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ANALYSIS

Biosecurity incentives, network effects, and entry of a rapidly spreading pest

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ABSTRACT

Protection against pest invasion is a public good. Yet the nature of private incentives to avoid entry is poorly understood. This work shows that, due to increasing returns or network effects, private actions to avoid entry are strategic complements. This means that compulsory action, at least by a subset of parties, can be an effective policy. Both heterogeneity in biosecurity costs and the effect of private actions on the extent of the invasion threat are shown to have ambiguous effects on the magnitude of welfare loss due to strategic behavior. Communicated leadership by some party is preferred to simultaneous moves, and it may be best if the party with highest biosecurity costs assumes a leadership role.

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1. Introduction

One of the many dimensions of globalization has been the unintended introduction of alien species into ecosystems. In some cases, the result has been drastic change in ecosystem equilibrium such that great harm has resulted. A host of economic issues arise when seeking to optimally control for these effects (Shogren and Tschirhart, 2005). The welfare and political aspects of Pigouvian taxes on transported goods, which can be hard to distinguish from trade tariffs, is one suite of issues that

has received attention (McAusland and Costello, 2004; Margolis et al., 2002). Another suite of issues pertains to the allocation of resources between prevention and ex-post management, including whether to accept an equilibrium level of invasion or attempt eradication (Perrings, 2005; Olson and Roy, 2002, *in press*). As with the trade literature, in these models a central authority uses instruments to trade off welfare benefits against the sum of private and social costs without detailing any human behaviors that give rise to these externalities. Indeed, the existing body of economic work on prevention has largely had

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an optimal control orientation whereby a central planner seeks to influence caretaking through a, possibly stochastic, control technology (Leung et al., 2005). Other research, in Batabyal and Beladi (2006), has taken an optimal queuing perspective to better understand socially optimal behavior at ports.

While these approaches are often well-justified when modeling government efforts to manage this class of problems, they assume a centralized approach that does not characterize the environment in which many important ecosystem protection decisions are made. In particular, these decisions are often made by unmonitored individuals who do not seek to maximize social welfare as they do not face the full consequences of their decisions. Thus, a game theory analysis is appropriate. The interest of the present work is in some behavioral features concerning the entry of a pest into an ecosystem. As we shall show, private decisions on entry endow the problem with apposite structure. For policy purposes, an important aspect of these unmonitored choices is the complementary effect they have on the marginal benefits others derive.

Consider the context of a lake where only a finite number of individuals have access to boating privileges. The lake is presently free of some rapidly spreading pest, be it a weed, microbe, mollusk, or small vertebrate. If the pest enters the lake it will colonize with certainty and reduce welfare to all users. Some action, perhaps boat inspection and cleaning prior to launch, eliminates the risk of entry. There are clearly externalities, as boat hygiene is a public good. All in the region benefit from the pest's absence without rivalry over the benefits, while non-acting firms cannot be excluded from the benefits.¹ But the action comes at a private cost.

Each boater's biosecurity decision depends upon her sense of what others are doing. If the sense is that few others clean then the threat of invasion in the near future is high and the expected marginal private benefit from action is low. If the belief is that most other boaters clean then this boater could be

the weakest link and the incentive to clean is strong. There is a network effect somewhat similar to the classic problem of encouraging the first few pioneers to buy a telephone or a high-definition television (Shy, 2001). Explicit information that others clean should encourage this boater to do so too.

The problem may be viewed as one of transboundary pollution. The study of strategic interactions across boundaries has received attention in a variety of contexts, acid rain for example (Murdoch et al., 1997; Maler and De Zeeuw, 1998). Among the few papers that study in a formal way strategic issues concerning invasive species are Fernandez (2006) and Batabyal and Beladi (2007). Fernandez's context is one of invasive species stock accumulation at trading ports and trade-proportional species flows between these ports. Ports choose privately optimal control strategies that do not adequately account for trade spillovers. In such a game, the activity of one port in controlling a pest should be a strategic substitute for activities at other ports. Batabyal and Beladi study tariff policy to induce credible price signals on exporter biosecurity actions for imperfect substitutes produced in Bertrand duopoly by a home firm and a foreign firm.

In Section 2, the basic 'weakest link' public bad model is laid out. The view that pest invasion is a public bad that can arise at the weakest link has been proffered by Perrings et al. (2002). The weakest link technology has been used in modeling by Horan et al. (2002) and by Horan and Lupi (2005), but neither of these have studied the nature of inefficiency under strategic behavior. The model is then used to show that biosecurity decisions are strategic complements across players. This is of policy relevance because multiple Nash equilibria may be supported where the lower action levels are clearly Pareto inferior. Government regulation that compels a readily monitored subset of agents to act may induce others to act, and so may increase the welfare of all without the need for transfers.

Section 3 illustrates the model for the case of two players and heterogeneous costs. It is shown that more cost heterogeneity can increase or decrease the extent of welfare loss relative to first-best. This ambiguous effect on welfare loss also applies to the magnitude of a player's contribution to the risk of invasion. The role of leadership in this game of strategic complements (Milgrom and Roberts, 1990; Vives, 1990, 2005) is considered in Section 4. Leadership by some player increases welfare, but imposing it on the player least likely to biosecure may be Pareto preferred because that party's incentives are most likely to be enhanced. So as to draw out some of the model's constraints and how they can be modified, the framework is adapted to accommodate a nonfinite set of decision makers with a value enhancement motive for biosecuring. A brief discussion on policy issues and further work concludes.

