ per unit time that it becomes diseased.[7] The value of $b(\cdot)$ is written as an unspecified function because it depends on the extent of infection in the region. We will return to specify this relationship in due course. If the action is not taken then the probability per unit time of becoming diseased changes to $b(\cdot)+q(\cdot)\in[b(\cdot),1]$. The value of $q(\cdot)$ also depends on the extent of infection in the region. For the diseased farm, there is probability $a(\cdot)\in[0,1]$ per unit time that the farm becomes disease-free. The value of $a(\cdot)$, too, depends on the extent of infection in the region, and we will return to this relationship when we are ready to close the model. All of $a(\cdot)$, $b(\cdot)$, and $q(\cdot)$ are assumed to be continuous and differentiable in the usual sense.

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[4] Some degree of information asymmetry in disease status is likely, but we will show that excessive levels of endemic disease need have nothing to do with observable disease status.

[5] Slight re-specifications of our model would allow for introducing human health externalities imposed on consumers. One way of doing this is to divide δ into δ_{farm} and δ_{human}, $\delta=\delta_{farm}+\delta_{human}$, where the farm internalizes δ_{farm} but where intervention is required for the farm to internalize δ_{human}.

[6] The sorts of costs we have in mind include costs of labor and supplies for cleaning, as well as management time to acquire information about, educate, and monitor workers, feed suppliers, transport contractors, and others who move regularly between farms. Other costs are veterinary prophylactic expenditures, and capital expenditures on such projects as buildings (perhaps especially ventilation systems) and boundary maintenance.

[7] For readers familiar with continuous-time treatment of Poisson processes, one may think of $b(\cdot)$ as the rate parameter. See Taylor and Karlin (1984) or Hoel, Port, and Stone (1987) for extensive developments on this tool and other related tools.

Solution

The decision on taking an action is essentially one of discounted present valuation of farms under the different decisions, and farm businesses are held to be infinitely lived entities.[8] Four valuations are of concern. One is that of farm value when the farm is disease-free and the action is taken, Φ_a^{DF}. Another is that of farm value when the farm is disease-free and the action is not taken, Φ_{na}^{DF}. The third is that of farm value when the farm is diseased and the action would be taken were it not diseased, Φ_a^{D}. And the fourth is that of farm value when the farm is diseased and the action would not be taken were it not diseased, Φ_{na}^{D}.

With continuous-time discount rate $r > 0$, a disease-free farm taking the action has asset value that must satisfy[9]

(1) $$r\Phi_a^{DF} = R - e + b(\cdot)(\Phi_a^{D} - \Phi_a^{DF}).$$

The left-hand side, $r\Phi_a^{DF}$, is the time value of the asset. It must equal the sum of instantaneous income per unit of time conditional upon being disease-free, $R - e$, and the expected capital loss that would arise were the state to change, $b(\cdot)(\Phi_a^{D} - \Phi_a^{DF})$.

On the other hand, a disease-free farm not taking the action has asset value that must satisfy

(2) $$r\Phi_{na}^{DF} = R + [b(\cdot) + q(\cdot)](\Phi_{na}^{D} - \Phi_{na}^{DF}).$$

Again, each side has an income stream interpretation. On the right-hand side the income flow from the present state is larger than in (1), but the probability rate of capital loss is also larger. A diseased farm that would take the action has asset value that must satisfy

(3) $$r\Phi_a^{D} = R - \delta + a(\cdot)(\Phi_a^{DF} - \Phi_a^{D}),$$

while a diseased farm that would not take the action has asset value that must satisfy

(4) $$r\Phi_{na}^{D} = R - \delta + a(\cdot)(\Phi_{na}^{DF} - \Phi_{na}^{D}).$$

[8] If sold, then a diseased farm would presumably fetch less than a disease-free farm.
[9] See page 436 in Shapiro and Stiglitz (1984). The adaptation to our context is straightforward.

Clearly there is a cut-off point, labeled $\hat{e}$ and as yet to be determined, such that (I) $\max[\Phi_a^{DF}, \Phi_{na}^{DF}] = \Phi_a^{DF}$ on $e \le \hat{e}$, and (II) $\max[\Phi_a^{DF}, \Phi_{na}^{DF}] = \Phi_{na}^{DF}$ on $e > \hat{e}$.[10]

Case I: Assume first that $e \le \hat{e}$ so that (1) and (3) are to be solved as a system, with solution

$$(5a) \quad \Phi_a^D = \frac{R}{r} - \frac{\delta[r + b(\cdot)]}{r[r + a(\cdot) + b(\cdot)]} - \frac{ea(\cdot)}{r[r + a(\cdot) + b(\cdot)]};$$

$$(5b) \quad \Phi_a^{DF} = \frac{R}{r} - \frac{\delta b(\cdot)}{r[r + a(\cdot) + b(\cdot)]} - \frac{e[r + a(\cdot)]}{r[r + a(\cdot) + b(\cdot)]}.$$

These equations might be best explained by taking the difference;

$$(6) \quad \Delta_a = \Phi_a^{DF} - \Phi_a^D = \frac{\delta - e}{r + a(\cdot) + b(\cdot)}.$$

The change in farm value arising from contracting the disease may be viewed as bond debt requiring payment of the cash-flow difference $\delta - e$ at discount rate $r + a(\cdot) + b(\cdot)$. It is certainly true that $\delta \ge e$ on $e \le \hat{e}$ because δ is at risk in the non-diseased state and e is incurred in that state with the hope of protecting against the loss of δ. If $b(\cdot)$ becomes larger then the change in farm value in (6) will become smaller. This is because the likelihood of shortly becoming diseased increases. Similarly, if $a(\cdot)$ becomes larger then the change in farm value will also become smaller. This is because the state of being diseased has become less consequential since the likelihood of soon revisiting the disease-free state has become larger.

Case II: Assume instead that $e > \hat{e}$ so that (2) and (4) are a system, with solution

$$(7a) \quad \Phi_{na}^D = \frac{R}{r} - \frac{\delta[r + b(\cdot) + q(\cdot)]}{r[r + a(\cdot) + b(\cdot) + q(\cdot)]};$$

$$(7b) \quad \Phi_{na}^{DF} = \frac{R}{r} - \frac{\delta[b(\cdot) + q(\cdot)]}{r[r + a(\cdot) + b(\cdot) + q(\cdot)]}.$$

In this case the difference is

$$(8) \quad \Delta_{na} = \Phi_{na}^{DF} - \Phi_{na}^D = \frac{\delta}{r + a(\cdot) + b(\cdot) + q(\cdot)} \ge 0,$$

[10] We have allocated $e = \hat{e}$ to the action. Throughout we maintain the convention that an agent

where two distinctions emerge relative to (6). Effort is not subtracted in the numerator because these firms do not take the biosecuring effort. The result is that a further discounting factor, $q(\cdot)$, is introduced in the denominator.

