Tracking uncertainties in mechanistic models
for risk assessment of pest control strategies

Virgile BAUDROT

CBGP – 24 septembre 2019

PhD 2013-2016 | Post-Doc 2016-2018 | Post-Doc 2018-2020

Modélisation des interactions trophiques impliquant des transferts de contaminants biologiques (*E. multilocularis*) et chimiques (ETMs)

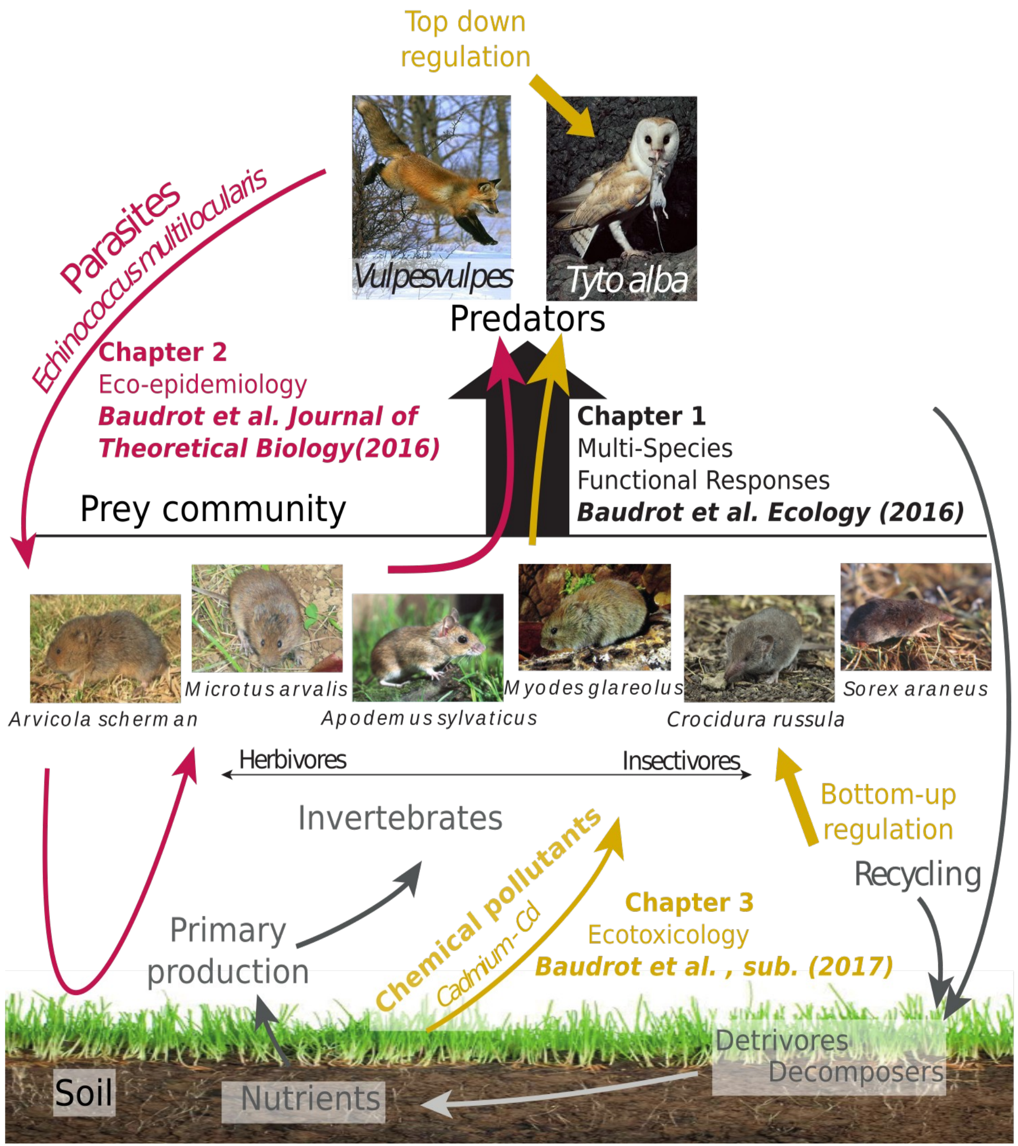
Director:

Francis Raoul

Co-supervisors:

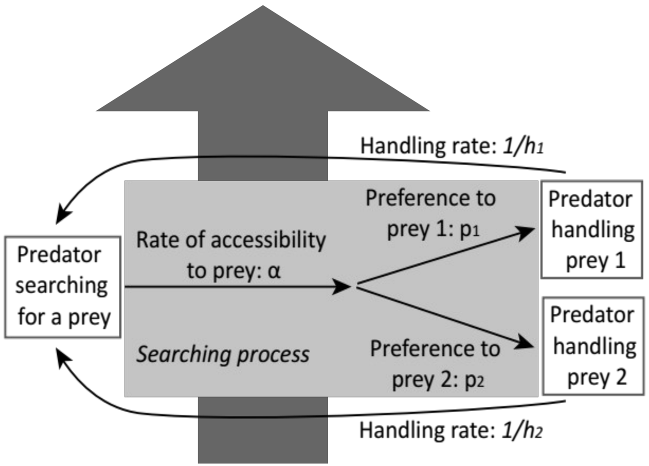
Clémentine Fritsch,

Antoine Perasso



Vulpes vulpes

Tyto alba



Arvicola scherman

Microtus arvalis

Myodes glareolus

Sorex sp.

$$\Phi_i(\vec{x}) = p_i(\vec{x}) \times \frac{\alpha(\vec{x})}{1+h\alpha(\vec{x})} = p_i(\vec{x}) \times \Theta(\vec{x})$$

Baudrot, V.; Perasso, A.; Fritsch, C.; Giraudoux, P. & Raoul, F. (2016) *The adaptation of generalist predators diet in a multi-prey context: insights from new functional responses* **Ecology**, 97, 1832-1841

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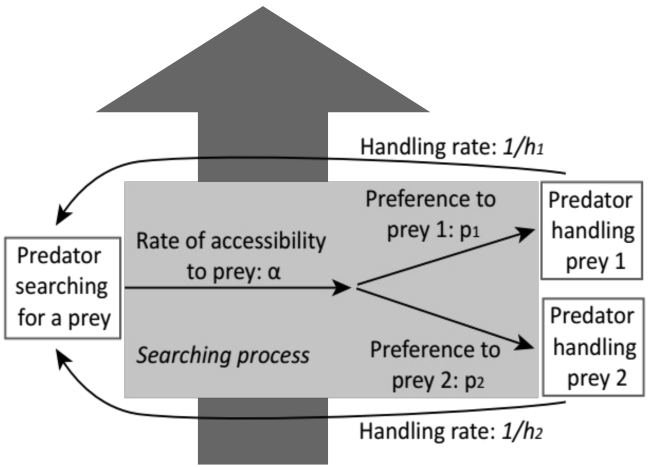


Arvicola scherman

Microtus arvalis

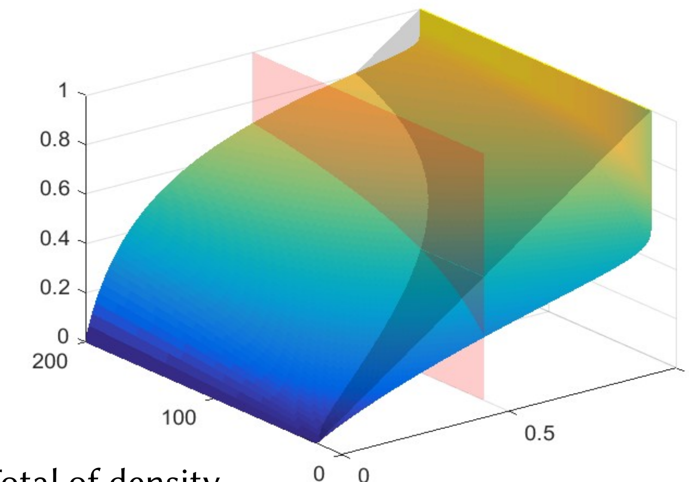
Myodes glareolus

Sorex sp.

Prey switching ...
... density dependent
... frequency dependent

$$\Phi_i(\vec{x}) = p_i(\vec{x}) \times \frac{\alpha(\vec{x})}{1+h\alpha(\vec{x})} = p_i(\vec{x}) \times \Theta(\vec{x})$$

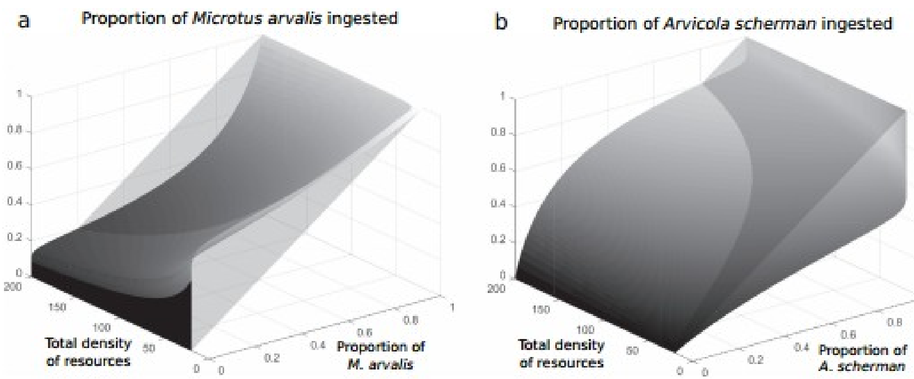
Prop. *A. scherman* ingested / *V. vulpes*

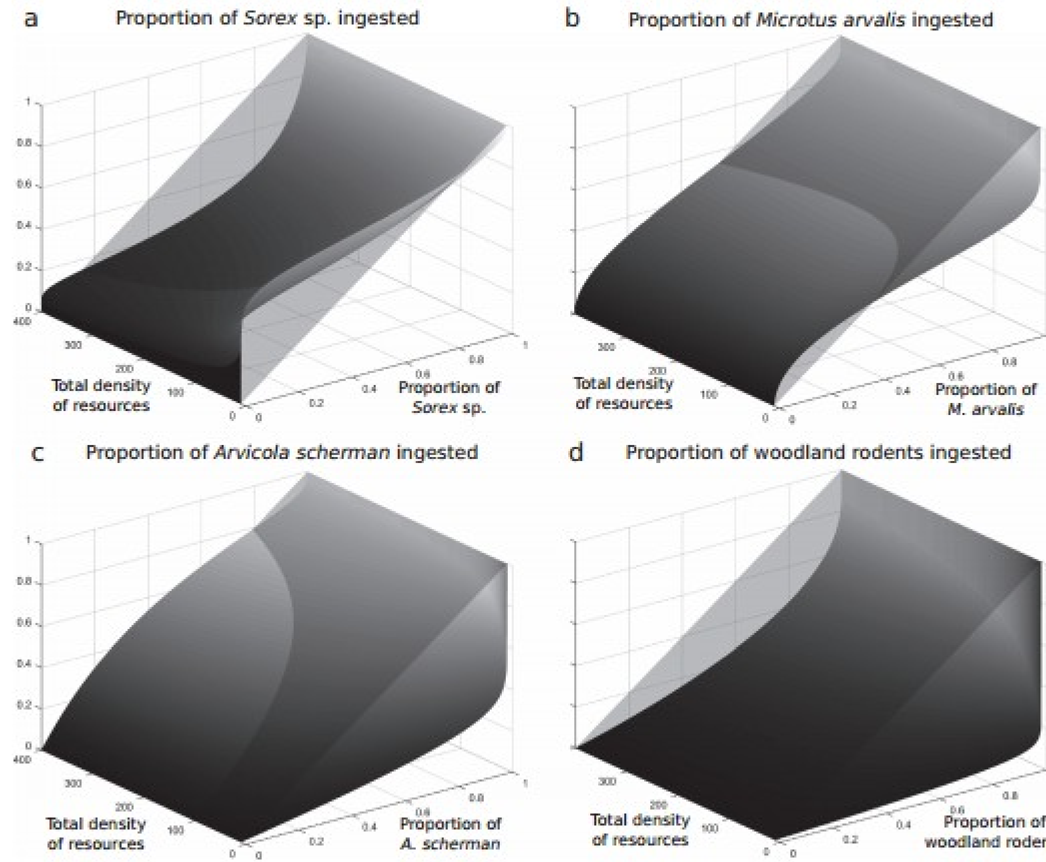


Total of density

Proportion available of *A. scherman*

Baudrot, V.; Perasso, A.; Fritsch, C.; Giraudoux, P. & Raoul, F. (2016) *The adaptation of generalist predators diet in a multi-prey context: insights from new functional responses* **Ecology**, 97, 1832-1841





