Published in final edited form as:

Ecohealth. 2018 June ; 15(2): 259–273. doi:10.1007/s10393-018-1329-2.

Managing Disease Risks from Trade: Strategic Behavior with Many Choices and Price Effects

Piyayut Chitchumnong and Richard D. Horan

Department of Agricultural, Food and Resource Economics, Michigan State University

Abstract

An individual's infectious disease risks, and hence the individual's incentives for risk mitigation, may be influenced by others' risk management choices. If so, then there will be strategic interactions among individuals, whereby each makes his or her own risk management decisions based, at least in part, on the expected decisions of others. Prior work has shown that multiple equilibria could arise in this setting, with one equilibrium being a coordination failure in which individuals make too few investments in protection. However, these results are largely based on simplified models involving a single management choice and fixed prices that may influence risk-management incentives. Relaxing these assumptions, we find strategic interactions influence, and are influenced by, choices involving multiple management options and market price effects. In particular, we find these features can reduce or eliminate concerns about multiple equilibria and coordination failure. This has important policy implications relative to simpler models.

INTRODUCTION

The importance of feedback mechanisms by which human behavior impacts and responds to infectious disease risks is increasingly recognized (Fenichel et al. 2011). Epidemiological feedbacks involve individuals' risk management decisions generating or mitigating public health and other economic risks associated with disease—including private risks and the broader societal risks. Behavioral feedbacks involve disease risks incentivizing the risk management decisions of at-risk individuals. Understanding both feedback processes is required to predict the course of an epidemic and to design policies encouraging producers to make economically efficient risk-management investments (i.e., investments that maximize expected economic net benefits of disease control to society) (Fenichel et al. 2011).

The strategic nature of behavioral feedback responses to disease risks has received comparatively little attention in prior literature (although there is some attention to strategic behavior in the related problems of invasive species and pest management; e.g., Fenichel et al. 2014). Strategic behaviors arise when individuals' economic risks (e.g., due to adverse health impacts to oneself or one's animal and plant stocks, such as livestock herds or plant nurseries), and therefore their private incentives for risk-management, are influenced by

others' risk management choices. For instance, office workers are at greater risk when sick co-workers come to the office. Such settings are typical of disease problems (Kremer 1996; Philipson 2000; Hennessy 2007, 2008; Wang and Hennessy 2014; Reeling and Horan 2015) because transmission depends jointly on the decisions of risk-producing and at-risk individuals. In particular, strategic behaviors may influence the movement of infectious animals and plants via trade (e.g., a livestock producer is at greater risk when neighboring herds import from a risky source, and these risks may affect his own import decisions), a major source of pathogen risks (Perrings et al. 2010; Daszak et al. 2000; Costello et al. 2007, The Economist 2014) and the focus of this article.

There are two types of strategic interactions (Bowles 2004; Vives 2005): strategic substitution, in which a neighbor's action substitutes for one's own action, and strategic complementarity, in which a neighbor's action is complementary to one's own action and makes one's action more valuable. More specifically, strategic substitution (complementarity) arises when one's marginal net benefits of taking an action diminish (increase) with a neighbor's action. Strategic complementarities may produce multiple equilibria involving different levels of disease protection—one in which everyone invests at high (low) levels, as the (lack of) joint investments makes investing a high (low) value activity—and hence different private and social net benefits (Bowles 2004; Vives 2005).¹ Which equilibrium occurs depends on producers' expectations about their neighbors' actions; undesirable (low-protection) outcomes arise when producers cannot coordinate their beliefs on the more privately beneficial (high-protection; but not necessarily the most socially beneficial or efficient) outcome—a situation known as coordination failure (Cooper and John 1988; Krugman 1991; Vives 2005). For instance, the Nash equilibrium of the classic prisoner's dilemma (Bowles 2004) is a type of coordination failure: individuals choose an inferior outcome even though they would both do better to coordinate their actions. Strategic substitution, in contrast, generally promotes a unique, stable outcome.

In unregulated settings, neither type of strategic relation is necessarily preferable to the other; the relative outcomes—and the relative efficiency of the various outcomes—will vary according to the specific problem and the available management options. However, if one behavioral scenario produced multiple equilibria, with the best outcome being the same as a unique outcome arising under another scenario, then the latter scenario would be preferable for its ability to avoid the risk of coordination failure. Multiple equilibria also hamper the ability to quantify infection risks since the risk-management behaviors influencing these risks can occur at different levels. Finally, multiple equilibria can prevent simple incentive policies from guiding individuals towards more efficient risk-management investments (Dasgupta and Maler 2004).

