Farmers' willingness to vaccinate against endemic animal diseases: A theoretical approach

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Abstract: The aim of this paper is to propose an analytical framework to explore farmers' vaccination decisions against endemic animal diseases. First, a theoretical model is developed to highlight how the characteristics of the vaccine influence the farmer's vaccination decisions over time and the resulting disease dynamics. Numerical simulations are then performed to illustrate the impacts of the different vaccine effectiveness parameters on these dynamics.

Keywords: Animal health economics, disease control, risk management, vaccination, model simulation

1. Introduction

Among the issues relating to livestock production, herd health management is of great concern for both farmers and policy makers. Herd health problems arise at different levels in the bovine sector. Thus, epidemic diseases (like Foot-and-Mouth Disease) are characterized by a low probability of occurrence but can have catastrophic consequences for the whole agricultural sector. On the other hand, endemic diseases (such as the Bovine Viral Diarrhoea virus – BVDv) also result in serious economic consequences for the bovine sector, since they are characterized at a local level by a relatively high probability of occurrence but are associated with more limited economic losses across herds. The management of epidemic diseases is generally driven by governments. For endemic diseases, farmers decide individually to control (or not) the disease, but because of the communicable nature of many of these diseases, externalities are likely to occur, implying a necessary collective management to control the spread or eradicate the disease. Various control strategies can be implemented to struggle endemic diseases. In the case of BVDv, an efficient and well-tried strategy is to test animals so as to determine their health status. This test, applied to a whole herd and scheduled regularly, provides an early detection of infected animals. Animals are generally culled when the infection is detected in order to stop the spread of the virus in the herd. This "test and cull" strategy can be easily implemented in dairy farms, where cows can be approached at each milking. However, vaccination remains useful and is the strategy adopted for suckling cows. Indeed, the control of livestock induces increased costs when animals are bred in grassland (distances, time consumption etc), leading some farmers to prefer vaccination for its lower cost and simplicity of implementation. Vaccination strategies can be voluntarily implemented by farmers in order to limit the probability of their herds getting infected as well as to reduce the severity of the disease in their herds. Depending on the local epidemiological context and on farmers' views, this vaccination strategy can be either accepted or rejected. As a consequence, a collective objective of reducing the prevalence (or eradication) of the disease in a given area is hardly reachable and highly dependent on individual disease control decisions. Thus, the epidemiological dynamics of such diseases greatly depends on farmers' individual disease control decisions.

Cattle breeding is a multiannual activity relying on intertemporal decisions and on long-run dynamic biological cycles (Chavas, 2000). Economic decisions at the farm level are generally the result of dynamic optimization processes, and the occurrence of an animal disease can largely and lastingly affect the herd dynamics as well as labor and capital dynamics, leading potentially to significant disruption on beef markets (Gohin *et al.*, 2013). However, the specific case of endemic diseases can be considered as a common risk faced by farmers. The occurrence of the disease at the farm level remains high over years, and within a year its presence/absence does affect the volume and price of the farm output but has no significant effect on the variations of the herd size, as endemic diseases are considered as manageable risks, from an economic point of view. Moreover, vaccination is a discrete and often yearly repeated decision.

The issue of vaccination decisions against endemic animal diseases has been rarely addressed in the animal health economics literature. In the case of Bovine Leukosis virus, management decisions have been proven to be linked to specific economic damages, but those various economic consequences are not the main drivers of farmers' decisions (Gramig *et al.*, 2010). This result provides information on the fact that farmers' behaviour may not only be driven by market incentives, but also by biological or medical ones. Nevertheless, this research does not establish any clear link between the evolution of the health status of a herd and the dynamics of vaccination adoption. The case of Johne's disease in dairy herds has also been studied in terms of epidemiological dynamics dependent on disease control decisions (Cho *et al.*, 2013). This research is focused on the collective control strategies, and highlights the different epidemiological effects of various control strategies in order to reduce the prevalence of Johne's disease. Adoption decisions are analyzed as disease control scenarios rather than in order to explain the fluctuations of the sanitary status of the herds. In a similar way, Rat-Aspert and Fourichon (2010) model the voluntary vaccination against BVDv and they highlight the incidence of economic trade-offs of farmers for vaccination within a SIR (Susceptible, Infected, Recovered) epidemiological model. In addition, the epidemiological status of a herd and the prevalence of a disease at a particular time in a farm are not only dependent on present and past individual actions, but also on neighbours' actions toward diseases. Indeed, each farmer's disease control decision gives rise to a positive externality as it has an incidence on the overall local level of prevalence of some diseases, leading to the fact that individual actions are interdependent: strategic substitutes in a farmer point of view, and strategic complements in an objective of collective management (Hennessy, 2007). Indeed, farmers may be under-encouraged to undertake disease control efforts as other farmers' actions already induce a lower probability of re-infection of their herds.

Those examples in the animal health economics literature all underline that a complex interplay between agricultural economics and epidemiology is at the center of concern on control strategies of endemic diseases. On the one hand, farmers' economic decisions are not only market-based, but also rely on biological and medical contexts. On the other hand, epidemiological dynamics is also greatly influenced by farmers' individual decisions (Rat-Aspert and Krebs, 2013).

Following these first developments in the economic literature on animal health management decisions in an evolving epidemiological context, our objective in this publication is to generalize previous economic works and to model farmers' individual vaccination decision at the farm level. In the case of diseases like BVDv, vaccination is a binary and yearly repeated decision, which depends i) on economic expected consequences of implementing vaccination, ii) on local epidemiological parameters, and iii) on specific characteristics of the vaccine. Following Gramig *et al.* (2010), we develop a theoretical model of adoption behaviour, insisting on the role of biological factors, with the objective to enhance both economic and epidemiological knowledge on disease dynamics and control strategies. Thanks to this model, epidemiological and risk dynamics are represented at the individual level, reflecting the dynamic impacts of vaccination decisions and the complex effect of past actions on current risk level and adoption decisions. In addition, we highlight the interdependent effects of individual decisions of vaccination, in order to reflect the existence of health decisions as strategic substitutes, as well as in order to give insights for a necessary collective action to reduce the disease prevalence. The overall objective of this research is to explicitly emphasize the interplay between economic decisions and epidemiological evolutions, and to build a bio-economic modeling framework in the purpose of coupling epidemiological and economic models for more realistic representations of the dynamics of endemic diseases.