2. Preventing entry

The basic technical model draws on joint production studies in Kremer (1993), Perrings et al. (2002), Horan et al. (2002), and Winter (2004). A region has N firms, labeled as $n \in \{1, 2, \dots, N\} = \Omega_N$. Each firm seeks to protect potential value to the extent V_n , and each can take a biosecuring action. The cost of this

¹ A variant on this context is the introduction of an infectious disease into an island farming ecosystem by a farmer who goes abroad on a farm tour. Although not a significant human health concern, Foot and Mouth disease caused great economic loss when introduced into Taiwan in 1997 and the United Kingdom in 2001. Taiwan had to kill about 3.5 million hogs, and suffered revenue losses of about \$1.5 billion per year for an indefinite period as it was locked out of export markets. The UK culled approximately 4.9 million sheep, 0.7 million cattle and 0.4 million pigs, with economic losses in the order of \$4 billion (General Accounting Office, 2002). As far as we know, the origins of these outbreaks have never been established with certainty. According to Scudamore (2002), then the UK Chief Veterinary Officer, a Northumberland pig farm with a license to feed processed waste food may have been the initial farm. The farmer was later convicted of failure to inform the authorities of the disease, as it was on the list of notifiable diseases. He was also convicted of feeding untreated waste, as he had a responsibility to treat what he had a license to feed. This latter point identifies a biosecurity action at the border of the 'UK animal feed region.' Feed, animals, humans, vehicles, and wind can carry the disease. Public measures to prevent entry include a large variety of activities at country borders, as well as public awareness programs. In the end, there is heavy reliance on voluntary behavior on the part of international travelers, especially those involved in the agriculture and food sector.

biosecurity action to each firm is $c_n \geq 0$, and an affected firm loses all of V_n .^{2,3}

The private action can be viewed as a firm's contribution to increasing the probability a public good is provided. For the lake example, one may wonder whether limited access means that the lake is a club good, where a means for denying access has been developed (Cornes and Sandler, 1986). With a golf club, access is conditioned on fees to support the course. With the lake, access cannot be conditioned on biosecurity behavior when such behavior cannot be monitored.

Private entry risks are independent, identically distributed Bernoulli random variables with realizations 0 and 1. Each firm can increase the probability it is not the originator of pest entry from $\sigma \in (0,1)$ to 1.⁴ Parameter σ can be viewed as the private contribution to invasion risk, or the entry threat. Firm biosecurity costs and the values firms seek to protect are assumed to be common knowledge. In addition we assume the worst-case, weakest link scenario in that the pest immediately spreads to all the region's firms if it enters.⁵ This means that all firms need to succeed in not being the originating firm if their own value is to be spared with certainty.

When no firm in the region incurs the cost then the expected payoff to the n th firm is $V_n \sigma^N$, while if k other firms incur the cost then the probability that the disease does not enter is σ^{N-k} and the expected profit to a non-acting firm is $V_n \sigma^{N-k}$. Payoff to the firm depends upon whether the firm has incurred the cost.

² Kremer's concern is with how heterogeneously skilled workers sort into teams for joint production, and how a natural increasing returns technology for team product affects equilibrium wage structures. Winter's paper studies 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 pest event state-conditional remunerations, V_n conditional on no pest entry, as being given and focus attention on the consequences for actions.

³ It should be understood that V_n is only the exposed value. Aspects of surplus not affected by the pest are ignored. The label 'firm' was chosen for want of some brief descriptor. It could be replaced by 'customer,' 'agent,' or 'player.'

⁴ The problem could be further articulated by writing $Pr(nis) = 1 - Pr(entry)Pr(esc|entry)$, where $Pr(nis)$ is the probability a firm is not the invasion source, $Pr(entry)$ is the probability the pest does enter through the firm's business activities, and $Pr(esc|entry)$ is the probability the pest escapes to become a region's problem given that it enters through the firm's business activities. In turn, $Pr(entry)$ could be made a decreasing function of some biosecurity-at-entry variable x_1 at unit cost w_1 , where $Pr(entry) = f(x_1)$. And $Pr(esc|entry)$ could be made a decreasing function of some biosecurity-at-exit variable x_2 at unit cost w_2 , where $Pr(esc|entry) = g(x_2)$. So $Pr(nis) = 1 - f(x_1)g(x_2)$ with cross-derivative $d^2Pr(nis)/dx_1 dx_2 = -[df(x_1)/dx_1][dg(x_2)/dx_2] \leq 0$. The within-firm decisions are substitutes. This would add some wrinkles to Proposition 1 below for the less developed model, where supermodular game theory is applied.

⁵ We recognize that pest spread to all the region's firms is unlikely. But, whether pest affected or not, all firms will suffer losses when the pest enters a region because unaffected firms have to become more vigilant in guarding their own perimeters. The model can be adapted to alternative scenarios on losses, but at a loss in tractability. Reed and Frost type non-spatial models of spread with emphasis on the statistical dynamics of spread exist, but are involved (Daley and Gani, 1999). Explicitly spatial models would be even more difficult to study analytically.