Most of the limited prior work on strategic interactions involving livestock or plant diseases (e.g., Hennessy 2007, 2008) models a single action affecting risks along a single pathway and finds the strategic relation depends on the pathway being managed. For instance,

¹Strategic complementarities stem from the properties of supermodular games and monotone comparative statics, which differ from convex analysis (Vives 2005). Accordingly, the multiple equilibria arising from strategic complementarities are not due to non-convexities associated with producers' objective functions (e.g., profits).

strategic complementarities stem from managing import volumes from risky areas to protect farms from import risks (Hennessy 2008), while strategic substitutability stems from biosecurity actions to reduce the likelihood of pathogen spread across neighboring farms (Hennessy 2007). Reeling and Horan (2015) expand on this by modeling a single action that affects risks along both pathways. They find strategic substitutability arises when a producer has sufficient control over his own risks whether or not his neighbor invests in protection. On the one hand, one's own protection becomes more effective in response to (or substitutes for) less protection from a neighbor. Alternatively, he can manage risks by free-riding if the neighbor makes the investment—the producer may invest less and still receive the same level of protection. This is not a lack of control but rather a choice to receive protection more cheaply; the producer *could* continue with the same level of investment to further reduce his exposure to risk, but he does not have to because some protection has been freely provided.

Strategic complementarity arises when a producer's own risks are relatively more dependent on neighbors' actions; one's investments become less effective when neighbors do not invest in protection. If complementarities dominate to produce multiple equilibria, then incentive policies designed to encourage efficient investments also will need to modify the strategic interactions to eliminate potential coordination failures.

In reality, producers make multiple choices affecting disease risks, often along multiple pathways. Prior research has not examined how different types of choices collectively affect strategic behavior, but instead have focused on a single choice or outcome affecting risks. While this is a common modeling approach in environmental economics, it is sometimes necessary to target multiple choices affecting risks. This is particularly true when outcomes are probabilistic (Shortle and Dunn 1986) or arise due to numerous ecological interactions (Fenichel and Horan 2016; Smith 2012). Prior research also has taken the prices of risk-management activities as fixed, not considering how price responses to changes in activity levels may impact the incentives for strategic behavior. These are important considerations, as all relevant choices, market responses, and strategic implications must be considered to accurately quantify infection risks and to develop public policies that can promote efficiency.

Our first contribution is to examine how a portfolio of private risk management actions may affect the strategic relations. A major finding is that having more risk mitigation options that act as strategic substitutes stabilizes the system, reducing the chance of multiple equilibria and coordination failure. Coordination failure occurs because, when neighbors confer less protection, then a producer's complementary forms of self-protection become less effective and the producer has fewer incentives to invest. But substitute forms of self-protection become more effective when neighbors confer less protection, effectively giving the producer greater control over his own risks and encouraging investments in this alternative form of protection. The effect is to stabilize the system, reducing concerns over multiple equilibria and coordination failure. Having a portfolio of options may also have important efficiency implications.

Our second contribution is to examine the role of import markets in pricing and allocating risks, and the implications for strategic risk management behaviors. This is particularly relevant to livestock disease problems, and so we base our analysis on an example of

livestock trade. Indeed, import markets are increasingly important as livestock producers tend to specialize in production at different animal life stages, resulting in the need to transport many live animals (Hennessy et al. 2005). Few studies have examined risk responses of live animal markets, and those that do have not examined the impacts on biosecurity choices and any associated strategic behavior. For instance, Hennessy et al. (2005) and Rich and Nelson (2007) examine how disease risks may affect aggregate livestock production and trade, but not local biosecurity decisions that may involve strategic interactions and could affect aggregate outcomes. In particular, Rich and Nelson's (2007) simulation of cattle trade with foot and mouth disease risks takes cattle supply and demand as given and independent of disease risks. Here we find market price responses can weaken strategic complementarities. For instance, if some importers increase their animal purchases from high-risk regions (a reduction in protection), this drives up the price of high-risk imports (since suppliers require a larger price to supply more) which discourages other producers' imports from these regions. If these price responses are sufficiently strong, they can have a stabilizing effect that reduces the potential for multiple equilibria and coordination failure.

METHODS

Our analysis is based on a mathematical model of livestock producers' risk management behavior that affects risks to one's own herd and to neighboring herds. We describe the general modeling framework here. Many mathematical details about this framework, the accompanying analysis, and numerical examples, are provided in a mathematical Appendix.

A Model of Disease Risks

We begin by describing the general disease setting, noting that our analysis is essentially rooted in the assumptions of prior models of transmission risks involving strategic behaviors (Hennessy 2007, 2008; Reeling and Horan 2015) to facilitate comparison with this prior work. The primary difference between the current framework and prior work is that we allow for multiple choices affecting multiple risks, as well as endogenously determined import prices (Hennessy et al. (2005) and Horan et al. (2015) model endogenous import prices but not strategic behavior).

