Journal of Agricultural and Resource Economics 36(2):242–262

Strategic Incentives in Biosecurity Actions: Theoretical and Empirical Analyses

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We model a game between two players taking biosecurity actions and characterize the Nash equilibria and their properties for the cases of strategic complements and substitutes. Implications of the theoretical model are investigated using data for biosecurity behavior among producers participating in a livestock exhibition. Biosecurity actions with own benefits and lasting impacts in home communities exhibit a positive relationship with behavior of the producers from geographically close areas. The number and probabilities of biosecurity actions taken by exhibitors are positively associated with the number of animals exhibited and they vary among commercial and hobby producers and across species/types of commercial production.

Key words: California, livestock disease, livestock exhibition, strategic complements, strategic substitutes

Introduction

Nonnative species and diseases (otherwise known as invasives) adversely affect both animal and plant species in agricultural production systems and ecosystems. An improved understanding of factors affecting biosecurity actions and regulatory mechanisms attempting to prevent the spread of invasives is exceptionally important,[1] because economic costs associated with failed biosecurity are substantial. For example, outbreaks of foot-and-mouth disease (FMD) in 2001 in the United Kingdom required the slaughter of more than six million animals, economic costs of over eight billion pounds and resulted incidents in forty-four other countries (National Audit Office, 2002). Scientists predict that the light brown apple moth, identified for the first time in the continental United States in California in 2007, will cause crop damages of $118 million each year if the species spreads and establishes itself throughout the United States (USDA-APHIS, 2009). Catastrophic outcomes are often caused by poor biosecurity actions of one or a small group of private agents. The above-mentioned FMD outbreak originated from poor biosecurity decisions of one livestock producer (National Audit Office, 2002).[2] While one poor decision can lead to significant adverse consequences, the individuals or groups who tend to make bad decisions and their reasons are not well understood. It is therefore imperative to examine what motivates decision makers to implement biosecurity actions.

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Review coordinated by Gary Brester.

[1] Biosecurity can be defined as "an ideal state of affairs in which measures are in place to prevent incursion and spread of [invasives], or the approach or principles used to achieve this state of affairs," and biosecurity actions may be taken to minimize the risk of invasive incursion and its outward transmission (FAO, World Bank, and World Organisation for Animal Health, 2007).

[2] Food waste was not properly processed before being fed to hogs (DEFRA, 2002).

Decisions about biosecurity are often influenced not only by private costs and benefits resulting from individual actions but also by other economic agents' biosecurity decisions. Thus, it is important to examine the strategic interactions among decision makers when analyzing private incentives for biosecurity actions and the effects of individual actions on aggregate biosecurity outcomes. In a two-player setting, biosecurity actions are strategic complements when the marginal benefit of own biosecurity action is an increasing function of the other decision maker's action. In this case, an increase in a decision maker's biosecurity action has a positive effect on the counterpart's incentive to increase her biosecurity action; that is, the best response functions are upward sloping. Biosecurity actions are strategic substitutes when the marginal benefit of own biosecurity action is decreasing in the other decision maker's action; in this case the best response functions are downward sloping.

Understanding the nature of biosecurity actions and the context in which they are implemented provides some intuition about whether the actions are strategic complements or substitutes. For example, strategic complementarity likely arises in situations where all involved parties must choose sufficiently high levels of actions for their collective choice to be effective (Burnett, 2006; Hennessy, 2008; Richards, Nganje, and Acharya, 2009). In the context of animal diseases, biosecurity actions can also be classified into two types: "bioexclusion" (keeping disease agents out of a unit) and "biocontainment" (keeping disease agents within a unit) (FAO, World Bank, and World Organisation for Animal Health, 2007). Strategic complementarity is likely to materialize for bioexclusion actions intended to protect some aggregate unit (e.g., village, industry) from disease introduction. Strategic substitutability is more likely to arise in situations where free-riding incentives are relatively strong. When the concepts of bioexclusion and biocontainment are applied at the level of individual herds, one's biocontainment actions benefit others' herds relatively more than one's own, while the benefit of bioexclusion actions mainly accrues to one's own herd. It is conceivable that, when many production units take biocontainment actions, one may have lower incentives to take bioexclusion actions to protect his/her own unit from disease introduction.

Existing theoretical literature on strategic incentives for biosecurity actions (Hennessy, 2007a,b, 2008) suggests that the effects of government interventions aimed at improving aggregate biosecurity levels depend critically on the nature of strategic interaction among private decision makers. A policy that improves on the non-cooperative outcome under strategic complements may have detrimental effects under strategic substitutes. For example, Hennessy (2007b) demonstrates in the context of a local livestock economy that when biosecurity investments are strategic substitutes, subsidies targeted at small backyard producers may result in overall welfare losses. Thus, sound policy-making requires knowledge of how economic agents would react to changes in their counterparts' biosecurity actions. However, we argue that in many practical settings one's biosecurity action consists of a combination of specific measures, each of which may serve multiple purposes, such that the nature of strategic interactions for overall biosecurity actions is not always apparent by casual observation. For example, a commercial livestock operation typically implements a set of biosecurity measures including vaccination, quarantine of newly purchased animals, and routine monitoring of animal health conditions. Some measures, such as disinfection of vehicles going in and out of a livestock operation, can serve both bioexclusion and biocontainment functions at the individual herd level. Since the combined effects of individual measures determine the overall biosecurity level, the strategic nature of an overall level of individual biosecurity actions can only be determined empirically. This calls for empirical testing for strategic complementarity and strategic substitutability.

In this article we analyze both theoretically and empirically what motivates private biosecurity actions, with special focus on strategic interactions among decision makers. We do so in the context of a livestock show where participants implement multiple biosecurity measures to protect their animals in preparation for, during, and after returning from the exhibition. A livestock show offers a unique natural experiment in terms of differential extent of externalities of the participants' biosecurity actions, depending on the timing and nature of the measures implemented. For example, while many biosecurity actions taken before a show will have direct benefits to other participants, actions taken after a show will have spillover effects on other livestock producers in the home community. Therefore, by studying the behavior of livestock exhibitors and holding producer and show characteristics constant, we can analyze how the nature of externalities affects strategic interactions among participants.

We begin by developing a theoretical model that underscores the nature of strategic incentives among livestock exhibitors to take biosecurity actions and draw implications regarding the effects of show characteristics on biosecurity actions. The model involves two producers who take biosecurity actions independently and simultaneously. We characterize the sets of Nash equilibria for the cases of strategic complements and strategic substitutes and relate these sets to dominance properties of the producers' strategies. We do not impose any assumptions on the producers' payoff functions except for the nature of strategic interactions (i.e., strategic complementarity/strategic substitutability). This allows us to underscore the properties of Nash equilibria and their comparative statics, which are driven solely by the nature of strategic interactions.

We then empirically investigate private biosecurity incentives using a dataset on biosecurity behavior among livestock producers participating in a California state fair livestock exhibition. To our knowledge, this article is the first to empirically estimate strategic interactions among livestock producers making biosecurity decisions. Our results suggest that biosecurity actions that have own benefits and lasting positive externalities beyond the exhibition are likely strategic complements, while few or no strategic interactions are found for those actions that have positive externalities to other exhibitors and minimal own benefits. We also find that the number and probabilities of biosecurity actions taken by exhibitors are positively associated with the number of animals taken to the livestock show and that biosecurity behavior varies between commercial and hobby producers and across species/types of commercial production.

