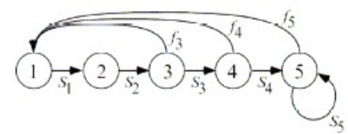
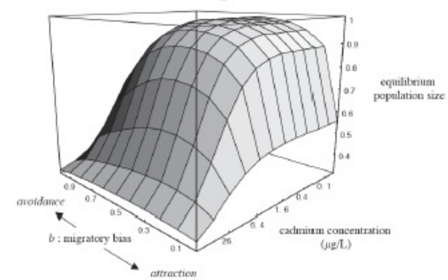
From toxicological to eco-toxicological effects :

how matrix population models can help to assess population sensitivity to contaminants in ecosystems



$$A = \begin{pmatrix} 0 & 0 & f_3 & f_4 & f_5 \\ s_1 & 0 & 0 & 0 & 0 \\ 0 & s_2 & 0 & 0 & 0 \\ 0 & 0 & s_3 & 0 & 0 \\ 0 & 0 & 0 & s_4 & s_5 \end{pmatrix}$$



Arnaud Chaumot

UR "Milieux aquatiques, écologie et pollutions"
laboratoire d'écotoxicologie
Cemagref Lyon

Cemagref
Science, water & land management

- **Why modeling population dynamics in ecotoxicology ?**

  diagnostic and predictive ecological risk assessment (ERA) of chemicals

- **Example 1 *Chironomus & pesticide***

  the demographic component of population sensitivity to toxics

  Example 2 *Metapopulation of brown trout*

  deciphering the complexity of population impacts

  Example 3 *Variability in aquatic invertebrates*

  between species & seasonal variability

- **Population modeling asks new questions in ecotoxicology**

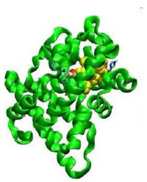
  variability of life histories at low phylogenetic levels
  adaptation of life histories to contamination ?

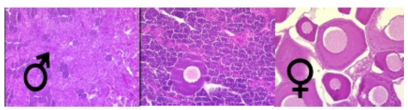
Why modeling population dynamics in ecotoxicology ?

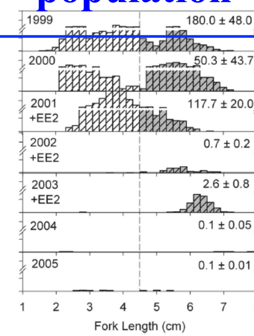
• multi-level effects of contaminants

molecule **cell** **tissue** **individual** **population** **community**

integration







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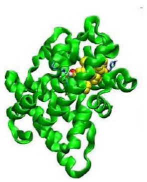

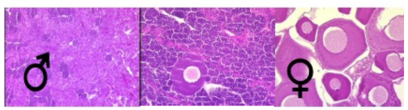

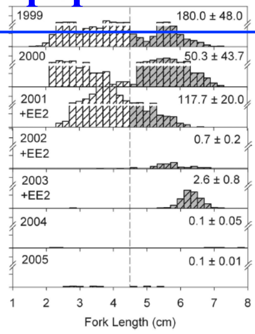

biomarkers **bioassays** **bioindicators**

(life history traits: survival, growth, reproduction)

• tools for assessing the possible adverse effects of chemicals

Why modeling population dynamics in ecotoxicology ?

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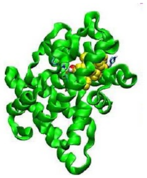
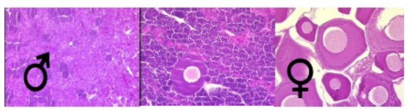
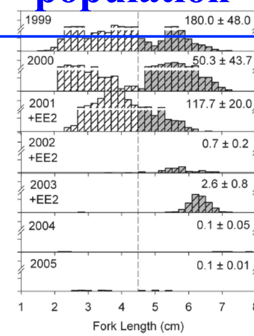






SPECIFICITY

biomarkers **bioassays** **bioindicators**

(life history traits: survival, growth, reproduction)

• tools for assessing the possible adverse effects of chemicals

• relevant levels for toxicity assessment: why not the population ?