Consider a region currently free of a particular livestock disease. This region has $N + 1$ homogeneous feedlots or producers, where N is the (fixed) number of neighbors for any particular producer. Homogeneity facilitates modeling a symmetric game among producers, simplifying matters by allowing us to focus on symmetric Nash equilibria (SNE) (see, e.g., Cooper and John 1988 and also Hefti 2013, who describes symmetric and asymmetric equilibria). Following Hennessy et al. (2005) and Horan et al. (2015), producers operate by importing young animals, feeding them to enhance their weight, and then selling them (e.g., for slaughter). We assume each producer imports one unit of cattle in each period (e.g., to fill the feedlot to its fixed capacity, which has been normalized to one; this assumption is innocuous given that we have a symmetric game). The net return to healthy cattle (i.e., revenue less feeding costs, excluding biosecurity and purchasing cost) is $R > 0$, where R is fixed because the region's output is small relative to the output market. Infection is analyzed

with the herd being the primary unit of analysis. An infected herd, which is identified as animals become symptomatic or when testing at slaughterhouses identifies infected animals and trace these back to individual producers, suffers a loss in value. Without loss of generality, we assume infected herds are detected and that these herds generate zero net return.

Young cattle are purchased in competitive, region-specific spot markets. In principle, there could be many suppliers, with each posing different levels of risk to the importer. We simplify matters and assume two regions that are modeled as aggregate sources of supply: a risk-free supplier or source that has no infected animals, and a risky source that has some infected animals. The health status of imported animals from the risky source is not known when the import decision is made (because it is too costly and difficult to ascertain each animal's health status with certainty; otherwise infection risks would be eliminated, which does not occur), but the probability of infection along this pathway is known.

Let $z \in [0,1]$ denote the proportion of animals that a representative producer imports from the risk-free source, at a per unit cost of w_0 . This price is taken to be fixed, as the risk-free source is a relatively large supplier with many potential customers, whereas the importing region under consideration is a sufficiently small importer that its purchases do not affect the price. The complementary relation $1-z$ denotes the proportion of animals imported from the risky source, at a smaller per unit cost of $w_r < w_0$ to reflect a price discount due to the risk of these imports. Given this specification, the representative producer's procurement costs are $zw_0 + (1-z)w_r$, which is increasing in z . This means z can be interpreted as any costly investment in risk reduction (e.g., testing imported cattle; we use only import share for simplification), as a larger z implies lower risk but larger costs.

We consider two cases for the risky import price. The first case, which follows the strategic behavioral models of Hennessy (2008) and Reeling and Horan (2015), assumes w_r is fixed just like the price of risk-free imports. The second case, which follows the non-strategic models of Hennessy et al. (2005) and Horan et al. (2015), assumes w_r is endogenous. Specifically, we assume the risky source is a relatively small supplier with fewer customers so that the overall imports of the importing region under consideration may affect the risky price w_r . Denote $w_r([N+1][1-Z])$ to be the inverse supply of risky animals to the importing region, where Z is the equilibrium import strategy (i.e., in a SNE, $z = Z$ for all producers) so that $1-Z$ indicates the proportion of imports coming from risky sources. Since N is fixed, we simplify the notation by writing inverse supply as a function of Z , i.e., $w_r(1-Z)$. We assume $w_r(0) < w_0$ and that price is increasing in the quantity supplied, $w_r' > 0$, which together imply that the risky price $w_r(1-Z)$ is less than the risk-free price w_0 for all values of Z . The price response arising in this second case is probably more realistic given the stigma associated with risky animals.

A producer's herd becomes infected via two pathways, import and spread. As import risks stem from risky imports, a producer can reduce his risk of infection via imports by importing more animals from the risk-free source; the probability of becoming infected via imports is decreasing in z . A producer is also at risk from spread of infection by neighbors who import from the risky source. A producer can protect his herd from spread risks with

biosecurity efforts, denoted $b \in [0,1]$, at an increasing, convex cost of $C(b)$. Neighbors' biosecurity efforts also have the effect of protecting one from spread risks. Denote neighbors' biosecurity efforts by the equilibrium biosecurity strategy B (i.e., in a SNE, $b = B$ for all producers). The probability of spread to a producer, therefore, declines when this producer or neighbors invest more in biosecurity or when neighbors import safer animals.

Denote the total probability a producer becomes infected along either pathway by $p(b, z; B, Z)$, which is decreasing in each argument. Several features of this relation deserve mention (see the Appendix for technical details). First, one's own risk management choices b and z have a complementary effect on reducing risks (or, equivalently, in providing protection by increasing $1-p$): they are more effective when used together. This does not mean a profit-maximizing equilibrium with more Z will also involve more b ; less b might be adopted because it becomes more effective and so less is needed. Second, neighbors' risk management choices B and Z are each complementary to z : z is more effective when B or Z is greater so that neighbors provide more protection. Third, it is ambiguous as to whether neighbors' risk management choices B and Z are (always or sometimes) complementary or substitutive to b , where substitutive means b is less effective when B or Z is greater. However, we do find that the choice B is substitutive to b when N is not too large, which we assume and which is consistent with Hennessy's (2007) assumptions. These relations are important because, as we describe below, they determine the nature of strategic behaviors.