While the theoretical literature on private incentives for biosecurity investments and other actions to prevent and control the spread of invasives is rapidly expanding (e.g., Bicknell, Wilen, and Howitt, 1999; Chi et al., 2002; Ranjan and Lubowski, 2005; Muhammad and Jones, 2008; Gramig, Horan, and Wolf, 2009),[3] only a handful of studies examine motives for limiting the spread of diseases and invasives in the context of strategic interactions between parties making biosecurity or food safety investments (Burnett, 2006; Hennessy, Roosen, and Jensen, 2005; Hennessy, 2007a,b, 2008; Ceddia, Heikkilä, and Peltola, 2008; Richards, Nganje, and Acharya, 2009). Several of the latter studies are closely related to the theoretical model in this article. Hennessy (2007b) analyzes private investment incentives to prevent disease introduction under strategic substitutability while Burnett (2006) and Hennessy (2008) consider the case of strategic complements. These studies make important contributions by providing behavioral explanations for the observations that have been made by veterinary and epidemiological researchers and regulators. In particular, the strategic frameworks developed in these studies make it possible to analyze potential causes of widely observed disparity in biosecurity levels between small backyard livestock operations and larger commercial operations (FAO, 2008; Ceddia, Heikkilä, and Peltola, 2008) and to design policy instruments intended to achieve higher aggregate biosecurity levels.

Empirical literature on individual biosecurity actions is limited. Chi et al. (2002) estimate the effectiveness of various biosecurity actions on dairy farms but not their determining factors. In contrast, Gramig and Wolf (2007) estimate both the effectiveness and adoption determinants of biosecurity practices intended for disease prevention on dairy farms. Bhattacharyya et al. (1997) estimate factors affecting the adoption of a newly available vaccine for beef cattle. We are not aware of an empirical study that estimates strategic interactions among biosecurity decision makers. Though in a different context, Shafran (2008) provides an empirical analysis similar to this study

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[3] A number of studies (e.g., Mahul and Gohin, 1999; Elbakidze and McCarl, 2006) deal with similar decision problems but at more aggregate levels (e.g., country). In this article we focus on a micro-level decision-making. For this reason, we do not consider, for example, the aggregate market effects of invasion, including export market closure and impacts on domestic prices.

by analyzing homeowners' choice of investment to protect their properties from wildfire risks; his estimation results reveal that neighboring homeowners' investments against wildfire are strategic complements.

The Model

In this section, we develop a stylized model to examine the strategic incentives involved in making decisions about biosecurity actions. We consider biosecurity decisions associated with participation in a livestock show; decisions regarding biosecurity must be made in preparation to, during, or after returning from the show. In a livestock show with two participants, producers 1 and 2 both face the threat of a set of animal diseases. The two producers independently and simultaneously decide on levels of biosecurity actions to protect their animals from potential infection.[4] In this example, we broadly define biosecurity actions as those that limit potential disease transmission from one animal to another and those that facilitate early detection of infection. Examples of specific measures include vaccination before the show, cleaning and disinfecting equipment, animal surveillance, and quarantine after the show. Each producer (i = 1, 2) chooses between three levels of biosecurity action: high level, H_i, low level, L_i, and no action, N_i.[5] The costs of these actions to producer i are equal to H_i, L_i, and 0, respectively. It is assumed that $H_i > L_i > 0$.

We assume that an individual producer's action imposes a positive externality on his or her counterpart by reducing the likelihood of secondary infection through his or her animals. Thus, the gross benefit (in terms of avoided losses due to infection) to producer i is a function of both producers' actions. The gross benefit function is denoted by $b_i(I_1,I_2)$, where I_i is producer i's action for i =1, 2. The functions $b_1(I_1,I_2)$ and $b_2(I_1,I_2)$ are increasing in both arguments, which reflects our assumption of positive externalities. We normalize the two producers' payoffs so that $b_1(N_1,N_2) = 0$ and $b_2(N_1,N_2) = 0$ and denote the game characterized in this section by G. Table 1 presents the normal form of G.[6]

The following definitions (Topkis, 1979; Bulow, Geanakoplos, and Klemperer, 1985; Vives, 1990; Milgrom and Roberts, 1990; Amir, 2003) prove to be very useful in discussing the model and its results:

Definition 1: Define the following total order $\succ_i$ for each producer i; $H_i \succ L_i \succ N_i$.[7] G is a game with *strategic complements*, or a *supermodular game*, if:

(c1) Player 1's marginal benefit from increasing his action is increasing in player 2's action:

$$b_1(H_1,H_2) - b_1(L_1,H_2) \geq b_1(H_1,L_2) - b_1(L_1,L_2) \geq b_1(H_1,N_2) - b_1(L_1,N_2), \tag{1}$$

$$b_1(L_1,H_2) - b_1(N_1,H_2) \geq b_1(L_1,L_2) - b_1(N_1,L_2) \geq b_1(L_1,N_2) - b_1(N_1,N_2), \tag{2}$$

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[4] The actions in our model could correspond to a single biosecurity measure or a group of multiple measures. Explicitly modeling and empirically estimating complementarity and substitutability between different measures for individual producers would be very useful (e.g., Athey and Stern, 1998; Miravete and Pernías, 2010), but is beyond the scope of this article.

[5] Assuming three rather than an arbitrary finite number of biosecurity action levels simplifies the presentation of our main results, which can be easily extended to the general case with any number of action levels. We could have also chosen to model a continuous strategy space rather than the case of discrete action levels, but this would have provided minimal benefits (if any) in terms of results and their exposition. The power and elegance of the theory of supermodularity is in large part due to the fact that it requires minimal assumptions on functional domains and no assumptions of "smoothness" of functional forms.

[6] Many effects of biosecurity decisions are long-lived. One limitation of our model is that it is not dynamic. However, the static model considered in this article is appropriate for the context of livestock exhibitions, which are one-time events. For dynamic models of disease prevention see, for example, Hennessy, Roosen, and Jensen (2005) and Gramig and Horan.

[7] This order is "natural" as it corresponds to the ranking of costs of different action levels and the ranking of their effect on the value functions.

Table 1. Normal Form of the Game

		Producer 2		
		$\boldsymbol{H}_2$	$\boldsymbol{L}_2$	$\boldsymbol{N}_2$
Producer 1	$\boldsymbol{H}_1$	$\begin{pmatrix} b_1(H_1,H_2)-H_1, \\ b_2(H_1,H_2)-H_2 \end{pmatrix}$	$\begin{pmatrix} b_1(H_1,L_2)-H_1, \\ b_2(H_1,L_2)-L_2 \end{pmatrix}$	$\begin{pmatrix} b_1(H_1,N_2)-H_1, \\ b_2(H_1,N_2) \end{pmatrix}$
	$\boldsymbol{L}_1$	$\begin{pmatrix} b_1(L_1,H_2)-L_1, \\ b_2(L_1,H_2)-H_2 \end{pmatrix}$	$\begin{pmatrix} b_1(L_1,L_2)-L_1, \\ b_2(L_1,L_2)-L_2 \end{pmatrix}$	$\begin{pmatrix} b_1(L_1,N_2)-L_1, \\ b_2(L_1,N_2) \end{pmatrix}$
	$\boldsymbol{N}_1$	$\begin{pmatrix} b_1(N_1,H_2), \\ b_2(N_1,H_2)-H_2 \end{pmatrix}$	$\begin{pmatrix} b_1(N_1,L_2), \\ b_2(N_1,L_2)-L_2 \end{pmatrix}$	$\begin{pmatrix} 0,0 \end{pmatrix}$

and

(c2) Player 2's marginal benefit from increasing his action is increasing in player 1's action:

$$(3) \qquad b_2(H_1,H_2)-b_2(H_1,L_2)\geq b_2(L_1,H_2)-b_2(L_1,L_2)\geq b_2(N_1,H_2)-b_2(N_1,L_2),$$

$$(4) \qquad b_2(H_1,L_2)-b_2(H_1,N_2)\geq b_2(L_1,L_2)-b_2(L_1,N_2)\geq b_2(N_1,L_2)-b_2(N_1,N_2).$$

