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JURY

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Introduction

This thesis is an effort to improve the way economic analysis is conducted in the fields of animal health (chapters 1 and 2) and risk communication (chapter 3). My interest relies on the evaluation of policies taking into account the heterogeneity of agents affected by the policy, but also highlighting the importance of the structure of a market or community and the way members of the community interact among them.

In the field of animal health, I am interested in the evaluation and design of optimal strategies to control infectious diseases. When looking at the existing literature, I realized that there was the need to evaluate the costs associated to the implementation of movement restrictions when trying to control the spread of an infectious disease. Although movement standstills are the main control strategy when a vaccine has not been developed, there was no serious evaluation of the costs and benefits associated with such policy.

Chapter 1, *Cost assessment of the movement restriction policy in France during the 2006 bluetongue virus episode (BTV-8)*, aims at evaluating the costs of the movement restriction policy (MRP) during the 2006 BTV-8 epidemic in France for the producers of 6- 9 month old charolais beef weaned calves (BWC). The producers of BWC represent an important sector of the French beef industry and they can be severely affected by movement standstills. In this chapter, I estimate the change in the number of BWC sold that was due to the movement restrictions using a multivariate matching approach, and I evaluate the economic effect of the MRP based on several scenarios that describe farms' capacity constraints, feeding prices, and the animal's selling price. The economic evaluation of the MRP shows a potential gain during the movement standstill period, but only for a scenario with no capacity constraints and food self-sufficiency. This gain remains limited and close to zero in case of a low selling price and when animals are held until they no longer fit the BWC market so that they cannot be sold as an intermediate product.

Capacity constraints represent a tremendous challenge to farmers facing movement restrictions and the fattening profit becomes negative under such conditions. The timing and length of the movement standstill period significantly affect the profitability of the strategy employed by the farmer.

These results should be useful for decision-makers who seek to calculate adequate subsidies/aid or to efficiently allocate resources to prevent future outbreaks. Moreover, the results of the first chapter are helpful to understand that farmers can change their strategy when facing the implementation of a movement standstill mainly because of the costs associated to the inability to move their animals. By changing their timing decision to sell they can avoid the costs associated to the standstill and maximize their gains. Ignoring that farmers adapt their behavior when a control policy is implemented can significantly bias the estimated benefits of such policy. These ideas worked as a motivation for the next chapter.

In chapter 2, *The impact of farmers' strategic behavior on the spread of animal infectious diseases*, a two-period economic model is proposed to understand the incentives and constraints that shape the farmers' decision to sell their animals. The strategic behavior of farmers is incorporated into a susceptible-infected epidemiologic model at the farm-level, such that the MRP can trigger premature sales of high-risk farms that significantly reduce the efficacy of the policy. The outcome of the MRP is estimated in a parameterized network via Monte Carlo simulations under different scenarios to quantify the effect of the anticipation effects. The economic model presented in this chapter, allows to identify the relevant variables associated with the behavioral response of farmers to the MRP and provide the arguments to justify financial aid to farmers by public health concerns and not only for equity.

When looking at the determinants of the heterogeneity of outcomes of the MRP, it is found that the dealers and livestock markets play very important role for the spread of an infectious disease. They work as amplifiers since they are involved in trading activities almost every single week and they have transactions with a large number of farms. Therefore, once a dealer or a market is infected, the disease can spread very fast to the rest of the agents involved in the livestock industry and the control of an epidemic becomes very difficult.

Just as in the livestock markets the infection of agents with a large number of connections are determinant for a fast spread of an infectious disease, in a community setting, agents that have great exposure with the rest of the community members can be used to diffuse a message as fast as possible. In chapter 3, *Taking advantage of diffusion effects in a network to increase the effectiveness of risk communication*, a model using social network tools is introduced to analyze the effectiveness of different risk communication strategies under budget constraints. When the structure of the network describing the links between the members in a community is at least partially known, diffusion effects can be exploited to more effectively communicate about a risk and the ways it may be mitigated. By directing communication to specific targets, accurate risk perceptions are achieved faster and for a larger share of the population than in a generalized random communication framework.

The overestimation of risks in a community can lead to the wasteful or counterproductive behavior intended to reduce the perceived risk. Therefore, increases in the effectiveness when communicating a risk can lead to improvements of the social welfare. At the end of the chapter the benefits of specific targeting are illustrated by an application to the health risks of consuming tap water in Nogales, AZ.

On the one hand, this thesis contains an empirical component that estimates the costs associated with the movement standstill in France during the 2006 bluetongue virus (BTV-8) outbreak. On the other hand, the theoretical content of this thesis try to provide new insights regarding two different questions: First, how the behavior of farmers can be incorporated into an epidemiological model to understand the effect of changes in the farmers' strategy on the benefits derived from the implementation of movement standstills; and second, how to improve the outcome of a risk communication campaign by specific targeting when the information can be transmitted among the members of a community. Therefore, this thesis ends up being a mix of empirical and theoretical contributions that put in perspective the relevance of economics in the analysis of problems where heterogeneity and the structure of the interaction networks play an important role.

As a result of enriching discussions with veterinarians and health scientists, the scope of this thesis extends from the field of economics to those of animal and human health. It is a contribution to the increasing efforts of conducting interdisciplinary research and to the design of methods to analyze problems in the field of animal health and risk communication with a more integral approach.

Chapter 1

Cost assessment of the movement restriction policy in France during the 2006 bluetongue virus episode (BTV-8)

Cost assessment of the movement restriction policy in France during the 2006 bluetongue virus episode (BTV-8)[*]

Abstract

This study aims at evaluating the costs of the movement restriction policy (MRP) during the 2006 BTV-8 epidemic in France for the producers of 6- 9 month old Charolais beef weaned calves (BWC), an important sector that was severely affected by the restrictions imposed. This study estimates the change in the number of BWC sold that was due to the movement restrictions, and evaluates the economic effect of the MRP. The change in BWC sold by producers located inside the Restriction Zone (RZ) was analyzed for 2006 by using a multivariate matching approach to control for any internal validity threat. The economic evaluation of the MRP was based on several scenarios that describe farms' capacity constraints, feeding prices, and the animal's selling price. Altogether, the present work shows the farmer's vulnerability to animal movement restrictions and quantifies the costs of the standstill. The results should assist decision-makers who seek to calculate adequate subsidies/aid or to efficiently allocate resources to prevent future outbreaks.

Keywords: Bluetongue, control policy, cost, cattle.

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1. Introduction

Bluetongue is a vector borne disease transmitted by Culicoides biting midges, with 26 serotypes recognized worldwide and 9 in Europe (Maan et al., 2012). High genetic diversity of the virus, high variability of its pathogenicity and few cross reactions plus low cross protection among different serotypes are described (Saegerman et al., 2007). Unlike other Bluetongue Virus (BTV) outbreaks, the serotype 8 epizootic was characterized by being detected initially in the north of Europe, starting in the Netherlands. In 2006 the BTV-8 was detected in five countries: Germany, Belgium, the Netherlands, France and Luxemburg. The expansion of the virus continued during 2007, reaching other countries such as the United Kingdom, Spain, and Italy.

Clinical signs of the BTV-8 are much more frequent in sheep flocks than in cattle herds. BTV-8 infection leads to extra morbidity, mortality and abortions, and to a decrease in the performance of dairy units (Elbers et al., 2008; Dercksen et al., 2007; Perrin et al., 2010; Zanella et al., 2012). Subclinical consequences of BTV-8 infection, including a decrease in the conception rate, have also been reported (Le Mezec et al., 2010) and in some cases economic effects estimated. For instance, the gross profit margin for beef farms due to the BTV-8 is estimated to have decreased between 6.1% and 17.7% (Mounaix et al., 2010).

One of the main policies implemented at the European level to prevent expansion of an animal infectious disease is the Movement Restriction Policy (MRP). Since 2000, the basic strategy is based on strict movement controls on animals coming from infected zones (Directive 2000/75/EC). Three zones are delimited: the infected zone (IZ), defined by a 20 km radius around the infected holding; the protection zone (PZ), which includes the infected zone and a 100-km radius around the infected holding; and the surveillance zone (SZ), with a radius of 50 km beyond the PZ. Animal movements from or to the IZ are forbidden. Animals are banned from leaving the PZ during periods of vector activity and vaccination may be applied under certain conditions. Restrictions in the SZ are similar to those imposed in the PZ (except that vaccination is forbidden because it interferes with the surveillance program). The rest of the territory is classified as the unscathed zone (UZ), where no movement restrictions exist.

In 2003, with Commission Decision 2003/828/EC some exemptions to the exit ban for animals leaving the restriction zones were established. However, for France one of the requirements was that the animal must be vaccinated or originated from a vaccinated herd. This remained with slight changes (Commission Decision 2004/550/EC) until 2005 when the requirements for moving animals outside a restriction zone were homogenized among all Member States (Commission Decision 2005/393/EC). Since then, besides the movement of vaccinated animals or movements during periods of vector inactivity, derogations to the MRP could be granted to farmers protecting their animals from culicoides attacks through the use of insecticides (before and during their transportation) and presenting negative results on serological or PCR tests conducted twice (not less than 7 days apart).

The major economic impact on the trade of ruminants due to the restrictions on international movements has been recognized (Dal Pozzo et al., 2009; MacLachlan et al., 2006; Tabachnick et al., 2008). However, no formal cost assessment has been done regarding the MRP and the only published estimate (5% of the market value of the animal) comes from expert opinion (Fofana et al., 2009; Carrasco et al., 2010). In order to avoid the costs associated with movement restrictions at the national level, countries such as Switzerland and the Netherlands decided to homogenize the zoning. Swiss authorities declared the whole country a single restriction zone at an early stage of the epidemic (Häsler et al., 2012). In the Netherlands, one month after the epidemic started the country was divided into an Infected Perimeter and a Protection Zone, with no Unscathed Zone (Velthuis et al., 2010). In contrast, France maintained the zoning during the 2006 and 2007 BTV-8 epidemics.

The French cattle industry accounts for 20% and 33% of the European dairy and suckling cows, respectively. Most of the 4 million suckling calves are born in winter and spring, and 1.4 million animals (mainly males) are sold yearly as beef weaned calves (BWC) around 6-9 months old (more than 1,000 million euros of value). Most (66%) are sent abroad (Loirette-Baldit, 2008), with others sold to fattening units in France. Exports are defined here as BWC sold and sent out of France, either within or outside the EU. For these calving systems, MRP has a huge impact: timing for selling is crucial to fulfill contracts with fattening barns abroad, and farms have some limited stocking capacity, in particular during winter. The vulnerability of this sector to movement restrictions was clearly recognized by policy makers who granted millions of euros of specific aid to the sector (NS-DGPEI/SDEPA/N2008-4019), and made it the objective of the earliest derogations regarding the MRP (NS-DGAL/SDSPA/N2006-8244). Movements between zones of equivalent status of different Member States were not subjected to the ban so farmers in the RZ could move their animals to countries such as Belgium, Netherlands, and some parts of Germany. However, the absence of specialized fattening units on these countries translates to a very low demand for French BWC there. Moreover, although in theory this derogation allowed the movement of animals from the French RZ to Italy (the main destination of French BWC), Italian authorities imposed a ban on animals coming from any RZ, which was not lifted before February 2007.

French authorities have admitted they did not expect the disease spreading to evolve as it did, leading to an underestimation of the financial requirements to fight the BTV spreading for the following year (Bricq, 2008). The increasing occurrence of epidemics and the integration of multinational markets (Ihle et al., 2009) raise an urgent need to evaluate the costs and benefits of the control strategies, including MRP. Authorities need more tools and data to shape the most efficient controls and to determine the size of the aid that would compensate the producers for losses. The goal of this study is to assess the economic costs associated with the MRP for BWC farmers during the 2006 BTV-8 epidemic. First the impact of the MRP on the sales for 2006 is estimated, and second an economical evaluation of the cattle affected by the MRP is conducted.

2. Materials and Methods

Data

Data on the characteristics of animals and their movement were obtained from the French National Bovine Identification Database (BDNI), whose contents have been described in the literature (see, e.g., Raboisson et al., 2011). Briefly, this database contains routine records for individual farms and animals. All births, deaths, purchases and sales are recorded by date by farmers in the BDNI. Reporting is mandatory and official controls are frequently carried out with potentially high penalties coming from the loss of aid linked to the Common Agricultural Policies. All data were geo-located at the municipal level for the present analysis. There are more than 36,000 municipalities in France, with a mean area of 15 km². For this study, medium/large farms with BWC producers with yearly average sales of 20 animals or more in 2005 and 2006 were included. Charolais beef weaned calves producers are used for the entire analysis. This is by far the most representative breed for this sector (41% of the 1.4 million BWC in 2005). Separate analyses are needed for suckling cows and calves of different breeds, which are produced using different farming systems in other locations.

Several variables were computed with the National Bovine Identification Database: the number of BWC sold in 2005 (Sales05), the mortality rate in 2005 (MortRate05), the average age of animals at the time of sale in 2005 (AvgAgeSale05), the number of births in 2005 (Births05), and the number of BWC sold from September 1st until December 21st, 2005, (in 2006, the vector was declared inactive on December 21st.).The export share in 2005 (ExpSh05) was calculated as the ratio between the number of BWC exported and the total number of BWC sold, the presence of a fattening operation within the BWC farm (FatUnit05) was coded as a dummy variable equal to 1 if the farm had at least 6 fattening animals in 2005 (as in Raboisson et al., 2011) and the number of livestock units in 2005 (LU05) is used as a measure of size, where units are calculated as the number of animal-years corrected by the age of the animal (see Raboisson et al., 2011).

During the epidemic, the IP, PZ, and SZ were defined on a weekly basis by the authorities. In the present study, the zones were gathered into a unique Restriction Zone (RZ) due to data limitations. Municipalities never in the RZ were considered in the Unscathed Zone (UZ). During 2006, the evolution of the RZ was limited (Fig. 1), and the expansion from the beginning of the epidemic went from 14% (5,255) to 21% (7,704) of the 36,685 municipalities belonging to the RZ at the end of December (unchanged until August 2007). Farms that changed status from UZ to RZ during the period being analyzed were not considered in this study.

Data on prices were extracted from different sources. Beef weaned calves' prices, published by France Agrimer for two markets (Clermont and Dijon) were used. The category retained was chosen according the estimated weight of the animal. While the quality of the animal has also an impact on the price, for the entire analysis the quality was fixed at the U category (on the scale EUROP, E being the best), which corresponds to most of the cases in the market. Prices of medicines considered for the treatment of diseases are market prices extracted from the tariff list of Centravet (http://www.centravet.fr), a wholesale veterinary product cooperative in France. Finally, to compute the weekly feeding costs, market prices were extracted, mainly from grainwiz.com, an on-line database. The price of grass-fed was fixed at 0.02 euros per kg dry matter, since no market prices are available.

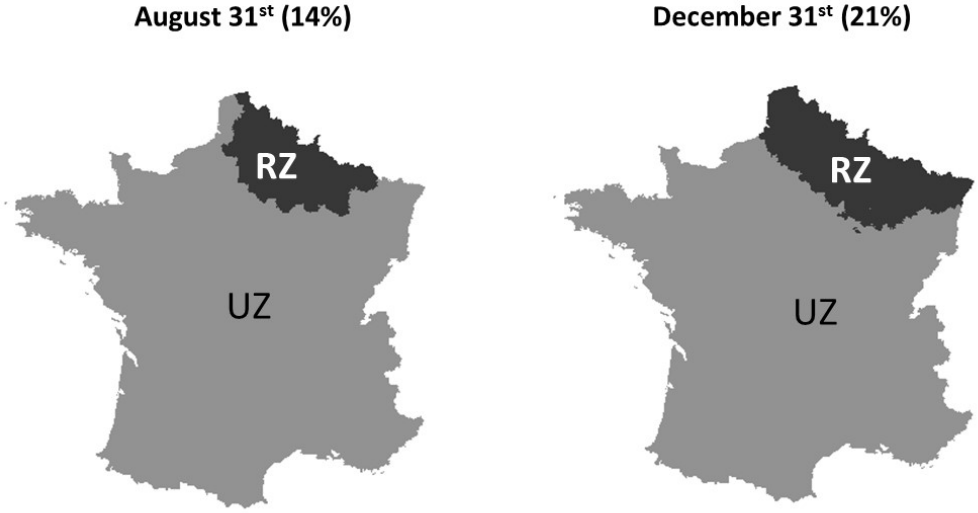

Fig. 1. Evolution of the Restriction Zone during 2006 in France due to the spread of the bluetongue virus. RZ = Restriction Zone, UZ=Unscathed Zone, 14% and 21% of the national municipalities were in the RZ in August and December, respectively.

Impact of the MRP on the sales of BWC

The MRP has an impact on sales because most French BWC are sold abroad or fattened in regions other than those where they were born, therefore a reduction in the sales of BWC coming from the RZ was expected. First this expectation was validated, and second it was quantified.

In the (first) validation step, each farm in the RZ is matched to a randomly selected control farm in the UZ using a single matching variable. Since a decrease in the sales of BWC coming from the RZ was expected in 2006 compared to 2005, the variable used for matching was the BWC accumulated sales from September to December 2005. This technique benefits from its simplicity and the fact that results do not depend on the specification of a regression model. For each farm in the RZ, n scores were constructed, where n represents the number of farms located at the UZ. Each score was constructed in the following way:

$$Score_{j\to i} = \left|Sales_j^{9-12(2005)} - Sales_i^{9-12(2005)}\right|$$

$$\forall j \in \{Farms\ in\ the\ UZ\}$$

$$\forall i \in \{Farms\ in\ the\ RZ\}$$

$$Sales_k^{9-12(2005)} = Number\ of\ animals\ sold\ from\ Sept\ 2005\ to\ Dec\ 2005\ by\ farm\ k$$

For each farm "i" in the RZ, the 100 farms with the lowest scores are chosen as the set of potential controls for farm "i" (PC_i). Note that there are as many PC sets as farms in the RZ (one PC set per farm) and a farm in the UZ could belong to more than one PC set. Finally, a random control group, of the same size as the set of farms in the RZ, is built by choosing randomly one farm from each PC_i. This last step is repeated 100 times, yielding 100 random control groups.

