

Biosecurity and Infectious Animal Disease

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Abstract

The spatial dimension of agricultural production is important when a communicable disease enters a region. This paper considers two sorts of biosecurity risk that producers can seek to protect against. One concerns the risk of spread: that neighboring producers do not take due care in protecting against being infected by a disease already in the region. In this case, producer efforts substitute with those of near neighbors. For representative spatial production structures, we characterize Nash equilibrium protection levels and show how spatial production structure matters. The other sort of risk concerns entry: that producers do not take due care in preventing the disease from entering the region. In this case, producer heterogeneity has subtle effects on welfare loss due to strategic behavior. Efforts by producers complement, suggesting that inter-farm communication will help to redress the problem.

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Biosecurity and Infectious Animal Disease

The control of communicable diseases has been an economic concern since at least the beginning of recorded history. While our understanding of biology has expanded dramatically in recent times, damage from such diseases and the costs of prevention remain a great concern to society. And the concern is not entirely about human diseases. An outbreak of foot and mouth disease in the United Kingdom in 2001 led to widespread disruption of civic life, especially in rural areas. This disease poses a remote concern for human health, but other communicable non-human diseases present larger risks. Strong consensus in the scientific community about the mutability and virulence of avian influenza has generated a global response in control and prevention, circa 2005.

These are examples of longstanding and recurrent problems that motivated the establishment of the OIE, what is now called the World Organization for Animal Health, in 1924. It works in collaboration with the Food and Agricultural Organization and the World Health Organization, both United Nations agencies, but has a more focused remit. Viewing veterinary services as a global public good vital for maintaining trade flows, the OIE has sought to provide a more transparent picture of global animal diseases, facilitate the transfer of veterinary information, foster cohesive international responses to disease control, and strengthen national disease control infrastructure.¹ Its routine activities include issuance of animal health code recommendations on such items as choice of production site, facilities design, environmental and manure management practices, record keeping, and protocols for entry onto premises. These biosecurity measures promote the public good in impeding the rate of spread across space but come at a private cost to growers. Infectious plant diseases are also a global concern, and natural forces are not the only propagators of infectious disease. Strong evidence has led some countries to believe that biological agents may be used as a tactic to cause physical harm and social disruption.

¹ See Otte, Nugent, and McLeod (2004) for extensive discussions on public good features of infectious animal diseases.

Two important features of communicable diseases are that they spread spatially and that actions by private parties to reduce spread are possible but at a cost. Recognition of these features is often manifested in public policies to prevent and control an outbreak. Ports, areas suspected of being infected, and their environs are often isolated. Public entities impose behavioral mandates and support information campaigns to encourage actions that will disrupt spread in any outbreak. The intent of this paper is to gain a better understanding of private incentives to protect against the introduction and spread of an infectious agricultural disease. We will do so by developing a model that emphasizes spatial relation in infection, the technology of prevention, and externalities across agent payoffs to biosecuring actions in a susceptible region.

The literature on the economics of communicable disease, though extensive, is not clearly focused on characterizing the nature of external problems that would motivate public involvement (Otte, Nugent, and McLeod, 2004). A surprisingly small body of work exists on the economics of communicable human diseases, notably in Geoffard and Philipson (1996, 1997) and Kremer (1996). Animal diseases have been the subject of formal models in McNerney (1996) and Chi *et al.* (2002), but the issue was on internal costs and not on how farms inter-relate. Mahul and Gohin (1999) provide a dynamic model of contagion that emphasizes sunk costs that may be incurred upon taking public action to control spread. A strongly related theme is that of controlling invasive species. Economic perspective on this issue is expanding rapidly but has been confined largely to public behavior given an assumed exogenous stochastic dynamic process for infection; see Olson and Roy (2002), Perrings (2005), and Shogren and Tschirhart (2005).²

The findings in Hennessy, Roosen, and Jensen (2005) are closest to those in the present work. The biosecuring decisions in that paper are whether to trade in young stock and the extent of production. Private benefits from trade in immature animals are shown to lead to socially

² But see Brown, Lynch, and Zilberman (2002), where the privately optimal barrier width is considered when seeking to protect against Pierce's disease in vineyards. While spatial, theirs is

excessive losses from an endemic communicable disease. Furthermore, communicable disease is shown to alter the format and scale of production. The model is not spatial and the analysis applies most directly to the extent of damage from a disease already entrenched in a region.

This paper provides a spatial model of private behavior to prevent the introduction and subsequent spread of infection. The emphasis is on protecting a farm's borders. We develop two variants on a model in which the nature of spatial production is explicitly specified. In the first variant, the emphasis is on the spread of a disease that has already entered. For farms arranged in a circle, we show how biosecuring actions are local substitutes and explain what this means for behavioral patterns under simultaneous-moves Nash equilibrium. We also consider a linear arrangement of farms in order to show how the model can be adapted, and to show how locational asymmetries can affect incentives to protect farm boundaries.

By contrast with actions to protect against spread, farm-level actions to protect against entry into the region are shown to be strategic complements. It is shown that all farms can benefit from compulsory actions to secure against entry, but it may only be necessary to compel the most efficient subset of producers because the others may follow of their own accord.

Complementarity also opens up possibilities for veterinary authorities and/or private industry groups to use communication networks in better securing a region against disease entry. It is suggested that some producers should seek to communicate their biosecuring behavior to others in order to coax further effort out of other farms in the region.

Model

A region has $N \geq 5$ farms labeled $n \in \{1, 2, \dots, N\} = \Omega_N$, and each farm is seeking to protect production to the value of $V_n > 0$.³ A farm infected by a disease loses all of this value. The farms are located on a circle; see figure 1. The circle topology was chosen because farms are

not an equilibrium model in the sense that grower interactions are not accounted for.

³ On $N \geq 5$, see footnote 4 below.

locationally symmetric on it. We could develop our model under a different spatial structure, and we will later illustrate with a linear spatial structure. But the circular topology facilitates in making most of the points we wish to make in this work.

Infection is very rare and can enter the region at some farm with probability θ , where each farm is equally likely to be the first infected. By “rare” we mean it is almost certainly true that at most one farm inside the region becomes infected from outside the region at any time. The first farm to be infected within a region is labeled as the “originating farm.” It will also be assumed that public authorities intervene to suppress a disease outbreak after the disease spreads to no more than the *four most proximate farms* (two on each side), if indeed it spreads at all.⁴ Farm-level caretaking is modeled through actions taken at the farm border. If infection has reached one of its direct neighbors, the farm will become infected with probability $a_n \in [0,1]$. We say that the n th farm takes comparatively less (more) care when the value of a_n is comparatively high (low). The grower can change this probability at a cost. Before considering cost of protection, however, let us look at the expected losses in revenue.

Farm 1 may be the first infected, and this occurs with probability θ . Or it may contract the disease from a neighbor. Clockwise is farm 2. If farm 2 is infected first, then farm 1 becomes infected through farm 2 with probability θa_1 . The originating farm’s probability does not enter the calculation because we assume a farm has no incentive to try to prevent the disease from exiting the farm. Counterclockwise is farm N . If it is infected first, then farm 1 becomes infected with probability θa_1 . Farms 3 and $N - 2$ may also be the source of infection to farm 1, where the respective probabilities that this occurs are $\theta a_1 a_2$ and $\theta a_1 a_N$. The overall probability that farm 1 is infected is $\theta + 2\theta a_1 + \theta a_1 a_2 + \theta a_1 a_N$.