Definition 2: Define the following total order $\succ_i$ for each producer i; $H_i \succ_i L_i \succ_i N_i$. G is a game with *strategic substitutes*, or a *submodular game*, if:

(s1) Player 1's marginal benefit from increasing his action is decreasing in player 2's action:

$$(5) \qquad b_1(H_1,H_2)-b_1(L_1,H_2)\leq b_1(H_1,L_2)-b_1(L_1,L_2)\leq b_1(H_1,N_2)-b_1(L_1,N_2),$$

$$(6) \qquad b_1(L_1,H_2)-b_1(N_1,H_2)\leq b_1(L_1,L_2)-b_1(N_1,L_2)\leq b_1(L_1,N_2)-b_1(N_1,N_2),$$

and

(s2) Player 2's marginal benefit from increasing his action is decreasing in player 1's action:

$$(7) \qquad b_2(H_1,H_2)-b_2(H_1,L_2)\leq b_2(L_1,H_2)-b_2(L_1,L_2)\leq b_2(N_1,H_2)-b_2(N_1,L_2),$$

$$(8) \qquad b_2(H_1,L_2)-b_2(H_1,N_2)\leq b_2(L_1,L_2)-b_2(L_1,N_2)\leq b_2(N_1,L_2)-b_2(N_1,N_2).$$

Note that since both value functions are increasing in the opponent's strategy, G is a supermodular (submodular) game with *positive spillovers* when conditions (1)-(4) (conditions (5)-(8)) are satisfied. Under conditions (5) and (6), $b_1(I_1,I_2)$ has *decreasing differences* in (I_1,I_2) (Topkis, 1998). Similarly, under (7) and (8) $b_2(I_1,I_2)$ has decreasing differences in (I_1,I_2). In contrast, under (1)-(2) and (3)-(4), respectively, $b_1(I_1,I_2)$ and $b_2(I_1,I_2)$ have *increasing differences* in (I_1,I_2). Thus, under strategic complementarity, a party's incentive to increase action is increasing in the opponent's action. As a result, the best-response curves are upward sloping. In contrast, under strategic substitutability a party's incentive to increase action diminishes as the opponent increases action and the best-response curves are downward sloping.

Whether a submodular or supermodular game arises typically depends on the nature of biosecurity actions and the context in which they are employed. Burnett (2006) and Hennessy (2008) model biosecurity actions as strategic complements when the aggregate biosecurity level is for the most part determined by individuals contributing less or the least (i.e., individual contributions are aggregated via weaker- or weakest-link technology). Similarly, Richards, Nganje, and Acharya (2009) argue that food safety investments by firms in the agro-food industry are weaker- or weakest-link public goods. In the context of a livestock exhibition, individual actions taken prior to the show in order to prevent bringing disease agents to the exhibition (i.e., bioexclusion at the show level) likely contribute to weaker- or weakest-link public good. Strategic complementarity would most likely arise if an action were intended to prevent an outbreak of a highly contagious animal disease that, once introduced into the show, could infect all participating animals.

On the other hand, Hennessy (2007b) models biosecurity actions taken by farms arranged along a circle to prevent disease introduction into and transmission within a community as strategic substitutes. In the current context of a livestock show, biosecurity actions that limit direct and indirect contacts of one's own animals from the other exhibitors' animals, especially those from neighboring stalls, have similar characteristics. In reality, a producer's biosecurity action is usually a combination of various measures whose joint effects determine the overall biosecurity level. In that case, it is of interest to determine whether the group of measures exhibits strategic substitutability or complementarity. Because both strategic complementarity and strategic substitutability scenarios are identified in the literature we analyze the equilibrium strategic interaction for both cases. In what follows, we assume without any loss of generality that neither player's payoffs for two different strategy profiles are equal to each other. Under this assumption, the players' best responses are unique.

Equilibrium Behavior under Strategic Complementarity

When G is supermodular it has a Nash equilibrium in pure strategies (Milgrom and Roberts, 1990). A supermodular game has the largest and smallest pure-strategy Nash equilibria in the given order.[8] Furthermore, a supermodular game with a unique pure-strategy Nash equilibrium is dominance solvable (i.e., using iterative deletion of strongly dominated strategies).

The following proposition follows immediately from Theorem 5 in Milgrom and Roberts (1990). To preserve completeness and to further elucidate the strategic incentives of the players, we provide a proof of the proposition in the appendix.[9]

Proposition 1: Suppose G is a supermodular game. Then,

(i) (N_1, N_2) is a Nash equilibrium if and only if neither N_1 nor N_2 are strongly dominated;

(ii) (H_1, H_2) is a Nash equilibrium if and only if neither H_1 nor H_2 are strongly dominated.

It follows immediately from Proposition 1 that if neither player has a strongly dominated strategy then (N_1, N_2) and (H_1, H_2) are both Nash equilibria. When H_1 and H_2 are strongly dominated while N_1 and N_2 are not, (L_1, L_2) is a Nash equilibrium if and only if $b_1(L_1, L_2) - b_1(N_1, L_2) > L_1 - N_1$ and $b_2(L_1, L_2) - b_2(L_1, N_2) > L_2 - N_2$. Similarly, when N_1 and N_2 are strongly dominated while H_1 and H_2 are not, (L_1, L_2) is Nash equilibrium if and only if $b_1(L_1, L_2) - b_1(H_1, L_2) > L_1 - H_1$ and $b_2(L_1, L_2) - b_2(L_1, H_2) > L_2 - H_2$.

We now turn to comparing the equilibrium behavior to the first-best actions that maximize total surplus: $b_1(I_1, I_2) + b_2(I_1, I_2) - I_1 - I_2$. Consider the case where the first-best is achieved

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[8] In our case, the order $\succ$ over strategy profiles is derived from the orders $\succ_1$ and $\succ_2$ as follows; $(I_1, I_2) > (I_1', I_2')$ if and only if $I_1 > I_1'$ and $I_2 > I_2'$.

[9] The proposition can be easily extended to the case with an arbitrary finite number of players and arbitrary strategy spaces. Specifically, the largest and smallest serially undominated strategies will constitute a Nash equilibrium of a game with strategic complements (Milgrom and Roberts, 1990).

when both producers choose high action levels: $b_1(H_1,H_2)+b_2(H_1,H_2)-H_1-H_2 \geq b_1(I_1,I_2)+b_2(I_1,I_2)-I_1-I_2$ for all (I_1,I_2). It follows immediately from Proposition 1 that the first-best action profile (H_1,H_2) cannot be an outcome of the non-cooperative strategic interaction between the two producers if and only if the high action level is strongly dominated for at least one of the producers. Under the latter scenario, the equilibrium outcome is characterized by underinvestment in biosecurity by at least one of the producers. This is the case frequently considered in applications of supermodular games. As the preceding discussion demonstrates, a suboptimal outcome requires that there exists a strategy that yields a strictly higher payoff than high action, irrespective of the opponent's strategy. In some circumstances, it is unlikely that this condition will be satisfied. For example, a producer may prefer to choose high action when the other producer also chooses high action, but not when the other producer chooses low or zero action. Intuitively, underinvestment in biosecurity materializes when higher actions benefit the others relatively more than oneself.

Next, consider the effect of changes in the general risk levels of disease introduction into the show on the non-cooperative and first-best biosecurity actions. One may expect that in a show with high risk levels of livestock disease introduction biosecurity actions will have large total and marginal effects on the benefits to the investing producers. Thus, it is likely that the first-best actions in this case will be relatively large. As for the effect of an increase in the risk level on the non-cooperative actions, it depends, among other things, on the effect of an increase in the risk level on the degree of strategic complementarity between the two producers' actions.[10] A show with high risk levels and a higher degree of strategic complementarity will tend to witness relatively high biosecurity actions.