To illustrate the effect of the MRP on the sales of farms in the RZ, the change in sales from 2005 to 2006 was computed for two different periods: period 1 from January to August, and period 2 from September to December. The results of the farms located in the RZ were compared to those of the random control groups.

In the second step aiming at quantifying the MRP's effect, a more complex selection process involving multiple-variable matching techniques was performed. Estimating the magnitude of this effect requires controlling for internal validity threats that could bias the results. For example, the end of one major coupled subsidy for BWC in December 2005 had to be taken into account to compare the sales coming from farms in the RZ in 2006 to those in 2005. Such a subsidy, given to male BWC kept on farm from 7 to 9 month old, may have influenced farm practices, in particular age of selling (Ridier et al., 2002). The best possible control group was defined using several previously defined demographic variables for 2005, such as: Sales05, Sales(Sept 1st to Dec 21st), ExpSh05, FatUnit05, Births05, LU05, MortRate05, and AvgAgeSale05.

The matching strategies considered were nearest neighbor and optimal matching (see Stuart, 2010, for explanation of matching techniques). The matching estimator was obtained using data from September 1st to December 15th, 2005 (period with no MRP) and 2006 (period with MRP). To avoid endogeneity issues, the export shares correspond to the period from January 1st until August 31st of each year. The main regression tested was:

$$log(sales_{i,t}) \sim Y_{06} + RZ_i + (RZ_i * Y_{06}) + ExpSh_{i,t} + FatUnit_{i,t} + Births_{i,t} + Mort_{i,t} + LU_{i,t} + e_{i,t},$$

where $sales_{i,t}$ = Number of BWC sold by farm i from September 1st to December 15th, at year *t*.

Y_{06} = Dummy variable (equal to 1 if year = 2006).

RZ_i = Dummy variable (equal to 1 if farm i was located in the RZ in 2006).

$ExpSh_{i,t}$ = Export share of farm i from January 1^{st} until August 31^{st} of year t.

$FatUnit_{i,t}$ = Dummy variable (equal to 1 if farm i has a fattening unit at year t).

$Births_{i,t}$ = Number of born animals in farm i, during year t.

$Mort_{i,t}$ = Mortality rate of farm i, during the year t.

$LU_{i,t}$ = Livestock units of farm i, during year t (size of farm).

$e_{i,t}$ = error term.

This regression recovers the sales change attributable to the MRP through the estimated coefficient of regressor $(RZ_i * Y_{06})$, which identifies the change from 2005 to 2006 on the number of BWC sold by farms located in the RZ. Since in 2005 there was no movement restriction, the interaction between the regressors of the zone (RZ_i) and year effects (Y_{06}) allows us to quantify the MRP effect. Regressions taking into account the interaction effects of the ExpSh and FatUnit with Y_{06} and RZ were also tested. Results are presented for the sample average farmer.

Costs associated with the movement restriction

The economic evaluation of the movement standstill on cattle quantifies the costs and gains to farmers in the RZ who are unable to sell their animals at the normal time. It is based on the calibration of different scenarios taking into account market prices, length of the standstill period, and farmers' characteristics.

The scenarios consider marketable animals that cannot be moved due to the MRP. The average age, seven months, matches the average age of marketable BWC at the first week of September 2006. Marketable BWC are defined as between 158 and 365 days old, according to observed sales from September to December 2005 (range = mean +/- 2 standard deviations). Parameter values associated with animal growth are calibrated to characteristics of the Charolais breed, while the feeding costs take into account the provision of pasture grass for outdoor housing before November and a diet based on hay and concentrate (75% corn and 25% soybean meal). Feed provision increases as the animal's weight increases.

The animals affected by the standstill are considered to be sold as BWC in the main part of the study. If they do not fit the BWC market to fattening units, due to their old age and heavy weight, one possibility for farmers is to slaughter them and sell them as meat. This possibility is analyzed in the sensitivity analysis with a selling price based on the price of meat and a 60% factor for converting kg live weight (lwt) to kg of carcass.

Multiple scenarios were considered to estimate the costs associated with the MRP (see the appendix included as electronic supplementary material for a detailed description of how these costs are computed). Costs include feeding, housing, and other miscellaneous costs. Since the MRP took place during Autumn-Winter, it is assumed that (except for the Outside scenario) the animals are moved indoors in early November, which is associated with additional risks and costs. Farmers were assumed to have no housing capacity constraint (scenarios 1.1 to 1.3), or to face a limited capacity constraint that modifies their decisions (scenarios 2.1 to 2.3, and Outside scenario). In the absence of a capacity constraint, only the opportunity and operational costs associated with the building used for housing are considered (scenarios 1.2, and 1.3). This cost is computed as the yearly amortization of a fattening building based on the average cost of constructing a fattening barn with 25 years of useful life and zero residual value plus the associated costs due to waste stocking and straw requirements (Bruel et al., 2010). In the presence of a capacity constraint, a boarding facility is considered except for the Outside scenario, and the housing costs are calculated according to three potential scenarios. Scenario 2.1 assumes that farmers rent a building (paying twice the opportunity and operational cost of housing) and feed the cattle themselves (paying half the market cost of feeding). Scenario 2.2 is similar, except that feed is bought on the market. In scenario 2.3, farmers house the animals in a full-care boarding facility and pay twice the housing opportunity and operational costs, the market prices of food and labor costs. In general, no labor costs associated with the care of animals and management of the herd were included except for scenario 2.3. The Outside scenario assumed market feeding prices. The objective of modeling different scenarios is to provide policy makers with information about how the costs of the standstill depend on farmers' characteristics.

Keeping the animal longer induces additional preventive measures (vaccination against respiratory diseases and deworming) and increases the risks of morbidity and mortality, in particular during winter, when the animals are moved to indoor housing (Table 1). The costs related to mortality and morbidity refer to the market value of the animal at the time of moving to indoor housing and the cost of healing sick animals (anti-inflammatory and antibiotic medicines).

Table 1
Input data to estimate movement restriction policy (MRP) related costs in France (2006)

Input	Value	Description/source
Growth of animal		Charolais
Initial Age	210 days	Average age of marketable BWC at Sept 2006 for communes in the RZ (BDNI)
Initial Weight	275 kg	Weight associated with a 7-months-old
Indoor housing months	November to March	Estimate
BWC market prices (€/kg lwt)		
Initial Price (28/08/2006)	2.93	France Agrimer (Charolais - class U - 300kg)
Baseline (01/01/2007)	2.33	France Agrimer (Charolais - class U - 450kg)
Alternative (16/02/2007)	2.17	France Agrimer (Charolais - class U - 450kg)
Mortality		
Mortality risk associated	1%	Knight et al. (1976)
BWC market prices (€/kg lwt)		
Price (30/10/2006)	2.63	France Agrimer (Charolais – class U - 350kg)
Outside scenario		
Mortality risk associated	6%	Estimate
Morbidity		
Morbidity risk associated	15%	Assie et al. (2007)
Market prices (€/100kg lwt)		
Anti-inflammatory	5	Veterinary catalog (Centravet)
Draxxin	10.65	Veterinary catalog (Centravet)
Outside scenario		
Morbidity (initial risk, relapse1, relapse2)	(50%,25%,25%)	Estimate
Loss in market value after 2 relapses	10%	Estimate
Preventive medicine		
Market prices		
Respiratory vaccine (Rispoval 3) (€/calf)	7	Veterinary catalog (Centravet)
Deworming (Ivomec D) (€/100kg lwt)	1.8	Veterinary catalog (Centravet)
Feeding Costs		
Market prices (€/ton)		
Corn [min,MAX]	[75.25 , 124.98]	Grainwiz
Soja bean meal [min,MAX]	[111.42 , 156.98]	Grainwiz
Herb (dry matter)	20	Dudouet et al. (2010)
Hay (wrapping)	90	Dudouet et al. (2010)
Housing opportunity and operational		
Average cost of a building (€/animal)	1,425.6	GIE Elevage des Pays de la Loire
Years of amortization	25	GIE Elevage des Pays de la Loire
Residual value	0	
Monthly cost of waste stocking per animal	17.47	GIE Elevage des Pays de la Loire
Market price of straw (€/ton)	21.0	Estimate
Daily straw required per animal (kg)	5.5	GIE Elevage des Pays de la Loire
Boarding costs		
Rent of building	2*Housing op-op cost	Estimate
Feeding costs	Market prices	Grainwiz
Daily work for 100 heads (hours)	2	Estimate
Wage per hour (€)	21.4	Estimate
Carcass conversion		
Kg lwt to kg conversion factor	60%	Dudouet et al. (2010)
Market prices (€/kg)		
Baseline (01/01/2007)	3.42	France Agrimer - Charolais (Slaughter beef steers – class U)
Alternative (16/02/2007)	3.39	France Agrimer - Charolais (Slaughter beef steers – cat U)

Due to the adverse environmental conditions during winter, extra morbidity, mortality, and a decreased average daily gain were considered for the Outside scenario.

Two frameworks are considered. First, a baseline framework that includes the movement standstill costs accumulated up to the end of 2006. The baseline framework is relevant for calendar year budget planning by governmental agencies. Moreover, it covers the period of the vector's activity which was declared to be over on December 18th, 2006 (NS DGAL/SDSPA/N2006-8302) so it is associated with the lifting of some restrictions. Second, the alternative framework extends through February 16th, 2007 when Italy removed its ban for French cattle. This effectively ended most of the movement restrictions.

3. Results

Impact of the MRP on the sales of BWC

Figure 2 shows the differences in the number of animals sold between 2006 and 2005 for the farms in the RZ and the random control groups. The left-hand side corresponds to the pre-epidemic period which describes the sales during January-August 2006 minus the sales during January-August 2005. For this period, the sales evolved in a similar way for all the farms (with increases between 800 and 2,200 animals). However, during the epidemic period (represented on the right-hand side of the graph) the sales during September-December 2006 minus the sales during September-December 2005 showed that the random control groups clearly outperformed the farms located in the RZ. The average increase in the animals sold was 240 for the control groups, while the farms located in the RZ registered an average decrease of 1,158 animals sold.

The differences in demographics between farms located in the RZ and those in UZ are significantly reduced after the multivariate matching (Table 2). Before matching, farms in the RZ have lower average age at sale, export share, and herd size (number of births and livestock units) compared with farms in the UZ. After matching, the differences are significantly reduced, especially the export share and the age at sale. The differences between the demographics of the RZ group and the control group are reduced under the nearest neighbor matching (Table 2, ratio 1:1), with negligible differences compared with the optimal matching (results not shown). As expected, the distribution of control farms in the UZ is concentrated in the two main Charolais production areas, Central France and West France (Fig. 3). With the implementation of the MRP the selling patterns of farms in the RZ changed dramatically due to the efforts of farmers to sell their calves (Fig. 4).

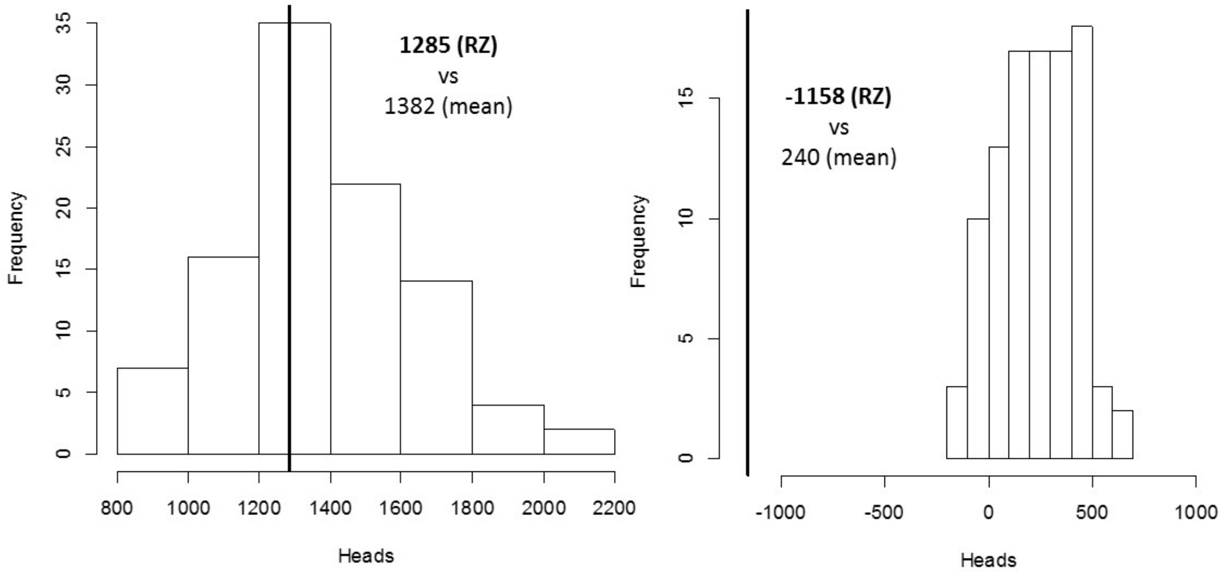

Fig. 2. Comparison of the number of sales between 2005 and 2006, for period 1 (January to august, left side) and period 2 (September to December, right side) periods, and for the Restricted zone (RZ) and the 100 control group (mean) in a bluetongue cost assessment in France (2006). Histograms represent the distribution of the 100 control group and the thick line the situation of the RZ. The 100 control group is matched with the farms in RZ on the overall number of sales from September to December 2005.

The regression results (Table 3) show an increase in BWC sales in 2006 compared to 2005, as well as a positive effect regarding the number of births, and negative effects related to mortality, herd size and the presence of a fattening unit within the farm.

The effect of the MRP on 2006 sales of a producer is estimated by combining the coefficients on RZ and on the interaction term (Y06:RZ) in regression 1. The implementation of the MRP decreased the sales of BWC of farmers located in the RZ compared with those outside the RZ by 20% [exp(0.07-0.29)-1].

The Italian ban on French cattle could make export-oriented farms more vulnerable to the MRP. Including the interaction effects of Export Share (regression 2) allows analysis of this heterogeneity. For export-oriented farms (Export Share = 1) the MRP leads to a reduction in 2006 sales of 23% [exp(0.12-0.35-0.13+0.10)-1] compared with similar farms outside the RZ. On the other hand, farms oriented to the national market (Export Share = 0) experienced a slightly smaller effect, a 21% [exp(0.12-0.35)-1] reduction in their sales compared with similar farms outside the RZ. Taking into account that the average farm has an export share of 34.6%, the implementation of the MRP led to a 21% [exp(0.12-0.35-(0.13-0.10)*34.6%)-1] reduction in the sales of an average farm located in the RZ compared with a similar farm located outside the RZ.

Table 2
Descriptive statistics in 2005 of farms in a bluetongue cost assessment in France (2006)[a]

Variable	Full Sample	Farms in RZ	Farms in UZ	Matching (Nearest 1:1)	
				RZ	Controls
Export share	67.54%	34.24%	68.89%	34.62%	34.61%
	(0.003)	(0.003)	(0.003)	(0.003)	(0.003)
Fattening unit[b]	7,292	299	6,993	281	285
Number of births	70.5	63.3	70.8	63.4	67.1
	(34.99)	(27.11)	(35.24)	(27.02)	(34.95)
Number of livestock units[c]	112.4	103.7	112.7	102.2	107.1
	(60.79)	(55.28)	(60.98)	(54.01)	(64.2)
Mortality rate[d]	5%	5.5%	5%	5.4%	5.4%
	(0%,17%)	(0%,18.7%)	(0%,16.9%)	(0%,18.4%)	(0%,18.5%)
Average age at sale (days)	306.3	290.1	307.0	289.5	292.2
	(49.53)	(39.34)	(49.79)	(39.29)	(51.89)
Sales (number of BWC)	34.36	30.60	34.51	30.12	31.59
	(18.38)	(14.16)	(18.51)	(12.99)	(17.7)
Sales (Sept 1st to Dec 21st)[d]	13	14	13	14	14
	(0,46)	(0,40)	(0,47)	(0,40)	(0,53)
Number of farms	11,416	443	10,973	418[e]	418

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[a] *These are mean values with their respective standard deviations in parentheses unless indicated otherwise.*
[b] *This is a dummy variable, equal to 1 if the farm has a fattening unit. For this variable the number of observations equal to 1 is reported.*
[c] *The livestock units are calculated weighting the number of animals by a given coefficient associated to the age of the animal.*
[d] *Due to the skewed distribution of this variable the median and the 2.5 and 97.5 percentiles are reported.*
[e] *The reduction in the number of farms is because only farms with full information were used for the matching procedure.*

Both models display a low R-squared, which suggest that farm-level results are affected by factors in addition to the independent variables considered in the regression model. Yet the purpose of the model is not to explain all the variability in the sales but to quantify the impact of the MRP (Y06*RZ) on them.

