On the optimal policy for infectious animal disease management: a principal-multiple agents approach

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Abstract

Infectious diseases, especially the zoonosis, pose a persistent challenge for both public health and livestock industry. This paper develops a principal multiple-agents model, in which public authorities incentivize heterogeneous agents to implement *ex ante* biosecurity effort to prevent the introduction of disease within their herds. From our main results, we show that the individual attributes (costs and risk heterogeneity) matter a lot to achieve the optimal incentive policy. In this lines, our results highlight that disease prevention is a weakest-link public good (see Hennessy and Wolf, 2018), in the sense the global welfare is challenged by the less efficient growers. Frictions, such as the trade-off between incentive payment and risk-sharing allows public authorities to take over the control of potential asymmetry of information.

Key words: Biosecurity effort, heterogeneity, principal multiple-agents model.

JEL code*: Q18, Q10, Q58.*

Introduction

Animal diseases are major societal issues. Their occurrence may involve substantial negative returns. At the farm level, direct economic losses include production losses, mortality and revenue forgone within-herd, while wider economic implications can involve significant damage (e.g. risk of trade ban) on both stock farming and the whole society (Rushton and Knight-Jones, 2015; Gohin and Rault, 2013). Several works have examined the global impact of animal diseases on the society. For instance, Philippidis and Hubbard (2005) showed that the trade ban on UK beef after the 2001 FMD outbreak had involved up to US$1.6 billion of revenue losses. In addition to these large and lasting economic effects, some animal diseases may also have major human consequences in the case of zoonosis. The increasing prevalence of bovine tuberculosis (bTB) in Europe is a typical case of economic and human public harm. Indeed, bTB is an infectious disease spreading in ruminant animals (domestic and wild) with a potential transmission to humans, implying that the health risk is not restricted to livestock sector. In this regard, one can consider animal health as a pure public good (Cornes and Sandler, 1996), whose provision and regulation require most of the time government[1] intervention.

Overall, animal disease management involves various activities carried out by private and public actors including *ex-ante* and *ex-post* management options. *Ex-post* economic impacts of animal disease outbreaks and policies of disease control and compensations remain expensive and they are socially costly (Huang et al., 2017). When contagious diseases are already established, control policies can be implemented in order to avoid the diffusion across herds. The control of diffusion often implies cullings of on-herd animals. This solution generates substantial losses for growers and involves huge public expenditures, not only for the control itself but also for financial compensations to growers[2] (Zilberman et al., 2012). Leulinghen-Bernesn

In order to avoid such sanitary risk and economic consequences, the priority for public authorities, notably in case of zoonosis remains the prevention (Häsler et al., 2012). This type of management (control of disease entry) relies on the adoption biosecurity practices by

[1] Note that, we do not distinguish the vocabulary "government" and "public authorities". They are used interchangeably in all the paper.
[2] As example, in France precisely the municipality of Leulinghen Bernesn in 2018, the detection of one animal infected of bTB has led to the culling of 250 animals of the herd.

farmers[3], a set of good practices meant to control the introduction and the diffusion of the disease across herds (Wang and Hennessy, 2015). It includes various activities, namely animal testing, surveillance, the quarantines, the culling. (Kobayashi and Melkonyan, 2011). Biosecurity practices exhibit public good attributes and generates economy of scope by protecting against unplanned diseases. In the former (i.e. public good aspect), the obtained sanitary quality is a public good in the case of zoonotic disease management because it reduces the risk of human and livestock infections. These benefits are neither rivals nor exclusives (Perrings et al., 2002). New user will not pay for its use. Nor does it diminish the quantity available to others. In the latter, (i.e. economy of scope), instead of directing the management towards a specific-disease (e.g. vaccination), biosecurity adoption provides protection against the entry of a large set of biological pathogens.

However at the farm level, trade-offs between *ex ante* and *ex post* management options remain, where *ex post* private disease costs and *ex ante* biosecurity expenditures compete. Following the neo-classical analysis, a grower is willing to provide effort for diseases management, provided that his expected benefit outweighs his cost (Chi et al., 2002; McInerney et al., 1992). The consequence of this rational behavior is that disease management might yield into positive disease tolerating as long as the required investment is not profitable (Wolf, 2005). In our context, the occurrence of a contagious and potentially zoonotic disease within a herd is to be detrimental not only to the infected herd, but also to surrounding farms (Beach et al., 2007) with possible fatal outcome for human health. Likewise, disease management, either prevention or stamp-out, is beneficial to others as it reduces their risk of infections (Wang and Hennessy, 2015). The market failure to consider this external cost (or benefit) leads to a private cost which does not reflect the social cost of disease management. As consequence, growers do not have any incentive to raise their private effort up to the social optimal level. The need of public intervention appears clearly at one side for public health protection (considering the zoonotic aspect), and at the second side, to rise the private effort up to a socially desirable level (externality aspect).

A growing literature focuses on the design and issues related to optimal policies to promote the adoption of private prevention and biosecurity practices. The main findings are that the full implementation of biosecurity in order to achieve the social optimum remains critical for three

[3] It important to stress that vaccination cannot be considered as the control of disease entry. Vaccine prevents only the expression of disease but does not control the entry.

identified points, namely market failure, information asymmetry and on-herd coslty biosecurity effort. The first which is classical in economics explains the existence of external effect (see Huang et al., 2017; Bicknell et al., 1999). Many researches have already highlighted the role of externalities and strategic behaviors in animal disease management (see for instance Hennessy (2007)). Information issues and the design of incentive payments are generally assessed through principal-agent models, which rely on a contractual relationship between two parties, namely the principal and the agent. Precisely, the principal-agent model examines how the principal may formalize the payment to incite the agent to act following his goal. Our concern is to assess how the public authority (principal) can design the incentive payment for biosecurity effort investment by the farmers (agents). Under perfect information, the first-best allocation corresponds to an incentive payment where the agent's payment is directly depending on his private effort. The outcome in this situation is Pareto-efficient, as there will be no any other allocation that will be preferred instead. However, biosecurity effort relies on many peculiar actions and it remains barely observable, making it almost not contractible. In this context, it will be infeasible or suboptimal to design a contract with respect to agents' effort (Gjesdal, 1982). Accordingly, growers can take benefit from this private information to maximize their utility. There is there the need to consider this asymmetry of information (*ex-ante* moral hazard) during the design of the payment scheme. Failing to observe the private biosecurity effort, a major point to consider is the design of an output-based contract, i.e. where the payment scheme is dependent on the agents results rather than on his efforts.

