Integrative modelling of pathogen spread through animal trade by accounting for farmers' control decisions

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Context

- **Pathogen spread** : Livestock disease.

  - Dynamic, stochastic.

- **Network structure** : Trade network.

  - Directed, weighted, scale-free, stochastic.

- **Human decision-making** : adoption of voluntary **control measures** (endemic unregulated disease).

  - Learning, imitation, etc.

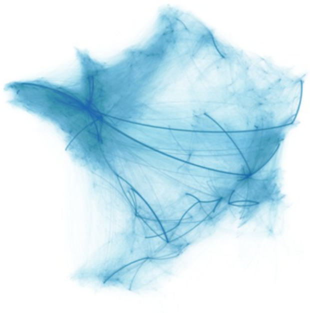


FIGURE – Cattle trade flows (dairy animals only) for year 2009. Source : Gaël Beaunée from French BDNI data base.

Integrative models

State of the art and Challenges

- Most research in behavioral epidemiology regarding the voluntary adoption of sanitary measures relies on the assumption of a homogeneous mixing population [Wang et al., 2016]. Ex : [Perrings et al., 2014]

  $\Longrightarrow$ network structure

- Research works on infectious diseases and the adoption of measures on networks normally does not (need to) consider individual human decision-making [Wang et al., 2016]. Ex : [Scaman et al., 2016]

  $\Longrightarrow$ human decision-making

- Research on behavior-disease dynamics focuses on human diseases, and has barely been applied to veterinary epidemiology yet [Horan et al., 2010]. Ex : [Kuga et al., 2019]

  $\Longrightarrow$ livestock disease

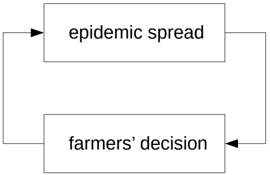
- Research that concerns farmers behavior focuses on regulated diseases, so farmers' strategic behavior consists on delaying the application of a central policy. Ex : [Tago et al., 2016].

  $\Longrightarrow$ unregulated diseases

Objective

Need for an **integrative model** that couples :

- The dynamics of a livestock epidemic on a regional scale with a network structure.
- The dynamics of farmers' behavior regarding the voluntary adoption of a control measure on the spread of the disease.



Epidemic model with demography on a meta-population trade-network

Intra-herd stochastic SIR model with demography (births, deaths) + trade network (inter-herd animal transfers). Modeled as a Continuous-time Markov Chain (CTMC).

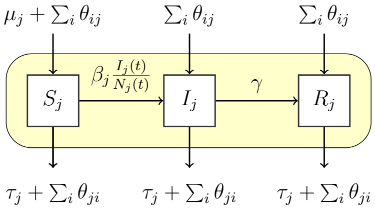


FIGURE – Graphical representation of the intra-herd transmission for any herd *j*

- β_j : infection rate in herd *j*.
- γ : recovery rate.
- τ_j : death rate in herd *j*.
- μ_j : birth rate in herd *j*.
- θ_{ji} : trade rate from herd *j* to herd *i*.

Farmer's dynamic decision problem

We suppose that each farmer $j = 1, ..., J$ searches to solve :

$$\min_{a_j^t} \mathbb{E}\left[C^t_{a_j^t}(j)\right] \quad ; \quad t = \Delta_d, 2\Delta_d, 3\Delta_d...$$

- $a_j^t \in \{0, 1\}$: **decision**, i.e. control decision taken at decision time t by farmer j. It is either equal to 1 (applying the measure at time t) or 0 (not applying it).
- $C^t_{a_j^t}(j)$ is the **cost** in herd j associated with the decision a_j^t taken at time t. Stochastic since depends on stochastic epidemic spread. The cost distribution associated with each possible decision is unknown to the farmers.

Farmer faces a dynamic decision problem under uncertainty.

Farmer's decision mechanism

We adopted an approach, inspired by [Kuga et al., 2019], [Wu and Zhang, 2013] etc. in which the result of a decision is evaluated after being applied and preferences are updated through time.

Algorithm : Exponential weighting mechanism with imitation

Input : $p_1^{\Delta_d}(j) := p_1^{init}\ \forall j\,;\ \kappa \geq 0\,;\ \rho \geq 0\,;\ Neigh(j, \overrightarrow{G}) = \{i; \theta_{ij} \neq 0 \text{ or } \theta_{ji} \neq 0\} \quad \forall j.$

For : $t = \Delta_d, 2\Delta_d, 3\Delta_d \ldots$ at each **decision time** :