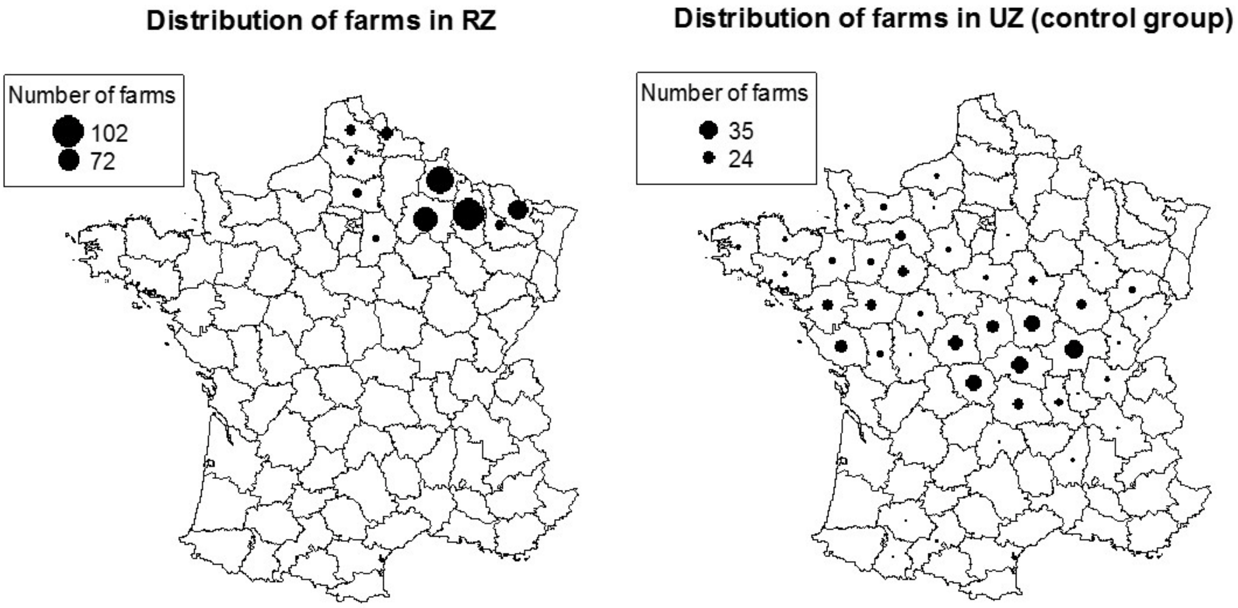

Fig. 3. Spatial distribution of farms in RZ and in UZ control group after the multivariable matching in a bluetongue cost assessment in France (2006).

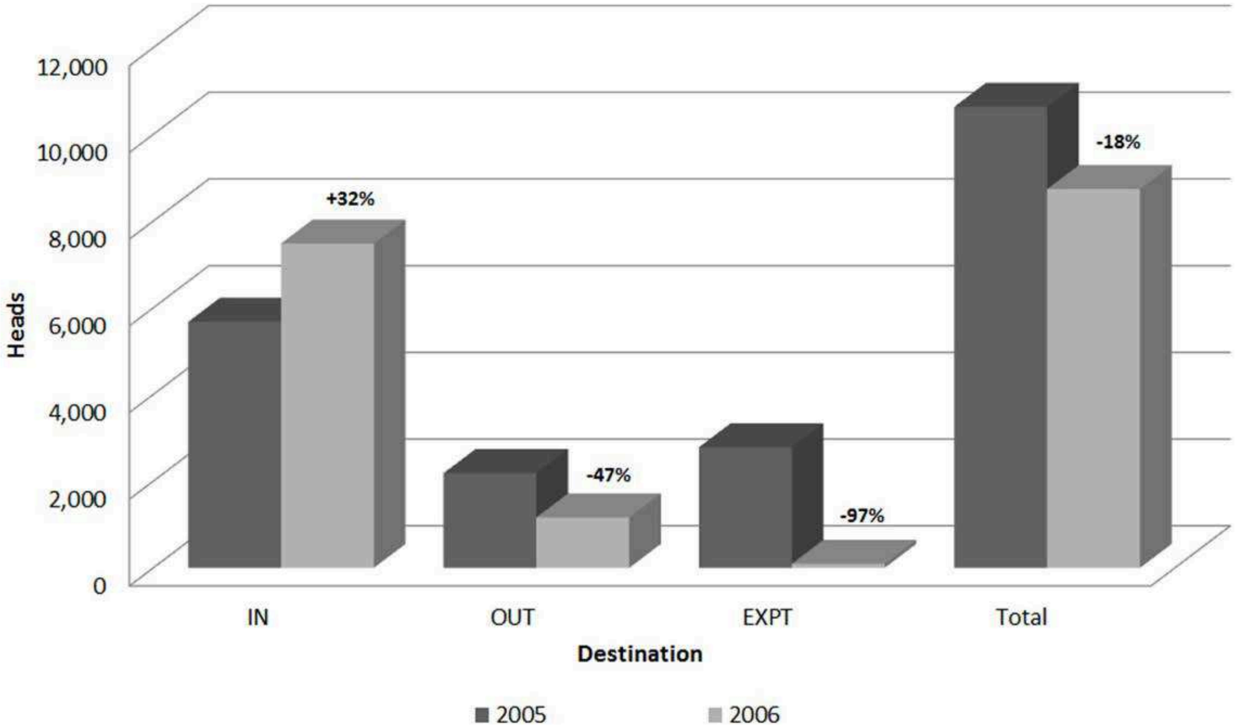

Fig. 4. Sales of BWC from 07th September to 21st December for municipalities located in the RZ in 2005 and 2006 in a bluetongue costs assessment study in France (2006). IN : sales within the RZ ; OUT : sales outside the RZ, EXPT : Sales to foreign country.

Table 3
Results of the regression after matching. Dependent variable: log(number of BWC sold)[a]

Variables	Regression 1			Regression 2		
	Coefficient	P	95% CI	Coefficient	P	95% CI
(Intercept)	2.21	<0.001	[2.04 , 2.39]	2.14	<0.001	[1.96 , 2.33]
Y06[b]	0.17	0.012	[0.04 , 0.30]	0.29	0.002	[0.10 , 0.47]
RZ[c]	0.07	0.272	[-0.06 , 0.20]	0.12	0.193	[-0.06 , 0.30]
Export Share	0.08	0.221	[-0.05 , 0.20]	0.26	0.058	[-0.01 , 0.52]
Fattening Unit	-0.11	0.026	[-0.21 , -0.01]	-0.11	0.030	[-0.21 , -0.01]
Births	0.01	<0.001	[0.01 , 0.01]	0.01	<0.001	[0.01 , 0.01]
Mortality	-0.01	0.017	[-0.02 , 0.00]	-0.01	0.016	[-0.02 , 0.00]
Livestock Unit	-0.003	<0.001	[-0.005 , -0.002]	-0.003	<0.001	[-0.005 , -0.002]
Y06:RZ	-0.29	0.001	[-0.47 , -0.12]	-0.35	0.006	[-0.60 , -0.10]
Y06:Export Share				-0.31	0.095	[-0.68 , 0.05]
RZ:Export Share				-0.13	0.460	[-0.47 , 0.21]
Y06:RZ:Export Share				0.10	0.695	[-0.41 , 0.62]
Adjusted R2	0.067			0.067		
AIC	3539.9			3541.3		

[a] Since the regression is in log-levels, the coefficients can be interpreted as the percentage change on the number of BWC sold per one unit change in the independent variable associated.
[b] Dummy variable equal to 1 if year = 2006
[c] Dummy variable equal to 1 if the farm belongs to the RZ when the MRP was implemented

Cost of the movement restriction

The costs per calf associated with the MRP according to each scenario are summarized in Table 4. A large part of the cost of the standstill depends on the housing constraint. With no capacity constraint, positive profits in every scenario are obtained for both baseline and alternative frameworks, but profits are reduced by approximately half if feed is bought at market prices (scenario 1.3). In case a capacity constraint, profits are always lower, although they remain positive in some scenarios. If a barn is rented, the result depends on the framework (scenario 2.1 compared to 1.1) but it always leads to a decrease in the profit (-55% under the Baseline and -74% under the Alternative). Additionally, if the feed is bought at market prices the profit is reduced by half under the Baseline framework, and leads to almost no profit (3.95 eur per BWC) if cattle are kept until February. Farmers putting their animals in a boarding facility (Scenarios 2.3) have a small but positive profit (21.7 euros per calf), but lose money under the alternative framework (-41 euros per calf). Finally, if the farmers leave their animals outside, both frameworks lead to small but positive profit. Recall that these are profits before labor costs, except for scenario 2.3 that includes labor costs indirectly since these are taken into account by the full-care boarding facility.

The sensitivity analysis (Table 5) considers extreme variations on the key parameters involved in the cost estimations. If animals are too-old-to-be-sold as BWC to fattening units and are slaughtered, the profit would be considerably reduced compared to selling as BWC. Changes in mortality and morbidity have lower impacts on profitability, except for the Outside scenario. Changes on the Average Daily Gain in weight (ADG) and feed costs lead to moderate changes in profits, which always remain positive without a capacity constraint but are negative when facing the capacity constraint. The BWC's price is the parameter with the highest impact on profit, whatever the scenario.

4. Discussion

Impact of the MRP on the sales of BWC

The matching procedure allows us to recover relevant information at the farm level in order to identify control farms that most resemble those in the RZ, and therefore obtain more appropriate comparisons. This procedure allows constructing counterfactuals in order to measure the MRP effect. Such a method is essential to control for independent contextual changes that occur simultaneously with the infection, such as modifications to the production-coupled subsidies and changes in the market prices of BWC between 2005 and 2006. The regional differences in the BWC selling prices did not change with the MRP implementation. Farmers might adopt mitigation strategies such as searching for commercial partners in the same sanitary zone, which end up reducing the impact of the standstill.

The single-variable matching points towards a large and significant decrease in the sales of holdings in the RZ due to the MRP. First, evidence for good selection of controls is obtained, since the increase in sales of the farms in the RZ during the pre-epidemic period is inside the domain of the controls (Fig. 2, left side). Second, the very large decrease in the average sales during the epidemic period for farms in the RZ compared to the controls is shown (Fig. 2, right side). This can be attributed to the MRP if the control groups are properly designed to control for internal

Table 4
Results for the estimation of the movement standstill cost in a bluetongue cost assessment in France (2006)

	No capacity constraint			Capacity Constraint			
	Scen 1.1	Scen 1.2	Scen 1.3	Scen 2.1	Scen 2.2	Scen 2.3	Outside
Assumptions							
Housing op-op Cost	N	Y	Y	N	N	N	N
Rent of building	N	N	N	Y	Y	N	N
Produce own food	Y	Y	N	Y	N	N	N
Boarding facility	N	N	N	N	N	Y	N
Baseline framework (Up to the end of 2006)							
Initial Age (days)	210	210	210	210	210	210	210
Initial Weight (kg)	275	275	275	275	275	275	275
Final Age (days)	329	329	329	329	329	329	329
Final Weight (kg)	455	455	455	455	455	455	443
Market Gain (€)	256.7	256.7	256.7	256.7	256.7	256.7	228.66
Mortality Cost (€)	-9.60	-9.60	-9.60	-9.60	-9.60	-9.60	-57.60
Morbidity Cost (€)	-8.57	-8.57	-8.57	-8.57	-8.57	-8.57	-40.49
Preventive Medicine (€)	-13.57	-13.57	-13.57	-13.57	-13.57	-13.57	-12.76
Feeding Costs (€)	-37.3	-37.3	-74.7	-37.3	-74.7	-31.5	-79.6
Housing op-op cost (€)	0.0	-51.4	-51.4	0.0	0.0	0.0	0.0
Housing costs[a] (€)	0.0	0.0	0.0	-102.8	-102.8	-171.6	0.0
Baseline summary							
Gains (€/animal)	256.7	256.7	256.7	256.7	256.7	256.7	228.7
Losses (€/animal)	-69.1	-120.5	-157.8	-171.8	-209.2	-234.9	-190.4
Total: Gains-Losses (€/animal)	187.60	136.21	98.88	84.83	47.49	21.78	38.26
Alternative framework (Up to February 16th, 2007)							
Initial Age (days)	210	210	210	210	210	210	210
Initial Weight (kg)	275	275	275	275	275	275	275
Final Age (days)	371	371	371	371	371	371	371
Final Weight (kg)	527	527	527	527	527	527	506
Market Gain (€)	336.5	336.5	336.5	336.5	336.5	336.5	291.01
Mortality Cost (€)	-9.60	-9.60	-9.60	-9.60	-9.60	-9.60	-57.60
Morbidity Cost (€)	-8.57	-8.57	-8.57	-8.57	-8.57	-8.57	-40.49
Preventive Medicine (€)	-13.57	-13.57	-13.57	-13.57	-13.57	-13.57	-12.76
Feeding Costs (€)	-60.5	-60.5	-121.0	-60.5	-121.0	-31.5	-127.7
Housing op-op cost (€)	0.0	-89.9	-89.9	0.0	0.0	0.0	0.0
Housing costs[a] (€)	0.0	0.0	0.0	-179.8	-179.8	-314.3	0.0
Alternative summary							
Gains (€/animal)	336.5	336.5	336.5	336.5	336.5	336.5	291.0
Losses (€/animal)	-92.2	-182.2	-242.7	-272.1	-332.6	-377.6	-238.6
Total: Gains-Losses (€/animal)	244.29	154.37	93.87	64.45	3.95	-41.05	52.44

[a] The housing costs refer to the cost of renting a building or paying a full-care boarding facility, depending on the scenario.

validity threats. In spite of the possibility of having one farm represented more than once in the random control groups, there is no evidence of farms being overrepresented.

Before the multivariate matching, one of the main observed differences is the higher export shares in the UZ compared to the RZ. Farms in the RZ were more locally oriented than farms in the UZ. This is in accordance with the older animals sold in the UZ, since foreign demand looks for heavier, and therefore older, BWC. After matching, any significant difference in the 2005 descriptive statistics between farms in the RZ and the farms in the UZ has vanished.

The result of the regression under matching shows that the MRP implementation (Y06:RZ) reduces sales by 20-21%. The partial rather than total loss of sales, is consistent with the derogations granted by the authorities to the movement of animals in the RZ in specific cases (previously described), as well as the implementation of mitigation strategies such as farmers' possibility to sell to a zone with the same status as theirs (Fig. 4). The fact that the existence of a fattening unit reduces the sales of calves implies a larger capacity of the farm to react with more flexibility: selling BWC or fattening them, depending on market dynamics.

The period just after the lifting of the movement restrictions could be associated with price disturbances due to the sudden introduction into the market of all the animals that were affected by the movement standstill (a positive shock on the supply of animals that can drive prices down). However, there is no significant change in the BWC prices at this time, which suggests that the excessive supply effect is negligible, perhaps due to the limited size of the RZ in 2006.

Among the limits of the analysis is its focus on medium and large producers of Charolais BWC. The extension of the results to other types of farms seems appropriate. Moreover, the regression model allows estimation of the standstill effect associated with the MRP, but does not represent a forecasting tool for BWC sales. The standstill effect is estimated after any mitigation strategy implemented by farmers and does not quantify the effect of the MRP without mitigation strategies.

Cost of the movement restriction

The positive gains of the scenarios without capacity constraints and food self-sufficiency (187 to 244 euros per calf if sold as BWC or 58.8 euros if sold to a slaughterhouse, Table 4) are in accordance with gross margins reported by the French Livestock Institute (Institut de l'Elevage). The gross profit margin of fattening activities ranges from 100 to 250 euros per animal, depending on the production system and the year, for an average 8 month-long fattening period (Falentin et al., 2008; Bellamy et al., 2010; Mischeler et al., 2012). Therefore the average gross profit margin per month ranges between 12 and 32 euros per animal, compared with 14 (58/4), 37 (244/6.5) and 46 (187/4) euros obtained in the present study. Such comparison should be used carefully, since the estimates are based on animals sold to slaughterhouses (French Livestock Institute) or as BWC (present study).

Table 5
Sensitivity analysis (€/animal) in a bluetongue cost assessment in France (2006)

		Baseline Scenarios					
Parameter	1.1	1.2	1.3	2.1	2.2	2.3	Outside
Sold as BWC (ref)	187.6	136.2	98.9	84.8	47.5	21.8	38.3
Sold as Carcass[a]	58.8	7.4	-29.9	-43.9	-81.3	-107.0	-87.1
ADG							
20%	271.7	220.3	182.9	168.9	131.6	105.8	116.7
-20%	103.5	52.2	14.8	0.8	-36.6	-62.3	-40.2
Mortality							
Twice	178.0	126.6	89.3	75.2	37.9	12.2	-19.3
Half	192.4	141.0	103.7	89.6	52.3	26.6	67.1
Morbidity							
Twice	179.0	127.6	90.3	76.3	38.9	13.2	-2.2
Half	191.9	140.5	103.2	89.1	51.8	26.1	58.5
BWC price							
10%	293.8	242.5	205.1	191.1	153.7	128.0	141.7
-10%	81.4	30.0	-7.4	-21.4	-58.8	-84.5	-65.2
Feed cost							
20%	150.3	98.9	24.2	47.5	-27.2	-52.9	-41.3
-20%	206.3	154.9	136.2	103.5	84.8	59.1	78.0

[a] A conversion factor of 60% was used

The positive gains after the animal standstill observed in scenarios 1.1 and 1.2 were expected, since calibrations were close to normal fattening activities. The profitability remains highly sensitive to the price of the BWC sold, as shown by the sensitivity analysis linked to BWC prices and to "sold as carcass" (scenario 1.1 and 1.2, Table 5). The incorporation of opportunity costs reflects the fact that even if farmers have no capacity constraint, the use of the barns for fattening excludes other activities, such as the stocking of cattle feed.

However, many farmers are likely to face capacity constraints during this season. In case of autumn calving, barns are already used for dams and young calves. In case of winter calving, dams enter barns during November and often little extra space is available, since winter-born calves stay a few weeks in barns. The scenarios with capacity constraints show lower profitability for farmers compared to no capacity constraint, and even losses in several cases. Such decrease in profitability is of 38% (baseline) and 58% (alternative) from scenario 1.2 to 2.1, where differences rely only on having space in a building (facing the opportunity and operational cost) or being obliged to rent a building in the area. The longer the rental period, the higher the decrease of profitability (differences between baseline and alternative). Therefore, capacity constraints can be considered as one of the biggest challenges to farmers facing movement restrictions.