The heterogeneity of farms is also an important feature to consider in our research. Indeed, farm characteristics (e.g. size, location), financial constraints and production yields are examples of individual attributes leading to different decisions from one farmer to another. Although the homogeneity assumption may remain relevant in other cases, heterogeneity between growers is crucial to consider here, especially due to the above-mentioned issue of external effects of the diseases and their management. Some literature focused on this question has highlighted the importance to consider the individual characteristics. For example, Huffman and Just (2000) examined in U.S. the incentive payment for research production, putting forwards researchers heterogeneity. They found that the take account of individual characteristics allows organizing research efficiently by modulating the payment to the attributes of researchers, unlike to the case of homogeneity[4]. Further, Levy and Vukina (2002) have demonstrated using a piece rate

[4] See Huffman and Just (2000), at page 840.

contract that the guarantee salary and the marginal payment do vary with individual abilities and individual attitude towards risks. One more example from Wang and Hennessy (2014) in a framework of a voluntary livestock disease control program, the authors have shown that the heterogeneity of participants matters, in the sense that the cost heterogeneity is determinant of full participation. However in their approach, the issue of information failure is overcome by the market, where disease-free animals are traded in a separate market from untested ones, which is only relevant when dealing with non-zoonotic diseases. In our case where the zoonotic disease is a public bad, the goal of public policy is to involve all farmers at once.

Thus, our research question in this paper is to reveal the role of the heterogeneity of farmers on the design of policies to incentivize biosecurity practices, when externalities and hidden information co-exist. In other words, we examine whether the introduction of heterogeneity matter for optimal policy design to support biosecurity implementation for infection risk prevention? By applying a principal multiple-agent approach, we derive the optimal payment and we analyze it in the applied case of livestock diseases management, *i.e.* how a government may consider individual properties to motivate growers so that they provide best biosecurity effort, enhancing thereby the total sanitary quality. We differentiate growers according to productivity of biosecurity, marginal cost of biosecurity, and the risk preference parameter.[5] Finally, we provide a numerical simulation to support our analytical results. The value of the parameter is collected from Mato-Amboage et al. (2018), in order to examine how the optimal policy moves on depending on whether growers are heterogeneous or not.

From the conceptual analysis, we find that the incentive payment provides to growers only partial insurance for the risk of revenue losses. The partial risk insurance takes over control the risk of moral hazard issue, by sharing the risk between government and growers. Then, we find that the marginal incentive related to neighbors' health sanitary is negative, indicating that neighbors' health quality is detrimental in incentive payment. Our analytical result exhibits a positive effect of productivity index on incentive payment, while the risk premium affects negatively this incentive payment. However, the more risk aversion growers get high net payment while the less risk aversion growers do get less. At last, we show through our numerical example that infectious disease control is a weakest link public good. Indeed, the

[5] Huffman and Just (2000), did the same specification in their production function.

increase of marginal cost for a grower leads to the decrease of the total health quality, highlighting that the wellbeing of the society relies on the least effective growers.

Model setting

We develop a principal-multiple agent model for animal infectious risk management, fashioned from Mato-Amboage (2018) and Huffman and Just (2000) except that we do introduce some additional parameters, which are absent in these latter: our model includes the production externality between growers and the compensation scheme includes too the neighboring health quality such specified in Mato-Amboage et al. (2018). However, the agents are assumed homogenous in the latter, while we put forwards here the effect of heterogeneity between growers on the contract. Growers are heterogeneous with respect to the marginal productivity (p_m), the marginal cost of biosecurity (c_m) and the risk preference parameter (η). The game which is output-based between the government and the growers are played following the timing described below (Figure 1). First, we assume at the beginning that the heterogeneity of parameters are perfectly observed by government. Second, government designs a menu of contract that growers are free to accept or reject. The game is ended if growers rejects the contract. Assuming the opposite, that is the contract is accepted, the game continues then growers provided biosecurity effort. Finally, government compensates each grower considering both his health quality and health quality of neighboring herd.

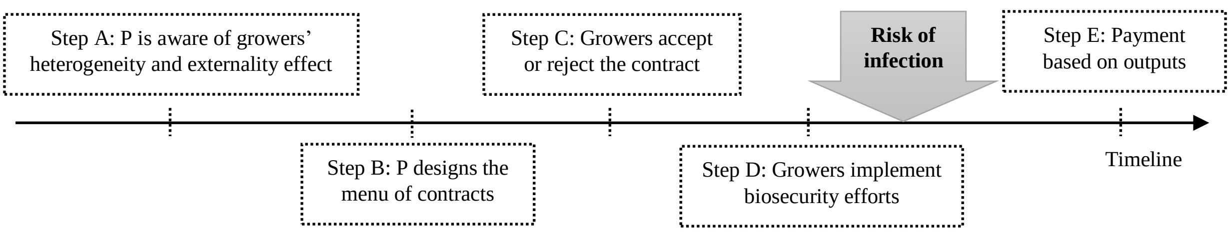

Figure 1: Timeline of the contract game between government–growers.

