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Livestock Disease Indemnity Design When Moral Hazard is Followed by Adverse Selection

Benjamin M. Gramig¹
Purdue University

Richard D. Horan
Michigan State University

Christopher A. Wolf
Michigan State University

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¹ Corresponding author: Dept. of Agricultural Economics, Purdue University, 403 W. State Street, West Lafayette, IN 47907-2056, USA. Ph: 765-494-4324. E: bgramig@purdue.edu.

Livestock Disease Indemnity Design When Moral Hazard is Followed by Adverse Selection

The outbreak of disease in domestic livestock herds is an economic problem and potential human health risk. Diseases that are highly contagious or have human health implications are often the target of government eradication programs. Farm-level public policies under these programs range from bounties for infected livestock to whole herd depopulation and farm decontamination.¹

When livestock is taken by the government for public health or economic reasons, the Fifth Amendment of the US Constitution specifies that just compensation must be provided for this private property taken for public use. This compensation takes the form of indemnity payments. The current federal compensation level is defined by the Animal Health Protection Act, Subtitle E of the Farm Security and Rural Investment Act of 2002. This requires that compensation shall be based on the fair market value, as determined by the Secretary of Agriculture, adjusted for any other compensation received for that event (i.e., disaster payments or perhaps even private market insurance). States may also offer compensation in the form of indemnities.

This paper focuses on the structure of indemnity payments, currently the primary form of public compensation, as the key mechanism for providing farm-level incentives to invest in biosecurity and to report when one's herd becomes infected. These actions have been fundamental issues of concern within public agencies responsible for livestock disease outbreak response (Ott 2006). However, it is not clear that existing indemnity programs adequately

¹ Off the farm, the United States Department of Agriculture's Animal and Plant Health Inspection Service (APHIS) provides inspection and quarantine services to prevent the introduction of disease across national borders and also coordinates response to disease outbreaks from within the country. Border measures that protect against incursion of disease are provided to protect the safety of the American food production system and to prevent infection of the domestic livestock industry.

address these issues. Existing indemnity payments represent an implicit insurance policy for livestock producers (at least with respect to the diseases for which indemnities are paid), but are really more akin to ad hoc disaster payments due to the lack of risk classification and underwriting involved. Indeed, these payments do not have the desirable risk pooling properties associated with insurance; there are no premiums based on the risk represented by an insured as part of a portfolio of policies, and all taxpayers fund the indemnities. Accordingly, the current structure of indemnities may not generate the desired level of private risk mitigation, thereby undermining the government's livestock disease risk management objectives.

Prior economic research dealing with livestock disease (e.g., Kuchler and Hamm 2000; Mahul and Gohin 1999; Bicknell, Wilen and Howitt 1999; Horan and Wolf 2005; Hennessy 2007) has also ignored incentive compatibility, at least in the presence of asymmetric information.² We use a principal-agent model to examine incentive compatibility in the presence of information asymmetry between the government and individual farmers.³ Individuals have private information about preventive biosecurity measures they adopt on their farms prior to outbreak (*ex ante*), and following outbreak (*ex post*) they possess private information about the disease status of their herd. We investigate how indemnities can be developed to ensure incentive compatibility between the government and private decision makers, and how these incentives influence the occurrence and magnitude of a disease epidemic. Our focus is on farm-level biosecurity choices and reporting of disease status.

² Prior economic research in this area has examined producer response to prices in conjunction with a government bounty program for scrapies in the U.S. (Kuchler and Hamm 2000), optimal actions to contain Foot and Mouth Disease outbreak in France (Mahul and Gohin 1999), the effect of government programs to eradicate disease on prevalence level and private control efforts in New Zealand (Bicknell, Wilen and Howitt 1999), the dynamics of optimally controlling infection from a disease which is transmitted between wildlife and livestock (Horan and Wolf 2005), and behavioral incentives when there is endemic disease in a decentralized setting (Hennessy 2007).

³ A less formal discussion of these issues may be found in Gramig et al. (2006).

We proceed by setting up our model of farmer decision-making in the following two sections. Next, we address the *ex post* problem of encouraging reporting of disease. We start with the *ex post* problem because, regardless of the *ex ante* actions taken by producers, reporting of disease status (as opposed to discovery by another party through transmission, slaughter, or testing) is required for timely government response to limit the spread of infectious disease and eradicate it. The length of time between outbreak and discovery is very important in determining the cost, duration, and severity of epidemic (UN-FAO). For these reasons, an incentive structure that results in reporting of any infection is of great interest for a social planner. After solving the *ex post* problem, we investigate the design of *ex ante* incentives for biosecurity investment together with *ex post* truthful disclosure. The characteristics of an incentive compatible indemnity rule are derived for the case of a risk averse agent (the farmer) and a risk neutral principal (government agency). We also compare the relative size of first-best indemnities (when there is no asymmetric information) and second-best indemnities (where there is information asymmetry). Finally, implications of the model results for public policy and indemnity design are considered and conclusions are offered.

A Model of On-Farm Decision Making

We develop a capital valuation model of the livestock enterprise fashioned after that of Hennessy (2007), who adapted the efficiency wage model of Shapiro and Stiglitz (1984) to the problem of livestock disease management. Our farmer decision model departs from Hennessy (2007) by (i) introducing risk aversion on the part of a single farmer (only briefly addressed by Shapiro and Stiglitz 1984), (ii) considering biosecurity *and* disease reporting decisions (whereas Hennessy focused exclusively on biosecurity), and (iii) by considering the role of indemnity payments on

farmer decisions. A diagram of the decision-making process described below is provided in Figure 1. The farmer is risk averse with an instantaneous utility function $U(\omega)$, where $U' > 0$, $U'' < 0$. Wealth, ω , is contingent on the disease state and farmer choices in our model.

The farmer will be in one of two disease states at any given point in time: susceptible (non-infected) or infected, denoted by sub-scripts S and I , respectively. In the susceptible state ($\theta=0$, where $\theta \in [0,1]$ is a random variable denoting the within-herd disease prevalence rate) farmers must choose their biosecurity effort level, b . Biosecurity reduces the probability of transitioning to the infected state, $P_{SI}(b)$, such that $\partial P_{SI}(b)/\partial b \leq 0$. Biosecurity also reduces the expected magnitude of a disease outbreak, should one occur. The conditional probability density function of θ is denoted $g(\theta|b)$, such that $G(\theta|b)$ is the twice continuously differentiable conditional cumulative distribution function with $\partial G(\theta|b)/\partial b \geq 0 \forall b$. The conditions imposed on G mean that G satisfies first-order stochastic dominance in the sense that the cumulative density for a given level of infection is non-decreasing (the desirable outcome) in biosecurity.⁴

The farmer has a baseline profit flow when disease-free, gross of any biosecurity investment, denoted by π_0 . Biosecurity efforts are made at a constant, per unit cost of w . These costs are incurred only in the susceptible state because, once infected, there is no incentive to maintain these efforts.⁵ The utility of wealth in the susceptible state can therefore be expressed as

$$(1) \quad U_S = U(\pi_0 - bw).$$

⁴ Because disease is a “bad”, higher outcomes of the random variable are *less* desirable and so what we normally refer to as the “dominated” distribution is relatively *more* attractive for our application. For $b_0 < b_1$, $G(\theta|b_1) \geq G(\theta|b_0)$ for all θ , where the inequality is strict for at least one value of θ .

