Journal of Agricultural and Resource Economics 47(2):355–372 ISSN: 1068-5502 (Print); 2327-8285 (Online)

doi: 10.22004/ag.econ.311029

Optimal Biosecurity Policy with Heterogeneous Farmers

Abdel Fawaz Osseni, Alexandre Gohin, and Arnaud Rault

Infectious animal diseases raise serious challenges for both public health and the livestock sector. We develop an original principal–multiple agent model for preventing these diseases that explicitly considers the heterogeneity of risk-averse farmers in addition to production externalities and *ex ante* informational asymmetries. Our results confirm that failing to consider farmers' heterogeneity generates Pareto-inefficient solutions. When using individual-based instruments, the government should cope with heterogeneity by increasing guaranteed payments and reducing average payments. However, when population-based instruments are the only available policy tools, increasing average payments is better for reducing moral hazard issues.

Key words: incentive program, individual-based instruments, population-based instruments, public good, public policy

Introduction

The recent global COVID-19 pandemic highlights the fragility of anthropogenic systems and our vulnerability to zoonotic diseases. Zoonoses represent more than 60% of emerging infectious human diseases (Jones et al., 2008), of which about 70% come from wildlife and only 30% from domesticated animals, thanks to existing control and surveillance measures. Recent scientific work has shown that preventing emerging diseases would be hundred times less expensive than trying to control them *ex post* (Dobson et al., 2020). The growing prevalence of such diseases may generate gradual negative impacts and may result in substantial negative returns, ranging from direct economic losses on livestock farms (e.g., production losses and mortality) to broad economic implications for society as a whole (e.g., trade bans), with the risk of substantial damage if the disease spreads to humans.

Recent examples of potentially zoonotic diseases include the bovine spongiform encephalopathy (mad cow disease) and influenza (e.g., avian influenza, swine influenza), which have struck many parts of the globe in recent decades. Control and prevention of bovine tuberculosis has recently become a growing concern among public health and agricultural authorities in Europe. Animal health in these contexts combines characteristics of private and public goods, requiring coordinated public action to regulate. For public authorities, the emphasis is therefore on disease prevention rather than on *ex post* management, as the health repercussions of diseases can be serious. A growing body of economic literature analyzes disease management trade-offs made by farmers within their farm systems and the optimal design of policy instruments considering different market failures. However, previous studies largely do not account for farmers' heterogeneity.

Abdel Fawaz Osseni (corresponding author) is a PhD student and Alexandre Gohin is a director of research in the Department of Economics at the National Institute for Agriculture, Food and Environment, Smart-Lereco research unit at Rennes, France. Arnaud Rault is a researcher in the Social Sciences, Agriculture and Food, Space and Environment Department of the BIOEPAR research unit at Nantes, France.

Review coordinated by Darren Hudson.

Our paper is driven primarily by a willingness to explicitly capture farmers' heterogeneous health decisions and their consequences for health policies. In all countries, livestock farms vary in many respects (e.g., location, size, economic situation, behavior). Livestock farmers will thus respond differently to biosecurity incentives, possibly impairing the efficiency of policy instruments. Our contribution is to fill this gap by defining the optimal incentive policies for animal health prevention in the presence of heterogeneous farmers.

We develop an innovative modeling framework of policy incentives that considers farmers' heterogeneity. This model takes into account two market failures that justify the policy intervention: production externality (due the public aspect of biosecurity) and *ex ante* informational asymmetry, which leads to moral hazard behaviors in the presence of risk. Many studies have already introduced informational asymmetry between the principal and the agent in their setting and implicitly assume that controlling the agent's action is prohibitively costly for the public authority. Then, farmers are differentiated according to their production costs of biosecurity, which provides a more realistic framework that may reinforce the problem of cost escalations resulting from various information asymmetries.

A well-established result under perfect information is that the first-best allocation corresponds to the case where the payment to the agent directly depends on his private effort. Biosecurity relies on numerous barely observable actions, leading to a possible suboptimal design of contracts with respect to agents' efforts (Gjesdal, 1982). Hence, livestock farmers can benefit from their private information to maximize their utility. In this context, as the public authority fails to observe private biosecurity, we design an output-based contract where the payment relates to the health outcomes of each agent. Concerning the principal, we assume that the public authority aims to maximize the overall health outcome at a lower public cost.

We highlight the need for collective and coordinated actions that leads to better health performance such in the case of many public goods problems, including weakest-link provision issues. Our results show how policy incentives can manage heterogeneous agents by providing differentiated payments to farmers. The numerical analysis highlights the crucial role of policy design in animal disease prevention. In particular, we underline that in addition to the external effects of contagious disease management, the policy is all the more efficient in dealing with heterogeneous levels of farmers' health practices with different policy instruments. We also reveal the suboptimality of policy packages that rely on constrained policy instruments.

Literature Review

A growing economic literature is devoted to assessing *ex post* consequences and *ex ante* optimal private and public actions. This literature stresses that *ex post* losses cannot be restricted to the livestock sectors. For instance, Philippidis and Hubbard (2005) estimate that the 2001 foot and mouth disease (FMD) outbreak in the UK resulted in over \$1.6 billion in economic losses, shared among numerous industries from the agricultural sector to the tourism sector. Gohin and Rault (2013) extend the previous analysis with a dynamic framework and find that the economic losses of such outbreaks last many years after animal health recovery.

Managing animal health involves a complex set of actions carried out by both private and public actors both for *ex ante* health risk prevention and *ex post* health care. To contain the spread of major contagious diseases, control policies can be implemented at a cost (e.g., culling and sanitary embargoes). The direct and indirect costs of zoonoses are estimated to have exceeded \$220 billion in recent decades (World Bank, 2010). To avoid such sanitary and economic consequences, public authorities can promote preventive measures (Häsler et al., 2012), such as on-farm biosecurity actions that apply a set of practices (i.e., animal testing, surveillance, quarantine and culling) meant to control the introduction (bioexclusion) and diffusion (biocontainment) of a disease across herds (Food and Agriculture Organisation of the United Nations, World Bank, and World Organisation for Animal Health, 2007; Kobayashi and Melkonyan, 2011). Biosecurity practices deserve particular attention because of their positive externalities, both at the farm and broader scales. First, such practices generate economies of scope by protecting against unplanned diseases. Indeed, implementing biosecurity practices provides protection not only from the targeted disease but also from a large set of pathogens sharing the same infection pathways. In this respect, Gramig and Wolf (2007) describe biosecurity as non-allocable because it is not restricted to disease-by-disease management. Second, biosecurity exhibits attributes of public goods because effective sanitary practices on farms reduce the infection risk to neighboring herds and humans, a benefit that is neither rival nor exclusive.

However, trade-offs at the farm level between *ex ante* and *ex post* management options remain where *ex post* losses and *ex ante* biosecurity expenditures compete. According to a neoclassical analysis, a farmer is willing to invest in disease management provided that his expected benefit outweighs his cost (McInerney, Howe, and Schepers, 1992; Chi et al., 2002). The consequence of this rational behavior is that disease management might lead to a tolerance of a level of disease as long as the required investment is not profitable (Wolf, 2005). When the farmer further fails to consider external effects, he will not dedicate private effort up to the social optimum. The need for public intervention appears essential for both protecting public health (considering the zoonotic aspect) and improving private biosecurity efforts to a socially desirable level (externality aspect). In this respect, Perrings et al. (2002) show in the case of communicable diseases that the level of protection available to society will be constrained by the efforts of the least diligent farmer, defined as the least effective provider. In other words, these authors characterize prevention as a weakest-link public good.

In response, a growing body of literature assesses various policies that foster private biosecurity practices. The main findings underline that the broad adoption of biosecurity is hampered by issues of externality, information asymmetry, costly efforts of on-farm herd biosecurity, and disincentives due to *ex post* compensation. Externality refers to the failure of markets to consider external costs (or benefits) when designing management policies (Bicknell, Wilen, and Howitt, 1999; Huang, Wang, and Zuo, 2017). Information asymmetry has various dimensions: The *ex ante* information issue has been well studied in relation to the concept of moral hazard. Classically, the issue implies the inability of authorities (i.e., contract designer) to observe farms' private efforts or farmers' full characteristics. Generally, this issue of incentive policies is considered based on incentive-compatibility constraints. Costly farm biosecurity efforts and *ex post* potential compensation can hinder optimal private actions (Fraser, 2018; Hennessy and Wolf, 2018). Biosecurity efforts involve farmers' financial capacity to invest in costly actions while expecting related benefits. The literature also shows that farmers' willingness to report cases of infection is related to the level of *ex post* compensation. Both factors may lead to a decline in preventative actions (Zilberman et al., 2012). Hennessy and Wolf (2018) indicate that the adverse selection issue can be solved by establishing levels of compensatory payments to hedge market prices.

