Individual and collective management of endemic animal diseases: an economic approach

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Introduction

The control of livestock diseases is a major concern for intensive animal production areas like Western France. Animal diseases are an important source of vulnerability due to the diversity of their impacts. They can create substantial shortfalls for farms, by degrading their technical and economic performance (production losses) and may lead, for some of them, to the loss of commercial opportunities. The control of animal diseases also implies the allocation of resources, both *ex ante* in terms of surveillance and prevention and *ex post* in order to mitigate the sanitary and economic consequences if the disease occurs (curative expenditure, for example). These shortfalls and cost induced by animal diseases weigh heavily on the economy of farms and have wider effect on the competitiveness of animal production chains. Beyond the direct impact of diseases on the livestock sector, animal diseases can have a broader impact on regional and national agricultural economies (animal feed, for example), as well as on firms engaged in the food processing of animal products.

The management of animal health is nevertheless complicated by the varying biological characteristics of the diseases and difficulties arising in their control. The most problematic element probably refers to the transmissible nature of many diseases; contagious pathogens may easily spread from one farm to another. Different transmission modes exist: direct contact between animals from different herds (contact over fences at pasture, for example), animal purchases, environmental contamination, exchanges of contaminated materials between farms… Some diseases are transmitted by animal vectors (insects, small mammals, wildlife). The communicability of pathogens gives rise to externalities, which imply that decisions taken at the farm level may have sanitary – and therefore – economic consequences for other farms with which the farm is related.

A farmer who decides to protect his herd against a particular disease by vaccinating or by adopting strict biosecurity measures (hygiene, quarantine, for example) would create a positive externality, in that its action would benefit to other farmers by lowering the infection pressure (risk of occurrence of the disease). Conversely, a farmer could be encouraged to behave as a free rider seeking to benefit from the efforts of its neighbours, without bearing the costs. This behaviour would generate a negative externality since this behaviour would help to maintain the disease within the geographic area considered. This results in strong interrelationships of individual decisions to control animal disease at the area level. Note also (by analogy with the atomicity assumption of perfect competition) that the epidemiological situation observed across a geographical area may only vary if a sufficient number of farmers in the area implement a given control measure. For communicable diseases, effectiveness of control measures will often depend on the ability to act in a coordinated manner across a group of operations (horizontal coordination).

This paper focuses on collective actions to control animal diseases, for which management decisions do not take place on a collective level, but is left to individual initiative (decentralized decision-making). This paper puts specific emphasis on endemic diseases that may not be regulated and their control involves horizontal coordination requirements. The aim of this work is to outline a conceptual framework for understanding the collective management of animal diseases and to present the main implications in terms of research needs.

The challenges of this research are at two levels. At the societal level, this research aims to make available to collective animal health managers more effective decision tools. These managers are involved in the definition of sanitary policies across an area (eradication, control of the spread of a disease). Management decisions are currently taken on the basis of epidemiological approaches which implicitly assume that the measures advocated by the collective manager will be systematically implemented by the farmers. These approaches generally omit that decisions to implement the measures are decided on a voluntary basis by each farmer on the basis of their own economic interests, regardless the collective goal promoted by the collective manager. This reasoning can lead the managers to make wrong decisions (waste of resources, wrong types of intervention …). The effectiveness of collective actions should be improved by introducing incentives to remove the potential obstacles to measures adoption by the farmers. From an academic point of view, the work outlined a challenge for economic analysis. Different tools exist in many sub-disciplinary fields (agricultural economics, but also human health economics, environmental economics, economics of risk and uncertainty, theory of agency, etc.) that could be judiciously combined to develop a relevant analytical framework. It also enriches standard economic approaches by integrating the contributions of epidemiological modelling. The main idea developed in this paper is the coupling of economic and epidemiologic models. The difficulty lies in the fact that individual decisions depend of an epidemiological context and, in return, the epidemiological context is influenced by individual decisions. The purpose of the work is the construction of a tool for decision support, by revisiting the terms of collective action in animal health management and taking explicitly into account the decentralized nature of decision-making process.

The implementation of this approach involves three steps that will be successively discussed in the paper, 1) the modelling of the farmer's individual decisions in regard to animal health management, 2) the coupling of epidemiologic and economic models to assess the outcomes at a collective level, and 3) the design of incentive mechanisms. The description of the conceptual framework is followed by a simple theoretical application to a particular disease, the PRRS. PRRS (porcine reproductive and respiratory syndrome) is a transmissible endemic disease that has an important impact on farms production. The transmission between farms may occur because of an infected neighboring farm or because of the purchase of infected animals. The management of the PRRS can be implemented at two levels (i) at the individual level by the farmer (biosecurity, vaccination, test and cull of infected animals, depopulation), and (ii) at the collective level, by implementing incentives for individual management.