Equilibrium under Strategic Substitutability

We now turn to examining behavior when biosecurity actions are strategic substitutes. Using the definition of submodularity we demonstrate in the appendix that:

Proposition 2: Suppose G is a submodular game. Then:

(i) (H_1,H_2) is a Nash equilibrium if and only if L_1 and N_1 are weakly dominated by H_1 while L_2 and N_2 are weakly dominated by H_2;

(ii) (L_1,H_2) is a Nash equilibrium only if L_1 weakly dominates N_1;

(iii) (H_1,L_2) is a Nash equilibrium only if L_2 weakly dominates N_2.

Thus, both producers will choose high actions in an equilibrium only under the relatively unlikely scenario where high actions weakly dominate all other strategies (part (i) of Proposition 2). A high action by one of the producers and a low action by the other producer is a Nash equilibrium only if the former's low investment weakly dominates the zero action (parts (ii) and (iii) of Proposition 2).

We now compare the non-cooperative actions with the first-best. Again, consider the case where the first-best is achieved when both producers choose high actions. It follows from Proposition 2 that the first-best action profile (H_1,H_2) is not an outcome of a non-cooperative strategic interaction between the two producers if and only if the high action for at least one of the producers does not weakly dominate the other strategies. Contrast this finding with the corresponding result for the case of strategic complements. There we have demonstrated that the first-best action profile (H_1,H_2) is not an outcome of a non-cooperative strategic interaction between the two producers if and only if the high action is strongly dominated for at least one of the producers. Since the former is a considerably less restrictive condition, in the absence of all other relevant information, one

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[10] The degree of strategic complementarity is characterized by the effect of I_2 on $b_1(I_1,I_2)-b_1(I_1',I_2)$ and the effect of I_1 on $b_2(I_1,I_2)-b_1(I_1,I_2')$.

may expect underinvestment in biosecurity to be more likely under strategic substitutes than under strategic complements.

Now consider the effect of changes in the general risk levels of disease introduction on the non-cooperative biosecurity actions. This effect depends, among other things, on how an increase in the risk level changes the degree of strategic substitutability between the two producers' actions.[11] A show with high risk levels and a higher degree of strategic substitutability will tend to witness a large variation in biosecurity actions.

Implications of the Model Results

We have determined and analyzed the sets of Nash equilibria for the cases of strategic complements and strategic substitutes. It was found that divergence (if any) between the non-cooperative and socially-optimal biosecurity actions depends critically on the nature of strategic interactions. For example, it was demonstrated that private underinvestment in biosecurity is more likely to occur when the actions are strategic substitutes than when they are strategic complements.

The impact of a change in a parameter of the game on the set of Nash equilibria will also be influenced by whether the producers' actions are strategic complements or strategic substitutes. In the current context, provision of biosecurity measures by the show operator or mandatory implementation of certain biosecurity actions are examples of policies intended to reduce disease introduction risk. In a supermodular game, the reduced disease risk will likely result in reduced actions by both producers 1 and 2. Thus, the public policy will have a crowding-out effect. In a submodular game, if producer 2 responds to the policy by reducing his biosecurity action, this may result in increased action by producer 1.

The above discussion suggests that it is important to reveal the nature of the strategic interaction in order to determine the socially optimal biosecurity levels, to evaluate whether they are achieved, and to uncover how they can be achieved. In most cases this latter task can only be accomplished by conducting an empirical examination of the strategic interactions among a group of producers.

Empirical Analysis of Biosecurity Actions

We conduct an empirical analysis of the nature of strategic incentives in biosecurity decision making using a dataset of livestock exhibitors at a California state fair. The data were collected through an on-site survey of livestock exhibitors at the 2005 California State Fair (Thunes and Carpenter, 2007). Researchers from the Center for Animal Disease Modeling and Surveillance (CADMS), University of California, Davis, visited the fair on three days during the twenty-three-day livestock exhibition. Two-page paper questionnaires were handed out to exhibitors present on those three days. The researchers waited while respondents filled out the questionnaires. Respondents were asked about biosecurity actions that were directly associated with the participation in the fair, as opposed to routine biosecurity practices: they were asked whether they took or were planning to take certain specific measures before, at, and after the fair.[12] They were also asked to report their home counties and other producer-specific information. Of the 137 producers surveyed, the majority came from California, representing 40 of its 58 counties. Three respondents came from Oregon and one from Arizona. Because of the manner in which we define producer "communities" (see below), we drop these non-California observations from the analyses. There were two respondents who did not indicate their home counties and one that did not bring any animals to the fair. These observations were also dropped, resulting in 130 observations. We also use county-level secondary data that characterize the respondents' home communities. County-level variables were selected from the 2002 Agricultural Census data (USDA-NASS, 2004).

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[11] Similarly to the degree of strategic complementarity, the degree of strategic substitutability is characterized by the effect of I_2 on $b_1(I_1,I_2) - b_1(I_1',I_2)$ and the effect of I_1 on $b_2(I_1,I_2) - b_1(I_1,I_2')$.

[12] We are not aware of biosecurity measures that were mandatory for participation.

Table 2 lists all of the variables used in the empirical analysis with their definitions and summary statistics. Survey respondents were given a list of biosecurity measures and asked whether they had taken or planned to take those. Survey responses suggest that most exhibitors took some biosecurity measures: only 6.9%, 10.8%, and 9.2% of the respondents took no measures before, at, and after the fair, respectively. Many biosecurity measures listed in the survey questionnaire pertain to cleaning and disinfecting equipment and other items, while others are for actions that would limit direct and indirect contacts between animals.

Depending on their nature and the timing of implementation, individual actions may cause positive externalities to other fair participants, other livestock operations in the home community, and/or their own animals that are left at home. The measures *before3-before5* characterize actions taken to avoid bringing disease agents to the fair, and hence to protect others' animals at the fair from potential infection through own animals (i.e., bioexclusion at the fair level). These actions do not have direct effects on own animals and, consequently, have a minimal effect on own benefits but a major effect on the benefits of other participating producers. In contrast, the measures *after2-after6* reflect actions to protect own animals left at home as well as the others' animals in the home community from infection risks associated with animals taken to the fair. The rest of the biosecurity measures (*before2* and *at2-at8*) protect own animals at the fair, protect others' animals at the fair, and protect own animals at home and others' animals in the home community. Because of these externalities, it is plausible that the latter two groups of biosecurity measures possess mixed characteristics of strategic complements and strategic substitutes. Given the focus of this study on strategic interactions, this distinction of the nature of externalities is important. The subsequent analyses maintain the grouping of biosecurity actions considered in the survey.

The Empirical Model

A number of recent articles develop rigorous and sophisticated estimation procedures for discrete games, with the majority of applications in the area of firms' market entry strategies (e.g., Bresnahan and Reiss, 1991; Draganska et al., 2008; Bajari, Hong, and Ryan, 2010; Vitorino, 2010). The available estimation methods for discrete games with complete information, however, are applicable only to cases with a relatively small number of players and often require the assumption of strategic complementarity for identification purposes (Vitorino, 2010).[13]

Our dataset likely reflects the equilibrium biosecurity behavior among 130 "rival" producers. Given the large number of players we limit our empirical focus to the determination of the nature of the average strategic interactions, and as a result the empirical analysis presented in this article is less ambitious than the empirical market-entry literature. Instead of attempting to construct a structural form representation that allows for parameter identification of the best response functions of individual producers, we work with aggregate and reduced form equations that correspond to a solution of the underlying strategic interaction. More specifically, we investigate the directions of the strategic interactions by regressing the biosecurity actions of individual producers on the average actions of the other participating producers from the same part of California and the average actions of the rest of the producers, along with other covaraites. This specification is based on the assumption that one's actions vary with the aggregate biosecurity level achieved through the contributions by the others, rather than the permutations of all the other individuals' actions.[14] The specification also allows us to test whether the strategic interactions are stronger among producers from geographically close locations.