Since buying food at market prices doubles the feeding costs, the profitability was reduced for scenario 1.3 compared to 1.2 and for scenario 2.2 compared to 2.1. The feeding costs are reduced under scenario 2.3, since they are included within the boarding facilities for the indoor period, and the remaining feeding costs account for the outdoor period (before November). The cost of a boarding facility ends up around 2.9 euros per calf per day, which seems reasonable, since the full-care boarding takes into account housing, feeding (including concentrates) and labor. The relevance of feeding costs is nicely reflected in the comparison of the baseline and alternative frameworks: farmers with no capacity constraint and producing their own food obtain better results under the alternative framework, but if the housing opportunity and operational costs are considered and their cattle's food is bought at market prices, they obtain better results under the baseline scenario. This result is driven by the evolution of grain prices during the first weeks of 2007, which registered significant increases (corn: +7%; soybean: +19%), while the BWC prices fell (-7%).

The contrast between the baseline and alternative frameworks varies among scenarios. A farmer with a capacity constraint has financial incentives for placing the animals in a boarding facility (scenarios 2.3) compared to leaving them outside because both lead to small but similar profit (22-38 euros per animal) under the baseline framework but work is needed for outside scenario and not for scenario 2.3. On the contrary, results suggest a preference for the outside solution compared to the boarding facilities solution (+52 vs -41 euros per animal) for a longer standstill period (alternative scenario), in spite of the work needed. This remains true when comparing renting a building with keeping the animal outside for the alternative scenario (+4 vs +52 euros per animal). In other words, with a long standstill period farmers with capacity constraints have more incentives to leave their animals outside and face higher mortality and morbidity rates than paying for a boarding facility.

The strategy of prematurely slaughtering animals that do not fit the BWC specifications significantly reduces the potential earnings of farmers, no matter the scenario. The only two scenarios that remain profitable reach low to very low gains so the interest in such activity remains questionable. In other words, without a capacity constraint the profitability of fattening under the MRP depends mainly on the matching between the characteristics of the farmer's product and the market demands. With a capacity constraint, losses are systematic in case of mismatch between the characteristics of animals in supply and demand. This is in accordance with the high sensitivity of the results to the BWC prices. This vulnerability to holding animals too-big-to-be-sold was clearly understood by policymakers and led to the assignment of specific aid to help farmers in this situation during the BTV-8 epidemic (NS-DGPEI/SDEPA/N2008-4020).

Farmers lacking the skills to efficiently fatten their animals and intending to do so could end up with meat of lower quality. A constant meat quality was considered in the present study. Since lower-quality meat receives lower prices, the costs of the MRP may be higher than our estimates. One way to reduce the vulnerability of farmers is by providing training on proper techniques oriented to optimize the growth and quality of the animals, such as optimal feeding strategies that take into account the availability of food in the area, the design of balanced diets, and the substitutability among diets taking into consideration the market circumstances. The right training on this aspect will have not only a direct impact on the growth and quality of the animal, but will also reduce the vulnerability of farmers to market volatility.

The analysis was restricted to the Charolais breed since it is the major breed of BWC producers in France. An evaluation of the total MRP costs at the national level could be based on the present work. The extrapolation of the present results to other breeds would be feasible due to known differences in the breeds' characteristics.

Saying which scenario is more likely to occur is complex. It depends on farmers' characteristics, market dynamics, infrastructure availability, the length of the standstill period, and other factors. However, it is possible to get some insight from the descriptive statistics of this study. In our sample of farms in the RZ, around 67% engaged in some fattening activities in 2005 (characterized by the dummy variable "Fattening unit" equal to 1, see Table 3). This provides an imperfect measure of their capacity constraints: farms that in the past have engaged in fattening activities are more likely to have loose capacity constraints and therefore will adapt better to a scenario with movement restrictions.

Under this assumption, the scenarios with no capacity constraint (1.1, 1.2, and 1.3) will be twice as likely as the scenarios with capacity constraint (2.1, 2.2, 2.3, and Outside). It could be said that two thirds of the farms will be facing some of the scenarios with no capacity constraint, while the rest will be in a situation depicted by one of the capacity constrained scenarios.

It is important to highlight that these numbers might be overestimated and should be taken as an upper bound (i.e., at least 33% of the farms will be facing a capacity constraint). The reasoning is the following: a farm might have the capacity to fatten some proportion of its annual production of calves but this capacity is limited and could be easily overwhelmed. In fact, many of these farms might have a fattening unit to fatten a proportion of their calves in case of a depressed market for young calves, i.e. as an insurance mechanism to reduce market shocks. However if their main activity is selling young calves this insurance mechanism will be limited.

From the farmer's perspective, the results of this study show that, if they do not face a capacity constraint, farmers will be more able to overcome the obstacles imposed during a standstill period by producing their own food. Under capacity constraints and without food self-sufficiency the answer is tricky: if the standstill period is short, the optimal strategy is to rent a building to lodge their animals; however, if the standstill period is expected to be long, leaving the animals outside is a better strategy. Therefore, if we consider that the standstill period is expected to be long, under the assumption of optimal behavior of farmers it could be said that 67% of them will be facing scenario 1.2 and the rest (33%) will be facing the Outside scenario.

Additional costs may not have been addressed in the present analysis and deserve further research. For example, liquidity constraints could influence the costs that farmers face due to their animals' standstill. To comply with extraordinary expenses farmers might request a bank loan and therefore the payment of interest becomes another cost to be considered.

The implementation of the MRP may restructure the cattle network, disturbing flows from the RZ and may enhance the participation of other areas. New tools such as social network analysis could be useful for further research on this topic.

Although other mitigation strategies could be imagined, the objective of this analysis is not to provide an exhaustive list but to present the most plausible scenarios seen in the field.

5. Conclusion

Nowadays, the Movement Restriction Policy (MRP) is considered as one of the main strategies to control the expansion of contagious animal diseases in Europe. The present study is the first formal quantification of the impact of such a measure, taking as a representative sector the breeders of beef weaned calves (BWC). In 2006, the MRP had a significant effect on the sales of BWC of -21% for the average farmer located in the restriction zone (RZ). The economic evaluation of the MRP unveils a potential gain during the movement standstill when there is no capacity constraint faced by the farm and food self-sufficiency. The gain remains limited and close to zero in the case of a low selling price, in particular if animals affected by the standstill do not fit any market, and are too big to be sold as BWC. This vulnerability associated with holding animals too-big-to-be-sold justifies governmental aid to farmers, in spite of an apparent gain.

Capacity constraints must be considered as one of the biggest challenges to farmers facing movement restrictions; a challenge that may lead to losses during cattle fattening. Results also showed that strategies of farmers with capacity constraints should be different depending on the length of the standstill period. Under certain conditions, farmers have stronger incentives to leave their animals outside where they face higher mortality and morbidity rates than paying for a boarding facility. Feed cost and food self-sufficiency are also determinants of the outcomes of different strategies. The results of this study can be seen as a powerful tool for farmers to decide which strategy to adopt according to their constraints and expectations on the length of the movement standstill period.

The present results are based on the 2006 epidemic which was localized in the Northeast of France. Since the most important area of BWC producers is the center of France, where the BTV-8 did not spread until 2007, the BTV-8 impact linked to MRP could be considerably higher in 2007 compared to 2006.

6. Supplementary materials

Computation of costs in a bluetongue cost assessment study in France (2006)

a) The final age at selling is defined as (in days):

$$\text{Final Age} = \text{Initial Age} + \text{number of weeks} * 7$$

$$\text{Number of weeks} = \begin{cases} 17 & Baseline\ framework \\ 23 & Alternative\ framework \end{cases}$$

Where the baseline and the alternative frameworks go from the beginning of the epidemic up to the end of 2006 and to the date when the Italian ban on French cattle was lifted, respectively.

b) The final weight (kg) at selling is defined as:

$$Final\ Weight = Initial\ Weight + \sum_{t=1}^{T} Gain_t$$

Where $Gain_t$ is the gain in weight (kg/month) at month t.

$$t = \begin{cases} 4 & Baseline\ framework \\ 6 & Alternative\ framework \end{cases}$$

$$Gain_t = ADG_t * number\ of\ days\ at\ month\ t$$

The Table A.1 of Average Daily Gains (ADG) is calibrated taking into account the average characteristics of the Charolais breed, the age of the animal, and the unfavorable conditions of cold weather for the outside scenario.

c) The market gain (kg) represents the difference in the market value of the animal when comparing the beginning and the end of the period being analyzed:

$$Market\ Gain = Final\ Weight * Final\ Price - Initial\ Weight * Initial\ Price$$

d) Mortality Risk

Since the mortality risk is associated to the return to indoor housing, we considered the average price at the end of October 2006 (2.63 eur/kg lwt) and the average weight at the same period (365 kg):

$$Mortality\ cost\ (€) = Mortality\ risk\ associated * Weight * Price$$

e) Morbidity Risk

Similarly to the mortality risk, morbidity risks are associated to the return to indoor housing so we consider the average weight at the end of October

$$Morbidity\ cost\ (€) = Morbidity\ risk\ associated * Morbidity\ cost$$

$$Morbidity\ cost = \sum_{i=1}^{N} P_i * doses_i$$

Where N is the number of treatments (an anti-inflammatory plus an antibiotic in the present work). Since the price of treatment is in euros per 100 kg of live weight it has to be multiplied by the weight of the calf/100; in our case is a 365kg calf so the number of doses is 3.65.

Due to adverse environmental conditions during winter, extra morbidity, mortality, and a decreased average daily gain were considered for the Outside scenario. Therefore, the losses due to morbidity risk for the outside scenario are:

$$Morbidity\ risk\ (€) = [Morbidity\ risk\ associated + p1 + p2] * Morbidity\ cost$$
$$-loss\ in\ market\ value * market\ value$$

Where p1 and p2 are the probabilities of relapse for the outside scenario and the loss in market value is associated to these relapses.

f) Preventive medicine is done on all animals when are sent back indoors at the beginning of the cold season:

$$Preventive\ medicine\ (€) = \sum_{i=1}^{N} P_i * doses_i$$

This is the cost for N treatments. In our study we considered a respiratory vaccine and a deworming treatment. The deworming treatment is in euros per 100 kg of live weight so it has to be multiplied by the weight of the calf/100; in our case is a 365kg calf so the number of doses needed is 3.65.

g) Feeding Costs

$$Feeding\ cost\ (€) = \sum_{t=1}^{T} Weekly\ feeding\ cost_t$$

$$\begin{aligned} Weekly\ feeding\ cost_t\ (€) = {} & P(grass)_t * Average\ daily\ consumption(herb)_t * 7 \\ & + P(hay)_t * Average\ daily\ consumption(hay)_t * 7 \\ & + P(conc)_t * Average\ daily\ consumption(conc)_t * 7 \end{aligned}$$

Where the concentrate used was a mixed of 75% corn + 25% soybean meal. The prices are on weekly basis and the average daily consumption levels were adjusted monthly according to the weight of the calf. The change of grass to hay is associated to the indoor housing (cold months). Table A.2 summarizes the diet of the animals for the different months.

When the farmer produces the food by himself we considered a 50% discount on the feeding cost. When a farmer pays for a boarding facility the feeding costs are considered only for the time the first 2 months, before the animals are sent to the boarding facility. For the outside scenario an additional 10% is charged to represent the increase on consumption, and on the other hand the costs are adjusted by the increase in mortality (-6%).

h) Housing opportunity and operational cost

The monthly opportunity and operational cost is the sum of three elements: the monthly amortization of a building per animal (MA), the average monthly cost associated to the building due to waste stocking (WS), and the average monthly cost associated to the building due to the need of straw (S).

$$MA = Average\ cost\ of\ building/(25 * 12 * average\ capacity)$$

$$WS = Yearly\ cost\ of\ waste\ stocking/(12 * average\ capacity)$$

$$S = Daily\ average\ straw\ requirement * P(straw)$$

The housing opportunity and operational costs are multiplied by the number of months when indoor confinement is required. The cost of the building and the waste stocking and straw requirements come from the same source (Bruel et al., 2010).

i) Housing costs

To incorporate the market gain of renting a building we compute them as twice the opportunity and operational cost. Finally, the when the animals are sent to a boarding facility we considered the cost of renting a building plus the market price of food (as described above) plus the labor costs:

$$Labor\ (€) = daily\ hours\ of\ work\ required * wage\ per\ hour$$

Table A.1. Gain in weight

Initial age	Average Daily Gain (ADG)		
	Month	Baseline	Outside
8	Sept	1.4	NA
9	Oct	1.6	NA
10	Nov	1.4	1.2
11	Dec	1.6	1.4
12	Jan	1.6	1.4
13	Feb	1.6	1.4

Table A.2. Feed consumption

Initial age	Average Daily Consumption (kg)			
	Month	Grass	Hay	Concentrate
8	Sept	2.48	0	4
9	Oct	2.6	0	5
10	Nov	0	3.18	4
11	Dec	0	3.58	4
12	Jan	0	3.1	5
13	Feb	0	2.72	6

Chapter 2

The impact of farmers' strategic behavior on the spread of infectious diseases in animals

The impact of farmers' strategic behavior on the spread of infectious diseases in animals

Abstract

Movement restriction is one of the main strategies to control the spread of animal infectious diseases. Neglecting the possibility that farmers will adapt their behavior when a control policy is implemented can significantly bias the estimated benefits of such policy. This paper shows how the movement restriction policy (MRP) becomes less efficient when behavioral responses of agents are taken into account. Combining an economic model of farmers' strategic behavior with an epidemiological model reveals how the MRP can trigger premature livestock sales by high-risk farms, significantly reducing the efficacy of the policy. The outcome of the MRP is estimated in a parameterized network via Monte Carlo simulations and additional measures to mitigate the problem are discussed. The economic model allows us to identify the variables associated with farmers' behavioral response to the MRP and shows that financial aid to farmers may be justified by public health as well as equity concerns. This paper contributes to constructing an interdisciplinary theory regarding the expansion of infectious diseases combining economic and epidemiologic elements.

Keywords: Behavioral response; movement restrictions; animal infectious diseases.

1. Introduction

Incorporating human reactions to analyze the spread of infectious diseases is a current trend in epidemiology (Ferguson, 2007). While some of these studies point to the existence of human preventive responses that can reduce the spread of the infection, such as the voluntary use of vaccines or masks that reduce the risk of being infected (Sahneh, et al., 2012; Del Valle, et al., 2005), others consider behavioral changes that lead to an increase in risky behavior that may mitigate disease control efforts (Blower, et al., 2000).

In the field of animal diseases, the human factor has been less-well analyzed. It has been shown that under certain conditions, culling of poultry to control an avian influenza outbreak can lead farmers to increase their farm size and as a consequence the number of infections increases (Boni, et al., 2013). Misbehavior of farmers and the emergence of underground markets have also been identified as consequences of implementing control strategies (Webster, 2004). Integrated epidemiological-economic models that incorporate feedback effects reflecting the influences of disease dynamics on incentives and behavior and the converse have been proposed as powerful methods to better understand the benefits and costs of control strategies for infectious diseases (Karl and Perry, 2011).

The findings on scale-free networks (Barabási, 1999), which characterize the structure of many real world networks, led to the construction of a theoretical basis to design control strategies. Applications not only for animal (Shirley and Rushton, 2005) but also for human diseases (Khan, 2009) and viral infection of computers (Pastor-Satorras and Vespignani, 2002) have been developed in recent years.

The main characteristic of scale-free networks is the existence of highly connected nodes (i.e. with a degree that greatly exceeds the average). These nodes are called hubs and are the main reason why a disease, technology, or fashion can spread through a scale-free network more quickly than through a random network (Barthélemy, et al., 2004).

The idea behind control strategies for infectious diseases, such as quarantine or vaccination (Pastor-Satorras and Vespignani, 2002), is that removing infected nodes or immunizing susceptible ones are efficient strategies to fight the spread of a disease. In scale-free networks, while random immunization of the population is very costly to arrest epidemics (Anderson, et al., 1992), targeted immunization of the most highly connected nodes (hubs) is very cost-effective (Callaway, et al., 2000).

One of the main policies to fight the spread of infectious diseases on farm animals is the movement restriction policy (MRP) (Jin, et al., 2004). In Europe, when an infectious disease is detected three zones are delimited over which different restrictions are implemented (European Commission, 2000).

In the absence of a vaccine, the MRP becomes the main strategy to control an infectious disease since it can be implemented as soon as the disease is detected. The efficiency of the MRP varies depending on the disease that is intended to be controlled. In general, the isolation of infected nodes will prevent the disease from spreading. However, the efficiency of this strategy depends on strong and debatable assumptions. It relies on surveillance protocols that detect the infection almost immediately, or that farmers will report truthfully if they detect an infected animal, which might impose large costs on them (Tago, et al., 2014). Even if the detection and removal of infected farms is perfectly efficient, if the disease is transmitted by vectors the MRP cannot by itself assure the end of an epidemic.

Under certain conditions, changes in farmers' behavior induced by the implementation of the MRP can reduce its benefits, making the policy ineffective and costly. This is due to the mismatch between the time of announcing the MRP (when an infectious disease is detected in a country) and the time of implementing the movement restriction in a specific region. This result holds even under the assumption of perfect compliance by farmers (no misbehavior) and it can be explained by reasoning similar to that of the so-called "green paradox" (Sinn, 2008). Therefore, possible changes in farmers' behavior of should be considered for the design of control strategies of infectious diseases.