Producer's Optimization Problem

Given the specification described above and elaborated on in the Appendix, the representative producer's objective is to choose z and b to maximize expected profit,

$$\max_{b,z} \pi(b, z; B, Z) = R - p(b, z; B, Z)R - C(b) - zw_0 - (1-z)w_r(1-Z). \quad (1)$$

Each producer makes import and biosecurity decisions, z and b , simultaneously while taking Z and B as given (i.e. treating these variables as parameters) because he does not have any direct control over them. Each producer will increase a particular risk management effort when the additional net benefits (profits) associated with the additional effort, or the marginal profits of the effort, are positive; he will decrease efforts when marginal profits are negative. Denote the marginal profits associated with b and z , respectively, by $\pi_b = \frac{\partial \pi}{\partial b}$ and $\pi_z = \frac{\partial \pi}{\partial z}$, respectively. The private optimum with $b \in (0,1)$ and $z \in (0,1)$ (known as an interior solution) occurs when the marginal profits of each decision equals zero:

$$\pi_b(b, z; B, Z) = 0; \quad \pi_z(b, z; B, Z) = 0. \quad (2)$$

The solution to (2) yields the behavioral responses for the choices b and z , denoted $b(B, Z)$ and $z(B, Z)$, which are strategic in nature due to the dependence on neighbors' choices. The dependence on neighbors' decisions occurs because the marginal profits of a producer's actions depend on neighbors' decisions. Corner solutions, in which one or more variables

lies at a boundary value, are also possible. For instance, $b = 0$ is optimal when $\pi_b(b, z; B, Z) < 0$ for all values of b , and $b = 1$ is optimal when $\pi_b(b, z; B, Z) > 0$ for all values of b . Analogous results hold for z .

First suppose there are no market price effects (i.e., when $w_r' = 0$). The previously-described complementarities of Z and B to z in reducing infection risks mean that increases in Z or B increase the marginal profits of z ; Z and B are therefore strategic complements to z . Likewise, the previously-described substitutive relation between B and b means that an increase in B reduces the marginal profits of b ; B is a strategic substitute to b . The strategic relation between b and Z is ambiguous and generally depends on the levels of all decision variables.

For the case where import prices from the risky region change as producers collectively manage their disease risk via trade (i.e., $w_r' > 0$), these market price effects represent an additional mechanism by which Z impacts marginal profits and hence the incentives driving strategic behaviors. Specifically, we find these market effects weaken the strategic complementarities between z and Z , with a sufficiently large market effect making these choices strategic substitutes. The intuition behind this result is as follows. As Z is increased so that purchases of risky imports decline, the price of risky imports also declines. In turn, a producer's marginal profits associated with risky purchases increases, equivalently reducing his marginal profits associated with safe purchases, z . Hence, a larger Z reduces the incentives for z —a substitution effect.

We have described how a particular producer solves his profit optimization conditions (2) given the choices of others. But all others do the same, so that all variables in the privately optimal outcome are simultaneously determined in a symmetric Nash equilibrium (SNE). Specifically, an SNE is an equilibrium in which each of the homogeneous producers in our model make identical decisions, thereby solving $x(Z, B) = Z$ and $b(Z, B) = B$, with no individual having an incentive to deviate. We define the SNE by the ordered pair (Z^*, B^*) .

Uniqueness and stability are desirable features of an SNE because they eliminate the chance of a coordination failure and make it easier to quantify and manage disease risks (Reeling and Horan 2015; Dasgupta and Maler 2004). Uniqueness means a single ordered pair solves (2) (rather than multiple possibilities), and stability means producers will return to the SNE after a small perturbation from this equilibrium. Only stable outcomes will emerge as viable equilibria. Because an SNE depends on strategic behaviors, so do existence and uniqueness properties.

Economic Efficiency from Society's Perspective

Finally, we characterize the economically efficient, or socially optimal, outcome as a benchmark for comparing the various SNE. Efficient effort levels maximize aggregate profits to importers plus economic surplus to exporters. The social optimality conditions are similar to those in (2), except that these conditions take into account the effects of a producer's decisions on his own profits and on neighbors' profits. For instance, the optimality conditions become

$$\pi_b(b, z; B, Z) + \pi_B(b, z; B, Z) = 0; \quad \pi_z(b, z; B, Z) + \pi_Z(b, z; B, Z) = 0, \quad (3)$$

where $\pi_B(b, z; B, Z) = \pi / B$ and $\pi_Z(b, z; B, Z) = \pi / Z$ are positive and reflect spillover benefits that a producer's own protection confers to neighbors. Failure to consider these spillover benefits in the private optimum (see condition (2)) means that producers tend to underinvest in at least one form of protection unless public policies encourage otherwise.

RESULTS

We now examine the uniqueness and stability of any SNE, with a particular focus on how these properties depend on strategic behaviors. This analysis is based upon a numerically-derived graphical analysis that illustrates several general mathematical results derived in the Appendix.