Suppose, as a Nash conjecture in a simultaneous-move game, a firm assesses that it is the dominant strategy for k other firms to incur the cost. Side payments between firms are explicitly ruled out in the analysis to follow. The expected payoff to the n th firm in question is then $V_n \sigma^{N-k-1} - c_n$ if it does act and $V_n \sigma^{N-k}$ if it does not. The firm's objective function is⁶

$$\max [V_n \sigma^{N-k-1} - c_n, V_n \sigma^{N-k}]. \quad (1)$$

The marginal private payoff to acting is $\Delta = V_n \sigma^{N-k-1} - V_n \sigma^{N-k} - c_n$ with derivative $d\Delta/dk = -V_n \ln(\sigma) \sigma^{N-k-1} (1-\sigma) \geq 0$. This ensures that the game is one of strategic complementarities, in the manner of Vives (1990, 2005) and Milgrom and Roberts (1990). We have, therefore,

Proposition 1. *The marginal value of action to a firm increases with the number of other firms that act. That is, actions are strategic complements.*

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 firm does (does not) act if⁷

$$\sigma^{N-k-1}(1-\sigma) > (<) \rho_n. \quad (2)$$

Given that costs and protected values are known to all, firm 1 will be identified by all as that most likely to biosecure. The threshold for this firm to act is $\sigma^{N-1}(1-\sigma) > \rho_1$, i.e., $k=0$ in Eq. (12).

If this threshold is met, then all other firms will arrive at the conjectural conclusion that firm 1 will take the biosecuring action and the threshold for the second firm to act is $\sigma^{N-2}(1-\sigma) > \rho_2$. In general, if iterated dominance arguments imply that all firms $i \in \Omega_{n-1}$ biosecure then the threshold for the n th firm to do so is⁸

$$H(n, \sigma) > \rho_n; \quad H(n, \sigma) \equiv e^{(N-n)\ln(\sigma)}(1-\sigma). \quad (3)$$

Notice that $H(n, \sigma)$ is not monotone in σ , and this is because σ performs two roles. It determines the level of the benefit if one does not biosecure, $V_n e^{(N-n+1)\ln(\sigma)}$, and it provides the proportional shift in benefit if one does biosecure. Depending on the values of the ρ_n , $n \in \Omega_N$, the game can conceivably have a large number of pure strategy equilibria where we will shortly develop on this point. What of mixed strategies? Actually, properly mixed strategies are unlikely to occur in this supermodular game as they tend to be unstable (Echenique and Edlin, 2004).

Due to Proposition 1, no Nash equilibrium will involve a firm acting when it should not do so under first-best. That is, all Nash equilibria will involve (weakly) insufficient levels of action. Indeed,⁹

Proposition 2. *A small subsidy to any one firm (weakly) increases social welfare.*

For the purpose of illumination, we will illustrate what Eq. (3) can reveal. Fig. 1 graphs the left- and right-hand sides of

⁶ We note in passing that theory implies a reduction in any c_n weakly increases the incentive for each producer to take their respective action.

⁷ Here, as elsewhere in the section, ties are assigned to non-action.

⁸ We use identity $e^{(N-n)\ln(\sigma)} \equiv \sigma^{N-n}$.

⁹ See Theorem 7, page 1267, in Milgrom and Roberts (1990) on welfare order among the set of Nash equilibria. In light of the complementarities, a small subsidy to any one firm (weakly) increases action by all firms.

Fig. 1 – Complete coordination failure in simultaneous-move game to prevent entry.

Eq. (3) as continuous functions. The two expressions are increasing in the value of n . For ρ_n , monotonicity is due to the logic of iterated dominance. Firms with the lowest cost to benefit ratio will be viewed as biosecuring first. For $H(n, \sigma)$, monotonicity is due to a stochastic version of increasing returns, i.e., the marginal value of protective action by a firm increases as the number of protecting firms increases. There is, in a sense, a network effect. In Fig. 1, $H(n, \sigma) = \rho_n$ at one value of n , $n = n^+ < N$, where we assume for simplicity that n^+ is a natural number.¹⁰ Since $H(n, \sigma)$ is initially smaller, however, a Nash equilibrium is for no firm to make the biosecurity investment. Another equilibrium is for all firms to act.

The no investment equilibrium would be an unfortunate outcome. Suppose that the first n^+ firms, i.e., those with the lowest cost to protected value ratio, are compelled by law to take the action. Then all remaining firms will find it advantageous to invest, and payoff to the first firm becomes $V_n - c_n$, rather than $V_n \sigma^N$. If $\rho_1 \in (\sigma^N, 1]$, then the first firm will be better off after being compelled. Similarly, if $\rho_n \in (\sigma^N, 1] \forall n \in \Omega_n$, then all compelled firms will be better off n for it. Indeed, if all producers are compelled to act then 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.¹¹

In Fig. 2 we have drawn ρ_n so that it is initially lower than $H(n, \sigma)$. Concentrate for the moment on the two thick, fully-traced curves. As $H(1, \sigma) > \rho_1$, the first firm does biosecure for sure. The investment occurs up to at least firm $\hat{n}$, which happens to be the unique point of intersection under our parameter choices. Suppose, for convenience of functional form, that $\rho_n = \psi_0 e^{\psi_1 n}$ in Fig. 2. Then Eq. (3) with equality solves as

$$\hat{n} = \frac{1}{\psi_1 + \ln(\sigma)} \ln\left(\frac{\sigma^N - \sigma^{N+1}}{\psi_0}\right), \quad (4)$$

where $\psi_1 + \ln(\sigma) > 0$ since the figure has unit costs on the marginal firm growing more rapidly than unit private benefits of protective actions.

