BIOSECURITY EXTERNALITIES AND INDEMNITIES FOR INFECTIOUS ANIMAL DISEASES

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Abstract

In animal agriculture, biosecurity decisions are dispersed across many herd owners. Choices impacting disease spread will be determined by impacts on private economic values, and so are economic externalities. However, externalities are not all alike. By way of three very distinct examples, we demonstrate how they differ and what these differences mean for approaches to policies seeking to manage them. The three examples are an endemic disease pool that can be managed by limiting sources and flows, an exotic disease that can be managed by way of communicated coordination, and an infrastructural support externality that can be managed by disease outbreak insurance. We pay particular attention to how concentration in animal herd ownership affects incentives for disease control.

JEL Classifications: D2, H4, Q1

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Introduction

By definition, an infectious disease is a disease that can spread from one biological entity to another. In profit-motivated agriculture, many biosecurity decisions of relevance to a region are dispersed across many animal herd owners and will be determined by impacts on private economic values. The biosecurity choices are economic externalities, in that the decisionmaker does not face the full consequence of choices made. However, externalities can differ greatly in form and implication. By way of three very distinct examples, we demonstrate how they differ and what these differences mean for approaches to policies intended to manage them.

The first example is that of an endemic disease pool that can be managed by limiting infection sources and flows. In this context, we show why private disease control efforts substitute for one another, thus reducing the incentive for each herd owner to manage the disease. The extent of the problem is likely worse when animal ownership is dispersed among many farms. The second example regards preventing entry of an exotic disease. We show that in this case, and up to a point, herd owners are well incentivized to make private disease control efforts. However, a concentrated herd ownership structure likely exacerbates the problem because smaller herd owners (e.g., backyard) have less incentive to use control efforts, and may be the weakest link. We argue that fostering communication among herd owners would likely reduce the extent of the public disease problem. The third example turns attention to an infrastructural support externality. Here when one farm, likely the least profitable, drops out, then the fixed costs of supporting sector-related infrastructure falls on fewer farms and so profitability among remaining firms declines. We show that disease outbreak insurance helps when managing this form of externality. However, in light of the role that government may play in deciding control measures, we also argue that it would be difficult to sustain a private sector animal disease outbreak insurance market.

Endemic Disease Pool Context

Model

Our concern here is with an infectious disease that a farm may contract in light of its presence in the ambient environment. Our reduced-form model of farm-level infection is as follows: There are $n \in \{1, 2, \ldots, N\} \equiv \Omega_N$ growers. At any point in time, the *n*th firm contributes time invariant flow $x_n > 0$ to the stock of infection on the *n*th farm. This flow can be controlled, and our intent is to characterize incentives to control this flow. Farm input at level z_n directly reduces x_n so that net infection flow to the *n*th farm becomes $x_n - z_n$, but we assume that incentives are such that $z_n \not\geq x_n$. The stock of infection on the *n*th farm at time *t* is given as $q_n(t)$, which is the share of the *n*th farm's herd that is infected. Some of this can escape into the external environment, henceforth referred to as the "pool." The rate of escape is $\alpha q_n(t)$ with $\alpha > 0$ (i.e., in proportion to stock $q_n(t)$). Of course, escape does not involve depleting the stock of infection on the farm. The on-farm stock of infection decays at rate $\eta q_n(t)$ with $\eta > 0$.

Infection also spreads the other way, from the pool to individual farms. The pool's stock of infection is $P(t)$ and the flow from the pool to each farm is given by $\beta P(t)$, $\beta > 0$. Finally, the pool's stock of infection changes at rate $x_p - z_p - \lambda P(t)$, $\lambda > 0$, where z_p is the extent of public effort to reduce direct infection flow into the public pool. As Figure 1 depicts, the flow equations are[1]

$$\begin{aligned} \frac{dq_n(t)}{dt} &= x_n - z_n - \eta q_n(t) + \beta P(t), \quad n \in \Omega_N; \\ \frac{dP(t)}{dt} &= \alpha \sum\nolimits_{n\in\Omega_N} q_n(t) + x_p - z_p - \lambda P(t). \end{aligned} \tag{1.1}$$