⁴ The five-at-most assumption on the extent of the outbreak is convenient but could be relaxed at only the cost of substantially more tedious algebra. Requirement $N \geq 5$ avoids having to remove double-counting, where the disease spreads to farms in both clockwise and counterclockwise directions.

In order to develop a general expression for the risk of infection for each farm $n \in \Omega_N$ we define $[n+i] = n+i - zN$ where z is an integer chosen such that $[n+i] \in \Omega_N$. That is, clock algebra (also called modular algebra) is used. For the n th farm, the probability of infection is

$$(1) \quad \omega_n = \theta + 2\theta a_n + \theta a_n a_{[n+1]} + \theta a_n a_{[n-1]}.$$

The overall expected loss in revenue to the region is

$$(2) \quad \mathcal{R} = \sum_{n \in \Omega_N} V_n \omega_n.$$

Finally, a prevention technology exists. Firms differ in their capacity to protect themselves and the cost of protection at entry probability level a_n is $C^n(a_n)$, a decreasing function. Private profit to a farm is $\mathcal{L}_n = V_n - V_n \omega_n - C^n(a_n)$, while the overall expected profit to the region is

$$(3) \quad \mathcal{L} = \sum_{n \in \Omega_N} \mathcal{L}_n.$$

We assume the region produces a small share of overall market output, so that consumer surplus may be ignored and \mathcal{L} represents social surplus. Since actions by farms $[n+1]$ and $[n-1]$ enter \mathcal{L}_n through ω_n , externalities exist and one should not expect market competition to support the maximization of (3).

Internal Security; Preventing Spread

In order to better understand protection incentives, we posit that the n th farm's cost of protection is $-\alpha_n \text{Ln}(a_n)$ where $\alpha_n > 0$. This ensures that the cost of not protecting at all is $-\alpha_n \text{Ln}(1) = 0$ while the cost of complete protection, where $a_n = 0$, is infinite. This, we believe, reflects reality to the extent that not protecting at all requires no expenditure, complete protection is prohibitively expensive, and the protection cost increases with an increase in the extent of protection.

Private Incentives

The n th farm's profit is

$$(4) \quad \mathcal{L}_n = V_n - V_n \omega_n + \alpha_n \text{Ln}(a_n), \quad n \in \Omega_N.$$

Insert (1) into (4) and differentiate to obtain $\partial^2 \mathcal{L}_n / \partial a_k \partial a_s \leq 0 \forall k, s \in \Omega_N, k \neq s$, i.e., farm biosecurity actions to prevent the spread of infection are strategic substitutes. This observation is noteworthy because it shows that the game being played is not of the type involving global strategic complementarities (Vives, 1990, 2005; Milgrom and Roberts, 1990). As we will see when studying external disease risks, where global complementarities do exist, the existence of complementarities provides policymakers with clear opportunities to strengthen defenses against disease risks. When private actions may substitute, however, the possibility exists that a public intervention can do more harm than good by indirectly discouraging important actions while directly encouraging less important actions.

Responses

From Nash conjectures on payoffs (4), the level of protection is chosen as a solution to

$$(5) \quad \begin{aligned} \mu^n(a) &= 0 \forall n \in \Omega_N; \\ \mu^n(a) &= \frac{d\mathcal{L}_n}{da_n} = -\theta V_n (2 + a_{[n+1]} + a_{[n-1]}) + \frac{\alpha_n}{a_n}. \end{aligned}$$

Solutions are denoted by a_n^* . Letting τ represent some exogenous parameter and assigning $\lambda_n = \alpha_n / [\theta V_n]$, (5) differentiates as

$$(6) \quad \begin{pmatrix} -\frac{\lambda_1}{(a_1^*)^2} & -1 & 0 & \cdots & -1 \\ -1 & -\frac{\lambda_2}{(a_2^*)^2} & -1 & \cdots & 0 \\ 0 & -1 & -\frac{\lambda_3}{(a_3^*)^2} & \cdots & 0 \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ -1 & 0 & 0 & \cdots & -\frac{\lambda_N}{(a_N^*)^2} \end{pmatrix} \begin{pmatrix} da_1^*/d\tau \\ da_2^*/d\tau \\ da_3^*/d\tau \\ \vdots \\ da_N^*/d\tau \end{pmatrix} = - \begin{pmatrix} \frac{1}{a_1^*} \frac{d\lambda_1}{d\tau} \\ \frac{1}{a_2^*} \frac{d\lambda_2}{d\tau} \\ \frac{1}{a_3^*} \frac{d\lambda_3}{d\tau} \\ \vdots \\ \frac{1}{a_N^*} \frac{d\lambda_N}{d\tau} \end{pmatrix}.$$

Local stability is satisfied if all eigenvalues of the $N \times N$ matrix have negative real parts, and we make this assumption (McKenzie, 1960; Dixit, 1986; Brualdi and Shader, 1995).

Example 1. If $\alpha_n = \alpha \forall n \in \Omega_N$ and $V_n = V \forall n \in \Omega_N$, with $\lambda = \alpha/[\theta V]$, then one solution is that of equal-actions, $a_n^* = a^* \forall n \in \Omega_N$, so that the only non-negative equal-actions solution to system (5) is⁵

$$(7) \quad a^* = 0.5\sqrt{1+2\lambda} - 0.5.$$

This is interior whenever $\lambda \in (0,4)$. The diagonal dominance sufficient condition for stability (Dixit, 1986) is assured in this case, since $\lambda/(a^*)^2 > 2$ implies $\sqrt{1+2\lambda} > 1$.

If $\tau = \lambda_1$, so that just one parameter changes from the common value of λ , then (6) becomes⁶

⁵ We know very little about solutions when the λ_n differ. One observation is that $N^{-1} \sum_{n \in \Omega_N} a_n^* + N^{-1} \sum_{n \in \Omega_N} a_n^* a_{[n+1]}^* = N^{-1} \sum_{n \in \Omega_N} \lambda_n$, i.e., solutions live on a curve such that the sum of the mean value of a_n^* and a spatial correlation statistic will not be affected by movements along the parameter simplex with fixed $\sum_{n \in \Omega_N} \lambda_n$ value. Public goods analyses and imperfect competition analyses, as in Salant and Shaffer (1999) or Anderson, de Palma, and Kreider (2001), have exploited related solution invariances but we do not see an opportunity for doing so in this case.