Problem definition and general framework

Modelling individual behaviours

The first step is to model the farmer's decision process in regard to animal disease management. The key assumption is that farmers behave rationally. The decision to implement – or not – a control measure is individually taken by farmers on the basis of their own economic calculation. Decisions to implement control measures are usually taken in a broader context of resource allocation, which implies a trade-off between disease management and other uses of scarce resources (money, labour). The challenge in modelling farmers' individual behaviours in relation to animal health is to take into account the fact that individual control decisions are taken in regard to a particular disease at two levels: (1) at the farm level, the sanitary status of the herd (within-herd prevalence, expression of the disease) will have an impact on production; (2) but also, in the case of a communicable disease, for a group of farms in contact, the expression of the disease (between-herd prevalence) will impact on the probability for a farm operating in an area to be infected due to animal purchases, neighbourhood contacts, airborne transmission, etc. To model these individual behaviours, it becomes necessary to model the impact of the disease on the production on the one hand, to establish a relationship between the output and the control inputs on the other hand. Finally, in the case of communicable diseases, the model should take into account the uncertain nature of the herd's infection.

In the economic literature, little attention has been paid to the formalization of farmer's behaviour in regard to animal disease control in a neoclassical way. This issue emerged in the late 1980s in the United Kingdom (McInerney, 1996). Based on the production function concept, basic microeconomic approaches were implemented 1) to show how the disease could alter the shape of the production function (McInerney, 1988), 2) to define the loss-expenditure frontier concept, which highlighted the tradeoffs made by the farmer between the production losses caused by the disease on the one hand, and control expenses on the other hand (McInerney, Howe and Schepers, 1992). The adopted approach is the minimization of the economic cost of the disease (understood as the sum of the losses induced by the disease and the control expenditures). In the 1990s, the question of the profile of the loss-expenditure frontier was discussed by Tisdell (1995), who also adapted McInerney's framework to the multiple diseases management. Finally, inspired by developments in the economic literature on pesticide use (damage abatement function), Chi et al. (2002) have finally taken in consideration the problem of modelling the farmer's behaviour in regard to animal diseases, with a particular focus on the trade-off between preventive and curative expenditures. In this latter work, the farmer's decisions are based on the level of the disease, which simultaneously covers the prevalence and severity. The main limitation of these first attempts to formalize the farmer's animal health decisions is that they consider a farm in isolation and do not take into account the fact that the farm faces a risk of infection. Decisions are taken in regard to the epidemiological situation of the herd, and the epidemiological situation within the herd is only influenced by the farmer's decisions. This assumption may only hold in the case of non-communicable diseases. For communicable diseases, it is reasonable to assume that the farmers take into account the herd's sanitary conditions (prevalence and severity of the disease) when taking his decisions in regard to disease control, but the risk of infection (or re-infection) of the herd remains influenced by the inter-herd prevalence in the geographical area

The modelling of farmers' individual behaviors in regard to animal disease management have to take into account: (1) the epidemiological situation of the herd, that leads to a first integration of epidemiological elements (within-herd model) because the possible evolutions of the herd's epidemiological situation will affect the actions implemented by the farmer, and; (2) the between-herd epidemiological situation, which constitute an external risk for the herd. The model should then take explicitly into account the risk and uncertainty which vitiates the decision-making process.

A crucial element for our concerns is the inclusion of time in our model The choice of a type of model (static vs. dynamic) is intimately linked to the livestock system considered which involves different length of longer or shorter rearing cycles of the respective disease and control measures available (single decision on the planning horizon vs. repeated decisions). For repeated decisions with fully reversible choice, a static model can be used. Rat-Aspert and Fourichon (2010) used a decision tree at each time step to formalize the decision of farmers. But when the decision is not fully reversible, and when evolution of the epidemiological state of the farm account for the decision, using dynamic programming seems necessary. This issue also raises the question of the planning horizon of the farmer (reasoning taking into account the dynamic reasoning versus steady state). The nature of the choice of farmers that is modellised (discrete choices such as vaccination or standard consumption model with continuous variable) leads to different tools. For a discrete choice, a decision tree can be used. In this case, the value of the income or utility in each terminal node can be calculated by a decision function. For a continuum of choice, farmers' choice to manage the disease must be modellised by the profit optimization of a production function.

Coupling of epidemiologic and economic models

The first step that modelled individual behaviours does not account for an important issue in animal diseases: for transmissible diseases, the sanitary situation of a farm (within-herd prevalence) has an impact on the sanitary situation in an area (between-herd prevalence), and vice versa. So, when a farmer protects his own herd, he also protects the other herds, by reducing the probability for other herds to be infected. Individual management of transmissible disease therefore creates a positive externality. This second step aims to evaluate the impact at a collective scale of decision taken at an individual scale by a large population of farmers. To that purpose, models designed to represent individual behaviours must be coupled with an epidemiologic model at a between-herd level, taking into account the spread of the disease when means of control are - or not - implemented at the scale of farms.