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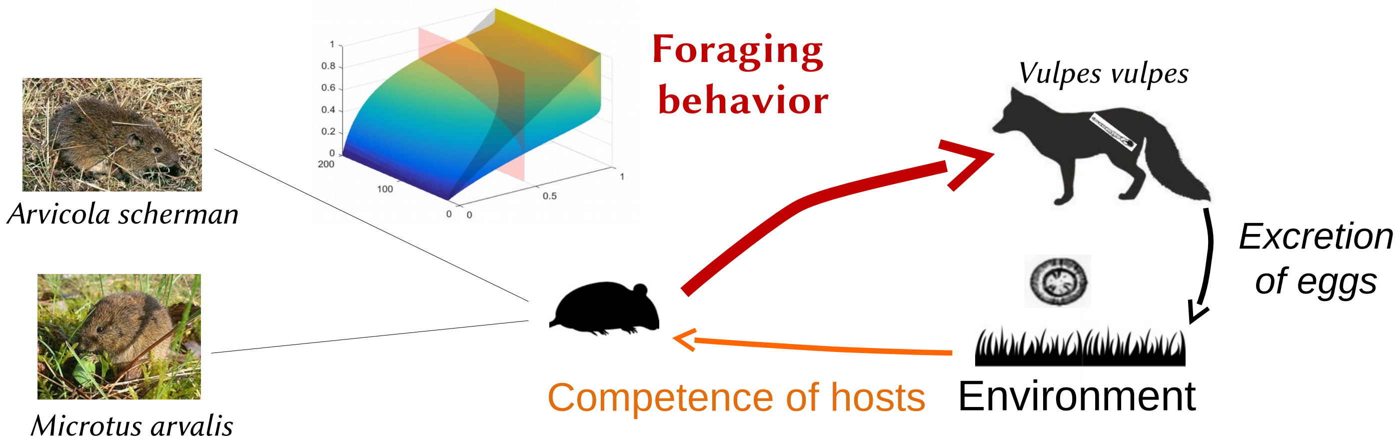

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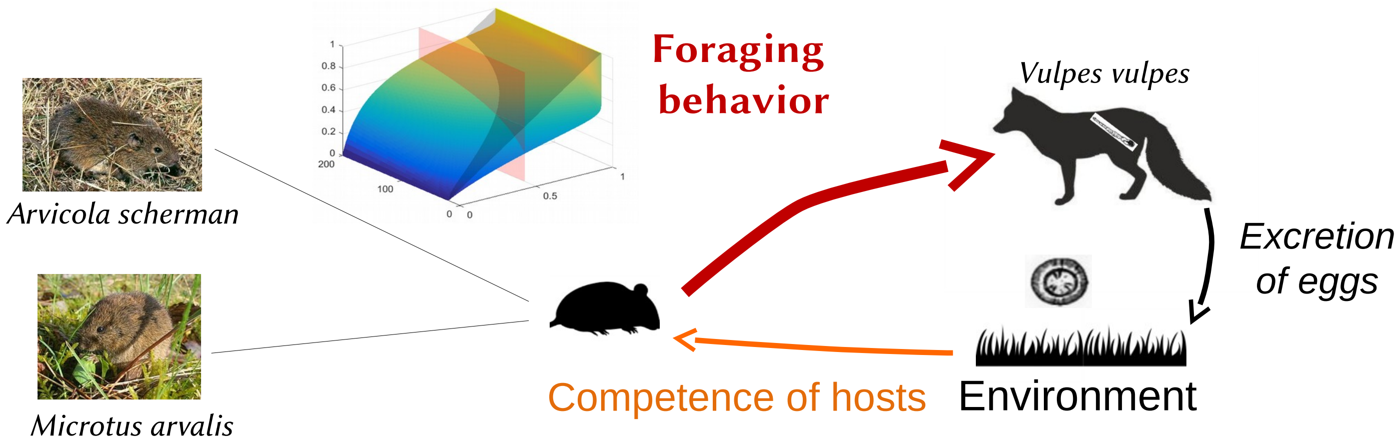


Basic reproductive number

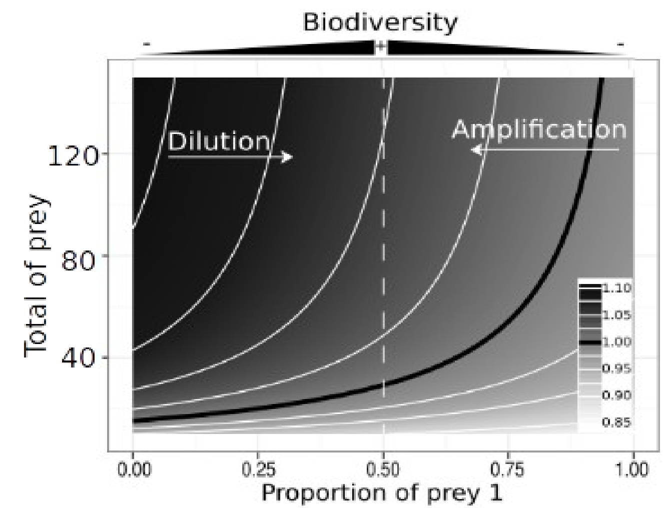
Foraging behavior (MSFR)

$$\mathcal{R}_0 = \sqrt{\frac{\eta z^*}{b(b_z+\mu)} \times \left(\Gamma_1\Phi_1(x_1^*,x_2^*) + \Gamma_2\Phi_2(x_1^*,x_2^*)\right)}$$

“Introduction” of susceptibles

Competence of hosts

hosts diversity & disease risk



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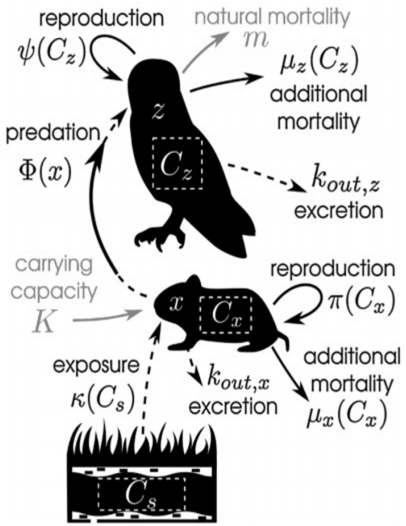

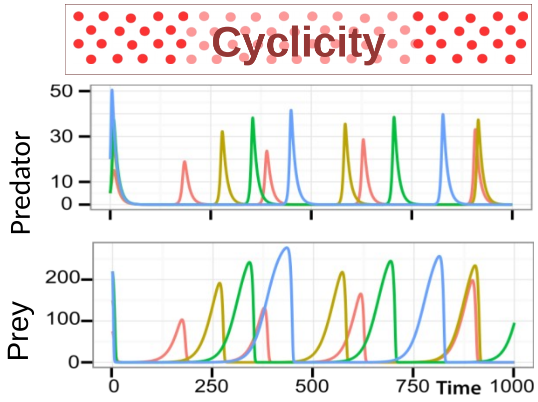

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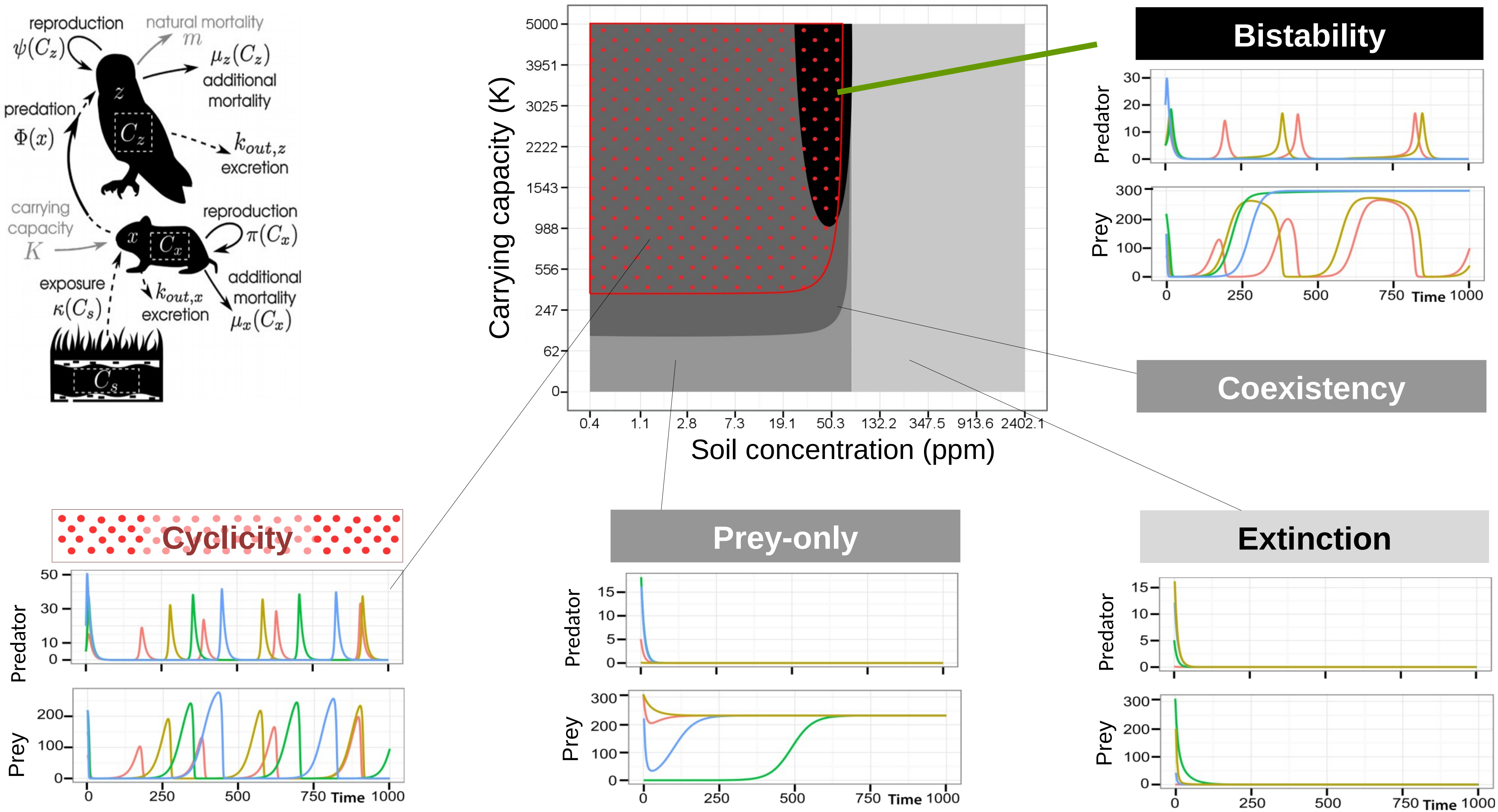

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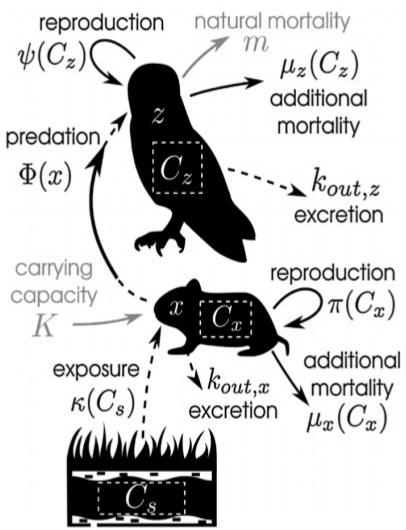