Our model considers a risk-neutral, profit-maximizer principal and two[6] risk-averse, utility-maximizer agents, referred to with subscript $i = \{1, 2\}$. Each grower implements biosecurity

[6] Note that two agents are sufficient to illustrate heterogeneity effects on optimal incentive policy design.

effort of magnitude $e_i \geq 0$, to secure (preventive measures) their herd against the infection risk. Following Gramig et al. (2009), biosecurity effort is relevant in susceptible[7] state. If one herd is infected, the herd owner could stop applying biosecurity, then looking for management measures[8]. The two growers are healthy at the beginning of the contract. We denote y_i the verifiable output (here health quality)[9] which represents outcome from biosecurity effort implemented within each herd i[10]. Considering the uncertainty nature of infections risk, we define a stochastic production function to reflect that the effectiveness of biosecurity effort can be challenged by other factors, whose control is out of growers' abilities. We define a production function $\{y_i = y_i(p_i^m, e_i, \theta, y_j);\ y_i \in \mathbb{R}^*\}$ which relies on individual biosecurity effort e_i, then marginal productivity of biosecurity effort p_i^m, specific to each grower. The marginal product can be associated to grower's intrinsic abilities (e.g. skill, routine effect, organization of work, etc.). θ $(= \partial y_i / \partial y_j)$ represents the preventive spillover indicator[11] across herds with positive sign, that is an improvement of one's health quality can only be positive for its neighbors. In absence of externality, θ equals to zero. Assuming θ is higher or equals to one $(\partial y_i / \partial y_j \geq 1)$, grower j's biosecurity effort generates more health quality to neighbors than himself. For consistency purpose, we assume that θ belongs to the interval $[0,1[$ (hereafter named Γ^θ). The uncertainty parameter (ε_i), likening to idiosyncratic production shock, is assumed identically and independently distributed across growers, with mean zero and variance σ^2. The function specified as:

[7] The vocabulary "susceptible" is used in epidemiology to designate healthy animals.

[8] It is important to mention that in case of some diseases (such as zoonotic diseases) management, growers must continue to apply biosecurity to limit the diffusion of the disease even this option might appear to be non-optimal economically

[9] The vocabulary of "output" commonly used to name the result yielding from production in principal-agent model is somewhat limited in our case, as the sanitary quality is not a physical product and non-marketable. We adopt this terminology for simplicity. It was the case in Wang and Park (2014) and Mato-Amboage et al. (2018). Nonetheless, there are others branches of economic, notably environment economy where researchers are able to give a monetary value to this output although non-marketable. For more details, the readers can see Osseni et al. (2019).

[10] Note that the superscript index i used to denote each agent may also be used to denote each herd, as one grower is assumed to hold only one herd.

[11] The expression "preventive spillover" effect has been used in Gramig and Wolf (2007) to describe how a practice directed towards a disease could implicitly lead to the prevention of another disease. Classically, this effect is known as *economy of scope* in economic literature. In our setting, we use it to characterize the positive externality of a biosecurity practice within a herd on neighbors' herds.

(1) $y_i = p_i^m e_i + \theta y_j + \varepsilon_i$

For simplicity reasons, the price is normalized to unity, so that y stands also for the monetary value of the output. Substituting y_j by its expression[12] in y_i, we obtain after some transformations $y_i = (p_i^m e_i + \theta p_j^m e_j + \varepsilon_i + \theta\varepsilon_j)/(1-\theta^2)$. By the analogy, the production function of grower j can be written as: $y_j = (p_j^m e_j + \theta p_i^m e_i + \varepsilon_j + \theta\varepsilon_i)/(1-\theta^2)$. The production of health quality involves a flow of costs C_i, whose function includes biosecurity effort e_i and the marginal production cost c_i^m. The cost function is:

(2) $C_i(c_i^m, e_i) = c_i^m e_i^2/2$

Compensation scheme

We design an output-based contract t_i between government and growers for biosecurity effort investment within herd. The transfer function is structured into three distinct parts: one fixed part α_i, which is a guarantee payment that the grower received regardless the quantity of output, and two other parts $\beta_i y_i$ and $\delta_i y_j$, relied on health quality within both herds (herds i and j). More precisely, β_i and δ_i are respectively output-based marginal incentives within herds i and j. The transfer scheme t_i is given by:

(3) $t_i(y_i, y_j) = \alpha_i + \beta_i y_i + \delta_i y_j$

The main objective of the government is to define the values of parameters α_i, β_i and δ_i which optimize his utility that is to achieve high health quality (socially desirable) at minimal cost. The expectation of this utility, defined by $\prod(t_i, e_i) = \mathbb{E}\left[\sum_i (y_i - t_i(y_i, y_j))\right]$ corresponds to the total health quality in monetary value net of the total transfer paid to growers. At growers' side,

[12] By symmetry, the production function of neighboring herd can be as: $y_j = p_j^m e_j + y_i + \varepsilon_j$.

the latter makes profit from the expected transfer[13] net of the production cost. To keep matter simple, we consider for each grower an exponential utility function U_i with constant absolute risk-aversion (CARA) properties, that is $U_i(T_i) = \mathbb{E}\left[-\exp(-\eta_i T_i)\right]$. Note η_i and T_i are respectively private risk preference parameter and private wealth which is the rewards t_i net of the cost of biosecurity: $T_i = \alpha_i + \beta_i y_i + \delta_i y_j - c_i^m e_i^2 / 2$.

Optimal transfer under risk and asymmetry of information

In this section we focus on the case where government do not have information about private biosecurity effort, so that the contract cannot be biosecurity effort-based. It may arise under this first assumption the moral hazard issue where growers would attempt to hide their private action by choosing an effort below the optimal level of biosecurity required. Also, this desire of cheating in biosecurity effort could be justified especially, since sanitary quality is treated as public good. One would expect that other's biosecurity effort reduce the risk of infection. As mentioned above, in this context, one could fail to prevent the introduction of the disease, expecting the protection from neighbors' herds. In this regards, the first-best allocation is no longer achievable. The incentive scheme is therefore designed at the second-best allocation. The latter implies the consideration of incentive compatibility (IC) constraint, which ensures that each grower's effort corresponds to the optimal $(\tilde{e}_i)$ that should be provided within his herd. However, growers do accept the contract, provided that the contract gives at least the same level of utility related to his best alternative, i.e. the reservation utility noted by $\underline{u}_i$. This constraint known as participation constraint (PC) can be defined by the minimum level of utility below which growers will prefer an alternative option than playing this game. At the second-best allocation, government problem through the following optimization problem:

(4) $$\underset{\alpha_i, \beta_i, \delta_i, \tilde{e}_i}{Max}\ E\left[\sum_i (y_i - t_i(e_i, e_j))\right]$$