- • diagnostic framework: specificity → biomarkers & in situ bioassays
- • predictive ERA: experimental approach → bioassays

Why modeling population dynamics in ecotoxicology ?

molecule cell tissue individual population community

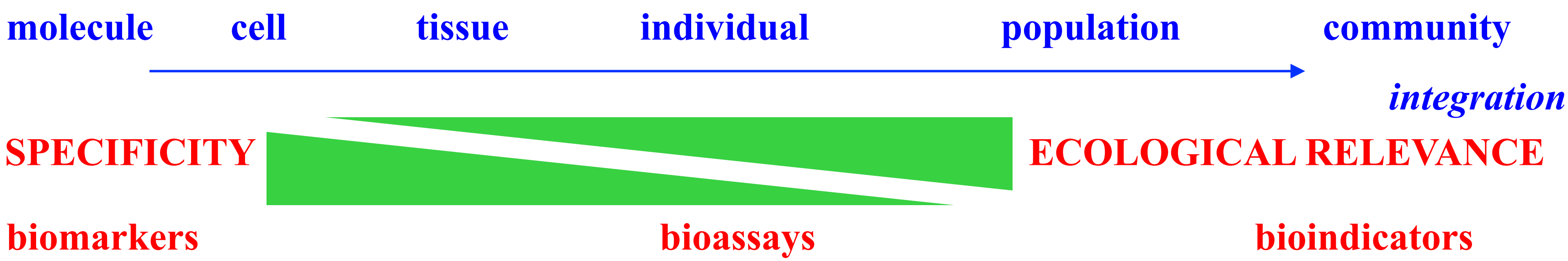
integration

SPECIFICITY

biomarkers bioassays bioindicators

- 80s → ranking of substances according to their potential toxicity

Why modeling population dynamics in ecotoxicology ?



- 80s → ranking of substances according to their potential toxicity
- 90s: society & environmental quality: new regulations to protect ecosystems

  role of contaminants ? → ecological relevance of ecotoxicological tools ?

  - diagnostic: *e.g.* EU WFD - restoration

    between chemical status / ecological status → complementary tools ?

    selection of relevant tools and interpretation framework

  - predictive ERA: *e.g.* REACH program

    protection goals: populations & ecosystems

From individual to population: bridging the gap

- Current ERA procedures:

data from bioassays on individual responses → toxicity thresholds

protection of populations (PNEC) : application of safety factors

- Population modeling was yet early identified as a relevant tool but not considered up to now in ERA procedure.

bioassay: survival, fertility, growth rate ….

→ **population model** → **demographic indicators**

- Recent initiatives (Galic et al 2010, CREAM project, Kramer et al 2011)

- Job for modelers but is it really a good idea ? What is the added value for a protection goal ?

Life history influence in the emergence of population impacts

- population effects are not a perfect mirror of individual effects.

PNAS

How risky is risk assessment: The role that life history strategies play in susceptibility of species to stress

John D. Stark*†, John E. Banks‡, and Roger Vargas§

Table 3. Comparison of the delay in population growth as a percentage of generation time

Species	50% mortality	50% reduction offspring	50% mortality and 50% reduction offspring
A. pisum	57	57	143
D. rapae	100	80	253
C. septempunctata	62	46	134
D. pulex	21	17	50
B. dorsalis	54	46	81
F. arisanus	85	63	180
F. vandenboschi	67	100	223

Values listed are percentages.

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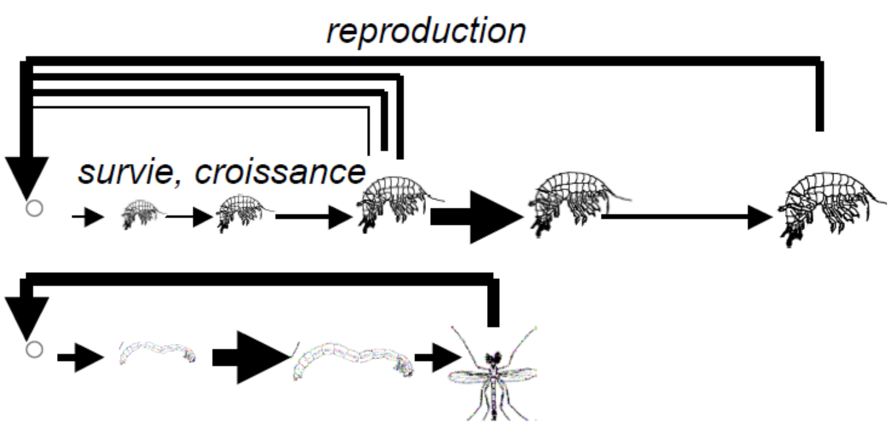