The coupling of economic and epidemiologic models is an idea that emerged nearly 20 years ago, leading in health economics to the sub-disciplinary field of economic epidemiology (Brito et al. 1991; Philipson, 1999 ; Gersovitz and Hammer, 2001 and 2003). It is only very recently that early works sought to transpose this approach to the issue of collective control of endemic animal diseases (Gramig, 2008; Rat-Aspert and Fourichon, 2010).

The main idea is that, in the case of a non regulated endemic disease, the individual decision of farmers to manage a disease at the herd level is made based on the health status of livestock and the local epidemiological context. The prevalence of the disease in the area, as well as the health status of the herd, are key elements in decision-making. The decision affects the local epidemiological context. The dynamic coupling of an epidemiologic model (which describes the evolution of the local epidemiological context based on the decisions taken by the farmers) and an economic model (which describes the decision making of farmers according to the local epidemiological context) allows combining, in a unified framework the contributions of economic and epidemiological approaches.

Design of incentive mechanisms

When the individual control of disease induces positive externalities, the efforts of farmers may be insufficient to achieve a collective optimum, since individual decisions do not usually take into account their impact on collective risk. In human health, Brito et al. (1991) have shown, for example, that a voluntary vaccination strategy is strictly dominated by a benevolent dictator status, maximizing the collective welfare (defined as the sum of individual utilities). The results of individual management of diseases at farm level may then differ in various respects of collective expectations, leading to a need to manage collectively this risk.

Producers may want to influence collectively the management of a disease and its impact in their area. Their goal may be epidemiological (disease eradication, limiting viral circulation) or economic (maximizing collective welfare). To do so, the collective decision-maker can develop individualized plans to control at the farm level (tests on farm animals, remediation). They can also incite farmers to control the disease (by providing financial incentives to management, through vaccination or through biosecurity measures, the implementation of control plans at the farm level). The establishment of networks of exchange of animals based on their health status is also possible. However, the success of collective action depends on their acceptance by farmers. Collective management of the disease can also include measures of risk sharing. Infection of livestock by the disease poses a risk, a mean for collective management of that risk is to pool it through insurance mechanisms. This pooling of risk may also impact on individual decisions of farmers.

Predicting the outcome of these collective actions of animal health management is complicated because it must take into account individual choices in the implementation of control actions. Thus, integration of collective actions in epidemiologic and economic models is a support tool for decision makers. It is introduced into the decision model an effect related to the means of collective management in place (financial incentives to individual management for example). This type of model allows to test scenarios and also to optimize means of collective control. It is important to distinguish two stages in the implementation of the action of control. As a first step, actions are implemented, they have an impact on the epidemiological situation. In a second step, equilibrium of the epidemiological situation is reached. This equilibrium may be endemic or control action may lead to eradication. Modelling should look at these two stages. The epidemiological desired equilibrium may be a result of the model (equilibrium maximizing the objective function of a manager) or may be exogenous to the model (when the manager's objective is epidemiological: eradication or reduction target in terms of prevalence). The search for the optimum balance does not require a dynamic model since the results at equilibrium can be calculated. However, for more complex models, the equilibrium values are taken from simulations of the evolution of the disease and the decisions of farmers obtained using dynamic models. This dynamic modeling is also necessary to optimize the means of achieving equilibrium in the case of an equilibrium set exogenously, but also to verify that the equilibrium is achievable in the case of an equilibrium optimizing the collective welfare. This objective function must take into account the costs for the manager and profits for farmers. The question of the function to be optimized depends on the purpose and means of the manager. Indeed, to take the example of farmers' health management groups, a large portion of the funds allocated to the control comes from contributions from farmers themselves. Since management is not regulated, looking for optimum balance incentives / penalties as proposed by Brito et al. (1991) does not seem possible (farmers' groups can easily provide incentives to management, but the introduction of penalties seems inconceivable). Collective management is thus a reallocation of resources from farmers.

Model application for PRRS

PRRS (porcine reproductive and respiratory syndrome) is a transmissible endemic disease that has an important impact on farms production. The transmission between farms may occur because of an infected neighboring farm or because of the purchase of infected animals. The management of the PRRS can be implemented at two levels. (i) At the individual level by the farmer (biosecurity, vaccination, test and cull of infected animals, depopulation), and (ii) at the collective level, by by implementing incentives for individual management.