⁶ Were the outbreak allowed to extend beyond five farms, then more entries on the square matrix of equation (8) would be non-zero and the matrix would not be as readily inverted. Main-diagonal and other symmetries of the square matrix facilitate inversion, so it would be easiest to generalize while retaining as much symmetry as possible.

$$(8) \quad \kappa \times \begin{pmatrix} 1+2\xi & -\xi & 0 & \cdots & -\xi \\ -\xi & 1+2\xi & -\xi & \cdots & 0 \\ 0 & -\xi & 1+2\xi & \cdots & 0 \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ -\xi & 0 & 0 & \cdots & 1+2\xi \end{pmatrix} \begin{pmatrix} da_1^*/d\lambda_1 \\ da_2^*/d\lambda_1 \\ da_3^*/d\lambda_1 \\ \vdots \\ da_N^*/d\lambda_1 \end{pmatrix} = \frac{1}{a^*} \begin{pmatrix} 1 \\ 0 \\ 0 \\ \vdots \\ 0 \end{pmatrix};$$

$$\kappa = 2 \left(\frac{1+2\lambda - \sqrt{1+2\lambda}}{1+\lambda - \sqrt{1+2\lambda}} \right) > 0; \quad \xi = \frac{\sqrt{1+2\lambda} - 1 - \lambda}{2(1+2\lambda - \sqrt{1+2\lambda})} < 0.$$

The system inverts as⁷

$$(9) \quad \begin{pmatrix} da_1^*/d\lambda_1 \\ da_2^*/d\lambda_1 \\ da_3^*/d\lambda_1 \\ \vdots \\ da_N^*/d\lambda_1 \end{pmatrix} = \frac{1}{\kappa a^* \Delta (\rho^N - 1)} \begin{pmatrix} 1 + \rho^N & \rho + \rho^{N-1} & \rho^2 + \rho^{N-2} & \cdots & \rho^{N-1} + \rho \\ \rho^{N-1} + \rho & 1 + \rho^N & \rho + \rho^{N-1} & \cdots & \rho^{N-2} + \rho^2 \\ \rho^{N-2} + \rho^2 & \rho^{N-1} + \rho & 1 + \rho^N & \cdots & \rho^{N-3} + \rho^3 \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ \rho + \rho^{N-1} & \rho^2 + \rho^{N-2} & \rho^3 + \rho^{N-3} & \cdots & 1 + \rho^N \end{pmatrix} \begin{pmatrix} 1 \\ 0 \\ 0 \\ \vdots \\ 0 \end{pmatrix}$$

$$= \frac{1}{\kappa a^* \Delta (\rho^N - 1)} \begin{pmatrix} 1 + \rho^N \\ \rho^{N-1} + \rho \\ \rho^{N-2} + \rho^2 \\ \vdots \\ \rho + \rho^{N-1} \end{pmatrix},$$

where $\rho = [\lambda + (1+2\lambda)^{1/4} (\sqrt{1+2\lambda} - 1)] / (\sqrt{1+2\lambda} - 1 - \lambda) < -1$ and $\Delta = (1+2\lambda)^{-1/4} > 0$. In this case, since $\kappa > 0$, $a^* > 0$, $\Delta > 0$, and $\rho < -1$, a small subsidy to any one grower will increase the level of protection taken by that grower.

However, if N is even, then $(\rho^{N-1} + \rho) / [\kappa a^* \Delta (\rho^N - 1)] < 0$ so that the two adjacent farms reduce protection in response to the increase in level of a farm's subsidy. This pattern repeats itself around the circle; farms at an odd minimum displacement from the subsidized farm will reduce protection in response to the farm-specific subsidy while farms at an even minimum displacement will increase protection. If N is odd then the denominator in

⁷ This matrix inversion also appears in a study of equilibrium production schedules under adjustment costs by Hennessy and Lapan (2004).

$(\rho^{N-1} + \rho)/[\kappa a^* \Delta(\rho^N - 1)]$ is negative while the numerator is positive since $\rho^{N-1} + \rho = (\rho^{N-2} + 1)\rho > 0$ on $N \geq 3$. In this case, too, the two adjacent farms will reduce protection in response to a subsidy on a specific farm's protective actions. Furthermore,

$(\rho^{N-i} + \rho^i)/[\kappa a^* \Delta(\rho^N - 1)] = -(\rho^{N-2i} + 1)\rho^i$ where the value of $\rho^{N-2i} + 1$ is negative (positive) whenever $N/2 \geq (<) i$. It is the oddness of the minimal displacement from the subsidized farm that determines another farm's response to the subsidy.

Social Inefficiency

From (4) and (5),

$$(10) \quad \left. \frac{d\mathcal{L}}{da_m} \right|_{\text{private optimum}} = -V_m \frac{d\omega_m}{da_m} - \sum_{\substack{n \in \Omega_N \\ m \neq n}} V_n \frac{d\omega_n}{da_m} + \frac{\alpha_m}{a_m} = -\sum_{\substack{n \in \Omega_N \\ m \neq n}} V_n \frac{d\omega_n}{da_m} \leq 0.$$

Notice, from (7), that if τ in (6) involved a shock to *all* λ coefficients along the ray $\lambda_n = \lambda \forall n \in \Omega_N$, then (9) would have $\text{sign } da_n^*/d\lambda \geq 0 \forall n \in \Omega_N$. This, together with equation (10), implies that subsidies on farm-level actions might be in order. However, from the peculiarities of responses in (9), it is plausible to suspect that a subsidy may not always increase welfare.⁸

Linear Topology

The intent of this subsection is to demonstrate the robustness of the modeling approach. To this end, we will replace the circular production structure with a three-farm linear topology. The farms are now located along a line segment, as illustrated in figure 2. In contrast with the circular topology, physical barriers (river, mountain, desert, ...) preclude direct spread from farm 1 to farm 3. For edge farms $n = 1$ and $n = 3$, infection can only come from one side. Farm profits are

⁸ For example, when actions are not equal in equilibrium then it is conceivable that a uniform subsidy on all actions depresses an important action to such an extent that overall welfare declines. In our inquiries, we did not identify analytic conditions under which this occurred.

$$\begin{aligned}
& \text{Farm 1: } V_1 - \theta V_1 - \theta V_1 a_1 - \theta V_1 a_1 a_2 + \alpha_1 \text{Ln}(a_1); \\
(11) \quad & \text{Farm 2: } V_2 - \theta V_2 - 2\theta V_2 a_2 + \alpha_2 \text{Ln}(a_2); \\
& \text{Farm 3: } V_3 - \theta V_3 - \theta V_3 a_3 - \theta V_3 a_3 a_2 + \alpha_3 \text{Ln}(a_3).
\end{aligned}$$

Upon setting $V_1 = V_2 = V_3 = V$, done for convenience, and denoting $\lambda_n = \alpha_n / [\theta V]$, the private (pure-strategy) optimality conditions may be written as

$$(12) \quad \text{Farm 1: } a_1 + a_1 a_2 = \lambda_1; \quad \text{Farm 2: } 2a_2 = \lambda_2; \quad \text{Farm 3: } a_3 + a_3 a_2 = \lambda_3;$$

yielding unique pure-strategy solution

$$\begin{aligned}
(13) \quad & \text{Farm } n \in \{1, 3\}: \quad a_n^* = \begin{cases} \frac{2\lambda_n}{2 + \min[2, \lambda_2]} & \text{if } 2\lambda_n \leq 2 + \lambda_2, \\ 1 & \text{otherwise;} \end{cases} \\
& \text{Farm 2:} \quad a_2^* = \begin{cases} 0.5\lambda_2 & \text{if } \lambda_2 \in [0, 2], \\ 1 & \text{otherwise.} \end{cases}
\end{aligned}$$

Notice the bias in the middle; if $\lambda_1 = \lambda_2 = \lambda_3 = \lambda \leq 2$, then $a_1^* = a_3^* = 2a_2^* / [1 + a_2^*] \geq a_2^*$ so that farm 2 takes most care. This is because the middle farm is immediately vulnerable to direct infection from the other two farms, whereas the edge farms are only immediately vulnerable to direct infection from the middle farm. Two failures must occur for one edge farm to infect the other.