Single vs. Multiple Choices with No Market Effects

Greater insight into the multi-choice model presented above is obtained via a comparison of single-choice versions of the model, which have been the focus of prior literature (Hennessy 2007, 2008; Reeling and Horan 2015). Indeed, prior livestock disease management models consisting of a single choice can be viewed as special cases of our current model. For instance, Hennessy's (2007) model of a single import choice is a variant of our model with biosecurity held fixed at some level B_0 (i.e., $b = B = B_0$). Hennessy's (2005) model of a single biosecurity choice is a variant of our model with imports held fixed at some level Z_0 (i.e., $z = Z = Z_0$).

We begin with the single-choice model for biosecurity, in which producers make their privately optimal choice of b given that imports are fixed at Z_0 . The behavioral response function, denoted $b(B, Z_0)$, will differ quantitatively but not qualitatively for different values of Z_0 . Our graphical analysis of this case in Fig. 1 is based on $Z_0 = Z^*$, to facilitate comparison with the two-choice model. Fig. 1, with B on the horizontal axis and b on the vertical axis, illustrates the SNE lies at the intersection of $b(B, Z_0)$ and the dashed 45° line. The slope of the response function is negative due to the combination of diminishing returns to b and strategic substitution of B for b . This negative slope means the behavioral response curve crosses the 45° line once, generating a unique SNE at B^* . For comparison, the efficient outcome in this one-choice model occurs at point E^e and involves more biosecurity efforts: individuals do not account for the social benefits that biosecurity generates in conferring protection to neighbors.

To analyze stability, interpret B as the average level of biosecurity effort and consider how the system might adjust if initially $B < B^*$, noting that the behavioral response to any B is given by the curve $b(B, Z_0)$. For $B < B^*$, the downward-sloping response curve indicates $b(B, Z_0) > B^*$. As more producers make this adjustment, B increases (hence the rightward arrow for the domain $B < B^*$). But these adjustments are tempered by the fact that a larger B reduces each producer's marginal profits due to strategic substitutability. Analogous but

opposite forces are at work for $B > B^*$, and so the arrows indicate the adjustments move the system to the SNE at E_0 .

Mathematically, the same conditions that guarantee uniqueness in this one-variable setting—namely, diminishing returns and strategic substitutability—also ensure stability of the SNE. Diminishing returns promotes a unique, stable outcome by reducing the marginal benefits of b for $b > b^*$, while at the same time increasing the marginal benefits of b for $b < b^*$. Strategic substitution promotes a unique, stable outcome by reducing the marginal benefits of b for $B > B^*$, while at the same time increasing the marginal benefits of b for $B < B^*$.

Now consider the single-choice model for imports, in which producers make their privately optimal choice of z given that biosecurity is fixed at B_0 . The behavioral response function, denoted $\alpha(Z, B_0)$, will differ quantitatively but not qualitatively for different values of B_0 . Our graphical analysis of this case in Fig. 2 is based on $B_0 = B^*$, to facilitate comparison with the two-choice model. The mathematical conditions for stability are unchanged in this case (concavity of profits and strategic substitution of Z for z). However, Z is a strategic complement for z , which means neither uniqueness nor stability are guaranteed; multiple SNE could arise when the degree of complementarity is sufficiently large relative to the degree of diminishing returns to z . Strategic complementarity means others' choices may counteract the stabilizing effects of diminishing returns: the investment incentives increase, even for $z > z^*$, when others are investing more (i.e., when Z is increased). Alternatively, the investment incentives decrease, even for $z < z^*$ when others invest less. The result could be multiple equilibria, with at least one being unstable.

Fig. 2 illustrates the behavioral response function $\alpha(Z, B_0)$, with Z interpreted as the average level of risk-free imports. In contrast to Fig. 1, the response function $\alpha(Z, B_0)$ in Fig. 2 is generally upward sloping due to the complementarity, with a short segment following the horizontal axis between the horizontal intersection of the curve and the origin (which is difficult to discern in the figure). Accordingly, $\alpha(Z, B_0)$ intersects the 45° line three times in Fig. 2, resulting in three SNE: points E_0 , E_1 , and E_2 . Each of these equilibria lies below the efficient equilibrium E^e , as individuals do not account for the social benefits that importing from the risk-free source generates in conferring protection to neighbors. However, E_0 is considerably preferred to the other SNE due to its proximity to the efficient outcome. The arrows, drawn based on an approach analogous to that taken for Fig. 1, indicate that E_0 and E_2 are stable whereas E_1 is an unstable. With multiple SNE, movement towards a particular equilibrium is driven by producers' expectations about the average import decision. The zero import protection outcome, E_2 , could emerge as the equilibrium due to coordination failure by which each producer expects others to adopt sufficiently low import protection efforts.