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[13] The estimation technique for discrete games with incomplete information presented by Vitorino (2010) allows for the test of the nature of strategic interactions. However, the computation is extremely demanding under the estimation technique, and it is beyond the scope of the present article given data availability. We are now in the process of collecting data that will allow for application of these estimation techniques for discrete games.

[14] This approach is similar to distributional interactions discussed by Manski (2010).

Table 2. Descriptive Statistics of Variables Used in the Analysis

Variable	Description	Obs.	Mean	St. Dev.
before1	No biosecurity taken before the fair (0/1)	130	0.069	0.255
before2	Vaccination (0/1)	130	0.615	0.488
before3	Disinfect truck/trailer (0/1)	130	0.377	0.486
before4	Disinfect boots/shoes (0/1)	130	0.192	0.396
before5	Visually inspect animals (0/1)	130	0.754	0.432
before6	Other measures (0/1)	130	0.100	0.301
at1	No biosecurity taken at the fair (0/1)	130	0.108	0.311
at2	Hand sanitizer use by visitors (0/1)	130	0.054	0.227
at3	Restrict touching of animals by visitors (0/1)	130	0.369	0.484
at4	Disinfect boots/shoes	130	0.092	0.291
at5	Hand sanitizer use after visiting others' pens (0/1)	130	0.392	0.490
at6	Restrict direct animal contacts with others' animals (0/1)	130	0.485	0.502
at7	No equipment sharing (0/1)	130	0.608	0.490
at8	Disinfect pen before use (0/1)	130	0.246	0.432
at9	Other measures (0/1)	130	0.123	0.330
after1	No biosecurity taken after the fair (0/1)	130	0.092	0.291
after2	Quarantine of animals brought back from the fair (0/1)	130	0.269	0.445
after3	Disinfect truck/trailer (0/1)	130	0.377	0.486
after4	Disinfect boots/shoes (0/1)	130	0.131	0.338
after5	Disinfect equipment (0/1)	130	0.408	0.493
after6	Wash clothing/tools (0/1)	130	0.669	0.472
after7	Other measures (0/1)	130	0.115	0.321
bio_a	Number of biosecurity measures taken out of *before3-5*	130	1.323	0.934
bio_b	Number of biosecurity measures taken out of *before2*, *at2-at8*	130	2.862	1.669
bio_c	Number of biosecurity measures taken out of *after2-after6*	130	1.854	1.398
B_{-ija}	Average value of *bio_a* by neighbors	130	1.296	0.193
NB_{-ija}	Average value of *bio_a* by non-neighbors	130	1.338	0.038
B_{-ijb}	Average value of *bio_b* by neighbors	130	2.887	0.588
NB_{-ijb}	Average value of *bio_b* by non-neighbors	130	2.937	0.134
B_{-ijc}	Average value of *bio_c* by neighbors	130	1.794	0.317
NB_{-ijc}	Average value of *bio_c* by non-neighbors	130	1.862	0.590
num	Number of animals brought to the fair	127	5.370	5.321
cdensity	County-level cattle population density (000 head/square miles)	130	0.085	0.091
cost	County-level farm production expenditure-output ratio	130	0.903	0.189
com_beef	Commercial beef cattle farm (0/1)	118	0.254	0.437
com_dairy	Commercial dairy cattle farm (0/1)	118	0.178	0.384
com_swine	Commercial swine farm (0/1)	118	0.051	0.221
com_sg	Commercial sheep or goat farm (0/1)	118	0.169	0.377

Notes: Neighbors are defined as all producers other than i in respondent i's home county j and all of its contiguous counties.

We proceed by grouping the biosecurity measures, as discussed earlier, according to the nature of externalities of each measure: group a includes the measures *before3-before5*, group b includes the measures *before2* and *at2-at8*, and group c includes *after2-after6*. We utilize three estimation approaches to investigate the directions of strategic biosecurity behavior among the fair participants for the three groups of biosecurity measures. In the first estimation procedure, we construct three count variables and estimate Poisson count models using these variables as dependent variables: *bio_a* represents the total number of measures adopted from group a, *bio_b* from group b, and *bio_c* from group c. In constructing the count variables, instead of a simple summation of the measures that assigns an equal weight to each of the measures, the aggregation process could use some kind of non-uniform weighting to account for potential differential efficacy and importance of biosecurity measures. However, we have used uniform weighting since we currently lack objective (or reliable subjective) weights for these measures.[15] Second, in order to account for endogeneity between own and others' biosecurity actions, we implement the instrumental variable estimation based on the generalized method of moments (GMM) approach using the count variables as the dependent variables. Third, we implement the instrumental-variable probit (IV probit) estimation by pooling the binary response variables for individual measures for each group of measures (e.g., for group a, the binary responses for *before3-before5* are pooled).

Let B_{ijk} denote the number of biosecurity measures of type $k = a,b,c$ that individual producer i from community j implements (used as the dependent variable in the first two estimation approaches) and B_{ijkl} the binary variable that takes the value of 1 if the individual implements measure l and 0 otherwise (for the third approach). For all three estimation approaches, we consider three sets of explanatory variables. First, to estimate the direction of the producer responses to others' actions, we include biosecurity actions taken by other producers as explanatory variables. In doing so, we consider *averages* of the other producers' actions. Let B_{ijk} denote the average number of biosecurity measures in group k taken by exhibitors other than i in respondent i's home county j and all of its contiguous counties and NB_{ijk} denote the average number of biosecurity measures taken by all the others (i.e., exhibitors that are not from own or contiguous counties).[16] A similar empirical specification is found in the context of estimating factors affecting homeowner investment decisions against wildfire risks (Shafran, 2008).[17] A significant and positive (significant and negative) coefficient on B_{ijk} or NB_{ijk} supports the hypothesis that individual actions are strategic complements (substitutes). When B_{ijk} or NB_{ijk} has a positive coefficient, a producer is more likely to expect a higher private benefit from taking an additional biosecurity action when the other producers are expected to implement a larger number of biosecurity measures.

Due to the difference in the nature of externalities, we expect differential effects of B_{ijk} and NB_{ijk} on B_{ijk} and B_{ijkl} across three types of biosecurity actions. For example, the measures in group a cause positive externalities equally to all of the other fair participants, and thus the strategic incentives are not expected to depend on the origin county of other producers. On the other hand, the measures in group b and group c have lasting impacts and cause positive externalities in their home communities. In these cases, we expect each producer to have "stronger" strategic interactions with neighboring producers (represented by B_{ijk}) than with the rest of the producers (represented by NB_{ijk}).

Second, we include a vector of producer-specific characteristics ($\boldsymbol{X}_i$) as explanatory variables. These variables are associated with the gross private benefit function $b_i(\cdot)$ and cost of biosecurity actions discussed in the theoretical section. The vector $\boldsymbol{X}_i$ includes the variable *num*, the number of animals taken to the fair, which ranged from 1 to 25, with a mean of 5.37 head per exhibitor (table 2). The incentives to protect own animals from infection at the fair are likely to increase with the number

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[15] Lynne, Shonkwiler, and Rola (1988) use a Tobit estimation to address a similar problem of potential measurement error in a dependent variable constructed by simple summation.

[16] Some counties have only one observation. Including observations from contiguous counties increases the number of observations used to calculate the averages.