Now in equilibrium we have

[1] Of course the linear form of the flow dynamics for $q_n(t)$ does not guarantee that $q_n(t) \in [0,1]$, so our model is to be viewed as an approximation.

$$
\begin{aligned}
&0 = x_n - z_n - \eta q_n(t) + \beta P(t), \quad n \in \Omega_N; \\
&0 = \alpha \sum\nolimits_{n\in\Omega_N} q_n(t) + x_p - z_p - \lambda P(t);
\end{aligned}
\tag{1.2}
$$

where we write the time-invariant solutions as $(\hat{q}_1, \hat{q}_2, \ldots, \hat{q}_N, \hat{P})$. Label $\hat{Q} = \sum\nolimits_{n\in\Omega_N} \hat{q}_n$, $X = \sum\nolimits_{n\in\Omega_N} x_n$ and $Z = \sum\nolimits_{n\in\Omega_N} z_n$, so that the first N equations in (1.2) can be aggregated to $\eta\hat{Q} = X - Z + \beta N\hat{P}$. The second equation in (1.2) yields $\lambda\hat{P} = \alpha\hat{Q} + x_p - z_p$. Solving these two equations obtains

$$
\hat{P} = \frac{\alpha(X-Z) + \eta(x_p - z_p)}{\lambda\eta - \alpha\beta N}; \qquad \hat{Q} = \frac{\lambda(X-Z) + \beta N(x_p - z_p)}{\lambda\eta - \alpha\beta N};
\tag{1.3}
$$

where $\lambda\eta > \alpha\beta N$ is assumed to ensure interior solutions. That is, disease decay rates need to be sufficiently large relative to disease spread rates or disease incidence will explode, and management activities would not be of the form we are presently considering.

To identify the steady-state level of ambient infection, from (1.2) we have $q_n(t) = [x_n - z_n + \beta P(t)]/\eta$, and so

$$
\begin{aligned}
&\hat{q}_n = \zeta_1(x_n - z_n) + \zeta_2(X_{\backslash n} - Z_{\backslash n}) + \zeta_3(x_p - z_p); \qquad X_{\backslash n} = X - x_n; \qquad Z_{\backslash n} = Z - z_n; \\
&\zeta_1 = \frac{\lambda\eta - \alpha\beta(N-1)}{\lambda\eta^2 - \alpha\beta\eta N}; \qquad \zeta_2 = \frac{\alpha\beta}{\lambda\eta^2 - \alpha\beta\eta N}; \qquad \zeta_3 = \frac{\beta}{\lambda\eta - \alpha\beta N}.
\end{aligned}
\tag{1.4}
$$

Equation (1.4) provides the equilibrium stock of infection on a given farm. One can check with reference to Figure 1 for intuitive responses to the model parameters.

The key points that I'd like to draw your attention to are these: Efforts targeted at reducing some x_n (and so q_n) and efforts targeted at reducing some x_k (and so q_k), $k \neq n$, are substitutes. By this we mean that $\partial\hat{q}_n / \partial z_k < 0$ and $\partial\hat{q}_k / \partial z_n < 0$. Also, $\zeta_1 - \zeta_2 = 1/\eta > 0$ so that the own-farm effect of targeting infection exceeds benefits derived from other farms targeting infection (i.e., the substitution is not perfect). Finally this pooled infection problem is essentially one of managing an impure public good (Cornes and Sandler 1986) where benefits from own provision of the good exceed benefits to others.

On-farm Choices

We turn now to on-farm damage. Each herd owner seeks to protect a livestock herd of potential value V_n against infection by an endemic disease. Here V_n represents net profit in a disease-free state and absent biosecurity costs. The cost of action z_n is given as $C(z_n)$ with marginal cost $C'(\cdot) > 0$ and second derivative $C''(\cdot) > 0$. Loss is given as share $\hat{q}_n$ so that production is given as $(1-\hat{q}_n)V_n$. The Nash-behavior grower solves

$$\max_{z_n} \quad [1-\zeta_1(x_n - z_n) - \zeta_2(X_{\backslash n} - Z_{\backslash n}) - \zeta_3(x_p - z_p)]V_n - C(z_n).,\tag{1.6}$$

with private optimality condition

$$\zeta_1 V_n - C'(z_n) = 0,\tag{1.7}$$

and Nash equilibrium choice (labeled superscripted ne) level

$$z_m^{\text{ne}} = H(\zeta_1 V_m); \qquad H(\cdot) \equiv C'^{-1}(z_m).\tag{1.8}$$