Comparing (5*b*) with (7*b*), the action is taken under the disease-free state if $\Phi_a^{DF} \geq \Phi_{na}^{DF}$ or

$$(9) \qquad J = \frac{\delta q(\cdot)}{r + c(\cdot) + q(\cdot)} \equiv \hat{e} \geq e; \qquad c(\cdot) = a(\cdot) + b(\cdot).$$

Calculate the difference between (6) and (8):

$$(10) \qquad \Delta_a - \Delta_{na} = \left[\Phi_a^{DF} - \Phi_a^{D}\right] - \left[\Phi_{na}^{DF} - \Phi_{na}^{D}\right] = \frac{\hat{e} - e}{r + c(\cdot)}.$$

Thus, the capitalized benefit to the farm upon having the good fortune of becoming disease-free is larger for those who act than for those who do not act on the cost set where farms do act, i.e., where $e \leq \hat{e}$. This also, not coincidently, characterizes the set of farms that do act.[11]

From (9), the measure of farms that would seek to biosecure were they disease-free is

$$(11) \qquad F(\hat{e}) \equiv F\left(\frac{\delta q(\cdot)}{r + c(\cdot) + q(\cdot)}\right).$$

Intuition would suggest that $b(\cdot)$ and $b(\cdot) + q(\cdot)$ should both be decreasing in the extent of adoption, as measured by the value of $F(\hat{e})$ or the value of $\hat{e}$. The probabilistic rate of farm infection for a given farm should decrease with the fraction of farms that biosecure, and this should be true whether (i.e., with $b(\cdot)$ probability rate) or not (i.e., with $b(\cdot) + q(\cdot)$ probability rate) the farm in question biosecures. As for $a(\cdot)$ it should be at worst invariant to, and perhaps increase with, the fraction of farms that biosecure. This is because there are then fewer opportunities to become infected, so that the effect of the extent of adoption on the value of $c(\cdot)$ is ambiguous.

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acts when indifferent.

[11] View the choice problem in the disease-free state as $\max[\Phi_a^{DF}, \Phi_{na}^{DF}]$, thus motivating the presence of these two arguments in (10). The other two arguments arise because of the linearity

As a reduced form we declare $a(\cdot)$, $b(\cdot)$, and $q(\cdot)$ to be functions of $\hat{e}$, where a more proper specification would be to write them as functions of the adopting set $[0,\hat{e}]$ under farm distribution $F(e)$.[12] It is important to make some comments at this point in order to avoid later confusion. It is most appropriate to think of functions $a(\cdot)$, $b(\cdot)$, and $q(\cdot)$ as functions of the set of disease-free herds. Set $[0,\hat{e}]$ may not always be an appropriate indicator in this regard. Policy interventions that target high-cost herds may render $\hat{e}$ to be an inappropriate reduced-form gauge of the extent of disease. But we defer on notation to accommodate this complication until the complication presents a modeling problem. From (9) we may write equilibrium as a solution to[13]

$$(12) \qquad J(\hat{e}) = \frac{\delta q(\hat{e})}{r + c(\hat{e}) + q(\hat{e})} \equiv \hat{e}.$$

For the continuum of farms this condition, which is the centerpiece of the paper, characterizes Nash equilibria.[14] If $e < \hat{e}$ then a farm with that e has no unilateral incentive to deviate from acting. If $e > \hat{e}$ then a farm with that e has no unilateral incentive to deviate from not acting.[15]

To establish the nature of equilibrium, differentiate $J(e) = \delta q(e)/[r + c(e) + q(e)]$ to obtain

$$(13) \qquad J_e(e) = \delta \frac{[r + c(e)]q_e(e) - q(e)c_e(e)}{[r + c(e) + q(e)]^2}.$$

If $c_e(e) \geq 0$ and $q_e(e) \geq 0$ then (13) implies there is a unique solution to (12) since $J_e(e) \leq 0$ $< d\hat{e}/d\hat{e} \equiv 1$. Suppose though that $c_e(e) < 0$, as would be the case when $a_e(e) = 0$. Then we

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of (5*a*) and (7*a*) in e.

[12] We could just as well write it as a function of the non-adopting set, $(\hat{e},\bar{e}]$.

[13] When (12) is written as $q(\hat{e})/[r + c(\hat{e}) + q(\hat{e})] \equiv \hat{e}/\delta$, it can be seen that both ratios are unit-less. Values $\hat{e}$ and δ are both $ per unit time quantities. Expressions r, $c(\hat{e})$, and $q(\hat{e})$ all have (expected) percent change per unit time interpretations.

[14] As we will use (12) extensively, it should be clear that an elementary understanding of fixed-point theory would be useful when working with our model. For an economic overview, we refer the reader to Milgrom and Roberts (1994) or Mas-Colell, Whinston, and Green (1995).

[15] Function $J(\hat{e})$ is continuous in $\hat{e}$. The domain of e, $[0,\bar{e}]$, is a non-empty, compact, convex set. From Brouwer's fixed-point theorem (p. 952 in Mas-Colell, Whinston, and Green 1995), the additional property that $J(\hat{e}):[0,\bar{e}] \rightarrow [0,\bar{e}]$ is *into* ensures the existence of a pure-strategy Nash

cannot rule out the possibility of multiple equilibria as depicted in figure 1. In it, there are three fixed-point solutions to (12). One, the middle one, is unstable to local perturbations. This is because $J(e) < e$ implies $\Phi_a^{DF} < \Phi_{na}^{DF}$ and such farms will not act. On the other side of this equilibrium, $J(e) > e$ implies $\Phi_a^{DF} > \Phi_{na}^{DF}$ so that these farms will act. In general, $J_e(e) < 1$ ensures the existence of at most one equilibrium.