Gramig, Horan, and Wolf (2009) consider both potential risks of moral hazard and adverse selection issues and develop a principal–agent model to examine a compensation scheme for both biosecurity efforts and the reporting of infected animals. The authors' model setting includes both an indemnity payment and a fine. The authors suggest that when simultaneously controlling hidden information and hidden efforts, policy planners must rely on a two-dimensional mechanism: an *ex ante* indemnity payment to support private effort and an *ex post* fine to prevent the development of opportunistic behaviors. This study, however, neglects interactions among agents, particularly the external effects of communicable disease, an important feature (Hennessy, 2007; Reeling and Horan, 2015). However, Mato-Amboage, Pitchford, and Touza (2019) allow for spillover effects considering two homogeneous agents. The authors suggest a coordinated contract approach for facilitating risk minimization and risk sharing, but they do not explicitly investigate agent heterogeneity.

Concerning heterogeneity, Wang and Hennessy (2014) analyze producers' incentives to participate in a voluntary program of livestock disease control. Considering that participation involves costly test operations, the authors show that incomplete participation may exist due to cost heterogeneity. However, their analysis focuses on pecuniary externalities and not on production externalities. Finally, Fraser (2018) performs a numerical simulation to highlight that the range of payments required to achieve the optimal incentive scheme is subject to individual parameters (i.e., farmers' risk preferences and the cost of biosecurity). Nevertheless, this last study does not consider externalities and multiple agents incentive schemes.

Economic applications in other fields provide useful insights. For instance, in analyzing optimal incentives for research activities, Huffman and Just (2000) find that individual characteristics allow an efficient organization of research. Using a piece-rate contract, Levy and Vukina (2002) also demonstrate that payments vary with individual abilities and individual attitudes toward risks.

Theoretical Framework and Analysis

We present a modeling framework representing an incentive contract for biosecurity actions with an emphasis on characterizing the effects of heterogeneity among farmers, health externalities and moral hazards. We consider a principal–agents game in which the principal (i.e., the government) incentivizes two heterogeneous agents (i.e., the farmers) to implement biosecurity actions within their herds in the context of infectious disease management.

Hypotheses and Model Setting

Our model of incentive contract—adapted from Mato-Amboage, Pitchford, and Touza (2019) and Levy and Vukina (2002)—makes two main contributions. First, we consider the farmers's heterogeneity in terms of effort costs. Second, we design a transfer scheme that prioritizes the public good aspect of biosecurity. More explicitly, we reward each farmer depending on the average (population) health performance on the one hand and his own relative health performance on the other. The incentive problem links a principal who is wealth maximizing and risk neutral to two farmers who are utility maximizing and risk averse, respectively indexed by $k = i, j$. The modeling can be generalized to several agents. We restrict our analysis to two agents to highlight the heterogeneous effects of farmers on incentive policies. Extending analyses to more agents could be of interest to evaluate how the number of farmers affects policy design.

Assuming that both farmers agree to participate in the contract, the principal specifies a profile of reward t_k to each k farmer, who will take an action of magnitude $e_k \geq 0$, earning the payment. The zero effort value indicates no biosecurity action, an outcome that can occur when the cost of self-prevention exceeds the cost of inaction. For instance, small farms (e.g., backyard producers) are less likely to implement biosecurity measures (Hennessy, 2007).

We use y_k to denote the observable performance characterizing the sanitary quality that results from biosecurity applied on farm k. In other words, y_k is the individual production of the health public good. Subscripts i and j denote what each agent applies to each farm, as long as one farmer is assumed to hold a single farm. The function of health performance on farm i is calculated as

$$y_i = e_i + \theta y_j + \varepsilon_i. \tag{1}$$

This relationship between farmers is captured by positive externality parameter θ, with $\theta \in [0,1]$. This specification of the externality parameter can be found in Choi (1993) and Mato-Amboage, Pitchford, and Touza (2019). We deliberately restrict our analysis of external effects to this externality parameter to put more emphasis on the effect of heterogeneity on public policy. In this analytical section, random shocks ε_i and ε_j are assumed to be noncorrelated and are drawn from a normal distribution with a mean of 0 and a variance of $\sigma^2_{\varepsilon_i} = \sigma^2_{\varepsilon_j} = \sigma^2$. Noncorrelation between shocks is purposely chosen to leave epidemiological issues aside. Moreover, our assumption remains realistic in most cases and at a large scale. As a robustness check, we provide the results of simulations relating to correlated shocks in a later section.

At the individual level, the realization of y_k occurs at a cost, ψ_k, which depends on both the actions taken and the agents themselves. The agents' influence is represented by the marginal cost and captures the heterogeneous abilities of the individuals. While heterogeneity can also be introduced through other parameters (e.g., risk preference, farm productivity, reservation utility), we concentrate in this paper on the marginal cost variable. Formally, we define for the kth farmer a quadratic cost function given by

$$\psi_k = \frac{c_k e_k^2}{2};\ k = i, j. \tag{2}$$

This specification ensures the convexity of the cost function with c_i being positive. The preservation of the public health good is meant to be guaranteed by the public authority through a mechanism of penalties/subsidies to the farmers engaging in health prevention measures. To do so, we define a linear contract between the principal and the kth agent as follows:

$$t_k = \alpha_k + \beta\bar{y} + \delta\left(y_k - \bar{y}\right);\ k = i, j, \tag{3}$$

where α_i is the guaranteed payment that farmer i receives regardless of his effort and health performance, β stands for the common payment for the average health situation resulting from all farmers' performance, and δ is an additional payment for farmers with better results, thus targeting the relative performance of each farmer. Accordingly, the public authority has three economic tools at its disposal to achieve the best public health outcome. The government's objective is to define the optimal values of parameters α_i, α_j, β, and δ that allow for the socially best health performance outcome (i.e., output) to be achieved at the lowest cost. We define the government's objective as $W = \sum_k (y_k - t_k)$, and its expected value is

$$E(W) = \frac{(\beta - 1)\left(e_i + e_j\right)}{\theta - 1} - \alpha_i - \alpha_j. \tag{4}$$

Last, we assume that both farmers exhibit constant absolute risk aversion (CARA) utility characterized by a negative exponential utility function. This feature is expressed for the kth farmer as $U_k = -\exp[-\eta_k \cdot (t_k - \psi_k)]$, where η_k is the risk attitude coefficient. Each farmer's objective can be expressed as certainty equivalent, denoted $CE(U_k)$, with

$$\begin{aligned} CE\left(U_k\right) = {} & \alpha_k + \beta \cdot \frac{e_k + e_{k'}}{2(1-\theta)} + \delta \cdot \frac{e_k - e_{k'}}{2(1+\theta)} \\ & - \frac{\eta_k \sigma^2}{2}\left(\frac{\beta^2(\theta+1)^2 + \delta^2(\theta-1)^2}{2\left(\theta^2-1\right)^2}\right) - \frac{1}{2}c_k e_k^2 \end{aligned} \tag{5}$$

for all $k = i, j$ and $k \neq k'$.