Setting $N\bar{V} = \sum_{m\in\Omega_N} V_m$, the sum of surpluses is

$$W = [1-\zeta_3(x_p - z_p)]N\bar{V} - \sum_{m\in\Omega_N}\left[\zeta_1 V_m(x_m - z_m) + \zeta_2 V_m(X_{\backslash m} - Z_{\backslash m}) + C(z_m)\right].\tag{1.9}$$

Insert (1.8) into objective function (1.9) to obtain total surplus under private actions as:

$$\begin{aligned} W^{\text{ne}} = {} & [1-\zeta_3(x_p - z_p) + (Z^{\text{ne}} - X)\zeta_2]N\bar{V} - \frac{1}{\eta}\sum_{m\in\Omega_N} V_m\left[x_m - H(\zeta_1 V_m)\right] \\ & - \sum_{m\in\Omega_N} C[H(\zeta_1 V_m)]. \end{aligned}\tag{1.10}$$

We now seek to measure concentration so that we can study its effects on private biosecurity incentives. The following approach to comparing concentration is from Marshall, Olkin, and Arnold (2009, p. 14).

Definition 1: Vector $S^{*} \equiv (s_1^{*}, s_2^{*}, \ldots, s_N^{*}) \in \mathbb{R}^N$ is *majorized* by $S^{**} \equiv (s_1^{**}, s_2^{**}, \ldots, s_N^{**}) \in \mathbb{R}^N$ (written as $S^{*} \prec S^{**}$) if $\sum_{i=1}^{k} s_{(i)}^{*} \geq \sum_{i=1}^{k} s_{(i)}^{**}$ $\forall k \in \Omega_N$ and $\sum_{i=1}^{N} s_{(i)}^{*} = \sum_{i=1}^{N} s_{(i)}^{**}$, where the $s_{(i)}$ are defined as order statistics, $s_{(1)} \leq s_{(2)} \leq \ldots \leq s_{(N)}$.

Equivalently, if one transfers some of a small s_i value to a large s_i value so that the former is smaller and the latter larger, then the result is a vector that majorizes the initial vector. As an example, consider $S^{*} \equiv (3,5,4)$ and $S^{**} \equiv (5,2,5)$. Now $3 \geq 2$, $3+4 \geq 2+5$ and $3+4+5 = 2+5+5$, so that $S^{*} \prec S^{**}$. Of the two, S^{**} is the more concentrated because one can transfer one unit from a "5" to the unit with "2," to bring a "5" to "4" and the "2" to "3," making the vector's coordinates more uniform. If we think of the coordinates as herd sizes, then the approach allows for a comparison of different herd ownership concentrations. Proof of the following is available in the appendix.

Proposition 1: Suppose that the flow of infection is constant across farms, or $x_m \equiv \bar{x}$ $\forall m \in \Omega_N$. Then in Nash equilibrium more dispersion in potential value in the majorization sense *i*) decreases equilibrium extent of disease, $\hat{Q}^{\text{ne}}$, whenever marginal cost is convex, or $C'''(\cdot) > 0$, and *ii*) increases welfare, W^{ne}.

Convex marginal cost, needed for item *i*) but not *ii*), seems reasonable as costs associated with biosecurity likely increase dramatically with a small increase in observed effectiveness. Consider the simple case of erecting a perimeter wall. If wall base scales with height then materials cost is in proportion to the square of height. But construction cost should increase dramatically with height as more elaborate scaffolding needs to be put in place to build at more elevated levels. On the other hand, it is hard to see why effectiveness against airborne biological invasion should increase dramatically with wall height. Point *i*) shows that animal stock concentration promotes the internalization of externalities if marginal costs become more convex as input use increases. Point *ii*) shows that not only does disease loss decline with increasing concentration of animals but costs are covered too, so that welfare increases.