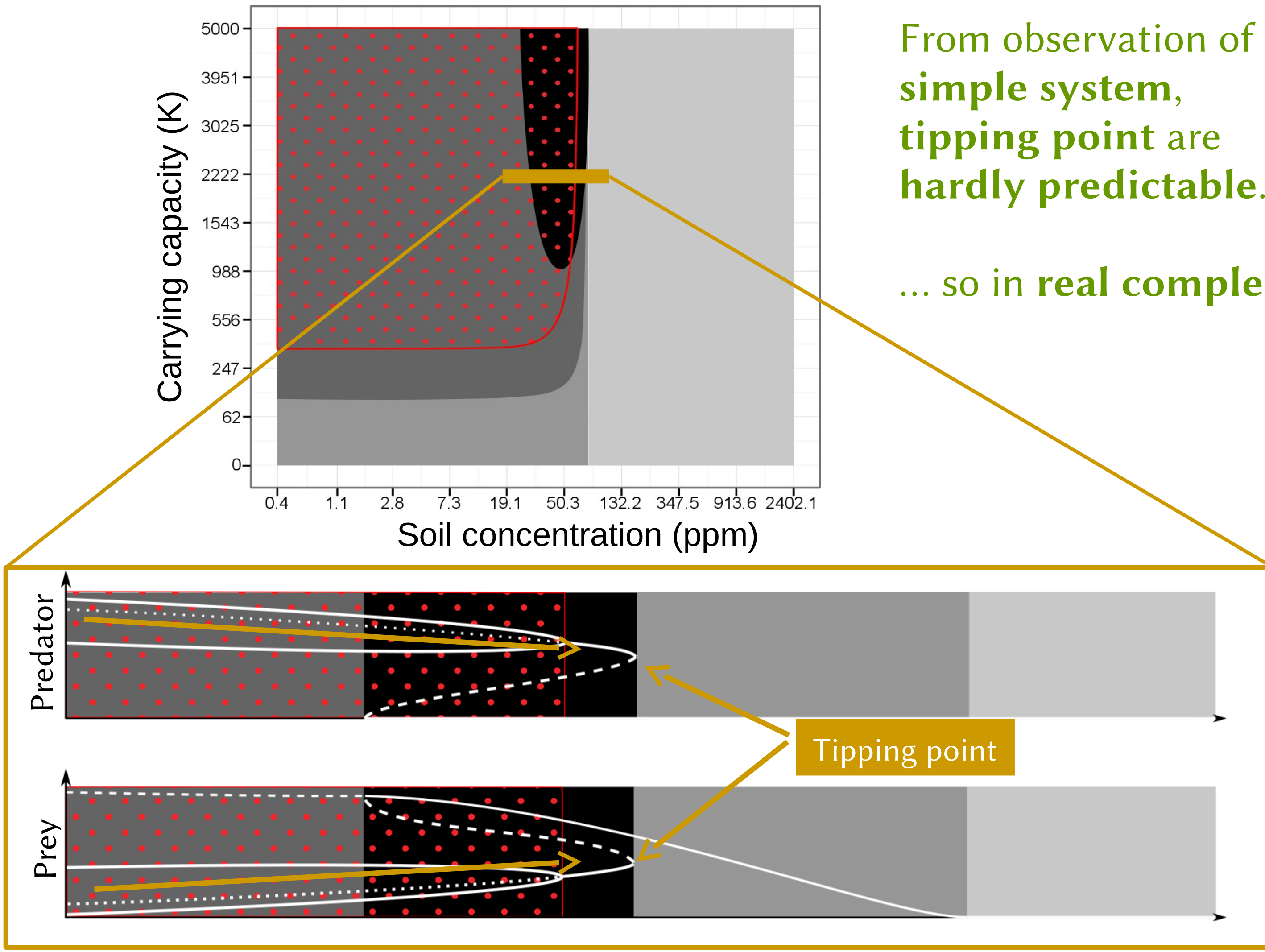

From observation of **simple system**, **tipping point** are **hardly predictable**…

… so in **real complex** !

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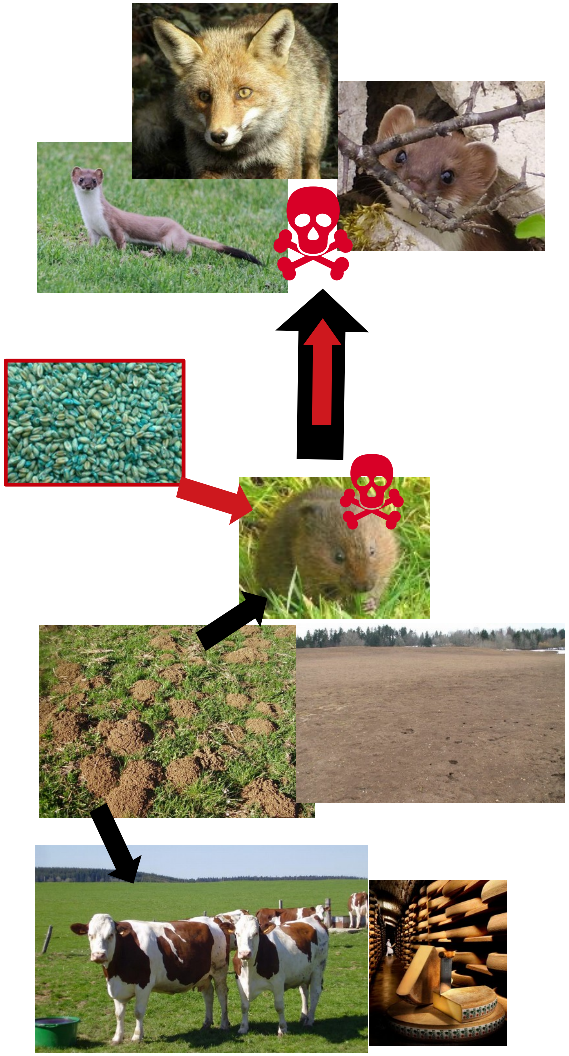
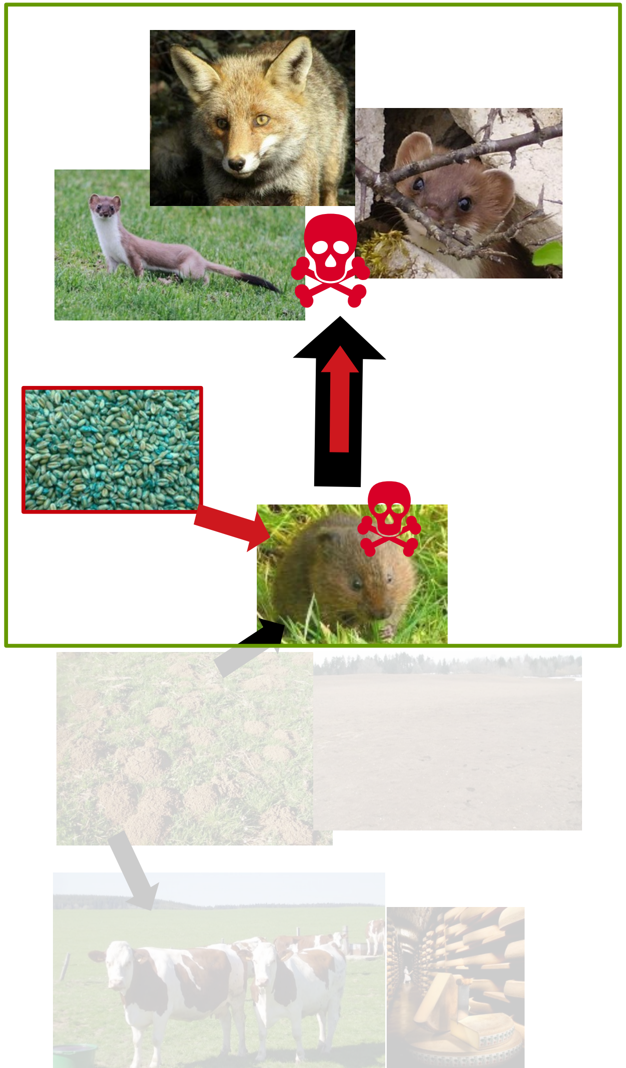
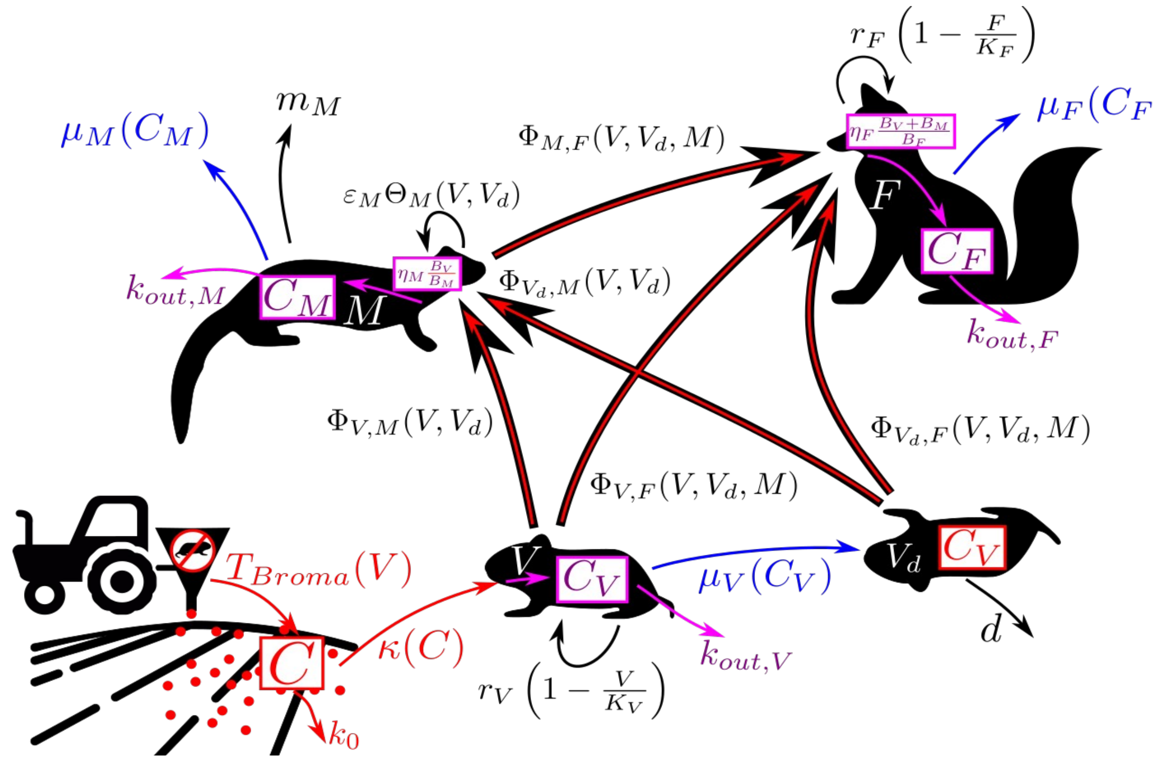


Fernandez-de-Simon, J. ; Baudrot, V. ; Coeurdassier, M. ; Lambin, X. & Giraudoux, P. (submitted) *The fine line between predator-prey regulation and farmer/poison-pest regulation: Managing rodent pests that are prey of specialists and generalists.*





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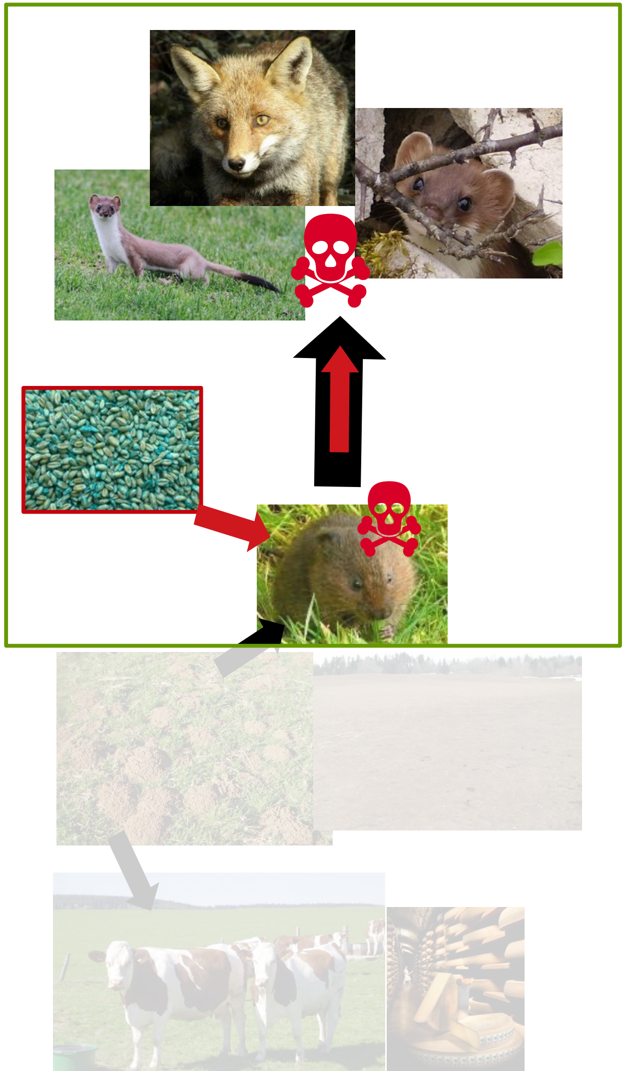