Optimal Solutions and Implications for Public Decision

Obtaining perfect information about private biosecurity efforts is not straightforward. In practice, the government may hire veterinary services to monitor health prevention practices applied on farms and then report on the implemented private efforts. However, such measures can be subject to high public expenditures, with the risk of the monitoring costs surpassing the compensatory payments. In this context, biosecurity efforts become scarce or even noncontractible, potentially leading to moral hazard issues with the incentive contract. Farmers may intentionally choose to provide an effort below the socially optimal level to take advantage of government. Accordingly, *ex ante* efforts are assumed to be noncontractible, while the *ex post* results are by measuring disease prevalence or observing signs of infection in carcasses (e.g., bovine tuberculosis). The asymmetry of information on private effort makes first-best allocation no longer achievable. The incentive scheme is therefore at the second-best option, which implies consideration of an incentive compatibility constraint (ICC). This ensures that the private effort corresponds to the optimal effort. In addition, the farmers accept the contract, provided that it matches at least their reservation utility (RU), or $\underline{u}_i$, which is the participation constraint (PC). As mentioned previously, the government seeks optimal values α_i, β, and δ, considering that each farmer provides his optimal biosecurity effort, e_i. The government's optimization problem is

(6) $$\max_{\alpha_i,\alpha_j,\beta,\delta} E(W),$$

subject to

(7) $$CE\left(U_k\right) \geq \underline{u}_k \text{ for all } k = i, j \text{ (PC);}$$

(8) $$e_k = \underset{e_k}{\operatorname{argmax}} \left(CE\left(U_k\right)\right) \text{ for all } k = i, j \text{ (ICC).}$$

Equation (8) corresponds to each farmer's optimization problem. Taking the first-order condition of equation (8) leads to each farmer's optimal effort, e_i. For the optimal solution, the participation constraint binds (Kuhn–Tucker conditions), implying $CE(U_i) = \underline{u}_i$. After optimization, the solutions of biosecurity incentive policy, t_i, are then revealed (derivations are reported in the appendix).

The optimal level of payment for the average health status is

(9) $$\beta = \frac{c_i + c_j}{c_i c_j \left(z_i + z_j\right) + c_i + c_j}.$$

The optimal level of payment for relative performance is

(10) $$\delta = -\frac{\left(c_i + c_j\right)\left(\theta + 1\right)}{\left(c_i c_j \left(z_i + z_i\right) + c_i + c_j\right)\left(\theta - 1\right)}.$$

The optimal level of the guaranteed payment for farmer i is given by

(11) $$\alpha_i = \underline{u}_i + \frac{\left(c_i z_i - 1\right)\left(c_i + c_j\right)^2}{2c_i \left(c_i c_j \left(z_i + z_j\right) + c_i + c_j\right)^2 \left(\theta - 1\right)^2},$$

where $z_i = \eta_i \cdot \sigma^2$ and $z_j = \eta_j \cdot \sigma^2$ is a farmer-specific index of risk premiums.[1]

Recall that parameters c_i, z_i, and θ are assumed to be positive during the analyses. Moreover, we interpret heterogeneity as a change in marginal costs of only one farmer with initial equal marginal costs. Solutions β and δ are equally linked to both farmers' attributes, so they are the same for all farmers.

The payment for average performance depends on both farmers' marginal costs and the risk premium index. The government defines β solely on the basis of the average health status of the farms, regardless of any influence of the externality. From equation (9), $\partial\beta/\partial c_j$ is negative (see the appendix), indicating that the payment for average health performance decreases when biosecurity marginal costs increase (i.e., when the ability to implement biosecurity decreases). This result implies that an increase in the marginal cost for at least one farmer is detrimental for all farmers. We also underline that the same analysis applies to the risk premium index because $\partial\beta/\partial z_j$ is negative. When the risk premium increases, for instance, due to greater risk aversion, the moral hazard issue (i.e., the farmer expends less effort while protected by the policy) becomes more stringent. Accordingly, the optimal level of the average payment decreases, resulting in more

[1] In accordance with the notation given by Huffman and Just (2000), this term is not the conventional risk premium per se, but it measures a characteristic of the farmer that is independent of the public incentive.

risks supported by farmers and fewer risks supported by the government. Obviously, full insurance will lower farmers' incentives to increase their private efforts up to the socially desirable level. This result is customary in the principal–agent literature (Laffont and Martimort, 2009).

Equation (10) shows that δ is positive. The government provides an additional subsidy for farmers whose relative performance is higher than the average, but it turns into a penalty for those with health performance below the average level. While β rewards the average level of health quality, δ incentivizes farmers to increase their private biosecurity efforts. Each payment to farmers is based on β, and it is adjusted downward or upward with δ. This result is similar to that given by Gramig, Horan, and Wolf (2009), who call for a bidimensional mechanism for biosecurity incentive contracts. From equation (10), the marginal payment for relative performance decreases when the marginal cost for at least one farmer increases ($\partial\delta/\partial c_j < 0$). It follows then that the failure to consider the heterogeneity of biosecurity production generates Pareto-inefficient solutions. The optimal levels of the guaranteed payments are more complex, including the reservation utilities, as expected. The partial derivative of α_i, equation (11), with respect to c_j is positive for $c_i z_i < 1$ and negative otherwise. Indeed, an increase in marginal biosecurity costs for farmer j makes farmer i less likely to participate in the biosecurity program, *ceteris paribus*. Accordingly, the guaranteed payment must be higher to induce the participation. However, we already find that an increase in marginal costs reduces the optimal levels of average and marginal payments. These reductions make farmers' participation in the biosecurity program more unlikely. Therefore, a trade-off appears in the design of policy instruments that depends on the risk aversion of the farmers. It appears that if a farmer with higher marginal costs is also highly risk averse, it is better to reduce his individual guaranteed payment with a lesser reduction of average and marginal payments.

From the solutions for the optimal levels of policy instruments, the optimal biosecurity effort for farmer i is

$$e_i = \frac{c_i + c_j}{(1-\theta)\left((c_i + c_j) + (z_i + z_j)\, c_i c_j\right) c_i}. \tag{12}$$

As expected, the optimal biosecurity effort provided by farmers negatively depends on their marginal costs at the optimal policy levels.

The expected health performance for a given farmer i is

$$E\left[y_i\right] = \frac{(c_i + c_j)(\theta c_i + c_j)}{(\theta - 1)^2(\theta + 1)\left[(c_i + c_j) + (z_i + z_j)\, c_i c_j\right] c_i c_j}. \tag{13}$$

Equation (13) shows that a farmer's health performance deteriorates when neighbors' marginal costs increase ($\partial E(y_i)/\partial c_j < 0$). The same analysis applies with an increase in the neighbors' risk premium index, (z_j), which puts forward benefits for every farmer to participate in collective health preservation. Each farmer must make sufficient biosecurity efforts to improve global welfare. The whole system may be at risk when even one farmer who fails to prevent the entry of diseases into his herd. This is consistent with Hennessy (2008), who shows that biosecurity for disease entry is strategically complement among farmers. All farmers must implement sufficient efforts to prevent the entry of a disease.

Let us consider, for example, a situation in which a farmer faces high marginal costs of biosecurity (e.g., a small herd) such that he is unable to apply sufficient biosecurity measures. This lack of effort applied to a herd will degrade its own health performance and put all surrounding herds at risk. This particular herd then becomes the focal point of infection from which a disease can spread to other herds. That is, the strengthening of social welfare implies the joint production of sufficient health outcomes from all farmers. In this respect, the rule of the weakest-link public good applies to biosecurity, notably when disease is a public bad (Perrings et al., 2002; Vicary and Sandler, 2002; Hennessy, 2008). Indeed, even if farmers who provide high biosecurity effort are better protected; the disease can still get into a country or any other spatial unit through the weakest control point.

Let us temporarily assume that farmers are risk neutral (RN), implying that when $\eta_i = 0$, the biosecurity effort becomes $e_i^{RN} = -\frac{1}{c_i(\theta-1)}$ and the health performance becomes aslerulion $y_i^{RN} = \frac{\theta c_i + c_j}{(\theta-1)^2(\theta+1)c_i c_j}$. When comparing these two relations to those in equations (12) and (13), it appears that farmers' risk aversion is detrimental to biosecurity investments in the presence of information asymmetry and therefore alters health performance from the first-best outcome.

The expected net transfer (i.e., expected transfer net of the optimal cost of biosecurity) received by farmer i is

$$E\left[t_i - \psi_i\right] = \underline{u}_i + \frac{z_i\left(c_i + c_j\right)^2}{2(\theta-1)^2\left(c_i + c_j + \left(z_i + z_j\right)c_i c_j\right)^2}. \tag{14}$$

The partial derivatives of the expected net transfer with respect to c_j and z_j—$\partial E[W]/\partial c_j < 0$ and $\partial E[W]/\partial z_j < 0$—are negative, indicating the detrimental effects of farmer j's marginal cost and of the risk premium index on farmer i's expected net compensation.