The first-best problem involves recognizing total value when making the biosecurity decision. In other words, solving

$$\max_{(z_1,\dots,z_N)} \quad \sum_{m\in\Omega_N}[1-\zeta_1(x_m-z_m)-\zeta_2(X_{\backslash m}-Z_{\backslash m})-\zeta_3(x_p-z_p)]V_m-\sum_{m\in\Omega_N}C(z_m). \qquad (1.11)$$

The social optimality conditions are

$$\frac{V_n}{\eta}+\zeta_2 N\bar{V}-C'(z_n)=0, \quad \forall n\in\Omega_N, \qquad (1.12)$$

and the socially optimum value is

$$z_n^{\text{so}}=H\left(\eta^{-1}V_n+\zeta_2 N\bar{V}\right). \qquad (1.13)$$

Notice that $z_n^{\text{so}}-z_n^{\text{ne}}=H(\eta^{-1}V_n+\zeta_2 N\bar{V})-H(\zeta_1 V_n)>0$ because $H(\cdot)$ is an increasing function and $\zeta_2 N\bar{V}>0$. Therefore, the socially optimum level of biosecurity exceeds the Nash equilibrium level and, furthermore, the difference depends on the value of ζ_2 = $\alpha\beta/(\lambda\eta^2-\alpha\beta\eta N)$. Thus the magnitude of the gap increases with how infectious the disease is, as reflected by the values of spread parameters α and β .

Proposition 2: Nash equilibrium biosecurity efforts are less than socially optimal, and the magnitude of the difference depends on the magnitude of spread parameters.

Suppose that veterinary authorities can act to reduce spread, perhaps through managing hygiene in transportation and at sales barns, by publically administered disease control schemes, or through education and outreach. They would have a two-fold effect on disease control because, in addition to directly reducing the extent of the infection pool, such actions would help strengthen the private payoffs that herd owners would receive for taking biosecurity actions.

Weakest Link in Disease Entry Context

We turn now to consideration of a disease not presently in a region, but where there is a risk of entry. For the sake of clarity, we present a polar extreme of how disease enters and spreads in a region. Probability of entry is greatest at the weakest link, which we take to be the farm that is least motivated to take biosecurity precautions. Thereafter the disease spreads instantly to all other farms in the region but there is some probability that each farm can stop entry at its border. This is a generalization of the well-known von Liebig and Sprengel law of the minimum technology, but where each link is managed independently. Independent management would suggest that private biosecurity costs will enter the decision calculus but benefits beyond the herd-owner's own farm are ignored.

To illustrate numerically, suppose that Farms A and B are in an otherwise isolated region. Farms A and B both avoid a $100 loss if the disease stays out. If either Farm A or B lets the disease in it will certainly spread to the other farm for sure. It costs the herd owner $20 to make some effort to be certain that the disease doesn't enter. If either farm doesn't make the effort then the disease enters that farm directly with probability 0.25. If Farm A knows that Farm B makes the effort then Farm A compares expected loss of 100*0.25 =25 with cost of 20 and also makes the effort. If Farm A knows that Farm B doesn't make the effort then Farm A expects baseline revenue of 100*(1-0.25) = 75 and then compares the expected loss of 75*0.25 = 18.75 with cost of 20. It is not rational for Farm B to take the action either. Thus, both farms can conclude that it is rational to biosecure or both farms can conclude that it is rational not to biosecure. A task of those seeking to coordinate disease management activities across the region is to help both farms coordinate on biosecuring.

A version of the context has been studied in Hennessy (2008). The natural response is to take no more biosecurity precautions than any other grower in the region. But the herd owner that will likely take the least biosecurity action will be the one with least to protect (i.e., the smallest herd owner). Thus, smaller herd owners will determine the overall risk of disease entry. But, in the spirit of Definition 1, if we transfer some animals from the larger herds to smaller herds then smaller herds are better incentivized to prevent entry. As they constitute the weakest link, a less concentrated herd structure may lead to a reduction in the likelihood of disease entry.

