Accounting for farmers' control decisions into models of pathogen spread through animal trade

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Presentation overview

1. Context and motivation

Endemic livestock diseases

2. Decentralised decision-making:

modelling human behaviour

3. Application on BVD extension

Endemic livestock diseases

- Metapopulation network: animal trade network
  - sub-populations: herds
  - movement of individuals: animal exchanges

Figure: Source: Gael Beaunée

- Disease spreading through animal trade has high chances of becoming endemic
  - Important economic & animal health impact
  - Yet, not as much efforts to eradicate compared to epidemics
    $\rightarrow$ control is not compulsory
  - Individual management: farmers decide alone $\Longrightarrow$ decentralised

Epidemiological modelling challenges

- Control on unstructured populations, on non-metapopulation networks or on small networks (e.g. [Perrings et al., 2014])

  ⟹ large metapopulation network

- Decentralised: control mostly without voluntary decision-making [Wang et al., 2016]

  ⟹ human behaviour

- Focus on human diseases (barely applied to veterinary epidemiology yet) [Horan et al., 2010] (e.g. [Kuga et al., 2019])

  ⟹ livestock disease

- Focus on regulated diseases (e.g. [Tago et al., 2016])

  ⟹ unregulated diseases

Decentralised decision-making:

modelling human behaviour

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Framework

Each **farmer** $j = 1, ..., J$ searches to make dynamic decisions regarding the adoption of a control measure in his/her own herd, that minimise a cost that depends on the disease spread

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

- $a_j^t \in \{0, 1\}$: **decision**, i.e. control decision taken at decision time t by farmer j
  - 1 (applying the measure at time t)
  - 0 (not applying it)
- $C^t_{a_j^t}(j)$: **cost** in herd j associated with the decision a_j^t taken at time t
  - Stochastic (depends on stochastic disease spread)
  - Unknown cost distribution associated with each possible decision

Farmer faces a dynamic decision problem under uncertainty

State of the art

Main issue

Representing human behaviour in a context of many networked agents

Some approaches:

- Evolutionary game-theory (EGT): focuses on the dynamics of strategy change in populations [Smith, 1982].
  - + stochastic & no rationality & cognitive constraints & imitation
  - - no learning
- Multi-armed bandits (MAB) [Auer et al., 2002] choose at each time among several possibilities to maximise an expected gain, with uncertainty in the result of the choice in advance.
  - + stochastic, learning, generic formalisation
  - - not human decision-maker

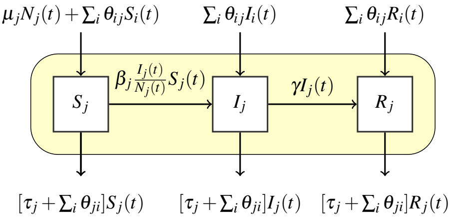
Our approach

- Elaboration of an integrative model that couples:
  - Epidemiological-demographic model on a metapopulation network
  - Farmers decision-making component: dynamics of farmers' behaviour regarding the **voluntary** adoption of a **control measure** on the spread of the disease → inspired by EGT and MAB
- Numerical explorations: simulations and sensitivity analyses

Epidemiological-demographic model

Classic intra-herd stochastic model with demography on a meta-population trade network

- SIR model, frequency-dependence
- Demography (births, deaths)
- Trade network (animal transfers)
- Modeled as: Continuous-time Markov Chain (CTMC)



- 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

Algorithm (Farmers' decision-making mechanism)

Input: 2 options $= \{0,1\}$, $p_1^{\Delta_d}(j) := p_1^{init}\ \forall j$, $\kappa \geq 0$, $\rho \geq 0$,
$B(j) = \{i; \theta_{ij} \neq 0 \text{ or } \theta_{ji} \neq 0\}; j = 1, ..., J$.