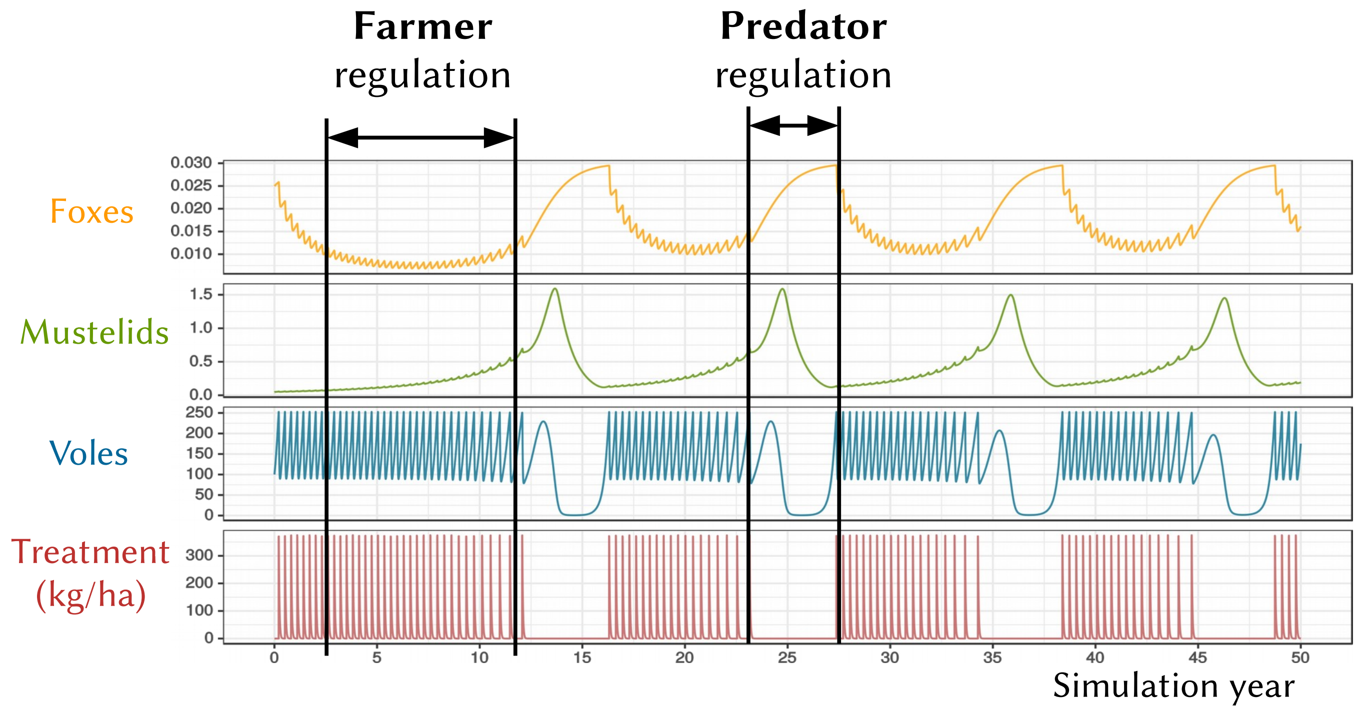

➡ **Buffer in time** to maintain **biocontrol**

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Implementation of Bayesian inference for TKTD models
A way to track the propagation of uncertainties in environmental risk assessment

Virgile BAUDROT
Sandrine CHARLES

"In biology, variability is the main invariant"
Guiseppe Longo & Francis Bailly (2006)
Mathématiques et sciences de la nature ; la singularité physique du vivant

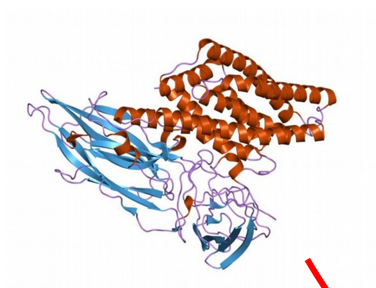
Mechanistic models

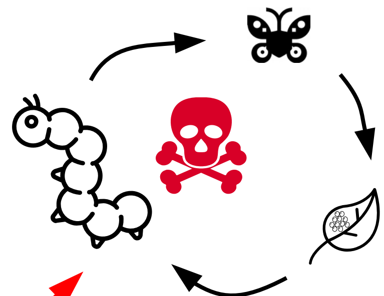
➡ **Challenge theories**

➡ **Application?**

Hazard identification

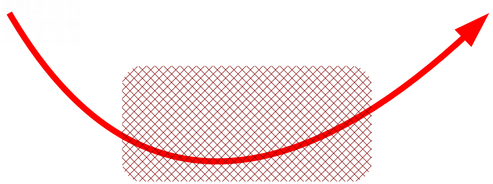
Product X **Species**





?

Hazard & Risk characterisation



Exposure profile

Risk identification

Hazard identification

Product x Species

Data

$$\mathcal{D} = \{\mathcal{E}, \mathbf{N}\}$$

- experimental design
- observation (survivors)

Calibration

Likelihood $\pi(\mathcal{D}|\theta)$

Mechanistic models

$\mathcal{M}(\theta)$, θ parameters

$\hat{\theta}(\mathcal{D})$ Point estimators of true parameters

Hazard identification

Product x Species

Data

$$\mathcal{D} = \{\mathcal{E}, \mathbf{N}\}$$

- experimental design
- observation (survivors)

Calibration

Likelihood $\pi(\mathcal{D}|\theta)$

Mechanistic models

$\mathcal{M}(\theta)$, θ parameters

$\hat{\theta}(\mathcal{D})$ Point estimators of true parameters

Risk identification

Exposure profile $\mathcal{E}'$

Prediction $\mathcal{R}\left(\mathcal{E}'|\hat{\theta}\right)$

Hazard identification

Product x Species

Data

$\mathcal{D} = \{\mathcal{E}, \mathbf{N}\}$

- experimental design
- observation (survivors)

Calibration

Likelihood $\pi(\mathcal{D}|\theta)$

Mechanistic models

$\mathcal{M}(\theta)$, θ parameters

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Risk identification

Exposure profile $\mathcal{E}'$

Prediction $\mathcal{R}\left(\mathcal{E}'|\hat{\theta}\right)$

Environmental Quality Standards

Lethal Concentration $LC(\mathcal{E}|x,t)$

Multiplication Factor $MF(\mathcal{E}'|x,t)$

Hazard characterisation

Risk characterisation

Hazard identification

Product x Species

Data

$\mathcal{D} = \{\mathcal{E}, \mathbf{N}\}$

- experimental design
- observation (survivors)

Calibration

Likelihood $\pi(\mathcal{D}|\theta)$

Mechanistic models

$\mathcal{M}(\theta)$, θ parameters

$\hat{\theta}(\mathcal{D})$ Point estimators of true parameters

Not dedicated to track

Uncertainties

Risk identification

Exposure profile $\mathcal{E}'$

Prediction $\mathcal{R}\left(\mathcal{E}'|\hat{\theta}\right)$

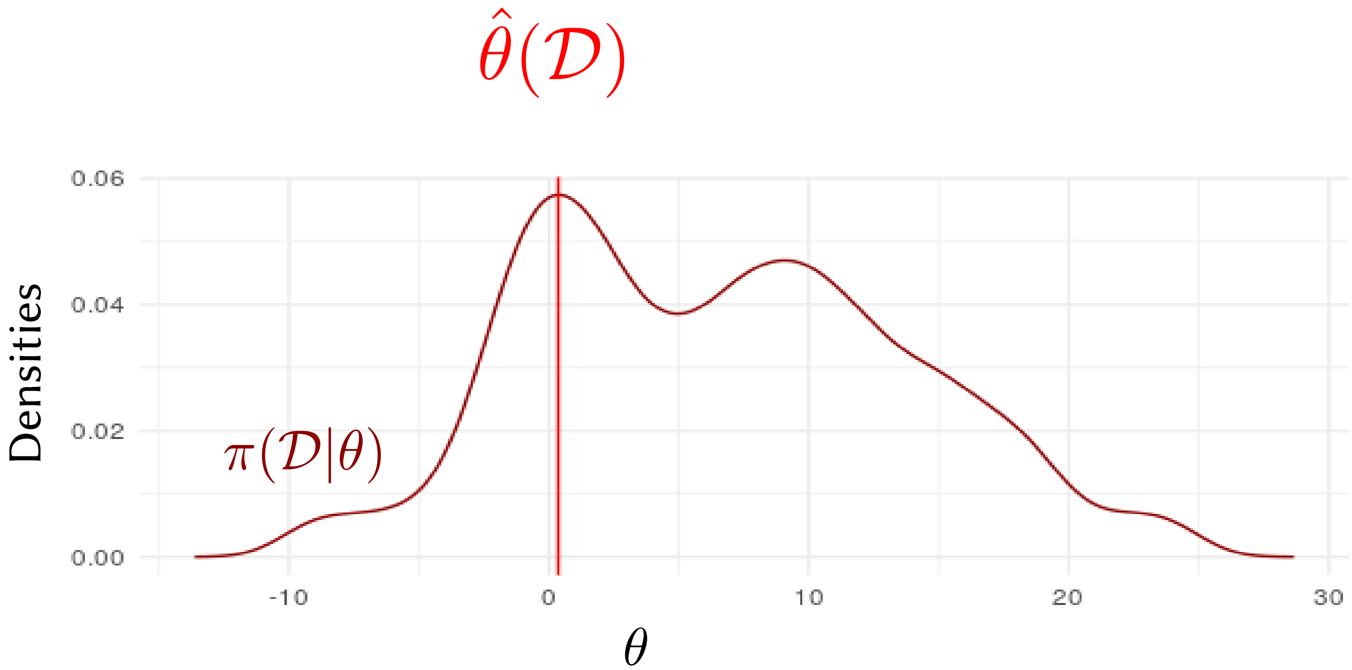
Environmental Quality Standards

Lethal Concentration $LC(\mathcal{E}|x,t)$

Multiplication Factor $MF(\mathcal{E}'|x,t)$

Hazard characterisation

Risk characterisation



Frequentist

- max likelihood

$$\hat{\theta}(\mathcal{D}) = \underset{\theta}{\operatorname{argmax}}\, \pi(\mathcal{D}|\theta)$$

Hazard identification

Product x Species

Data

$\mathcal{D} = \{\mathcal{E}, \mathbf{N}\}$

- experimental design
- observation (survivors)