[13] The expected transfer conditional on biosecurity effort received by each grower is expressed as: $E(t_i) = \alpha_i + \beta_i (p_i^m e_i + \theta p_j^m e_j / 1 - \theta^2) + \delta_i (p_j^m e_j + \theta p_i^m e_i / 1 - \theta^2)$. By assuming that $\varepsilon_i \overset{iid}{\sim} N(0, \sigma^2)$, the variance of the payment can expressed as: $VAR(t_i) = VAR\left[(\beta_i + \delta_i \theta)\varepsilon_i / (1-\theta^2) + (\beta_i \theta + \delta_i)\varepsilon_j / (1-\theta^2)\right] = \sigma^2 \left[(\beta_i + \theta\delta_i)^2 + (\beta_i \theta + \delta_i)^2\right] / (1-\theta^2)^2$

(5) Subject to: $E\left[-\exp\left(-\eta_i(t_i(e_i,e_j)-C_i(c_i^m,e_i))\right)\right]\geq \underline{u}_i$

(6) And $\tilde{e}_i = \underset{e_i}{\text{argmax}}\left\{E\left[-\exp\left(-\eta_i(t_i(e_i,e_j)-C_i(c_i^m,e_i))\right)\right]\right\}$

Where $E(\cdot)$ is the expectation operator, $i=\{1,2\}$ and $i\neq j$. The equation (5) is the participation constraint. The equation (6) corresponds to the incentive-compatibility constraints and refers to grower's optimization problem. Computing the expectation of growers' utility, the incentive-compatibility can be restated as follows:

(7) $\tilde{e}_i = \underset{e_i}{\text{argmax}}\left\{\alpha_i+\beta_i\cdot\frac{p_i^m\tilde{e}_i+\theta p_j^m\tilde{e}_j}{1-\theta^2}+\delta^i\cdot\frac{p_j^m\tilde{e}_j+\theta p_i^m\tilde{e}_i}{1-\theta^2}-\frac{\eta_i}{2}VAR\left[t_i(e_i,e_j)\right]-\frac{1}{2}c_i^m e_i^2\right\}$

Where "*VAR*[·]" is the variance computed in footnote 13. To solve the government's problem we rely on the *First-order Approach*, which consists of replacing agent's optimization problem by its first-order condition (FOC) in government problem. Taking the FOC of equation (6) with respect to the biosecurity effort e_i, we obtain the optimal biosecurity effort[14]:

(8) $\tilde{e}_i = p_i^m(\beta_i+\theta\delta_i)\big/c_i^m(1-\theta^2)$

The relation (8) indicates a positive correlation between the biosecurity effort and the marginal productivity of effort. Growers are more motivated to implement biosecurity effort as the marginal productivity increases. The marginal cost is negatively related to biosecurity effort, meaning that the motivation for biosecurity declines with the increase of marginal cost. Both relations are intuitive. Deeply analysis should be provided after determining the value of the parameters α_i, β_i and δ_i. After computing the expectation of government utility, the formulation of government optimization problem then becomes:

(9) $\underset{\tilde{\alpha}_i,\tilde{\beta}_i,\tilde{\delta}_i}{Max}\ \sum_i\left[\frac{(1-\beta_i)(p_i^m\tilde{e}_i+\theta p_j^m\tilde{e}_j)}{1-\theta^2}-\frac{\delta^i(\theta p_i^m\tilde{e}_i+p_j^m\tilde{e}_j)}{1-\theta^2}-\alpha_i\right]$

[14] By analogy, the optimal biosecurity for grower j can written as: $\tilde{e}_j = p_j^m(\beta_j+\theta\delta_j)\big/c_j^m(1-\theta^2)$.

$$\text{(10)} \qquad \text{Subject to: } \left\{ \begin{bmatrix} \alpha_i + \beta_i \cdot \dfrac{p_i^m \tilde{e}_i + \theta p_j^m \tilde{e}_j}{1-\theta^2} + \delta_i \cdot \dfrac{p_j^m \tilde{e}_j + \theta p_i^m \tilde{e}_i}{1-\theta^2} \\ -\dfrac{\eta_i}{2} \operatorname{var}\left[t_i(\tilde{e}_i, \tilde{e}_j) \right] - \dfrac{1}{2} c_i^m \tilde{e}_i^2 \end{bmatrix} \geq \underline{u}_i \right\}, \quad i = 1,2 \text{ and } i \neq j .$$

The Kuhn-Tucker conditions will be necessary and sufficient to characterize the solution of the problem, considering the properties the utility functions (U_i is increasing and convex). At the optimal solution, the constraint participation must bind (i.e. satisfied as an equality), otherwise the solution will imply inefficiency and government could be made better off by reducing the level of the transfer (Chavas, 2004). In this respect, the relation (5) becomes $CE(U_i) = \underline{u}_i$. We now substitute the relation (8) in (9) and (10). After some transformation, we obtain:

$$\text{(11)} \quad \tilde{\alpha}_i = \underline{u}_i - \frac{(\beta_i + \theta\delta_i)^2 x_i}{2(1-\theta^2)^2} - \frac{(\beta_j + \theta\delta_j)(\theta\beta_i + \delta_i) x_j}{(1-\theta^2)^2} + \frac{(\beta_i^2 + (\theta\delta_i)^2 + 4\theta\beta_i\delta_i + (\theta\beta_i)^2 + \delta_i^2) z_i}{2(1-\theta^2)^2}$$

Note that $x_i = p_i^{m^2} / c_i^m$ and $z_i = \eta_i \sigma^2$ correspond respectively to grower "productivity index" and grower "risk-premium". The former characterizes the trade-off made by each grower between the marginal productivity of biosecurity and its marginal cost.