• population sensitivity to contaminants: **2 components** (~Van Straalen 1994)

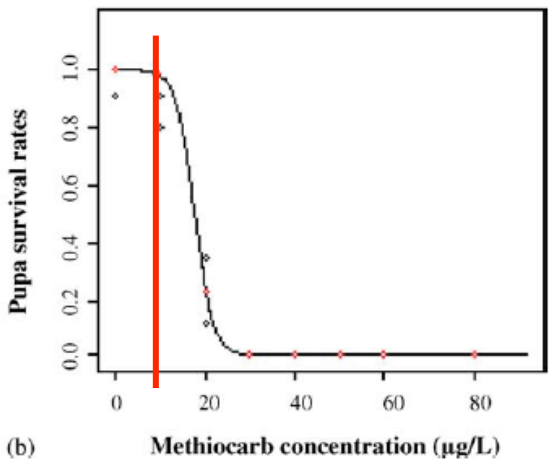
toxicological sensitivity & demographic sensitivity

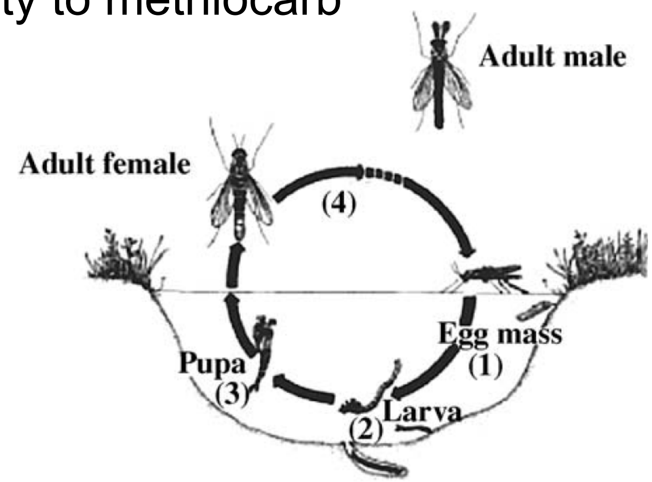
→ Matrix population models & perturbation analysis (Caswell 1996)

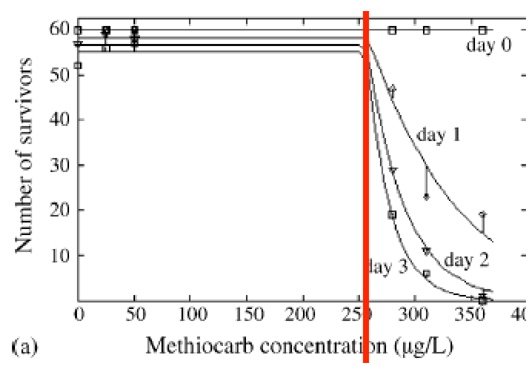
Life history influence : Example 1 *Chironomus & pesticide*

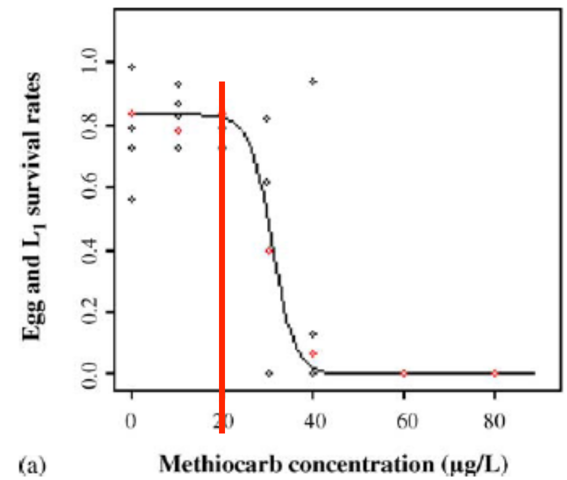
Lopes et al 2005

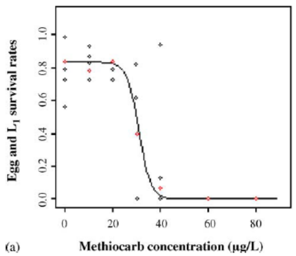
- toxicological sensitivity to methiocarb