Finally, consider the two-choice model. Building on the adjustment processes modeled in Figs. 1 and 2, we follow Dixit (1986) and treat B and Z as state variables that adjust as a dynamic system ($\dot{B} = dB/dt$ and $\dot{Z} = dZ/dt$, where time t is time) based on marginal profits. Specifically, changes in the average values of biosecurity efforts and risk-free imports are proportional to individual producers' marginal profits associated with b and z , respectively, when $b = B$ and $z = Z$. B increases ($\dot{B} > 0$) when the marginal profits of biosecurity are positive ($\pi_b(b, z; B, Z)|_{b=B, z=Z} > 0$), given the current values of B and Z ; B declines ($\dot{B} < 0$)

when marginal profits are negative ($\pi_b < 0$). These adjustments are shown by the vertical phase arrows in Fig. 3, a phase plane. Biosecurity efforts are held constant when marginal profits are zero ($\pi_b = 0$), illustrated by the $\dot{B} = 0$ isocline. At each value of Z , the $\dot{B} = 0$ isocline represents the associated SNE value of B for the single-choice model involving B . Analogous adjustments in Z occur based on the sign of π_z , with adjustments illustrated in Fig. 3 by the horizontal phase arrows and with no adjustments occurring along the $\dot{Z} = 0$ isocline. At each value of B , the $\dot{Z} = 0$ isocline represents the associated SNE value of Z for the single-choice model involving Z . An interior SNE occurs where the isoclines intersect so that B and Z are simultaneously constant and solve $\pi_b = \pi_z = 0$, as in optimality condition (2).

The negative slope of the $\dot{B} = 0$ isocline is due to Z being a strategic substitute for b . Points on this isocline are stable since the arrows point towards it. The $\dot{Z} = 0$ isocline is U-shaped due to the ambiguous strategic relation between b and Z . The downward-sloping portion of the isocline arises when Z is a strategic complement to b , with points on this portion of the isocline being unstable. The upward-sloping portion of the isocline arises when Z is a strategic substitute to b , with points on this portion of the isocline being stable. The SNE of the two-choice model is the intersection of the isoclines, and it is unique at point E_0 .

The conditions under which a unique, stable SNE arises are less stringent in the two-choice model than in the one-choice model when Z is a strategic substitute for b . Intuitively, the stability conferred by a sufficiently strong strategic substitute relation (as demonstrated in the single-choice model for biosecurity) can offset the instability arising from a strategic complement relation. Note that an insufficiently strong strategic substitute relation may still result in multiple equilibria in the two-choice model.

For an alternative perspective on the one-choice and two-choice models, notice that the single-choice model for z is represented in Fig. 3 by fixing biosecurity at the SNE level, B^* , and considering dynamics in the horizontal direction. The dashed horizontal line occurs at B^* and crosses the $\dot{Z} = 0$ isocline at three points due to the U-shaped nature of this isocline, indicating three SNE for Z : E_0 , E_1 , and E_2 . These points correspond to the SNE depicted in Fig. 2, with the same stability properties. This situation arises when B is unable to adjust to changes in Z .

When B is able to adjust, then points E_1 and E_2 cannot be SNE because B^* is not the optimal biosecurity response given the values of Z at these points. Rather, the optimal response for each value of z lies on the $\dot{B} = 0$ isocline, which exceeds B^* for any $Z < Z^*$. Hence, $\dot{B} > 0$ in this region. An increase in biosecurity enhances the marginal productivity of individual import protection that would induce producers to raise the import protection effort, $\dot{Z} > 0$. As a result, the adjustment process moves the system towards the equilibrium point E_0 . Uniqueness and stability of the SNE outcome is more likely to arise when producers have more choices—and hence more flexibility—to take control over managing their risks.

The single-choice model for b is represented in Fig. 3 by fixing safe imports at the SNE level, Z^* , and considering dynamics in the vertical direction. Here there is no qualitative difference between the one-choice and two-choice models—having more choices does not

affect uniqueness or stability. However, having more choices will generally give producers more flexibility to improve risk management and therefore to increase profits (Varian 1993).

The economically efficient outcome is indicated as point E^e in Fig. 3. This outcome involves more risk-free imports than in the private optimum, as the spillover benefits of this reallocation are significant and have the effect of reducing risks relative to the private optimum—regardless of the biosecurity effort used. In consequence, it is efficient to save on protection costs by reducing biosecurity efforts relative to the private optimum. The efficient outcome of the two-choice model involves significantly different effort choices than in either of the single-choice models. In particular, the efficient biosecurity incentives implied by Fig. 1 would be much too large. If risky imports were taxed at the efficient level according to Fig. 3, it is easy to show that only a very small biosecurity incentive would be required to generate efficient efforts in this choice.

The Impact of Market Effects

Fig. 4 illustrates the phase plane for the same numerical example used to draw Fig. 3, except that Fig. 4 includes market price effects: the price of risky imports increases with the level of those imports ($w_r' > 0$). As the marginal profits of biosecurity are independent of the price of risky imports, the price effects have no bearing on the $\dot{B} = 0$ isocline; it is the same as in Fig. 3. The price effects shift the $\dot{Z} = 0$ isocline to the right and alter its shape.