for $t = \Delta_d, 2\Delta_d, 3\Delta_d ...$ — At each decision time

for $j = 1, ..., J$ — Each farmer

- $a_j^t \leftarrow Bernoulli(p_1^t(j))$ — Makes decision using current probability of applying the measure
- $C_{a_j^t}^t(j)$ — Observes associated cost
- $j^* \leftarrow Unif(B(j))$ — Selects one neighbor in trade network
- $(a_{j^*}^t, C_{a_{j^*}^t}^t(j^*))$ — Observes neighbor's decision and cost
- Updates the probability of applying ($k = 1$) and not applying the measure ($k = 0$)

$$p_k^{t+\Delta_d}(j) = \frac{p_k^t(j) e^{-\kappa C_k^t(j) - \rho C_k^t(j^*)}}{p_k^t(j) e^{-\kappa C_k^t(j) - \rho C_k^t(j^*)} + p_{1-k}^t(j) e^{-\kappa C_{1-k}^t(j) - \rho C_{1-k}^t(j^*)}}$$

where for $l = j, j^*$: $C_k(l) = 0$ if $k \neq a_j^t$.

Explanation of the algorithm

$$odds_1^{t+\Delta_d}(j) = \frac{p_1^{t+\Delta_d}(j)}{p_0^{t+\Delta_d}(j)} = \frac{p_1^t(j) e^{-\kappa C_1^t(j) - \rho C_1^t(j^*)}}{p_0^t(j) e^{-\kappa C_0^t(j) - \rho C_0^t(j^*)}}$$

$$odds_1^{t+\Delta_d}(j) = odds_1^t(j) \times e^{(1-2a_j^t)\kappa C_{a_j^t}^t(j) + (1-2a_{j*}^t)\rho C_{a_{j*}^t}^t(j^*)}$$

$\Longrightarrow$ **Stochastic** behaviour, **learning**, **cognitive and social** considerations

- j and j^* vaccinated $\Longrightarrow$ $odds_1(j)$ j vacc. decrease
- j and j^* did not vaccinate $\Longrightarrow$ $odds_1(j)$ vacc. increase[1]
- j and j^* made diff. decisions $\Longrightarrow$ $odds_1(j)$ depend on $\kappa C_1^t(j)$ vs $\rho C_0^t(j)$
  $\rightarrow$ action with lower weighted cost

[1] or stay the same

A cost function for a given control measure: vaccination

Vaccine (partially) protects from infection in $]t; t + \Delta_d]$

Cost function of the decision

$$C^t_{a^t_j}(j) = \frac{\overbrace{[CF_v + CU_v N_j(t)]}^{\text{vaccination}} a^t_j + \overbrace{\phi r N_{S_j \to I_j}(t, t + \Delta_d)}^{\text{infection}}}{\underbrace{\Delta_d \overline{N_j}(t, t + \Delta_d)}_{\text{normalisation}}}$$

- 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
- r : monetary value of a healthy animal
- $0 \leq \phi \leq 1$: rate of reduction of r if animal gets infected
- $N_{S_j \to I_j}(t, t + \Delta_d)$: no. of infections in herd j over the period
- $\overline{N_j}(t, t + \Delta_d)$: mean size of herd j over $[t, t + \Delta_d[$

Numerical exploration

Fixed setting: 5000 herds, fixed demographic parameters, fixed simulated network structure (scale-free, $\sim$ **Finistère department**)

Epidemiological parameters (4)

- $1/\gamma = 90$ days (long infection duration)
- local $R_0 \sim 2.0$
- **Epidemic scenario**
  - Prop. of infected herds $= 0.1$
  - Prop. of infected animals $= 0.15$

Economic parameters (4)

- r (healthy animal value)
- ϕ (loss of animal value if inf.)
- CF_v (fixed cost of vacc.)
- CU_v (vaccine cost/animal)

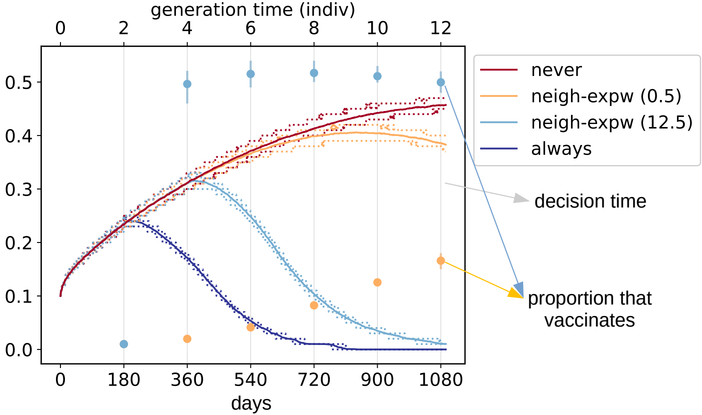
Decision-related parameters (5)