The sum of surpluses for an interior solution is

$$\begin{aligned}
(14) \quad & W = 3V - 3\theta V - \theta V(a_1^* + 2a_2^* + a_3^*) - \theta V a_1^* a_2^* - \theta V a_3^* a_2^* \\
& + \theta V \lambda_1 \text{Ln}(a_1^*) + \theta V \lambda_2 \text{Ln}(a_2^*) + \theta V \lambda_3 \text{Ln}(a_3^*) \\
& = 3V - 3\theta V - \theta V(\lambda_1 + \lambda_2 + \lambda_3) + \theta V \lambda_1 \text{Ln}\left(\frac{2\lambda_1}{2 + \lambda_2}\right) + \theta V \lambda_2 \text{Ln}(0.5\lambda_2) + \theta V \lambda_3 \text{Ln}\left(\frac{2\lambda_3}{2 + \lambda_2}\right).
\end{aligned}$$

A subsidy on the cost for farm 1 in the form of some intervention that decreases the value of α_1

has welfare effect $-dW / d\lambda_1 = -\overset{\text{sign}}{\text{Ln}}[2\lambda_1 / (2 + \lambda_2)] \geq 0$. This, reassuringly, means that welfare

increases with a subsidy. A subsidy directed toward farm 2 has welfare effect $-dW / d\lambda_2 = \overset{\text{sign}}{(}$

$(\lambda_1 + \lambda_3) / (2 + \lambda_2) - \text{Ln}(0.5\lambda_2)$. This is also positive for interior solutions, $\lambda_2 \in [0, 2)$.

As for first-best, the social optimality conditions are

$$(15) \quad \begin{array}{ll} \text{Farm 1: } & a_1 + a_1 a_2 = \lambda_1; \\ \text{Farm 2: } & a_1 a_2 + 2a_2 + a_3 a_2 = \lambda_2; \\ \text{Farm 3: } & a_3 + a_3 a_2 = \lambda_3. \end{array}$$

To illustrate, when $\lambda_1 = \lambda_2 = \lambda_3 = \lambda$ then any first-best solution must satisfy $a_1^{fb} = a_3^{fb}$.⁹ The first-best requirement on the middle farm is $a_2^2 + (1 + 0.5\lambda)a_2 - 0.5\lambda = 0$ with unique positive solution

$$(16) \quad a_2^{fb} = \frac{-1 - 0.5\lambda + \sqrt{(1 + 0.5\lambda)^2 + 2\lambda}}{2}.$$

Notice that $da_2^{fb}/d\lambda \geq 0$ and $\text{Lim}_{\lambda \rightarrow \infty} a_2^{fb} = 1$. In contrast with (13) where no protection is sometimes privately optimal, farm 2 should make no effort only when cost of effort becomes infinite. Comparing with Nash conjectures choice $a_2^* = 0.5\lambda$, we have

$$(17) \quad \frac{a_2^{fb}}{a_2^*} = \frac{-1 - a_2^* + \sqrt{(1 + a_2^*)^2 + 4a_2^*}}{2a_2^*} \leq 1$$

since $(1 + a_2^*)^2 + 4a_2^* \leq (1 + 3a_2^*)^2$. Even though it takes most care, the middle farm does not protect enough.

For the edge farms, first-best actions are

$$(18) \quad a_1^{fb} = a_3^{fb} = \frac{2\lambda}{1 - 0.5\lambda + \sqrt{1 + 3\lambda + 0.25\lambda^2}},$$

so that $a_1^{fb} \leq a_1^*$ if $2.25\lambda^2 \leq 0.25\lambda^2$, a false statement. Thus, the edge farms react by protecting too much even though they take less care than does the middle farm. Observe too that a_1^{fb} and a_3^{fb} are increasing in λ along $\lambda_1 = \lambda_2 = \lambda_3 = \lambda$, with $a_1^{fb} = a_3^{fb} = 1$ at $\lambda = 4/3$. By contrast with

⁹ Fixing a_2 at any admissible value, W in (14) is symmetric and concave in the choices of a_1 and a_3 . This means that any admissible choice (a_1^{fb}, a_3^{fb}) such that $a_1^{fb} \neq a_3^{fb}$ delivers lower welfare than $(\hat{a}_1^{fb}, \hat{a}_3^{fb}) = ((\hat{a}_1^{fb} + \hat{a}_3^{fb})/2, (\hat{a}_1^{fb} + \hat{a}_3^{fb})/2)$, a contradiction since convexity of the action space ensures that the average is admissible.

the middle farm, it may be optimal for the edge farms to make no effort. This is because the middle farm's action is a substitute and the middle farm takes appropriate care in first-best.

External Security; Preventing Entry

To this point the focus has been on preventing the spread of infection within a region. We turn now to actions that prevent entry. As before, each farm in $n \in \Omega_N$ seeks to protect value to the extent V_n . Now, however, the biosecuring action each farm can take pertains to entry into the region. The behavior under consideration might involve careless importation of assets such as livestock and equipment, or allowing visits onto a farm by bird, rodent, and human disease carriers.

Each farm can increase the probability the farm is not the originating farm from $\sigma = 1 - \theta$ to 1. The cost of this action to each farm is $c_n \geq 0$, and an infected farm loses all of V_n . Farm biosecurity costs and the values farms seek to protect are assumed to be common knowledge. In this section we control for the issue of intra-region spread by assuming the disease immediately spreads to all the region's farms if it enters. This means that all farms need to succeed in not being the originating farm if their own produce is to be spared.

When no farm in the region incurs the cost then the expected profit to the n th farm is $V_n \sigma^N$, while if k other farms incur the cost then the probability that the disease does not enter is σ^{N-k} and the expected profit to a non-acting farm is $V_n \sigma^{N-k}$. Profit to the farm depends upon whether the farm has incurred the cost. Suppose, as a Nash conjecture in a simultaneous-move game, a farmer assesses that it is the dominant strategy for k other farms to incur the cost. The payoff to the n th farm in question is then^{10,11}

¹⁰ This model is similar to, and the technical framework is largely inspired by, Winter's (2004) study of motives for discrimination among identical team members under contract. The concern there is with optimal design of remuneration schemes to elicit joint actions. We take disease

$$(19) \quad \text{Farm that} \begin{cases} \text{does act:} & V_n \sigma^{N-k-1} - c_n; \\ \text{does not act:} & V_n \sigma^{N-k}. \end{cases}$$

Without loss of generality, assign firm labels such that $\rho_1 \leq \rho_2 \leq \dots \leq \rho_N$ where $\rho_n = c_n / V_n$.

The farm does (does not) act if¹²

$$(20) \quad \sigma^{N-k-1}(1-\sigma) > (\leq) \rho_n.$$

Given that costs and protected values are known to all, farm 1 will be identified by all as the farm most likely to invest. The threshold for this farm to act is $\sigma^{N-1}(1-\sigma) > \rho_1$. If this threshold is met, then all other firms will arrive at the conjectural conclusion that farm 1 will take the biosecuring action and the threshold for the second farm to act is $\sigma^{N-2}(1-\sigma) > \rho_2$. In general, if iterated dominance arguments imply that all firms $i \in \Omega_{n-1}$ act, then the threshold for the n th farm to act is

$$(21) \quad e^{(N-n)\text{Ln}(\sigma)}(1-\sigma) > \rho_n.$$

Figures 3 and 4 graph the left- and right-hand sides of (21) as continuous functions. In both graphs, the two expressions are increasing in the value of n . For ρ_n , monotonicity is by construction while for $e^{(N-n)\text{Ln}(\sigma)}(1-\sigma)$ monotonicity is due to a stochastic version of increasing returns. In figure 3, $e^{(N-n)\text{Ln}(\sigma)}(1-\sigma) = \rho_n$ at one value of n , $n = n^+ < N$, where we assume for simplicity that n^+ is a natural number. Since $e^{(N-n)\text{Ln}(\sigma)}(1-\sigma)$ is initially smaller, however, the

state-conditional remunerations, V_n conditional on no disease, as being given and focus attention on the consequences for actions.