2. Modelling framework

In this section we detail the economic and biological modelling assumptions taken into account in our farmer's vaccination decision model. In particular, we focus on the dynamic components of individual decision and on the complex interplay between production objectives and epidemiological dynamics.

2.1. Basic assumptions for the producer behaviour

Given our objective of understanding the trade-off between vaccinating or not vaccinating a beef cattle herd against an endemic disease (like BVDv), we first define the farmer's annual profit function as follows:

$$\pi_t = p_t.Q_t - v_t.H_t = p_t.f(H_t) - v_t.H_t \qquad \text{(Eq. 1)}$$

where p_t is the market price of the livestock output, $Q = f(H_t)$ is the quantity of output, H_t the size of the herd, and v_t the production cost per animal in the herd.

We acknowledge that this specification of the profit function is rather simplistic as the objective function of cattle producers generally consists in a dynamic optimization of their production and consumption levels, where decision variables include capital and investment level, labour allocation, evolution of the herd size, *etc*. But in the context of a vaccination decision against an endemic disease, we make the realistic assumption that each farmer is able to pursue his normal activity regardless of the presence or absence of the disease. In other words, we consider that the effect of the endemic disease, which is considered as a common risk at the farm level, is negligible in terms of variations of the overall size of the herd and on long-run investment decisions.

Basically, the presence of an endemic disease can be introduced in the profit function (Eq. 1) through a simplified damage function. The disease is characterized by a severity parameter γ_t, which represents a share of decrease in the output volume due to the effect of the disease on the herd. The higher the value of this parameter, the higher the severity of the disease. The disease is also characterized by a probability of re-infecting the herd α_t, which stands for the risk of being re-infected at time t. The higher the value of α_t, the higher the probability of re-infection. The severity γ_t of the disease can be viewed as an internal source of economic risk for the farmer, and the probability of occurrence α_t as an external one. As a consequence, the vaccination decision results from a trade-off, a comparison between alternative practices related to the characteristics of the disease and to the characteristics of the vaccine. This simplistic relation was previously used in animal health economics literature (see Rat-Aspert and Fourichon (2010), for example) but does not reflect the intrinsic dynamic nature of vaccination. If the assumption of comparison of alternative annual profit situations is realistic in the case of endemic diseases, the dynamic nature of disease probability deserves a particular specification to model the vaccination dynamics.

2.2. Risk dynamics, alternative decisions and the disease-dependent factors

Farmers face uncertainty when deciding whether to vaccinate or not to vaccinate their herds against an endemic disease. The starting assumption in our model is that the disease is already present in the herd at time $t - 1$ and that its presence induces production losses with a given severity γ_{t-1} ($\gamma_t \in [0; 1]$). At time t, the farmer knows the severity of the disease in the previous period, but he is not able to predict if the herd will be re-infected in the current period. However, we consider that the farmer is able to predict the extent of the worsening ψ of the severity of the disease if the herd gets re-infected by the disease at time t. In other words, each farmer has perfect information on the severity of the disease, so that at each time period the severity dynamics is:

$$\gamma_t = \begin{cases} \gamma_{t-1}.(1+\ \psi) & if\ D_t = 1 \\ \gamma_{t-1} & if\ D_t = 0 \end{cases} \tag{Eq. 2}$$

In addition, we assume that the farmer perfectly knows the specific characteristics of the vaccine. The vaccination cost per animal is w_t and the vaccination is assumed to be applied to the whole herd H_t, leading to an overall cost of vaccination for each farm is $w_t.H_t$. Moreover, the effectiveness parameters of the vaccine are also known: vaccination has a double effect of lowering the severity of the disease in a proportion φ ($\varphi \in [0; 1]$) while reducing the probability of re-infection of the herd in a proportion θ ($\theta \in [0; 1]$). The profit function for each farmer can then be expressed in two ways, depending on the farmer's vaccination decision V_t.

$$\pi_t = \begin{cases} p_t.(1-\gamma_t).f(H_t) - v_t.H_t & if\ V_t = 0 \\ p_t.(1-\gamma_t.(1-\varphi)).f(H_t) - v_t.H_t - w_t.H_t & if\ V_t = 1 \end{cases} \tag{Eq. 3}$$

To sum up, four distinct situations may be encountered and can be quantified by the farmer, related to the re-infection (or not) of the herd by the disease D_t and to the farmer's decision to vaccinate (or not) his herd V_t. Those situations all have different probabilities of occurrence depending on farmer's vaccination decision.

In terms of probability, the disease risk is noted α_t; this probability of disease evolves over time.

$$\alpha_t = \begin{cases} \alpha_{t-1} & if\ V_t = 0 \\ \alpha_{t-1}.(1-\theta) & if\ V_t = 1 \end{cases} \tag{Eq. 4}$$

Eq. 4 indicates that vaccination lowers the probability of re-infection of the herd in a proportion θ, and otherwise this probability is assumed to remain constant. This reflects the evolution of disease risk, and we assume that the farmer has perfect expectations on this current re-infection risk.