The weakest link setting raises other issues. If small farms are the concern then targeting these may be an effective approach to reducing the overall risk of disease entry. This targeting could be through subsidies or other carrots, or through efforts to close these farms down. In addition, communication in itself may improve biosecurity levels across the sector. In Nash equilibrium, each herd owner assumes that everyone decides independently and takes the actions of others as given. However, herd owner actions complement, or reinforce, in protecting against a common external threat. If herd owners are of the view that others don't take much care then they may agree not to take much care either. Similarly if herd owners are of the view that others do care then, in any herd owner's mind, it becomes increasingly likely that his/her action will be important in deterring entry. Coaxing herd owners to protect and providing credible communication that others are protecting may gird herd owners to take biosecurity more seriously. Such communication could come in many forms.

A noteworthy feature of many industry sectors in much of the world is the well-developed civic structure surrounding the sector. Adam Smith (1976, p. 152) took a dim view of industry associations, writing

> "People of the same trade seldom meet together, even for merriment and diversion, but the conversation ends in a conspiracy against the public, or in some contrivance to raise prices. It is impossible indeed to prevent such meetings, by any law which either could be executed, or would be consistent with liberty or justice. But though the law cannot hinder people of the same trade from sometimes assembling together, it ought to do nothing to facilitate such assemblies; much less to render them necessary."

However, on this the single-mindedness of Smith’s gaze may have been the product of a less technologically developed time. Business interests are not always in conflict with consumer interests. Efforts to pool information and coordinate on addressing technical problems that impede an industry can add to the welfare of all concerned. Such industry efforts are very evident in animal disease management programs around the world (see for example, OECD 2012). Communication can also be fostered through organizational structures that facilitate knowledge and technology transfer, as can be the case with the cooperative and contracting business formats that are common in animal agriculture.

Business Continuity, Insurance and Regulation Moral Hazard

Taiwan was the world’s third largest pork exporter during the mid-1990s, exporting about 30% of its production to the Japanese market. In 1997 a Foot and Mouth Disease outbreak occurred on the island, closing its export markets. Through to 2013, the country has suffered sporadic disease recurrances and has never regained lost market shares (Felt, Gervais, and Larue 2011). The sector’s production structure has changed dramatically, in large part because sector players have lost confidence that any investments will be adequately rewarded.

Although Taiwan’s pork industry troubles are more complex, here we turn to how business continuity risk can undermine a sector’s vitality. In particular we focus on a role for insurance to secure business continuity were a disease to occur. There are *N* farms and each produces output of value V_n. If a disease occurs then all farms are afflicted and value declines to $V_n - \delta$. The farms equally share the cost of an input with fixed costs *F*. These costs can be of many forms. Animal breeding and feed used to be provided on-farm, but are generally purchased in modern production systems. In addition, animal agriculture increasingly relies on private sector management and information services that supply benchmark data, analytical tools and other inputs while environmental consultants seeking to better manage a herd’s environmental footprint are also purchased. In many cases there is a large fixed cost component to the supply of these inputs.

The hazard rate for the disease is given as the constant value b while that for recovery is given as the constant value a. It is readily shown that, with continuous time discount rate r, the capital values for diseased and disease-free states are

$$\Phi^{DF} = \frac{V_n - F/N}{r} - \frac{\delta b}{r(r+a+b)}; \qquad \Phi^{D} = \frac{V_n - F/N}{r} - \frac{\delta(r+b)}{r(r+a+b)}. \tag{3.1}$$

See Hennessy (2007) for details.

Now firms with negative capital value in the diseased state exit. These are the firms with

$$V_n < \frac{\delta(r+b)}{r+a+b} + \frac{F}{N} \equiv \Psi^{\cancel{\text{Ins}}}(N). \tag{3.2}$$

If one such firm exits then the floor below which another firm exits increases to $\Psi(N-1)$, as shown in Figure 2. The unbroken curve represents $\Psi^{\cancel{\text{Ins}}}(N)$ and is declining in N toward asymptotic value $\delta(r+b)/(r+a+b)$. The less steeply sloped line represents output values in descending order. The curves intersect at value $N^{\cancel{\text{Ins}}}$ so that firms with output values of $V^{\cancel{\text{Ins}}}$ or higher will participate. The larger the participation rate is beyond $N^{\cancel{\text{Ins}}}$ the more profitable high-value farms will be. If fewer than $N^{\cancel{\text{Ins}}}$ farms participate then none of the other farms will either.