- Δ_d (duration of decision and of vacc. efficacy)
- e_v (efficacy of the vaccine)
- p_1^{init} (initial prob. of vacc.)
- κ (sensitivity of the farmer to his/her own cost)
- ρ/κ (ratio of sensitivity of the farmer to the cost of a neighbor and κ)

$\Longrightarrow$ 13 parameters, studied through **Sensitivity Analysis** [Saltelli et al., 2008]

Simulation results Disease spread over 3 years

Proportion of infected herds ($\kappa = 0.5$ and $\kappa = 12.5$)

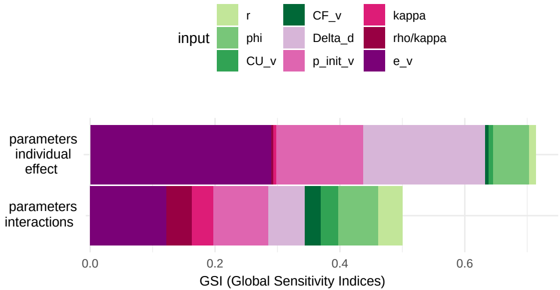


Farmers' sensitivities to costs, κ and $\rho(= \kappa/2)$, determine:

- proportion vaccinating from the second decision time
- how quickly inter-herd prevalence declines.

SA results (2nd experiment: means of all outputs)

- Epidemiological parameters fixed



- Most influential parameters (main effect)
  - e_v **vaccine efficacy** (+)
  - Δ_d **decision step** ($-^*$)
  - p_v^{init} **initial probability of vaccinating** ($+^*$)

* impact on limiting disease spread.

To sum up

- Original integrative model coupling two sub-models:
  - Stochastic disease spread on a meta-population network with demography.
  - Farmer's decision model.
    - Farmer's decision problem
    - Farmer's decision mechanism.
- Model studied through simulations and sensitivity analysis.
- Generic model: other epidemiological models, other control measures

  → Information is transmitted only by trade network

4. Application on BVD

RESEARCH

Learning and strategic imitation in modelling farmers' dynamic decisions on Bovine Viral Diarrhoea vaccination

Lina Cristancho-Fajardo[1,2*], Elisabeta Vergu[1], Gaël Beaunée[2], Sandie Arnoux[2] and Pauline Ezanno[2]

BVD: Bovine Viral Diarrhoea

Consequences: economic, animal well-being

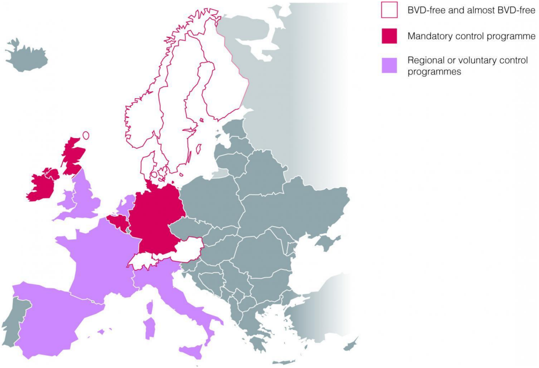


Figure: BVDV control in Europe [Metcalfe, 2019]

Introduction in a herd

- **pasture** proximity
- **trade**

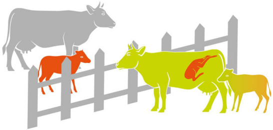


Figure: (Source GDS)

Within-herd level:

- During gestation: vertical transmission or abortion
- Horizontal transmission

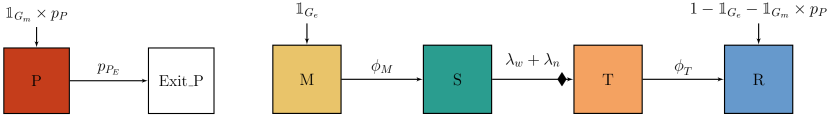
BVD model (individual-based stochastic model)