¹⁰ This single-crossing is happenstance because ρ_n , viewed as a continuous function, could cross $H(n, \sigma)$ no time or multiple times as it increases.

¹¹ Under free-riding, the firm would be disposed to deviate when all other firms engage in first-best behavior. In our model, the incentive to deviate weakens as more firms act. It remains the case, though, that marginal private benefit differs from marginal social benefit at first-best.

Now consider the set of first-best actions. By analog with Eq. (1), the change in social welfare due to action by a firm is

$$\text{Firm that} \begin{cases} \text{does act : } N\bar{V}\sigma^{N-k-1} - c_n - \{\text{costs to } k \text{ acting firms}\}; \\ \text{does not act : } N\bar{V}\sigma^{N-k} - \{\text{costs to } k \text{ acting firms}\}; \end{cases} \quad (5)$$

where $N\bar{V} = \sum_{n \in \Omega_N} V_n$. Note first that the iterated dominance order in which firms 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 also biosecure under first-best because the action threshold is always lower under first-best. A second point to note is that social welfare may be convex in the number of biosecuring firms as higher-cost firms change from not biosecuring to biosecuring. This was the case in Fig. 1, as can be seen by graphing the vertical gap $H(n, \sigma) - \rho_n$ between functions.

Suppose $V_n = \bar{V} \forall n \in \Omega_N$ and the welfare function is concave in the number of firms, as in Fig. 2. Then first-best solves $H(n, \sigma) = \rho_n / N$ with value n^{fb} . Fig. 2 also depicts how the social welfare solution compares with the solution under private incentives, see the broken curve. Under cost structure $\rho_n = \psi_0 e^{\psi_1 n}$, then the optimal number of firms acting (with least cost first) is given by

$$n^{fb} = \frac{1}{\psi_1 + \ln(\sigma)} \left[\ln(N) + \ln\left(\frac{\sigma^N - \sigma^{N+1}}{\psi_0}\right) \right] = \hat{n} + \frac{\ln(N)}{\psi_1 + \ln(\sigma)} > \hat{n}. \quad (6)$$

An expression for optimal subsidy is rather apparent; reduce a firm's ρ_n value from c_n / V_n to $c_n / [NV_n]$.

In summary, the points we make in this section are quite intuitive. Firms depend on each other when seeking to prevent pest entry. Knowledge that others biosecure strengthens a firm's incentives to do so because this knowledge increases the marginal impact of the firm's action. If firms know about the costs and benefits of prevented entry to others then each firm can deduce who will act anyway. This process of logical inference may lead some to act who, *prima facie*, might not be considered to be good candidates for acting. Nonetheless, small subsidies in this system of complementary actions can promote biosecurity throughout the system and increase expected social surplus. We will consider next the role that cost heterogeneity has on private solutions to the problem.

Fig. 2 – Under-provision in simultaneous-move game to prevent entry.

3. Illustrating effects of cost heterogeneity

Costs and protected values are unlikely to be common across firms. For the lake example, the number of times a boat has to be cleaned will depend upon how often it is taken away from that lake. The cost of each cleaning will depend upon the boat type, and the disposition of boaters to the physical work involved. In order to strip the model down to its bare essentials when considering cost heterogeneity, a two-firm region is considered. Suppose that parameters are $V_1=V_2=2$, $c_1=1-\delta$, and $c_2=1+\delta$ with $\delta \in [0,1]$ so that the sum of costs is constant.

Expected welfare is 2 if both firms biosecure. First-best behavior is determined by the actions supporting

$$\max_{\{2 \text{ act}, 1 \text{ acts}, 0 \text{ act}\}} \text{Social Surplus} = \max [4\sigma^2, 4\sigma + \delta - 1, 2] \quad (7)$$

so that social first-best involves

$$\begin{aligned} \text{A) : none act if} & \quad \{2\sigma^2 \geq 1 \text{ and } 4\sigma^2 \geq 4\sigma + \delta - 1\}; \\ \text{B) : firm 1 only acts if} & \quad \{4\sigma + \delta \geq 3 \text{ and } 4\sigma + \delta - 1 > 4\sigma^2\}; \\ \text{C) : both firms act if} & \quad \{3 > 4\sigma + \delta \text{ and } 1 > 2\sigma^2\}. \end{aligned} \quad (8)$$

Fig. 3 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 firms (area C) or neither firms (area A). Indeed, if $\delta \in [0, 3 - 2\sqrt{2})$ then action by exactly one firm is not optimal. If, though, $\sigma \geq 1/\sqrt{2}$ then optimal behavior can only be for at most one firm to biosecure because firm 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,

$$\begin{aligned} \text{A') : none act if} & \quad \{2\sigma^2 \geq 2\sigma + \delta - 1\}; \\ \text{B') : firm 1 only acts if} & \quad \{2\sigma + \delta - 1 > 2\sigma^2 \text{ and } 2\sigma + \delta \geq 1\}; \\ \text{C') : both firms act if} & \quad \{2\sigma + \delta - 1 > 2\sigma^2 \text{ and } 1 > 2\sigma + \delta\}. \end{aligned} \quad (9)$$

Fig. 4 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 $2\sigma + \delta - 1 > 2\sigma^2 \geq 0 > 2\sigma + \delta - 1$. Area B' has a redundant second inequality, since $2\sigma + \delta - 1 > 2\sigma^2 \geq 0$ implies $2\sigma + \delta > 1$. The area contains parameter

Fig. 3 – First-best choices over space $(\sigma, \delta) \in [0,1]^2$.