⁵ There may be instances in which biosecurity efforts continue after infection (e.g., to prevent greater infection), but modeling this feature unnecessarily complicates the analysis without impacting the qualitative results.

In the infected state, the farmer must decide whether to report infection. Disease reporting is modeled as a mixed strategy, denoted $r \in [0,1]$ (where $r=1$ means always report and $r=0$ means never report). Reporting results in government testing, verification of infection, and culling of infected animals to eradicate the disease. The farmer is compensated for any culled animals with a government transfer denoted by $\tau(\theta)$. Culling results in two types of losses for the farmer—a loss of asset value $\lambda(\theta)$ ($\lambda'(\theta) > 0$) associated with the livestock itself and consequential losses from business interruption $\chi(\theta)$ ($\chi'(\theta) > 0$). Business interruption losses may vary widely depending on the characteristics of the individual operation affected and possibly disease characteristics. For instance, the presence or absence of breeding stock or having high fixed costs associated with a specific capital asset (e.g., a dairy or egg laying operation) could contribute to the magnitude of business interruption losses. The farmer's instantaneous utility when he/she reports, denoted by the super-script R , is given by $U_I^R(\pi_0 - \lambda(\theta) - \chi(\theta) + \tau(\theta))$.

When a farmer does not report disease, then detection is still possible via government disease surveillance activities. Surveillance activities detect non-reported infection with exogenous probability q and fail to detect non-reported infection with probability $(1-q)$.⁶ Detection leads to government culling of infected animals. Compensation in this case is given by $\tau(\theta) - f$. The term $\tau(\theta)$ is the same as occurs under reporting. The term f can be viewed as a fine for not reporting. In what follows, we simply refer to $\tau(\theta)$ as the government transfer and f as the fine.

If the infection goes undetected, the farmer will attempt private culling of infected

⁶ Government disease surveillance is modeled as being exogenous to reflect the fact that ongoing surveillance activities prior to any reporting or discovery of outbreak are conducted based on prior budgetary commitments independent of a given disease outbreak.

animals. In this case there is no indemnity payment. Rather, privately culled animals are sold at salvage value $\sigma(\theta)$. Whether infection is discovered by the government or not, all infected farms that do not report incur asset value losses and associated consequential losses due to the cull (as occurs under reporting).

Given this specification, the expected instantaneous utility from not reporting is given by $qU_I^C(\pi_0 - \lambda(\theta) - \chi(\theta) + \tau(\theta) - f) + (1-q)U_I^{NC}(\pi_0 - \lambda(\theta) - \chi(\theta) + \sigma(\theta))$. The overall expected utility of wealth in the infected state, conditional on the current level of infection, can therefore be expressed as

$$(2) \quad U_I(r, \tau(\theta), f, \theta) = rU_I^R(\pi_0 - \lambda(\theta) - \chi(\theta) + \tau(\theta)) + (1-r) \left(qU_I^C(\pi_0 - \lambda(\theta) - \chi(\theta) + \tau(\theta) - f) + (1-q)U_I^{NC}(\pi_0 - \lambda(\theta) - \chi(\theta) + \sigma(\theta)) \right).$$

Equations (1) and (2) are individual components of a farm's inter-temporal decision-making process. In the next section we incorporate state transition probabilities to derive the system of equations that represents the full scope of the farmer's dynamic problem.

Fundamental Asset Equations

Define V_S to be the expected lifetime utility of the decision maker in the susceptible state. Using the continuous time discount rate ρ , we can define ρV_S to be the “time value” of the livestock asset when susceptible (Hennessy 2007, p.702). Similarly, let V_I be the expected lifetime utility in the infected state. This notation gives rise to the “fundamental asset equations” (Shapiro and Stiglitz 1984, p.436)⁷

⁷ Equations (3) and (4) are derived following Shapiro and Stiglitz (1984, p.436). Focusing on V_S , we examine expected lifetime utility when decisions are made over small intervals of size $[0, t]$:

(3a) $V_S = U_S(b)t + (1 - \rho t)[P_{SI}(b)tE_\theta[V_I] + (1 - P_{SI}(b)t)V_S]$. Note that $(1 - \rho t) \approx e^{-\rho t}$. Equation (3) is obtained by solving (3a) for V_S and evaluating it as $t \rightarrow 0$. Equation (4) is derived similarly. An implicit assumption

$$(3) \quad \rho V_S = U_S(b) + P_{SI}(b)(E_\theta[V_I] - V_S),$$

$$(4) \quad \rho V_I = U_I(r, \tau(\theta), f, \theta) + P_{IS}(r)(V_S - V_I),$$

where E_θ is the expectations operator with respect to θ and $P_{IS}(r)$ is the transition probability from the infected to the susceptible state. We assume reporting disease ensures that infected farms return to the susceptible state with a transition probability equal to one. However, private culling may not be as effective and only results in transition to the susceptible state with probability $h < 1$. Accordingly, $P_{IS}(r) = r + (1 - r)[q + h(1 - q)]$.

The time value of the susceptible livestock asset in (3) equals the sum of the instantaneous utility in the susceptible state, $U_S(b)$, and the expected capital loss if the disease state changes from susceptible to infected, $P_{SI}(b)(E_\theta[V_I] - V_S)$. Because the post-transition level of infection is unknown to farm managers in the susceptible state, the expected capital loss associated with this state transition is a function of the expectation of the lifetime stream of utility in the infected state.

Similarly, the time value of the infected livestock asset in (4) equals the sum of the expected instantaneous utility in the infected state, $U_I(r, \tau(\theta), f, \theta)$, and the expected capital gain from transitioning to the susceptible state $P_{IS}(r)(V_S - V_I)$. The expectations operator is not needed in (4) because the infected farmer is assumed to know the current infection level.

Equations (3) and (4) may be solved as a system to yield

$$(5) \quad V_S(b, E_\theta[V_I]) = \frac{U_S(b) + P_{SI}(b)E_\theta[V_I]}{\rho + P_{SI}(b)}, \text{ and}$$

in this formulation is that farm businesses are “infinitely lived entities”, as is assumed in Hennessy (2007, p.702) and Shapiro and Stiglitz (1984, p.435).

$$(6) \quad V_I(b, r, \tau(\theta), f, \theta, E_\theta[V_I]) = \frac{U_I(r, \tau(\theta), f, \theta) + P_{IS}(r) \left[\frac{U_S(b) + P_{SI}(b) E_\theta[V_I]}{\rho + P_{SI}(b)} \right]}{\rho + P_{IS}(r)}.$$

Equation (5) shows the lifetime expected utility from being in the susceptible state to be an annuity value. If there was no chance of transitioning to the infected state (i.e., $P_{SI} = 0$), then lifetime utility when susceptible equals the annuity value U_S/ρ (i.e., U_S is received into perpetuity). When there is a chance of becoming infected (i.e., $P_{SI} > 0$), the annuity value changes in two ways: (i) a risk premium, P_{SI} , is added to the risk-free rate ρ to yield a risk-adjusted discount rate that reduces the annuity value associated with the susceptible state to $U_S/(\rho + P_{SI})$; (ii) we must account for the expected annuity value that accrues in the infected state, $E_\theta[V_I]/(\rho + P_{SI})$, weighted by the probability of transitioning to that state.