Social Optimum

Note that the long-run stationary probabilities of a farm's disease states are[16]

$$\begin{aligned} &\text{Prob}[\text{diseased} \mid e \le \hat{e}] = m(\cdot), \qquad m(\cdot) = \frac{b(\cdot)}{a(\cdot) + b(\cdot)}; \\ &\text{Prob}[\text{diseased} \mid e > \hat{e}] = u(\cdot), \qquad u(\cdot) = \frac{b(\cdot) + q(\cdot)}{a(\cdot) + b(\cdot) + q(\cdot)}. \end{aligned} \tag{14}$$

Observe that $\text{Prob}[\text{diseased} \mid e \le \hat{e}] < \text{Prob}[\text{diseased} \mid e > \hat{e}]$, i.e., the action reduces the probability of disease. Using (14), (5*a*), (5*b*), (7*a*), and (7*b*), cancellations allow us to write the social optimization problem as

$$\mathcal{L} = \frac{R}{r} - \frac{1}{r}\min_{e^*} \quad \left(\delta m(e^*)\int_{e \le e^*} dF(e) + [1 - m(e^*)]\int_{e \le e^*} e dF(e) + \delta u(e^*)\int_{e > e^*} dF(e)\right). \tag{15}$$

Two aspects of expression (15) warrant comment. One is that the interior minimization problem makes no reference to r so that the social optimum in stationary equilibrium is independent of r. This is despite the relevance of r in (12). In stationary equilibrium, farms transition between diseased and disease-free states but the discounted present value consequences of this are a wash in the aggregate. This is because the flows of farms from and to a particular disease state just balance.

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equilibrium.

[16] See page 256 in Taylor and Karlin (1984) or page 94 in Hoel, Port, and Stone (1987) for extensive developments on stationary probabilities for Poisson-type models. The $\text{Prob}[A \mid B]$ notation indicates the probability of state A given condition B.

The other aspect is that the minimization problem may be broken into three sorts of losses. One is $\delta m(e^*)\int_{e\le e^*} dF(e)$, where $\int_{e\le e^*} dF(e)$ is the measure of farms taking the action and $m(e^*)$ is the equilibrium fraction of the time an action-taking farm is diseased. One is $[1-m(e^*)]\int_{e\le e^*} edF(e)$, where $\int_{e\le e^*} edF(e)$ is the cumulation of action costs over action-taking farms while $1-m(e^*)$ is the equilibrium fraction of the time an action-taking farm is disease-free and incurring the action cost flow. There is also $\delta u(e^*)\int_{e>e^*} dF(e)$, where $\int_{e>e^*} dF(e)$ is the measure of farms not taking the action when disease-free and $u(e^*)$ is the equilibrium fraction of the time that such farms are diseased.

When Action-Taking Farms are Disease-Free

To better understand the optimization problem, assume that $b(\cdot)\equiv 0$ so that a farm taking the action is certainly disease-free, $m(\cdot)\equiv 0$. The social welfare optimization problem in (15) reduces to

$$(16)\qquad \mathcal{L}=\frac{R}{r}-\frac{1}{r}\min_{e^*}\ \left[\int_{e\le e^*} edF(e)+\delta u(e^*)|_{b=0}\int_{e>e^*} dF(e)\right];\qquad u(e^*)|_{b=0}=\frac{q(e^*)}{a(e^*)+q(e^*)};$$

and the optimality derivative is

$$(17)\qquad e^* f(e^*)-\delta u(e^*)|_{b=0}\ f(e^*)+\delta u_e(e^*)|_{b=0}\int_{e>e^*} dF(e)=0.$$

Write this as

$$(18)\qquad \delta\frac{\int_{e>e^*} dF(e)}{f(e^*)}=\frac{\delta u(e^*)|_{b=0}-e^*}{u_e(e^*)|_{b=0}}.$$

The right-hand side of (18) is increasing if $u(e)|_{b=0}$ is decreasing and convex.[17] These are reasonable assumptions because $u(e^*)$ is the long-run equilibrium probability of becoming diseased if not an action-taker; see (14). Appealing to the plausibility of diminishing marginal returns, an increase in the extent of private effort should decrease that probability and at a decreasing rate. The left-hand side of (18) is decreasing if $f(e^*)/\int_{e>e^*} dF(e)$ is increasing, i.e., if the hazard rate is increasing. This is the standard assumption of monotone hazard rate, as applied in the mechanism design literature (see p. 267 in Fudenberg and Tirole 1991).

In addition, from (12), if the left- and right-hand expressions in (18) are evaluated at some $\hat{e}$ solving (12) then we have $\delta u(\hat{e}) - \hat{e} > 0$ and $[\delta u(\hat{e}) - \hat{e}]/u_e(\hat{e}) < 0$.[18] Since the left-hand side of (18) is positive, the value of this $\hat{e}$ (arbitrarily chosen when (12) has multiple fixed points) must be too small relative to e^*. To restore equilibrium for optimal social choice condition (18), $\hat{e} \to e^* > \hat{e}$ so that the left-hand side decreases in value and the right-hand side increases in value. Therefore, under the assumptions that $b(\cdot) \equiv 0$, $u(e)$ is decreasing and convex and $\mathrm{Ln}\left[\int_{s>e} dF(s)\right]$ is concave in e, then those taking the action should do so and more should also do so, i.e., $[0,\hat{e}] \subset [0,e^*]$.

Policy Issues

In this section we discuss some policy implications of the model, as developed to this juncture.

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[17] Differentiate to obtain $\delta - 1/[u_e(e^*)|_{b=0}] - [\delta u(e^*)|_{b=0} - e^*]u_{ee}(e^*)|_{b=0}/[u_e(e^*)|_{b=0}]^2$. This expression is positive if $u_e(e^*)|_{b=0} < 0$, $u_{ee}(e^*)|_{b=0} > 0$, and $\delta u(e^*)|_{b=0} < e^*$. But the left-hand side of (18) is positive under an interior equilibrium while $u_e(e^*)|_{b=0} < 0$ has been assumed. Therefore, $\delta u(e^*)|_{b=0} < e^*$.

[18] From (12), if $b = 0$ then $\hat{e} = \delta q(\hat{e})/[r + a(\hat{e}) + q(\hat{e})] < \delta q(\hat{e})/[a(\hat{e}) + q(\hat{e})] = \delta u(\hat{e})|_{b=0}$ so that $\delta u(\hat{e})|_{b=0} - \hat{e} > 0$.

Point 1: *If there are multiple equilibria, then the highest $\hat{e}$ value is preferred.*

In light of (18) the likelihood is that too few farms take the action. In light of (12) and figure 1, the highest among these equilibria will support the largest level of social welfare.[19] The question then becomes how to sustain the highest equilibrium. This leads to our next point.

Point 2: *Relative loss determines the incentive to take the action.*

Equation (12) shows that an increase in the value of δ shifts equilibrium values of $\hat{e}$ upward; see figure 2. While this may seem intuitive to the point of being obvious, the policy implications may not be at all intuitive. We will comment on some of these policy implications now and defer others until we develop the model further.