The dynamics of the disease severity and of the re-infection probability are conditional on farmer's vaccination decision, which is a binary choice and hinges on the relative levels of expected profits when the farmer adopts vaccination $E(\pi^{V=1})$ or not ($E(\pi^{V=0})$). The farmer will decide to vaccinate his herd when:

$$E(\pi^{V=1}) \geq E(\pi^{V=0}) \tag{Eq. 5}$$

More precisely, those two expected profits are determined *a priori* by the farmer and they can be written considering the expected probability of re-infection of the herd. The expected profit of non-vaccination is:

$$\begin{aligned} E(\pi^{V=0}) = \quad & (1-\alpha_{t-1}).[p_t.(1-\gamma_{t-1}).f(H_t) - v_t.H_t] \\ & +\alpha_{t-1}.\left[p_t.\left(1-\gamma_{t-1}.(1+\ \psi)\right).f(H_t) - v_t.H_t\right] \end{aligned} \tag{Eq. 6}$$

On the other hand, the expected profit of vaccination is built in a similar way.

$$\begin{aligned} E(\pi^{V=1}) = \quad & \left(1-\alpha_{t-1}.(1-\theta)\right).[p_t.(1-\gamma_{t-1}.(1-\varphi)).f(H_t) - v_t.H_t - w_t.H_t] \\ & +\alpha_{t-1}.(1-\theta).[p_t.(1-\gamma_{t-1}.(1+\psi).(1-\varphi)).f(H_t) - v_t.H_t - w_t.H_t] \end{aligned} \quad \text{(Eq. 7)}$$

Eq. 7 can also be rewritten as follows :

$$E(\pi^{V=1}) = E(\pi^{V=0}) - w_t.H_t + \gamma_{t-1}.p_t.f(H_t).\left(\varphi + \alpha_{t-1}.\psi.(\varphi + \theta - \varphi\theta)\right) \quad \text{(Eq. 8)}$$

This simplified expression allows us to rewrite Eq. 5 as a relation between the vaccination costs and the potential benefit of vaccination.

$$w_t.H_t \leq \gamma_{t-1}.p_t.f(H_t).\left(\varphi + \alpha_{t-1}.\psi.(\varphi + \theta - \varphi\theta)\right) \quad \text{(Eq. 9)}$$

In Eq. 9, the trade-off between vaccination and non-vaccination is clearly expressed as a threshold cost of vaccination. Vaccination is choosen as long as its cost does not exceed the cost of the disease at time $t-1$ (at severity γ_{t-1}) multiplied by an expression mixing its past probability of occurrence (α_{t-1}), the increase in severity of the disease when the herds becomes infected, and the effects of the vaccine on the severity of the disease and on the probability of re-infection of the herd.

This bio-economic model integrates both economic components and epidemiological ones, and it allows for risk dynamics depending on the evolution of the epidemiological context. The re-infection of the herd is an uncertain event, and the on-farm level of disease can only be smoothed through preventive/curative methods, like vaccination in the case of BVD. The analytical model built here focuses on individual decisions and on basic epidemiological assumptions. Improvements of this model can enhance knowledge on the dynamics of vaccination decision, by including long-run choices and interdependent actions of farmers within a geographic area.

2.3. Lasting effects of vaccination and incidence of collective action

In the model developed in the previous subsection, we considered that the effectiveness of vaccination only last one period. Indeed, Eq. 2 states that the evolution of the severity of the disease only depends on the possibility of re-infection of the herd, and not on farmer's previous vaccination decisions. In reality, and especially concerning endemic diseases like BVD, a herd vaccination at time t is not only beneficial for the current period, but it also leads to a persistence of the immunity of the herd on the long run, mainly the following year ($t+1$). One the other hand, a non-vaccination decision induces a lowering of the immunity of the herd, meaning that the herd is more sensitive to the disease if it has not been immunized by the vaccination the year before. Following this statement, Eq. 2 can be rewritten as follows:

$$\gamma_t = \begin{cases} if\ V_{t-1} = 0 & \begin{cases} if\ D_t = 0 & \gamma_{t-1}.(1+\rho) \\ if\ D_t = 1 & \gamma_{t-1}.(1+\rho).(1+\psi) \end{cases} \\ if\ V_{t-1} = 1 & \begin{cases} if\ D_t = 0 & \gamma_{t-1}.(1-\varphi') \\ if\ D_t = 1 & \gamma_{t-1}.(1-\varphi').(1+\psi) \end{cases} \end{cases} \quad \text{(Eq. 10)}$$

where ρ ($\rho \in [0;1]$) represents the increase in severity of the disease at time t due to the absence of vaccination at time $t-1$ *i.e.* the growing naivety of the herd to the disease, and φ' ($\varphi' \in [0;1]$) is the persistent effect of vaccination on the immunization of the herd. This complex expression of disease severity conditional on past individual actions does not fundamentally change the form of the equations defining the farmer's decision (Eq. 5 to 9), but as it allows for lasting effects of vaccination/non-vaccination, it influences both the epidemiological dynamics and the health decisions.

In addition, the model is focused on individual decisions. However, as stated by Hennessy (2007), within a geographic area all individual health actions/inactions induce positive/negative externalities for neighbouring farms. In order to reflect the positive externality of vaccination, Eq. 4 can be modified as follows:

$$\alpha_t = \begin{cases} \alpha_{t-1}.\left(1-\beta.\frac{N_t^v}{N}\right) & if\ V_t = 0 \\ \alpha_{t-1}.(1-\theta).\left(1-\beta.\frac{N_t^v}{N}\right) & if\ V_t = 1 \end{cases} \qquad \text{(Eq. 11)}$$

where N is the total number of farms in the area, N_t^v represents the number of vaccinating farms at time t and β is a parameter ($\beta \in [0;1]$) standing for the influence of others vaccinating on individual probability of getting re-infected. In an animal health management perspective, this relation aims at highlighting the crucial importance of collective action in order to reduce the prevalence of endemic diseases.