Finally, the optimal government objective is given by

$$E[W] = \frac{\left(c_i + c_j\right)^2}{2(\theta-1)^2\left(c_i + c_j + \left(z_i + z_j\right)c_i c_j\right)c_i c_j} - \underline{u}_i - \underline{u}_j. \tag{15}$$

From relation (15), $\partial E[W]/\partial c_i < 0$ and $\partial E[W]/\partial z_i < 0$. In the case of risk-neutral farmers, the total expected payoff for the government becomes $E(W^{RN}) = \frac{c_i + c_j}{2(\theta-1)^2 c_i c_j} - \underline{u}_i - \underline{u}_j$. It then follows that the government is better off when the contract involves farmers with a low marginal cost of biosecurity production and low levels of risk aversion.

Considering individual attributes in the incentive contract allows us to achieve Pareto-efficient solutions and favors farmers' full participation. This result is consistent with Wang and Hennessy (2014), who show that cost heterogeneity matters a great deal for full participation in a voluntary contract. Our results are also consistent with Levy and Vukina (2002) and Fraser (2018), who emphasize the need to consider farm-specific parameters to design optimal incentives. Considering that the diseases involve external costs, the inefficiency of biosecurity production is detrimental not only to farmers' own performance but also to all other farmers and therefore to society as a whole. Indeed, a failure to prevent disease entry within a herd may affect diffusion across other herds but also to humans through food chain processes (e.g., zoonotic diseases). Ensuring the welfare of society overall implies a certain level of health performance within every herd. These results corroborate Perrings et al. (2002), Vicary and Sandler (2002), Sandler and Arce M. (2003), and Hennessy (2008) in the sense that biosecurity is the weakest-link public good. Our incentive scheme accordingly suits public good insights for two reasons. All farmers must increase their level of health performance to increase the value of β; then, unvirtuous behaviors are in part under control over parameter δ, where the payment is relatively performance based.

The previous theoretical results highlight the impacts of farmers' cost heterogeneity in a particular setting where the government can mobilize several policy instruments: individual-based guaranteed payments and average and marginal payments. In practice, some governments may not be able to activate numerous instruments and hence may experience difficulties managing the participation of all farmers. We also assume the presence of uncorrelated biosecurity shocks. In the empirical section below, we remove these simplifications progressively.

Numerical Analysis

We apply our previous model with parameters defined, following Mato-Amboage, Pitchford, and Touza (2019). In this empirical section, the assessment of the impacts of farmers' heterogeneity is again restricted to variation in marginal costs of biosecurity. Indeed, we consider $c_1 = 1$, and we

Table 1. Optimal Values for the Individual-Based Flexible Policy

θ		**0**			**0.5**			**0.75**	
c_2	**1**	**1.5**	**2**	**1**	**1.5**	**2**	**1**	**1.5**	**2**
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
W	0.668	0.522	0.451	2.675	2.090	1.806	10.764	8.409	7.264
β	0.665	0.624	0.599	0.663	0.622	0.598	0.658	0.619	0.595
δ	0.672	0.630	0.604	2.029	1.901	1.824	4.908	4.581	4.385
α_1	−0.110	−0.097	−0.090	−0.435	−0.388	−0.360	−1.655	−1.535	−1.446
α_2	−0.110	−0.032	0.001	−0.435	−0.121	0.009	−1.666	−0.402	0.117
e_1	0.668	0.627	0.602	1.339	1.256	1.206	2.718	2.546	2.443
e_2	0.668	0.418	0.301	1.339	0.837	0.603	2.718	1.698	1.222
y_1	0.668	0.627	0.602	2.679	2.232	2.009	10.870	8.730	7.679
y_2	0.668	0.418	0.301	2.679	1.953	1.607	10.870	8.245	6.981
t_1	0.334	0.294	0.271	1.341	1.179	1.087	5.494	4.828	4.447
t_2	0.334	0.228	0.180	1.341	0.916	0.724	5.482	3.739	2.949

progressively increase c_2 from 1 (in which case the two farmers are homogeneous) to 2 (as farm incomes greatly vary among farms in all countries). We also consider different levels of production externality $\theta = \{0; 0.5; 0.75\}$. We first assume that biosecurity shocks are uncorrelated and that variances amount to 0.25. Risk aversion is calibrated to 2 for both farmers. Finally, rather than performing the certainty equivalent approximation, we draw 100,000 biosecurity shocks from the normal distribution to compute the farmers' expected utilities. Below we consider three policy environments. The first policy environment assumes that the government can mobilize all policy instruments with individual-based guaranteed payments. We call this policy the individual-based flexible policy, which corresponds to the case considered in the analytical section. Then, we move to the second policy environment in which the government defines a unique guaranteed payment. We call this policy the population-based flexible policy. Finally, the third policy environment further constrains the policy instruments by excluding the marginal payments. We call this policy the rigid policy.

Table 1 presents the results obtained from the first policy environment. Column 1 represents the case without externalities and with identical marginal biosecurity costs. As expected, the two farmers behave in the same way by dedicating the same efforts, which lead to the same level of health performance. The farmers receive, accordingly, the same amount of payment. The optimal levels of marginal/average payments are similar (approximately 0.67), while the specific payment is negative and hence is a penalty. The marginal/average payments stimulate biosecurity provisions by farmers and simultaneously their income. The specific penalty decreases the farmers' income to their reservation utility and saves public costs.

In column 3 of Table 1, farmer 2's marginal cost has doubled. At the optimum, the levels of policy instruments are significantly modified. We observe a reduction in marginal/average payments (from 0.67 to 0.6), while the specific penalty is removed for farmer 2. The logic of the new levels of instruments is as follows: Farmer 2's higher marginal cost leads to lessened biosecurity effort from this farmer and accordingly poorer health quality performance than that of farmer 1. If the government increases the marginal payment, this will support farmer 1's production but further decrease farmer 2's production. Due to the convexity of the cost function, the increase in farmer 1's production will be lower than the absolute decrease in farmer 2's production. Overall, this would decrease total biosecurity production while increasing budget outlays. Accordingly, the optimal policy involves a reduction of the level of marginal payment. In this case, farmer 2's income of further deteriorates to lower than his reservation utility and thus farmer 2 will no longer participate in the program. To keep farmer 2 in the program, the government reduces (or removes) farmer 2's specific penalty. These new levels of policy instruments modify the decisions of farmer 1, who makes less effort and receives fewer net subsidies. Farmer 2's biosecurity effort drops from 0.67 to 0.3, and his compensation declines as well (from 0.33 to 0.18). Accordingly, government welfare decreases from 0.67 to 0.45.

These empirical results perfectly support the previous analytical results. We also report in column 2 of Table 1 the results for the case in which farmer 2's marginal cost is 1.5. We obtain intermediate results, as expected. Indeed, the optimal results appear monotone and concave with respect to the value of farmer 2's marginal cost, which is linked to the convexity assumption of the cost function.

Columns 4–6 and 7–9 of Table 1 introduce moderate (0.5) and high (0.75) externality effects, respectively. Consistent with the theoretical results, we find that the optimal levels of average payments do not depend on the externality parameter. However, this parameter significantly changes the other variables. For instance, substantial changes can be observed in the marginal payment. The latter changes from 0.67 (column 1, $\theta = 0$) to 2.03 for $\theta = 0.5$) (column 4) and reaches 4.91 for $\theta = 0.75$) (column 7), corresponding to increases of 200% and 630%, respectively. Similarly, the government's expected welfare improves from 0.67 to 2.67 for the former and to 10.76 for the latter, which means that the optimal policy delivers much gain when externalities are significant than in the absence of policy (in which case expected benefits are 0 for all actors).