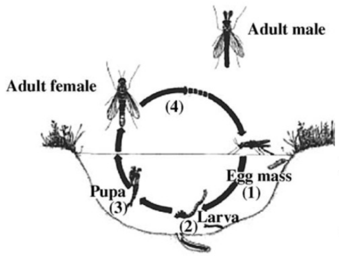


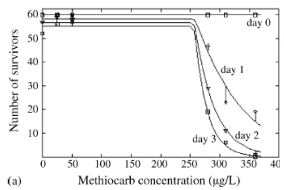


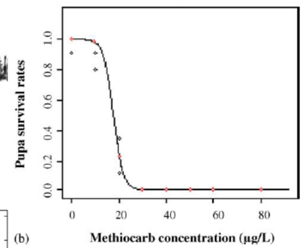










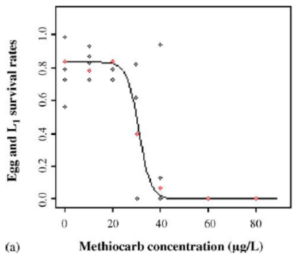


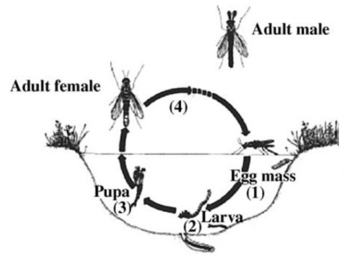
individual effects

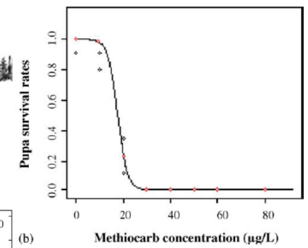
Leslie model

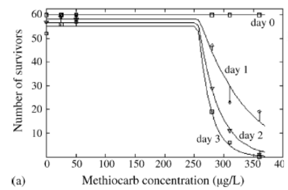
$$
\mathbf{L}_{(C)} = \begin{pmatrix}
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & F \\
S_{2,1}(C) & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & S_{3,2}(C) & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & S_{4,3}(C) & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & S_{5,4}(C) & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & S_{6,5}(C) & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & S_{7,6}(C) & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & S_{8,7}(C) & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & S_{9,8}(C) & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & S_{10,9}(C) & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & S_{11,10}(C) & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & \ddots & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & S_{z,z-1}(C) & 0
\end{pmatrix}
$$

Egg | L_1 | L_2 | L_3 | L_4 | Adult









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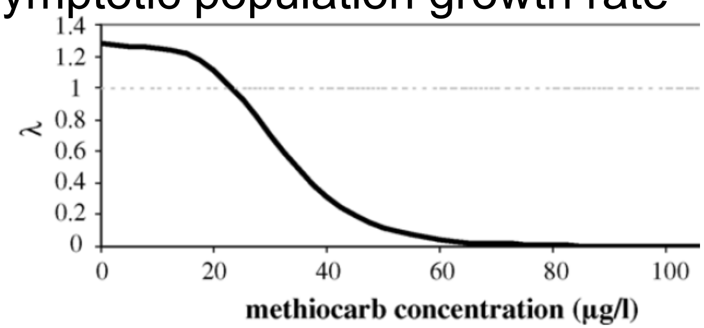
\end{pmatrix}
$$

Egg L_1 L_2 L_3 L_4 Adult

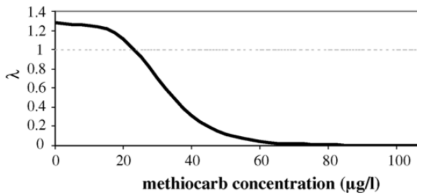
asymptotic population growth rate



population effects

$$\lambda = f(C)$$

Deciphering life history influence: perturbation analysis

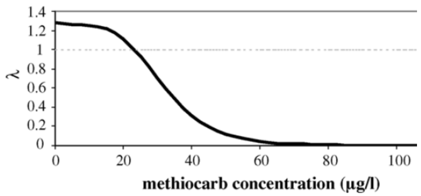


$$\lambda = f(C)$$

$$\frac{\partial \lambda}{\partial C} = \sum_{x,y} \frac{\partial \lambda}{\partial l_{xy}} \frac{\partial l_{xy}}{\partial C}$$

population sensitivity

Deciphering life history influence: perturbation analysis



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population sensitivity

demographic sensitivities

toxicological sensitivities

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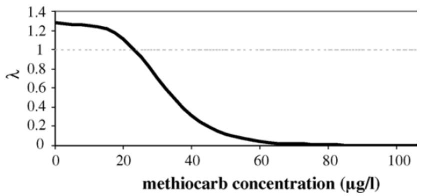