Individual decision

Production function

The impact of the disease on farms is modelised following McInerney (1996). We first develop a production function :

$$Q = f(X \,/\, \overline{N}, \overline{K})$$

Q, the flow of output (slaughtered animals), depends on the use of variable inputs X (food, labor…) on the stock of breeding herd (*N*, the number of sows) and other fixed resources (K). The incidence of the disease on the shape of this function is to reduce Q for any level of inputs.

The shape of the function f is an important issue. We use a function based on zootechnical relations (as Chavas, 1999). rather than a classical microeconomic function such as the Cobb Douglas or Leonitef function, because that allows to pass on the impact of the disease on known zootechnical parameters.

For the swine production, we assume that the number of sows (*N*) is limited by the size of the barns (K). Given a reproduction rate *k*, the number of offspring by time step is denoted by $h = k \cdot N$. Sows are facing a death rate δ_N by time step, and the culling rate of the sows is S_N by time step. We assume a constant number of sows.

We assume that the replacement of sows is made by purchase of reproductive gilts. So, all the animals are used to produce slaughter pigs. We assume a feed conversion ratio (FCR) from weaning of the piglets to finish is equal to $FCR = a + b \cdot LW$ (Aubry et Al, 2004) The Feed conversion ratio is the ratio between the daily feed consumption (ΔX) and the average daily gain (adg) , or the ratio between marginal consumption dR and marginal growth dLW.

$$FCR = \frac{\Delta X}{\text{adg}} = \frac{dX}{dLW} = a + b \cdot LW$$

Solving the differential equation, assuming that the living weight at the beginning of post-weaning is equal to *c*, gives:

$$LW = \frac{-a + \sqrt{b^2 \cdot c^2 + a^2 + 2 \cdot a \cdot b \cdot c + 2 \cdot X \cdot b}}{b}$$

$$Q = N \cdot k \cdot (1 - \delta_s) \cdot \left(-a + \sqrt{b^2c^2 + a^2 + 2abc + 2X \cdot b} \Big/ b \right) + N \cdot LW_N \cdot (S_N - \delta_N)$$

With LW_N the living weight of slaughtered sows.

$$Q(A) = \mathrm{x} + y \cdot (z + A)^{0.5} \qquad with \begin{cases} \mathrm{x} = \dfrac{N \cdot k \cdot (1 - \delta_s) \cdot a}{b} + \mathrm{N} \cdot LW_N \cdot (\mathrm{S_N} - \delta_\mathrm{N}) \\ \mathrm{y} = N \cdot k \cdot (1 - \delta_s) \cdot \sqrt{2/b} \\ z = \dfrac{(a + bc)^2}{2b} \end{cases}$$

That finally looks like a Cobb Douglas function.

Impact of the disease on the production function

Within herds, the virus spreads rapidly with up to 85 to 95% of pigs in a herd becoming sero-positive within two to three months after the introduction of an infected animal (Zimmerman, 2006). Given these epidemiological characteristics we consider two types of herd status in the model : S Susceptible, corresponding to a « healthy » herd, and I Infectious, corresponding to a "diseased" herd. According to Zimmerman (2006) the PRRS has an important impact on the reproduction rate, and also on the feed conversion ratio. By optimizing the production function, we can calculate the income of a farm with disease and without disease, assuming that the PRRS increases the value of b (increase in feed conversion ratio) and decreases the value of k (decrease in reproduction rate)

So, we have two different production functions, $Q(A)$ and $Q^d(A)$, the production function for a farm with a herd of status S or I, respectively.

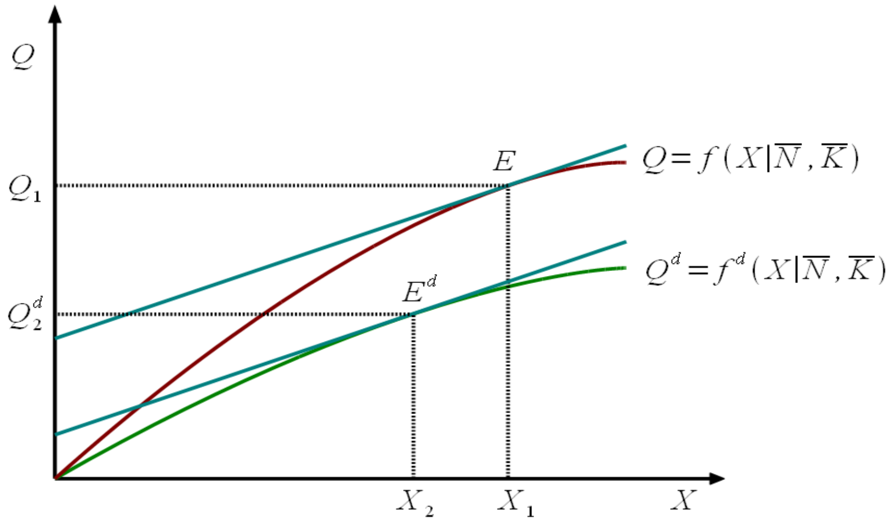

Figure 1. *Production function with* (Q^d) *and without disease* (Q)

The optimization of the income of farmers by this production function, subject to P_X and P_Q, the prices of an unit of aliment and of an unit of living weight allow to calculate π_S and π_I, the income for a farmer with a Susceptible or an Infectious herd, respectively.