Risk identification

Exposure profile $\mathcal{E}'$

Prediction $\mathcal{R}\left(\mathcal{E}'|\hat{\theta}\right)$

Bayesian inference

Calibration

Likelihood $\pi(\mathcal{D}|\theta)$

$\times$

Priors $p(\theta)$

$\propto$

Posterior $p(\theta|\mathcal{D})$

Mechanistic models

$\mathcal{M}(\theta)$, θ parameters

'Cost': param. probability structure

Gain: integrates uncertainty

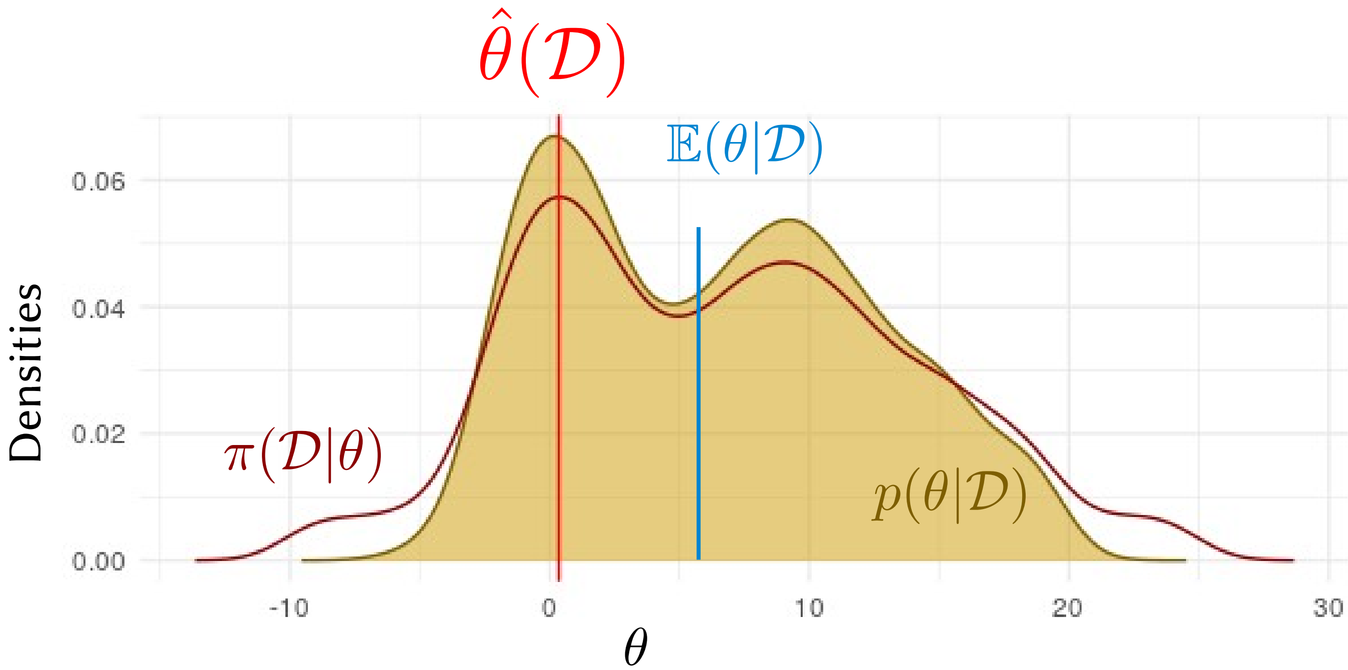
Environmental Quality Standards

Lethal Concentration $LC(\mathcal{E}|x,t)$

Multiplication Factor $MF(\mathcal{E}'|x,t)$

Hazard characterisation

Risk characterisation



Frequentist

➡ max likelihood

$$\hat{\theta}(\mathcal{D}) = \underset{\theta}{\operatorname{argmax}}\, \pi(\mathcal{D}|\theta)$$

Bayesian

$$p(\theta|\mathcal{D}) \propto \pi(\mathcal{D}|\theta) \times p(\theta)$$

➡ probability structure on the parameter space

Toxicokinetic **Toxicodynamic**

$$\frac{dD_{surv}(t)}{dt} = k_d \left(C_{ext}(t) - D_{surv}(t)\right)$$

$$h(t) = h_+ \max_{0 \leq \tau \leq t} (D_{surv}(\tau) - z, 0) + h_b$$

$$S_{SD}(t) = \exp\left(-\int_0^t h(\tau)\, d\tau\right)$$

Toxicokinetic — **Toxicodynamic**

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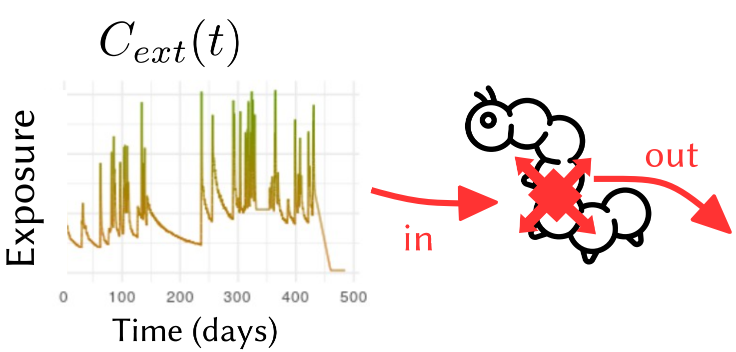

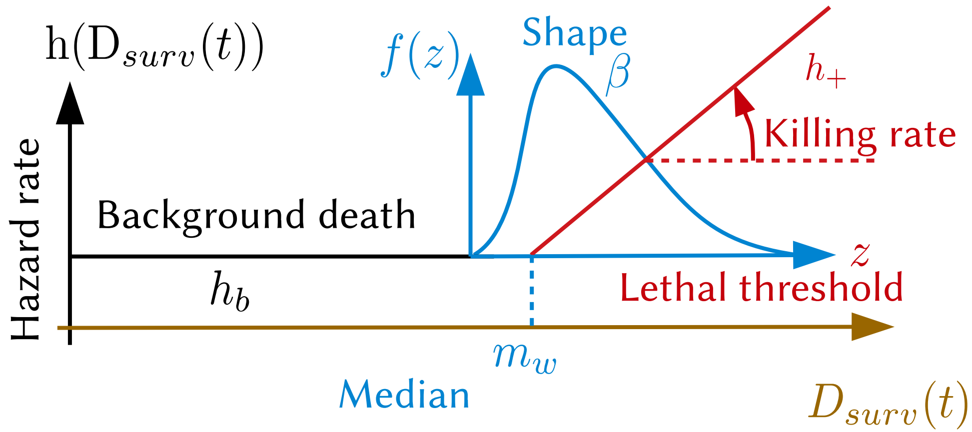

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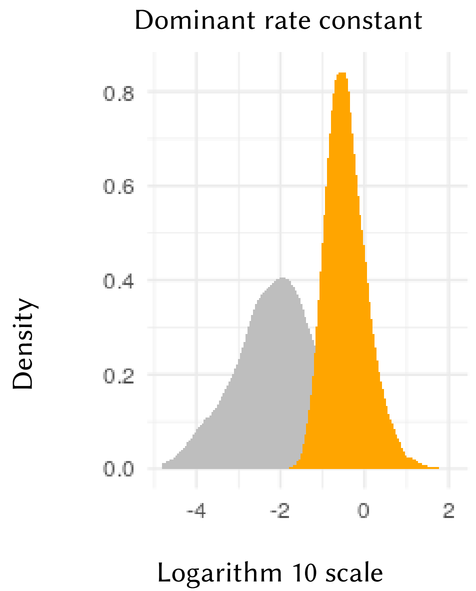
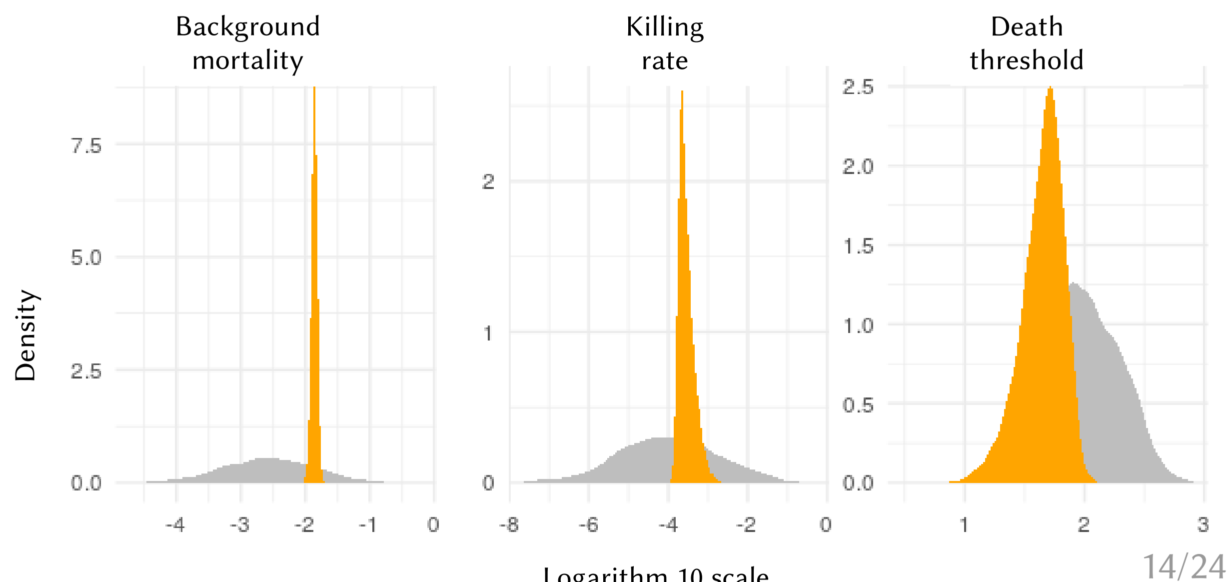
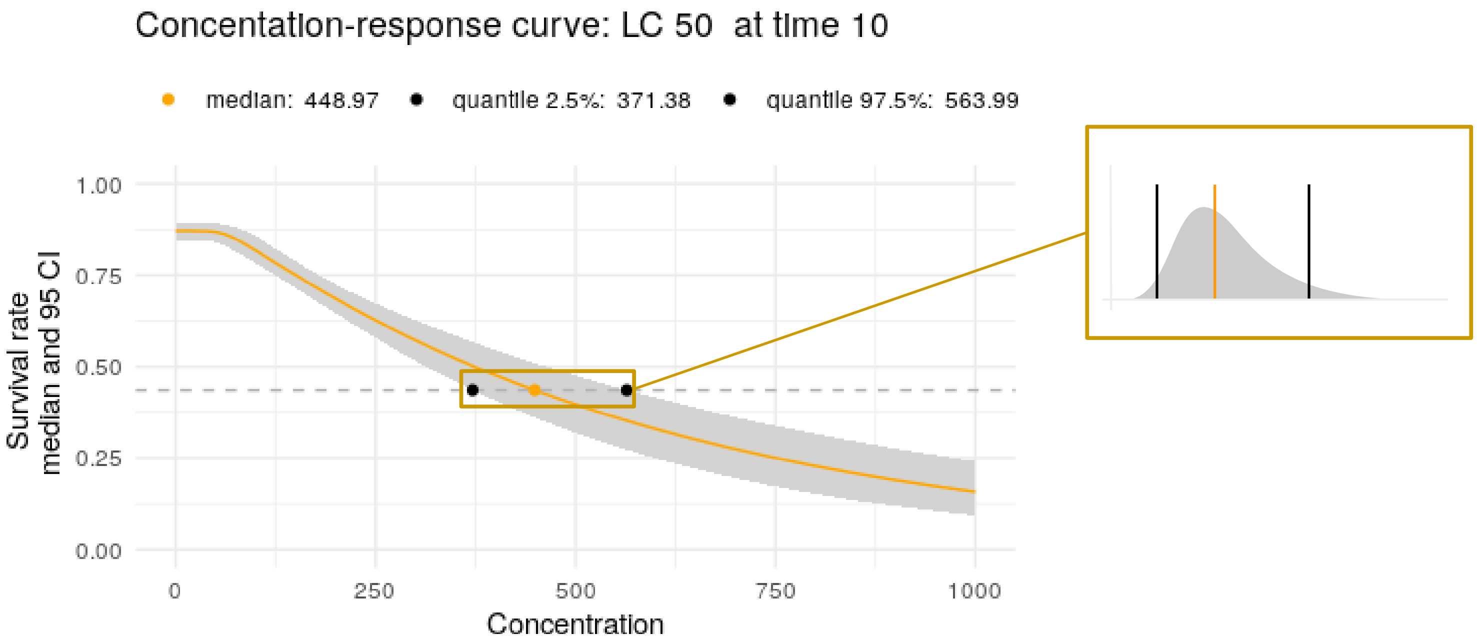
Bayesian inference $\pi(\mathcal{D}|\theta) \times p(\theta) \propto p(\theta|\mathcal{D})$