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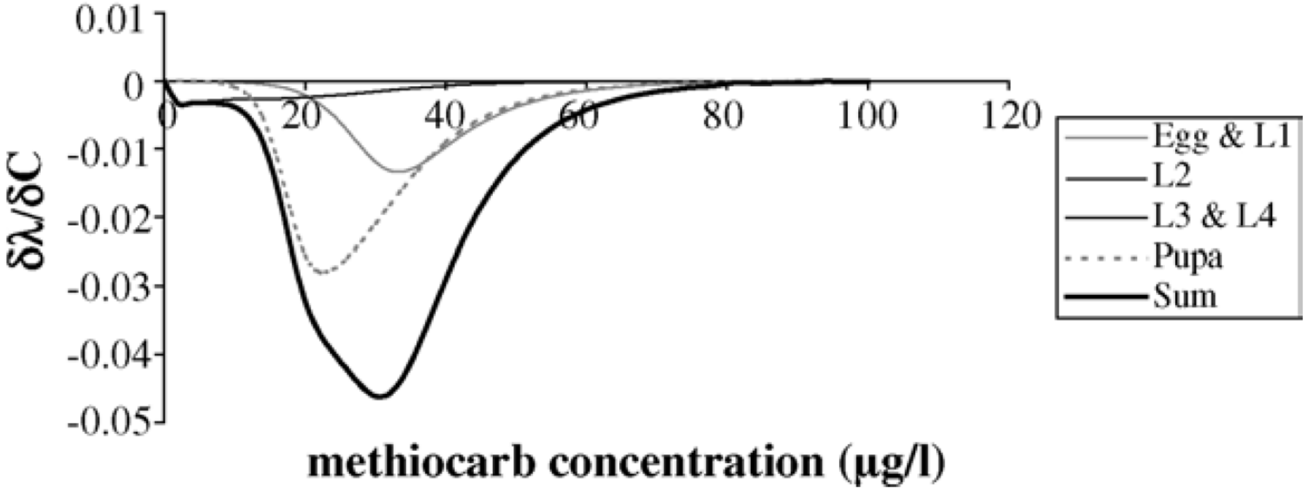
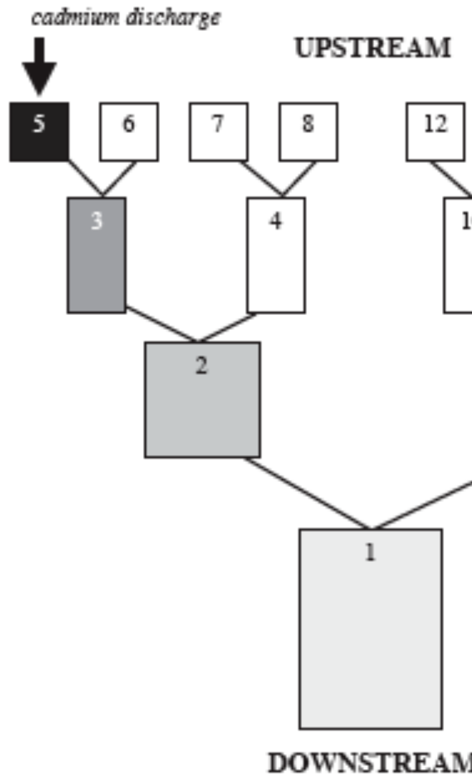
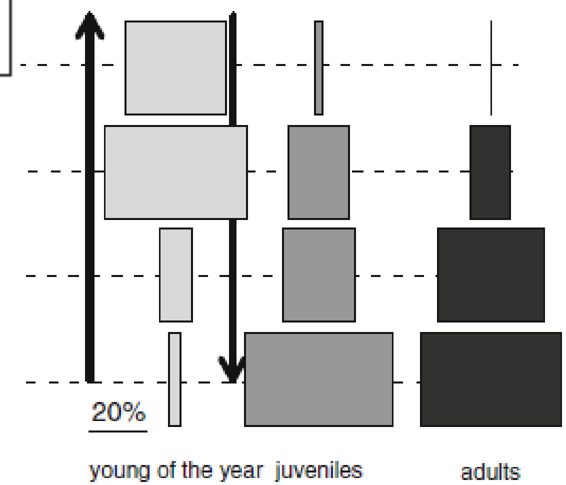