Fig. 4 – Nash simultaneous-move choices over space $(\sigma, \delta) \in [0,1]^2$.

pairs such that the marginal private benefit of action by the second firm is low relative to the high marginal cost. The δ interval (viewing vertical sections) for which the first firm will act vanishes when $\sigma \rightarrow 0$. This is because the prospects of success are negligible given that the second firm 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 Figs. 3 and 4, we see that no counterpart to area C in Fig. 3 exists in Fig. 4, while there exist $(\sigma, \delta) \in [0,1]^2$ values such that both firms should biosecure but neither do.

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 firm biosecures expands under simultaneous moves when compared with first-best. Areas B and B' are not comparable since cases where two firms should biosecure have only one doing so and cases where one firm should biosecure have neither doing so. In no instance does a firm 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, then both firms should biosecure while neither do. Here, the firms are sufficiently similar that both firms come to the same conclusion and this is not to act. When σ is low and δ is high, though, firm 1 only has the incentive to biosecure since it is too costly for firm 2 to do so. At intermediate σ and high δ values then firm 1 acts and only firm 1 should act, so that first-best is attained in our discrete model.

Fig. 5, which overlays Fig. 4 on Fig. 3, identifies non-monotonicities in the welfare loss effects of parameter values. In it the indicator couple (I, J) gives (# firms that act, # firms that

Fig. 5 – Non-monotone welfare losses due to strategic behavior as (σ, δ) values change.

Fig. 6 – Welfare under Nash simultaneous moves as entry threat parameter increases.

should act). Two areas have simultaneous moves Nash equilibrium that support first-best. They are check marked (✓), are labeled as T_2 and T_5 , and are connected only at point $[1,1]$ to the upper right. Welfare loss occurs for parameters in cross marked areas (✗), which are labeled as T_1 , T_3 , and T_4 .

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 . We can conclude that the welfare loss due to strategic behavior is not monotone in entry threat parameter 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. We can conclude that the welfare loss due to strategic behavior is also not monotone in cost heterogeneity parameter δ . Two (1,1) permutations do not occur. Permutation (2,1) is not possible due to Proposition 1 and its consequence that no firm will biosecure when it should not. Permutation (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.

As to how sensitive the welfare (and not welfare loss) level is to entry risk parameter σ and cost heterogeneity parameter δ under strategic behavior, consider Fig. 4 again. Welfare under simultaneous moves Nash equilibrium is $4\sigma^2$ in area A' while it is $4\sigma + \delta - 1$ in area B' . The boundary between these areas is determined by the solution to $4\sigma + 2\delta - 2 = 4\sigma^2$, i.e., the firm 1 comparison between biosecuring or not when firm 1 reasons that firm 2 will do nothing. So welfare at the boundary switches from $W(\sigma, \delta) = 4\sigma + 2\delta - 2$ in A' to $W(\sigma, \delta) = 4\sigma + \delta - 1$ in B' , a change of $1 - \delta \geq 0$. In this case, welfare under strategic action is increasing in cost heterogeneity parameter δ . A high δ parameter value induces one firm to biosecure, and that is better than none. But take a horizontal cross-section at $\delta = \delta^0$ that cuts through B' and label the intersecting points as $\hat{p} = (\hat{\sigma}, \delta^0)$ and $\tilde{p} = (\tilde{\sigma}, \delta^0)$, $\hat{\sigma} < \tilde{\sigma}$. Observe that $\lim_{\sigma \uparrow \hat{\sigma}} W(\sigma, \delta) = 4\hat{\sigma} + 2\delta - 2 < \lim_{\sigma \downarrow \tilde{\sigma}} W(\sigma, \delta) = 4\tilde{\sigma} + \delta - 1$ whereas $\lim_{\sigma \uparrow \tilde{\sigma}} W(\sigma, \delta) = 4\tilde{\sigma} + \delta - 1 > \lim_{\sigma \downarrow \hat{\sigma}} W(\sigma, \delta) = 4\hat{\sigma} + 2\delta - 2$. As depicted in Fig. 6, it can be seen that welfare is not monotone in entry threat parameter σ .¹²

In conclusion, the heterogeneity of entry prevention costs matters. It is never the case that firms who should not act actually do so in our game. But when costs are sufficiently

dispersed then, in our illustration, one among two firms acts whereas neither acts when costs are not dispersed. In other circumstances though (with lower average cost), both will act when costs are not dispersed whereas only one will act when costs are sufficiently heterogeneous. The high cost firm will not act because its cost is high and it does not capture the surplus its action provides to the firm that does act.