[17] Shafran (2008) tests the hypothesis that homeowners' investment decisions to protect their homes from a potential wildfire depend on their neighbors' investment levels. In his estimation model, Shafran (2008) includes a term for others' actions, constructed as a weighted average of investment levels by all of the others in the dataset. The weights in his model are based on the geographical proximity between homes. A similar variable construction for others' actions may be applicable in our case. Unfortunately, we do not have information about how the stalls were situated at the fair or the information on the exhibitors' home locations other than their origin counties. In a future project on biosecurity behavior of commercial livestock producers, we plan to collect and use geo-referenced data of producer locations.

of animals brought to the fair. As a result, the variable *num* is expected to have a positive coefficient and to be more important in explaining the decision for measures in groups *a* and *b* than in group *c*. The vector $\boldsymbol{X}_i$ also includes other individual characteristics such as livestock species and types of operation (e.g., hobby vs. commercial). The type and scale of home operation are expected to affect the gross private benefits, especially the benefits from actions that have externalities to own animals that were left at home (i.e., measures in group *c* and to a lesser extent in group *b*). Information about the total herd size (in addition to the animals taken to the fair) is available only for commercial units and thus we only control for the types and species of the commercial operations.[18] More than half of the exhibitors (54%) came from commercial livestock operations. The variables *com_beef*, *com_dairy*, *com_swine*, and *com_sg* characterize the species and operation types of commercial units that our California sample represents. Many are mixed-species operations, and these categories are not mutually exclusive. The most common commercial operation type is beef cattle, followed by dairy cattle, and small ruminants (sheep and goat).

Finally, the third set of explanatory variables is a vector of community-specific characteristics ($\boldsymbol{Z}_j$) that are expected to affect the net private benefit of biosecurity actions. To analyze the effects of perceived disease risks on individual biosecurity decisions examined in the theoretical section, we would wish to include variables that are related to disease risk of the livestock show (e.g., size of the show, participant characteristics, animal species the show accommodates, and the time of the year it takes place). However, the dataset includes only one livestock event and there would be no variation in such variables across observations. Alternatively, the estimation models include a variable that is likely associated with disease risk of producer home community, namely livestock population density (animal disease risk is higher and disease spread is faster in an area with more concentrated livestock population). We use the cattle population density, *cdensity*, since cattle are the major livestock species in most counties represented in the sample.[19] In addition to general animal disease risk level, *cdensity* likely captures producers' overall awareness about and experience with biosecurity actions against infectious animal diseases. The vector $\boldsymbol{Z}_j$ also includes the variable *cost*, which is constructed as the general farm production expenditure divided by the value of the total agricultural output for each county. *Cost* captures a part of the variation in the profitability of agricultural production across counties, which is supposedly related to the cost of biosecurity actions and thus is expected to be negatively related to biosecurity actions.

In a Nash equilibrium, the levels of B_{ijk} or B_{ijkl} and B_{ijk} and NB_{ijk} are simultaneously determined. To address the statistical problem of endogeneity, in the second and third estimation approaches, B_{ijk} and NB_{ijk} are instrumented. Choosing appropriate instruments is challenging, because they need to be highly correlated with others' biosecurity actions but not with own actions. We use as instruments the average levels of the variables included in $\boldsymbol{X}_i$ and $\boldsymbol{Z}_j$ calculated for each individual and for the two geographical areas defined above (i.e., averages for home county, *j*, plus all contiguous counties and averages for the rest of the counties). The rationale for instrument choice is that average levels of explanatory variables likely explain the average actions of respective groups of producers (i.e., B_{ijk} and NB_{ijk}) but not individual variations (i.e., B_{ijk}). Indeed, use of these instruments was empirically validated based on the tests of overidentifying restrictions as in Davidson and MacKinnon (1993, p. 235): in the OLS regressions of B_{ijk} on the original explanatory variables and the chosen instruments, the coefficients on the instruments were collectively not different from zero according to F-tests for all three *k*.

The resulting estimation specifications are the following. For the Poisson regression, following Cameron and Trivedi (1998), the log-likelihood function for our model can be written as:

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[18] The information is available only for totals of all species. As a result, interaction terms between the commercial herd size and its species could not be constructed.

[19] County area information obtained from the NACO (National Association of Counties) website is also used. The statistics are available at

$$\ln L(\boldsymbol{\beta}_k) = \sum_{i=1}^{n} \{B_{ijk}\boldsymbol{Q}'_{ijk}\boldsymbol{\beta}_k - exp(\boldsymbol{Q}'_{ijk}\boldsymbol{\beta}_k) - \ln B_{ijk}!\}, \tag{9}$$

where:

$$\boldsymbol{Q}'_{ijk}\boldsymbol{\beta}_k = \beta_{0k} + \beta_{1k}B\_{ijk} + \beta_{2k}NB\_{ijk} + \boldsymbol{X}'_i\boldsymbol{\beta}_{3k} + \boldsymbol{Z}'_j\boldsymbol{\beta}_{4k}, \tag{10}$$

and β_{0k}, β_{1k}, β_{2k}, $\boldsymbol{\beta}_{3k}$, $\boldsymbol{\beta}_{4k}$ denote the coefficients to estimate (bold characters indicate vectors). Similarly, for the GMM estimation we specify a linear model:

$$B_{ijk} = \gamma_{0k} + \gamma_{1k}B\_{ijk} + \gamma_{2k}NB\_{ijk} + \boldsymbol{X}'_i\boldsymbol{\gamma}_{3k} + \boldsymbol{Z}'_j\boldsymbol{\gamma}_{4k} + \varepsilon_{ijk}, \tag{11}$$

where γ_{0k}, γ_{1k}, γ_{2k}, $\boldsymbol{\gamma}_{3k}$, $\boldsymbol{\gamma}_{4k}$ are the coefficients to estimate; ε_{ijk} is the error term; and B_{ijk} and NB_{ijk} are instrumented. Finally, for the IV probit estimation, we specify:

$$\text{Prob}(B_{ijkl} = 1) = \Phi(\boldsymbol{R}'_{ijk}\boldsymbol{\theta}_{kl}), \tag{12}$$

where:

$$\boldsymbol{R}'_{ijk}\boldsymbol{\theta}_{kl} = \theta_{0k} + \theta_{1k}B\_{ijk} + \theta_{2k}NB\_{ijk} + \boldsymbol{X}'_i\boldsymbol{\theta}_{3k} + \boldsymbol{Z}'_j\boldsymbol{\theta}_{4k} + \sum_{l} \theta_{5kl}d_{kl}. \tag{13}$$

$\phi(\cdot)$ is a normal cumulative distribution function; d_{kl} is a dummy variable indicating biosecurity measure l in group k; θ_{0k}, θ_{1k}, θ_{2k}, $\boldsymbol{\theta}_{3k}$, $\boldsymbol{\theta}_{4k}$ and θ_{5kl} are the coefficients to estimate; and B_{ijk} and NB_{ijk} are instrumented.

Estimation Results

Tables 3, 4, and 5 report three sets of regression results for biosecurity action groups *a*, *b*, and *c*. For all count model estimations, the Poisson specification is not rejected based on the deviance-statistic goodness of fit test or the likelihood ratio test. For the IV probit estimation, the conditional maximum-likelihood estimator is used for groups *a* and *b*, while Newey's two-step estimator is used for group *c* due to difficulties with convergence. All estimation procedures were conducted using Stata 10.1. Although the three estimation approaches are based on different distributional assumptions, the estimated directional effects (i.e., the signs of the coefficients on the explanatory variables) are identical except for four cases: the constant in group *a* and NB_{ijk}, *com_swine*, and the constant in group *b* (the coefficients on NB_{ijk} and *com_swine* are all insignificant).

Variables of special interest are B_{ij} and NB_{ij}. For group *a*, the coefficient on B_{ij} is not significantly different from zero, while that on NB_{ij} is significant and negative in the Poisson model but not significant in the GMM or IV probit models. This result suggests that there is little or no strategic interaction among exhibitors, regardless of their origin, for actions to protect the fair itself from infection. As discussed earlier, the existing literature typically considers these types of actions to collectively form weaker- or weakest-link public goods, suggesting that strategic complementarity among the players' actions is likely to materialize (e.g., Burnett, 2006; Hennessy, 2008). Our empirical results do not support such expectations.