Between-herd level

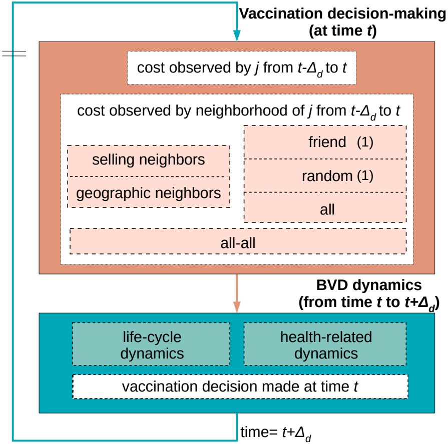
- Indirect contact with infected animals in neighbouring herds through **pasture** (max radius of **2km**): 0 to 20 neighbours (6 in average)
- Direct introduction of infected animals through **trade** movements: FCID (French Cattle Identification Database)

Within-herd level

- **Life-cycle** dynamics
- **Health-state** dynamics

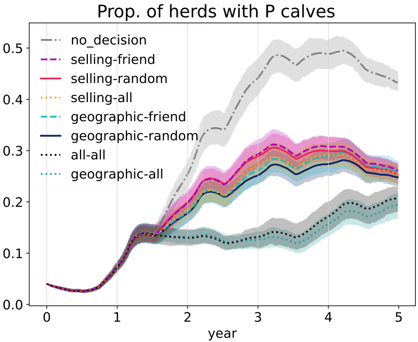


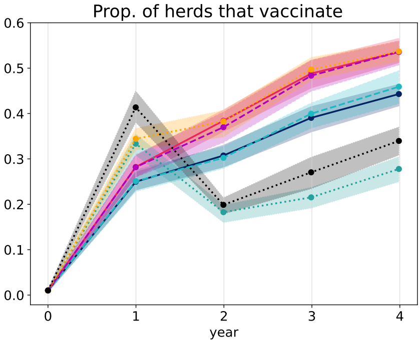
Vaccination and BVD



$$C^j_{a_j(t-\Delta_d)}(t) = \frac{\overbrace{c_v(t-\Delta_d,t)}^{\text{vacc. breeding females}} \times a_j(t-\Delta_d) + \overbrace{c_i(t-\Delta_d,t)}^{\text{infections (P + T)}}}{\underbrace{N_{\to G}(t-\Delta_d,t)}_{\text{normalisation}}}$$

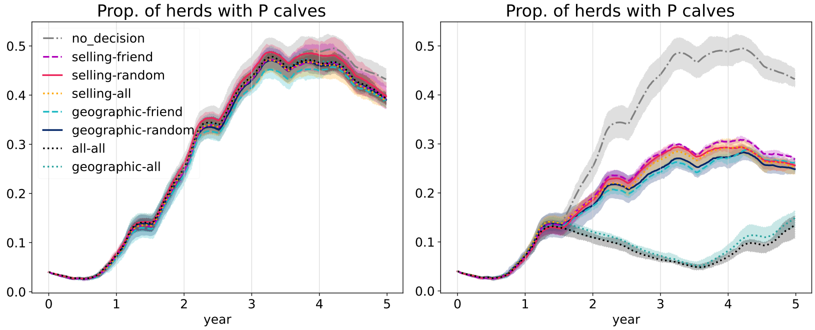
Simulation results ($\kappa = 1$, $\rho = 0.5$)





- All information from geographic neighbours seems most useful. In accordance with [Gates et al., 2013, Qi et al., 2019]
- No significant differences when observing only one neighbour

SA results: varying κ $(\rho/\kappa = 0.5)$



(a) $\kappa = 0.01, \rho = 0.005$ (b) $\kappa = 10, \rho = 5$

Conclusions

Context

- Infectious disease spreading on large metapopulation network
  $\Longrightarrow$ livestock disease on animal trade network
- Dynamic decision-making processes to control spread
  - Decentralised : local control (each farmer)

Contributions

- Build integrative model for pathogen spread over an animal trade network accounting for farmers' dynamic decision-making regarding the adoption of a health measure
- Extend the integrative model and apply it to a relevant real-life disease (BVD)

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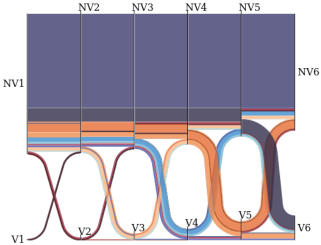
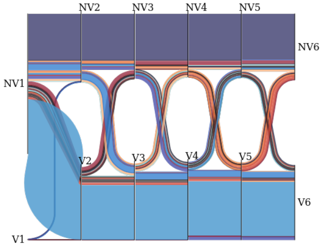
Perspectives