An alternative is for firms to support an actuarially fair insurance program in which amount ρ is put aside in each year and amount υ is returned in the diseased state. Then fair premium, set up in a disease-free environment satisfies $\rho = b\upsilon/(r+a+b)$ so that (3.1) becomes

$$\Phi^{DF,\text{Ins}} = \frac{V_n - \rho - F/N}{r} - \frac{(\delta-\upsilon)b}{r(r+a+b)}; \qquad \Phi^{D,\text{Ins}} = \frac{V_n - \rho - F/N}{r} - \frac{(\delta-\upsilon)(r+b)}{r(r+a+b)}. \tag{3.3}$$

In this case, firms with negative capital value in the diseased state are those for which

$$V_n < \frac{(\delta-\upsilon)(r+b)}{(r+a+b)} + \rho + \frac{F}{N} \equiv \Psi^{\text{Ins}}(N). \tag{3.4}$$

Now,

$$\Psi^{\text{Ins}}(N) - \Psi^{\cancel{\text{Ins}}}(N) = \frac{(\delta - \upsilon)(r+b)}{r+a+b} + \rho + \frac{F}{N} - \frac{\delta(r+b)}{r+a+b} - \frac{F}{N} = \rho - \frac{\upsilon(r+b)}{r+a+b} < 0. \qquad (3.5)$$

Insurance causes the floor to decline and so more firms remain in the business. Figure 2 also depicts $\Psi^{\text{Ins}}(N)$, as the intermittently broken curve below that for $\Psi^{\cancel{\text{Ins}}}(N)$. This curve intersects the output value curve at value N^{Ins}, the new lower-threshold participation rate below which the regional production system collapses. In this way, insurance is a means to secure support for input and output networks so that the supply system does not collapse before recovery.

But consider now the actual environment in which a private sector insurance market for highly contagious animal diseases would exist. Almost inevitably, government representatives will decide emergency plans to manage the disease. Government costs can take many forms, including those to the exchequer and political support costs. If no market insurance is available then a government may have to provide indemnities for political reasons, and perhaps also as a matter of promoting efficiency by seeking to avoid the sector's collapse. These costs may affect other management decisions, such as how many animals to condemn for immediate slaughter. If market insurance was taken out widely by herd owners then the government might decide to increase the likelihood of ultimately stamping out the disease (rather than face Taiwan's problem of repeated recurrence) by condemning more animals for slaughter as the government does not cover the cost of indemnification. This is an instance of regulatory moral hazard where, again, behavior adjusts to incomplete internalization of the consequences of the behavior.

No government could commit to refraining from more costly approaches to disease management or be bound by some independent review of policy choices, even were such a review possible given time constraints. The possibility that disease management choices would change to the detriment of the insurer could affect the extent of insurance coverage offered and rates charged. Regulatory moral hazard might in itself undermine the market's viability.

Conclusion

By their very nature, infectious diseases that can be managed by changing behavior involve externalities. This paper has characterized some of these externalities, and has sought to point toward implications for disease management. There are two central points to be drawn. One is that, to be effective, coordinated centralized disease management strategies must recognize the implications of decentralized production. Many biosecurity actions and pertinent information lays with organizations that are neither controlled by the center nor possessed with incentives that are wholly consistent with the system as a whole. A more concentrated production system MAY be easier to work with as far as disease management is concerned, but that supposition is not to be taken for granted.

The other point is that context matters. Although broad stylization of disease problems is inevitable if meaningful general lessons are to be extracted, a one-size-fits-all characterization does not exist. We have pointed to instances where public and private goals can be quite strongly aligned, as perhaps with the task of keeping a pest out of a region, and also to instances where they can diverge, as with free-riding to better control the extent of an endemic disease.

If one generality does exist it is that patiently communicating and listening likely helps over an extended duration when educating and reminding herd owners of how they can contribute to a sector's general well-being. An economist's view on why is that it may help transform herd owners' views on how far-thinking other herd owners are, and that transformation can be mutually reinforcing. Public animal health authorities already know this, although likely with their own take on the matter where trust may be what is emphasized. But it bears repetition as it may get little hearing when a sector is in crisis.