Equation (6) illustrates a similar valuation of the expected flow from the capital asset, though conditioned on starting in the infected state and accounting for the probability of transitioning to the susceptible state. Note that the term in brackets in equation (6) represents $V_S(b, E_\theta[V_I])$, as derived in equation (5). If there were no chance of transitioning to the susceptible state (i.e., $P_{IS} = 0$), then lifetime utility equals the annuity value U_I/ρ if U_I were received in perpetuity. As with equation (5), because there is a chance of returning to the susceptible state (i.e., $P_{IS} > 0$), the discounted stream of benefits takes this into account via the risk-adjusted discount rate $(\rho + P_{IS})$ and the transition probability-weighted annuity value that accrues in the susceptible state,

$$P_{IS} V_S(b, E_\theta[V_I]) / (\rho + P_{IS}).$$

Expressions (5) and (6) are not in reduced form since they both have expected lifetime utility from infection, $E_\theta[V_I]$, on the right hand side (RHS). To eliminate $E_\theta[V_I]$ from the RHS,

take the expectation of both sides of (6) with respect to θ , isolate $E_\theta[V_I]$ and substitute the expression back into (5) and (6). The resulting implicit functions are

$$(7) \quad V_S(b, r, f) = \frac{U_S(b)(\rho + P_{IS}(r)) + P_{SI}(b)E_\theta[U_I]}{\rho(\rho + P_{IS}(r) + P_{SI}(b))} \text{ and}$$

$$(8) \quad V_I(b, r, \tau(\theta), f, \theta) = \frac{U_I(r, \tau(\theta), f, \theta) + P_{IS}(r) \left[\frac{U_S(b)(\rho + P_{IS}(r)) + P_{SI}(b)E_\theta[U_I]}{\rho(\rho + P_{IS}(r) + P_{SI}(b))} \right]}{\rho + P_{IS}(r)}.$$

Note that the expression in square brackets in (8) is equal to (7).

The general form of these equations is similar to the comparable equations derived in Hennessy (2007, p.702-703). However, the specific formulations are more complicated than in Hennessy (2007, p.702). The level of complexity is greater because (i) his model includes a single binary action while we account for two separate continuous choices selected by the farmer, and (ii) we focus on the asymmetric information problem and the design of indemnification policy which involves business interruption and consequential losses along with government disease surveillance, none of which are treated in the earlier work.

The Indemnity Design Problem

We use the asset value equations to solve the overarching problem of indemnity design that achieves public objectives for private biosecurity investment and disease reporting behavior. In practice, we normally think of indemnification in connection with private insurance or government-subsidized risk management programs like crop and flood insurance. Even though indemnities are required when takings occur via a government-directed cull, indemnities are also intended to serve a public risk management function by providing incentives to report infectious

disease and to invest in preventive biosecurity (Ott 2006). For these reasons, we concern ourselves with the design of an indemnification scheme that achieves government risk management objectives. Later, we also discuss whether existing compensation schemes are in conflict with stated risk management objectives in the presence of information asymmetry.

Recall that our proposed payment structure pays one amount, $\tau(\theta)$, to an infected farmer who reports, and a lesser amount, $\tau(\theta) - f$ (which may be negative), to an infected farmer who does not report and is caught. As we describe in detail below, our proposed indemnity structure uses government transfers $\tau(\theta)$ to address *ex ante* moral hazard (biosecurity actions) and fines f to address *ex post* adverse selection (disease reporting). We will begin our analysis with the reporting problem, in which a fine is imposed in response to a given reporting strategy, r : $f=0$ when $\theta=0$ or when $\theta>0$ and the farmer's strategy is $r=1$; $f>0$ otherwise when the farmer is caught. This structure, which involves one value of f for each action—reporting or not, given $\theta>0$ —is analogous to how adverse selection problems have been addressed in the literature (Rothschild and Stiglitz, 1976). The fines mimic a “menu of contracts” which induces the agent to reveal private information. We introduce fines because reporting, which yields social benefits, is outside the scope of constitutionally-required compensation for takings. In the next section, we propose a method for setting the fine so that it achieves the desired reporting behavior.

The moral hazard problem is addressed by setting the transfer, $\tau(\theta)$. Here the government's transfer to the farmer is based on θ , which is observed (verified as a result of testing) after infection is discovered or reported. The transfer influences the farmer's incentives to take biosecurity actions because the likelihood of becoming infected is influenced by b . We might therefore expect a lower marginal payment for larger infection rates. This would mimic

the risk sharing property of deductibles or co-pays commonly used to address moral hazard problems in the principal-agent literature (Laffont and Martimort, 2002), the crop insurance literature (Chambers, 1989), and the broader insurance literature (Arrow, 1963; Raviv, 1979).

In the presence of both adverse selection and moral hazard, some combination of the instruments used to address both types of information problems individually can be expected to induce the desired biosecurity investment and reporting behaviors from the agent in the current application. However, to simplify the exposition, we discuss the different components of the indemnity rule ($\tau(\theta)$ and f) individually. We proceed by addressing each of the two parts of the information problem in reverse chronological order. That is, we propose a way to solve for the indemnification scheme that will (i) lead the farmer to report any infected animals to the government, thereby revealing his/her hidden information, and (ii) create incentives for the government's desired level of biosecurity investment, thereby solving the hidden action problem.

The Adverse Selection Problem—Reporting

Reporting is assumed to be socially desirable (all other things equal) because early detection of infection limits the duration of a disease outbreak event and has been found to be the most important factor in minimizing total economic damages from a livestock disease epidemic (UN-FAO 2002). The government's objective is to set fines in such a way that reporting of suspected disease always occurs. The farmer is the agent in our principal-agent framework and we assume he/she chooses a reporting strategy, $r \in [0,1]$, to maximize his/her discounted utility stream in the infected state, given by (8). This means that the marginal incentive to report (positive, negative or zero) is given by the sign of $\partial V_I(b, r, \tau(\theta), f, \theta) / \partial r$, and the associated Kuhn-Tucker conditions imply the optimal private reporting strategy.

The principal wants to set the fine so that the agent always finds reporting to be privately

optimal. The difficulty is that the marginal incentives to report will differ depending on both b and θ , each of which are unobservable to the principal. The principal must therefore set a single fine such that the agent finds it optimal to report regardless of the values of b and θ .

Specifically, the fine is set so that reporting occurs even when the marginal incentives to report are at their minimum value. The minimum value of the marginal incentives to report are given by the expression

$$(9) \quad \Lambda(f) = \min_{\forall b, \theta} \left[\lim_{r \rightarrow 1} \left(\frac{\partial V_I(b, r, \tau(\theta), f, \theta)}{\partial r} \right) \right].$$

Choosing f such that $\Lambda(f) \geq 0$ for all values of b and θ ensures that the farmer always has a non-negative marginal incentive to report. That is, as long as the agent, when operating at the margin, is indifferent between increasing and decreasing his/her reporting strategy, then the farmer will have a positive incentive to report for any value of $\theta > 0$. This concept is depicted graphically in Figure 2.⁸ Here b is taken as given and the dashed curve indicates that the farmer will not have a positive incentive to report disease for all levels of θ when $f=0$. We denote by f^* the fixed fine that achieves $\Lambda(f^*)=0$ and ensures a non-negative marginal incentive to report over the range of θ .