- Evaluate impact of
  - type of network
  - relative temporal scale of the epidemiological and decision-making dynamics
- Perfect information: of scores (centralised) & of costs (decentralised)
  - Issue: unrealistic assumption → information difficult to gather
  - Perspective: consider **noisy/partial information**
- Separate decision-making processes (centralised vs decentralised)
  - Issue: in reality both farmers & social planner can adopt control measures for the same disease
  - Perspective: **coupling centralised-decentralised** decision-making
    - Farmers: behaviour adaption? (anticipation)
    - Social planner: incentives for farmers? (subsidies, information platforms)

Vaccination decision patterns



(a) $\kappa = 0.5$



(b) $\kappa = 12.5$

SA outputs

Epidemiological

- Proportion of infected herds at final time T
- Mean proportion of infected animals at final time T (over infected herds at time T)
- Proportion of herds infected at least once
- Mean number of new infectious animals in herds that got infected at least once
- Mean rate of new infectious (over susceptible animals) in herds that got infected at least once

Economic

- Total economic cost of the disease spread

Decision-related

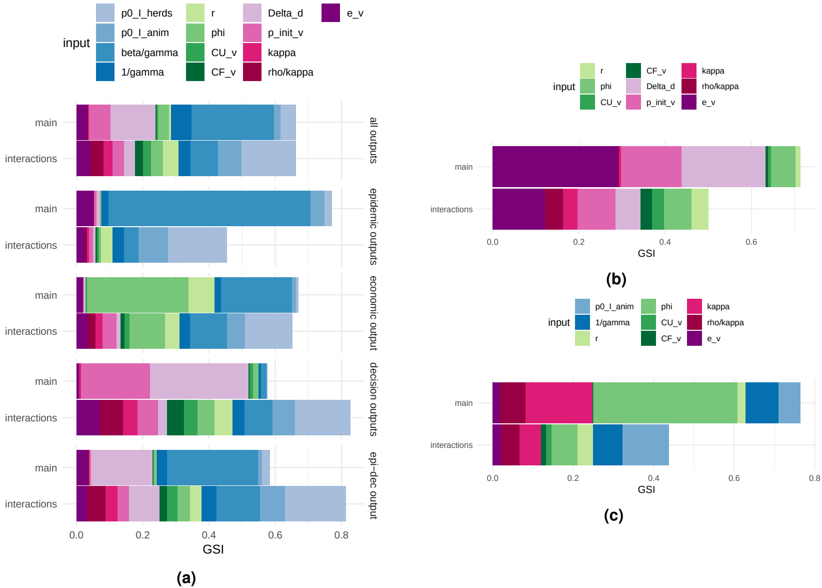
- Mean proportion of herds that vaccinate, over the different decision times. Not including first decision
- Proportion of herds according to each vaccination aggregated pattern (without first decision):
  [never; $\leq$ half of the time but not never; $>$ half all of the time but not always]

Epidemiological-decision related (1):

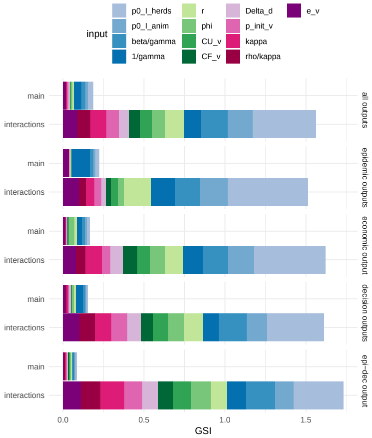
- For each group of herds defined by the vaccination aggregated patterns (without first decision):

  Ratio of the cumulative number of new infections over the cumulative number of susceptible animals, for the herds of the pattern that got infected at least once

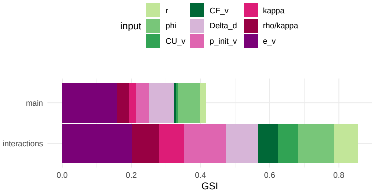
SA results (means of all outputs)