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APPENDIX

Proof of Proposition 1: Equilibrium extent of disease is given as

$$\hat{Q} = \frac{\lambda X - \lambda \sum_{n \in \Omega_N} H(\zeta_1 V_n) + \beta N(x_p - z_p)}{\lambda \eta - \alpha \beta N}, \tag{A.1}$$

so the issue resolves to what happens $\sum_{n \in \Omega_N} H(\zeta_1 V_n)$. It is readily shown that $\partial z_n^{\text{ne}} / \partial V_n = \zeta_1 / C''(\cdot) > 0$ and $\partial^2 z_n^{\text{ne}} / \partial V_n^2 = -\zeta_1^2 C'''(\cdot) / [C''(\cdot)]^3 > 0$ under convex marginal cost. Thus $H(\zeta_1 V_n)$ is convex. This is relevant because an increase in the majorization sense increases the sum of convex functions (Marshall, Olkin, and Arnold 2009, p. 101). It follows that the equilibrium extent of disease decreases as the region's animals become more concentrated in larger herds.

On the second part,

$$W^{\text{ne}} = [1 - \zeta_3(x_p - z_p)]N\bar{V} - \sum_{m \in \Omega_N} \left[\zeta_1 V_m (x_m - z_m^{\text{ne}}) + \zeta_2 V_m (X_{\setminus m} - Z_{\setminus m}^{\text{ne}}) + C(z_m^{\text{ne}}) \right]. \tag{A.2}$$

Due to summation across firms, this function is symmetric in the V_n evaluations. In other words, if we relabeled the firm index and also reassigned firm parameter values in the same way then welfare would not change. Also, due to the envelope theorem (Mas-Colell, Whinston, and Green 1995, pp. 964-966), when assessing the effects on welfare of an infinitesimal change in some V_n we may ignore effects that are mediated through the *n*th firm's biosecurity choice, z_m^{ne}. So we may write

$$\frac{\partial W^{\text{ne}}}{\partial V_n} = 1 - \zeta_3(x_p - z_p) - \zeta_1(x_n - z_n^{\text{ne}}) - \zeta_2(X_{\setminus n} - Z_{\setminus n}^{\text{ne}}). \tag{A.3}$$

Given that $x_m \equiv \bar{x} \; \forall m \in \Omega_N$, (A.3) implies

$$\begin{aligned}\frac{\partial W^{\text{ne}}}{\partial V_n}-\frac{\partial W^{\text{ne}}}{\partial V_k}&=\zeta_1(z_n^{\text{ne}}-z_k^{\text{ne}})+\zeta_2(Z_{\backslash n}^{\text{ne}}-Z_{\backslash k}^{\text{ne}})\\&=(\zeta_1-\zeta_2)(z_n^{\text{ne}}-z_k^{\text{ne}})+\zeta_2(z_n^{\text{ne}}-z_k^{\text{ne}}+Z_{\backslash n}^{\text{ne}}-Z_{\backslash k}^{\text{ne}})=\frac{(z_n^{\text{ne}}-z_k^{\text{ne}})}{\eta},\end{aligned}\tag{A.4}$$

so that

$$\left(\frac{\partial W^{\text{ne}}}{\partial V_n}-\frac{\partial W^{\text{ne}}}{\partial V_k}\right)(V_n-V_k)=\frac{(z_n^{\text{ne}}-z_k^{\text{ne}})(V_n-V_k)}{\eta}.\tag{A.5}$$

As z_m^{ne} is increasing in the value of V_m, it follows that

$$\left(\frac{\partial W^{\text{ne}}}{\partial V_n}-\frac{\partial W^{\text{ne}}}{\partial V_k}\right)(V_n-V_k)\geq 0.\tag{A.6}$$

This is the Ostrowski condition (Marshall, Olkin, and Arnold 2009, p. 20) on a symmetric function and functions satisfying it are larger upon majorization. That is, a more dispersed vector of farm outputs increases welfare under Nash equilibrium.