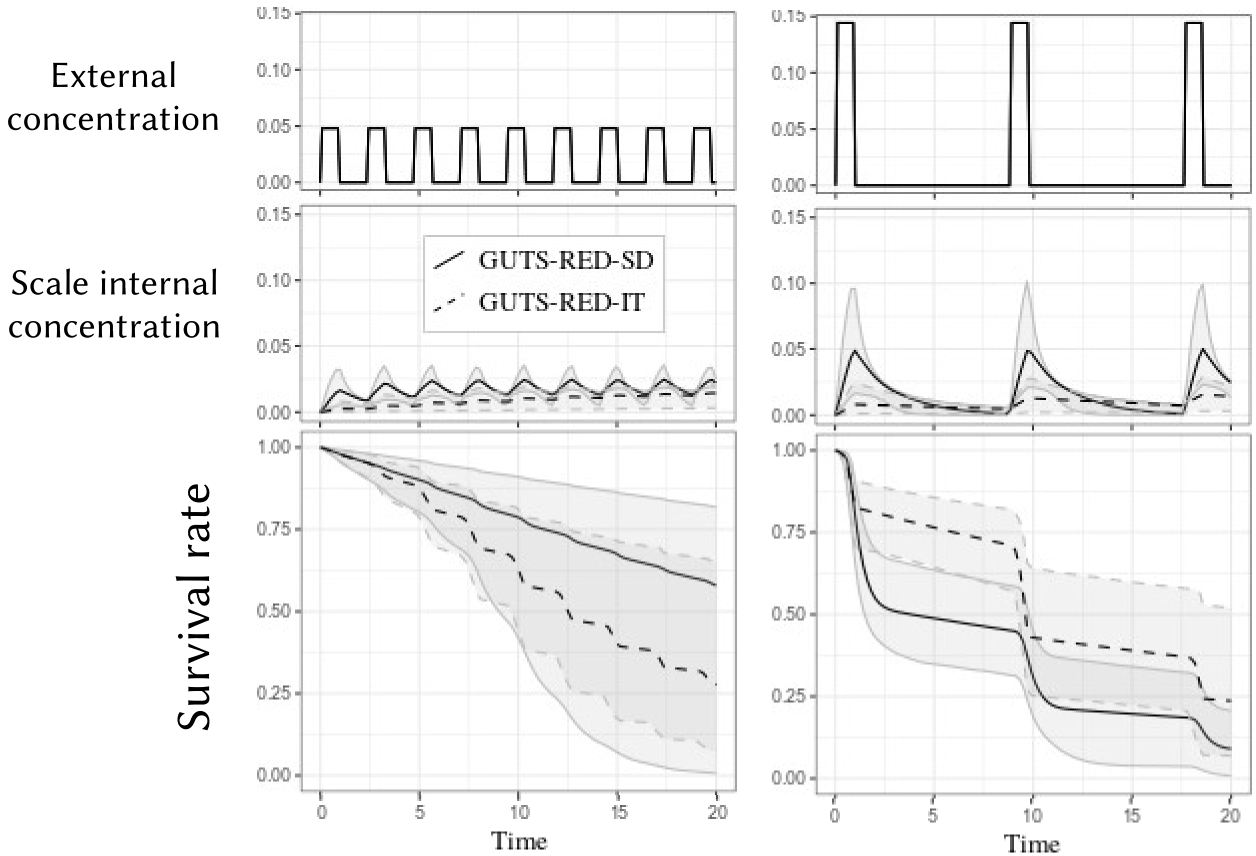
Uncertainties around Environmental Quality Standard

$LC(\mathcal{E}|x,t)$



Baudrot, V. ; Preux, S, ; Ducrot, V. ; Pavé, A. and Charles, S. (2018) *New insights to compare and choose TKTD models for survival based on an inter-laboratory study for* Lymnaea stagnalis *exposed to Cd.* **Env, Science & Tech**. 52(3) 1582-1590.
Baudrot, V. and Charles, S. (2019) *Recommendations to address uncertainties in environmental risk assessment using toxicokinetic-toxicodynamic models.* **PCI Ecology (2018) => Scientific Reports**. 9(11432)

Uncertainties propagation over **new exposure** profiles



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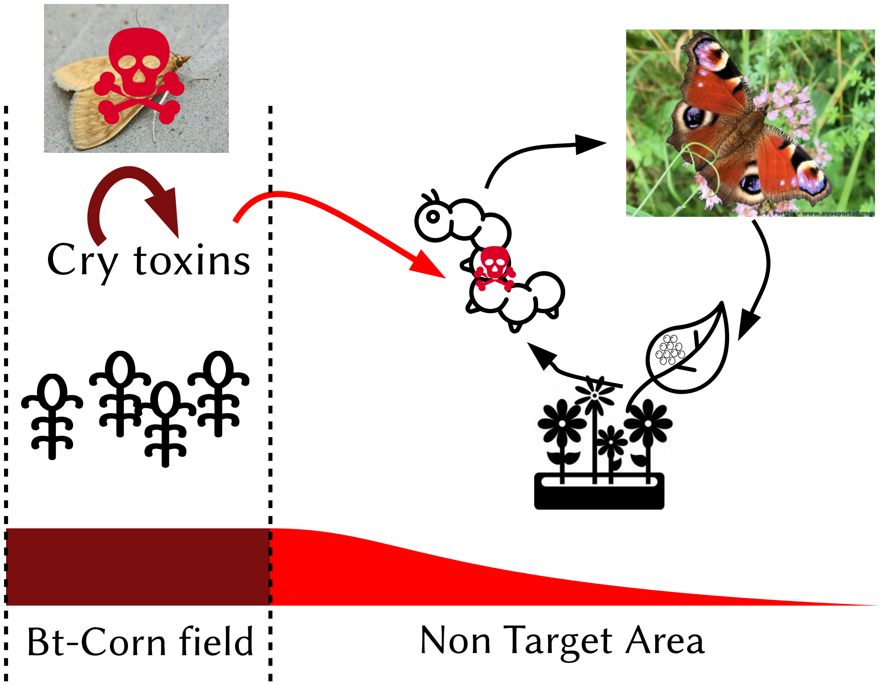
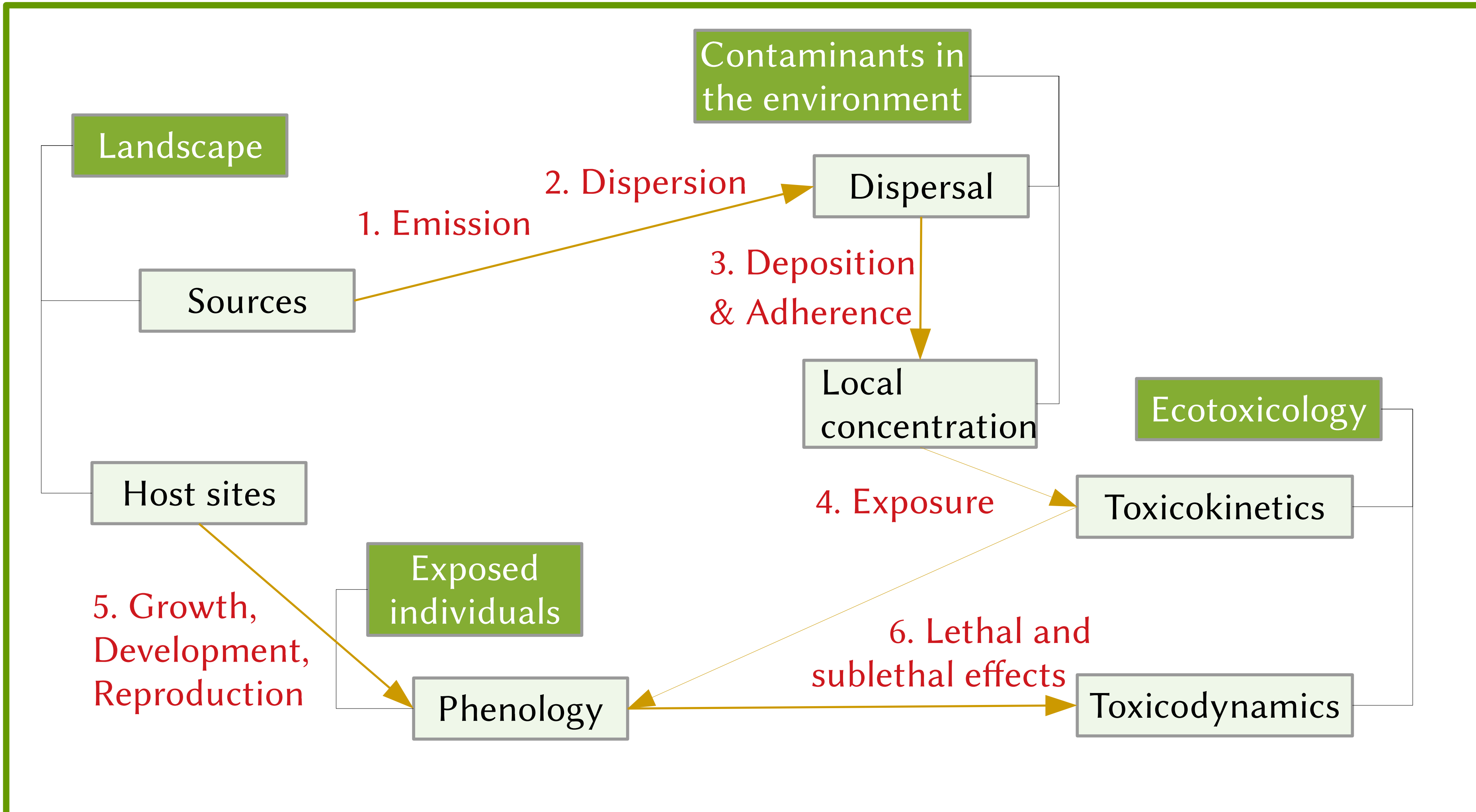
Baudrot, V. and Charles, S. (2019) *Recommendations to address uncertainties in environmental risk assessment using toxicokinetic-toxicodynamic models.* **PCI Ecology (2018) => Scientific Reports**. 9(11432)

BriskaR - A spatio-temporal exposure-hazard model for assessing environmental risk of Bt-maize on Non-Target Lepidoptera

Virgile BAUDROT
Samuel SOUBEYRAND
Antoine MESSÉAN
Andreas LANG
Stefanescu CONSTANTI





Walker, E.; Leclerc, M.; Rey, J.-F.; Beaudouin, R.; Soubeyrand, S. & Messéan, A.(2017) A Spatio-Temporal Exposure-Hazard Model for Assessing Biological Risk and Impact Risk Analysis, Wiley Online Library.

Mechanistic models $\mathcal{M}(\theta)$ parameters θ	Data $\mathcal{D} = \{\mathcal{E}, \mathcal{O}\}$ experiment $\mathcal{E}$; observations $\mathcal{O}$

1. Emission

Fields: C_n

Spatio-temporal emission:

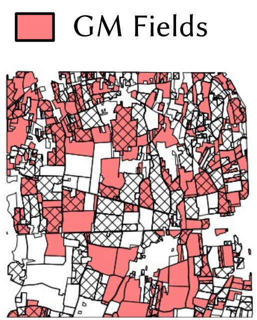
$$\tilde{E}(x,t) = \sum_{n \in N} \mathbf{1}(x \in C_n) E_n(t)$$

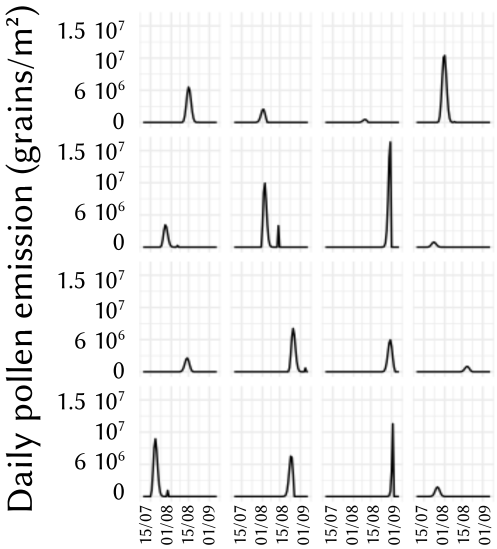
2. Dispersion

Dispersal kernel: $K(x,t)$

Contaminant intensity:

$$\lambda^{disp}(y,t) = \int_{\Omega} \tilde{E}(x,t) K(y-x) dx$$





Mechanistic models $\mathcal{M}(\theta)$ parameters θ	Data $\mathcal{D} = \{\mathcal{E}, \mathcal{O}\}$ experiment $\mathcal{E}$; observations $\mathcal{O}$	Prediction $\mathcal{R}(\mathcal{E}'\|\hat{\theta}(\mathcal{D}))$ environment $\mathcal{E}'$; inference params. $\hat{\theta}(\mathcal{D})$

1. Emission

Fields: C_n

Spatio-temporal emission:

$$\tilde{E}(x,t) = \sum_{n \in N} \mathbf{1}(x \in C_n) E_n(t)$$

2. Dispersion

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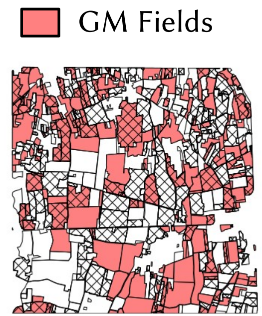