¹¹ The marginal private value of acting is $\Delta = V_n \sigma^{N-k-1} - V_n \sigma^{N-k} - c_n$ with derivative $d\Delta/dk = -V_n \text{Ln}(\sigma) \sigma^{N-k-1}(1-\sigma) \geq 0$. This ensures that the game is one of strategic complementarities, in the manner of Vives (1990, 2005) and Milgrom and Roberts (1990). We will not pursue the comparative statics implications of this, but do note that the theory implies that a reduction in *any* c_n weakly increases the incentive of *each* producer to take their respective action. The effects of a producer-specific subsidy on preventing entry differ markedly from a producer-specific subsidy on preventing spread.

equilibrium is for no farm to make the investment. This *may* be unfortunate indeed, for suppose that the first n^+ farmers are compelled by law to take the action. Then all remaining farmers will find it advantageous to invest, and welfare to the first farmer becomes $V_n - c_n$, rather than $V_n \sigma^N$. If $\rho_1 \in (\sigma^N, 1]$, then the first farm will be better off after being compelled. Similarly, if $\rho_n \in (\sigma^N, 1] \forall n \in \Omega_{n^+}$ then all compelled farmers will be better off for it. Indeed, all producers may have to be compelled to act and all may be better off when compared with absent an across-the-board mandate. The problem is in part one of free riding and in part one of a failure to coordinate.¹³

In figure 4, concentrate on the two fully traced curves. There, $e^{(N-1)\text{Ln}(\sigma)}(1 - \sigma) > \rho_1$ so that the first farm does make the investment. The investment occurs up to farm \hat{n} , which happens to be the unique point of intersection under our parameter choices. Suppose that $\rho_n = \psi_0 e^{\psi_1 n}$ in figure 4, so that

$$(22) \quad \hat{n} = \frac{1}{\psi_1 + \text{Ln}(\sigma)} \text{Ln} \left(\frac{\sigma^N - \sigma^{N+1}}{\psi_0} \right),$$

where $\psi_1 + \text{Ln}(\sigma) > 0$ since unit costs on the marginal farm grow more rapidly than unit private benefits of protective actions.

Now consider the set of first-best actions. By analog with (19), the change in social welfare due to action by a farm is

$$(23) \quad \text{Farm that} \begin{cases} \text{does act:} & N\bar{V}\sigma^{N-k-1} - c_n; \\ \text{does not act:} & N\bar{V}\sigma^{N-k}; \end{cases}$$

¹² Here, as elsewhere in the section, ties are assigned to non-action.

¹³ Under free riding, the grower would be disposed to deviate when all other growers engage in first-best behavior. In this case, the incentive to deviate weakens as more farms act. It remains the case, though, that marginal private benefit differs from marginal social benefit at first-best.

where $N\bar{V} = \sum_{n \in \Omega_N} V_n$. Note first that the iterated dominance order in which farms behaving under private incentives are viewed as taking the action is not necessarily consistent with their marginal contributions to social welfare. It will always be the case, however, that the set acting under simultaneous-moves Nash behavior will act under first-best because the action threshold is always lower under first-best.

If $V_n = \bar{V} \forall n \in \Omega_N$, then first-best solves $e^{(N-n)\text{Ln}(\sigma)}(1-\sigma) = \rho_n / N$. Figure 4 also depicts how the social welfare solution compares with the solution under private incentives; see the broken curve. Under cost structure $\rho_n = \psi_0 e^{\psi_1 n}$, the optimal number of farms acting (with least cost first) is given by

$$(24) \quad n^{fb} = \frac{1}{\psi_1 + \text{Ln}(\sigma)} \left[\text{Ln}(N) + \text{Ln} \left(\frac{\sigma^N - \sigma^{N+1}}{\psi_0} \right) \right] = \hat{n} + \frac{\text{Ln}(N)}{\psi_1 + \text{Ln}(\sigma)} > \hat{n}.$$

An expression for optimal subsidy is rather apparent; reduce a farm's ρ_n value from c_n / V_n to $c_n / [NV_n]$. We will consider next the role that cost heterogeneity has on private solutions to the public goods problem.

Example 2. Suppose in a two-farm region that $V_1 = V_2 = 2$, $c_1 = 1 - \delta$, and $c_2 = 1 + \delta$. So long as $\delta \in [0, 1]$ then first-best behavior is

$$(25) \quad \begin{aligned} A): & \text{ none act if } \{4\sigma^2 \geq 2 \text{ and } 4\sigma^2 \geq 4\sigma + \delta - 1\}; \\ B): & \text{ farm 1 only acts if } \{4\sigma + \delta \geq 3 \text{ and } 4\sigma + \delta - 1 > 4\sigma^2\}; \\ C): & \text{ both farms act if } \{3 > 4\sigma + \delta \text{ and } 2 > 4\sigma^2\}. \end{aligned}$$

Figure 5 depicts the regions over $(\sigma, \delta) \in [0, 1] \times [0, 1]$. The three characterizing curves intersect at $(\sigma, \delta) = (1/\sqrt{2}, 3 - 2\sqrt{2})$. Area A is defined by $\sigma \geq \max[1/\sqrt{2}, 0.5 + 0.5\sqrt{\delta}]$, while area B is given by $0.5 + 0.5\sqrt{\delta} > \sigma \geq 0.75 - 0.25\delta$. Area C is the remaining set, $\min[1/\sqrt{2}, 0.75 - 0.25\delta] > \sigma$. It can be seen that low-cost heterogeneity ($\delta \approx 0$) favors action by both farms (area C) or

neither farms (area A). Indeed, if $\delta \in [0, 3 - 2\sqrt{2})$ then action by exactly one farm is not optimal.

If, though, $\sigma \geq 1/\sqrt{2}$ then optimal behavior can only be for at most one farm to act because farm 2 has cost of at least 1 and the social gain from acting is small whenever $\sigma \geq 1/\sqrt{2}$.

On the other hand, in a game of simultaneous-moves on biosecuring actions,

$$(26) \quad \begin{aligned} A') &: \text{none act if } \{2\sigma^2 \geq 2\sigma + \delta - 1\}; \\ B') &: \text{farm 1 only acts if } \{2\sigma + \delta - 1 > 2\sigma^2 \text{ and } 2\sigma + \delta \geq 1\}; \\ C') &: \text{both farms act if } \{2\sigma + \delta - 1 > 2\sigma^2 \text{ and } 1 > 2\sigma + \delta\}. \end{aligned}$$

Figure 6 depicts the areas over $(\sigma, \delta) \in [0, 1] \times [0, 1]$. Area C' is empty since, for our cost and value parameters, the two conditions generate the contradiction $2\sigma^2 \geq 0 > 2\sigma + \delta - 1$. Area B' has a redundant first inequality, since $2\sigma + \delta - 1 > 2\sigma^2 \geq 0$ implies $2\sigma + \delta > 1$. The area contains parameter pairs such that the marginal private benefit of action by the second farm is low relative to the high marginal cost. The δ interval (viewing vertical sections) for which the first farm will act vanishes when $\sigma \rightarrow 0$. This is because the prospects of success are negligible given that the second farm is not biosecuring. The δ interval in area B' also vanishes when $\sigma \rightarrow 1$, since the marginal private benefit of action is negligible.