More importantly, we find that the previous monotone and convex impacts of heterogeneity on optimal policy levels still prevail. The design of homogeneous contracts with nonidentical farmers leads to suboptimal solutions. If the government wrongly assumes that both farmers have unit marginal costs while farmer 2's correct marginal cost is 2, farmer 2 no longer participates in the biosecurity program, and his effort becomes nil, while farmer 1's effort remains unchanged (equal to 1.339 with moderate externality). The expected biosecurity production from farmer 1 decreases to 1.786 due to the absence of effort from farmer 2. Then, farmer 2's expected biosecurity production decreases to 0.893 only due to farmer 1's effort. Overall expected biosecurity production decreases to 2.679 compared to 3.616 if the government correctly considers farmers' heterogeneity. However, the government saves all payments made to farmer 2, while payment to farmer 1 remains nearly unchanged (1.359). Overall, the objective of the government decreases to 1.32 and hence by 27% compared to the optimal policy design.

To ensure the participation of the two farmers in the contract, we remove guaranteed payment included in the incentive policy, replacing it with a guaranteed subsidy of 0.015 in the case of moderate externality parameter. Thanks to the subsidy, the participation constraint of the farmer 2 just binds while being strictly higher than 0 for the farmer 1. Indeed, this policy to ensure full participation by giving more transfer to farmers is suboptimal. Compared to the optimal policy, we observe an increase of both farmers' biosecurity effort, leading then to the improvement of the average health performance (from 1.81 to 2.01). However, the level of the transfer has increased with the consequence of the decrease of the government objective by 27%. Due to the subsidy, farmer 1's expected profit increases by 2.51 times compared to the optimal policy.

Let us consider the opposite situation, in which farmer 2 becomes more efficient (his marginal biosecurity cost decreases to 0.5), while the government still believes that both farmers are equally efficient (both marginal costs are equal to 1). In this case, farmer 2 provides more biosecurity than the government expects. Due to the marginal payment component, this farmer receives more payments. However, farmer 1 receives less marginal payment and no longer wants to participate in the program, which again leads to a suboptimal situation. The government can prevent this new suboptimal situation by initially providing more guaranteed payments to ensure the participation of both farmers. In this case, the less efficient farmer continues to participate in the program. This new policy remains suboptimal because it does not consider heterogeneity, with the more efficient farmer now benefiting from expected profits much higher than his reservation level.

More precisely, with moderate externalities, the optimal policy levels when farmer 2's marginal costs equal 0.5 become 0.74 for the average payment, 2.29 for the marginal payment, -0.52 for the guaranteed payment to farmer 1, and -1.68 for the guaranteed payment to farmer 2. With these levels, the government objective reaches 4.51. If the government decides to implement the

Table 2. Optimal Values for the Population-Based Flexible Policy

θ		0			0.5			0.75	
c_2	1	1.5	2	1	1.5	2	1	1.5	2
	1	2	3	4	5	6	7	8	9
W	0.668	0.481	0.409	2.674	1.925	1.636	10.755	7.729	6.557
β	0.665	0.767	0.816	0.662	0.765	0.812	0.643	0.770	0.811
δ	0.672	0.388	0.275	2.033	1.171	0.834	4.984	2.795	2.016
α	−0.110	−0.129	−0.129	−0.431	−0.510	−0.511	−1.508	−2.070	−2.033
e_1	0.668	0.577	0.546	1.339	1.155	1.090	2.710	2.338	2.198
e_2	0.668	0.385	0.273	1.339	0.770	0.545	2.710	1.559	1.099
y_1	0.668	0.577	0.546	2.678	2.054	1.817	10.840	8.016	6.910
y_2	0.668	0.385	0.273	2.678	1.797	1.454	10.840	7.571	6.281
t_1	0.334	0.278	0.242	1.341	1.113	0.969	5.463	4.552	3.950
t_2	0.334	0.203	0.167	1.341	0.813	0.666	5.463	3.307	2.684

optimal policy defined with homogeneous farmers ($c_1 = c_2 = 1$) while increasing the guaranteed payments from −0.435 to −0.415 to ensure participation, the government objective reaches only 3.54, a 22% reduction. Farmer 2's expected profit significantly increases as he does not support the correct penalty level (i.e., the negative of the guaranteed payment).

The second policy environment implements a restriction whereby the specific guaranteed payments are identical for both farmers (see Table 2). We previously highlighted the relevance of these payments. The consequence is the deterioration of biosecurity efforts and production and hence of expected government welfare. More importantly, we find that the optimal levels of the average payment are now positively related to the marginal cost and hence to heterogeneity. The logic of this opposite result is as follows: When farmer 2's marginal cost of biosecurity increases, this farmer is less willing to participate in the biosecurity program. If the government increases the unique guaranteed payment, it will favor farmer 2's participation in the biosecurity program but simultaneously give more benefits to farmer 1. The government can try to save public budgets by reducing the value of the average payment. The effects of these two changes in terms of biosecurity provision will be a production increase by farmer 2 (due to his participation in the program) but less provision from farmer 1 (due to reduced incentives while he enjoys a greater guaranteed payment). The net effect is a reduction in biosecurity provision. Accordingly, increasing the unique guaranteed payment is not optimal. However, it is optimal to decrease this payment and motivate farmer 2's participation in the program by increasing the average payment. This strategy is again beneficial for farmer 1, and the government should reduce the marginal payment accordingly. For instance, let us consider a case with moderate externality (columns 4–6 of Tables 1 and 2). When the two farmers are identical, the two policy environments lead to the same policy instruments (average payment of 0.66, marginal payment of 2.03, and guaranteed payment of −0.43). When farmer 2's marginal cost increases to 2, the optimal marginal payment decreases to only 1.82 under the first policy environment and to 0.83 under the second policy environment.

These results underline that the effects of heterogeneity on the optimal policy levels depend on the policy instruments available to the government, which is again confirmed by the results obtained from our third policy environment (see Table 3). Here, both farmers receive the same levels of payment, which are based on a unique guaranteed payment and the average payment. We find that the optimal level of the unique guaranteed payment increases considerably (from −0.98 to −0.28 with moderate externality, columns 4–6) as farmers become more heterogeneous (equivalently as farmer 2's marginal cost increases). However, the optimal level of the average payment is slightly reduced (from 0.99 to 0.75 with moderate externality), which again differs from the second policy environment because the government can no longer manage the efforts of the low-cost farmer with the marginal payment. As expected, we find that the impact on government welfare is worse when the government has fewer instruments to cope with two market failures and heterogeneous agents.

Table 3. Optimal Values under the Rigid Policy

θ		0			0.5			0.75	
c_2	1	1.5	2	1	1.5	2	1	1.5	2
	1	2	3	4	5	6	7	8	9
W	0.500	0.347	0.281	1.994	1.386	1.123	7.924	5.514	4.472
β	0.999	0.833	0.750	0.994	0.83	0.747	0.986	0.822	0.741
α	−0.249	−0.116	−0.070	−0.985	−0.458	−0.278	−3.854	−1.783	−1.085
e_1	0.499	0.416	0.375	0.994	0.83	0.747	1.973	1.645	1.482
e_2	0.499	0.278	0.187	0.994	0.553	0.374	1.973	1.096	0.741
y_1	0.499	0.416	0.375	1.988	1.475	1.246	7.891	5.639	4.659
y_2	0.499	0.278	0.187	1.988	1.291	0.996	7.891	5.325	4.236
t_1	0.249	0.173	0.140	0.991	0.69	0.559	3.928	2.725	2.212
t_2	0.249	0.173	0.140	0.991	0.69	0.559	3.928	2.725	2.212

The analysis of the three policy environments highlights a close link between the instruments of incentive policy and their effectiveness. We find that the government objective is maximized under the first policy environment, where the government employs all instruments available to the incentive scheme. The other cases that involve fewer instruments are found to be less effective in stimulating biosecurity efforts, thus leading to a decline in global health performance. The design of a homogeneous contract for heterogeneous farmers offers two possibilities to the designer. The government may either consider everyone efficient, thereby overestimating the efficiency of some, or consider everyone inefficient. In the first case, our simulation allows us to conclude that overestimation leads to nonparticipating farmers and hence to fewer biosecurity provisions. In the second case, underestimating farmer efficiency (i.e., assigning incorrectly high marginal costs) will lead to windfall gains to the efficient farmer and a nonoptimal provision of biosecurity efforts.