The Moral Hazard Problem—Biosecurity Investment

Given that f^* ensures reporting, we now turn to the government's problem of designing transfer payments, $\tau(\theta)$, that provide incentives for biosecurity investment. As indicated above in relation to deductibles or co-pays used to address moral hazard problems, some amount of risk sharing between the government and the farmer will be necessary to solve the hidden action

⁸ Figure 2 does not reflect the shape of any particular functional form for V_I , rather it is provided to shore up the intuition associated with the proposed method for setting fines so that reporting occurs.

problem. This can be seen very easily by a quick comparison of the instantaneous utility of wealth in the susceptible state and in the infected state (when $r = 1$) for the special case in which the farmer is fully indemnified against all losses: $\tau(\theta) = \lambda(\theta) + \chi(\theta)$. In this case, utility when infected reduces to $U_I = U(\pi_0)$, which is not dependent on biosecurity and is strictly greater than utility when susceptible if there is *any* positive investment in biosecurity $U_S = U(\pi_0 - bw)$. In this situation, it is not clear why anyone would biosecure and it suggests that farmers will need to bear some share of the risk of disease-related losses for there to be incentive to invest in biosecurity. The question we turn to now is how the government should structure indemnities to facilitate risk sharing in a constrained-efficient manner (that is, an indemnity that is second-best due to asymmetric information regarding the biosecurity action).

Assume the government takes into account the private net benefits of livestock production, $V_S(b, 1, f^*)$, the expected external damages associated with the disease,

$$\beta(b) \left(\int_0^1 D(\theta) g(\theta | b) d\theta \right), \text{ and the expected social cost of government transfers,}$$

$$\beta(b) \kappa \left(\int_0^1 \tau(\theta) g(\theta | b) d\theta \right). \text{ The function } D(\theta) \text{ (with } D'(\theta) > 0 \text{) represents external damages due to}$$

infection. The term $\beta(b) = P_{SI}(b) / [\rho(\rho + P_{IS}(1) + P_{SI}(b))]$ (with $\beta' < 0$) is a risk-adjusted discount factor accounting for the fact that damages only arise and government transfers are only made if the system transitions to the infected state, and that this transition can occur numerous times in the future (β is the coefficient on $E_\theta[U_I]$ in equation (7) when $r = 1$). The coefficient $\kappa > 0$ represents the constant marginal cost of diverting funds to the indemnity program, which

may include transactions costs (Alston and Hurd 1990).⁹

Given this specification, the government's objective function in setting transfers to induce biosecurity effort is

$$(10) \quad \begin{aligned} & \max_{\tau(\theta), b} V_s(b, 1, f^*) - \beta(b) \left(\int_0^1 [D(\theta) + \kappa \tau(\theta)] g(\theta | b) d\theta \right), \\ & \text{s.t. } b \in \arg \max_{\hat{b}} V_s(\hat{b}, 1, f^*) \end{aligned}$$

where the use of fine f^* drives r to 1, the agent's unobservable choice of biosecurity effort constrains the principal, and "argmax" denotes the set of arguments that maximize the objective function that follows.

Denote $\alpha(b) = (\rho + P_{IS}) / (\rho(\rho + P_{IS} + P_{SI}))$, which is the risk-adjusted discount factor associated with the outcome U_s . Then we can write equation (7), evaluated at $r=1$ and f^* , as

$$(11) \quad V_s(b, 1, f^*) = U_s(b) \alpha(b) + \beta(b) \int_0^1 U_I^R(1, \tau(\theta), \theta) g(\theta | b) d\theta.$$

Equation (11) is the focus of farmer decision making in the susceptible state. By the revelation principle (Myerson 1979; Dasgupta, Hammond and Maskin 1979), the constraint in (10) ensures the agent's optimal choice of biosecurity effort \hat{b} is constrained to be b , the government's desired level of investment. The regulator chooses $\tau(\theta)$ to maximize farmer utility while taking into account the cost of indemnities, monitoring, and response to outbreak required to implement the chosen disease risk management policy. The agent's first-order condition (FOC) with respect to b implies the optimal private choice. We substitute the agent's FOC for the constraint in problem (10) so that it can be written as

⁹ Because ours is a model of a single agent we do not account for market or social benefits associated with private livestock production, but this model could be extended to a multi-agent setting which would realistically consider such broader social benefits or costs.

$$(12) \quad \begin{aligned} & \max_{\tau(\theta), b} V_s(b, 1, f^*) - \beta(b) E_\theta[D(\theta) + \kappa\tau(\theta)] \\ & \text{s.t. } \frac{\partial V_s(b, 1, f^*)}{\partial b} = 0 \end{aligned} .$$

The approach of substituting the farmer's FOC in for the constraint is called the first-order approach (FOA) (see, e.g., Ross 1973, Harris and Raviv 1979, Holmström 1979, Mirrlees 1999, Rogerson 1985, Hyde and Vercammen 1997). The FOA is valid as a general solution method for problem (10) when the convexity of the distribution function condition (CDFC) and the monotone likelihood ratio condition (MLRC) are satisfied (Mirrlees 1999, Rogerson 1985). We assume both of these conditions are satisfied in what follows. The CDFC is satisfied by $\partial^2 G(\theta|b)/\partial b^2 \geq 0$. The conditional probability density function of disease satisfies the MLRC if $g_b(\theta|b)/g(\theta|b)$ is non-increasing in θ (Milgrom 1981).¹⁰ Whitt (1980) proved that the MLRC implies first-order stochastic dominance (FOSD), and is therefore a slightly stronger condition than FOSD.

Because it may be hard to garner intuition from $g_b(\theta|b)/g(\theta|b)$, Milgrom (1981) provides an alternative explanation of the relevance of the MLRC in terms of the government's ability to infer the agent's hidden actions from the observation of θ . He describes the MLRC in terms of a principal who has a prior over the agent's choice of effort (b), observes the outcome realized (θ), and then updates her prior to calculate a posterior on the biosecurity effort choice. Denote the posterior probability distribution of b given observed outcome θ by $F(b|\theta)$. Using Milgrom's (1981) results, the nature of disease is such that the MLRC is equivalent to

$$\theta_0 \leq \theta_1 \Rightarrow F(b|\theta_1) \geq F(b|\theta_0) \quad \forall b, \text{ where } \theta_0 \text{ is a more favorable signal than } \theta_1 \text{ that the agent}$$

¹⁰ Milgrom (1981) finds the term should be non-decreasing in θ , but in his model the action has the opposite effect on the distribution as our action b . Accordingly, the sign is reversed here.

exerted the desired level of biosecurity effort.¹¹ The importance of the assumptions about the nature of the MLRC will become clearer when the conditions for divergence from the first-best indemnity and the implications of the model for indemnity design are considered below.

Using the FOA, the Lagrangian for the government's problem is

$$(13) \quad \mathcal{L} = V_s(b, 1, f^*) - \beta(b)E_\theta[D(\theta) + \kappa\tau(\theta)] + \mu \left(\frac{\partial V_s(b, 1, f^*)}{\partial b} \right)$$

where μ is the shadow value of the constraint. The existence of the constraint, due to the farmer's freedom to make their own biosecurity decision, renders this a second-best problem. In the Appendix we illustrate that $\mu > 0$ because the government would like the farmer to increase his investment in biosecurity given the optimal indemnity payment. That is, the optimal indemnity here is only second-best due to the information problem; a first-best indemnity could be used to attain greater welfare in the absence of information asymmetry (in which case μ would optimally vanish). Holmström (1979) also finds such a result.