Comparing figures 5 and 6, we see that no counterpart to area C in figure 5 exists in figure 6, while there exist $(\sigma, \delta) \in [0, 1]^2$ values such that both farms should act but neither does act. Furthermore, $A' \supset A$ since $4\sigma^2 - 4\sigma + 1 = 2\sigma^2 - 2\sigma + 1 + 2\sigma(\sigma - 1) \leq 2\sigma^2 - 2\sigma + 1$. This means that the parameter set such that neither farm biosecures expands under simultaneous moves when compared with first-best. Areas B and B' are not comparable since cases where two farms should biosecure have only one doing so and cases where one farm should biosecure have neither doing so. In no instance does a farm biosecure when it should not.

The σ and δ parameters each have ambiguous effects on how private and optimal solutions relate. For low σ and low δ values, both farms should act while neither do. Here, the farms are

sufficiently similar that both farms come to the same conclusion and this is not to act. When σ is low and δ is high, though, only farm 1 has the incentive to biosecure since it is too costly for farm 2 to do so. At intermediate σ and high δ values then farm 1 acts and only farm 1 should act, so that first-best is attained in our discrete model. Figure 7, which overlays figure 6 onto figure 5, identifies non-monotonicities in the welfare loss effects of parameter values. In it the indicators (I, J) give (# farms that act, # farms that should act). Two areas, check marked (\checkmark) and connected only at point [1,1] to the upper right, have sequential-move Nash equilibrium that support first-best. Welfare loss occurs for parameters in cross marked areas, \times . For any $\delta \in (0.5, 1)$, a horizontal cross-section shows first-best being supported at intermediate and very high values of $\sigma \in [0, 1]$, but not at low and high values of σ . For $1/\sqrt{2} < \sigma < 1$, a vertical cross-section shows first-best being supported at low and high δ values but not at intermediate values. Two (I, J) permutations do not occur. While $(2, 1)$ is not possible given our model structure, $(2, 2)$ would identify an area had we chosen $c_1 = c - \delta$, and $c_2 = c + \delta$ with c having value sufficiently close to 0.

Leadership in Internal and External Security Games

As is well known, the capacity to communicate ones actions to other players in a game has consequences for game equilibrium. What is less clear, however, is whether society or other players can be better off for this. In what follows we will consider how the timing of moves affects incentives to engage in actions to avoid disease contraction in both our internal security and external security models.¹⁴

¹⁴ It is not generally true that the first mover has an advantage, and we will identify a situation in which the first mover is strictly worse off. See Dixit and Skeath (2004) for discussions on gains from order of move.

Internal Security

The case of leadership in the circular topology is involved, so we will confine our analysis to linear topologies. Considering the three-farm linear topology, system (12) identifies that the farm 2 reaction function is independent of actions by the other farms. The middle farm could manipulate behavior by the edge farms but has no incentive to do so. While middle-farm behavior affects edge-farm profits, edge farms have no capacity to manipulate behavior by the middle farm. Therefore, the order of movement by producers has no effect on equilibrium.

One aspect of the three-farm linear topology generalizes to the N -farm linear topology; namely, the irrelevance of first-movement by an edge farm when compared with simultaneous moves. However, the order of movement by interior farms is relevant as the following analysis of the four-farm linear topology illustrates.¹⁵ In it, the reaction functions are given by

$$(27) \quad \begin{array}{ll} \text{Farm 1: } & a_1 + a_1 a_2 = \lambda_1; \\ \text{Farm 2: } & 2a_2 + a_2 a_3 = \lambda_2; \\ \text{Farm 3: } & 2a_3 + a_2 a_3 = \lambda_3; \\ \text{Farm 4: } & a_4 + a_3 a_4 = \lambda_4. \end{array}$$

If $\lambda_1 = \lambda_2 = \lambda_3 = \lambda_4 = \lambda > 0$, then symmetry under simultaneous movement implies $a_1^* = a_4^*$ and $a_2^* = a_3^*$ so that the only symmetric positive actions equilibrium for the middle farms is given by $a_2^* = a_3^* = \sqrt{1 + \lambda} - 1$ and the edge farms react according to $a_1^* = a_4^* = \lambda / \sqrt{1 + \lambda}$.

If farms 1 or 4 move first, (27) shows that equilibrium will not change. Suppose, though, that farm 2 moves first. Farm 3 reacts according to $a_3 = \lambda / (2 + a_2)$. As with Stackelberg oligopoly, the early mover will force responsibility onto the later mover. In the case of an oligopoly, the responsibility concerns controlling market output. In our case, it concerns controlling spread of disease from farm 4. Farm 4 may well benefit because its only neighbor is forced to take more care. Farm 1, on the other hand, is more likely to lose from the farm 2 endeavor to manipulate farm 3 caretaking.

¹⁵ This is the graph in figure 2 except that there are four dots, three connecting lines, and two middle farms.

External Security

For our external security model, presented around equation (19), we consider a two-farm region and compare a simultaneous-moves equilibrium with the case in which farm 1 moves first. When farm 1 decides first, then it will recognize its capacity to manipulate the farm 2 action. In particular, if farm 1 acts then farm 2 will act whenever $1 - \sigma > \rho_2$. When both act, then profit to farm 1 is $V_1 - c_1$. If farm 1 acts and $1 - \sigma \leq \rho_2$, then profit to farm 1 is $V_1\sigma - c_1$. If farm 1 does not act and $\sigma - \sigma^2 > \rho_2$ then profit to farm 1 is $V_1\sigma$. Finally, if farm 1 does not act and $\sigma - \sigma^2 \leq \rho_2$ then profit to farm 1 is $V_1\sigma^2$.

Summarizing, there are three critical regions for the value of ρ_2 . These are

$$(28) \quad A): \rho_2 < \sigma - \sigma^2; \quad B): \sigma - \sigma^2 \leq \rho_2 < 1 - \sigma; \quad C): 1 - \sigma \leq \rho_2;$$

and are depicted in panel a) of figure 8. For area A , farm 1 can be sure that farm 2 will act regardless of the farm 1 decision. Therefore the increment in farm 1 profit due to action is $V_1 - c_1 - V_1\sigma$, so that the farm acts if $1 - \sigma > \rho_1$. This is area A' (the sum of areas C' and $A' - C'$) in panel b) of figure 8. For area B , as given in (28), farm 2 replicates the decision of farm 1. The increment in farm 1 profit is $V_1 - c_1 - V_1\sigma^2$, so that the farm acts if $1 - \sigma^2 > \rho_1$. This is area B' (the sum $C' + [A' - C'] + [B' - A']$) in panel b), and area A' is a subset. The third area identified in (28), labeled C , is where farm 2 will not act regardless of the prior farm 1 action. Action by farm 1 then changes own profit by $V_1\sigma - c_1 - V_1\sigma^2$ so that the action will be taken whenever $\sigma - \sigma^2 > \rho_1$. This parameter area, labeled as C' , is contained in area A' so that $C' \subseteq A' \subseteq B'$.