- **For :** $j = 1, \ldots, J$ each **farmer** :
  - $a_j^t \sim Bin(p_1^t(j))$ **chooses decision** according to his/her current probability
  - $a_j^t \rightarrow C^t_{a_j^t}(j)$ **observes cost**.
  - $j^* \sim Unif\{Neigh(j, \overrightarrow{G})\}$ **selects neighbor in the trade network**
  - $a_{j*}^t \rightarrow C^t_{a_{j*}^t}(j^*)$ **observes neighbor's decision and cost**
  - Let $C^t_{1-a_j^t}(j) = 0 = C^t_{1-a_{j*}^t}(j^*)$. **Update the probability** of applying the measure :

$$p_1^{t+\Delta_d}(j) = \frac{p_1^t(j) e^{(-\kappa C_1^t(j) - \rho C_1^t(j^*))}}{p_1^t(j) e^{(-\kappa C_1^t(j) - \rho C_1^t(j^*))} + p_0^t(j) e^{(-\kappa C_0^t(j) - \rho C_0^t(j^*))}}$$

A cost function for a given control measure

Protective vaccine

If the vaccine is applied on a susceptible animal in herd j at time t, the rate of transmission towards that susceptible during the period $]t; t + \Delta_d]$ is : $\beta_j^v = \beta_j(1 - e_v)$; $0 \leq e_v \leq 1$ is the **efficacy** of the vaccine.

Cost function of applying the measure or not :

$$C^t_{a^t_j}(j) := \frac{[CF_v + CU_v N_j(t)]a^t_j + \phi r N_{S_j \to I_j}(t, t + \Delta_d)}{\Delta_d \overline{N_j}(t, t + \Delta_d)}$$

- r := **monetary value** of a healthy animal.
- $0 \leq \phi \leq 1$:= **rate of reduction** of r if the animal gets infected.
- CU_v := **unitary cost** of the vaccine (per animal).
- CF_v := **fixed cost** of the vaccination (per herd).
- $N_j(t)$: = size of herd j at time t.
- $N_{S_j \to I_j}(t, t + \Delta_d)$: = no. of infections in herd j over the period.
- $\overline{N_j}(t, t + \Delta_d)$: mean size of herd j over $[t, t + \Delta_d[$

Scheme of the integrative model

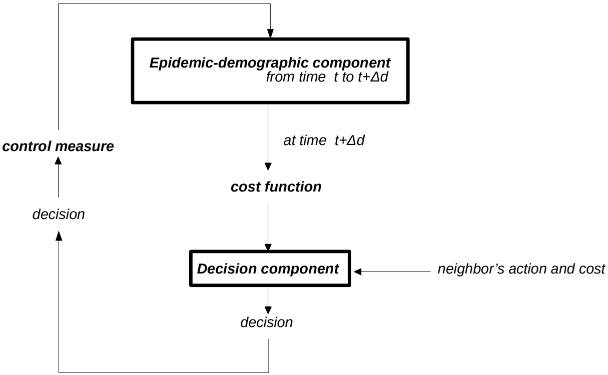


FIGURE – Schematic representation of the integrative epidemic-decision dynamics for a herd j

Parameters of the model

Fixed simulation setting : 5000 herds, fixed demographic parameters, fixed simulated network structure (∼ *Finistere*)

Epidemic parameters :

1. Prop. of initially infected nodes : 0.1
2. Prop. of infected animals in initially infected nodes : 0.15
3. $1/\gamma$: 90 (days)
4. β/γ : 2.0

Economic parameters :

5. Healthy animal value *r* : 2000 (euros)
6. Loss of healthy animal value (ϕ) : 0.8
7. Fixed cost of the vaccine : 50 (euros)
8. Unit cost of the vaccine : 5 (euros)

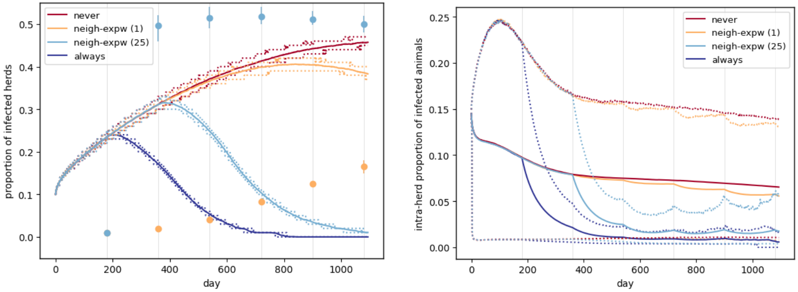
Decision-related parameters :

9. Protection efficacy of the vaccine : 1
10. Duration of decision (and of vaccine efficacy) : 180 (days) $\sim$ 6 months.
11. Initial probability of vaccinating : 0.01
12. κ (Sensitivity of the farmer to his/her own cost) : 1 or 25
13. ρ/κ (Ratio of sensitivity of the farmer to the costs of any neighbor and κ) : 0.5

Simulation results

Epidemic spread over 3 years

- Global gain of vaccination does not concern intra-herd prevalence but inter-herd prevalence.
- Farmers' sensitivity to costs, κ and $\rho(=\kappa/2)$, determine the proportion that vaccinates from the second decision time, and how quickly the inter-herd prevalence declines.