Following Holmström (1979), pointwise optimization with respect to $\tau(\theta)$ yields the following necessary condition, which must hold for all θ

$$(14) \quad \frac{\partial U_I^R(1, \tau(\theta), \theta)}{\partial \tau(\theta)} - \kappa = -\mu \frac{\partial^2 V_s(b, 1, f^*)}{\partial b^2} = -\mu \frac{\partial U_I^R(1, \tau(\theta), \theta)}{\partial \tau(\theta)} \left[\frac{\beta'(b)}{\beta(b)} + \frac{g_b(\theta|b)}{g(\theta|b)} \right].$$

Condition (14) implicitly defines $\tau^{SB}(\theta)$, the second-best indemnity as a function of θ .

Specifically, condition (14) can be used to derive

¹¹ It should be noted that the interpretation of the MLRC in the current context of a malady is different than the examples most often found in the literature because lower realized values of the random variable prevalence represent the desirable outcome, whereas in the typical wage contract example higher values of the random variable output are desirable and signal greater effort.

$$(15) \quad \tau^{SB}(\theta) = \lambda(\theta) + \chi(\theta) - \pi_0 + U'^{-1} \left(\frac{\kappa}{1 + \mu \left[\frac{\beta'(b^{SB})}{\beta(b^{SB})} + \frac{g_b(\theta | b^{SB})}{g(\theta | b^{SB})} \right]} \right)$$

where b^{SB} is the second-best value of b . This transfer payment compensates the farmer for asset and business interruption losses, net of disease-free profits, plus a positive inverse marginal utility term that arises due to risk-aversion. Substituting this expression into U_I^R , we find that instantaneous wealth in the infected state equals the final term in (15). This term ensures the farmer's utility in the infected state depends on the level of infection – that is, the farmer bears some risk for his biosecurity choices. The level of risk borne by the farmer depends on the argument of U'^{-1} .

The final term in equation (15) is a diminishing function (due to risk aversion) of its argument, which is a ratio of the marginal cost of diverting funds to indemnities to the marginal information costs arising from the hidden action. If the government was not constrained by the farmer's biosecurity choice, then $\mu=0$ and the argument would equal the marginal cost of diverting funds to indemnities. With $\mu>0$, the term $\beta' / \beta + g_b / g$ reflects a tradeoff between the farmer's ability to withhold private information and the government's ability to access this information. By maintaining private information about his/her level of biosecurity effort, the farmer is the sole provider of biosecurity protection in its bilateral relationship with the government and thus can operate as a monopolist who exerts information power. Alternatively, accessing this private information allows the government to exert monopsony power as the sole purchaser of biosecurity efforts (via the incentives provided by the indemnity payment).

Information is therefore the key to exerting each of these powers, which ultimately determines

the amount of risk the government can induce the farmer to bear and the information rents the farmer can earn as a result of hidden action.

Though the government cannot observe b directly, it can make inferences about the choice of b by observing the realized value of θ . These inferences are made based on knowledge of the term g_b / g , as indicated above in our discussion of the MLRC, and also the term β' / β . Holmström (1979, p.79) points out that the term g_b / g is simply the derivative of the maximum likelihood function $\ln[g(\theta|b)]$, when b is taken as an unknown variable, and suggests that g_b / g measures how strongly one is inclined to infer from θ that the agent did not undertake the assumed action. The larger is g_b / g , the more the government is willing to believe the farmer took the required actions and is therefore willing to increase the payment $\tau^{SB}(\theta)$. Essentially, the farmer is able to take advantage of his/her information power for larger values of g_b / g .

Now consider the term β' / β . This term can be written as $\beta' / \beta = (\rho\alpha / [b^{SB}])\epsilon_{PSI,b}$, where $\epsilon_{PSI,b} = P'_{SI}(b^{SB})b^{SB} / P_{SI}(b^{SB})$ measures how responsive the transition probability to the infected state is to biosecurity efforts. The larger is $|\beta' / \beta|$ (since $\beta' / \beta < 0$), the less likely is a transition to the infected state. If $|\beta' / \beta|$ is large and an infection occurs (which the government will know about due to reporting), the government can infer that the farmer likely did not undertake sufficient biosecurity efforts. Accordingly, the government reduces $\tau^{SB}(\theta)$ when $|\beta' / \beta|$ is known to be large, thereby exerting information power in response to farmer reporting. This means that farmers bear more risk in situations where their biosecurity efforts are more likely to prevent infection.

Finally, the following adjoint equation is also necessary

$$(16) \quad \frac{\partial \mathcal{L}}{\partial b} = \frac{\partial V_s(b, 1, f^*)}{\partial b} - \frac{\partial \{\beta(b)E_\theta[D(\theta) + \kappa\tau(\theta)]\}}{\partial b} + \mu \left\{ \frac{\partial^2 V_s(b, 1, f^*)}{\partial b^2} \right\} = 0.$$

Using the agent's FOC, condition (16) reduces to

$$(17) \quad \mu \left\{ \frac{\partial^2 V_s(b, 1, f^*)}{\partial b^2} \right\} = \frac{\partial \{\beta(b)E_\theta[D(\theta) + \kappa\tau(\theta)]\}}{\partial b}.$$

Condition (17) determines μ while the constraint in (12) determines b^{SB} .

First-best versus second-best

How do second-best outcomes compare to the first-best outcomes? The first-best choice of biosecurity is the one that the government would choose to make on its own, not having to rely on the farmer to make the choice. Accordingly, the first-best outcome arises when there are no constraints on the government's problem – that is, the regulator is neither constrained by the farmer's first order condition nor is truthful disclosure an issue, so that there is neither an *ex post* adverse selection nor an *ex ante* moral hazard problem. In this case, $\mu=0$ so that condition (16) becomes

$$(18) \quad \begin{aligned} \frac{\partial V_s(b, 1, f^*)}{\partial b} &= \frac{\partial \{\beta(b)E_\theta[D(\theta) + \kappa\tau^*(\theta)]\}}{\partial b} \\ &= \beta'(b) \int_0^1 [D(\theta) + \kappa\tau^*(\theta)] g(\theta | b) d\theta + \beta(b) \int_0^1 [D(\theta) + \kappa\tau^*(\theta)] g_b(\theta | b) d\theta, \end{aligned}$$

where $\tau^*(\theta)$ is the first-best indemnity schedule. Condition (18) implicitly defines the first-best level of biosecurity, b^* . This condition indicates that b^* equates the marginal expected private costs of biosecurity with the marginal impact of biosecurity on the sum of expected damages and indemnity costs. The first RHS term after the second equality is negative since $\beta' < 0$. The final RHS term is also negative since both D and τ^* are increasing in θ (we show $\tau^{*'}(\theta) > 0$ in equation

(20) below) and since G exhibits FOSD with respect to b . Accordingly, $\partial V_S(b, 1, f^*) / \partial b < 0$ in the first-best outcome. As $\partial V_S(b, 1, f^*) / \partial b = 0$ in the second-best case (in which the farmer's response to the indemnity matters), condition (18) indicates that $b^* > b^{SB}$: the government would ideally have the farmer invest more in biosecurity than the farmer would choose for him or herself. The first-best strategy involves requiring farmers to adopt $b = b^*$ (which is verifiable with no hidden action) in order to be eligible for an indemnity payment of $\tau^*(\theta)$ if they become infected. If farmers adopt $b < b^*$, then no indemnity payment would be made post infection.