One may think of this parameter space containment as follows. The set $(\sigma, \rho_1) \in C'$ contains values for which the leader will take the action anyway, i.e., even when farm 2 will not follow. The set difference $A' - C'$ is an expansion of set C' . It accounts for the recognition that in this

case farm 1 knows that farm 2 will take the action anyway, where the actions complement. Set $B' - A'$ is an expansion of set A' , and the motive for this expansion is strategic. In this case, farm 1 takes the action only because farm 2 is then coaxed into acting. This strategic motive for communication has arisen elsewhere for models of a form similar to ours. It is related to the notion of seed money in a fund-raising drive (Andreoni, 1998; Potters, Sefton, and Vesterlund, 2005). More directly, in Hennessy, Roosen, and Miranowski (2001) the issue is quality protection for a food system when surplus is shared according to the Shapley value. In two papers by Winter (2005, 2006), the design of workplace structure in the form of job hierarchies and office layout such that communication is facilitated is found to elicit better performance from workers.

A comparison with simultaneous moves is in order. There, for $\rho_1 < \rho_2$, firm 1 moves if $\sigma - \sigma^2 \geq \rho_1$ and firm 2 moves if $1 - \sigma \geq \rho_2$. The one difference between simultaneous moves and first movement by farm 1 is the absence of the strategic incentive, as identified in area $B' - A'$ of figure 8, panel b). In that area, joint profit changes from $V_1\sigma^2 + V_2\sigma^2$ to $V_1 + V_2 - c_1 - c_2$. For the parameter values in question the change is positive and, furthermore, the profits of both farms increase. Thus leadership by one farm, and it can be either farm, cannot decrease profits for either farm relative to simultaneous moves and may increase profits for both.

Finally, suppose that $\rho_1 < \rho_2$ and a policymaker can influence which, if it must be one or the other, farm moves first. When farm 1 moves first then there are three regions to consider:

$$\begin{aligned}
 (29) \quad & A): \text{ both act} && \{1 - \sigma^2 > \rho_1 \text{ and } 1 - \sigma > \rho_2\}, && \text{Joint profit is } && V_1 + V_2 - c_1 - c_2; \\
 & B): \text{ farm 1 only acts} && \{\sigma - \sigma^2 > \rho_1 \text{ and } 1 - \sigma \leq \rho_2\}, && \text{Joint profit is } && V_1\sigma + V_2\sigma - c_1; \\
 & C): \text{ neither act otherwise,} && && \text{Joint profit is } && V_1\sigma^2 + V_2\sigma^2.
 \end{aligned}$$

Figure 9, panel a), describes the choice set in $(\rho_1, \rho_2) \geq (0, 0)$ space where farm 1 moves first and condition $\rho_1 < \rho_2$ precludes from consideration the wedge below the bisector.

On the other hand, when farm 2 moves first then joint profits are

$$\begin{aligned}
(30) \quad & A): V_1 + V_2 - c_1 - c_2 \quad \{1 - \sigma^2 > \rho_2 \text{ and } 1 - \sigma > \rho_1\}; \\
& B): V_1\sigma + V_2\sigma - c_1 \quad \{1 - \sigma^2 \leq \rho_2 \text{ and } \sigma - \sigma^2 > \rho_1\}; \\
& C): V_1\sigma^2 + V_2\sigma^2 \quad \text{otherwise.}
\end{aligned}$$

Notice that the profit possibilities are the same, but the areas change.¹⁶ Panel b) shows how this occurs. Area A, per (29), expands by rectangle $R^B + R^C$, where R^B switches from that of action by farm 1 only to that of action by both farms and R^C switches from that of action by neither farm to that of action by both farms.

Considering area R^C , joint surplus changes from $V_1\sigma^2 + V_2\sigma^2$ to $V_1 + V_2 - c_1 - c_2$. Since both $1 - \sigma^2 > \rho_2$ and $1 - \sigma^2 > \rho_1$ in R^C , we can be sure that $V_1 + V_2 - c_1 - c_2 > V_1\sigma^2 + V_2\sigma^2$. Not only does joint surplus increase but also both farms gain from leadership by farm 2 rather than farm 1. It may seem surprising that farm 2 should lead when $\rho_1 < \rho_2$, and the reason is illuminating. In this area, the farm ρ_i values are sufficiently close that strengthening farm 2 incentives (through getting it to internalize more consequences of its action by leading) elicits action by farm 2. This occurs because farm 2 anticipates that farm 1 will then act upon seeing an increase in marginal private value of its own action, as a consequence of the prior farm 2 action.

Considering area R^B , joint surplus changes from $V_1\sigma + V_2\sigma - c_1$ to $V_1 + V_2 - c_1 - c_2$. Writing the change in joint surplus as $V_1(1 - \sigma) + V_2(1 - \sigma - \rho_2)$, we are sure that $V_2(1 - \sigma - \rho_2) < 0$ on interior points of R^B . By contrast with area R^C , the leader would prefer to follow. While $V_1(1 - \sigma) > 0$ on interior points of R^B , the value of V_1 can be an arbitrarily small positive number so that circumstances exist where leadership by farm 2 reduces joint surplus. This occurs

¹⁶ Farm 2 never has the incentive to act alone when it moves first. This is because $\sigma - \sigma^2 > \rho_2$ implies $\sigma - \sigma^2 > \rho_1$ whenever $\rho_2 > \rho_1$. That leading farm 2 will not act alone distinguishes (30) from (29). In (30), the conditions for farm 2 to act are $1 - \sigma^2 > \rho_2$ and $1 - \sigma > \rho_1$ where the second condition is due to the necessity that farm 1 also acts. The only other case where action occurs is when farm 1 acts alone, i.e., where $\sigma - \sigma^2 > \rho_1$ and $1 - \sigma^2 \leq \rho_2$.

when ρ_1 is comparatively small and V_1 is also small, i.e., c_1 must be very small. In such circumstances, it is socially inefficient to elicit action by farm 2 when that farm would have in any case benefited from action by farm 1. This is unlikely to apply, however, if scale economies exist in the cost of biosecuring.

Discussion

Comparisons across political and economic systems, as well as across organizational forms, have taught us that institutional structure matters in how it modifies human behavior. International and national agencies seeking to protect against disease entry have tended to place much emphasis on developing public health capacities. Infectious disease epidemics, though, often arise because of oversights in system design and/or lapses in human behavior. In order to appreciate such biosecurity vulnerabilities, it is necessary to agree upon and understand in some detail the economic nature of relevant human behavior. The intent of this paper has been to develop an economic model of some human aspects of the infectious disease threat.

As far as it was developed in this paper, the spread variant of our model was largely descriptive. A stronger policy component was developed for the entry variant. In particular, a policy to compel at least some growers (in practice, likely the largest growers) to each take a biosecuring action may elicit the action from each of the less readily monitored smaller growers. In addition, public or private endeavors to communicate dispositions toward a biosecuring action concerning entry may well lead to more extensive use of the threat-reducing action.

Inevitably the model could be adapted to better reflect reality, but at the cost of increasing model complexity. The assumption that all parties know the costs and benefits to others could be relaxed through positing a Bayesian game version, but the qualitative results should not be affected. The model might also be extended to endogenize interactions between scale of production and equilibrium disease threat levels, to allow for repeated interactions, and to include private actions that reduce the probability of disease exits from a farm. How any scale

economies in biosecurity costs might affect behavior is a matter of importance for parts of the world where backyard production is widespread. In order to better prepare for animal health epidemics, an extension of immediate policy relevance would be to study farm operator incentives to report suspect events when the extent of spread is stochastic but partially controllable.