In Fig. 4, the $\dot{Z} = 0$ isocline is now only upward sloping and stable to reflect Z being a global strategic substitute for z . Contrast this to Fig. 3, where the uniqueness of the SNE requires the $\dot{B} = 0$ isocline to lie above the upward sloping portion of the $\dot{Z} = 0$ isocline. Multiple SNE could arise in Fig. 3 if the $\dot{B} = 0$ isocline were to shift downward, or the $\dot{Z} = 0$ isocline upward, such that the isoclines intersect in two places. In contrast, uniqueness of the SNE is not sensitive to the relative locations of the isoclines in Fig. 4, which means that the market effects have eliminated the chance of multiple SNE.

The $\dot{Z} = 0$ isocline has shifted rightward relative to Fig. 3 so that the SNE moves from E_0 to E_M with the equilibrium value of Z increasing and the equilibrium value of B decreasing. Intuitively, as more producers import from the risky source, the price of those imports now increases due to the price effects, leading producers to substitute safe imports for risky imports. With fewer risky imports, less biosecurity is needed and so the equilibrium value of B declines.

Finally, note that the distance between E_M and E^e in Fig. 4 is less than the distance between E_0 and E^e in Fig. 3. Partly, this result occurs because of how the SNE has adjusted in Fig. 4 due to the price effects, as just described. Interestingly, whereas price effects move the SNE closer to the efficient outcome, they could make it harder for incentive policies to move the system from the SNE to the efficient outcome. The reason is that any efforts to further reduce risky imports will reduce the price of these imports, thereby producing an offsetting incentive effect.

CONCLUSION

Because livestock diseases are transmitted from herd to herd, the risk management actions taken by one producer to protect his own herd generally confers some protection to neighboring herds. In turn, these impacts to others may affect others' incentives to protect their own herds. The result is that strategic interactions are key components of livestock disease risks. Understanding this strategic behavior is important for predicting infection risks as well as for designing incentives to influence disease management. In particular, a key concern raised by prior work (Hennessy 2007, Reeling and Horan 2015) is that strategic interactions could result in multiple equilibria, whereby risk management choices could vary depending on individuals' expectations of their neighbors' actions. Coordination failure, in which producers make too few investments in protection, can arise in this setting if individuals believe their neighbors' risk-management actions will fall below some threshold level.

Prior work (Hennessy 2007, 2008; Reeling and Horan 2015) has largely focused on simple models involving a single management choice, with the type of strategic interaction determined by how the choice affects infection probabilities, and also fixed prices. Our present analysis shows that our understanding of strategic interactions is enhanced by considering multiple management options and market price effects. In particular, we find that allowing for multiple choices and price effects can reduce or eliminate concerns about multiple equilibria and coordination failure. Multiple choices enhance stability (reducing the risk of multiple equilibria) by giving producers more control over their own risks and being less reliant on the choices of others—thereby reducing the types of strategic effects that can lead to multiple equilibria. Market price adjustments can further facilitate this stability by increasing the cost of pursuing “extreme” strategies that might be consistent with coordination failure.

These results have important policy implications. Efficiency-enhancing incentive policies, for instance, generally require one policy instrument (e.g., tax, subsidy) for each management task (Tinbergen 1952). In the case of multiple equilibria, additional instruments may be required to shift threshold boundaries (e.g., E1 in Fig. 2) to eliminate the possibility of coordination failure. Our results here illustrate that multiple equilibria may be less of a concern in realistic settings, which means that fewer and simpler instruments may be required.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

Acknowledgments

We gratefully acknowledge funding from the USDA National Institute of Food and Agriculture, Grant #2011-67023-30872, grant #1R01GM100471-01 from the National Institute of General Medical Sciences (NIGMS) at the National Institutes of Health, and NSF grant #1414374 as part of the joint NSF-NIH-USDA Ecology and Evolution of Infectious Diseases program.