Thereafter, we substitute the condition (11) into government's problem, then maximize the problem with respect to β_i and δ_i. The optimal solutions to the problem are:

$$\text{(12)} \quad \tilde{\beta}_i = -x_i / (\theta^2 - 1)(x_i + z_i)$$

$$\text{(13)} \quad \tilde{\delta}_i = \theta x_i / (\theta^2 - 1)(x_i + z_i)$$

The fixed payment (α^i) of the transfer is obtained by substituting the conditions (12) and (13) into condition (11). We obtain thus:

$$\text{(14)} \quad \tilde{\alpha}_i = \underline{u}_i - x_i^2 (x_i - z_i) / 2(\theta^2 - 1)^2 (x_i + z_i)^2$$

As results, we find at first that the compensation scheme adopted maximizes both growers and government expected payoffs. This context stands as motivation for both parties to play the game. The expected total surplus refers to the gross payoff of government net of both the cost biosecurity and the cost of the risk. Such the cost of biosecurity, this result shows that uncertainty is also a degrading factor of expected total payoff. The second result refers to hidden information management. We have shown above that with respect to our model setting, the spillover indicator is positive. From equation (12), we find that individual marginal incentive is positively correlated with the productivity index $(\partial\tilde{\beta}_i/\partial x_i > 0)$[15]. In this regard, growers with low value of productivity index receive low marginal incentive, contrary to those with high productivity index, who do expect high marginal incentive, *all things equal*. The derivate of this effect $(\partial\beta_i/\partial x_i)$ with respect to production externality, that is $(\partial^2\beta_i/\partial x_i\partial\theta)$[16], is positive. These results indicate at first that the increase of productivity index generates the increase of the level of marginal incentive and at the second side, this effect is of increasing scale with respect to θ. We can afford to conclude that, in the context of interaction between growers, the effect of individual parameters on incentive design relies on the intensity of this dependency. Both the productivity index and externality are determinant to design the incentive policy for heterogeneous growers. Third, equation (12) reveals a negative correlation[17] $(\partial\tilde{\beta}_i/\partial z_i < 0)$ between individual marginal payment $\tilde{\beta}_i$ and his risk premium $z_i = \eta_i\sigma^2$, indicating that the increase of grower's risk premium decreases the marginal payment received. Indeed, high risk-averse growers will be less-sensitive to the incentive, which fully relies on uncertain output $(y \sim y\,|\,e,\varepsilon)$, *ceteris paribus*. Providing high incentive for those types of growers will accordingly be Pareto-inefficient. Since the optimal incentive translates into the optimal biosecurity effort (equation (8)), it clearly appears that optimal payment reflects a "trade-off" between the incentive and the risk-sharing. Besides, this result highlights that growers are partially insured against the risk of income losses (either the increase of σ^2 or η_i). A fully insurance for income risk will lower of course growers' incentive to rise private effort up to the socially desirable level. In this context of partial insurance, growers will feel compelled to biosecure sufficiently in order to prevent themselves against potential income losses that would be uninsured by the program. The term $(1-\theta^2)z_i$ in the equation (12) captures this friction of information asymmetry between both parties. The risk sharing between the principal and the agents have been examined in several papers in economics literature and were broadly defended in the context of animal diseases management by Gramig et al. (2009), and Hennessy et al. (2018). Fourth, the risk premium exhibits positive correlation with the optimal fixed payment

[15] From the relation (9): $\partial\tilde{\beta}_i/\partial x_i = -z_i/(\theta^2-1)(x_i+z_i)^2$.

[16] From equation (9): $\partial^2\tilde{\beta}_i/\partial x_i\partial\theta = 2\theta z_i/(\theta^2-1)^2(x_i+z_i)^2$.

[17] From relation (7): $\partial\tilde{\beta}_i/\partial z_i = x_i/(\theta^2-1)(x_i+z_i)$.

with the condition $3x_i > z_i$. To keep the high risk averse growers, at least, to their reservation utility, government must adjust the fixed payment upwards so that to insure the additional risk acceptance, irrespective of any level of production (i.e. the level of health quality produced). Assuming that the risk premium approaches infinity, both marginal incentives ($\tilde{\beta}_i$ and $\tilde{\delta}_i$) become zero and the optimal contract boils down to the fixed salary $\underline{u}_i$. In this respect, since the principal is risk neutral, he bears all the risk without requiring a premium. Fifth, from equation (13), we find that the optimal incentive of neighbor output-based (δ_i) is negative. This result, examined yet in Mato-Amboage et al. (2018), indicates that the transfer received by a grower decreases when the health quality increase at neighboring herds. Through this negative effect, government control (i.e. reduce) for each grower the exposure to neighbor's risk (ε_j). Mato-Amboage et al. (2018) did the same analysis in the case of common risk exposure[18].

The positive correlation between the marginal incentive and externality indicator calls for coordination management. Indeed, growers received more incentive as well as the positive production externality increases. Though growers are disadvantaged when their neighbors' health quality increases through δ_i, they are at the same time get more incentive when they belongs to good health quality environment.

Implication of optimal incentive scheme

The optimal biosecurity effort under the optimal incentive is given by:

$$(15) \qquad \tilde{e}_i = -\frac{p_i^m x_i}{c_i^m(\theta^2 - 1)(x_i + z_i)}$$

The total expected health quality for both growers is:

[18] Although we do not specify common shocks in our modelling, this might exist implicitly as both random variables (specified in the production function of each grower) are assumed identical and exogenous. Our idiosyncratic shock could be assimilate to common shocks for example in the case where both growers belongs to the same environment.

(16) $$\mathbb{E}\left[y_i\right] = \frac{x_i^2}{(\theta^2-1)^2(x_i+z_i)} + \frac{\theta x_j^2}{(\theta^2-1)^2(x_j+z_j)}$$

The expected transfer, under the optimal incentive is:

(17) $$\mathbb{E}\left[t_i(\tilde{e}_i,\tilde{e}_j)\right] = \underline{u}_i + \frac{x_i^2}{2(\theta^2-1)^2(x_i+z_i)}$$

And each grower's expected wealth $\mathbb{E}\left[T_i\right]$ (i.e. expected transfer net of the optimal cost of biosecurity) is given by:

(18) $$\mathbb{E}\left[T_i(\tilde{e}_i,\tilde{e}_j)\right] = \underline{u}_i + \frac{x_i^2 z_i}{2(\theta^2-1)^2(x_i+z_i)^2}$$

The total expected payoff of government is:

(19) $$\mathbb{E}\left[\prod(\tilde{e}_i,\tilde{e}_j)\right] = \sum_i \left[\frac{x_i^2}{2(\theta^2-1)^2(x_i+z_i)} + \frac{\theta x_j^2}{(\theta^2-1)^2(x_j+z_j)} - \underline{u}_i\right] \qquad \text{with } i \neq j$$

From equation (15) the optimal biosecurity effort is positively correlated with agent's productivity index and negatively correlated with the risk premium. Growers will provide more biosecurity effort as long as they are more efficient for its production. At the same time, the increase of aversion towards risk will lowers growers' motivation for biosecurity investment. The same analysis holds for the health quality (equation (16)), since the biosecurity effort translates into the latter. Besides, equation (16) shows that the health quality is improved when the neighbors get more efficiency. Accordingly, the total output will positively correlated to the most effective grower and negatively related to the least effective growers. This result highlights that animal disease management is a weakest link public good in the sense that the well-being of the society could be challenged by the least effective growers. The partial derivate of the expected payment with respect to the productivity exhibits a positive sign[19] (for all value of $\theta, x_i, z_i > 0$), indicating that growers receive more payment with the increase this factor. Since this payment translates into grower's expected wealth (equation (18)), growers with high productivity index are wealthier than those with low productivity index, *all things equal*[20].