Now consider how the first-best and second-best indemnities compare. The first-best indemnity, $\tau^*(\theta)$, is the special case of (15) in which $\mu=0$ and b is evaluated at b^* . Assuming $b^{SB} \approx b^*$, then we find that the following must hold¹²

$$\begin{aligned}
 (i) : \tau^{SB}(\theta) < \tau^*(\theta) & \Leftrightarrow \frac{g_b(\theta | b^{SB})}{g(\theta | b^{SB})} + \frac{\beta'(b^{SB})}{\beta(b^{SB})} < 0 \\
 (19) \quad (ii) : \tau^{SB}(\theta) > \tau^*(\theta) & \Leftrightarrow \frac{g_b(\theta | b^{SB})}{g(\theta | b^{SB})} + \frac{\beta'(b^{SB})}{\beta(b^{SB})} > 0.
 \end{aligned}$$

Condition (19) indicates that farmers receive information rents, relative to the first-best case, under the conditions defined by (19ii), while the government reduces payments below the first-best level under the conditions defined by (19i). The relative payment levels in (19) are a result of the same tradeoffs that arose in the second-best payment levels defined by (15): they depend on the realized value of θ , which the government views as evidence of the farmer's unobservable biosecurity effort.

¹² As noted above, $b^{SB} < b^*$. However, we make the assumption, here and in what follows, that $b^{SB} \approx b^*$ to simplify the presentation. This does not affect the qualitative results, but would affect the quantitative results (e.g., such as the level of θ where $\tau^{SB}(\theta) = \tau^*(\theta)$). The sign of (19i) and (19ii) follow from the derivative rule for inverse functions and the risk aversion of the farmer.

Define the single level of infection at which $\tau^{SB}(\theta) = \tau^*(\theta)$ as θ^* , such that

$g_b(\theta^* | b^{SB}) / g(\theta^* | b^{SB}) + \beta'(b^{SB}) / \beta(b^{SB}) = 0$. This means that $\tau^{SB}(\theta) < \tau^*(\theta)$ for $\theta > \theta^*$, and $\tau^{SB}(\theta) > \tau^*(\theta)$ for $\theta < \theta^*$. How small is θ^* ? It should be small enough to infer that sufficient biosecurity efforts have been undertaken. In particular, θ^* is smaller than the value of θ , denoted $\tilde{\theta}$, at which $g_b(\tilde{\theta}) = 0$. This point in the distribution is of interest because for $\theta < \tilde{\theta}$ the marginal benefit of biosecurity, in terms of reducing the cumulative density of prevalence, is increasing. A smaller θ yields even larger marginal benefits of biosecurity.

By structuring indemnities according to (19), the government provides very strong incentives for a farmer to undertake significant biosecurity efforts. If the government observes $\theta > \tilde{\theta}$ it will pay farmers for culled animals at a lower rate than it would if it could observe biosecurity actions directly; this is because a relatively high level of infection suggests a small likelihood of private biosecurity effort. Even for observed levels of infection $\theta^* < \theta < \tilde{\theta}$, the level of effort inferred by the government is still sufficiently low that the farmer cannot extract any information rents from the government. Only if the level of observed infection falls below the critical value θ^* will the government be convinced that the agent has invested in biosecurity at a high enough level to give up information rents to the farmer.

The relationship between the prevalence level and size of indemnities is also of great interest. To evaluate the slope of $\tau^{SB}(\theta)$, differentiate condition (14) with respect to θ to get

$$(20) \quad \tau'(\theta) = \lambda'(\theta) + \chi'(\theta) + \left(\frac{U'}{-U''} \right) \frac{\mu \frac{\partial (g_b(\theta | b^{SB}) / g(\theta | b^{SB}))}{\partial \theta}}{\left(1 + \mu \left[\frac{g_b(\theta | b^{SB})}{g(\theta | b^{SB})} + \frac{\beta'(b^{SB})}{\beta(b^{SB})} \right] \right)},$$

where $U' = \partial U_I^R / \partial \omega$ and $U'' = \partial^2 U_I^R / \partial \omega^2$. The first two RHS terms are positive and equal the slope of the first-best indemnity $\tau^*(\theta)$ (since $\mu=0$ in the first-best case). The third term arises in the second-best case, and the sign of this term depends on the value of θ . In the third RHS term, $(U' / (-U'')) > 0$ for a risk averse agent, the numerator is negative by the MLRC, and the sign of the denominator is determined by the sign of $\gamma = g_b(\theta | b^{SB}) / g(\theta | b^{SB}) + \beta'(b^{SB}) / \beta(b^{SB})$ and the relative magnitude of terms, which for a given b depends on θ .

Several different possibilities for the shape of $\tau^{SB}(\theta)$ relative to that of $\tau^*(\theta)$ are depicted in Figure 3. For very low levels of θ , $\tau^{SB}(\theta) > \tau^*(\theta)$. The second-best indemnity may be initially increasing or decreasing based on the sign of equation (20). This is because $\gamma > 0$ for low values of θ , making the third RHS term in (20) negative and the sign of $\tau'(\theta)$ ambiguous. The negative third term means the slope of $\tau^{SB}(\theta)$ is initially less than the slope of $\tau^*(\theta)$, so that these curves eventually intersect and become equal at θ^* . When $\theta > \theta^*$, then $\gamma < 0$ and the denominator of the third RHS term is of ambiguous sign. Denote $\hat{\theta}$ (with $\hat{\theta} > \theta^*$) to be the value of θ such that the denominator of the third RHS term vanishes; the slope of the second-best indemnity goes to $-\infty$ and there is a discontinuity in the graph of $\tau^{SB}(\theta)$. This means the slope of $\tau^{SB}(\theta)$ becomes negative prior to $\hat{\theta}$. If $\hat{\theta} < 1$, this suggests that for any observed prevalence $\theta^* < \theta < \hat{\theta}$, the second-best indemnity should be paid at a level below the first-best level to maintain the appropriate incentives to invest in b .¹³

¹³ It should be noted that for $\theta > \hat{\theta}$ the slope of the second-best indemnity is expected to be $+\infty$ as you approach $\hat{\theta}$ from the right. This suggests that it is possible that the first- and second-best indemnities cross again at another point $\theta > \hat{\theta}$, but it does not seem likely that an information reward would be optimal at high levels of θ . Moreover, whether or not $\hat{\theta}$ falls within the unit interval is unknown.

While it is mathematically possible for the slope of the second best indemnity function to be positive and/or negative over the range of θ , an indemnity schedule that is monotonically decreasing in the prevalence level, such as $\tau_1^{SB}(\theta)$, would provide the strongest incentives for biosecurity.¹⁴ In such cases the information rents paid to the farmer would be strictly decreasing with prevalence up until $\theta = \theta^*$. Beyond this point, the reduction in payments relative to the first-best case would be increasing. Biosecurity incentives would seem to be weaker under the curves labeled τ_2^{SB} and τ_3^{SB} , which seem contrary to the government's objective.