However, the design of individual-based contracts is not straightforward, notably due to the collection of private information. The solutions under consideration include the hiring of control agents such as veterinarians to monitor disease control expenditures on farms. Otherwise, the government could design a homogeneous contract based on the less efficient farmer. The selection of either solution requires a cost–benefit analysis of the costs of the information collected and the payoffs forgone under a homogeneous contract. The former option permits the achievement of the first-best solution, while the latter option ensures the full participation of all farmers in the contract.

To date, we have assumed that biosecurity shocks are uncorrelated across farmers. We now remove this assumption, maintain the same variance for the two shocks, and assume a positive coefficient of correlation (0.75). Table 4 reports the results with moderate externality. Columns 1–3 report the results obtained from our first policy environment. The optimal levels of policy instruments are different from those obtained assuming away correlated shocks. Assuming similar marginal costs, the optimal average payment is much lower (0.21 compared to 0.66 in Table 1), the marginal payment is higher (4.32 compared to 2.02) and the guaranteed payment is no longer a penalty (−0.43 compared to 0.97). The logic is that the correlation between shocks makes individual efforts from farmers more valuable for the government, resulting an increase in the marginal payment. However, the optimal level of the average payment decreases (as anticipated from equation 9). More importantly, we again find that farmers' heterogeneity in terms of marginal costs matters a great deal. In this first policy environment, more heterogeneity leads to lower optimal average and marginal payments. The guaranteed payment to the less efficient farmer increases to induce his participation. However, the guaranteed payment to the more efficient farmer becomes a penalty.

For the second policy environment in columns 4–6 (third policy environment in columns 7–9), we obtain results similar to those of the noncorrelated case: higher heterogeneity among farmers leads to higher (lower) optimal average payments and higher guaranteed payments (in both cases).

Table 4. Optimal Values for All Scenarios under $\theta = 0.5$ Simulated with Correlated Shocks

Policy Environments	Individual-Based Flexible			Population-Based Flexible			Rigid		
c_2	1	1.5	2	1	1.5	2	1	1.5	2
	1	2	3	4	5	6	7	8	9
W	3.287	2.644	2.326	3.285	1.965	1.53	1.454	1.009	0.818
β	0.205	0.198	0.193	0.201	0.342	0.381	0.729	0.606	0.545
δ	4.318	4.169	4.075	4.326	2.512	1.918	–	–	–
α_1	0.970	0.274	-0.039	0.983	0.311	0.182	−0.332	−0.107	−0.037
α_2	0.972	1.327	1.468	0.983	0.311	0.182	−0.332	−0.107	−0.037
e_1	1.644	1.587	1.552	1.643	1.179	1.021	0.729	0.606	0.545
e_2	1.644	1.058	0.776	1.643	0.786	0.510	0.729	0.404	0.273
y_1	3.288	2.822	2.586	3.286	2.096	1.701	1.457	1.078	0.909
y_2	3.288	2.469	2.069	3.286	1.834	1.361	1.457	0.943	0.727
t_1	1.644	1.532	1.464	1.644	1.312	1.092	0.730	0.506	0.409
t_2	1.646	1.114	0.864	1.644	0.654	0.439	0.730	0.506	0.409

Therefore, our main results remain robust to the inclusion of correlations between biosecurity shocks.

Discussions

Our findings have valuable policy implications. Public incentive policies for either *ex ante* biosecurity efforts or *ex post* reporting are interesting tools of infectious disease management. Public policies aimed at involving farmers more broadly in health prevention remain crucial and are key to limiting sanitary, economic, and social implications of infectious disease management, which is especially true for sanitary crises (e.g., exotic and/or zoonotic diseases), whose effects extend beyond financial shocks within herds. Public support for private investment in biosecurity measures undoubtedly leads to important public expenditures, but the literature also shows that the *ex post* consequences of health shocks lead to countless losses, including financial losses, morbidity and mortality in animals, and employment. This observation converges to Pavleska and Kerr (2020), who show that public price support in infected states up to the level of prices in a noninfected state reduces incentives to smuggle. Since farmers are aware that they will be paid for infected animals, they will be willing to disclose each case as it is detected. While this relationship aims to motivate private effort, it also cautions producers against potential perverse behaviors.

Our compensation model has two implications. The model permits compensation for overall biosecurity efforts and at the same time controls individual behavior from the payment relating to the difference in health quality. Individuals showing above average health quality are positively compensated, while those showing below average health quality are negatively compensated. These results converge to Pavleska and Kerr (2020), who point out the need for penalty mechanisms that deter farmers from participating in illicit trade. Likewise, Gramig, Horan, and Wolf (2009) note the efficiency of a two-dimensional mechanism incentive policy including a bonus for private action and a fine for potential cheating. Although considering heterogeneity among farmers allows for the design of a personalized contract, its implementation can be difficult, particularly in terms of collecting individuals' information. Since biosecurity is a public good, a public policy implying partial participation will be detrimental to society. In failing to propose a personalized contract, the government will trade a part of the payoff to a homogeneous contract to ensure the full participation of all farmers.

Our analytical solutions show that both the government and farmers are better off when farmers have low marginal costs and exhibit low levels of risk aversion. From our numerical simulation, the efficiency of public policy is related to the quality of instruments used within the incentive scheme.

Some limitations and extensions of this work deserve comment. First, we do not consider the production of marketable output by farmers sold on the markets. One extension would involve specifying the production function with marketable goods as $\boldsymbol{Y}_i = f(e_i, \boldsymbol{I}_i)$, where $\boldsymbol{Y}_i$ is the vector of on-farm outputs (e.g., health quality, marketable products, and other), e_i denotes biosecurity effort, and $\boldsymbol{I}_i$ is the vector of other inputs. Dividing production such that $f(e_i, \boldsymbol{I}_i) = f(e_i) + f(\boldsymbol{I}_i)$ implies the separability assumption, which can be questionable. Indeed, this assumption suggests that the production of animal products and health management practices is disjointed. Second, assumptions of risk aversion among agents could raise questions of behavioral biases. Further analyses considering risk-, uncertainty- and loss-related behaviors will improve the principal–agent model in the context of infectious disease management.

Conclusion

This research focuses on the problems of animal disease prevention policies by using a principal multiagent approach in which we emphasize major issues in animal health management: imperfect information on private biosecurity efforts, production externalities among farmers, and heterogeneity in individual abilities. From our analytical and numerical results, we define the optimal incentive design and identify the type of farmers most likely to participate in the contract defined by the government. We demonstrate that an optimal contract must account for individual properties. The homogeneity assumption was found to be confusing, resulting in policy solutions that do not generate first-best outcomes. Specifically, we observe that both the government and farmers are better off when farmers exhibit low aversion to risk, low levels of production uncertainty, and low marginal costs. Finally, we find the need to cooperate and coordinate biosecurity actions between farmers to reach a better social health performance such in the case of many public goods provision.

The present research provides innovative material for the design of *ex ante* control policies targeting animal diseases such as bovine tuberculosis. The disease is not routinely detected in live animals (with local exceptions), and information on the disease is most often only revealed postmortem at the slaughterhouse. Therefore, preserving national disease-free status is crucial because it not only limits the risk of interspecies contamination but also allows for continuity of international trade in animal products. This status is ensured by proactive policies designed to prevent the emergence and/or spread of the disease and therefore by providing incentives to implement biosecurity practices. Our research explicitly addresses this issue, and we pay particular attention to the public nature of health. At the societal and agricultural levels, the implementation of a policy as defined in this paper can meet these objectives. In addition, since biosecurity practices are not disease specific but are more generally aimed at improving the overall health conditions of herds, our policy design can reduce multiple disease risks at once. In terms of extension, it could be interesting to reassess this problem within a bioeconomic framework to capture the effect of biological dynamics on private decisions of biosecurity.

[First submitted September 2020; accepted for publication April 2021.]

References

Bicknell, K., J. E. Wilen, and R. E. Howitt. "Public Policy and Private Incentives for Livestock Disease Control." *Australian Journal of Agricultural and Resource Economics* 43(1999): 501–521. doi: 10.22004/ag.econ.117214.

Chi, J., A. Weersink, J. A. VanLeeuwen, and G. P. Keefe. "The Economics of Controlling Infectious Diseases on Dairy Farms." *Canadian Journal of Agricultural Economics* 50(2002): 237–256. doi: 10.1111/j.1744-7976.2002.tb00335.x.