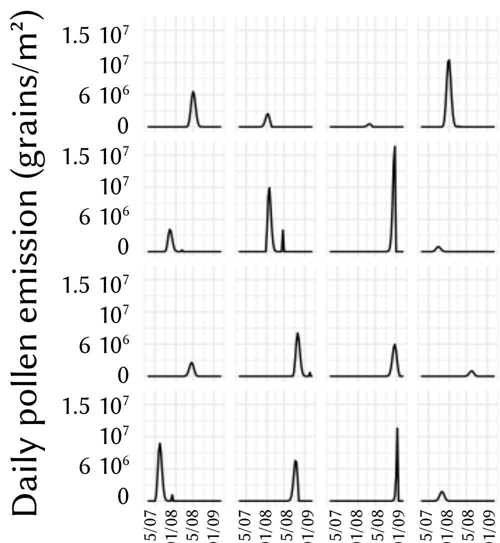

Convolution computed with Fast Fourrier Transform

$$\tilde{E} \otimes K(y,t) = \mathcal{F}^{-1}\left(\mathcal{F}(\tilde{E})\mathcal{F}(K)\right)$$

Mechanistic models $\mathcal{M}(\theta)$
parameters θ

3. Deposition & Adherence

$$\lambda_{local}(y,t) = (1-\alpha(Z(t)))\,\lambda_{local}(y,t-1) + \beta\lambda_{disp}(y,t)$$

4. Exposure

5. Development

$$\delta_0(T) = \exp(\rho T) - \exp\left(\rho T_{max} - \frac{T_{max}-T}{\Delta}\right) + \lambda$$

- $r(T)$: development rate
- T: temperature
- T_{max} : upper survival temperature
- ρ, Δ, λ : other parameters to fit

Mechanistic models $\mathcal{M}(\theta)$
parameters θ

Data $\mathcal{D} = \{\mathcal{E}, \mathcal{O}\}$
experiment $\mathcal{E}$; observations $\mathcal{O}$

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$$\delta_0(T) = \exp(\rho T) - \exp\left(\rho T_{max} - \frac{T_{max} - T}{\Delta}\right) + \lambda$$

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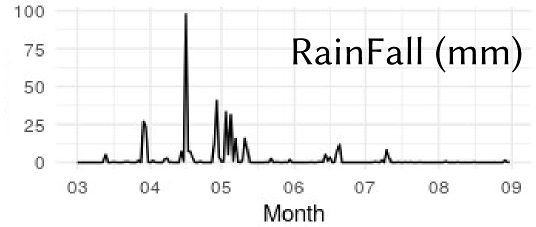
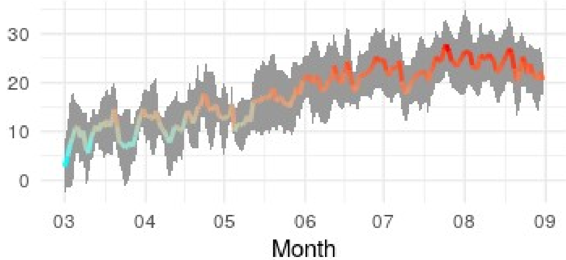
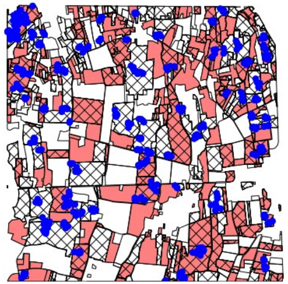


Temperature (mean, [min,max])



Larvae sites



Mechanistic models $\mathcal{M}(\theta)$ parameters θ	Data $\mathcal{D} = \{\mathcal{E}, \mathcal{O}\}$ experiment $\mathcal{E}$; observations $\mathcal{O}$	Prediction $\mathcal{R}(\mathcal{E}'\|\hat{\theta}(\mathcal{D}))$ environment $\mathcal{E}'$; inference params. $\hat{\theta}(\mathcal{D})$

3. Deposition & Adherence

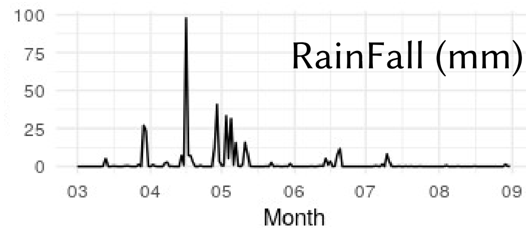
$$\lambda_{local}(y,t) = (1 - \alpha(Z(t)))\,\lambda_{local}(y,t-1) + \beta\lambda_{disp}(y,t)$$

4. Exposure

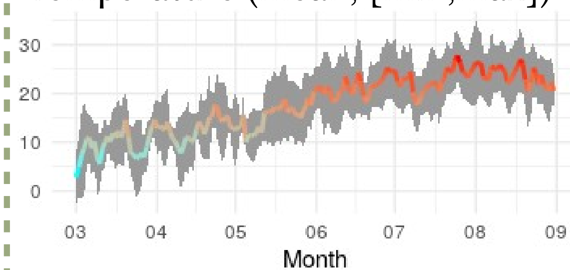
5. Development

$$\delta_0(T) = \exp(\rho T) - \exp\left(\rho T_{max} - \frac{T_{max} - T}{\Delta}\right) + \lambda$$

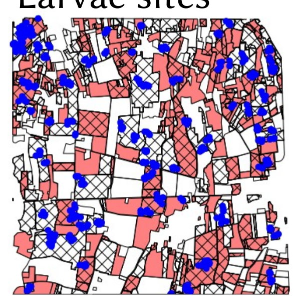
- $r(T)$: development rate
- T: temperature
- T_{max} : upper survival temperature
- ρ, Δ, λ : other parameters to fit



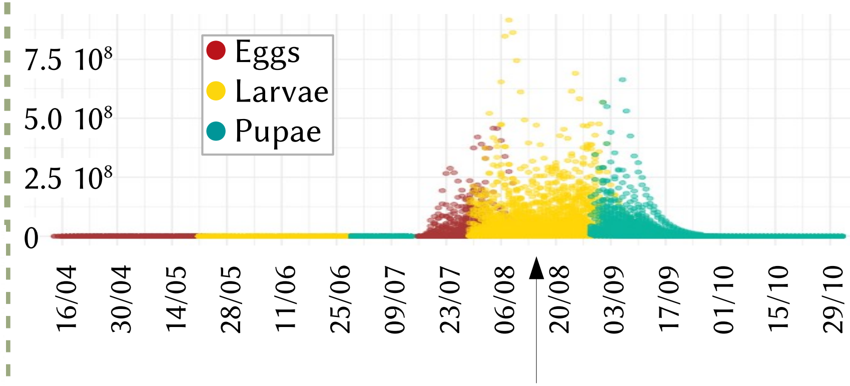
Temperature (mean, [min,max])



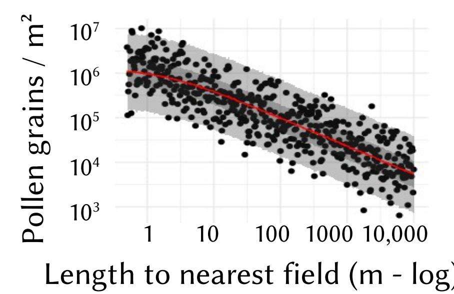
Larvae sites



Exposure nbr grains / m²

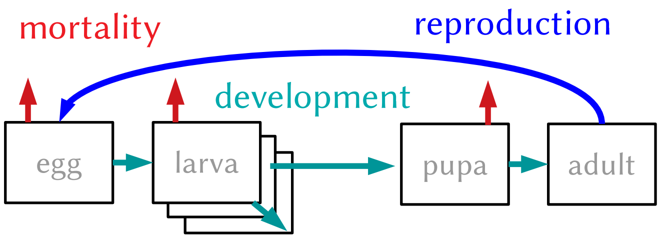


Exposure profile 15/08



Mechanistic models $\mathcal{M}(\theta)$

parameters θ



6.1 Sublethal on Repro.

$$R(t) = R_0(t) \times \exp\left(-H^{+}_{repro}(t)\right)$$

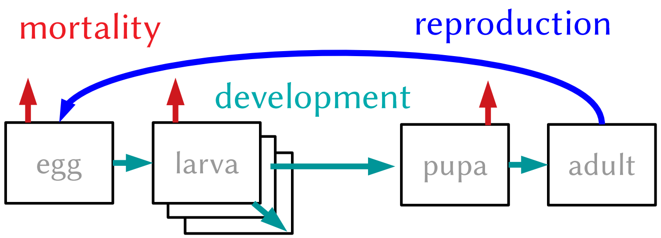
$$N_{G+1}(t) = R(t) \times \mathrm{NID}_G(t)$$

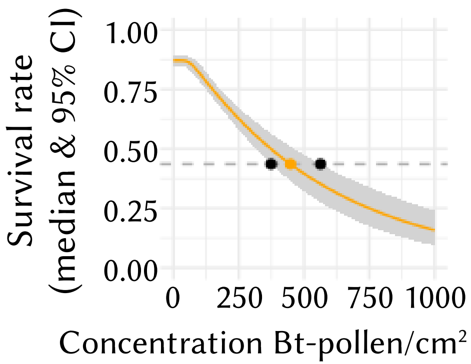
6.2 Sublethal on Growth

$$\delta(t) = \delta_0(t) \times \exp\left(-H^{+}_{dev}(t)\right)$$

Mechanistic models $\mathcal{M}(\theta)$
parameters θ

Data $\mathcal{D} = \{\mathcal{E}, \mathcal{O}\}$
experiment $\mathcal{E}$; observations $\mathcal{O}$





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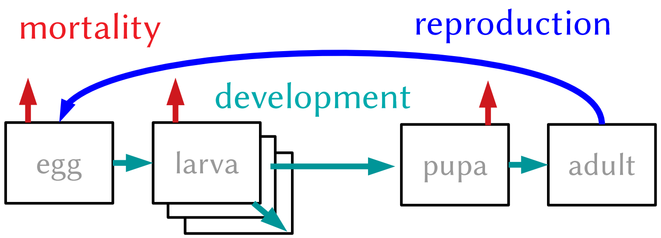