(a) Inter-herd prevalence. Mean, 10th and 90th percentiles over runs. Points are the mean, 10th and 90th percentile of the proportion of herds that vaccinated at each decision-time with $\kappa = 1$ (orange) and $\kappa = 25$ (light blue).

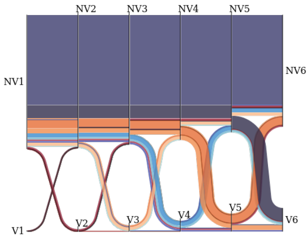
(b) Intra-herd prevalence. Mean of means, 10th percentile of the 10th percentiles, and 90th percentile over 90th percentiles, over runs and herds.

FIGURE – Temporal dynamics of the epidemic spread for each of the four vaccination scenarios over 50 runs.

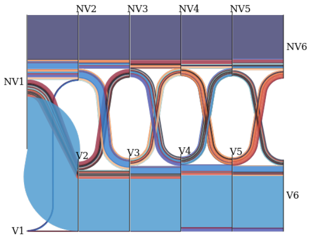
Simulation results

Decision patterns over 3 years

- At each decision time a group of herds change their immediately previous decision. The group of herds that changes its immediately previous decision is not always the same.



(a) $\kappa = 1$, $\rho/\kappa = 0.5$



(b) $\kappa = 25$, $\rho/\kappa = 0.5$

FIGURE – Temporal dynamics of the vaccination decisions using the proposed decision mechanism with different values of κ and ρ. NV stands for not vaccinating, while V for vaccinating. Each color represents a different vaccination pattern, where the width of the bars is proportional to the frequency of the pattern. Results for one run.

Sensitivity Analysis

Sensitivity Analysis (SA) was used in order to study how much the **variation** in each input of the model contributes to the variation of the model's outputs [Saltelli et al., 2008].

- **Inputs :** 13 parameters in total (slide 11). Other parameters were fixed as specified earlier.
- **Outputs :** we considered several outputs corresponding to the three model components : epidemic, economic, decision-related.
- **Fractional Factorial design** with 5 levels (IV-resolution design), and **ANOVA** [Van Schepdael et al., 2016] : 625 parameter combinations. Since the model is stochastic, we did 50 runs for each parameter combination.

Multivariate sensitivity analyses : PCA + ANOVA .[Lamboni et al., 2011]

Outputs

Epidemic :

1. Proportion of infected herds at final time T.
2. Mean proportion of infected animals at final time T (over infected herds at time T).
3. Proportion of herds infected at least once.
4. Mean number of new infectious animals in herds that got infected at least once.
5. Mean rate of new infectious (over susceptible animals) in herds that got infected at least once.

Economic :

6. Total economic cost of the epidemic.

Decision-related :

7. Mean proportion of herds that vaccinate, over the different decision times. Not including first decision.
8. Proportion of herds according to vaccination aggregated pattern :
[Never vaccinate, $\leq$ than half of the time but not never, $>$ than half all of the time but not always]. Not including first decision.

Epidemic-decision related :

9. For each group of herds defined by the vaccination aggregated patterns : Cumulative number of new infections / cumulative number of susceptible animals, over the herds of the pattern that got infected at least once. Not including first decision.

SA results

2nd experiment : means of all outputs

When fixing epidemic parameters, the most influential parameters on the variation of the mean over runs are the vaccine efficacy and the duration of the decision, followed by the initial probability of vaccinating.

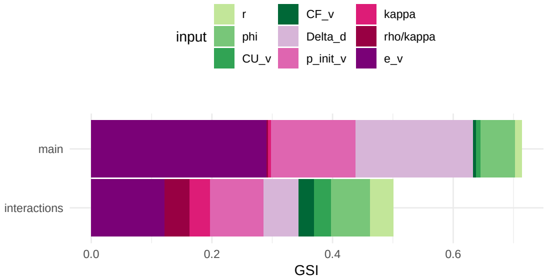


FIGURE – Global Sensitivity Indices (GSI) of the retained dimensions by the PCA on the means over runs of all outputs in the second experiment. Sensitivities are split in main effect and two-factor interactions.

The **duration** of the decision, i.e. the time between two consecutive decisions, had a **negative impact on vaccination**, and therefore on limiting the disease spread.

Conclusion

- Elaborated an original **integrative model** coupling two sub-models :

A. **Meta-population stochastic epidemic** on an **explicit graph** with demography.

+

B. **Farmer's decision model.**

- Farmer's **decision problem**
  - Binary decision on a control measure.
  - Cost : function of the epidemic spread and therefore of the decision.
- Farmer's **decision mechanism**.
  - Learning.
  - Stochastic behavior.
  - Imitation.

- Model studied through **simulations** and **sensitivity analysis**.

→ First publication : to be submitted.

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