We use a susceptible-infected epidemiological model at the farm level to analyze diseases that can be transmitted through a trade network (characterized by the existence of hubs) and a geographical network, so it captures the characteristics of vector-borne diseases or airborne viruses whose plumes can travel long distances. A two-period economic model is used to understand how the MRP can change the behavior of farmers located close to the restriction zone and to derive the conditions that trigger anticipatory sales. To analyze the effect of the MRP on the spread of an infectious disease (with and without anticipation effects), Monte Carlo simulations are performed using a semi-parameterized trade network, using centrality measures coming from the French cattle trade network (Rautureau, 2011) and a geographical network, simplified by a square lattice. The loss in efficiency due to the anticipatory sales is estimated as well as the factors associated with the network structure that explain the heterogeneity in the results. Finally, a mechanism to correct for the anticipation effect is proposed based on the economic model.

2. Results

Modelling the spread of a vector-borne disease and the MRP

To study the spread of an infectious disease under different scenarios a scale-free network is constructed following the characteristics of the French cattle network fully described by Rautureau et al. (2011). In order to capture the differences between the weekly and the annual networks, different types of nodes are characterized (farms, markets, and dealers) and associated with a type-specific probability of selling that has been parameterized following information on the real French cattle network. Dealers and markets are identified as the hubs on this network and randomly assigned to the nodes of the network with highest degree.

To capture some of the heterogeneity of the network, the probability of selling (for which a range of values is reported) is considered as a random variable following a uniform distribution over the range obtained from the French cattle network (Tables S1 and S2).

The model is adapted to vector-borne diseases by considering an additional transmission channel. When dealing with vector-borne diseases the infection can propagate even if the infected nodes are efficiently isolated from the trade networks because susceptible nodes are exposed to infection through (a) commercial flows and (b) geographical proximity to infected nodes. The incorporation of both channels has been highlighted as a desirable feature for realistic epidemiologic models (Turner, et al., 2012). An additional geographic network capturing the increased risk of infection of nodes located close to infected ones has to be taken into account.

The geographic network is simplified by a square lattice in which each node is connected to its immediate neighbors. Both networks have the same number of nodes, and are associated through a one-to-one correspondence that randomly assigns the node's location which remains fixed throughout the simulations. The infection is introduced by randomly infecting one node at the first period and the spread of the infection is analyzed by counting the number of infected nodes up to 300 time periods.

The disease spreads following a susceptible-infected (SI) model at the farm-level. Susceptible nodes that are linked directly to an infected node in either of the two networks (trade and geographic) become infected with probability λ. The detection of an infected farm depends on the diagnosis tools and the subclinical profile of the disease, so the probability of detecting a farm that is infected is γ. Finally, α represents the degree of compliance with the MRP, so nodes detected as infected are removed from the trade network with probability α (Fig. S1).

As shown by Figure 1A, when there is perfect compliance with the movement restrictions (α=1), if the channel of transmission is restricted to the trade network (non-vector-borne diseases) the MRP is a very efficient control strategy and if the detection tools are perfect it can immediately stop the spread of the disease. In cases where the disease can be transmitted through both the geographic and the trade networks (as in the case of vector-borne diseases), the outbreak cannot be contained since the geographic channel cannot be shut down by the MRP. However, the MRP helps to slow the epidemic. In either case, the effectiveness of the MRP is severely reduced when γ is reduced (Fig. 1B).

Modelling the strategic behavior of farmers and the MRP

To understand the implications of the MRP on the behavior of farmers we consider a model where a seller of cattle has to choose when to sell his animals. If the farmer decides to sell at period t he receives the market price per live weight kilogram (p_t) multiplied by the weight of his animals (w_t). If the farmer decides to keep his animals and wait for the next period, he faces the costs associated with keeping the animals for an additional period such as feeding and labor costs, represented by c.

To simplify the problem assume two periods, no market risk ($p_1 = p_2 = p$), and certainty about the animals' weight gain according to a growth parameter d (i.e. $w_2 = w_1*(1+d)$). If after both periods the farmer decides not to sell he will receive an outside option value V, which is assumed to be lower than the revenue obtained when selling. This discount comes from the fact that the demand for livestock is associated with very specific characteristics and if the animals become too old or big, the farmers will have difficulty placing his animals in the market.

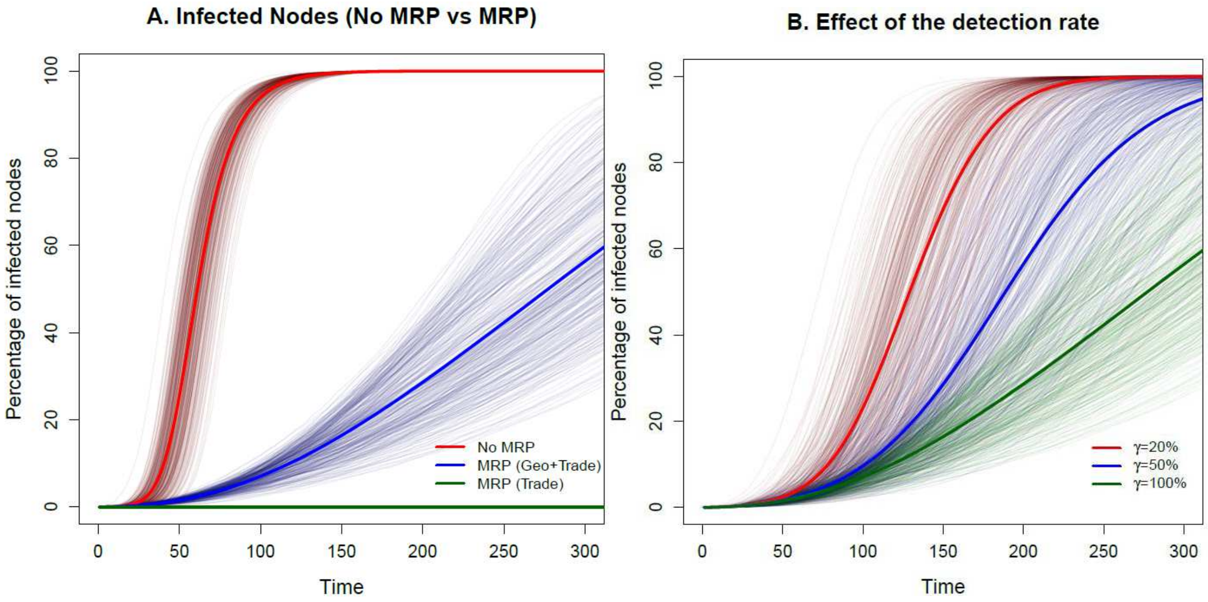

Fig. 1. Accumulated number of infected nodes. Results of 300 simulations (average results in thick lines) and the parameters used during the simulations are: infection rate λ=5% and control rate α=100% for MRP scenarios. **(A)** Detection rate γ=100%. Two scenarios to analyze the MRP: the disease can be transmitted only through the trade network (green line); the disease can be transmitted through both, the trade and the geographic networks (blue lines). **(B)** Spread of disease under different detection rates.

For this analysis, the interesting case is when farmers are willing to wait in the first period and sell in the second. This happens when the gain obtained by the growth of the animals is larger than the cost of keeping them one more period. The condition that characterizes these farmers is: $c < p*w_1*d$.

If an infectious disease is detected at $t=1$, a farmer sufficiently close to the infected zone will face the risk of the restriction zone (RZ) expanding to include his farm in the next period. If at $t=2$ the farmer is located into the RZ he will not be able to sell. Anticipating this, the farmer may sell his animals prematurely (in the first period). It can be shown that a farmer with a perceived probability of being located in the RZ equal to q_i will decide to sell prematurely if:

$$q_i > \frac{p * w_1 * d - c}{p * w_1 * (1 + d) - V} \equiv \hat{q} \tag{1}$$

The link between the economic and the epidemiological model is made through the geographical network. We assume that farms located next to the RZ, such that at least one of their neighbors is located in the RZ, will perceive a high risk of entering the RZ by second period, so $q_i > \hat{q}$.

Loss in efficiency due to the anticipation effects

Strategic behavior of agents can significantly alter the outcome of the MRP. The anticipation effects increase the speed of infection, and for high subclinical rates the benefits of the MRP are severely reduced (Fig. 2). Although there exists some overlap of the results of the simulations under different scenarios, the mean trajectory of infected nodes under the MRP with anticipation effects is significantly higher than in the case without anticipation effects. Such overlapping disappears when the 15% most extreme outcomes are omitted from the analysis (Fig. S2).

The efficiency of the MRP can be quantified by an index defined as the proportional increase in the time-weighted number of uninfected nodes associated with a policy (i.e., the proportional increase in the area above the curve of accumulated infected nodes due to the policy) (Fig. S3). Notice that this index measuring the efficiency of the control policy ranges from 0 to infinity, where 0 is associated with a policy that has no effect on slowing the spread of the disease. The efficiency index goes from 1.06 without anticipation effects to 0.41 when anticipation effects are considered.

Rank-correlation analysis of heterogeneity

The heterogeneity of the outcomes among simulations can be explored by evaluating the rank-correlation between the number of infected farms in a specific period and variables that could explain the heterogeneity. We propose three variables that could potentially explain the heterogeneity in outcomes for each scenario: the number of farms connected to the initially infected farm (degree); the inverse of the sum of the shortest paths between the initially infected farm and all other nodes (closeness); and the time period at which the first market or dealer (hub) is infected.

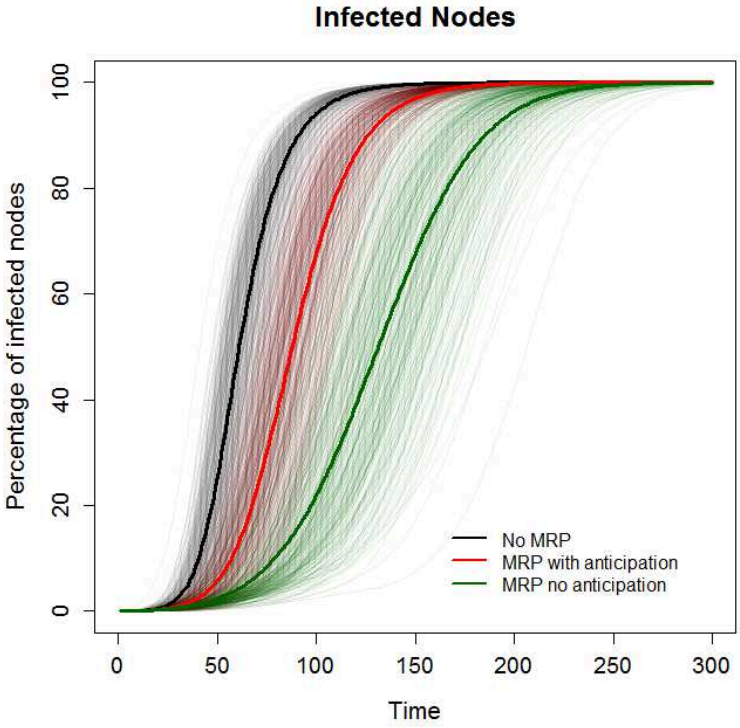

Fig. 2. Effect of the anticipation effects on the outcome of the MRP. Comparison of the accumulated number of infected nodes for a disease transmitted through both, the geographic and trade networks. The efficiency of the MRP decreases when anticipation effects are considered. These are average results over 300 simulations and the parameters used during the simulations are infection rate λ=5%, detection rate γ=20%, and control rate α=100%.

While the degree and closeness of the initially infected node is positively rank-correlated with the speed of spread of the disease, it is the time period at which the first market or dealer is infected which can explain most of the heterogeneity in the simulations (Fig. 3). This relationship is negative and stronger when no policy control takes place (R = -0.88) than when the MRP is implemented (R = -0.66 with anticipation, and R = -0.53 without anticipation).

Mechanisms to correct the behavior of farmers

The economic model serves as a tool not only to identify the drivers of behavioral responses but also to find mechanisms that correct such responses in case they decrease the social welfare.

A transfer to farmers in the RZ is proposed as a mechanism to avoid, or at least reduce, the anticipatory behavior of farmers. The size of the transfer (denoted by *T*) is determined such that it makes farmers with probability of getting into the restriction zone the next period qi indifferent between anticipating and waiting. The analytical solution of such a transfer is:

$$T(q_i) = \begin{cases} \left[\dfrac{p * w_1}{q_i} - (V - c)\right] - \left(\dfrac{1 - q_i}{q_i}\right) * \left[p * w_1 * (1 + d) - c\right] & q_i > \hat{q} \\ 0 & o.w. \end{cases} \qquad (2)$$

The size of the transfer can be calibrated using information on prices, evolution of animals' weight, and production costs. We used data corresponding to the resurgence of the French BTV-8 epidemic in 2007 with market prices corresponding to young beef calves of the Charolais breed (Fig. 4). The transfer is expressed as a function of the subjective probability of having one's cattle immobilized in the near future. For probabilities above the threshold ($\hat{q}$) the transfer is positive and increases at a decreasing rate with an upper bound at $p * w_1 - (V - c)$.

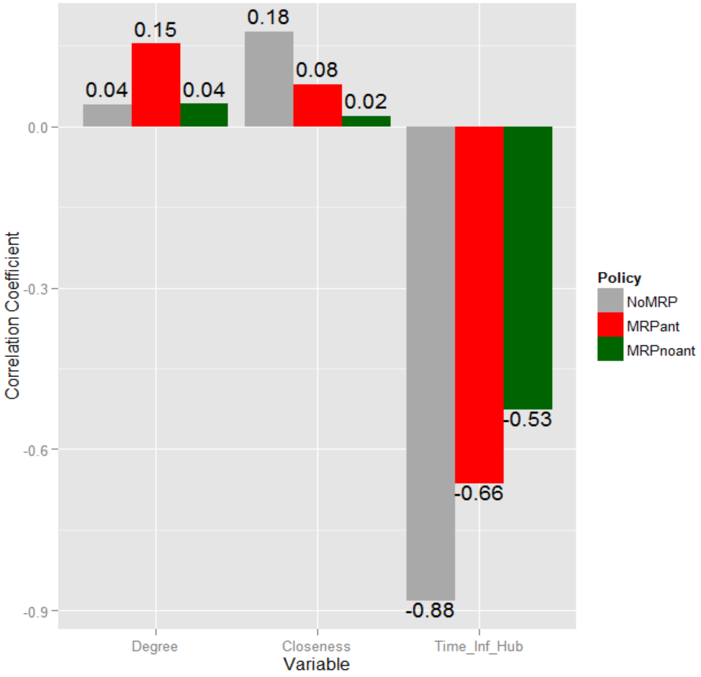

Fig. 3. Rank correlation coefficient analysis. Due to the large differences between the outcomes under different scenarios, the number of infected nodes was computed for NoMRP at period t=61, for MRPant at period t=88, and for MRPnoant at period t=131. These periods correspond to timing at which 50% of the nodes were infected according to the average trajectory.

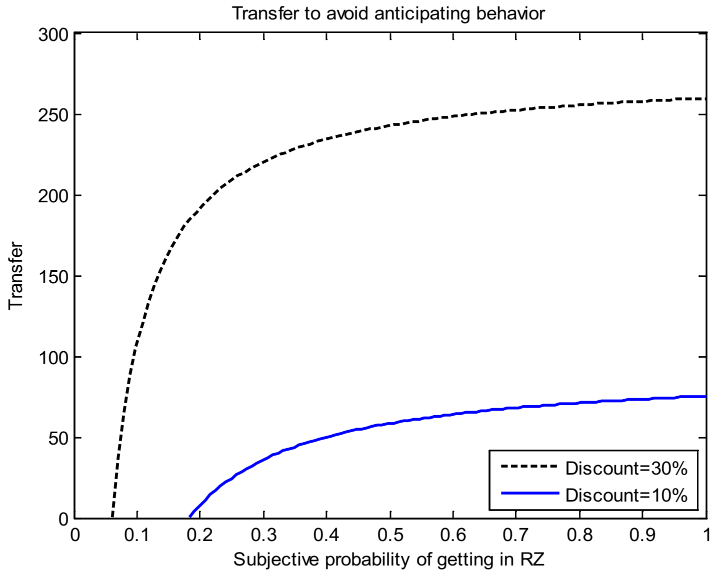

Fig. 4. Transfer required to avoid anticipating behavior. The transfer is a function of the subjective probability of getting in the RZ in the next period (q) for different discounts of the outside option (V). The model is calibrated using French data for August 30th, 2007 and estimates on the weight evolution of a Charolais calf: $p=2.56$ eur/kglwt; $w_1=350$ kg; $d=10/350$; $c=8.73$ eur; $V=p*w_1*Discount$.

3. Discussion

The efficiency of the MRP is significantly reduced when facing a vector-borne disease (transmission through both the geographic and commercial channels) and this can be explained by the incapacity of the policy to control the spread by vectors. However, the MRP restricts the transmission of the disease to the geographical channel whose network has no hubs and therefore the speed of spreading is significantly slower than through the trade network. It has been found that in the case of diseases considered to be transmitted through close-contact animal-to-animal, such as the foot-and-mouth disease, the plumes of the virus can be dispersed over long distances (Gloster, et al., 1981). Therefore, considering both the geographic and trade networks can be important for some non-vector-borne diseases.

The subclinical profile of a disease is an obstacle for the implementation of the MRP. The MRP becomes significantly less efficient when the rate of subclinical cases is high since infected nodes that have not been diagnosed as such spread the disease through both networks until their infection is detected. The length of time between the infection and control has been highlighted as crucial in the literature (Ferguson, et al., 2001). A similar reasoning holds for diseases with long incubation periods or countries with poor detection tools. In the present study, changes in the efficiency of implementation of the control policy (α) have analogous results to changes in the detection rate (γ) since the effective removal of the infected nodes depends on $\alpha * \gamma$.