Life history influence : Example 2 *Metapopulation of brown trout*

Chaumot et al 2002, 2003; Charles et al 2010





3 age classes

- **multi-regional Leslie model**

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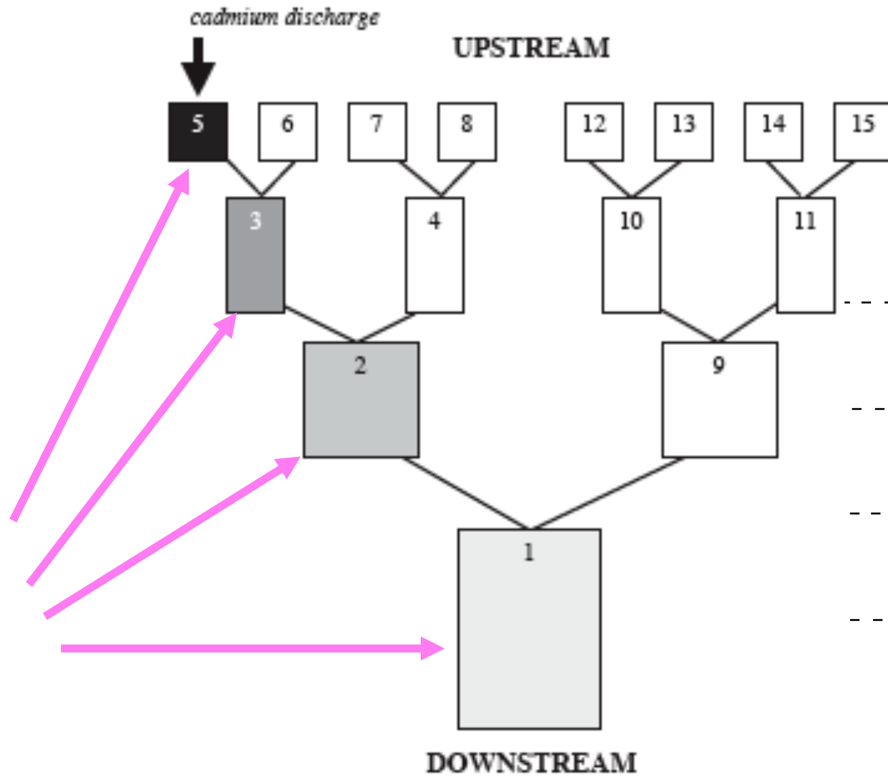
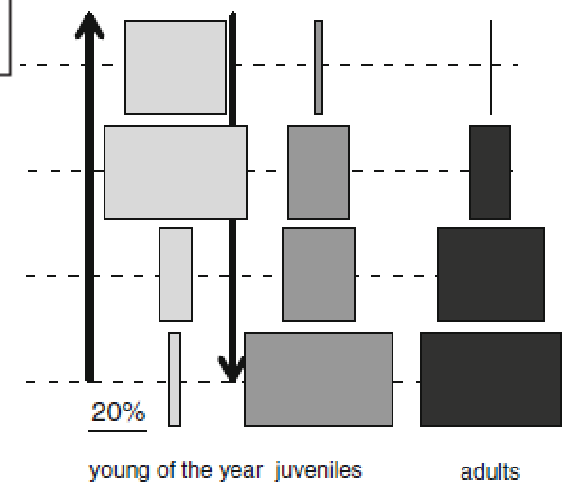
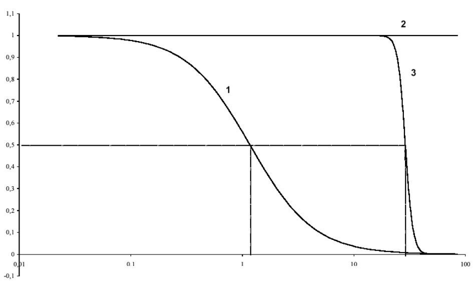