3. Simulations

In this section, we simulate the dynamics of an endemic livestock disease resulting from the farmer's participation/non participation in a voluntary vaccination program. We consider a representative suckling farm, whose characteristics are the following:

Parameter	Value	Description
p	2000	Output price (€)
v	1400	Production cost (€ per animal)
w	15	Vaccination cost (€ par animal)
$Q = f(H)$	90	Quantity of output
H	90	Herd size

These parameters are representative of the structure of suckling farms in the French bovine sector (Institut de l'Elevage, 2012). We assume that the value of these parameters remain constant over time. The disease considered in the simulations is a standard endemic one, characterized by a relatively high initial probability of re-infection of the herd ($\alpha_0 = 0.5$) and by a relatively low initial level of severity ($\gamma_0 = 0.2$). At each simulation period, if the herd gets re-infected, the severity of the disease increases in a proportion $\psi = 0.05$ (invariant over time).

The model is simulated 1000 times, over a 50 year horizon. Simulated farms only differ in terms of actual re-infection, which is modelled as a random event so that for each period farmers make their expectations upon an uncertain event. Vaccination is allowed from the first period of simulation.

The results of the simulations are presented below. As the multiple effects of both the epidemiologic situation and the vaccination have a rather complex influence on the farmer's decision, we disentangle those effects by analyzing sequentially the specific consequences of the different vaccination parameters on the farmer's vaccination decisions.

3.1. Behaviour when vaccination is only effective in the current period

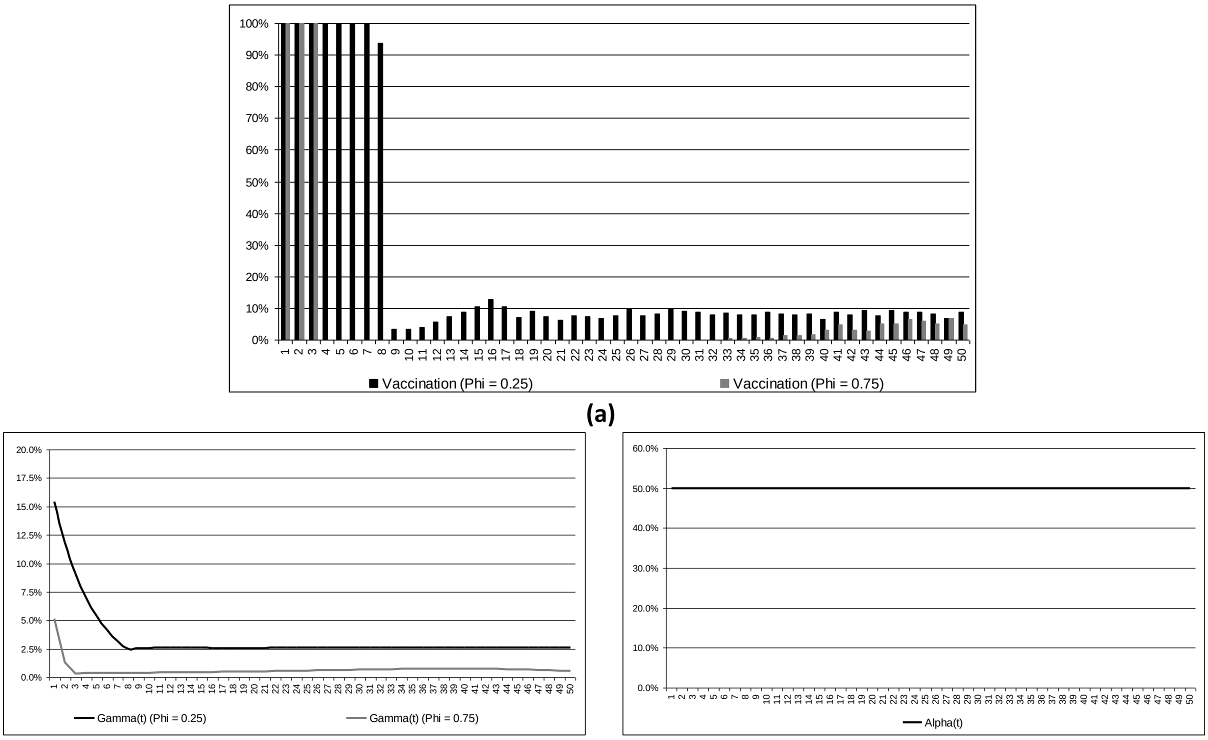
In this first subsection we consider the basic case of our model, where the vaccination has no persistent effects on the immune status of the herd. In this section we aim at evidencing the way the farmer’s decision is influenced by the primary characteristics of the vaccine.

- **Vaccination has no impact on the current risk of re-infection**

In this first setting, we assume that vaccination plays a role in lowering the severity of the disease ($\varphi > 0$), but has no incidence on the probability of re-infection ($\theta = 0$). Thus, by vaccinating his herd, the farmer only decreases the severity of the disease (*i.e.* he minimizes his output losses by lowering γ_t). He decides to vaccinate (at the current time period) as long as the observed (past) severity of the disease exceeds a vaccination threshold such that:

$$\gamma_{t-1} \geq \frac{w_t.H_t}{p_t.f(H_t).(\varphi + \alpha_0.\psi.\varphi)} \tag{Eq. 12}$$

This threshold ratio (right side of Eq. 12) remains constant over time. Vaccination induces a lower severity until this strategy become unprofitable compared to non-vaccination. The farmer faces a (constant) external risk of re-infection, and vaccination starts again when γ_{t-1} grows back above this fixed vaccination threshold.