In contrast to group *a*, the coefficient on B_{ij} is positive and significant for groups *b* and *c* (with the exception of the GMM estimation for group *c*), suggesting strategic complementarity, while that

Table 3. Regression Results for Group *a* (*before3-before5*)

	Poisson	GMM	IV Probit
B_{ija}	0.30	0.85	0.52
	(0.31)	(0.70)	(0.95)
NB_{ija}	-2.77^{**}	-0.48	-1.98
	(1.24)	(3.36)	(4.04)
num	0.03^{***}	0.03^{**}	0.04^{***}
	(0.01)	(0.02)	(0.02)
cdensity	-0.20	-0.47	-0.16
	(0.42)	(1.05)	(0.98)
cost	0.09	0.25	0.08
	(0.42)	(0.51)	(0.48)
com_beef	-0.36^{***}	-0.39^{***}	-0.49^{***}
	(0.11)	(0.12)	(0.18)
com_dairy	0.13	0.16	0.15
	(0.13)	(0.22)	(0.23)
com_swine	0.54^{***}	0.94^{**}	0.88^{***}
	(0.11)	(0.38)	(0.32)
com_sg	0.14	0.26	0.22
	(0.18)	(0.23)	(0.20)
Constant	3.40	0.51	-1.09^{***}
	(2.20)	(5.34)	(0.18)
before3_dummy			-1.74^{***}
			(0.19)
before4_dummy			2.52
			(6.58)
Observations	115	115	345
R-squared	0.03	0.14	
Log Likelihood	-150.30		1,086

Notes: Significance levels of 0.01, 0.05, and 0.1 are denoted by three, two, and one asterisks (***, **, *), respectively. Robust standard errors in parentheses for Poisson and GMM regressions; standard errors in parenthesis for IV-probit regression. Log pseudo likelihood and pseudo R-squared are reported for Poisson regression. Conditional maximum-likelihood estimator is used for IV-probit regression.

on NB_{ij} is insignificant in all cases. Thus, biosecurity actions implemented by other participants coming from neighboring areas are strategically important, while strategic interdependence is not found among those coming from other parts of the state. This is consistent with our expectation that strategic interactions are “stronger” among producers from neighboring areas, because these biosecurity measures impose externalities on other producers in the home communities. However, the direction of the indicated strategic interaction is not necessarily consistent with the strategic substitutability assumptions typically made for biosecurity measures to protect own herds (e.g., Hennessy, 2007b). Again because the same measure can usually serve both as a bioexclusion and biocontainment measure and because the overall biosecurity of a producer is determined by combinations of individual measures, the eventual nature of strategic interactions seems largely an empirical question.

Further, since the three groups contain physically similar biosecurity measures, differences in results between group *a* and group *b*/*c* models likely reflect differences in the nature of externalities associated with each group of measures. Thus, predictions of a theoretical model may be misleading if the model is based on an assumption regarding the direction of strategic interaction that does not

Table 4. Regression Results for Group *b* (*before2, at2-at8*)

	Poisson	GMM	IV Probit
B_{ijb}	0.20*	0.70*	0.36**
	(0.12)	(0.39)	(0.15)
NB_{ijb}	−0.27	0.24	0.20
	(0.63)	(1.89)	(0.69)
num	0.02**	0.06**	0.02**
	(0.01)	(0.02)	(0.01)
cdensity	0.56	0.04	0.68
	(0.74)	(1.82)	(0.71)
cost	0.28	0.50	0.45
	(0.23)	(0.82)	(0.29)
com_beef	−0.03	−0.09	−0.03
	(0.11)	(0.26)	(0.11)
com_dairy	−0.26**	−0.60*	−0.33**
	(0.11)	(0.34)	(0.15)
com_swine	0.15	−0.02	0.22
	(0.24)	(0.68)	(0.21)
com_sg	0.18	0.48	0.22*
	(0.12)	(0.30)	(0.12)
Constant	0.86	−0.64	1.02***
	(2.14)	(6.46)	(0.18)
before2_dummy			−1.19***
			(0.26)
at2_dummy			0.35**
			(0.18)
at3_dummy			−0.79***
			(0.22)
at4_dummy			0.46***
			(0.18)
at5_dummy			0.65***
			(0.18)
at6_dummy			1.02***
			(0.18)
at7_dummy			2.88
			(2.41)
Observations	115	115	920
R-squared	0.04	0.18	
Log Likelihood	−203.00		2,415

Notes: Significance levels of 0.01, 0.05, and 0.1 are denoted by three, two, and one asterisks (***, **, *), respectively. Robust standard errors in parentheses for Poisson and GMM regressions; standard errors in parenthesis for IV-probit regression. Log pseudo likelihood and pseudo R-squared are reported for Poisson regression. Conditional maximum-likelihood estimator is used for IV-probit regression.

take into account the extent and nature of externalities of biosecurity actions. In our application, where the nature of the payoff function $b_i(\cdot)$ is not known *a priori*, we can infer from the estimation results that conditions for strategic complements (1)-(4) likely apply to the biosecurity actions for groups b and c while conditions for strategic substitutes (5)-(8) likely apply to the biosecurity actions in group a.

Table 5. Regression Results for Group *c* (*after2-after6*)

	Poisson	GMM	IV Probit
B_{ijc}	0.66**	1.50	0.83*
	(0.33)	(0.93)	(0.50)
NB_{ijc}	1.13	3.42	1.88
	(2.26)	(4.49)	(2.60)
num	0.01	0.02	0.02
	(0.01)	(0.02)	(0.01)
cdensity	0.33	1.06	0.45
	(0.70)	(1.17)	(0.79)
cost	−0.06	−0.11	−0.10
	(0.27)	(0.60)	(0.35)
com_beef	−0.28**	−0.52**	−0.31**
	(0.15)	(0.26)	(0.14)
com_dairy	−0.17**	−0.52*	−0.21
	(0.09)	(0.29)	(0.17)
com_swine	0.52***	1.25**	0.77***
	(0.17)	(0.59)	(0.26)
com_sg	0.33**	0.94***	0.42***
	(0.15)	(0.31)	(0.16)
Constant	−2.70	−7.30	−1.10***
	(4.75)	(9.59)	(0.18)
after2_dummy			−0.77***
			(0.18)
after3_dummy			−1.60***
			(0.20)
after4_dummy			−0.68***
			(0.17)
after5_dummy			−4.54
			(5.62)
Observations	115	115	575
R-squared	0.05	0.16	
Log Likelihood	−186.00		

Notes: Significance levels of 0.01, 0.05, and 0.1 are denoted by three, two, and one asterisks (***, **, *), respectively. Robust standard errors in parentheses for Poisson and GMM regressions; standard errors in parenthesis for IV-probit regression. Log pseudo likelihood and pseudo R-squared are reported for Poisson regression. Newey's two-step estimator is used for IV-probit regression.

Regression results for other explanatory variables are as follows. We find a positive and significant relationship between the number and probability of the biosecurity actions and the variable *num* in group *b* models. The net benefit of biosecurity actions during a fair is likely greater for livestock exhibitors bringing more animals. The coefficient on the variable *num* is also positive and significant in group *a* models. This may be partially a result of scale economies associated with these biosecurity measures, most of which involve disinfecting equipment and other items. On the other hand, the coefficient on *num* is insignificant in group *c* models. It is likely that the relevant scale indicator for measures taken after the fair is the overall operation scale and not the number of animals taken to the fair.

The coefficients on the variables used to capture community characteristics (*cdensity* and *cost*) are insignificant in all models. We conjectured that *cdensity* may capture general disease risk level, awareness, and experience with biosecurity, but no such effect is detected in the data. It is likely that general farm expenditure is unrelated to the costs of implementing biosecurity measures listed in the questionnaire.