Bureaucratic costs imposed on farm businesses that become diseased may be a form of increasing δ beyond market penalties. While bureaucracy imposes a burden on taxpayers and also incurs grower transactions costs, the result may be a lower level of endemic disease and the social gains may more than offset the social losses. It is important to bear in mind that the bureaucracy cost need bring with it no disease fighting benefit. Its actions may in no way assist in the technical problems associated with eliminating the disease from a farm, and still it can serve a positive function. Regulatory restrictions that have little direct merit may also have similar effect. For example, a diseased farm may be denied the right to sell produce into a premium market (e.g., liquid milk) even though the disease has no impact on the quality of that product.

The point we are making comes close to, but is not the same as, the efficiency wage argument. There, the problem is one of moral hazard in the face of imperfect monitoring where there are no non-market spillovers beyond the principal and agent in an employment relationship.

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[19] Continuity, together with $J(e):[0,\bar{e}]\rightarrow[0,\bar{e}]$ into, ensures that the largest equilibrium (call it e_H) involves $J(e_H-\varepsilon)>e_H-\varepsilon$ for the smallest $\varepsilon>0$, $e_H-\varepsilon\in[0,\bar{e}]$, such that $J(e_H-\varepsilon)\neq e_H-\varepsilon$ and $J(e_H+\varepsilon)<e_H+\varepsilon$ for the smallest $\varepsilon>0$, $e_H+\varepsilon\in[0,\bar{e}]$, such that $J(e_H+\varepsilon)\neq e_H+\varepsilon$. Unless $J_e(e)|_{e=e_H}=1$, e_H is stable.

Here, the problem is that non-action creates an external effect in increasing the pool of infectious disease.

Point 3: *If* $\delta = 0$ *then no farm takes the action.*

Solution $\hat{e} = 0$ is then the unique Nash equilibrium solution to (12). In this case, first-best is supported because the disease causes no deterioration in production. However, consider the different context where disease causes no deterioration in production but the produce is a health risk.[20] Then $\hat{e} = 0$, first-best would not be supported, and market or non-market intervention might improve market performance. Public awareness campaigns might increase demand for verified private labeling on the disease status of the originating herd. As with campaigns to control bovine tuberculosis and brucellosis, though, produce condemnation may be deemed the more effective approach (Smith 1958).

Point 4: *A high discount rate reduces the action threshold.*

Equation (12) shows that an increase in the value of r shifts equilibrium values of $\hat{e}$ downward. In countries with inefficient capital markets or low stocks of capital available for investment, one would expect higher levels of endemic disease. This is because the present value of the private gain from attaining disease-free status is discounted heavily. The reason is distinct from that of high endemic disease levels because of capital constraints at the public level, often referred to as a reason for disease problems in less developed countries (Leonard 2000).

Point 5: *Some technical innovations can reduce social welfare.*

Suppose that $b(\cdot) \equiv b(e, \theta)$ where $b_\theta(e, \theta) < 0$. Parameter θ represents a technical innovation that reduces the probability of contracting a disease. In (12), the left-hand side of the relation increases with an increase in θ so that $d\hat{e}/d\theta \geq 0$. As there is likely insufficient action taking, the innovation should increase social welfare. To see this, evaluate (15) not at the optimum but rather under equilibrium market choice $\hat{e}$ so that social welfare may be written as

[20] See footnote 5.

$$\text{(19)}\qquad \begin{aligned} \mathcal{L}(\hat{e},\theta) &= \frac{R}{r} - \frac{1}{r}\left(m(\hat{e},\theta)\int_{e\le\hat{e}} (\delta - e)dF(e) + \int_{e\le\hat{e}} edF(e) + \delta u(\hat{e},\theta)\int_{e>\hat{e}} dF(e)\right); \\ m(e,\theta) &= \frac{b(e,\theta)}{a(e)+b(e,\theta)}; \qquad u(e,\theta) = \frac{b(e,\theta)+q(e)}{a(e)+b(e,\theta)+q(e)}. \end{aligned}$$

We then have

$$\text{(20)}\qquad \frac{d\mathcal{L}(\hat{e},\theta)}{d\theta} = -\frac{1}{r}\frac{\partial m(\hat{e},\theta)}{\partial\theta}\int_{e\le\hat{e}} (\delta - e)dF(e) - \frac{\delta}{r}\frac{\partial u(\hat{e},\theta)}{\partial\theta}\int_{e>\hat{e}} dF(e) + \frac{\partial\mathcal{L}(\hat{e},\theta)}{\partial\hat{e}}\frac{\partial\hat{e}}{\partial\theta}.$$

The first two right-hand terms are certainly positive. We have argued that an increase in $\hat{e}$ likely increases the value of $\mathcal{L}(\hat{e},\theta)$, while (12) suggests that $\partial\hat{e}/\partial\theta \ge 0$. It seems reasonable to conclude, then, that $d\mathcal{L}(\hat{e},\theta)/d\theta \ge 0$ in this case.

Now consider instead the case where the innovation affects $a(\cdot)$ only; that $a(\cdot) \equiv a(e,\theta)$ with $a_\theta(e,\theta) > 0$ so that the innovation increases the probability of returning a diseased herd to the disease-free state. Upon assuming for the sake of simplicity that $b(\cdot) \equiv 0$, social welfare may be written as

$$\text{(21)}\qquad \mathcal{L}(\hat{e},\theta) = \frac{R}{r} - \frac{1}{r}\int_{e\le\hat{e}} edF(e) - \frac{\delta}{r}u(\hat{e},\theta)\int_{e>\hat{e}} dF(e); \qquad u(\hat{e},\theta) = \frac{q(\hat{e})}{a(\hat{e},\theta)+q(\hat{e})}.$$

The total derivative is

$$\text{(22)}\qquad \frac{d\mathcal{L}(\hat{e},\theta)}{d\theta} = -\frac{\delta}{r}\frac{\partial u(\hat{e},\theta)}{\partial\theta}\int_{e>\hat{e}} dF(e) + \frac{\partial\mathcal{L}(\hat{e},\theta)}{\partial\hat{e}}\frac{\partial\hat{e}}{\partial\theta}.$$

The first right-hand term is positive, while we also know that $\partial\mathcal{L}(\hat{e},\theta)/\partial\hat{e} \ge 0$ under the conditions $u(e)$ decreasing and convex, and $\text{Ln}\left[\int_{s>e} dF(s)\right]$ concave in e. From (12) we have that $\partial\hat{e}/\partial\theta \le 0$ so the sign of the total derivative is ambiguous. The technical innovation may, through reducing the cost of becoming diseased, discourage action taking to such an extent that the positive direct effect of the innovation is overwhelmed.