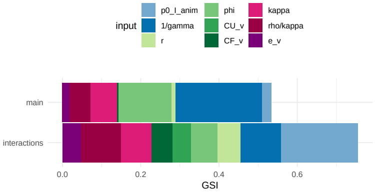
SA results (variances of all outputs)



(a)



(b)



(c)

BVD model Life-cycle

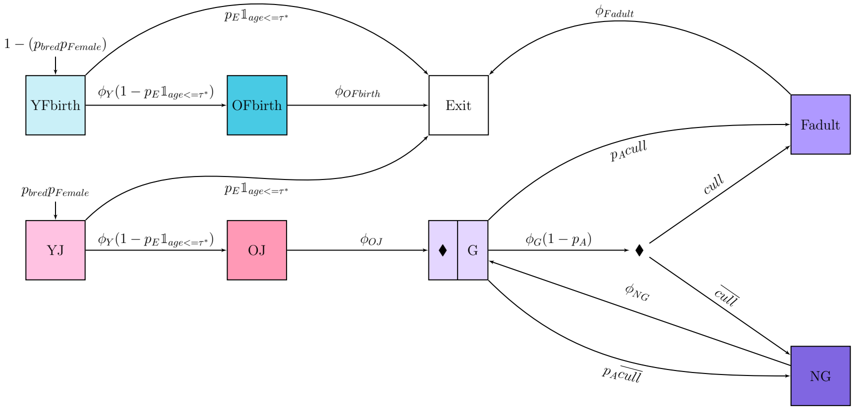
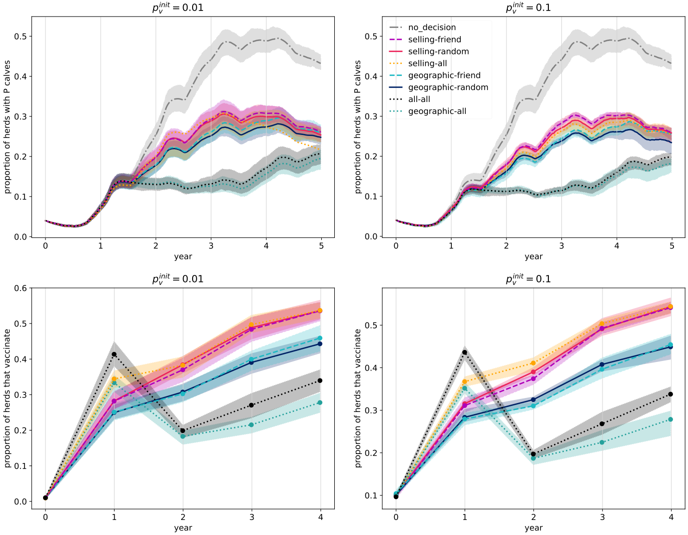
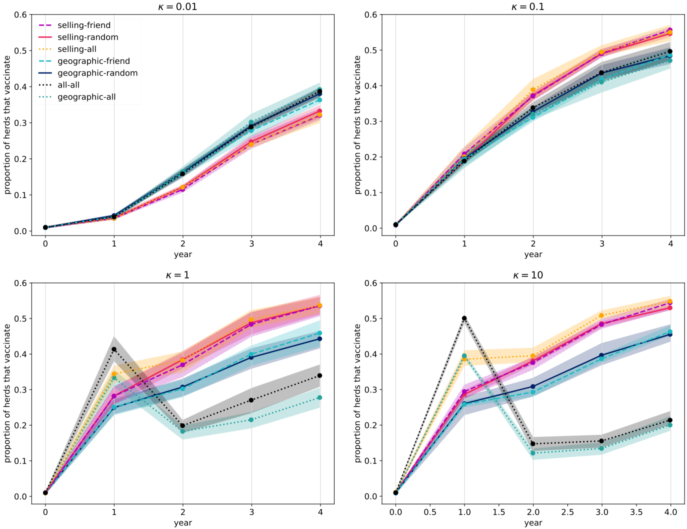


Figure: YJ (young juvenile), OJ (old juvenile), YFbirth(young fattened from birth), OFbirth(old fattened from birth), G(gestating), NG(non-gestating), Exit(culled)

BVD: varying p_v^{init}



BVD: varying κ ($\rho/\kappa = 0.5$)



BVD: varying κ and ρ