Choi, Y. K. "Managerial Incentive Contracts with a Production Externality." *Economics Letters* 42(1993):37–42. doi: 10.1016/0165-1765(93)90170-H.

Dobson, A. P., S. L. Pimm, L. Hannah, L. Kaufman, J. A. Ahumada, A. W. Ando, A. Bernstein, J. Busch, P. Daszak, J. Engelmann, M. F. Kinnaird, B. V. Li, T. Loch-Temzelides, T. Lovejoy, K. Nowak, P. R. Roehrdanz, and M. M. Vale. "Ecology and Economics for Pandemic Prevention." *Science* 369(2020):379–381. doi: 10.1126/science.abc3189.

Food and Agriculture Organisation of the United Nations, World Bank, and World Organisation for Animal Health. *The Importance of Biosecurity in Reducing HPAI Risk on Farms and in Markets*. Rome, Italy: Food and Agriculture Organisation of the United Nations, 2007.

Fraser, R. "Compensation Payments and Animal Disease: Incentivising Farmers Both to Undertake Costly On-Farm Biosecurity and to Comply with Disease Reporting Requirements." *Environmental and Resource Economics* 70(2018):617–629. doi: 10.1007/s10640-016-0102-7.

Gjesdal, F. "Information and Incentives: The Agency Information Problem." *Review of Economic Studies* 49(1982):373–390. doi: 10.2307/2297362.

Gohin, A., and A. Rault. "Assessing the Economic Costs of a Foot and Mouth Disease Outbreak on Brittany: A Dynamic Computable General Equilibrium Analysis." *Food Policy* 39(2013): 97–107. doi: 10.1016/j.foodpol.2013.01.003.

Gramig, B. M., R. D. Horan, and C. A. Wolf. "Livestock Disease Indemnity Design When Moral Hazard Is Followed by Adverse Selection." *American Journal of Agricultural Economics* 91(2009):627–641. doi: 10.1111/j.1467-8276.2009.01256.x.

Gramig, B. M., and C. A. Wolf. "Estimating Within-Herd Preventive Spillovers in Livestock Disease Management." *American Journal of Agricultural Economics* 89(2007):1219–1225. doi: 10.1111/j.1467-8276.2007.01087.x.

Häsler, B., W. Gilbert, B. A. Jones, D. U. Pfeiffer, J. Rushton, and M. J. Otte. "The Economic Value of One Health in Relation to the Mitigation of Zoonotic Disease Risks." In J. S. Mackenzie, M. Jeggo, P. Daszak, and J. A. Richt, eds., *One Health: The Human-Animal-Environment Interfaces in Emerging Infectious Diseases,* Berlin, German: Springer, 2012, 127–151. doi: 10.1007/82_2012_239.

Hennessy, D. A. "Biosecurity and Spread of an Infectious Animal Disease." *American Journal of Agricultural Economics* 89(2007):1226–1231. doi: 10.1111/j.1467-8276.2007.01088.x.

———. "Biosecurity Incentives, Network Effects, and Entry of a Rapidly Spreading Pest." *Ecological Economics* 68(2008):230–239. doi: 10.1016/j.ecolecon.2008.02.023.

Hennessy, D. A., and C. A. Wolf. "Asymmetric Information, Externalities and Incentives in Animal Disease Prevention and Control." *Journal of Agricultural Economics* 69(2018):226–242. doi: 10.1111/1477-9552.12113.

Huang, Z., J. Wang, and A. Zuo. "Chinese Farmers' Willingness to Accept Compensation to Practice Safe Disposal of HPAI Infected Chicken." *Preventive Veterinary Medicine* 139(2017): 67–75. doi: 10.1016/j.prevetmed.2017.02.002.

Huffman, W. E., and R. E. Just. "Setting Efficient Incentives for Agricultural Research: Lessons from Principal–Agent Theory." *American Journal of Agricultural Economics* 82(2000): 828–841. doi: 10.1111/0002-9092.00084.

Jones, K. E., N. G. Patel, M. A. Levy, A. Storeygard, D. Balk, J. L. Gittleman, and P. Daszak. "Global Trends in Emerging Infectious Diseases." *Nature* 451(2008):990–993. doi: 10.1038/nature06536.

Kobayashi, M., and T. A. Melkonyan. "Strategic Incentives in Biosecurity Actions: Theoretical and Empirical Analyses." *Journal of Agricultural and Resource Economics* 2(2011):242–262. doi: 10.22004/ag.econ.117152.

Laffont, J.-J., and D. Martimort. *The Theory of Incentives: The Principal-Agent Model.* Princeton, NJ: Princeton University Press, 2009.

Levy, A., and T. Vukina. "Optimal Linear Contracts with Heterogeneous Agents." *European Review of Agriculture Economics* 29(2002):205–217. doi: 10.1093/eurrag/29.2.205.

Mato-Amboage, R., J. W. Pitchford, and J. Touza. "Public–Private Partnerships for Biosecurity: An Opportunity for Risk Sharing." *Journal of Agricultural Economics* 70(2019):771–788. doi: 10.1111/1477-9552.12315.

McInerney, J. P., K. S. Howe, and J. A. Schepers. "A Framework for the Economic Analysis of Disease in Farm Livestock." *Preventive Veterinary Medicine* 13(1992):137–154. doi: 10.1016/0167-5877 (92)90098-Z.

Pavleska, M., and W. A. Kerr. "Importer's Risk, Smuggling and the Role of Incentives in the Management of Animal Diseases." *Ecological Economics* 175(2020):106,672. doi: 10.1016/j.ecolecon.2020.106672.

Perrings, C., M. Williamson, E. B. Barbier, D. Delfino, S. Dalmazzone, J. Shogren, P. Simmons, and A. Watkinson. "Biological Invasion Risks and the Public Good: an Economic Perspective." *Conservation Ecology* 6(2002):art1. doi: 10.5751/ES-00396-060101.

Philippidis, G., and L. Hubbard. "A Dynamic Computable General Equilibrium Treatment of the Ban on UK Beef Exports: A Note." *Journal of Agricultural Economics* 56(2005):307–312. doi: 10.1111/j.1477-9552.2005.00006.x.

Reeling, C. J., and R. D. Horan. "Self–Protection, Strategic Interactions, and the Relative Endogeneity of Disease Risks." *American Journal of Agricultural Economics* 97(2015):452–468. doi: 10.1093/ajae/aau106.

Sandler, T., and D. G. Arce M. "Pure Public Goods versus Commons: Benefit-Cost Duality." *Land Economics* 79(2003):355–368. doi: 10.2307/3147022.

Vicary, S., and T. Sandler. "Weakest-Link Public Goods: Giving in-Kind or Transferring Money." *European Economic Review* 46(2002):1501–1520. doi: 10.1016/S0014-2921(01)00103-9.

Wang, T., and D. A. Hennessy. "Modelling Interdependent Participation Incentives: Dynamics of a Voluntary Livestock Disease Control Programme." *European Review of Agricultural Economics* 41(2014):681–706. doi: 10.1093/erae/jbt038.

Wolf, C. A. "Producer Livestock Disease Management Incentives and Decisions." *International Food and Agribusiness Management Review* 8(2005):46–61. doi: 10.22004/ag.econ.8179.

World Bank. "People, Pathogens and Our Planet, Volume 1âĂŕ: Towards a One Health Approach for Controlling Zoonotic Diseases." Report 50833-GLB, World Bank, Washington, DC, 2010. Available online at https://documents.worldbank.org/en/publication/documents-reports/documentdetail [Accessed February 18, 2020].

Zilberman, D., T. W. Sproul, S. Sexton, and D. Roland-Holst. "The Economics of Zoonotic Diseases: An Application to Avian Flu." In D. Zilberman, J. Otte, D. Roland-Holst, and D. Pfeiffer, eds., *Health and Animal Agriculture in Developing Countries,* Springer, 2012, 59–76. doi: 10.1007/978-1-4419-7077-0.