Voluntary Depopulation Scheme

Consider now the situation in which the only regulatory intervention is that the government buys out a herd when the owner comes forth truthfully, out of self-interest, to report owning a diseased herd. The herd is culled with compensation such that farm value becomes K, and it is assumed that this certainly clears disease from the farm. The farm is then put back into production.

Two private decisions are now to be made on each herd, but they are never made at the same time. In the disease-free state the decision on taking the biosecurity action has to be made. In the diseased state, and more precisely immediately upon contracting the disease, the decision on reporting to the government has to be made. Table 1 delineates the four cases that emerge. We will consider each of the four cases in turn, and we will then identify the values in (e,K) space such that a farm makes this pair of decisions.

Case A: (a,nc), *or act when disease-free and do not report for culling when diseased.* We have already solved for this case in (5) above. Using subscript notation, per table 1, to characterize the two actions now available the solution is

$$(23) \qquad \Phi^{D}_{a,nc} = \frac{R}{r} - \frac{\delta[r+b(\cdot)]}{r[r+a(\cdot)+b(\cdot)]} - \frac{ea(\cdot)}{r[r+a(\cdot)+b(\cdot)]}; \qquad \Phi^{DF}_{a,nc} = \Phi^{D}_{a,nc} + \frac{\delta - e}{r+a(\cdot)+b(\cdot)}.$$

Case B: (na,nc), *or do not act when disease-free and do not report for culling when diseased.* We have also already solved for this case in (7) above. The solution is

$$(24) \qquad \Phi^{D}_{na,nc} = \frac{R}{r} - \frac{\delta[r+b(\cdot)+q(\cdot)]}{r[r+a(\cdot)+b(\cdot)+q(\cdot)]}; \qquad \Phi^{DF}_{na,nc} = \Phi^{D}_{na,nc} + \frac{\delta}{r+a(\cdot)+b(\cdot)+q(\cdot)}.$$

Case C: (na,c), *or do not act when disease-free and do report for culling when diseased.* We have not solved for this problem and must return to first principles. Instead of (2) and (4), recognize that farm value upon succumbing to the disease is K so that the fundamental equations become $r\Phi^{DF}_{na,c} = R + [b(\cdot)+q(\cdot)](\Phi^{D}_{na,c} - \Phi^{DF}_{na,c})$ and $\Phi^{D}_{na,c} = K$. The system solves as

$$(25) \qquad \Phi^{D}_{na,c} = K; \qquad \Phi^{DF}_{na,c} = \Phi^{D}_{na,c} + \frac{R - rK}{r+b(\cdot)+q(\cdot)}.$$

Case D: (a,c), *or act when disease-free and do report for culling when diseased.* We have not solved for this problem either. Instead of (1) and (3), acknowledging that farm value upon succumbing to the disease is K requires $r\Phi^{DF}_{a,c} = R - e + b(\cdot)(\Phi^{D}_{a,c} - \Phi^{DF}_{a,c})$ and $\Phi^{D}_{a,c} = K$. The system solves as

$$(26) \qquad \Phi^{D}_{a,c} = K; \qquad \Phi^{DF}_{a,c} = \Phi^{D}_{a,c} + \frac{R - e - rK}{r + b(\cdot)}.$$

When Case A Is Chosen

The two criteria that must be satisfied in order for this to this occur are $\Phi^{D}_{a,nc} > \Phi^{D}_{a,c}$ and $\Phi^{DF}_{a,nc} \geq \Phi^{DF}_{na,nc}$. Upon using (23), (24), and (26), this reduces to

$$(27) \qquad \frac{(R - rK)[r + a(\cdot) + b(\cdot)] - \delta[r + b(\cdot)]}{a(\cdot)} \equiv \hat{e}(K) > e; \qquad \hat{e} \geq e.$$

Both e and K need to be relatively low in order for this case to apply. Further pertinent comments on each of the cases are provided in appendix A.

When Case B Is Chosen

The two criteria that must be satisfied in order for this to occur are $\Phi^{D}_{na,nc} > \Phi^{D}_{na,c}$ and $\Phi^{DF}_{na,nc} > \Phi^{DF}_{a,nc}$. This reduces to

$$(28) \qquad \frac{R}{r} - \frac{\delta[r + b(\cdot) + q(\cdot)]}{r[r + a(\cdot) + b(\cdot) + q(\cdot)]} \equiv \Phi^{D}_{na,nc} > K; \qquad \hat{e} < e.$$

For this case to apply, e needs to be relatively high and K needs to be relatively low.

When Case C Is Chosen

The criteria that must be satisfied in order that this occur are $\Phi^{D}_{na,c} \geq \Phi^{D}_{na,nc}$ and $\Phi^{DF}_{na,c} > \Phi^{DF}_{a,c}$, or

(29) $K \geq \Phi^{D}_{na,nc}; \qquad e > e^{+}(K) \equiv \dfrac{(R - rK)q(\cdot)}{r + b(\cdot) + q(\cdot)}.$

In this case, e and K should be comparatively large.

When Case D Is Chosen

The criteria that must be satisfied are $\Phi^{D}_{a,c} \geq \Phi^{D}_{a,nc}$ and $\Phi^{DF}_{a,c} \geq \Phi^{DF}_{na,c}$. These resolve to

(30) $\hat{e}(K) \leq e \leq e^{+}(K).$

This case occurs when K is sufficiently high to make culling attractive, and e is low enough to elicit action but not so low that capital value under a "no cull" decision rises beyond K.