Risk of infection, probability of eradication

Without any mean of management, farmers with a Susceptible herd are facing a probability of infection that depends on the prevalence in herds (ie. The proportion of infectious herds in the area). So, we assume a probability of infection that is dencity-dependent (Hoch, 2007). The probability of infection at each time step *t* is $\beta \cdot I_t$, with I_t being the prevalence of the disease at time *t* and β being the transmission rate parameter. We assume that, at each time step, Infected herds can become susceptible with a probability $\propto$.

Individual means of management

We assume two possible individual means of management. The depopulation method: total depopulation followed by repopulation with PRRS-free replacement pigs (Andreasen et al., 1998), that allow to eradicate the PRRS in a farm, and a set of biosecurity means (quarantine, purchase of animals control, staff and visitors control) that decreases the risk of infection for susceptible farms by a factor γ. We assume that the costs of means of management are fixed costs, the cost of the depopulation is P_{dep}, and the cost of the biosecurity is P_{bio}, at each time step of the model. So, ceteris paribus, the implementation of a means of management has no impact on the optimum value of input and output given by the production function.

Dynamic optimization

Because the depopulation is an irreversible mean of management, depopulation as an impact on the courant income and on future incomes. The farmer faces uncertainty about future status of his herd, and so, future values of his income. To take into account the impact of choice on the future, we use dynamic programming. Assuming that farmer is risk neutral and makes decisions so as to maximize the expected present value of net income over an infinite planning horizon, this corresponds to the following optimization problem.

$$E^* = \mathrm{Max}\left(\sum_{t=0}^{\infty}(1+r)^{-t} \cdot E(\pi_t)\right)$$

Where $E(\pi_t)$ is the expected value of the income at time t, and $(1+r)^{-t}$ is the discount factor, with r being the discount rate reflecting time preferences. $E(\pi_t)$. We assume that farmers have myopic behavior regarding the evolution of the prevalence between herds during time, but they perform rational expectations regarding the probability of infection in their farm, assuming a constant prevalence in the area. Because farmers assume they will facing the same risk over time, and because the model has Markov property, in the dynamic optimization, we assume that farmers will follow one of these four policies :

1. No mean of management
2. Biosecurity if S and nothing if I
3. Nothing if S and depopulation if I
4. Biosecurity if S and depopulation if I

The optimization problem consists to choose the policy that maximize the expected present value of net income E^*. This corresponds to the following optimization problem :

$$E^* = \mathrm{Max}(E_1, E_2, E_3, E_4)$$

With E_1, E_2, E_3, E_4 the expected income flow of a farmer applying respectively policy 1,2,3,4, with

$$E_1 = \frac{1+r}{r} \cdot \left(\pi_I \cdot \frac{\beta \cdot I}{\beta \cdot I + \alpha} + \pi_S \cdot \left(1 - \frac{\beta \cdot I}{\beta \cdot I + \alpha}\right)\right) - \frac{1+r}{r + \beta \cdot I + \alpha} \cdot (\pi_s - \pi_I) \cdot \frac{\beta \cdot I}{\beta \cdot I + \alpha}$$

$$E_2 = \frac{1+r}{r} \cdot \left(\pi_I \cdot \frac{\beta \cdot I \cdot \gamma}{\beta \cdot I \cdot \gamma + \alpha} + (\pi_S - P_{Bio}) \cdot \left(1 - \frac{\beta \cdot I \cdot \gamma}{\beta \cdot I \cdot \gamma + \alpha}\right)\right) - \frac{1+r}{r + \beta \cdot I \cdot \gamma + \alpha} \cdot (\pi_s + P_{bio} - \pi_I) \cdot \frac{\beta \cdot I}{\beta \cdot I \cdot \gamma + \alpha}$$

$$E_3 = \frac{1+r}{r} \cdot \left[\beta \cdot I \cdot \left(\pi_I - P_{dep}\right) + (1 - \beta \cdot I) \cdot \pi_S\right]$$

$$E_4 = \frac{1+r}{r} \cdot \left[\beta \cdot I \cdot \gamma \cdot \left(\pi_I - P_{dep}\right) + (1 - \beta \cdot I \cdot \gamma) \cdot (\pi_S - P_{Bio})\right]$$

Details of the calculations are available in annex 1. This optimization scheme allows finding the best policy for farmers in different situations, especially for different values of prevalence (figure 2).