4. Leadership

As is well-known from the standard Stackelberg quantity-setting game and elsewhere, the capacity to communicate ones action commitments to other players has consequences for game equilibrium. What is less clear, however, is the set of contexts under which society and other players can be better off for this. In what is to follow we will consider how the timing of moves affects incentives to engage in actions to avoid pest entry.¹³ Continuing the two-firm context, we compare simultaneous moves equilibrium with the cases where firm 1 moves first and where firm 2 moves first.

When firm 1 decides first, then it will recognize its capacity to manipulate the firm 2 action. In particular, if firm 1 biosecures then firm 2 will also do so whenever $1 - \sigma > \rho_2$. When both biosecure, then profit to firm 1 is $V_1 - c_1$. If firm 1 acts and $1 - \sigma \leq \rho_2$, then payoff to firm 1 is $V_1\sigma - c_1$. If firm 1 does not act and $\sigma - \sigma^2 > \rho_2$ then payoff to firm 1 is $V_1\sigma$. Finally, if firm 1 does not biosecure and $\sigma - \sigma^2 \leq \rho_2$ then payoff to firm 1 is $V_1\sigma^2$.

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

$$A) : \rho_2 < \sigma - \sigma^2; \quad B) : \sigma - \sigma^2 \leq \rho_2 < 1 - \sigma; \quad C) : 1 - \sigma \leq \rho_2; \quad (10)$$

and they are depicted in Panel a) of Fig. 7. For area A, firm 1 can be sure that firm 2 will biosecure regardless of the firm 1 decision. Therefore the increment in firm 1 payoff due to action is $V_1 - c_1$ (when both act) less $V_1\sigma$ (when only firm 2 acts), so that the firm acts if $1 - \sigma > \rho_1$. This is area A' (the sum of areas C' and $A' - C'$) in Panel b) of Fig. 7. For area B in Panel a), as given in Eq. (10), firm 2 replicates the decision of firm 1. Leadership confers on firm 1 the ability to manipulate to strategic advantage the firm 2 decision. The increment in firm 1 payoff upon biosecuring is $V_1 - c_1$ (when both act) less $V_1\sigma^2$ (when neither firm acts), so that firm 1 acts if $1 - \sigma^2 > \rho_1$ and $\sigma - \sigma^2 \leq \rho_2 < 1 - \sigma$. For ρ_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 Eq. (10), labeled C in Panel a), is where firm 2 will not act regardless of the communicated firm 1 commitment. Action by firm 1 then changes own payoff from $V_1\sigma^2$ to $V_1\sigma - c_1$ so that the action will be taken whenever $\sigma - \sigma^2 > \rho_1$. This parameter area, labeled as C' in Panel b), is contained in area A' so that $C' \subseteq A' \subseteq B'$. The areas are

$$A') : \rho_1 < 1 - \sigma; \quad B') : \rho_1 < 1 - \sigma^2; \quad C') : \rho_1 < \sigma - \sigma^2. \quad (11)$$

¹² Ball endings on the left- and right-hand segments in Fig. 6 are to assign values at discontinuity points. Remember, points of indifference have been assigned to non-action.

¹³ It is not generally true that the first mover has an advantage. See Dixit and Skeath (2004) for discussions on gains from order of move.

Fig. 7 – Role of communication in coordinating equilibrium.

One may think of this parameter space containment as follows. The set $(\sigma, \rho_1) \in C'$ in Panel b) contain values for which the leader will take the action anyway, i.e., even when firm 2 will not follow. The set difference $A' - C'$ is an expansion of set C' . It accounts for the recognition that in this case firm 1 knows that firm 2 will biosecure 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, firm 1 biosecures only because firm 2 is then coaxed into acting. This strategic motive for communicated commitment 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 et al., 2005). More directly, two applied theory papers by Winter (2006a,b) find that better performance is elicited from workers when the design of workplace structure through job hierarchies and office layout facilitates communication.

A comparison with simultaneous moves under the iterated dominance criterion is in order. There, for $\rho_1 < \rho_2$, firm 1 moves if $\sigma - \sigma^2 \geq \rho_1$ as it knows that if it doesn't move then firm 2 won't either. Firm 2 moves if both $\sigma - \sigma^2 \geq \rho_1$ and $1 - \sigma \geq \rho_2$. The one difference between simultaneous moves and first movement by firm 1 is the absence of the strategic incentive, as identified in area $B' - A'$ of Fig. 7, Panel b). In that area, joint payoff 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 payoffs of both firms increase.

Fig. 8 – Actions when under firm 1 leadership, $\rho_1 < \rho_2$.

Fig. 9 – Actions when under leadership changes from firm 1 to firm 2, $\rho_1 < \rho_2$.

Compare now actions and welfare when different firms move first. Invoking Fig. 7, when $\rho_1 < \rho_2$ and firm 1 moves first then there are three regions to consider:

- A) : both act $\{1 - \sigma^2 > \rho_1 \text{ and } 1 - \sigma > \rho_2\}$,
Joint payoff is $V_1 + V_2 - c_1 - c_2$;
- B) : firm 1 only acts $\{\sigma - \sigma^2 > \rho_1 \text{ and } 1 - \sigma \leq \rho_2\}$,
Joint payoff is $V_1\sigma + V_2\sigma - c_1$;
- C) : neither act otherwise,
Joint payoff is $V_1\sigma^2 + V_2\sigma^2$.