Figure 3 depicts the parameter values for which each of the four possible cases arise. Supporting analysis is provided in appendix A. We turn now to the effect of the buyout program on the extent of disease. This depends very much on whether $K \geq \Phi^{D}_{na,nc}$. If $K < \Phi^{D}_{na,nc}$, then no culling occurs so that (Case A) $F(\hat{e})$ herds are diseased $100m(\cdot)$ percent of the time while (Case B) $N - F(\hat{e})$ herds are diseased $100u(\cdot)$ percent of the time. If $K \geq \Phi^{D}_{na,nc}$, then culling occurs immediately upon contraction of disease when Cases C or D apply. This means that (Case A) $F(\hat{e})$ herds are diseased $100m(\cdot)$ percent of the time, (Case D) $F(e^{+}) - F(\hat{e})$ herds are diseased zero percent of the time, and (Case C) $N - F(e^{+})$ herds are diseased zero percent of the time. Noticing, from figure 3, that $\min[\hat{e}, \bar{e}] = \hat{e}$ on $K < \Phi^{D}_{na,nc}$ and $\min[\hat{e}, \bar{e}] = \bar{e}$ on $K \geq \Phi^{D}_{na,nc}$, write $\tilde{e} \equiv \min[\hat{e}, \bar{e}]$ so that the set of *diseased farms* is described by the implicitly defined function

(31) $w(\tilde{e}, K) = \begin{cases} F(\tilde{e})m[w(\tilde{e}, K)] + [N - F(\tilde{e})]u[w(\tilde{e}, K)], & K < \Phi^{D}_{na,nc}; \\ F(\tilde{e})m[w(\tilde{e}, K)], & K \geq \Phi^{D}_{na,nc}. \end{cases}$

Rather than (12), the set of acting farms should now satisfy[21,22]

[21] We refer the reader back to the discussion just before equation (12). This is where the

$$(32) \qquad J(\tilde{e},K)=\frac{\delta q[w(\tilde{e},K)]}{r+c[w(\tilde{e},K)]+q[w(\tilde{e},K)]}\equiv\tilde{e}.$$

The solution to fixed-point problem (31)-(32) is not at all trivial since $\tilde{e}$ enters $w(\tilde{e},K)$ in involved ways and (31) is an implicit function. But note the following concerning (31) and (32). Write

$$(33) \qquad \mathrm{T}=\begin{cases} F(\tilde{e})m[w(\tilde{e},K)]+[N-F(\tilde{e})]u[w(\tilde{e},K)]-w(\tilde{e},K), & K<\Phi^{D}_{na,nc}; \\ F(\tilde{e})m[w(\tilde{e},K)]-w(\tilde{e},K), & K\geq\Phi^{D}_{na,nc}. \end{cases}$$

With $m_w[w]\geq 0$ and $u_w[w]\geq 0$, assume that $1>F(\tilde{e})m_w[w(\tilde{e},K)]+[N-F(\tilde{e})]u_w[w(\tilde{e},K)]$ so that T is decreasing in w.[23] This is true when $K<\Phi^{D}_{na,nc}$ and even more strongly so when $K\geq\Phi^{D}_{na,nc}$. Figure 4 describes the context. The thick arrow shows that the measure of diseased farms contracts inwards as the value of K increases. Thus, $m_w[w]\geq 0$, $u_w[w]\geq 0$, and $1>F(\tilde{e})m_w[\cdot]+[N-F(\tilde{e})]u_w[\cdot]$ ensure that

$$(34) \qquad \frac{\partial w(\cdot)}{\partial K}\leq 0,$$

where partial differential operator ∂ recognizes that $\tilde{e}$ also depends on K.

Furthermore,

$$(35) \qquad \frac{d}{dw}\left(\frac{\delta q(w)}{r+c(w)+q(w)}\right)=\delta\frac{[r+c(w)]q_w(w)-q(w)c_w(w)}{[r+c(w)+q(w)]^2}.$$

With $q_w(w)>0$ (since the probability rate increment due to not biosecuring should increase with the stock of diseased farms), if $c_w(w)\leq 0$ then (34) implies that the effect of an increase in the

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complication in the reduced-form presentation of fixed-point relation (12) occurs.

[22] To be clear, the argument $\hat{e}$ in the functions $q(\cdot)$ and $c(\cdot)$ of (12) represented the fraction of farms that biosecure when disease-free. In (32), the argument w in functions $q[\cdot]$ and $c[\cdot]$ captures the fraction of farms that are diseased. Thus, the functions are not quite the same across equations but the probability relationship captured is the same.

[23] That $m_w[w]\geq 0$ and $u_w[w]\geq 0$ is because the probability a farm is diseased should increase with the region-wide extent of disease.

value of K is to induce a discrete downward shift to the left-hand side of the defining identity in (32) when K surpasses value $\Phi^{D}_{na,nc}$. Figure 5 illustrates.

Now suppose that $K \geq \Phi^{D}_{na,nc}$ so that $w(\tilde{e},K) = F(\tilde{e})m[w(\tilde{e},K)]$ and

$$(36) \qquad \frac{\partial w(\tilde{e},K)}{\partial \tilde{e}} = \frac{f(\tilde{e})m[w]}{1 - F(\tilde{e})m_{w}[w]} > 0,$$

since we have already assumed that $1 > F(\tilde{e})m_{w}[w(\tilde{e},K)]$. The economics of the positive relationship between the extent of biosecuring and the extent of disease is that biosecuring and culling tend to be substitutes in reducing the extent of disease. From $K \geq \Phi^{D}_{na,nc}$, we are in the branch of (31) such that farms with biosecurity cost above $\tilde{e}$ cull immediately upon contracting the disease and so are only diseased for an instance.[24]

Finally, from (34), (36) and $\partial \tilde{e}/\partial K = \partial \min[\hat{e},\bar{e}]/\partial K \leq 0$ in figure 3, we have[25]

$$(37) \qquad \frac{dw(\tilde{e},K)}{dK} = \overbrace{\frac{\partial w(\tilde{e},K)}{\partial K}}^{-sign} + \overbrace{\frac{\partial w(\tilde{e},K)}{\partial \tilde{e}}}^{+sign}\overbrace{\frac{\partial \tilde{e}}{\partial K}}^{-sign} \leq 0.$$

Thus, the extent of disease does increase with an increase in K even though the increase in K elicits less biosecuring behavior. Indirect effect $[\partial w(\tilde{e},K)/\partial \tilde{e}][\partial \tilde{e}/\partial K]$ could be considered to be a moral hazard effect because the herd buyout program provides insurance against contracting the disease.[26] Thus, by draining the stock of endemic disease the voluntary depopulation scheme could well reduce the incentive to take the protective action. There may be some crowding out so that the scheme is not likely to be as effective as a straightforward ex ante calculation might suggest.

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[24] On the other branch of (31), $u[\cdot] \geq m[\cdot]$. Differentiation of $w(\tilde{e},K) = F(\tilde{e})m[\cdot] + [N - F(\tilde{e})]u[\cdot]$, and use of $1 > F(\tilde{e})m_{w}[\cdot] + [N - F(\tilde{e})]u_{w}[\cdot]$ reverses the sign of (36).

[25] While the derivative is not defined where $\hat{e} = \bar{e}$, the limits from both sides are non-positive.