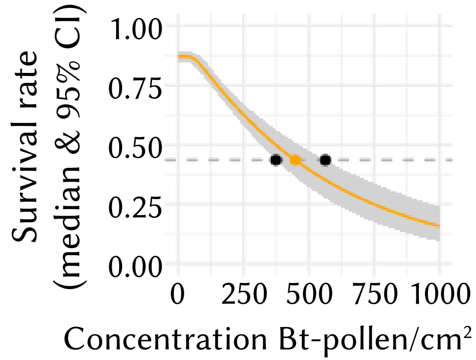

➡ **In average, everything is fine...**

... risk is in the quantiles

6.1 Sublethal on Repro.

$$R(t) = R_0(t) \times \exp\left(-H^+_{repro}(t)\right)$$

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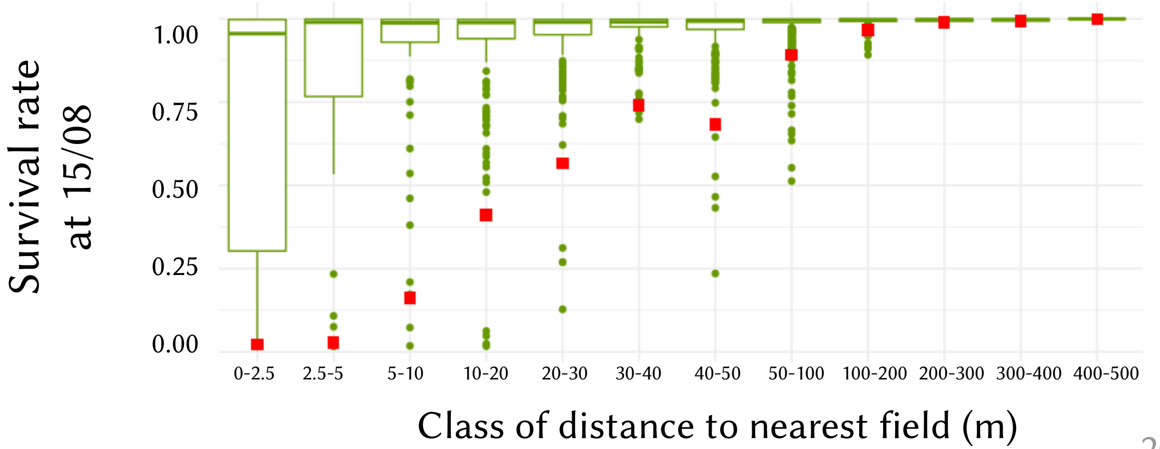
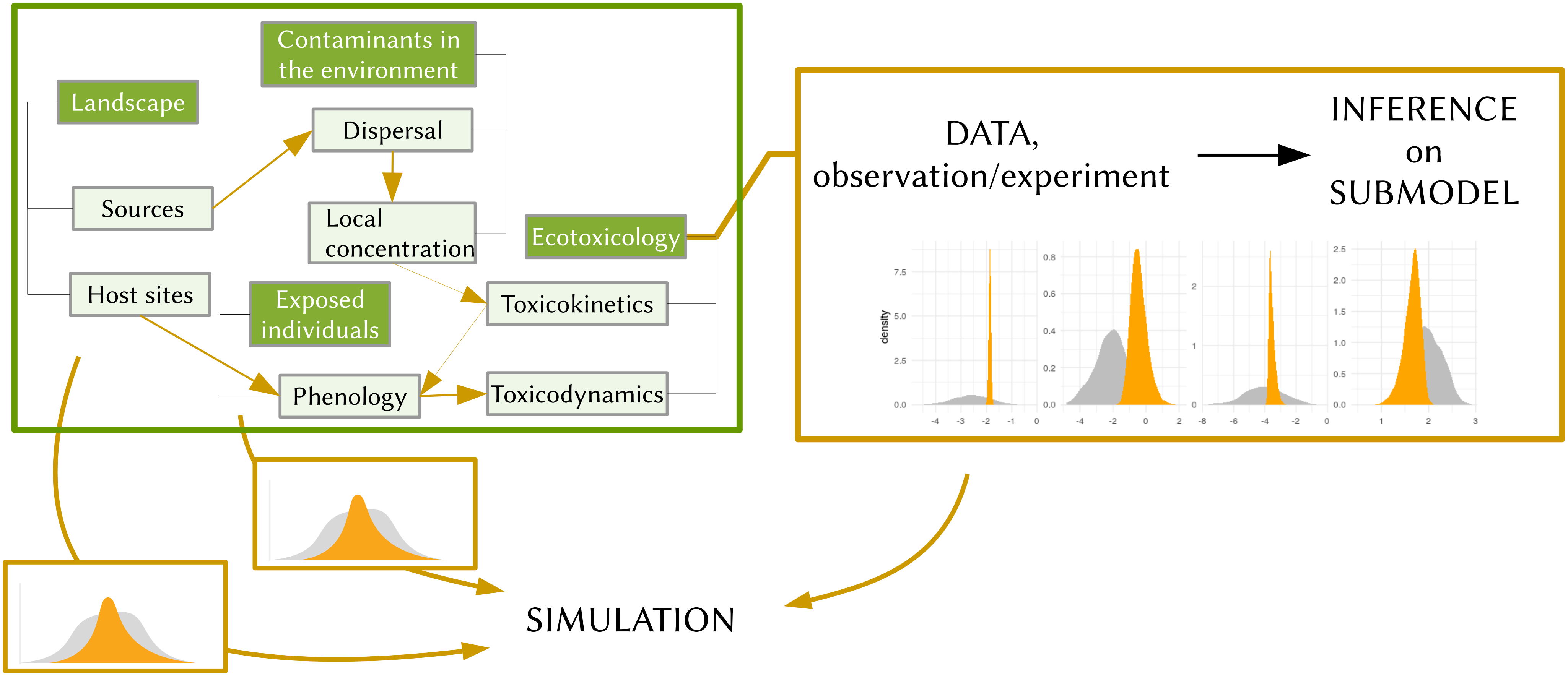
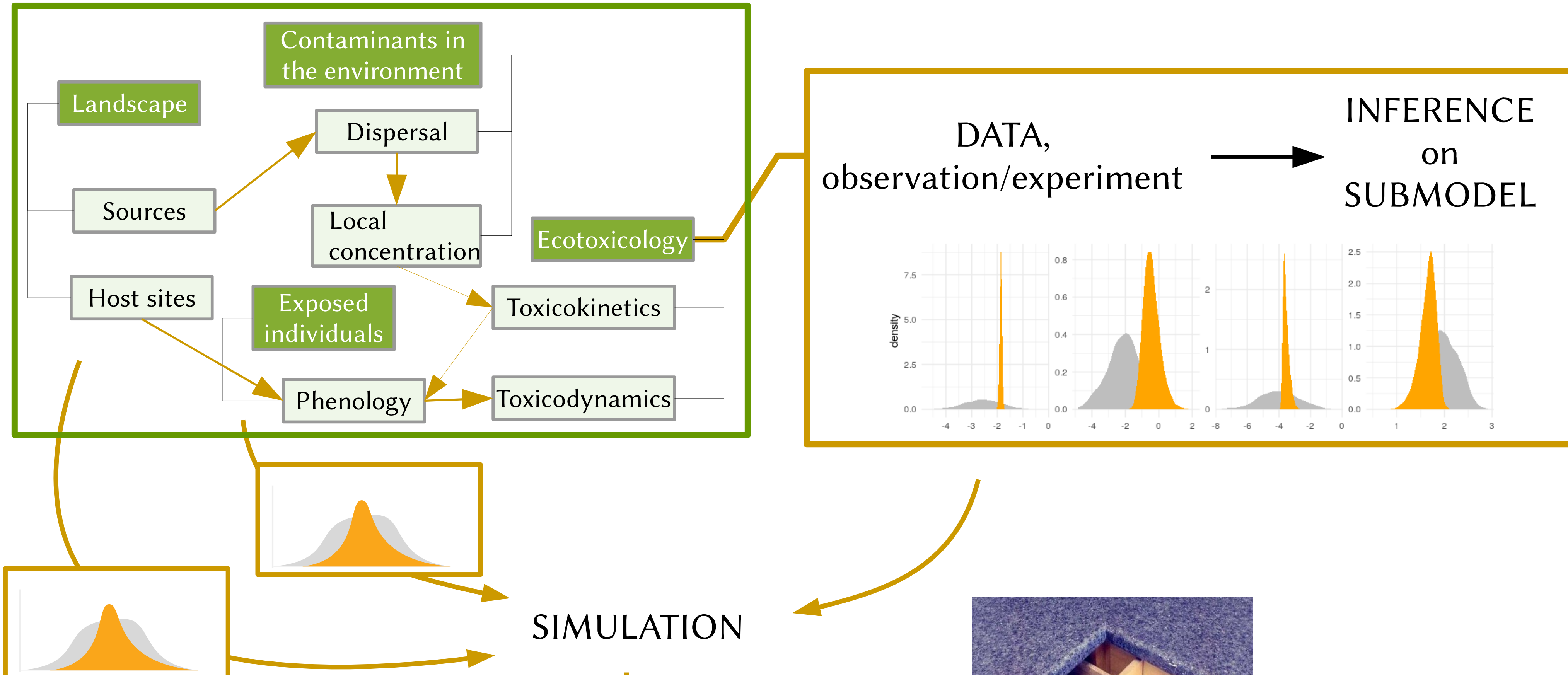
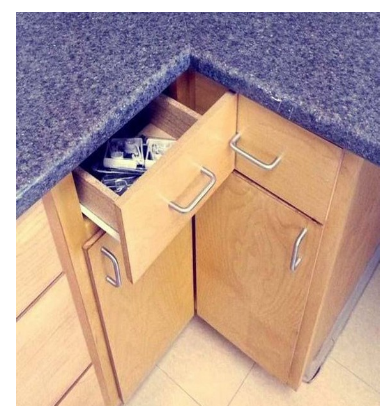



Contaminants in the environment
Landscape
Dispersal
Sources
Local concentration
Ecotoxicology
Host sites
Exposed individuals
Toxicokinetics
Phenology
Toxicodynamics
DATA, observation/experiment
INFERENCE on SUBMODEL
density
SIMULATION



SIMULATION

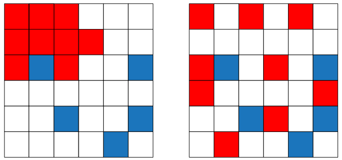
GLOBAL SENSITIVITY ANALYSIS



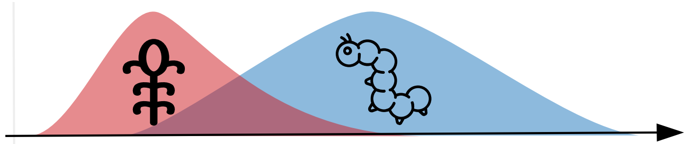
- *2 unitary tests*
- *0 integration test*

➡ **3 driving factors of sensitivity** (need further investigation)

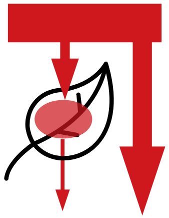
1. Aggregation of GM fields (SPATIAL)



2. Overlapping deposition ↔ sensitive stage



3. Loss and Adherence of pollen



Leclerc, M.; Walker, E.; Messéan, A. & Soubeyrand, S. (2018) Spatial exposure-hazard and landscape models for assessing the impact of GM crops on non-target organisms. **Science of the Total Environment**, 624, 470-479

1. Review/Build/Rebuild a set of model of pest-control strategies
⟶ Open Agent Based Model/Plateform
2. Assessment of their environmental impact
⟶ Space, Time, Trophic Link, Evolution
3. Uncertainty analysis (Sensitivity, Bayesian inference)
⟶ lack of knowledge (inputs, output, latent variables)

Perspectives of Researches

1. Review/Build/Rebuild a set of model of pest-control strategies
→ Open Agent Based Model/Plateform
2. Assessment of their environmental impact
→ Space, Time, Trophic Link, Evolution
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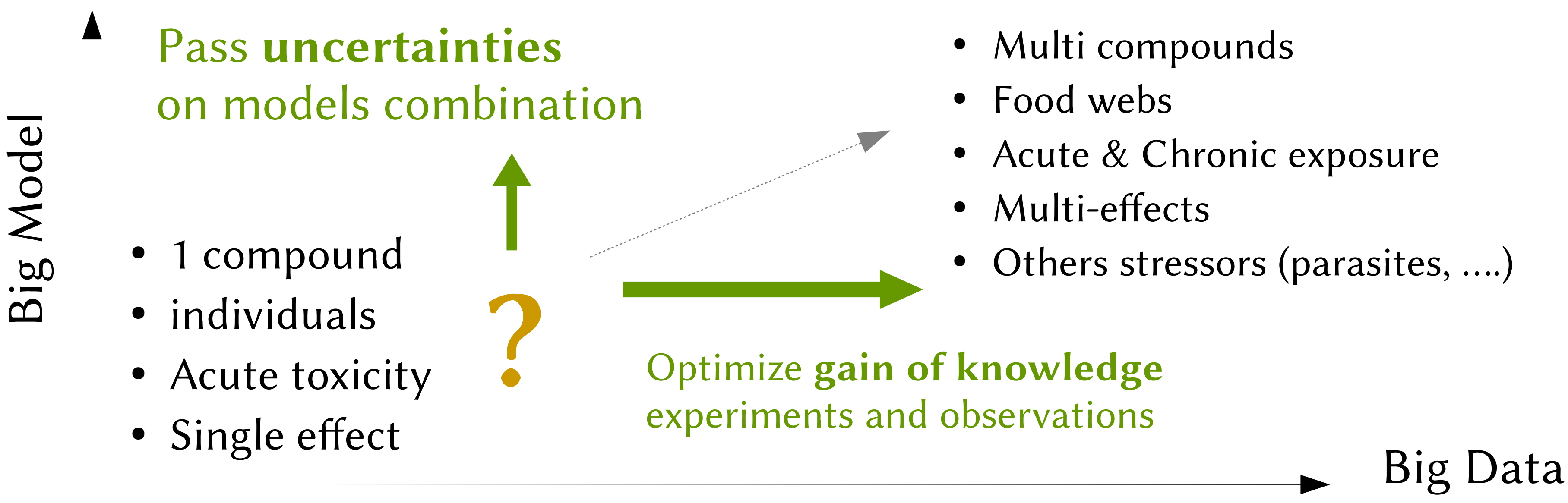
→ lack of knowledge (inputs, output, latent variables)



Thank you for your attention