The extent to which observed prevalence is a good signal of actual preventive biosecurity effort is clearly important for implementing the indemnity schedule, $\tau^{SB}(\theta)$. It is conceivable that for diseases that are extremely contagious (i.e., Foot and Mouth Disease, Highly Pathogenic Avian Influenza, Exotic Newcastle's Disease, or Classical Swine Fever) an individual's herd could become infected regardless of the extent of biosecurity measures taken *ex ante*. For this reason, a "one size fits all" policy that only pays indemnities on the basis of observed prevalence levels is likely to be problematic in practice.

This does not preclude a disease-specific indemnification rule which would pay farmers $\tau^{SB}(\theta)$ for all but the most infectious diseases and pay them according to $\tau^*(\theta)$ during outbreaks of highly contagious diseases (where observed prevalence is not a good signal of effort). Indemnifying farmers in this disease-specific manner does not diminish reporting incentives

¹⁴ For $\theta < \hat{\theta}$, the condition required for a monotonically decreasing second-best indemnity schedule like $\tau_1^{SB}(\theta)$ in Figure 3 is $\lambda'(\theta) + \chi'(\theta) < [U' / (-U'')] [\mu [\partial(g_b(\theta | b) / g(\theta | b)) / \partial \theta] / (1 + \mu \gamma)]$. This condition may be reasonable in practice because $\lambda'(\theta) + \chi'(\theta)$ is likely a very small positive quantity at lower values of θ . Alternatively, the condition that gives rise to the increasing segments of τ_2^{SB} and τ_3^{SB} over the relevant range of θ is $\lambda'(\theta) + \chi'(\theta) > [U' / (-U'')] [\mu [\partial(g_b(\theta | b) / g(\theta | b)) / \partial \theta] / (1 + \mu \gamma)]$ for that range of θ .

because of the use of f^* ; also, if low prevalence levels are verified when responding to an outbreak involving such pernicious diseases, this could be treated as an even stronger signal that the farmer made a significant investment in biosecurity and such behavior should be rewarded by paying $\tau^{SB}(\theta) > \tau^*(\theta)$. The World Organization for Animal Health (Office International des Épidémiologies or OIE) maintains a list of diseases that must be reported to the international community. The OIE's list of reportable diseases (formerly called "List A" diseases) could serve to determine which diseases should be associated with such a disease-specific indemnification rule—that is, diseases on the list are compensated on the basis of $\tau^*(\theta)$ (with information rents if low prevalence is verified) and all other disease losses are indemnified according to $\tau^{SB}(\theta)$. An indemnification rule similar to that implemented in Belgium and the Netherlands seems to match the suggested indemnity from our model (Horst et al. 1999). This indemnification rule is briefly discussed below.

Policy Implications

Our model uses two distinct mechanisms to provide incentives for biosecurity and truthful disclosure: (i) indemnities to achieve desired levels of biosecurity, and (ii) fines that induce disclosure of disease status (alternatively, these mechanisms can be viewed as a differential indemnity schedule based on whether an infected farmer reports or not). By using two distinct policy instruments, individually designed with each information problem in mind, it is possible to create clear incentives for farmers to behave in a manner that is consistent with government risk management objectives.

Status quo indemnification for livestock disease losses by USDA has paid producers on the basis of "compensation value" equal to "fair market value assuming disease-free status" (Ott

2006, p.72). This amount is necessarily greater than the true market value of diseased animals culled by the government and is intended to create incentives for reporting. The government has also recognized that unless farmers face some uncompensated losses as a result of outbreak they cannot be expected to take preventive biosecurity measures and thus does not compensate farmers for consequential losses when issuing indemnities. Animal health authorities have relied on a single mechanism—indemnities—to facilitate both *ex ante* biosecurity effort and *ex post* reporting. By using a single mechanism to induce biosecurity and reporting simultaneously, the incentives for each individual private action are not clear.

Direct comparison of the relative magnitude of *status quo* indemnities and the second-best indemnities implied by our analysis is not possible, but the major difference is the shape of the indemnity schedules implied by the different policies. *Status quo* policy suggests the indemnity schedule is strictly increasing in θ (just like the first-best indemnity, $\tau^*(\theta)$, depicted in Figure 3), while the second-best indemnity implied by condition (19) is declining over at least some segment of the range of θ . It is not at all clear how the incentives created by the *status quo* policy facilitate the government's joint objectives. An upward sloping indemnity schedule, in the absence of any penalty for not reporting, may actually create incentives *for* infection when you consider that the *status quo* has sought to use indemnities based on the disease-free fair market value of livestock as a means of resolving the *ex post* adverse selection problem.

In an effort to induce early reporting, Belgium and the Netherlands no longer compensate producers for dead animals and only partially compensate them for diseased stock (Horst et al. 1999). This approach, arrived at as a result of these countries' experiences with Classical Swine Fever and Foot and Mouth disease, shares some important elements with our second-best indemnities. First, while there is not an explicit fine for not reporting, there is a penalty to

waiting to report since dead animals fetch no payment. This feature can help to achieve incentive compatibility with reduced or eliminated monitoring costs. Second, partial compensation for already-infected animals shifts some of the risk to farmers, as do our payments. An indemnity plan that does not shift risk in this fashion may actually create incentives for infection, which could be one problem associated with *status quo* U.S. policy.

The discussion of incentive compatibility applies not only to public policy but also to the development of private insurance for livestock disease protection. If private coverage is available to farmers, the incentives provided by livestock insurance contracts could potentially be in competition with the objectives of policy while satisfying the individual objectives of producers (i.e., income smoothing as risk management). Careful consideration in the design of private market coverage for livestock disease losses is required in order to ensure that public policy and private risk management products are jointly incentive compatible. Also, design of public policy should take into account the role that private coverage could play in achieving public policy objectives and how government decisions may hinder or bolster private markets for insurance. If this is not the case then the constrained efficient result analyzed here will not be achievable.

Appendix

Generalize the farmer's FOC, which is the constraint in problem (12), to be

$$(A1) \quad \frac{\partial V_S}{\partial b} = c ,$$

where c is a constant. $c=0$ for the farmer's problem, while we indicated in condition (18) that $c=c^*<0$ for the first-best outcome. Using this notation, the Lagrangian is

$$(A2) \quad \mathcal{L} = V_S(b, 1, f^*) - \beta(b)E_\theta[D(\theta) + \kappa\tau(\theta)] + \mu\left(\frac{\partial V_S}{\partial b} - c\right)$$

From (A2), we can derive $-\mu = \partial\mathcal{L}/\partial c$. Clearly, $\left.\frac{\partial\mathcal{L}}{\partial c}\right|_{c=0} < 0$: an increase in c when $c=0$ means

the solution moves farther away from the first-best outcome of $c^* < 0$, implying a reduction in welfare. Hence, $\mu > 0$.