[26] Whether the reduction in the equilibrium level of disease justifies the losses due to culled stock is beyond the scope of the present analysis, as it would involve extending the model to

Action to Become Disease-Free

In this section we ask whether changing the action from one of securing against a disease to one of increasing the likelihood of becoming disease-free changes the nature of the results. Suppose that the only action concerns the effort to become disease-free and it may be taken only when the farm is diseased. Its effect is to increase $a(\cdot)$ to $a(\cdot)+q(\cdot)$, whereas before, non-action increased $b(\cdot)$ to $b(\cdot)+q(\cdot)$. As before, four values are of concern. These are farm value when the farm is (*i*) diseased where the action is taken, Φ_a^D; (*ii*) diseased where the action is not taken, Φ_{na}^D; (*iii*) disease-free where the action is taken, Φ_a^{DF}; and (*iv*) disease-free where the action is not taken, Φ_{na}^{DF}. In all other regards, the model is the same as that which supports (12) above. The solution is outlined in appendix B. The analysis supports the biosecurity action criterion

$$(38) \qquad e \le \hat{\hat{e}} = \frac{\delta q(\cdot)}{r + a(\cdot) + b(\cdot)};$$

with properties almost identical to those of (12).

Conclusion

This paper has developed a model of endemic animal disease that emphasizes economic incentives. The model is quite versatile in that it can be used to study diseases in which only livestock productivity is affected and diseases in which only the health of consumers is affected. The model emphasizes the role of punishment in strengthening the incentive to protect against disease. This role may induce welfare reduction upon the event of an exogenous technical innovation that makes regaining disease-free status easier. The model also points to a place for well-functioning capital markets in reducing the extent of endemic disease. In order to demonstrate the model's potential for policy analysis, the policy of voluntary reporting for herd buyout was developed in some detail.

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accommodate salvage value.

The analysis might be expanded upon in at least three directions. First, a stationary equilibrium has been assumed. A better understanding of adjustment paths would be helpful when seeking to better understand responses to external (e.g., weather) and policy-induced shocks. Methods in Kimball (1994) could be useful in this regard. The second regards the accuracy of tests for a disease. For that issue, our model would have to be adapted to accommodate false positive and false negative readings when disease status cannot be established from profitability. A speculation is that a test improvement that better identifies herd recovery may reduce the incentive to biosecure and so may reduce social welfare.

The third issue is to introduce scale-related heterogeneities into the model. The relationship between size and endemic disease warrants scrutiny because backyard production has been suggested as a key propagating factor in disease outbreaks (Olsen *et al.* 2005; Tiensin *et al.* 2005). In addition, agricultural policies that pass the World Trade Organization test of being decoupled may encourage smaller growers to stay in business and so may reduce the rate of consolidation in animal production (Chau and De Gorter 2005). Biosecurity costs are unlikely to be scale-neutral. Some, such as acquiring specialized knowledge of diseases, are likely to carry a high fixed cost component. On the other hand, larger production units are more vulnerable to heavy losses upon disease entry. Absent strong comparative advantage in the form of labor or feed costs, production is unlikely to be concentrated in regions with severe endemic disease problems. If a traditional production region with initially fragmented production also has weak incentives to protect against disease, the region may be stuck in an inefficient equilibrium. Farms in the region may not adopt technical innovations that involve an increase in scale because of the disease environment.

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Appendix A

When Case A is chosen: A point to note is that $\partial\bar{e}(K)/\partial K = -r[r + a(\cdot) + b(\cdot)]/a(\cdot) \leq 0$, i.e., that one bound on the maximum e value declines with an increase in the level of buyout compensation. Note also that $\bar{e}(K) = 0$ if

$$\text{(A1)} \quad \hat{K}_0 \equiv \frac{R}{r} - \frac{\delta[r + b(\cdot)]}{r[r + a(\cdot) + b(\cdot)]} > 0,$$

while $\bar{e}(K = 0) = R + (R - \delta)[r + b(\cdot)]/a(\cdot)$. In particular,

$$\text{(A2)} \quad \bar{e}(K = 0) - \hat{e} > 0.$$

This means that the two bounds specified in (27) intersect on the space $(K, e) \in [0, \bar{e}] \times [0, \infty)$ for $\bar{e} > \hat{e}(K = 0)$.

When Case B is chosen: From (A1) and $q(\cdot) > 0$, we have that $\hat{K}_0 > \Phi^D_{na,nc}$ so the set of K values supporting Case A extends beyond the set of K values supporting Case B.

When Case C is chosen: Note, $d\bar{e}(K)/dK < de^+(K)/dK < 0$. Also,

$$\text{(A3)} \quad e^+(K = 0) - \hat{e} > 0; \qquad \bar{e}(K = 0) - e^+(K = 0) > 0;$$

so that $\bar{e}(K = 0) > e^+(K = 0) > \hat{e}$. Finally, use (27) and (29) to show that $\bar{e}(K) = e^+(K)$ when

$$\text{(A4)} \quad K = \frac{R}{r} - \frac{\delta[r + b(\cdot) + q(\cdot)]}{r[r + a(\cdot) + b(\cdot) + q(\cdot)]} = \Phi^D_{na,nc}; \qquad \bar{e}(K) = e^+(K) = \hat{e} = \frac{\delta q(\cdot)}{r + a(\cdot) + b(\cdot) + q(\cdot)}.$$

When Case D is chosen: Is (30) this ever satisfied? If it is, then

$$\text{(A5)} \quad \frac{(R - rK)[r + a(\cdot) + b(\cdot)] - \delta[r + b(\cdot)]}{a(\cdot)} \leq e \leq \frac{(R - rK)q(\cdot)}{r + b(\cdot) + q(\cdot)},$$

so that

$$\text{(A6)} \quad \frac{R - rK}{r + b(\cdot) + q(\cdot)} \leq \frac{\delta}{r + a(\cdot) + b(\cdot) + q(\cdot)}.$$

This will be true whenever $K \geq \Phi^D_{na,nc}$.

Appendix B

The asset value equations are

(B1) $r\Phi_a^D = R - \delta - e + [a(\cdot) + q(\cdot)](\Phi^{DF} - \Phi_a^D)$, diseased farm taking action;

(B2) $r\Phi_{na}^D = R - \delta + a(\cdot)(\Phi^{DF} - \Phi_{na}^D)$, diseased farm not taking action;

(B3) $r\Phi_a^{DF} = R + b(\cdot)(\Phi_a^D - \Phi^{DF})$, disease-free farm taking action;

(B4) $r\Phi_{na}^{DF} = R + b(\cdot)(\Phi_{na}^D - \Phi^{DF})$, disease-free farm not taking action.