(a)

(b)

(c)

Figure 1. Evolution (a) in the proportion of vaccinating herds, (b) in the severity of the disease, (c) and in the probability of re-infection of the herd

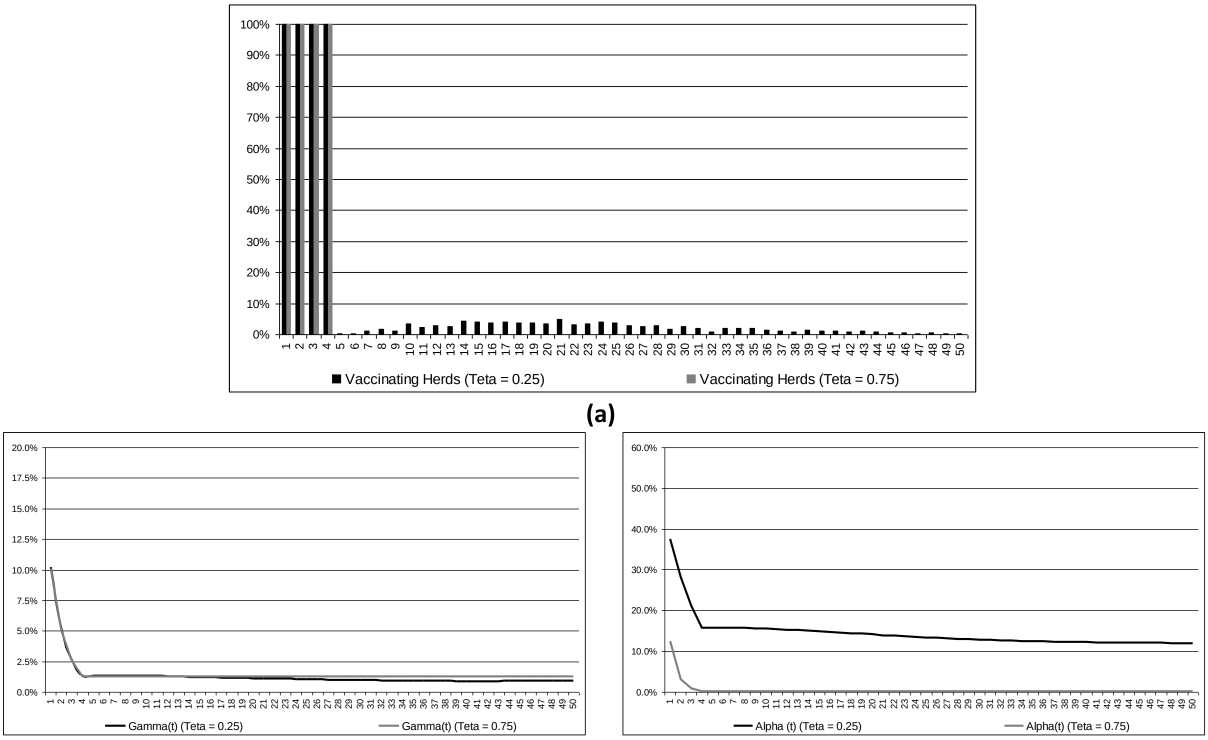
Figure 1 shows that the effectiveness of vaccination logically influences the length of the initial vaccination period. For a relatively moderate effectiveness of vaccination on the reduction of severity of the disease ($\varphi = 0.25$), eight time periods are necessary to lower its impact until vaccination is considered as less profitable than dealing with the disease. On the contrary, a relatively high efficiency ($\varphi = 0.75$) obviously allows farmers for a shorter period of vaccination (3 time periods). In addition, a lower effectiveness of vaccination induces a higher average level of severity, causing sporadic vaccination decisions when the herds are re-infected by the disease.

- **Effect of vaccination on the external risk of infection**

We now consider a non-trivial effect of the vaccination on the probability of re-emergence of the disease in the herd ($\theta > 0$). The consequence of this effect is that the probability of being re-infected varies over time, and depends on farmer's vaccination decision. As a consequence, one can consider that in the farmer's point of view, the observed severity threshold of vaccination becomes dynamic. Eq. 12 can be rewritten as follows:

$$\gamma_{t-1} \geq \frac{w_t . H_t}{p_t . f(H_t) . \left(\varphi + \alpha_{t-1} . \psi . \left(\varphi + \theta(1-\varphi)\right)\right)} \qquad \text{(Eq. 13)}$$

The probability of being re-infected α_t decreases over time as long as the farmer decides to vaccinate, so that mechanically the vaccination threshold is raised by the decrease of α_t.



(a)

(b) (c)

Figure 2. Evolution (a) in the proportion of vaccinating herds, (b) in the severity of the disease, (c) and in the probability of re-infection of the herd ($\varphi = 0.5$)

Simulation results (*Figure 2*) show that in the long run, for a given severity effect of vaccination ($\varphi = 0.5$), the greater its impact on the reduction of the probability of re-infection (θ) increases, the lower the probability of re-infection. As a logical consequence, in such a vaccination context, farmers tend to massively decide to vaccinate during the first periods of simulation until the probability of re-infection is very low, and then they pursue their usual activity on the long run with no vaccination. Sporadic vaccination occurs when anindividual herd becomes re-infected.

One interesting result of this simulation is that on the long run, the average severity of the disease tends to be greater when θ is high than when it is low. Indeed, after first years of vaccination to reduce the expected and observed losses, farmers consider that the threshold severity has to be greater than initially to decide to re-vaccinate the herd. As the probability of being re-infected lowers, farmers deal with a higher level of losses if the herd becomes re-infected.