[19] $\partial\mathbb{E}\left[t_i(\tilde{e}_i,\tilde{e}_j)\right]/\partial x_i = x_i(x_i+2z_i)/2(\theta^2-1)^2(x_i+z_i)^2 > 0$

[20] $\partial\mathbb{E}\left[T_i(\tilde{e}_i,\tilde{e}_j)\right]/\partial x_i = x_i z_i^2/(\theta^2-1)^2(x_i+z_i)^3 > 0$

Likewise from equation (19), the differential of government expected payoff with respect to the productivity index shows that government expects more payoff by contracting with high effective growers (i.e. high productivity index). From the two previous results, both growers and government are better-off when growers are effective for health quality production. Then, the differential of the expected payment with respect to risk premium reveals that the high risk averse growers receive less payment than those with low risk aversion. Unlike to the expected payment, from equation (18), the high risk averse growers are wealthier than those with low risk aversion when $x_i > z_i$. This result is due to the fact that the high risk averse growers implement low biosecurity effort, and accordingly support low biosecurity cost. These results have been examined in Huffman and Just (2000). Assuming either growers are risk neutral $(\eta_i = 0)$ or a deterministic production function $(\sigma^2 = 0)$, i.e. absence of uncertainty, the biosecurity effort becomes $\tilde{e}_i^{rn} = -p_i^m / c_i^m(\theta^2 - 1)$ and the health quality becomes $\tilde{y}_i^{rn} = x_i + \theta x_j / (\theta^2 - 1)^2$. These two equations, comparing to equations (15) and (16), reveal that the risk aversion demotivates biosecurity investment and reduce the health quality from the first-best production. Still with risk neutral growers, the total expected payoff of government becomes $\sum_i \left[\left(x_i / 2(\theta^2 - 1)^2 \right) + \left(\theta x_j / (\theta^2 - 1)^2 \right) - \underline{u}_i \right]$. comparatively to the case of risk averse growers, these results highlight that government could design a transfer scheme that made him better off when the contract involves growers with high productivity of biosecurity low marginal cost of production, and low risk averse growers.

Numerical analysis

The table 1 presents the values of parameters for the numerical simulation. These value are defined following Mato-Amboage et al. (2018).

Parameters	agent 1	agent 2
externality	0.5 à 0.9	
mean of random variable	0	
variance of random variable	0.5	
marginal cost of biosecurity	1	1; 2; 3;
risk preference parameter	2	2; 2.5; 3

Table 1: Parameters for numerical simulation

For the numerical analysis, we focus attention mainly on the marginal cost and risk preference parameter to examine the effect of growers' heterogeneity on the optimal contract. We test the model with different values of marginal cost $c_j^m = \{1;2;3\}$ and the risk preference parameter $\eta_j = \{2;2.5;3\}$ for agent j. We consider distinctively the case with externality to those without externality. In the former, we test three different values of externality $\theta = \{0.5;0.6;0.7;0.8;0.9\}$, to analyze at one side the discrepancy between the policy with and without externality and at other side to examine the scale of the effect for additional unit (0.1) of dependency. To keep generality, we set the reservation utility to zero, corresponding to the case of $\underline{u}_i(w=0)$. The table 2 present the effect of production externality on the optimal transfer, the biosecurity effort, the health quality and government expected payoff.

c_m^i	$c_m^1 = c_m^2 = 1$						$c_m^1 = 1$ and $c_m^2 = 2$					
θ	0	0.5	0.6	0.7	0.8	0.9	0	0.5	0.6	0.7	0.8	0.9
t^1	0.35	1.42	2.25	4.12	10.02	46.14	0.35	1.42	2.25	4.12	10.02	46.14
t^2	0.33	1.32	2.08	3.8	9.44	45.7	0.12	0.49	0.77	1.38	3.37	19.57
e^1	0.69	1.4	1.77	2.41	3.82	8.61	0.69	1.4	1.77	2.41	3.82	8.61
e^2	0.66	1.32	1.66	2.25	3.59	8.4	0.25	0.49	0.62	0.83	1.3	3.41
y^1	0.69	2.75	4.32	7.82	18.61	85.12	0.69	2.2	3.34	5.87	13.51	61.51
y^2	0.67	2.7	4.25	7.72	18.49	85.02	0.25	1.6	2.63	4.94	12.12	58.77
Π	**0.68**	**2.71**	**4.25**	**7.61**	**17.63**	**78.29**	**0.47**	**1.89**	**2.96**	**5.3**	**12.23**	**54.57**

Table 2: Simulated variables

This table shows that the expected transfer increase with the increase of the production externality, whether or growers have the same marginal cost. Since this one translates into the optimal biosecurity effort, it leads to the increase of the optimal effort, and the increase of both health quality and government payoff. From this table, we also show that the production externality exhibits an increasing return effect on the selected variables. The increasing return effect of production externality can be clearly viewed through the figure 2 plotted below. It is an illustration of correlation between government expected payoff and the production externality. In either case (i.e. homogenous or heterogeneous assumption), government is better of when the optimal transfer scheme takes into account the production externality between growers. Likewise, growers also are better off when the production externality exists.