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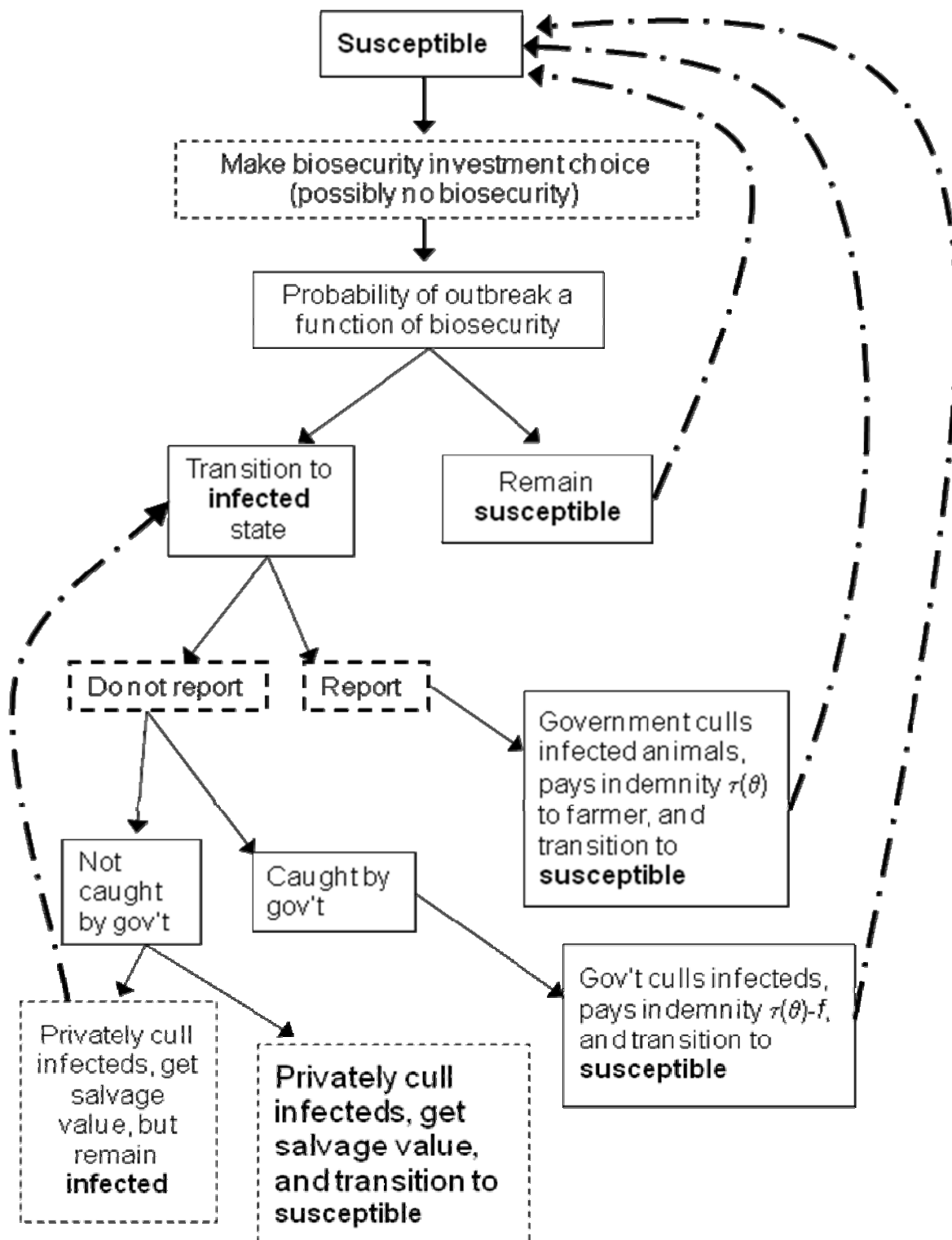


Figure 1. Individual farmer decision tree: disease states in bold and farmer choices in dashed boxes

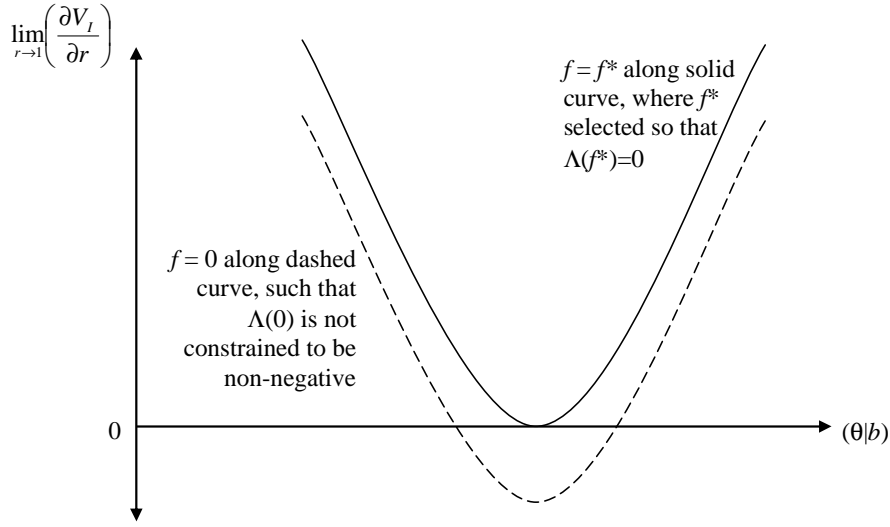


Figure 2. Fines f are set to ensure positive marginal incentives to report for all prevalence levels θ .

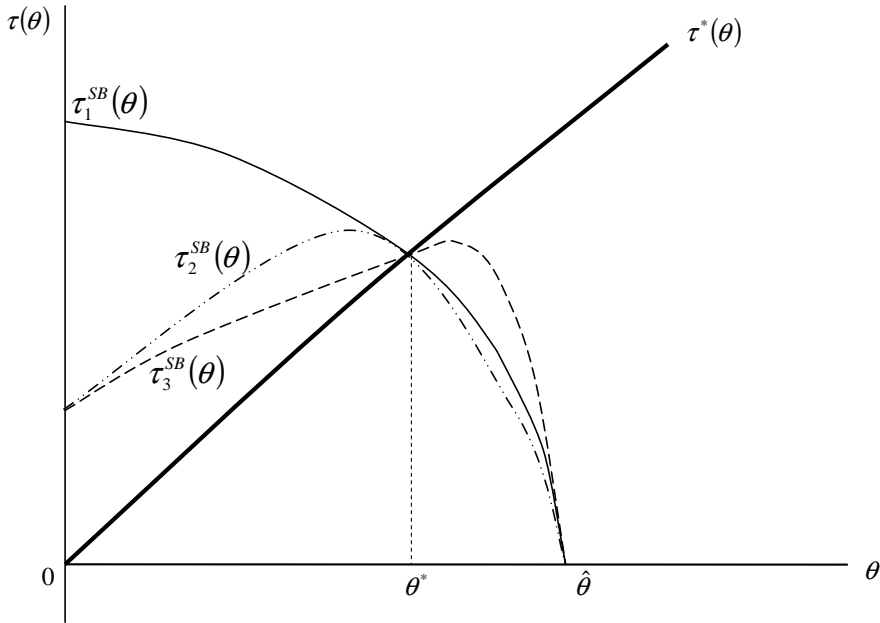


Figure 3. Possible shapes for the first-best indemnity payment schedule, $\tau^*(\theta)$, and the second-best indemnity payment schedule, $\tau^{SB}(\theta)$.