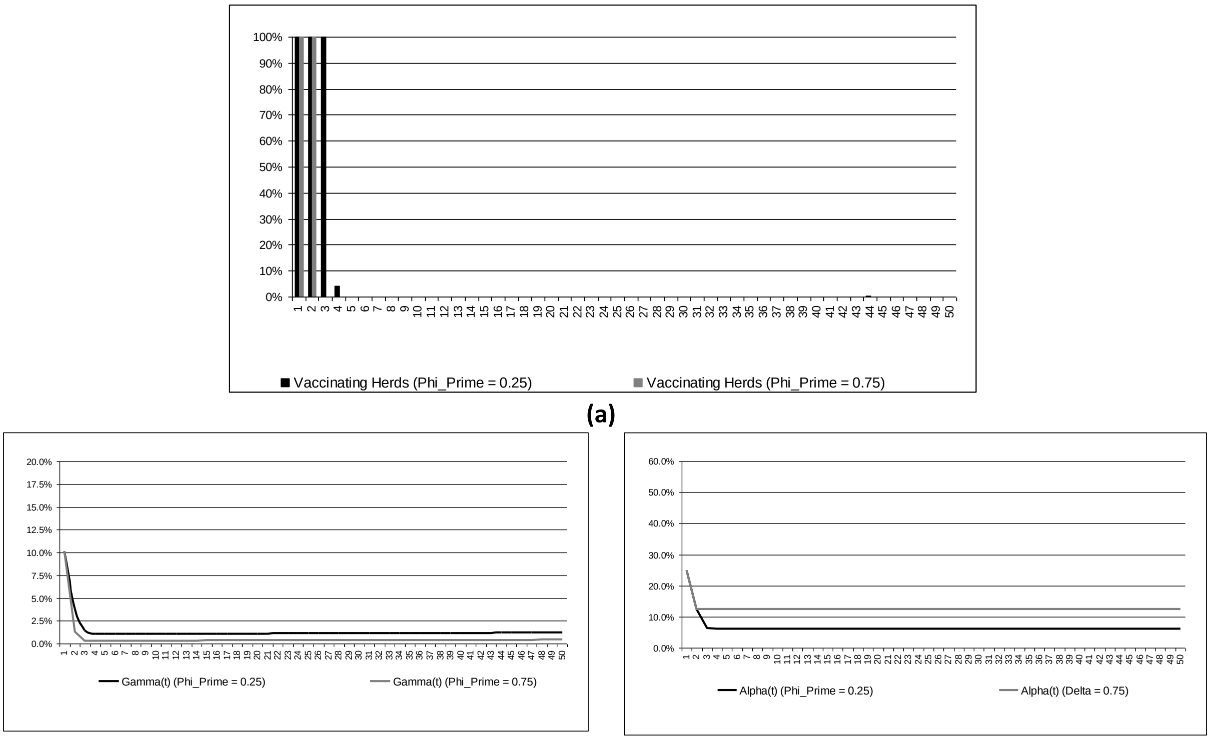
3.2. Past decisions drive the current re-infection risk

As explained previously in this paper, one major issue about annual vaccination against endemic diseases is that it may not only be effective immediately (*i.e.* the year of vaccination) but also have some persistent effects on the immune status of the herd the following year. The counterpoint is that non-vaccination tends to increase on long run the herd naivety to the disease as the immune status of the herd decreases, allowing the pathogen to spread again within the herd.

- **Persistent effects of vaccination on the reduction of the severity of the disease**

When vaccinating one year against an endemic disease, one can rely on a residual effect of vaccination the following year. This assumption is motivated by the fact that the herd acquires immunity, which decreases over time but may still be significant after one year. Formally, the persistence of this positive effect of the vaccination induces a discouragement of farmers for vaccinating anew.

These persistent effects cause an acceleration in the decrease of the disease severity compared to the previously discussed situation (only immediate effects of the vaccine). The possibility offered to farmers to vaccinate causes a long-run lowering of the average severity of the disease, and due to this reduced economic losses, re-vaccination occurs very rarely.



(a)

(b)

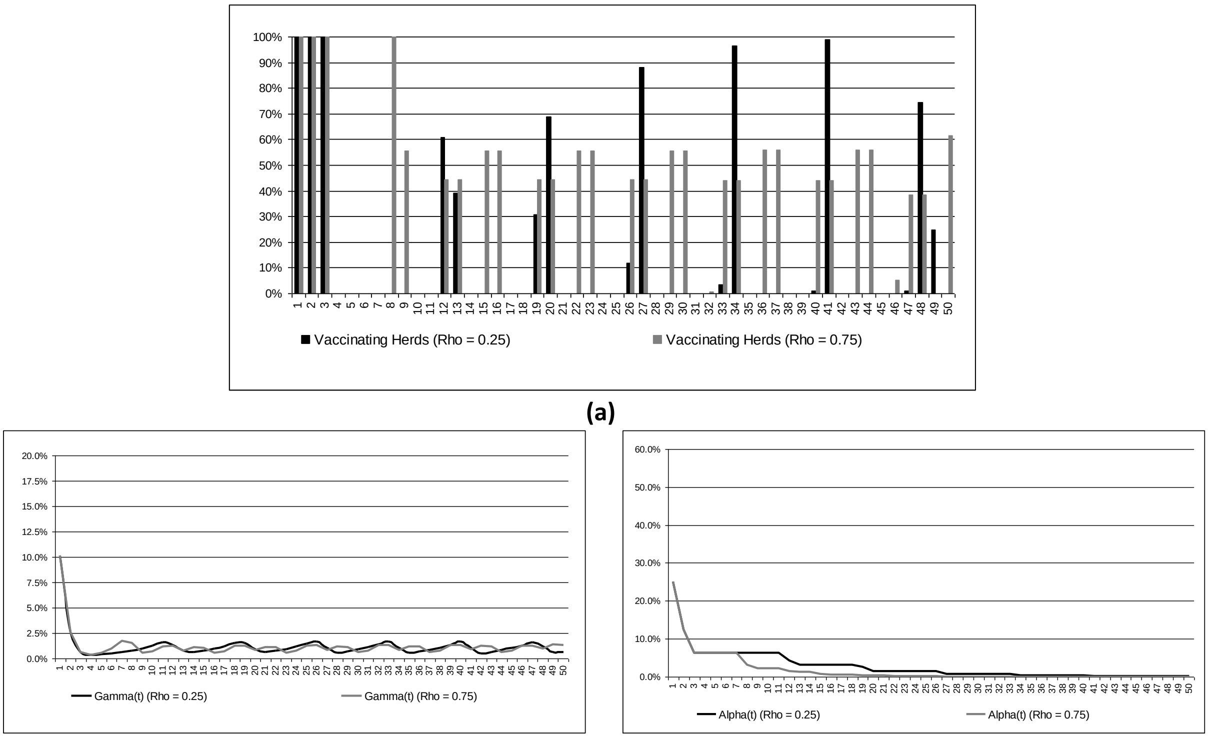
(c)