The introduction of the strategic behavior of farmers into the analysis significantly reduces the efficiency of the MRP. According to the efficiency index proposed above, the anticipatory behavior of farmers facilitates the spreading of the disease and reduces the efficiency of the policy by 61%. When the MRP is implemented farmers that perceive a high risk of getting into the restriction zone will prefer to sell prematurely to avoid the costs of movement restriction. In the case of vector-borne diseases, holdings located close to the RZ have a higher risk of becoming infected, and if the rate of subclinical cases is high or the incubation period is long, their infection may be unnoticed and their premature sales become a risk factor.

As the rank-correlation analysis shows, the longer the hubs remain uninfected, the slower the epidemic will spread. On the one hand, the role of hubs as amplifiers of disease spreading is reduced with the implementation of the MRP, but on the other hand, complementary strategies to control the infection spread focused on the immunization of hubs will be less efficient. This trade-off between the benefits of implementing the MRP and the decrease in efficiency of complementary strategies (focused on the immunization of hubs) should be taken into account when designing an integrated control strategy.

Notice that the risk imposed by the anticipatory behavior is not related to the farmer's compliance with the rules, so anticipatory effects may occur even when farmers report honestly and comply with the movement restrictions. The key element in the model is that the detection tools are not perfect (or the latent period of the disease is long) so a farm could unknowingly sell infected animals.

A monetary transfer is proposed as a simple mechanism to avoid the change in behavior of farmers affected by the policy. In practice, this transfer can be directed to a specific type of farmer since not all farmers have incentives to anticipate. For example, the MRP affects farms specialized in dairy products to a lesser extent than farms specialized in the production of young beef weaned calves, which are sold to fattening units as intermediary products. In fact, during the 2006-2008 bluetongue outbreak the French government provided financial aid only to farmers whose revenue generated by the sale of livestock represented at least 50% (C-DGPEI/SDEPA/C2007-4027) or to the producers of young beef weaned calves (NS-DGPEI/SDEPA/N2008-4019).

Financial aid for farmers located in the RZ reduces the costs associated with movement restrictions and therefore discourages premature sales. When the risk of entering the RZ is significantly larger than a critical threshold ($q_i > \hat{q}$), the transfer is positive. In equation (2), the first element of the transfer ($[p * w_1]/q_i - V - c$) represents the gain from selling prematurely adjusted by the risk of entering the RZ compared with waiting and being unable to sell in the second period. The second element ($(1-q_i)/q_i * [p * w_1 * (1+d) - c]$) represents the discount due to the uncertainty of the event. This discount is given by the odds of not getting into the RZ in the next period that multiplies the gain of selling in the 2nd period.

If the risk of entering the RZ is too high ($q_i \rightarrow 1$) then the discount goes to zero and the government should fully compensate the farmers to avoid the anticipation effects. The rationale for this discount is that the government benefits from the incentive of the seller to wait and sell in the second period (which is the dominant strategy), and therefore does not need to offer the full transfer.

When anticipation effects are considered as a risk factor for the spread of the disease, giving financial aid to farmers facing movement restrictions becomes an issue of public health and the arguments in favor of this measure become stronger. In the past, the rationale for providing financial aid to farmers affected by the MRP was compensatory. We suggest that the provision of financial aid to the affected sector is supported by public health concerns when farmers' strategic behavior can accelerate the spread of a disease.

Additional measures that help in the control of infectious diseases can be classified in three categories: measures oriented to reduce the transmission rate such as vaccination or the use of insecticides in the case of vector-borne diseases; measures oriented to increase the detection rate such as the adoption of new technologies (e.g., thermal scanners) and the implementation of preventive protocols; and measures oriented to detect high-risk zones to target the surveillance.

The third type of measures is only possible through the collection of accurate data and the construction of more reliable models to use these data. The European effort of constructing national databases to register all the cattle movements is a significant advance and should be extended to other species.

Network analysis of the spread of disease that incorporates human responses to policy provides new insight into the efficacy of alternative control measures. Extensions to risk-averse agents and multiple periods are possible.

The current study considers both geographic and commercial networks as potential channels of disease transmission and highlights the relevance of incorporating economic and behavioral elements to evaluate control strategies. However, the work remains theoretical and in order to identify temporal and spatial risk factors of disease spreading the landscape and meteorological conditions should be included in the analysis as well as real data regarding the movement of animals.

4. Materials and Methods

Two-period model to elucidate the anticipating behavior as an optimal strategy

Consider a risk neutral agent who has to choose between selling or not selling in each period ($t=\{1,2\}$). At any time period t, if the farmer decides to sell he receives $I_t = p_t * w_t$, where I_t is the farmer's income at period t, p_t is the market price of cattle at period t (in euros per live weight kg), and w_t is the total weight of the animals being sold at period t. If the farmer decides to keep his animals and wait for the second period, $I_1 = -c$, where c represents the costs associated with keeping the animals for an additional period such as feeding and labor costs. To simplify the problem assume that there is no market risk such that $p_1 = p_2 = p$, and the animals' gain of weight is given by the growth parameter d (i.e. $w_2 = w_1*(1+d)$). If the farmer decides not to sell in period $t=2$ he receives an option value V. If the farmer faces rigid capacity constraints we can assume that V is small enough such that the dominant strategy for the farmer at $t=2$ is to sell (i.e. $V<p*w_1*(1+d)$). Then, if the gain from waiting one period is larger than the costs of keeping the animals (i.e. $c< p*w_1*d$), the strictly dominant strategy is to wait and sell at $t=2$. From now on assume that the parameters of our model are such that the agent's dominant strategy is to sell at period 2.

If an infectious disease is detected at $t=1$, a farmer sufficiently close to the infected zone will face the risk of being located at the RZ in the next period (with probability q_i). If at $t=2$ the farmer is located in the RZ he will not be able to sell. Then the farmer will decide to anticipate and prematurely sells if $p*w_1 > q_i *(V-c)+(1- q_i)*(p*w_1*(1+d)-c)$. We can derive the following expression: $q_i > (p*w_1*d-c)/(p*w_1*(1+d)-V) \equiv \hat{q}$. The right hand side of the expression can be interpreted as a threshold for q. If the farmer perceives a risk of being in the RZ in the next period higher than $\hat{q}$, then he will prefer to sell at $t=1$. If the gain from trading in the first period is larger than the option value associated with not selling minus the costs of keeping the animals one period (i.e. $[V-c] < p*w_1$) the existence of $0< \hat{q} <1$ is assured.

Derivation of the transfer required to discourage anticipating behavior of farmers

The transfer T that makes the agent indifferent between selling and waiting solves the equation: $p*w_1= q_i *[(V-c)+T]+(1- q_i)*[p*w_1*(1+d)-c]$. The left-hand side of the equation corresponds to the certain income that the farmer could receive by selling at the first period, while the right-hand side represents the expected income that the farmer would receive if he waits, under the assumption that if he gets into the RZ the government would pay him T. Therefore, the transfer as a function of q is: $T(q_i) = [(p* w_1)/q_i – (V-c)] – (1-q_i)/q_i * [p*w_1*(1+d)-c]$.

Under the assumptions we have made, $T'(q_i) = q_i^{-2}*(p*w_1*d-c)>0$, so the transfer required to discourage farmers from anticipating is increasing in q, and $T''(q_i) = - q_i^{-3}*(p*w_1*d-c)<0$, so it is concave.

5. Supplementary materials

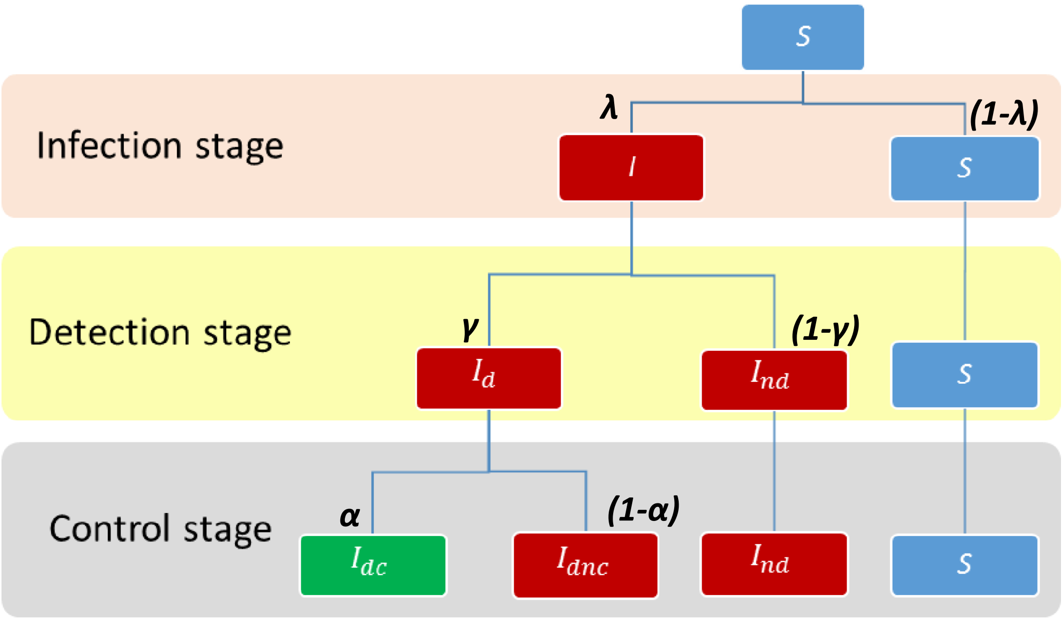

Fig. S1. SI epidemiological model. The diagram represents one time period. It starts with a susceptible node at risk of infection. At the infection stage, the node changes to infected status with probability λ; otherwise it retains the S-status during the whole period. At the detection stage, an infected node is detected with probability γ and adopts the I_d-status; otherwise it takes the I_{nd}-status. When disease is detected the node is removed from the network with probability α. Nodes with I_{nd}-status and those with I_d-status that are not removed (I_{dnc}) remain in the network at least until the next time period when they are again at risk of being detected or removed.

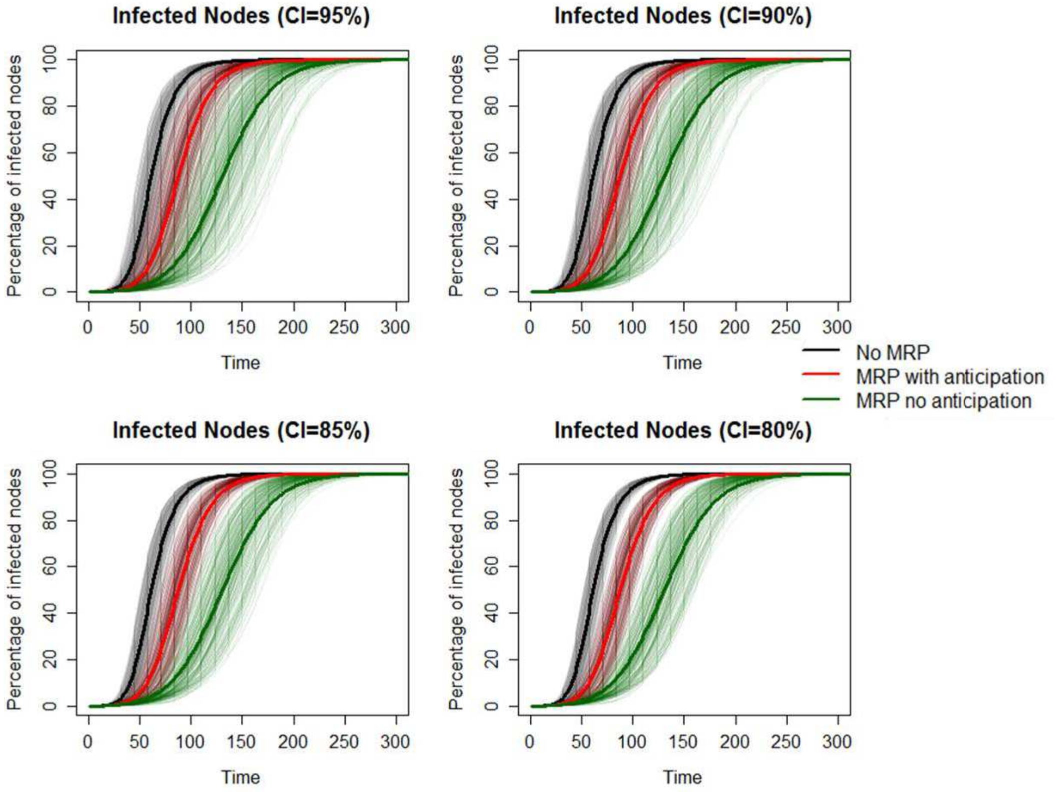

Fig. S2. Overlapping of different scenarios. Comparison of the accumulated number of infected nodes for a disease transmitted through both, the geographic and trade networks, and omitting the most extreme results of the simulations. These are average results over 300 simulations and the parameters used during the simulations are infection rate λ=5%, detection rate γ=20%, and control rate α=100%.

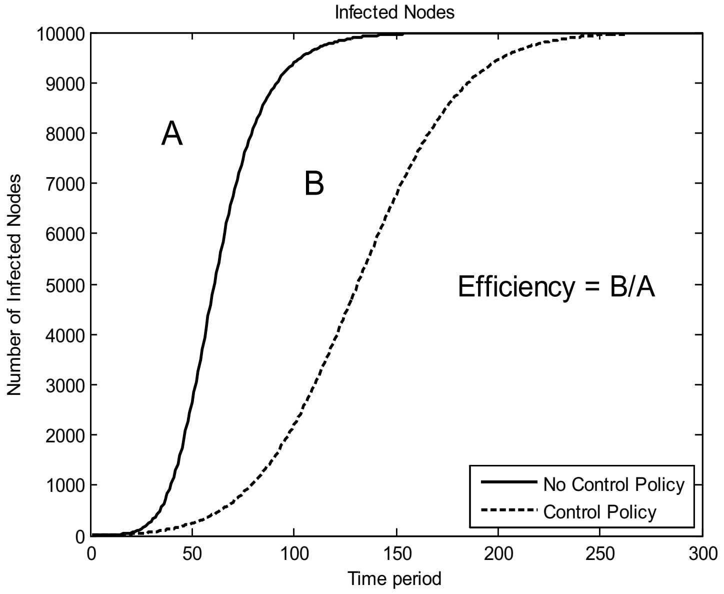

Fig. S3. Efficiency index. The ratio of the areas B/A is proposed as index of efficiency of a policy. These areas are determined by the average number of infected nodes with and without control policy. Area A is fixed in the model and B is policy specific.

Table S1. Main characteristics of the French cattle trade network. Characteristics of the French cattle trade network described by Rautureau (2011) and the associated parameters used to simulate the trade network for the simulations.

	Rautureau (2011)	Model
Size (number of nodes)	244,097	10,000
Farms (number)	242,706	9,942
(% of total nodes)	99.43%	99.42%
Dealers (number)	1,315	54
(% of total nodes)	0.54%	0.54%
Markets (number)	76	4
(% of total nodes)	0.03%	0.04%
Type of network	Scale-Free	Scale-Free
gamma	2.15	2.15

Table S2. Calibration of the probability of selling. Weekly number of farms, dealers, and markets with commercial activity in a specific week and the probability of selling associated used in the

	Rautureau (2011)	Model
	Weekly involved *	Probability of selling**
Farms (mean)	48,179	18.9%
(min - max)	(32,920 - 58,605)	(13.6% - 24.1%)
Dealers	1,001	72.5%
(min - max)	(865 - 1,042)	(65.8% - 79.2%)
Markets	66	85.6%
(min - max)	(57 - 73)	(75.0% - 96.1%)

* This variable represents the number of nodes that have at least one transaction for a specific week.

** This probability is computed as a function of the weekly involved variable

Chapter 3

Taking advantage of diffusion effects in a network to increase the effectiveness of risk communication

Taking advantage of diffusion effects in a network to increase the effectiveness of risk communication

Abstract

The effective communication of risk faces multiple obstacles fueled by several factors such as misperceptions of the exposed population or distrust of the institutions in charge of the communication. The overestimation of risks in a community can lead to the wasteful or counterproductive behavior intended to reduce the perceived risk. In this paper a model using social network tools is introduced to analyze the effectiveness of different risk communication strategies under budget constraints. When the structure of the network describing the links between the members in a community is at least partially known, diffusion effects can be exploited to more effectively communicate about a risk and the ways it may be mitigated. By directing communication to specific targets, accurate risk perceptions are achieved faster and for a larger share of the population than in a generalized random communication framework. The model is illustrated by an application to the health risks of consuming tap water in Nogales, AZ.

Keywords: Risk; Communication; Bottled water; Social networks.

1. Introduction

Risk communication and risk perception are closely related and interact with each other. Without taking into account the potential biases on risk perception and its sources, the effectiveness of risk communication would be compromised. Multiple factors have been detected to influence judgment and choices through risk misperception such as visceral emotions (Lerner and Keltner, 2000) and culture (Douglas and Wildavsky, 1982).

Trust is another element that plays a crucial role in risk communication to bypass the obstacles of accurate risk perception. The level of trust in the authorities responsible for providing the information regarding a certain hazard can determine the success or failure of a risk communication program (Siegrist, 2000).

Problems that lead to risk perception biases are hard to overcome without trust, such as stigma (Edelstein, 1988). Products can be stigmatized following a hazardous event or a scandal, leading to millions in losses to industries related. Examples of this stigmatization can be found for different industries such as the strawberry industry in California (Powell, 2000) due to a microbial outbreak or the beef industry in Europe due to the mad cow epidemics (Vogel, 1995).