References

- Cachon GP, Netessine S. Game theory in supply chain analysis. In: Simchi-Levi D, Wu SD, Shen M, editors *Handbook of Quantitative Supply Chain Analysis: Modeling in the E-Business Era*. Amsterdam: Kluwer; 2004. 13–65.
- Chitchumnong P. Multiple Choices, Strategic Interactions, and Market Effects in Livestock Disease Risk Management. Master's Plan B Paper. East Lansing: Department of Agricultural, Food, and Resource Economics, Michigan State University; 2015.
- Conrad JM, Clark CW. *Natural resource economics: notes and problems*. Cambridge University Press; 1987.
- Cooper R, John A. Coordinating coordination failures in Keynesian models. *The Quarterly Journal of Economics*. 1988; 103(3):441–463.
- Costello C, Springborn M, McAusland C, Solow A. Unintended biological invasions: Does risk vary by trading partner? *Journal of Environmental Economics and Management*. 2007; 54(3):262–276.
- Dasgupta P, Mäler K. The economics of non-convex ecosystems: Introduction. *Environmental and Resource Economics*. 2003; 26(4):499–525.
- Daszak P, Cunningham AA, Hyatt AD. Emerging infectious diseases of wildlife--threats to biodiversity and human health. *Science*. 2000; 287(5452):443–449. [PubMed: 10642539]
- Debreu G. A social equilibrium existence theorem. *Proceedings of the National Academy of Sciences*. 1952; 38(10):886–893.
- Dixit A. Comparative statics for oligopoly. *International Economic Review*. 1986; 27(1):107–122.
- The Economist. Where demand for meat grows, so does the risk of an outbreak. 2014. Jan 18, <http://www.economist.com/news/international/21594347-where-demand-meat-grows-so-does-risk-outbreak-zoonose>
- Fenichel EP, Richards TJ, Shanafelt DW. The control of invasive species on private property with neighbor-to-neighbor spillovers. *Environmental and Resource Economics*. 2014; 59(2):231–255. [PubMed: 25346573]
- Fenichel EP, Horan RD. Tinbergen and tipping points: Could some thresholds be policy-induced? *Journal of Economic Behavior & Organization*. 2016; 132:137–152.
- Fullerton D, West SE. Can taxes on cars and on gasoline mimic an unavailable tax on emissions? *Journal of Environmental Economics and Management*. 2002; 43(1):135–157.
- Gramig BM, Horan RD, Wolf CA. Livestock disease indemnity design when moral hazard is followed by adverse selection. *American Journal of Agricultural Economics*. 2009; 91(3):627–641.
- Hefti AM. Uniqueness and stability in symmetric games: Theory and Applications. Working Paper, Department of Economics, University of Zurich; 2013.
- Hennessy DA, Roosen J, Jensen HH. Infectious disease, productivity, and scale in open and closed animal production systems. *American Journal of Agricultural Economics*. 2005; 87(4):900–917.
- Hennessy DA. Biosecurity and spread of an infectious animal disease. *American Journal of Agricultural Economics*. 2007; 89(5):1226–1231.
- Hennessy DA. Biosecurity incentives, network effects, and entry of a rapidly spreading pest. *Ecological Economics*. 2008; 68(1–2):230–239.
- Horan RD, Fenichel EP, Finnoff D, Wolf CA. Managing dynamic epidemiological risks through trade. *Journal of Economic Dynamics and Control*. 2015; 53:192–207. [PubMed: 25914431]
- Kremer M. Integrating behavioral choice into epidemiological models of AIDS. *The Quarterly Journal of Economics*. 1996; 111(2):549–573.
- Krugman P. History versus expectations. *The Quarterly Journal of Economics*. 1991; 106(2):651–667.
- Perrings C, Mooney H, Lonsdale M, Burgeil S. Globalization and invasive species: policy and management options. In: Perrings C, Mooney H, Williamson M, editors *Bioinvasions and Globalization: Ecology, Economics, Management and Policy*. Oxford: Oxford University Press; 2010. 235–250.
- Philipson T. Economic epidemiology and infectious diseases. In: Anthony JC, Joseph PN, editors *Handbook of Health Economics*. New York: Elsevier; 2000. 1761–1799.

- Rich KM, Winter-Nelson A. An integrated epidemiological-economic analysis of foot and mouth disease: applications to the Southern Cone of South America. *American Journal of Agricultural Economics*. 2007; 89(3):682–697.
- Reeling CJ, Horan RD. Self-protection, strategic interactions, and relative endogeneity of disease risks. *American Journal of Agricultural Economics*. 2015; 97(2):452–468.
- Shortle JS, Dunn JW. The relative efficiency of agricultural source water pollution control policies. *American Journal of Agricultural Economics*. 1986; 68(3):668–677.
- Smith MD. The new fisheries economics: incentives across many margins. *Annual Review of Resource Economics*. 2012; 4(1):379–402.
- Tinbergen J. *On the Theory of Economic Policy*. Amsterdam: North-Holland; 1952.
- Varian HR. *Microeconomic Analysis*. 3. New York: W.W. Norton and Co; 1993.
- Vives X. *Oligopoly Pricing: Old Ideas and New Tools*. MIT Press; 1999.
- Vives X. Complementarities and games: new developments. *Journal of Economic Literature*. 2005; 43(2):437–479.
- Wang T, Hennessy DA. Modelling interdependent participation incentives: Dynamics of a voluntary livestock disease control programme. *European Review of Agricultural Economics*. 2014; 41(4): 681–706.

Figure 1.
The single-choice model for B when $z=Z=Z^*$

Figure 2.
The single-choice model for Z when $b=B=B^*$

Figure 3.
The two-choice model without market effects

Figure 4.
The two-choice model with market effects