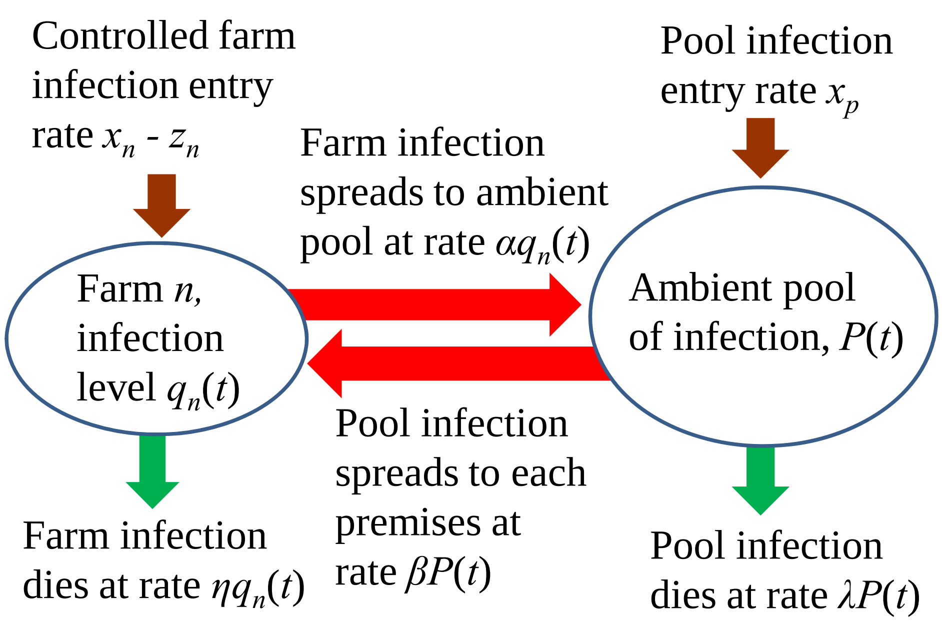

Figure 1. Model of animal disease, entry, spread, and control.

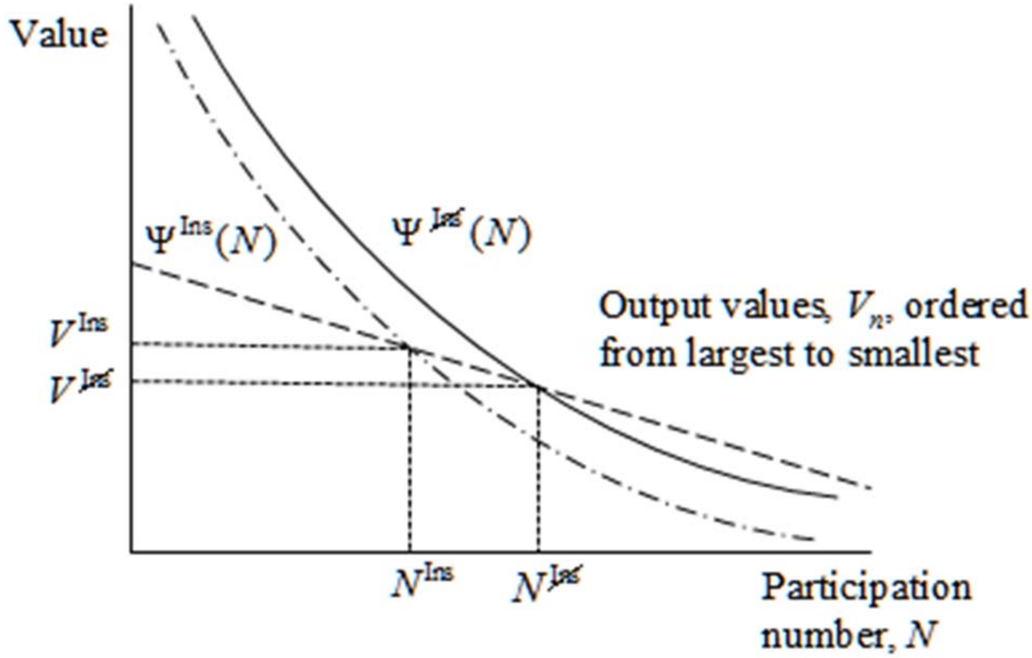

Figure 2. Roles of Insurance and Infrastructure Fixed Costs in Determining Sector Participation.