Fig. 8 describes the choice set in $(\rho_1, \rho_2) \geq (0, 0)$ space where firm 1 moves first and condition $\rho_1 < \rho_2$ precludes from consideration the wedge below the bisector.

On the other hand, when firm 2 biosecures first then the joint payoff is:

- A) : $V_1 + V_2 - c_1 - c_2 \begin{cases} 1 - \sigma > \rho_2 \text{ and } 1 - \sigma > \rho_1, \\ \text{or } 1 - \sigma^2 > \rho_2 \geq 1 - \sigma \text{ and } 1 - \sigma > \rho_1 \geq \sigma - \sigma^2 \end{cases}$;
- B) : $V_1\sigma + V_2\sigma - c_1 \begin{cases} 1 - \sigma \leq \rho_2 \text{ and } \sigma - \sigma^2 > \rho_1 \end{cases}$;
- C) : $V_1\sigma^2 + V_2\sigma^2$ otherwise.

(13)

For B) in Eq. (13), only firm 1 acts, condition $\sigma - \sigma^2 > \rho_1$ ensures that firm 1 will act unilaterally while $1 - \sigma \leq \rho_2$ ensures that firm 2 will not act even in the knowledge that firm 1 will biosecure later regardless. For A) in Eq. (13), which involves action by both firms, condition $1 - \sigma > \rho_1$ ensures that firm 1 will biosecure if firm 2 does while condition $1 - \sigma > \rho_2$ ensures that firm 2 will biosecure in the knowledge that firm 1 will follow. But there is another parameter set under which both will biosecure. When firm 2 leads, if $1 - \sigma^2 > \rho_2 \geq 1 - \sigma$ then firm 2 would not biosecure as a follower, but might do so if its communicated action could change the action of firm 1. This occurs when $1 - \sigma > \rho_1 \geq \sigma - \sigma^2$.

The payoff possibilities are the same as under leadership by firm 1, but the supporting parameters differ.¹⁴ Fig. 9 shows how this occurs. Area A, per Eq. (10), expands by rectangle D where

¹⁴ Firm 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 firm 2 will not act alone distinguishes Eq. (13) from Eq. (12).

actions under parameters in set D sublime from action by neither firm to action by both firms. In area D , joint surplus changes from $V_1\sigma^2 + V_2\sigma^2$ under firm 1 leadership to $V_1 + V_2 - c_1 - c_2$ under firm 2 leadership. Since both $1 - \sigma^2 > \rho_2$ and $1 - \sigma^2 > \rho_1$ in parameter area D , 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 both firms gain from leadership by firm 2 rather than firm 1. It may seem surprising that firm 2 should lead when $\rho_1 < \rho_2$, and the reason is illuminating. In this area, the firm ρ_i values are sufficiently close that strengthening firm 2 incentives (through getting it to internalize more consequences of its action by leading) elicits action by firm 2. This occurs because firm 2 rationalizes that firm 1 will then biosecure upon seeing an increase in marginal private value of its own action, as a consequence of the prior firm 2 action.

Considering now the parameter set to the left of D , as defined by $E = \{(\rho_1, \rho_2) : (\rho_1, \rho_2) \in [0, \sigma - \sigma^2] \times [1 - \sigma, 1 - \sigma^2]\}$. One may wonder why firm 2 does not biosecure under these circumstances. In this case, joint surplus would change from $V_1\sigma + V_2\sigma - c_1$ when firm 1 leads and only it biosecures to $V_1 + V_2 - c_1 - c_2$ were leadership by firm 2 to elicit the biosecurity investment by both firms. 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 E . Firm 2 would expect to lose and would not act. But then the surplus to firm 1 becomes $V_1\sigma^2$ if it does not biosecure and $V_1\sigma - c_1$ if it does biosecure. The difference, $V_1\sigma(1 - \sigma) - c_1$, is positive in this area since $\sigma - \sigma^2 \geq \rho_1$. Thus, the set (ρ_1, ρ_2) for which firm 1 only biosecures does not change regardless of who leads. In this area, firm 2 knows that firm 1 will biosecure anyway and takes advantage of the situation by free-riding in leadership. It does not have the strategic motive that it had in area D . Overall, the advantage of allowing firm 2 to lead is that $1 - \sigma^2 > \rho_2 \geq 1 - \sigma > \rho_1 \geq \sigma - \sigma^2$ is possible given $\rho_2 > \rho_1$, and then handing additional strategic motivation to firm 2 will ensure that both firms act.

Proposition 3. *In this game leadership by some firm is preferred by both firms, when compared with simultaneous moves. Leadership by the firm with the higher ρ_i is weakly preferred by both firms when compared with leadership by the other firm.*

What policy implications do these observations have? In many cases a government will have limited capacity to elicit leadership. It can, as it often does, require publicly owned entities to biosecure and to publicize their biosecurity actions. A government can also provide a milieu that fosters private sector leadership through public information campaigns that suggest ways in which the private sector can coordinate. It is likely, though, that larger firms will take the lead. It is perhaps unlikely that firms with high ρ_i will lead as they may have less to protect.