Appendix

Let us denote the function of health performance for farmer i as

$$y_i = e_i + \theta y_j + \varepsilon_i; \text{ and } y_j = e_j + \theta y_i + \varepsilon_j. \tag{A1}$$

By replacing y_j in equation of y_i, we have

$$y_i = \frac{e_i + \theta e_j}{1-\theta^2} + \frac{\varepsilon_i + \theta\varepsilon_j}{1-\theta^2} \text{ and } y_j = \frac{e_j + \theta e_i}{1-\theta^2} + \frac{\varepsilon_j + \theta\varepsilon_i}{1-\theta^2} \tag{A2}$$

The average health performance is thus

$$\bar{y} = \frac{e_i + e_j}{2(1-\theta)} + \frac{\varepsilon_i + \varepsilon_j}{2(1-\theta)}. \tag{A3}$$

The difference between the farmers' performance and the average performance is given by

$$y_i - \bar{y} = \frac{e_i - e_j}{2(1+\theta)} + \frac{\varepsilon_i - \varepsilon_j}{2(1+\theta)} \text{ and } y_j - \bar{y} = \frac{e_j - e_i}{2(1+\theta)} + \frac{\varepsilon_j - \varepsilon_i}{2(1+\theta)} \tag{A4}$$

Let us denote $E(t_k)$ and $Var(t_k)$ the expected transfer and the variance of the transfer function for the kth farmer is

$$E(t_k) = \alpha_k + \beta\frac{e_k + e_{k'}}{2(1-\theta)} + \delta\frac{e_k - e_{k'}}{2(1+\theta)}; \tag{A5}$$

$$Var(t_k) = Var\left[\frac{\beta(\varepsilon_k + \varepsilon_{k'})}{2(1-\theta)} + \frac{\delta(\varepsilon_k - \varepsilon_{k'})}{2(1+\theta)}\right]. \tag{A6}$$

Under the assumption that the shocks are independent and normally distributed ($\varepsilon_i \sim i.i.d.$ and $\sigma^2_{\varepsilon_i} = \sigma^2_{\varepsilon_j} = \sigma^2$), we obtain

$$Var(t_k) = \sigma^2 \cdot \frac{\beta^2(\theta+1)^2 + \delta^2(\theta-1)^2}{2(\theta^2-1)^2}. \tag{A7}$$

The farmer kth optimization problem is

$$\tilde{e}_k = \underset{e_k}{\operatorname{argmax}}\left\{\alpha_k + \beta\frac{e_k+e_{k'}}{2(1-\theta)} + \delta\frac{e_k-e_{k'}}{2(1+\theta)} - \frac{\eta_k\sigma^2}{2}\left(\frac{\beta^2(\theta+1)^2+\delta^2(\theta-1)^2}{2(\theta^2-1)^2}\right) - \frac{1}{2}c_k e_k^2\right\}. \tag{A8}$$

The first-order condition with respect to e_k leads to the optimal biosecurity effort:

$$\tilde{e}_k = -\frac{\beta(\theta+1) - \delta(\theta-1)}{2(\theta^2-1)c_k}. \tag{A9}$$

Then, the government problem boils down to maximize $\sum_k E(y_k - t_k)$ under the participation and the incentive compatibility constraints. The problem is thus

$$Max_{\alpha_i,\alpha_j,\beta,\delta}\left(\frac{(\beta-1)(\tilde{e}_i + \tilde{e}_j)}{\theta-1} - \alpha_i - \alpha_j\right), \tag{A10}$$

subject to the following:

$$\begin{aligned} &\alpha_k + \beta\frac{\tilde{e}_k + e_{k'}}{2(1-\theta)} + \delta\frac{\tilde{e}_k - \tilde{e}_{k'}}{2(1+\theta)} - \frac{z_k}{2}\left(\frac{\beta^2(\theta+1)^2 + \delta^2(\theta-1)^2}{2(\theta^2-1)^2}\right) - \frac{1}{2}c_k\tilde{e}_k^2 \geq u_k \text{ (PC)} \\ &\text{and } \tilde{e}_k = -\frac{\beta(\theta+1) - \delta(\theta-1)}{2(\theta^2-1)c_k} \quad \text{for all } k = i, j \text{ (from A9)}, \quad \text{(ICC)} \end{aligned} \tag{A11}$$

where $z_k = \eta_k \sigma^2$ is a farmer-specific index of risk premium as in Huffman and Just (2000). Thanks to CARA utility properties, the participation constraint binds, implying that $CE(U_k) = \underline{u}_k$. In this respect, from each participation constraint, we can obtain distinctly the expressions of α_i and α_j based on other parameters. After replacing these latter in the objective function, we reach an optimization problem without constraint. Then, the efforts variables are replaced by their optimal results into the problem. The maximization with respect to β and δ leads to the optimal solutions (see equations 9–11 in the main text).

Throughout the development, we assume that parameters θ, c_i, c_j, z_i and z_j are positive. The partial derivatives of the results are

$$\text{(A12)} \qquad \frac{\partial \beta}{\partial c_j} = -\frac{c_i^2 (z_i + z_j)}{(c_i + c_j + (z_i + z_j) c_i c_j)^2};$$

$$\text{(A13)} \qquad \frac{\partial \beta}{\partial z_j} = -\frac{(c_i + c_j) c_i c_j}{(c_i + c_j + (z_i + z_j) c_i c_j)^2};$$

$$\text{(A14)} \qquad \frac{\partial \delta}{\partial c_j} = \frac{(c_i + c_j) c_i c_j (\theta + 1)}{(c_i + c_j + (z_i + z_j) c_i c_j)^2 (\theta - 1)};$$

$$\text{(A15)} \qquad \frac{\partial \delta}{\partial z_j} = \frac{c_i^2 (z_i + z_j)(\theta + 1)}{(c_i + c_j + (z_i + z_j) c_i c_j)^2 (\theta - 1)};$$

$$\text{(A16)} \qquad \frac{\partial \alpha_i}{\partial c_j} = -\frac{(c_i + c_j)(z_i + z_j)(c_i z_i - 1)}{(c_i + c_j + (z_i + z_j) c_i c_j)^3 (\theta - 1)^2};$$

$$\text{(A17)} \qquad \frac{\partial \alpha_i}{\partial z_j} = -\frac{(c_i + c_j)^2 c_j (c_i z_i - 1)}{(c_i + c_j + (z_i + z_j) c_i c_j)^3 (\theta - 1)^2};$$

$$\text{(A18)} \qquad \frac{\partial E(y_i)}{\partial c_j} = -\frac{(1 + 2(z_i + z_j) c_2) \theta c_i^2 + ((z_i + z_j) c_2 (\theta + 1) + 2\theta) c_i c_j + \theta c_j^2}{(c_i + c_j + (z_i + z_j) c_i c_j)^2 c_j^2 (\theta + 1)(\theta - 1)^2};$$

$$\text{(A19)} \qquad \frac{\partial E(y_i)}{\partial z_j} = -\frac{(c_i + c_j)(\theta c_i + c_j)}{(c_i + c_j + (z_i + z_j) c_i c_j)^2 (\theta + 1)(\theta - 1)^2};$$

$$\text{(A20)} \qquad \frac{\partial E(t_i - \psi_i)}{\partial c_j} = -\frac{(c_i + c_j)(z_i + z_j) z_i c_i^2}{(c_i + c_j + (z_i + z_j) c_i c_j)^3 (\theta - 1)^2};$$

$$\text{(A21)} \qquad \frac{\partial E(t_i - \psi_i)}{\partial c_j} = -\frac{(c_i + c_j)^2 c_i c_j z_i}{(c_i + c_j + (z_i + z_j) c_i c_j)^3 (\theta - 1)^2};$$

$$\text{(A22)} \qquad \frac{\partial W}{\partial c_j} = -\frac{\left(\left(\frac{1}{2} + (z_i + z_j) c_i\right) c_j + \frac{c_i}{2}\right)(c_i + c_j)}{(c_i + c_j + (z_i + z_j) c_i c_j)^2 c_j^2 (\theta - 1)^2};$$

$$\text{(A23)} \qquad \frac{\partial W}{\partial z_j} = -\frac{(c_i + c_j)^2}{2 (c_i + c_j + (z_i + z_j) c_i c_j)^2 (\theta - 1)^2}.$$