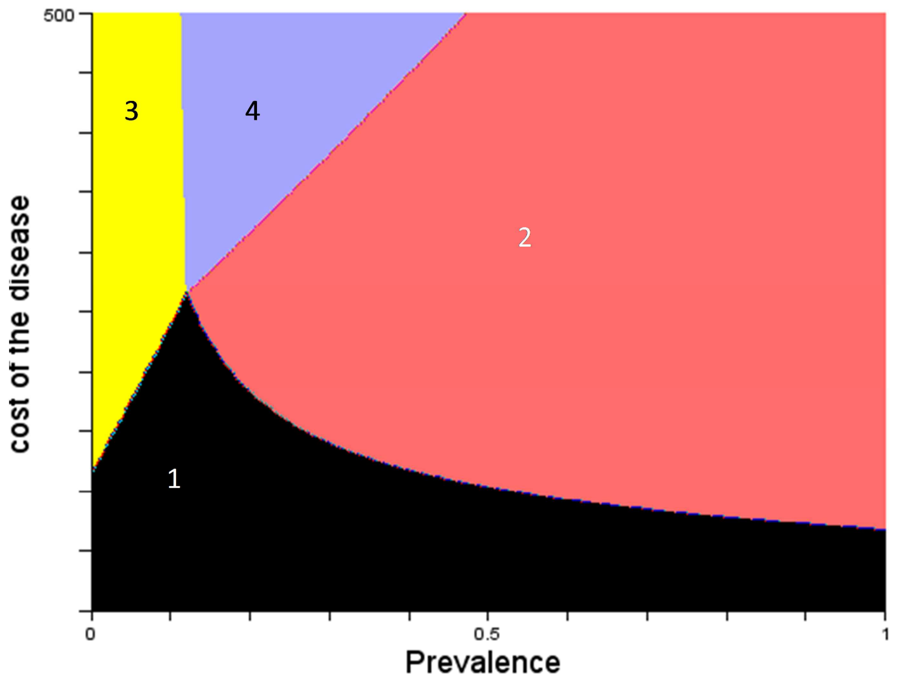

Figure 2: *Choice maximizing discounted farm income flow, depending on the prevalence and on the value of losses due to the disease, ceteris paribus (policies: 1. nothing, 2. biosecurity, 3. Depopulation 4. depopulation if infected and biosecurity, 4. Biosecurity)*

Coupling of decision and epidemiological models

The coupling of epidemiological and decision models allows to study the positive externality due to the implementation of means of management by farmers in an area.

We use a classical stochastic individual-based "Susceptible Infectious" model. It modelises the propagation during time of the PRRS between herds in a group of farm, according with the previous assumptions. So, it takes into account the possibility of biosecurity measures for Suceptible herds, that decrease the risk of infection and the possibility of depopulation for Infectious herds, that allows eradication (figure 3).

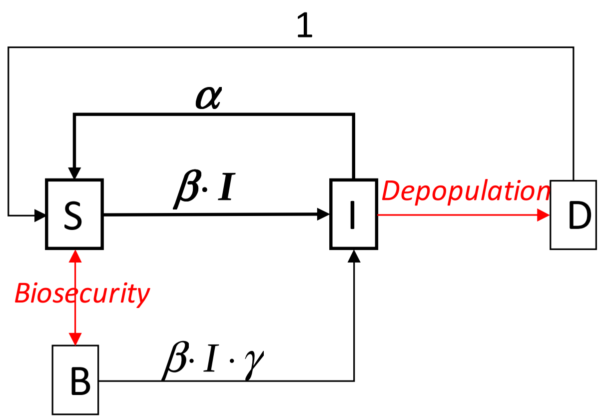

Figure 3. *: Model SI with depopulation and biosecurity: probability of state transition between S (susceptible) I (infectious) B (susceptible + biosecurity) and D (Infectious implementing depopulation)*

At each time step, farmers choose the policy that optimizes their expected income flow, regarding the prevalence in the area. We assume that evolution of the epidemiological situation has no impact on the market of farms' inputs and outputs. This assumption is valid if the area of interest has no market power, that is to say, it represents a small area in an open market. The population of farms is assumed to be heterogeneous in its economic parameters (which influence the decision in each farm). The coupling of the decision model and of the epidemiologic model allows us to follow the evolution of prevalence and farmers' choices in time.