Figure 3. Evolution (a) in the proportion of vaccinating herds, (b) in the severity of the disease, (c) and in the probability of re-infection of the herd ($\varphi = 0.5$, $\theta = 0.5$)

As shown in *Figure 3*, if the severity effect of vaccination is moderate (*e.g.* $\varphi' = 0.25$), the severity of the disease tends to reach a higher level than if the vaccine has a stronger persistence (*e.g.* $\varphi' = 0.75$). However, the probability of re-infection remains greater when the persistence of the effects of the vaccine is high, because the length of the initial vaccination period was shorter and thus induced a lower decrease of the probability of re-infection.

- **Loss of herd immunity due to non-vaccination**

A non vaccination decision causes a reduction of the herd’s immunity in the following year. The pathogen is then likely to spread again within the herd, leading to an increase in the losses induced by the disease, even in the absence of re-infection. When the herd becomes re-infected, due to the reduced herd immunity, the consequences of a re-infection in terms of severity of the disease tend also to become more important. These persistent negative effects of non vaccination play a positive role on the re-vaccination decisions.



(a)

(b) (c)

Figure 4. Evolution (a) in the proportion of vaccinating herds, (b) in the severity of the disease, (c) and in the probability of re-infection of the herd ($\varphi = 0.5$, $\theta = 0.5$, $\varphi' = 0.5$)

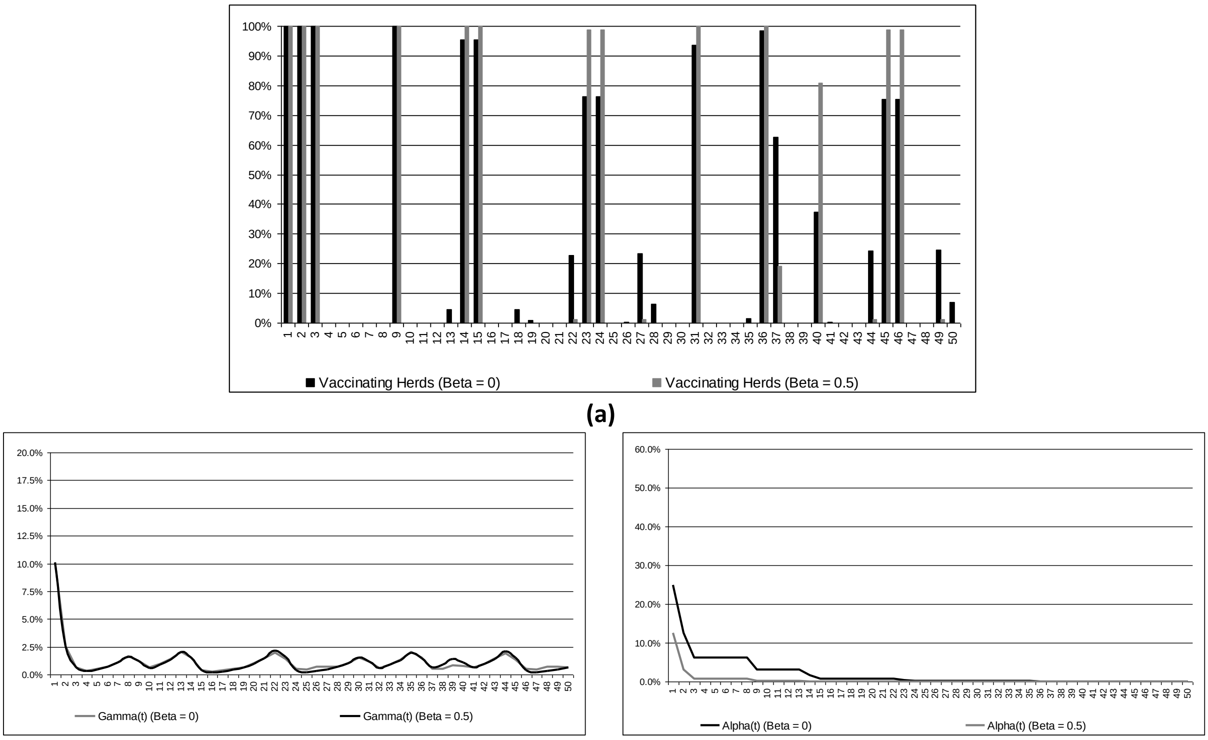
As observed in *Figure 4*, simulated results exhibit that once the severity of the disease has decreased below the vaccination threshold, the vaccination strategy is not adopted any more (after 3 periods). Non-vaccination leads to the re-circulation of the pathogen within the herd, inducing an increase in the average severity of the disease. The vaccination threshold is then reaches again, and the farmer decides to re-vaccinate his herd. We can thus observe fluctuations in the severity of the disease over time.

The evolutions observed for the probability of re-infection are also specific, since we can observe a stepwise decrease of this probability over time. This illustrates the cumulative beneficial effects of successive vaccination campaigns, reducing lastingly the external risk of becoming re-infected.