Again, there are two cases.

Case I: Assume first that $e \le \hat{e}$ so that (B1) and (B3) apply. Solve to obtain

(B5*a*) $\Phi_a^D = \frac{R}{r} - \frac{[r + b(\cdot)][\delta + e]}{r[r + a(\cdot) + b(\cdot) + q(\cdot)]}$;

(B5*b*) $\Phi_a^{DF} = \frac{R}{r} - \frac{b(\cdot)[\delta + e]}{r[r + a(\cdot) + b(\cdot) + q(\cdot)]}$.

Case II: Assume next that $e > \hat{e}$ so that (B2) and (B4) apply. Solve to obtain

(B6*a*) $\Phi_{na}^{DF} = \frac{R}{r} - \frac{b(\cdot)\delta}{r[r + a(\cdot) + b(\cdot)]}$;

(B6*b*) $\Phi_{na}^D = \frac{R}{r} - \frac{[r + b(\cdot)]\delta}{r[r + a(\cdot) + b(\cdot)]}$.

We then have $\Phi_a^D = \Phi_{na}^D$ when

(B7) $\hat{\hat{e}} = \frac{\delta q(\cdot)}{r + a(\cdot) + b(\cdot)}$

Upon comparing with (12) from before we have that $\hat{\hat{e}} > \hat{e}$ if and only if $q(\cdot) > 0$, which is true. All else equal, more firms will adopt a technology that increases the instantaneous probability rate of becoming disease-free than will adopt a technology that increases the instantaneous probability rate of staying disease-free. All other effects are as before.

Table 1. Decision Environment for Each Farm under Voluntary Depopulation Scheme

		Diseased state	
		Do not cull	Cull
Disease-free state	Act	(a, nc), Case A	(a, c), Case D
	Do not act	(na, nc), Case B	(na, c), Case C

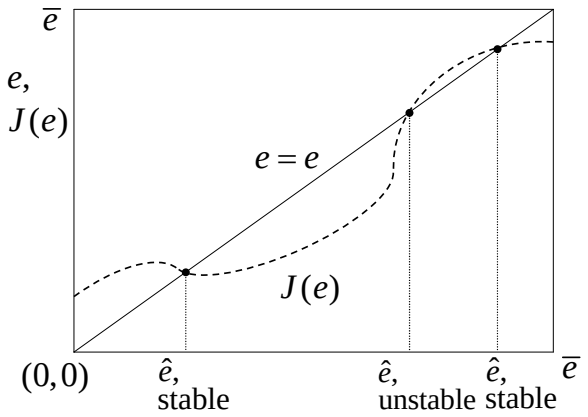

Figure 1. Stable and unstable equilibria for farm sets taking precaution against contracting endemic disease

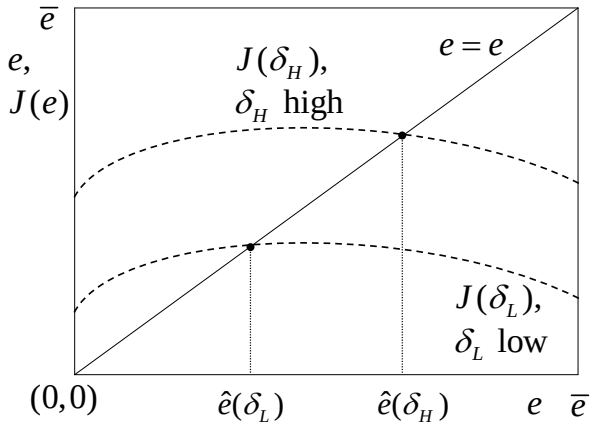

Figure 2. Effect of δ on incentive to act

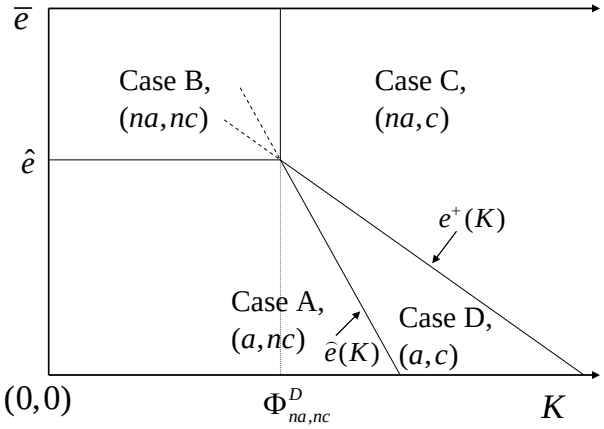

Figure 3. Buyout value and biosecurity costs supporting the four different cases

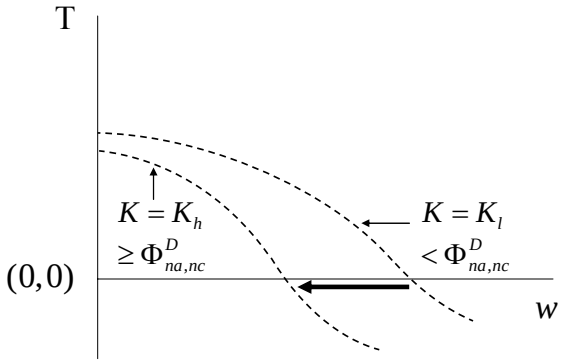

Figure 4. Fixed point for w, the measure of diseased farms, as buyout payment changes

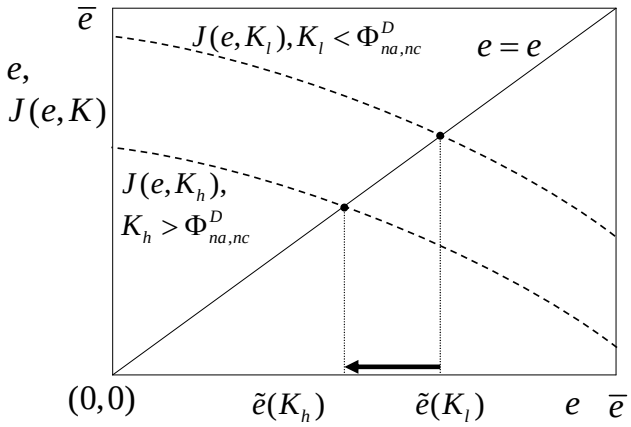

Figure 5. Voluntary depopulation scheme and acting farms