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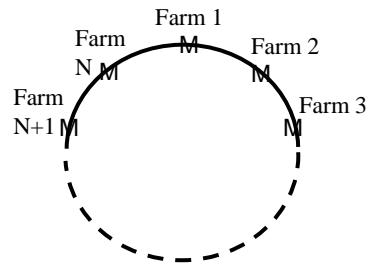


Figure 1. Farms located on a circle

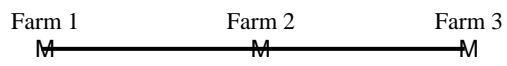


Figure 2. Three farms located on a line

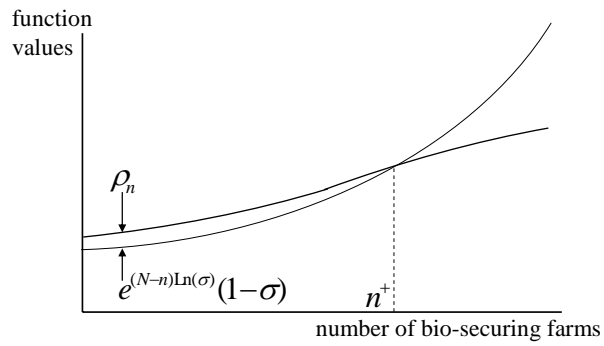


Figure 3. Complete coordination failure in simultaneous move game to secure region from outside infection

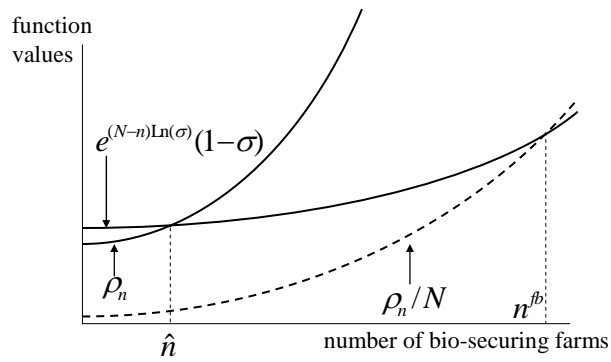


Figure 4. Under-provision in simultaneous move game to secure region from outside infection

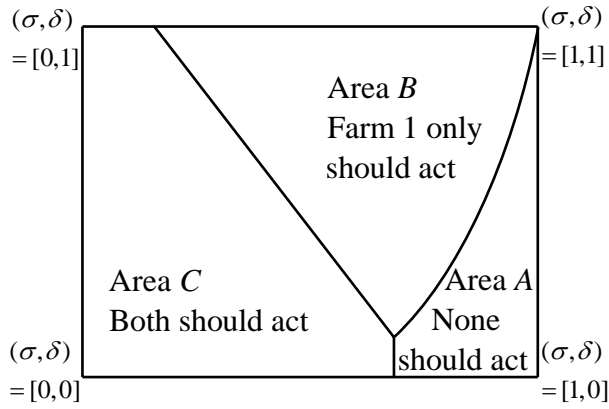


Figure 5. First-best choices over space $(\sigma, \delta) \in [0, 1]^2$

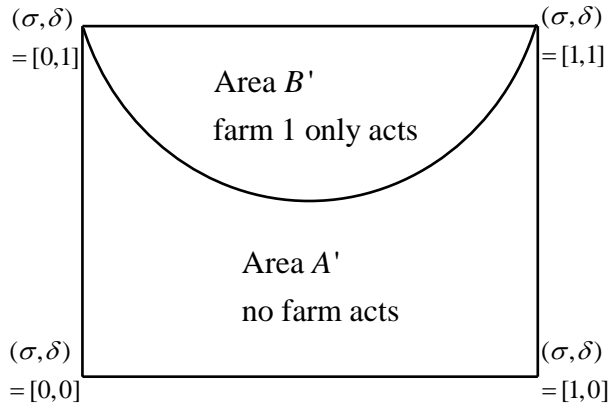


Figure 6. Nash sequential-move choices over space $(\sigma, \delta) \in [0, 1]^2$

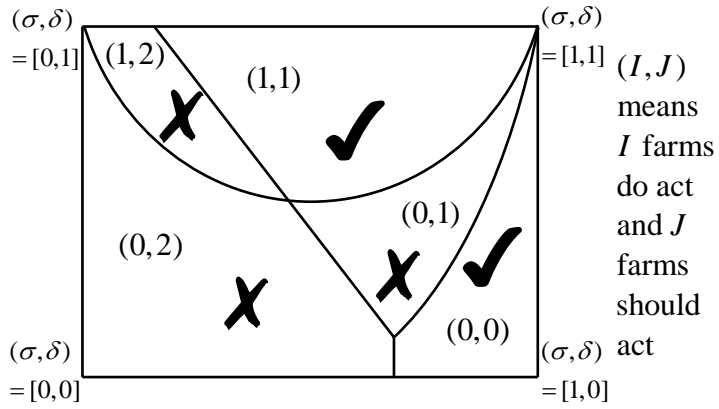


Figure 7. Non-monotone welfare losses due to strategic behavior as (σ, δ) values change

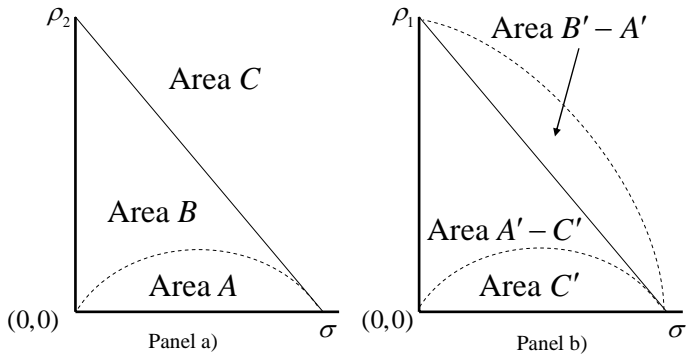


Figure 8. Role of communication in coordinating equilibrium

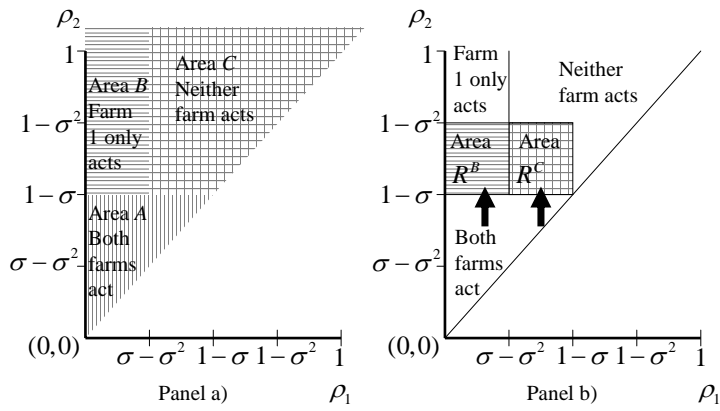


Figure 9. Actions and profits when leadership changes from farm 1 to farm 2, $\rho_1 < \rho_2$