In addition, one can notice that the higher the permanent negative effects of non-vaccination are, the shorter the cycle in the severity of the disease becomes (inducing more frequent vaccination campaigns), and the faster the reduction of the probability of re-infection occurs.

3.3. The interdependent actions of farmers in collective management of endemic diseases

On can rely on the fact that at the individual level, the disease probability is driven not only by the farmer’s own decisions, but also by other farmers’ ones. Thus, one can reasonably consider that within a small region, the individual probability of re-infection is lowered when a high proportion of farmers in the region decide to vaccinate their own herd.



(a)

(b) **(c)**

Figure 5. Evolution (a) in the proportion of vaccinating herds, (b) in the severity of the disease, (c) and in the probability of re-infection of the herd ($\varphi = 0.5$, $\theta = 0.5$, $\varphi' = 0.5$, $\rho = 0.5$)

The model developed in this paper can be used to illustrate this phenomenon. We consider that the 1000 simulated herds are constitutive of a small geographic area, and that the probability of re-infection is linked to the proportion of herds in which vaccination is implemented at the current period.

Figure 5 shows that on average, the results observed follow the same trend than the one described in the previous subsection for the evolutions over time of the proportion of vaccinating herds and the severity of the disease. The main difference lies in the fact that the impact of vaccination on the probability of re-infection is stronger when considering the between-herd component. This latter result demonstrates the primordial importance of the large implication of farmers in the collective management of endemic diseases.

4. Conclusion

The dynamics of endemic livestock diseases is highly dependent on both epidemiologic variables as economic ones. In this publication, we developed an analytical theoretical framework aiming at assessing the dynamics of agricultural decisions towards vaccination against endemic diseases. Preliminary results of this simplified model permits to highlight various behavioral types towards vaccination as functions of the effectiveness parameters of the vaccine, and we assess their resulting implications in terms of disease dynamics in the herds. One main objective of this paper is to be part of an integrated epidemiological-economic model. Epidemiological usually omit farmers' decisions and disease control is commonly defined as an exogenous component. The purpose of our model is to transform production choices as endogenous outputs of a coupled model, so as to take the choice dynamics into account in order to better reflect the evolutions of any epidemiological context of endemic livestock disease.

A first application is to model the control of BVD for suckling herds. In this bio-economic research, the next research step will include a more realistic specification of the agricultural supply. Indeed, even if our model already gives useful insights, an analysis of other decision variables like labor and capital (and any of their respective constraints) will help improve knowledge on economic determinants of health control strategies. A detailed herd structure and dynamics will also better display the productive conditions and the specific health actions manageable for various categories of cattle (e.g. calves, heifers, cows). From an epidemiological point of view, endemic diseases often have different effects on those categories.

This paper draws the basis for research of optimal management policies against endemic diseases. It must be viewed as only a first step in the analysis of the biological and economic determinants and constraints concerning curative health decisions at the farm level. Recent agricultural research already drew some bases about risk aversion and loss aversion (Bocquého et al, 2013). The management of endemic diseases is obviously dependent on their specific probabilities of occurrence as well as the potential losses they induce, which in turn strongly defines the farmer's behaviour for their control. The design of individual behaviours under loss aversion may also highlight various decision processes over different reference points in decision making. It may help enhance knowledge on non-optimal Nash equilibriums when heterogeneous farmers are involved. In addition, Mahul and Gohin (1999) showed a possible gain from waiting about the virulence of FMD before public action when the probability of the disease is not too high. In the case of transmissible endemic diseases, an application at the farm level may give new insights on the dynamics of disease control. Those extensions of research will surely help design optimal management policies and enhance knowledge on microeconomic agricultural behavior.

References

Bocquého. G.; Jacquet. F.; Reynaud. A. (2013). Expected utility or prospect theory maximisers? Assessing farmer's risk behaviour from field experiment data, *European Review of Agricultural Economics*, in press, 1-38.

Chavas, J.P. (2000). On information and market dynamics: The case of the U.S. beef market, *Journal of Economic Dynamics and Control*, 24: 833-853.

Cho, J.; Tauer, L.W.; Schukken, Y.H.; Smith, R.L.; Lu, Z.; Grohn, Y.T. (2013). Cost Effective Control Strategies for Johne's Disease in Dairy Herds, *Canadian Journal of Agricultural Economics*, 61: 583-608**.**

Gohin, A.; Cordier, J.; Krebs, S.; Rault, A. (2013). Dynamic Impacts of a Catastrophic Production Event: The Foot-and-Mouth Disease Case, *Risk Analysis*, 33: 480-492.

Gramig, B.M.; Wolf, C.A.; Lupi, F. (2010). Understanding Adoption of Livestock Health Management Practices: The Case of Bovine Leukosis Virus, *Canadian Journal of Agricultural Economics*, 58: 343-360.

Hennessy, D.A. (2007). Biosecurity and Spread of an Infectious Animal Disease, *American Journal of Agricultural Economics*, 89: 1226-1231.

Institut de l'Elevage (2012). *Résultats 2010 des exploitations bovins viande. Estimation des revenus pour 2011. Résultats nationaux*.

Mahul, O., Gohin, A. (1999). Irreversible decision making in contagious animal disease control under uncertainty: an illustration using FMD in Brittany, *European Review of Agricultural Economics*, 26 (1), 1-38.

Rat-Aspert, O.; Fourichon, C. (2010). Modelling collective effectiveness of voluntary vaccination with and without incentives, *Preventive Veterinary Medicine*, 93: 265-75.

Rat-Aspert, O.; Krebs, S. (2013). Économie des actions collectives de maîtrise des maladies animales endémiques : Proposition d'un cadre d'analyse [Collective management of communicable endemic animal diseases: developing a bio-economic framework], *Economie rurale*, 338: 47-59.

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