As expected, the dummy variables representing livestock species/operation types of commercial units are most important in explaining decisions to take post-fair biosecurity actions: all four dummy variables for commercial beef, dairy, swine, and small ruminant operations are statistically significant in the models for group *c* (except for *com_dairy* in IV probit estimation). Across the three biosecurity action groups we find that relative to non-commercial producers, commercial cattle producers (beef or dairy; *com_beef* or *com_dairy*) take fewer biosecurity measures or the probability of taking each measure is lower. This is counterintuitive, because cattle are usually more valuable per head than other livestock species. On the other hand, commercial swine producers (*com_swine*) and sheep or goat producers (*com_sg*) tend to take more biosecurity measures or the probability of taking each measure is higher. In general, swine producers are very conscious about biosecurity because of the intensive nature of swine production, where animals are housed in a relatively small area and a disease can quickly spread throughout the population. Thus, the positive and significant coefficients on *com_swine* are sensible. However, dairy herds in California are also intensive, but the coefficients on this dummy variable are negative or insignificant. While these producers are commercial livestock producers at home, they were exhibitors of show animals when surveyed. The regression results obtained may reflect the value of livestock as show animals and may not necessarily be generalizable to biosecurity behavior among commercial livestock producers.

Summary and Discussion

We developed a theoretical model and conducted an empirical analysis of biosecurity strategic incentives. We theoretically modeled a game between two heterogeneous players taking biosecurity actions. We have characterized the set of Nash equilibria for both the cases of strategic complements and strategic substitutes, established the relationship between the non-cooperative and first-best biosecurity levels, and examined how changes in general risk level affect the players' strategic incentives. Although our theoretical model is based on a two-producer game, one can invoke the theory of supermodular and submodular games to extend most of the results to the case of any finite number of producers. Results of the theoretical model suggest that overall effectiveness of some policies will depend on the relative magnitude of strategic complementarity, strategic substitutability, and the scale of externalities of these actions. In these cases, sound policy-making should be based on an empirical analysis of biosecurity behavior of individual producers.

The results of our theoretical model, as well as those in some other studies on the strategic biosecurity investments, constitute rather straightforward applications of the theory of supermodular games (Topkis, 1979). In contrast to the received theoretical literature on the strategic biosecurity investments, however, we have chosen to present results that are driven solely by the structure of supermodularity/submodularity rather than by assumed functional forms on the players' payoff functions.

Empirically, we used behavioral data on biosecurity actions of livestock exhibitors in California to investigate whether their biosecurity actions are strategic complements or substitutes. We find no indication of strategic interactions for biosecurity measures that yield large positive externalities to other exhibitors with minimal own benefits. In contrast, for biosecurity measures that have own benefits and lasting positive externalities beyond the fair, we find an indication of strategic complementarity, whose strength depends on the geographical distance between the participants' home communities. Coupled with the results of the theoretical section, these empirical findings suggest that within the setting considered in the article underinvestment in biosecurity is less likely to occur and that investments by a show operator to mitigate disease risk will likely result in reduced biosecurity actions by participants. We also find that the number of animals taken to the fair is positively associated with biosecurity actions and that biosecurity behavior varies between commercial and hobby producers and across species/types of commercial production.

One limitation of the empirical analysis presented in this article is that the results obtained for biosecurity actions among livestock exhibitors may not be easily applicable to routine biosecurity behavior among general livestock producers. Another potential problem is the way variables B_{ij} and NB_{ij} are constructed, particularly in the use of "average" actions by the other producers and the choice of own and contiguous counties to represent a "community" in which producers strategically interact. We consider only the average of the other producers' biosecurity actions, because estimation of a producer's strategic response to each of the other producers' actions is not practical. Alternative methods of aggregation (for example, averaging by farm size or farm type) may capture differing characteristics of the "others" and are worth investigating. The geographical extent of "community" relevant for strategic decision making regarding biosecurity actions against livestock diseases, by itself, is an important empirical question. Thus, collection of cross-sectional data using a survey covering all types of livestock producers, which would include questions regarding subjective definition of the "others" that matter to their decision making, is a natural next step to obtain more robust results.

Finally, in addition to biosecurity actions to control contagious livestock diseases the strategic incentives analyzed in this article characterize many other economic interactions. In fact, the theoretical and empirical models in this article can be applied to any problem where an undesirable agent spreads spatially across boundaries and an economic agent's action to prevent the event or mitigate the spread causes positive externalities to parties subject to the same biophysical process.[20] For example, many problems of invasive species prevention and control/eradication fall under this class of games. Food-safety investments by actors in agro-food value chains (Richards, Nganje, and Acharya, 2009) and homeowners' incentives to prevent wildfires near their homes to protect their homes (Shafran, 2008) also have many key characteristics in common with the strategic incentives examined. Theoretical and empirical analyses of private strategic incentives and the resulting aggregate outcomes for this class of problems have a considerable potential to generate valuable practical implications.

[Received March 2010; final revision received June 2011.]

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[20] To make our model truly spatial one would have to add at least one more player to the game and impose conditions on the benefit functions that are related to the physical distance between the players. The approach for modeling space in Smith, Sanchirico, and Wilen (2009) should provide a useful building block for constructing this type of extension of our model.

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Appendix

Proof of Proposition 1: First, we state and prove the following lemma for producer 1 which, together with an identical lemma for producer 2, leads to the proposition:

Lemma 1:

(a) L_1 is strongly dominated by H_1 if and only if $b_1(H_1,N_2) - H_1 > b_1(L_1,N_2) - L_1$.

(b) L_1 is strongly dominated by N_1 if and only if $b_1(N_1,H_2) - N_1 > b_1(L_1,H_2) - L_1$.

(c) N_1 is strongly dominated by H_1 if and only if $b_1(H_1,N_2) - H_1 > b_1(N_1,N_2) - N_1$.

(d) N_1 is strongly dominated by L_1 if and only if $b_1(L_1,N_2) - L_1 > b_1(N_1,N_2) - N_1$.

(e) H_1 is strongly dominated by L_1 if and only if $b_1(L_1,H_2) - L_1 > b_1(H_1,H_2) - H_1$.

(f) H_1 is strongly dominated by N_1 if and only if $b_1(N_1,H_2) - N_1 > b_1(H_1,H_2) - H_1$.

Proof: We only prove part (a) of the Lemma. Proofs of the other parts are based on similar arguments. Producer 1 strictly prefers H_1 to L_1 when producer 2 chooses N_2 if and only if the inequality in (a) holds. By supermodularity, if the inequality in (a) is satisfied producer 1 will strictly prefer H_1 to L_1 when producer 2 chooses L_2 or H_2. Hence, L_1 is strongly dominated by H_1. *QED*

Consider part (i) of the proposition. It follows from parts (c) and (d) of Lemma 1 that if N_1 is not strongly dominated then N_1 is the best response to N_2. By symmetry, if N_2 is not strongly dominated then N_2 is the best response to N_1. Thus, (N_1,N_2) is a Nash equilibrium of the game. The proof of part (ii) is similar. Specifically, it follows from parts (e) and (f) of Lemma 1 that if H_1 is not strongly dominated then H_1 is the best response to H_2. By symmetry, if H_2 is not strongly dominated then H_2 is the best response to H_1. Thus, (H_1,H_2) is a Nash equilibrium. *QED*

Proof of Proposition 2: We only prove part (i) as the other parts have similar proofs. Suppose that (H_1,H_2) is a Nash equilibrium. Then, $b_1(H_1,H_2) - b_1(L_1,H_2) \geq H_1 - L_1$, which combined with submodularity implies that $H_1 - L_1 \leq b_1(H_1,L_2) - b_1(L_1,L_2) \leq b_1(H_1,N_2) - b_1(L_1,N_2)$. Hence, H_1 weakly dominates L_1. The proofs that H_1 weakly dominates N_1, and that H_2 weakly dominates L_2 and N_2 follow the same lines. *QED*