5. Large number of firms

It is clear from Eq. (3) above that the incentive to act at all recedes to zero as the number of non-acting firms becomes sufficiently large. But the private incentive to biosecure survives with an arbitrarily large firm set if the private gain arises not from risk mitigation but from enhancing protected value. Suppose that the number of firms was infinitely large and cost is $\lambda_0 e^{\lambda_1 z}$ for the 100z percentile firm, as ranked from

lowest cost to highest, with $\lambda_0 > 0$ and $\lambda_1 > 0$. Scale $\sigma \in (0, 1)$ such that the probability of entry is σ whenever a null set of firms act and is 1 whenever all act, i.e., the overall risk of entry is σ^{1-z} when the lowest 100z percentile firm biosecure.

Let protected value be V to firms that do not biosecure and $V + \delta$ to firms that do. So firms have a common level of protected value, but differ in protection costs. And in addition to contributing towards the common effort to protect from entry, an investment also enhances the firm's value to be protected by magnitude δ . Consider investment in a boat cleaning pad at one's lakeside home. Although the investment may increase property value, if the lake loses its appeal due to pest infestation then the market value of this investment will likely fall along with that of the property as a whole.

Iterated dominance implies that lower-cost firms act and payoffs are as follows:

$$\text{Firm that } \begin{cases} \text{does act : } (V + \delta)\sigma^{1-z} - \lambda_0 e^{\lambda_1 z}; \\ \text{does not act : } V\sigma^{1-z}. \end{cases} \quad (14)$$

Notice that the firm's biosecurity decision does not affect the exponent on σ because the firm's contribution to entry risk is negligible. Under assumption $\lambda_1 > -\ln(\sigma)$, to allow for interior solutions, it can be concluded that the threshold fraction of firms that will biosecure is given by

$$\hat{z} = \frac{\ln(\delta) + \ln(\sigma) - \ln(\lambda_0)}{\lambda_1 + \ln(\sigma)}. \quad (15)$$

From derivatives

$$\frac{d\hat{z}}{d\ln(\sigma)} = \frac{1 - \hat{z}}{\lambda_1 + \ln(\sigma)} > 0; \quad \frac{d\ln(\sigma^{1-\hat{z}})}{d\ln(\sigma)} = \frac{(1 - \hat{z})\lambda_1}{\lambda_1 + \ln(\sigma)} > 0; \quad (16)$$

it follows that the incentive to biosecure increases as the entry risk parameter increases (so that there is lower entry risk). Furthermore, the effect on overall expected gain $\delta\sigma^{1-\hat{z}}$ is two-fold positive. There is a direct effect, as given by $1 - \hat{z}$. There is also an indirect effect, through encouraging the action. By contrast with the small numbers situation, where in addition the protected value does not depend on the action, an increase in σ always increases social welfare.

6. Discussion

Comparisons across political and economic systems, as well as across organizational forms, have taught us that institutional structures matter in how they modify human behavior.

International and national agencies seeking to protect against pest entry have tended to place much emphasis on developing public infrastructure. To some extent, this is as it should be since such agencies have strongest influence over public decisions. Entry though, often arises due to 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 pest invasion threat. In particular, beliefs among individuals making decentralized biosecurity decisions can be self-fulfilling. If a sufficient number

have forlorn beliefs about the effectiveness of their biosecurity efforts against a pest, then the pest is likely to invade. But the sense among decision makers that their peers are more optimistic will elicit actions across the board that justify the optimism. A policy to compel at least some firms (in practice, likely the largest) to each take a biosecuring action may elicit the action from each of the less readily monitored smaller firms. In addition, public or private endeavors to credibly communicate dispositions toward a biosecuring action concerning entry may well lead to more extensive use of the threat-reducing action.

Some modifications to the above model may allow for an analysis of how private incentives can be engaged to stamp out a pest that has become entrenched in an ecosystem. Suppose, for sub-regions within a region, enough is known about sub-region eradication costs, and re-infestation probabilities given partial eradication. Suppose too that sub-regions are ranked by some optimally chosen index that accounts for how costly it would be to clear the sub-region and how disruptive partial clearance would be for the pest's resilience. Clearing out the sub-regions by rank order may strengthen decentralized incentives to clear other sub-regions subsequently. In practice, issues arising in pest eradication policy under limited resources have revolved around two strategies. One is to first tackle costly-to-clear pest reservoirs from which the pest can readily re-emerge. The other is to take a blanket approach that devotes fewer resources to key sub-regions in the hope that the pest will be poorly positioned to re-invade from any sub-region. Frustrated by remission under the blanket approach through the 1970s and 1980s, multinational organizations coordinating to eradicate rinderpest found greater success with the targeted approach (Zamiska, 2006).

The story relayed herein is inevitably incomplete in other ways too. As alluded to above, spatial aspects matter for biosecurity against pests already in an ecosystem. So as to spread 30 miles from point A to point C, a pest may need safe haven at around the midpoint, say point B. Private biosecurity decisions at B will not adequately account for spillovers to C. The actions at B and C are substitutes and not complements, as was the case in our entry model. In such circumstances, the incentive to free-ride may be strong. Consistent with Hennessy (2007), it may be that smaller firms with less to lose tend to free-ride at the expense of larger firms. In addition, a firm at B has strong incentives to prevent entry to its premises at B but weaker incentives to prevent exit. A finer characterization of what biosecurity actions do will be needed when modeling private incentives to limit spatial spread within a region.

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