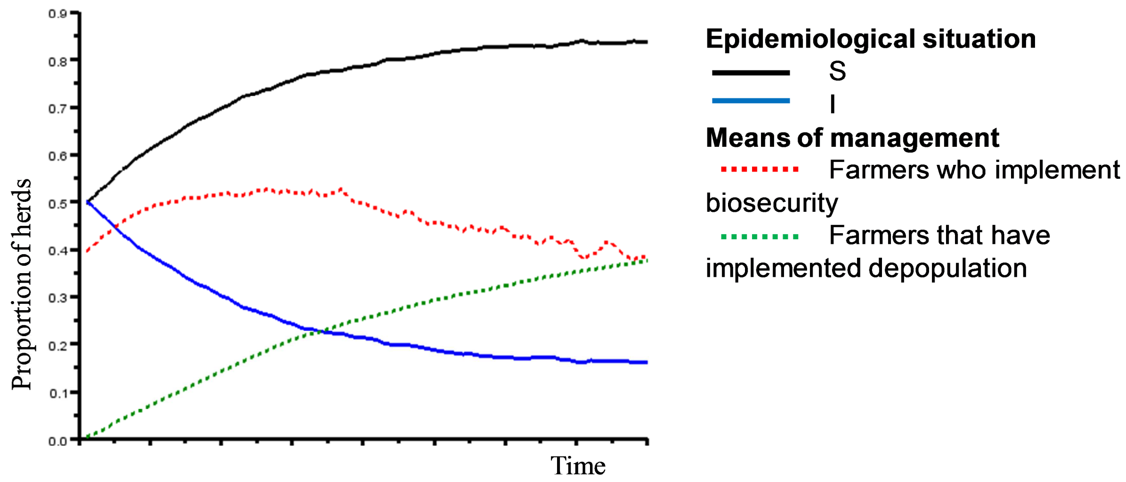

Figure 4. *- Evolution over time of the proportions of herds susceptible (S), infected (I) , and proportion of herds that implement means of management (Biosecurity: and depopulation)*

Because of the decrease in prevalence, the proportion of susceptible farmers that implements biosecurity measures decreases. At the same time, the proportion of farmers that have implemented depopulation increases. The proportions of susceptible herds and Infectious herds reach equilibrium.

Incentive mechanisms

Incentive mechanisms consist, for a collective manager, in subsidizing means of individual management, decreasing its cost to the farmer. Figure 4. shows the impact of different levels of incentives to the biosecurity measures on the prevalence and on the implementation of measures by farmers at the epidemiological equilibrium.

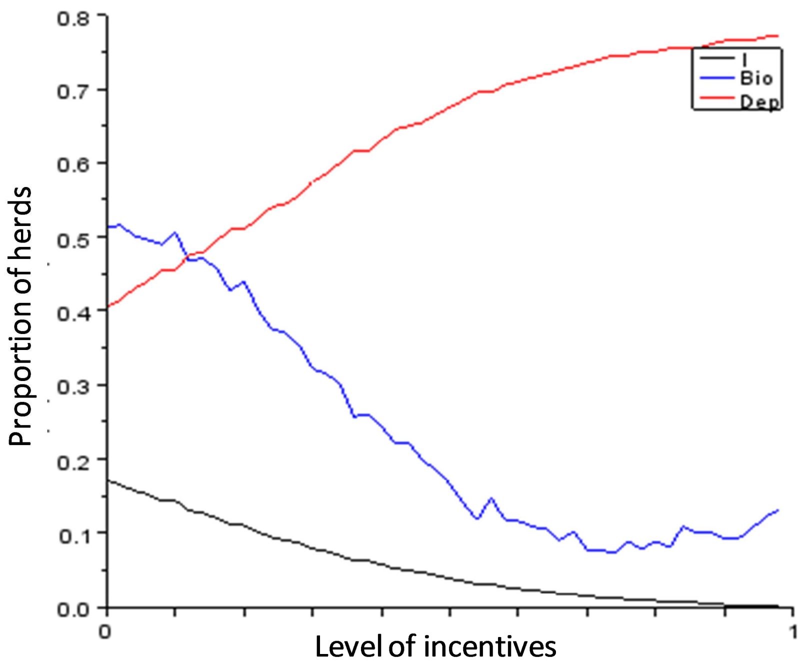

Figure 5: *Incentives for biosecurity. Prevalence (I) and proportion of farmers that agree to implements measures of biosecurity (Bio) and depopulation (Dep) for a given proportion of the cost of the biosecurity subsidized.*

The higher is the level of subsidies, the lower is the prevalence in the area. But we can also see that an increase in the subsidies for biosecurity leads, contrary to intuition and common sense, to a decrease in the use of the biosecurity in farms. This decrease is due to the fact that farmers prefer biosecurity (the prevention) when the prevalence is high, and depopulation (the cure) when the prevalence is low. So, an increase in the value of the subsidies can lead to a decrease in its costs for the collective manager, and improves the epidemiological situation by decreasing the prevalence in the area.