The interaction between hazardous events and psychological, social, and cultural factors can lead to the heightening or attenuation of individual and social perceptions of risks (Renn, 1991). This effect is known as social amplification of risk and involves a "transmitter", commonly the mass media, and the interpersonal network of the population at risk (Lofstedt, 2006). But just as the interpersonal network works as a channel to amplify a risk, it can be a useful tool for risk communication too. Risk information can be diffused along a network similarly to technology (Ryan and Gross, 1943), viruses (Shirley and Rushton, 2005), or teaching ideas (Oettinger, 1969).

Over the last decade the study of social networks has been increasingly developed. The findings on scale-free networks have been useful to characterize and understand how networks are structured in the real world (Barabási and Albert, 1999). Compared to random networks, scale-free networks are characterized by the existence of highly connected nodes called hubs. These hubs are the main reason why a message or virus can be diffused very quickly through a social network (Barthélemy, et al., 2004).

The effectiveness of a risk communication campaign depends on the channel used to inform the exposed population as well as on the way the message is designed. It has been proposed that the more entertaining and personalized a message is, the more effective it will be (Valente and Fosados, 2006). However, personalized messages can be very costly, especially when a communication campaign is oriented to a large population.

Opinion leaders are identified as key elements for a successful implementation of a program. They serve as role models for the rest of the people and can legitimate and validate an external message. Methodologies to identify these leaders have been proposed (Valente and Pumpuang, 2007), but no universal and consistent method can be argued (Green, et al., 2009).

The effectiveness of personalized messages along with the existence of leaders and diffusion effects in social networks are the elements exploited in this article to propose an effective design of risk communication campaigns. The rest of the article is organized as follows. In Section 2, a social network model is proposed to understand how information is diffused in a community. In addition, an application to the health risk of consuming tap water in Nogales, AZ is introduced to calibrate the model. In Section 3, the results of the Monte Carlo simulations are presented and discussed along with limitations and possible extensions. Finally, Section 4 provides the conclusions.

2. Methodology

2.1. Social Network Model

Consider a network where each node represents an agent (an individual or a household). For simplification, assume that agents face one single hazard and r_i represents agent i's perceived risk associated to the hazard (e.g., risk of illness). Notice that this is a subjective measure which in principle varies among the population.

Assume that individuals act to reduce a risk if and only if the perceived risk exceeds a threshold of acceptable risk $\hat{r}$. If the perceived risk is above the threshold (i.e. $r_i > \hat{r}$) agent i engages in averting behavior by adopting preventive measures such that the perceived risk is shifted down to the acceptable level ($r_i - \hat{r} = 0$). The approach employed to model the relation between risk perceptions and preventive measures, although oversimplified, allow us to illustrate the main points of the paper.

The adoption of preventive measures is represented by the dummy variable π_i:

$$\pi_i = \pi(r_i - \hat{r}) = \begin{cases} 1 & U(0, c_i) > U(r_i - \hat{r}, 0) \\ 0 & o.w. \end{cases}$$

The cost of adopting preventive measures is represented by c_i and U is the utility function whose parameters are the gap between the perceived and the acceptable risk $(r_i - \hat{r})$ and the cost of adopting preventive measures. The cost of adopting preventive measures is not necessarily financial, for example, an agent can reduce the risk of a deadly car accident by purchasing a safer but more expensive car (financial cost), or simply by using the seat belt (non-financial cost).

Assume that while the perceived risk is private information, the adoption of measures to avert the hazard is public information. Also, it is assumed that authorities have more information than the average population such that they know the hazard's objective risk (r^*). Therefore, a risk communication campaign would be suitable in the following cases:

a) Averting behavior is optimal but it is not adopted by agent *i* ($r_i - \hat{r} \leq 0$ and $r^* - \hat{r} > 0$). In this case by increasing the perceived risk of the population averting behavior can be promoted.
b) Averting behavior is not optimal but it is adopted by agent *i* ($r_i - \hat{r} > 0$ and $r^* - \hat{r} \leq 0$). In this case by decreasing the perceived risk of the population savings can be achieved from discouraging unnecessary averting behavior.

In both cases a risk communication campaign could lead to an increase on social welfare by correcting risk misperceptions and avoiding deviations from the optimal behavior to avert the hazard. In this case the message of the campaign is $\forall i \colon r_i = r^*$.

At every time period *t* the agents can update their risk perception (and therefore their preventive measures to avoid the hazard). The updating can take place due to the influence of a risk communication campaign or by social influence. We refer to social influence as the diffusion of information through the network, i.e. the peer effect.

A limited budget for the risk communication campaign is assumed such that the maximum amount of resources that can be spent is B. The population exposed to the hazard is of size *N* and the cost of the campaign is proportional to the actual population being targeted T ($T \leq N$). The campaign can be targeted to different people by changing the amount spent in each person.

The probability of agent i updating his risk perception to the objective level, i.e. $P(r_i = r^*)$, is increasing on the portion of the budget assigned to inform that specific agent b_i ($b_i < B$). This specification captures the fact that personalized messages are more effective but also more expensive. The deliverance of brochures to the whole exposed population is an example of a large coverage but low personalization campaign; while the visit of a group of experts to a subset of the exposed households to personally inform and provide hard evidence about the risk can be seen as a low coverage but high personalization campaign.

One possible specification for the updating process due to a risk communication campaign implemented at period t is:

$$P(r_{i,t} = r^* | b_{i,t}) = \begin{cases} \frac{b_{i,t}}{b^*} & if\ \ b_{i,t} \leq b^* \\ 1 & otherwise \end{cases}$$

Where b^* is a threshold on the individual expenditure above which people is convinced about the objective risk level. Such specification is appropriate for information campaigns for which hard evidence is possible to collect, such as environmental risks or food related risks. When objective and measurable evidence is provided, the agents update their risk perception to the objective level independently of their initial perception. Once an agent updates his risk perception to the objective level, it will not change unless a new message arrives.

For the second mechanism of risk updating (social influence) we will consider that whenever the risk communication campaign is effective for an agent, he will effectively transfer the message to his peers (who will accept it and therefore update their risk perception to r^*) with probability $q_{i,t}$. The variable $q_{i,t}$ can be seen as the degree of influence[2] that agent *i* has on his peers at time *t*.

This influence can be modeled such that the message is continuously communicated by convinced agents (permanent), or it is communicated only for a limited time (temporary). If the influence is active only during the first *K* periods since adoption, then $\forall (t - k_i) > K: q_{i,t} = 0$, where k_i is the time period at which agent *i* adopted the message. From now on *K* will be referred to as the persistence parameter of the communication campaign.

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[2] It can also be seen as the level of trust that community puts on agent *i* at time *t*.

By assuming independence on the way agents influence each other, the probability of agent i updating his risk perception to the objective level (r^*) due to social influence at period *t* is:

$$P\left(r_{i,t} = r^* \middle| I_{i,t}\right) = 1 - \prod_{j \in I_{i,t}} \left(1 - q_{j,t}\right)$$

Where $I_{i,t}$ is agent *i*'s set of peers (nodes in the network directly connected to node *i*) transferring the message of the risk communication campaign at period *t*.

2.2. Application to health risk of consuming tap water in Nogales, AZ

In recent years, alternatives to tap water have gained popularity among the world population, even in countries where tap water is generally safe such as the U.S. (Gleick, 2010). One of the main reasons of this increase in bottled water is related to the perceived risk of drinking tap water (Anadu and Harding, 2000), which in many cases could be overestimated. For example, a study in Nogales, AZ, found that people consider tap water to be significantly more risky than smoking and as risky as drinking and driving (Victory, et al., 2014).

In the U.S., municipal water systems serving 25 people or more are subject to the federal Safe Drinking Water Act, and therefore the water is routinely tested for harmful substances (Bullers, 2002). According to 2012 data published by the Arizona Department of Environmental Quality, 0% of the samples collected in the county of Santa Cruz (where Nogales is located) were positive for E. Coli and just 0.7% were positive for any coliform (Safe Drinking Water Information System).

Despite the surveillance and treatment efforts to provide safe drinkable water, the average household at Nogales spends more than two hundred times the cost of tap water in some alternative perceived as safer (Victory, et al., 2014). In a community with 36.5% of the people living below the federal poverty level (U.S. Census Bureau, 2012) the reallocation of households' resources from bottled water to other necessities could lead to welfare improvements. One way to achieve this is through an effective communication of the objective risk related to consuming tap water.

Some studies have proposed that agents are more willing to adopt behaviors that others in their same social network have already adopted (Scherer and Cho, 2003). This social influence can be seen as one of the most challenging obstacles for people to accept tap water as safe to drink in

Nogales because: studies have shown that immigrants from countries with poor drinking water quality are less likely to drink tap water (Hobson, et al., 2007); the Nogales community has a very large proportion of people with Hispanic or Latino origins (95%) with a predominance of Mexican origins (90% out of the people with Hispanic or Latino origins) (U.S. Census Bureau, 2010); and it has been documented that Mexico has the highest rate of bottled water consumption in the world (IDB, 2010).

Besides the convenience of easy access to drinkable water, the climate conditions (average temperature in summer around 95F), and the poverty levels align the incentives to drink tap water in this community, but these are offset by the perceived health risk. Therefore, a campaign to effectively communicate the objective risk associated with drinking tap water can improve the total welfare of the community by saving resources that nowadays are used to finance non-optimal averting behavior (bottled water).

Two strategies for a risk communication campaign will be analyzed. The first one is extensive in the sense that it targets the whole community by assigning the same share of the budget for each member ($\forall i, b_i = \frac{B}{N}$) and ignores the structure of the social network. The second strategy is intensive in the sense that it concentrates the budget to inform a specific subset of the community about the objective risk, taking into account the structure of the social network ($b_i \in [0, B], \sum_{i=1}^{N} b_i = B$).

The main targets of the intensive strategy should be those that deliver the highest benefits with respect to social influence. The idea is to select hubs (highly connected nodes) as targets and concentrate the resources to be sure of being communicating effectively the risk to these hubs.

The selection of the main targets is crucial for the second strategy to be effective, and the characteristics of the community can be used to identify them. Nogales is a community composed of 6,601 households (in 2010) with a large Hispanic population (95%). Hispanic populations are characterized by the important role that religion plays in their personal life and community affairs, so in the case of Nogales religious institutions become an attractive target for communication campaigns.

In order to parameterize the model, information regarding the religious affiliation and trust in religious institutions are needed. Since there is no information about religious affiliation in

Nogales, U.S. average figures are used instead. It has been estimated that 70% of the Hispanic population in the U.S. is Catholic (Perl, et al., 2006), and around 55% of Hispanic Catholics in the U.S. attend mass at least once a month (CARA, 2013), with 21% attending at least once every week. Moreover, according to the 2013 Gallup survey on confidence in institutions (Gallup, 2013) 48% reported to have high levels ("great deal" and "quite a lot") of confidence on the "church or organized religion", and 32% reported to have "some" confidence.

These descriptive statistics can be seen as information regarding the social network of Nogales community. Only two churches exist in this community, so they are natural targets for the risk communication campaign. By communicating effectively the safeness of drinking tap water to the leaders of the churches, the message can be diffused to the rest of the network.

To compare the two strategies we perform Monte Carlo simulations following the transmission model previously described on a semi-parameterized scale-free network[3]. The degree of influence ($q_{i,t}$) of the two nodes identified as churches is derived directly from the data collected by the Gallup survey, whose responders with high levels of confidence in the church account for 48% of the sample. Since we do not have information regarding the influence of every household in the community, for the rest of the network the degree of influence is derived from the relative degree of each node with respect to the maximum degree in the network (excluding both churches)[4], and assumed to be constant over time:

$$q_i = \frac{degree_i}{\max\limits_{j \in J}\{degree_j\}}$$

,where $degree_i$ is the number of connections that household i has in the community and J is the set of households in the community excluding the parameterized ones (the churches). By

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[3] We simulate a scale free network with parameter λ=2.5 (so the probability of a node having k neighbors is given by $P(k) = k^{-\lambda}$), and 6,600 nodes (mimicking the number of households in Nogales). Once the network was constructed, the two nodes with highest degree were modified adding random connections to match the degree associated to each of the churches considering that the percentage of Hispanic population in Nogales (95%), the percentage of catholic among Hispanic population in the USA (70%), and the percentage of Hispanic Catholics that attend Mass every week (21%). Additionally, it is assumed that both churches have the same number of followers.

[4] More complex ways to model the degree of influence can be thought, for example, we can consider both, the degree of the node sending the message and the degree of the receiver, and consider that high-degree nodes have more influence on similar peers, but low-degree nodes will be more influential on low-degree peers.

modelling the degree of influence in this way the nodes with more connections are also more influential.

The so called “random” strategy considers that the budget is equally split among the whole population (N), therefore $\forall i \colon b_i = \frac{B}{N}$. On the other hand, the “specific target” strategy first assigns the budget, up to b^*, to the identified hubs and the remaining is equally distributed among the rest of the population. In our application these hubs are the leaders of the two churches in Nogales. For budgets smaller than $2 * b^*$, two types of specific-target strategies are considered: a first strategy assigning b^* to one of the hubs and the remaining budget assigned to the other one, and a second strategy where the budget is equally distributed among the hubs $\frac{B}{2}$.

The strategies are evaluated under different scenarios, which are defined by combinations of budgets (relative to b^*) and persistence levels. Notice that in a network with N nodes, a budget of $N*b^*$ would lead to adoption by the whole network in period 1. However this would require extremely large budgets in real world applications, so in our simulations we will focus on relatively small budgets. In the baseline scenario we will consider a budget $B = 2 * b^*$, and a 4-period persistence. Different budgets and persistence levels are considered for the sensitivity analysis.

To compare the strategies under different scenarios, a measure of the efficiency is proposed using the mean trajectory of adopters derived from each strategy. Define the efficiency index as the proportional time-weighted number of adopter nodes associated with a strategy after 100 periods of being implemented (i.e., the area below the curve of accumulated adopter nodes under a specific strategy divided by 100*N). Notice that this index ranges from 0 to 1, where 0 is associated with a totally ineffective communication campaign (zero adopters), and 1 is associated with a campaign that makes the whole population to adopt at the first period.

3. Results and Discussion

The efficiency index of both strategies under different scenarios are summarized in Table 1. According to the proposed measure, in all scenarios the specific-target strategy dominates the random strategy.

The expected number of initial adopters is equal to 2 under both strategies. However, after 100 periods the average share of the population who adopts the message is 73.5% under the specific-target strategy, compared with 29.9% under the random-target strategy. The mean trajectory for both strategies is displayed in Figure 1A.

In the framework of Nogales and assuming a 58 gallons (2013's Beverage Digest figure) of water consumed annually per-capita (exclusively for drinking purpose), the benefits associated with a 73.5% adoption rate of the tap water safety message would lead to yearly savings on the order of 840,000 to 2 million USD[5], without accounting for non-monetary benefits. On the other hand the yearly benefits linked to the 29.9% adoption rate of the random-target strategy are between 340,000 and 815,000 USD. In average, more than 800,000 USD in annual savings could be achieved by the specific-target strategy compared with the random one.

Table 1. Efficiency index for random-target and specific-target strategies

	Budget					
Persistency	Baseline (2b*)		2.5x (5b*)		5x (10b*)	
	Random	Specific	Random	Specific	Random	Specific
4 periods	0.25	0.69	0.42	0.69	0.58	0.69
100 periods	0.64	0.90	0.78	0.90	0.84	0.90

Although Figure 1A is informative, the story behind these trajectories cannot be inferred without looking at the whole set of simulations. Figure 1B shows that the random strategy basically has two different set of outcomes. In the first one, which materializes in more than 50% of the simulations, the effect of the communication campaign dies out almost immediately since the initial adopters are not able to convince their peers to adopt the message[6]. The second set of outcomes is characterized by the efficiency of the initial adopters to convince their peers and the final outcome is very similar to those of the specific target strategy.

The adoption rate of the message during the first periods is crucial for the success of the campaign. In order for the communication campaign to be successful, a sufficient number of households should adopt the message during the first periods, after which diffusion effects are well set in place and small amount of heterogeneity is observed in the trend of adopters.

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[5] The range is stablished by the cost associated to bottled water. Estimations of the cost of bottled water go from 200 times to 1,000 times higher than tap-water, for which the price is estimated around 45 cents per 100 gallons (Victory, et al, 2014). For the construction of the intervals we decided to use 200x and 500x to establish the limits.

[6] These outcomes are hard to visualize in the graph since they all overlap and display as a single horizontal line. Supplementary figure S1 shows the same results in more detail.

The mean trajectories of the number of households adopting (Fig. 1A) can be seen as the expected outcome of the strategies associated to the original ones, which are useful to compare the efficiency of both strategies. The bimodality of the random strategy is not captured by the mean trajectory, but the comparison of the strategies by this measure remains valid nevertheless[7].