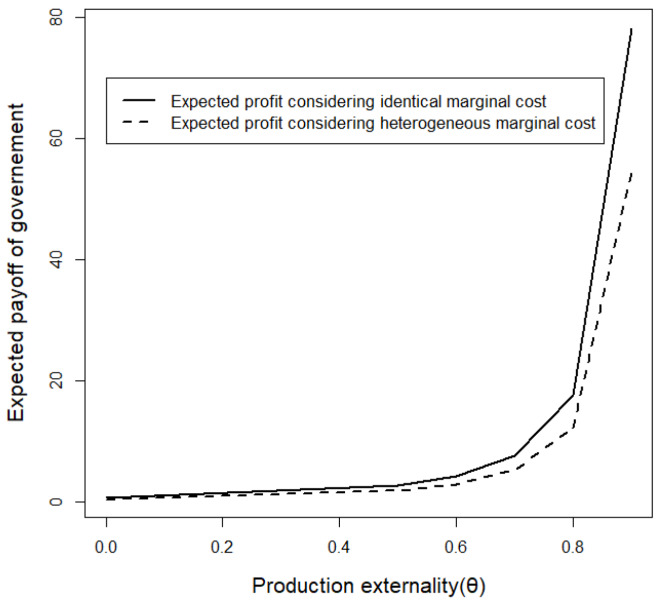

Figure2: Correlation between government expected payoff and production externality.

Concerning the heterogeneity, if grower 2 for example is less effective (c_j^m equals to 2 instead of 1) than it is assumed (due to homogeneous assumption), it will lead to an overpayment of grower 2. If externality parameter is 0.9, grower 2 whose right payment is 19.57 will receive 45.7 instead, corresponding to 57.17% of overpayment. This situation causes an overestimation of government payoff of approximatively 30.3%. The consequence of neglecting private features will generate Pareto-inefficient solutions and reduce government expected payoff from the first-best outcome. Likewise, the total health quality decreases as one of the two growers becomes less effective. These results put forwards that the infection risk management is subject to the effectiveness of the less provider of protection. In this regards, government would prefer for incentive contract scheme the type of grower that face lower marginal cost (parameter of efficiency) rather than those with higher marginal cost. The same applies for risk preference parameter. It indicates that the less growers are averse to risk the better are both government and growers. This result highlights that the risk bearing by growers is Pareto-inefficient in the sense that it puts the solution further away from its first-best. Accordingly, as it is the case with the marginal cost, government would prefer for incentive contract, growers with lower risk preference parameter. While the production externality is welfare-improving, the acknowledgment of private features allows to implement personalized contract which considers the conditions of production within each herd.

Discussion

This paper examines analytically the principal-agents model in the context of animal disease prevention, considering moral hazard, externality and heterogeneity of growers. The main objective of this work is to revisit the structure of the incentive payment for *ex-ante* biosecurity effort when growers have heterogeneous attributes (i.e. non-identical). This research shows its originality because it stands out from the classical literature on incentive payments. Although the incentive theory is broadly documented in economic literature[21], very few examples are related to animal disease management. Kuchler and Hamm (2000) led a seminal research revealing the 40-years evolution of farmers' willingness to report infected sheep with scrapie in US according to different levels of incentive indemnity. The authors found that when the fixed indemnity is lower than the market price of sheep, fewer diseased animals are reported. Conversely, the reported cases increase when the indemnity is higher than market price. Hennessy and Wolf (2018) confirm this observation by demonstrating that the adverse selection issue can be overcome by establishing levels of compensatory payments to hedge market prices. Gramig et al. (2009) develop a principal-agent model to examine a compensation scheme for both biosecurity efforts and reporting operation of infected animals. Their model setting includes both an indemnity payment and a fine. As Hennessy and Wolf (2018), they suggest that when controlling simultaneously hidden information and hidden efforts, policy planners must rely on a two-dimensional mechanism, namely an *ex ante* indemnity payment to support private effort and an *ex post* fine to prevent the development of opportunistic behaviors. Despite these findings, these works neglect the interactions among agents, in particular the external effects of communicable disease and of their management, which is shown to be an important feature of herd management and its associated health risks (see Hennessy (2007) and Reeling and Horan (2015)). Thus, this type of analysis fails to design optimal policies whenever interactions exist among growers' decisions. Wang and Park (2014) do consider multiple agents in the livestock indemnity design by developing a principal multi-agents model. They set a relative performance evaluation (RPE) indemnity where moral hazard and a common uncertainty between growers are taken into account. They reveal that RPE indemnity is applicable in two cases, when (i) significant correlation exists between the diseases prevalence across herds, and (ii) the effectiveness of biosecurity is low. However, in this paper the diverse

[21] Here are few example of rigorous works based on incentives theory in economics: Holmstrom (1979); Shavell (1979); Sappington and Demski (1983); Mookherjee (1984), etc.

agents are still assumed homogenous. Wang and Hennessy (2014) study producers' incentive to participate to a voluntary program of livestock disease control when the incentives are interdepend. Considering the participation involves costly test operation, the authors show incomplete farmer participation owing to cost heterogeneity. Based on the work of Hennessy and Wolf (2018), Fraser (2018) performs a numerical simulation to highlight that the range of payments to achieve the optimal incentive scheme is subject to individual parameters, namely the level of growers risk preference, the cost of biosecurity, etc. This work highlights the need to consider private attributes in the incentive payment scheme. Finally, Mato-Amboage et al. (2018) allow for spillover effects within two homogenous agents. They suggest a coordinated contract approach to facilitate the risk minimization and risk sharing. However, this paper fails to consider the heterogeneity between agents.