Conclusion

Because of feedbacks between farmers' individual decisions and disease spread, it is necessary for the study of endemic communicable and non-regulated diseases, to couple an epidemiologic model describing the evolution of the disease in an area and an economic model describing farmers' decisions based on the health status of their livestock and local epidemiological context. This conceptual framework presented here should be the basis for the development of integrated models, for testing and optimizing tools for collective control of animal diseases. The implementation of this framework for diseases of interest is an important research issue in the field of animal health economics. The coupling of economics and epidemiology can found another application for externalities due to asymptomatic carrying of pathogens. In this latter case, the externality affects the transformer who can be interested in the management of the disease.

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Annex 1. Calculation of expected income flow for each policy

Let P_t be the probability of a herd to be in state I at time t, and p be the probability of infection and q the probability of eradication.

$$P_t = P_{t-1} \cdot (1-q) + (1-P_{t-1}) \cdot p$$

Assuming a herd of status S at t=0 (so, I_0=0), we can derivate

$$P_t = p \cdot \frac{1+(1-p-q)^t}{p+q}$$

So, for the policy 1, we have

$$p = \beta \cdot I \qquad and \qquad q = \alpha$$

With I the prevalence at t=0.

The expected income at time t $\mathrm{E}(\pi_t|1)$ is given by

$$\mathrm{E}(\pi_t|1) = P_t \cdot \pi_I + (1-P_t) \cdot \pi_S$$

$$\mathrm{E}_1 = \sum_{t=0}^{\infty} (1+r)^{-t} \cdot \mathrm{E}(\pi_t|1)$$

$$\mathrm{E}_1 = \sum_{t=0}^{\infty} (1+r)^{-t} \cdot \left[\left(\pi_I \cdot \beta \cdot I \cdot \frac{1+(1-\beta \cdot I-\alpha)^t}{\beta \cdot I+\alpha}\right) + \left(\pi_S \cdot \left(1-\beta \cdot I \cdot \frac{1+(1-\beta \cdot I-\alpha)^t}{\beta \cdot I+\alpha}\right)\right)\right]$$

$$\mathrm{E}_1 = \frac{1+r}{r} \cdot \left(\pi_I \cdot \frac{\beta \cdot I}{\beta \cdot I+\alpha} + \pi_S \cdot \left(1-\frac{\beta \cdot I}{\beta \cdot I+\alpha}\right)\right) - \frac{1+r}{r+\beta \cdot I+\alpha} \cdot (\pi_s - \pi_I) \cdot \frac{\beta \cdot I}{\beta \cdot I+\alpha}$$

For policy 2, $p = \beta \cdot I \cdot \gamma$ and $q = \alpha$ and we replace π_S by $\pi_S + P_{bio}$

$$\mathrm{E}_2 = \frac{1+r}{r} \cdot \left(\pi_I \cdot \frac{\beta \cdot I \cdot \gamma}{\beta \cdot I \cdot \gamma+\alpha} + (\pi_S - P_{Bio}) \cdot \left(1-\frac{\beta \cdot I \cdot \gamma}{\beta \cdot I \cdot \gamma+\alpha}\right)\right) - \frac{1+r}{r+\beta \cdot I \cdot \gamma+\alpha} \cdot (\pi_s + P_{bio} - \pi_I) \cdot \frac{\beta \cdot I \cdot \gamma}{\beta \cdot I \cdot \gamma+\alpha}$$

For policy 3, we assume that when his herd is infected, farmer implements depopulation measure. So, at each time step, the expected income $\mathrm{E}(\pi_t|3)$is given by

$$\mathrm{E}(\pi_t|3) = \beta \cdot I \cdot (\pi_I - P_{dep}) + (1-\beta \cdot I) \cdot \pi_S$$

$$\mathrm{E}_3 = \sum_{t=0}^{\infty} (1+r)^{-t} \cdot [\beta \cdot I \cdot (\pi_I - P_{dep}) + (1-\beta \cdot I) \cdot \pi_S]$$

$$\mathrm{E}_3 = \frac{1+r}{r} \cdot [\beta \cdot I \cdot (\pi_I - P_{dep}) + (1-\beta \cdot I) \cdot \pi_S]$$

For policy 4, $p = \beta \cdot I \cdot \gamma$ and $q = \alpha$ and we replace π_S by $\pi_S + P_{bio}$

$$\mathrm{E}_4 = \frac{1+r}{r} \cdot [\beta \cdot I \cdot \gamma \cdot (\pi_I - P_{dep}) + (1-\beta \cdot I \cdot \gamma) \cdot (\pi_S - P_{Bio})]$$