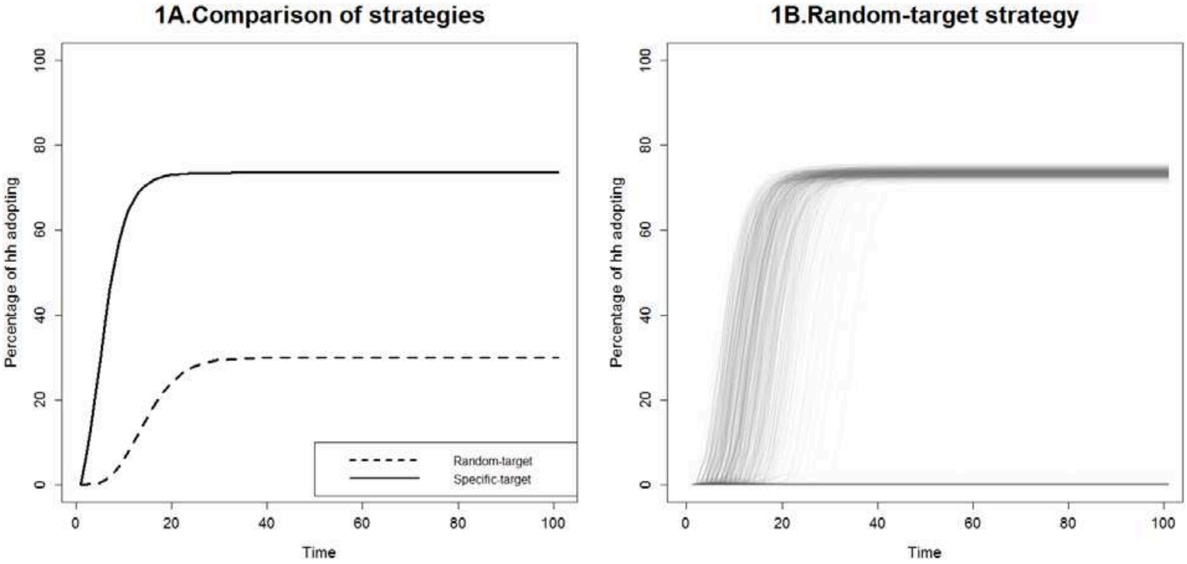

Fig 1. Accumulated number of households adopting the message of the risk communication campaign. These are results over 1,000 simulations, with 6,600 nodes, a 4-period persistence, a small budget ($B = 2 * b^{*}$), and the degree of influence of the nodes identified as churches equal to 0.48. **(1A)** According to the mean trajectory of households adopting the specific target strategy is significantly more effective than the random strategy. **(1B)** Trajectories of the 1,000 simulations under the random-target strategy.

Regardless the strategy being implemented, there is a share of the population that never adopts. These are nodes with a small number of neighbors which have small number of connections too. These hard-to-reach nodes are also hard to convince since the credibility of their peers is low by construction.

Budget effect

The effectiveness of the random-target strategy increases with the size of the budget, while the effectiveness of the specific-target strategy remains unchanged (except for very large budgets such that a large share of the population adopts since the first period).

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[7] A risk-neutral decision maker is indifferent between strategies providing the same expected outcome, indifferently of their associated variance, while a risk-averse would prefer strategies with lower variance, and might even prefer strategies with lower expected outcome but lower variance (certainty-equivalent strategy).

As the budget increases, the outcomes of the two strategies converge and the gains of targeting the hubs is lost. However, as Figure 2 shows, the increase in the budget required to match the effectiveness of both strategies might be large.

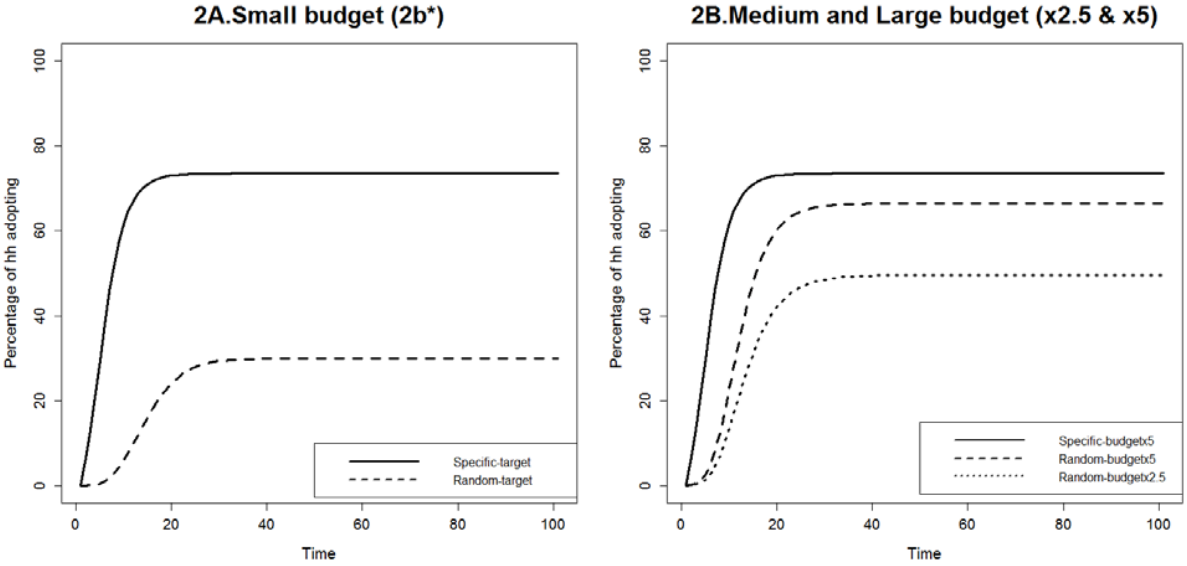


Fig 2. Accumulated number of households adopting the message of the risk communication campaign. These are mean results over 1,000 simulations, with 6,600 nodes, a 4-period persistence, and the degree of influence of the nodes identified as churches equal to 0.48. **(2A)** When the budget is small ($B = 2 * b^*$) the specific-target strategy is significantly more effective than the random strategy. **(2B)** As the budget increases, the outcomes of both strategies approach.

Notice that the outcome of the specific-target strategy is not affected by the increase in the budget. In fact, the benefits of an increase in the budget are overwhelmed by the benefits associated to the initial targeting. Both type of benefits are received only in the first period, but the final outcome depends more on the structure of the network than on the initial number of adopters (unless this is very large).

When the budget is smaller than in the baseline scenario ($B < 2 * b^*$) it is no longer possible to target the campaign in such a way that both hubs adopt with certainty. If we consider half the budget of the baseline scenario ($B = b^*$) then it could be split equally among the hubs (so the probability of adopting would be 0.5 for both), or it could be assigned completely to one of these hubs. By construction both hubs have the same number of edges so there is no difference between targeting one or the other.

Figure 3 displays the mean outcomes when $B = b^*$. There are 3 strategies represented, the random-target strategy and two specific-target strategies: the first one assigns the whole budget to send the message to only one of the hubs, while the second one splits the budget equally so the budget assigned to each of the hubs is $\frac{B}{2} = \frac{b^*}{2}$. The dominant strategy is to assign the whole budget to one of the hubs because if the budget is split, there is a 25% chance of none of the hubs adopting the message and therefore the message is never transmitted through the network.

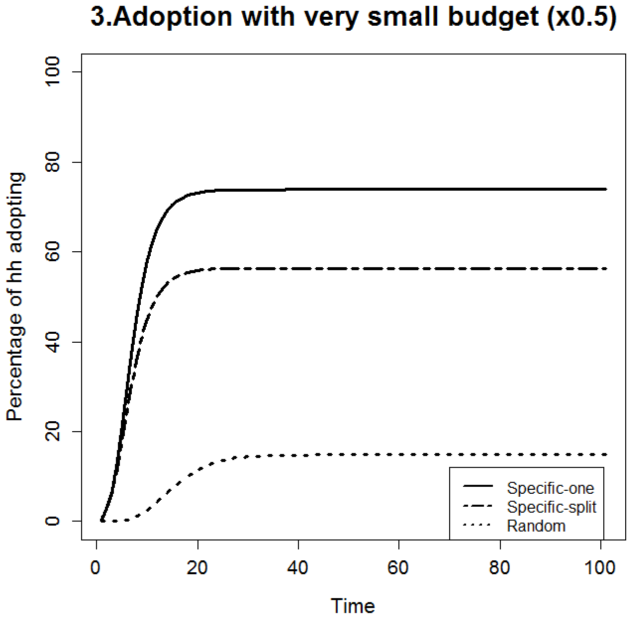


Fig 3. Accumulated number of households adopting the message of the risk communication campaign. These are mean results over 1,000 simulations, with 6,600 nodes, a 4-period persistence, a very small budget ($B = b^*$) and the degree of influence of the nodes identified as churches equal to 0.48. The label "Specific-one" refers to the strategy that assigns the whole budget to one of the hubs; "Specific-split" refers to the strategy that assigns half of the budget to each of the hubs; "Random" refers to the random-target strategy.

Persistence effect

The persistence parameter associated to the diffusion of the message is one of the most relevant parameters for the final outcome of any strategy. It reduces the advantage of the specific-target strategy, whose benefits are reduced to the speed of adoption and it becomes less relevant for the final outcome (share of adopters) (Figure 4).

Since the credibility of the households is not perfect (equal to 1), the fact of extending the number of periods during which an adopter transmit the message to his peers increases the probability of adopting the message for all nodes, including those hard to reach and hard to convince. Since the adoption process is independent over time, the probability of adopting the message for a node linked to n adopters increases by $1-\prod_{k=1}^{n}(1-q_k)$ for every additional period on the persistence of the strategy (where q_k is the influence of peer k).

Therefore any efforts to convince people about their relevance in communicating the message continuously over time could lead to large improvements on the outcome of a communication campaign under any strategy.

In situations where households face costs to communicate the message to their peers, the advantages of the diffusion effects can be severely dampened and the dominance of the specific-target strategy over the random-target could disappear since the expected number of households convinced by each strategy at the very first period (when the communication campaign is launched) is the same for both strategies. Also, in a community characterized by a fragmented network the extensive random-target strategy could lead to better outcomes by making individuals of different sectors to adopt.

The current framework does not deal with the heterogeneity on the risk perception of the agents (low versus high r_i) and considers that the agents' decision to adopt (due to the communication campaign or to the peer effect) is independent from their initial perception. Moreover, it is assumed that the adoption of preventive measures is a binary choice. Extensions to our model could help to understand the heterogeneity on the preventive measures adopted by the agents (partial risk reductions).

It is important to highlight that there are multiple ways to model the diffusion and adoption of the message coming from a risk communication campaign. The framework explored in this document is restrictive in some dimensions and has its drawbacks, but it accomplish the main objective which is to explore the benefits of specific targeting in a risk communication campaign under a limited budget.

4. Conclusions

In a risk communication campaign whose objective is to eliminate subjective biases in a population associated to the risk of a specific activity, exploiting the way information diffuses along a social network can lead to better outcomes. The benefits of using the network characteristics to find the optimal targets for the campaign can be large, especially when the budget is small. However, as the budget increases the benefits of specific targeting are reduced because the difference between both strategies is reduced and in the limit, when the budget is sufficiently large in order to convince the whole population, both strategies are exactly the same and lead to the same outcomes. The cost-effectiveness of the strategies depends on the size of the budget, and for large budgets both strategies are equally cost-effective.

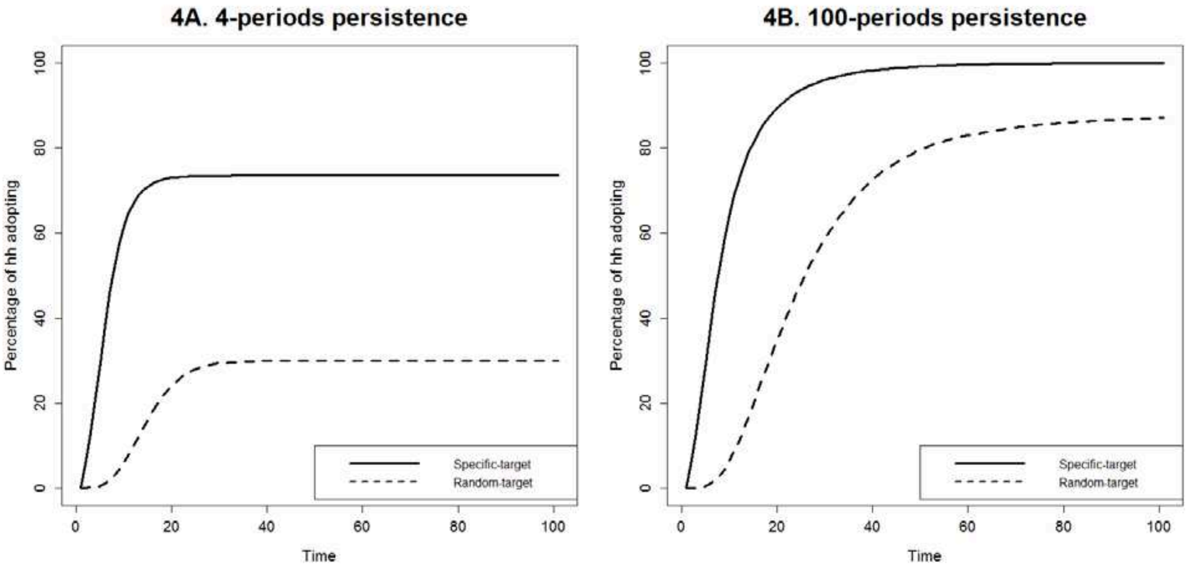


Fig 4. Accumulated number of households adopting the message of the risk communication campaign. These are mean results over 1,000 simulations, with 6,600 nodes, a small budget ($B = 2 * b^*$), and the degree of influence of the nodes identified as churches equal to 0.48. **(4A)** Outcome of the specific-target and random-target strategies with a 4-periods persistence. **(4B)** Outcome of the specific-target and random-target strategies with a 100-periods persistence.

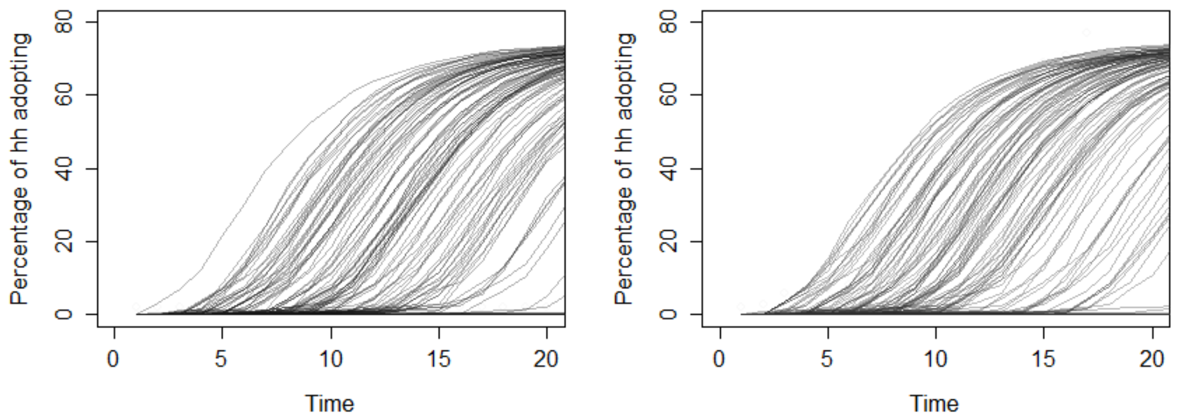
The persistence at which adopters transmit the message to their peers becomes a key parameter for the final outcome under any strategy. The whole idea of exploiting the diffusion effects relies on the ability of households to convince their peers to adopt the message. Risk communication campaigns should emphasize the importance of adopters' active participation to achieve the best possible outcome.

In the case of a campaign looking to eliminate biases regarding the perceived risk of drinking tap water in Nogales, AZ, the specific-target strategy could lead to additional savings around 800,000 USD per year, compared with the random-target strategy.

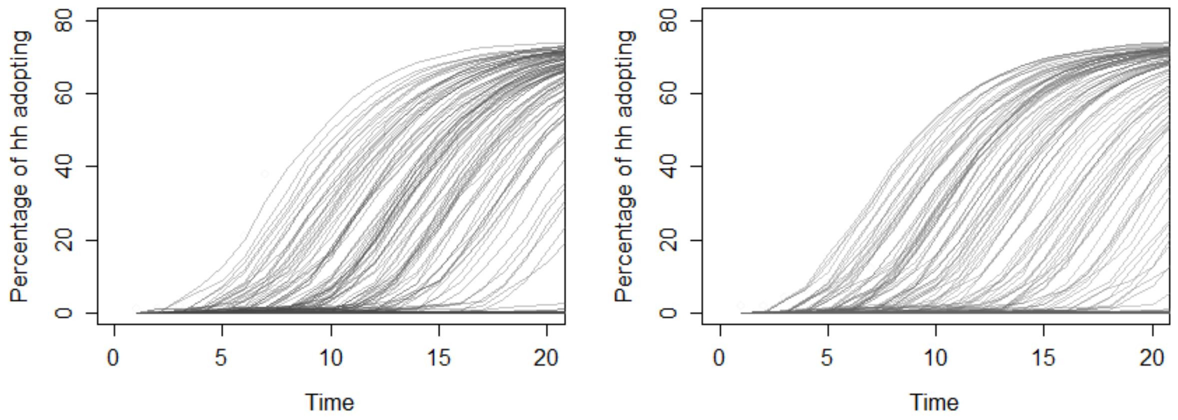
The identification of hubs might be a difficult and expensive task but the benefits from identifying them can easily overcome such costs, therefore re-allocation of resources from the size (extension) of the campaign to the identification of key targets make sense even in cases with tight budget constraints.

These results can be seen as evidence advocating for regional and small-scale interventions rather than big-scale ones in the design of risk communication campaigns. Governmental agencies or NGOs looking to efficiently communicate risks associated to certain activities should analyze the characteristics of the population to which they are addressing since the success of their campaign might depend on it.

5. Supplementary material


S1A.Random-target strategy (1:250)

S1B.Random-target strategy (250:500)


S1C.Random-target strategy (500:750)

S1D.Random-target strategy (750:1000)

Fig S1. These are the same results displayed in Fig. 1B but using amplified scale and displayed in sets of 250 outcomes each to observe with more detail the adoption of the message over the first 20 periods. They correspond to the results of the random-target strategy over 1,000 simulations, with 6,600 nodes, a 4-period persistence, a small budget ($B = 2 * b^{*}$), and the degree of influence of the nodes identified as churches equal to 0.48. Although the results of the simulations are not strictly parallel lines, the homogeneity regarding the degree of the households creates this effect.

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