Unlike Mato-Amboage et al. (2018) where agents are assumed homogenous, our development puts forwards the heterogeneity of growers and the production externality. We innovately develop these analyses by providing more insights about the factors that affect the optimal allocation of incentive and then by defining the type of growers the more likely to increase the total health quality, thereby reducing the global risk of infection. Overall, our analytical results are qualitatively in line with Huffman and Just (2000), except regarding the neighboring effect which gives more precision about the structure of payment. Our results are almost consistent with Mato-Amboage et al. (2018), except the notable effect of heterogeneity highlighted in our case. Our model reveals the important implications about the effect of incentive on risk management, especially self-protection against disease entry into a herd. We observe that incentive payments are effective tools to motivate *ex-ante* biosecurity effort for diseases entry prevention. Due to the problem of information asymmetry, the structure of public incentive has implications on the risk-sharing, by partially insuring growers for income risk. In this regards, the gross payment declines when growers operate in more uncertain environment, comparatively to the no risky situation. This result is consistent with Gramig et al. (2009); Mato-Amboage et al. (2018) and Hennessy and Wolf (2018). The net payment however increases with the risk premium parameter, indicating that the net payment is high for highly risk-averse growers and low for weakly risk-averse growers, *ceteris paribus*. This is assignable to the increase of fixed salary, whose purpose is to pay growers for the increase of risk bearing. In both the analytical model and numerical simulation we show that the homogeneity assumption is very strong and potentially detrimental to the first-best outcome. The overestimation of private marginal cost for example will imply the miscalculation of the selected variables (biosecurity effort, health quality, payoffs, etc.). This situation implies payoff forgone for government and accordingly a loss of welfare for the whole of society. There is a surplus only generated for growers whose private cost is overestimated. Assuming growers are homogenous, those whose real cost is under the defined-level will participate while the group whose real cost is over the defined-level would reject the contract. It results in incomplete participation in case of voluntary contract or an increase of cheating behaviors in case of compulsory contract. This result converges to Wang and Hennessy (2014) whose paper indicated that the cost heterogeneity matter a lot for full participation to voluntary contract. Furthermore, we show that in addition to private cost, the individual risk preference also matters for choice-making about biosecurity effort. Growers with low aversion to risk invest more in biosecurity than their counterpart who are more risk averse. This non-trivial result deserves comments. Basically, risk-averse growers are interesting because they are likely to implement high preventive measures to reduce the likelihood of disease occurrence (Niemi and Heikkilä, 2011). However in our case the transfer scheme is designed so that the biosecurity effort relies mainly on the marginal incentive (β^i). Owing to the asymmetry of information, the trade-off displayed between risk and incentive makes the marginal incentive decrease with the increase of aversion to risk (demonstrated yet above). In this respect, the more risk-averse is the grower, the less he receives incentive. Since the latter translates into the biosecurity effort, growers who are more risk-averse will invests less in self-protection, with the consequence of the decrease government expected payoff. Government should be better-off to contract with growers who have low marginal cost and low aversion to risk. The efficiency of biosecurity production (allusion to productivity index) is beneficial not only for growers, but also to the whole society. The decrease of efficiency of a grower is also detrimental to the whole of society, pointing thereby the infection risk prevention is the "weakest-link" public good. The consideration of growers' heterogeneity allows to design a personalized contract, modulated to the private attributes of each grower. Finally, we show that the effect of individual attributes relies on the intensity of production externality. The latter exhibits an increasing return effect on the biosecurity effort, the level of transfer and consequently on both growers and government expected payoffs. The take to account of positive external effect improve the welfare of the society.

However, some limitations and extensions of this work deserve too comments. First, as mentioned, our model has emphasized the case that the principal and the agents are all able to perfectly observe the type of growers. It nevertheless seems realistic to think that other levels of information asymmetries may exist, particularly between farmers, and which would deserve to be specifically modelled. Second, basically the on-herd production function including marketable goods can be written as $\mathbf{Y}^i = f(e^i, \mathbf{I}^i)$ where $\mathbf{Y}^i$ is the vector of on-herd output (i.e. health quality, marketable products and other), e^i biosecurity effort and $\mathbf{I}^i$ the vector of other inputs. Splitting the production so that $f(e^i, \mathbf{I}^i) = f(e^i) + f(\mathbf{I}^i)$ implies the separability assumption, which can be questionable. Indeed, this assumption means that the production of animal products and health management practices are disjoint. Modelling growers' utility focusing only on the health quality production (i.e. separability of output) appears to be a limit of our work and it has to be applied with caution. Third, the risk-aversion assumption on the agents could raise questions of behavioral biases. Obviously, the risk-averse growers will ask for higher payment than those who are risk neutral. Further analysis is required on this concern to improve the agency model in the context of infectious disease management in the future. Fourth, for extension concern, it could be interesting to re-assess this agency problem into a bio-economic framework in order to capture the effect of biological dynamics on private decision of biosecurity. Gramig et al. (2009) is an example of work which considered this feature in the absence of multiple agents' specification.

Conclusion

This research focuses on the problem of disease prevention using principal multi-agents approach with imperfect information on private biosecurity effort. We examine this policy for *ex-ante* disease management considering the asymmetry of information, the production externality effect between growers, and the heterogeneity of private properties, which are here marginal productivity of biosecurity, marginal cost of biosecurity and individual's risk preference. Thanks to a numerical example, we defined the optimal incentive design and we identified the type of growers most likely to participate in the contract defined by the government. We have showed that the payment scheme adopted by government fits well the intended policy, in the sense that it optimizes the joint expected payoff. Then, we demonstrated the necessity to account for individual properties to design the optimal contract. Homogeneity assumption has been revealed as confusing hypothesis which keeps the solution away from the first-best outcomes. Precisely, we observe that both government and growers are better-off when growers have small aversion to risk (η^i), face less uncertainty of production (σ^2) and high productivity index (x^i). We observe that the effect of these private properties relies on the intensity of the preventive spillover across herds, which exhibits increasing return effect on biosecurity effort, health quality and payoffs. Finally, we find that the health quality is the weakest-link public good in the sense the welfare of the society could be challenged by the least effective grower. This result is consistent with (Hennessy and Wolf, 2018). This research brings innovative material for the design of *ex ante* control policies against animal diseases such as bovine tuberculosis for example. Indeed, bTB is a long-term growing concern across Europe, and the disease is found in cattle throughout all European countries with variable rates. In addition, the disease is not routinely detected on live animals (with local exceptions) and most of the time information on the disease is only revealed post-mortem at the slaughterhouse. Therefore, the preservation of national disease-free status is crucial because it not only limits the risk of interspecies contamination but also allows the continuity of international trade in animal products. This status is ensured by proactive policies to prevent the emergence and/or spread of the disease, and therefore by providing incentives to implement biosecurity practices. In this paper, 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 is able to meet these objectives. In addition, since biosecurity practices are not disease specific but more generally aimed at improving the overall health conditions of herds, our policy design is able to reduce multiple disease risks at once. Further research developments are expected to assess the cross-effects of such policy for the support of cattle farms competitiveness.

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