3 age classes

toxicological effects



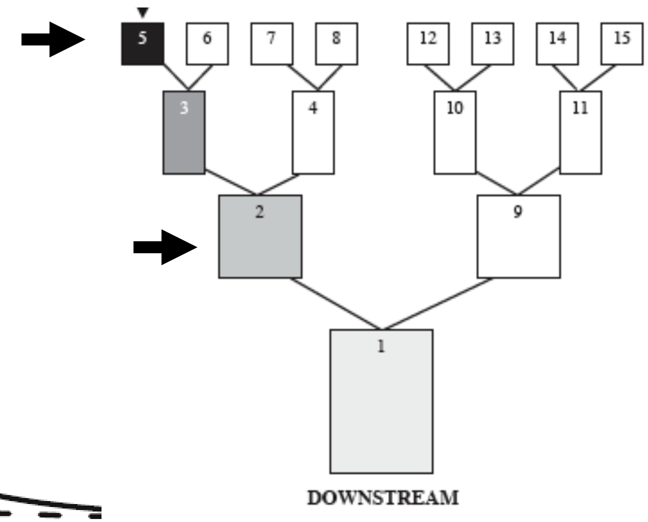
Cadmium µg/L

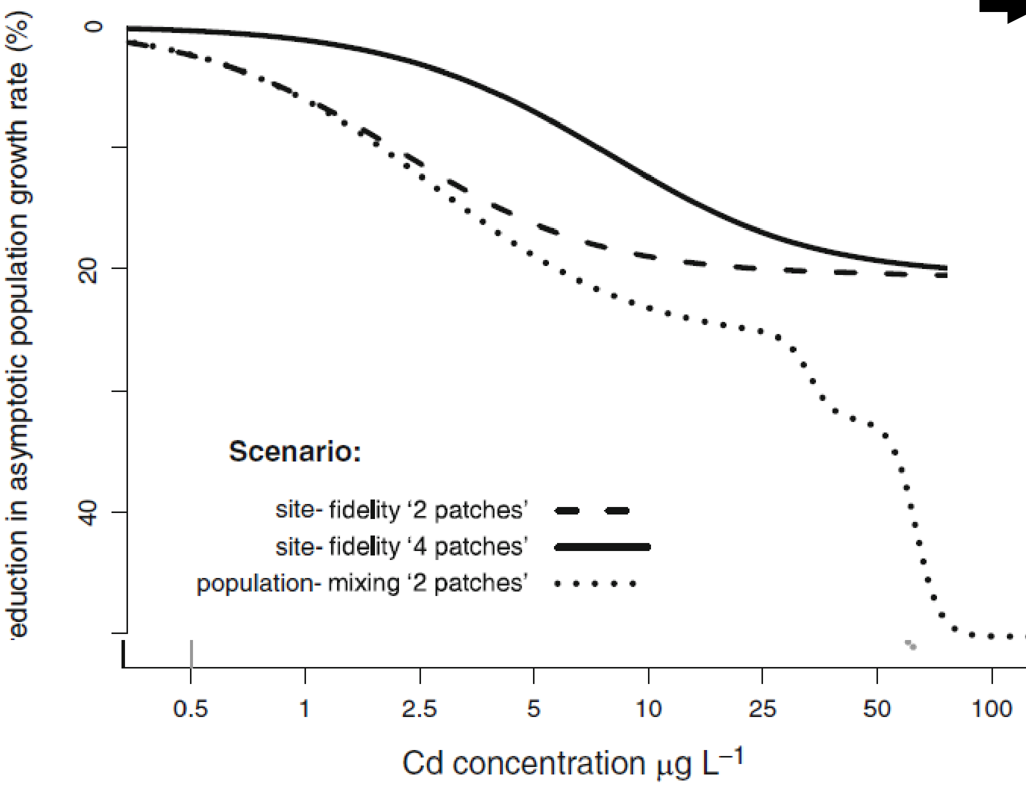
- **multi-regional Leslie model**

$$\mathbf{A}(c) = \begin{bmatrix} \mathbf{O} & \mathbf{O} & \mathbf{M_U}(c)\,\mathbf{F}(c)\,\sqrt{\mathbf{S}_3(c)} \\ \mathbf{S}_1(c) & \mathbf{O} & \mathbf{O} \\ \mathbf{O} & \mathbf{S}_2(c)\,\mathbf{M_D} & \mathbf{S}_3(c) \end{bmatrix}$$

Complexity of population response

$$\lambda = f(C)$$

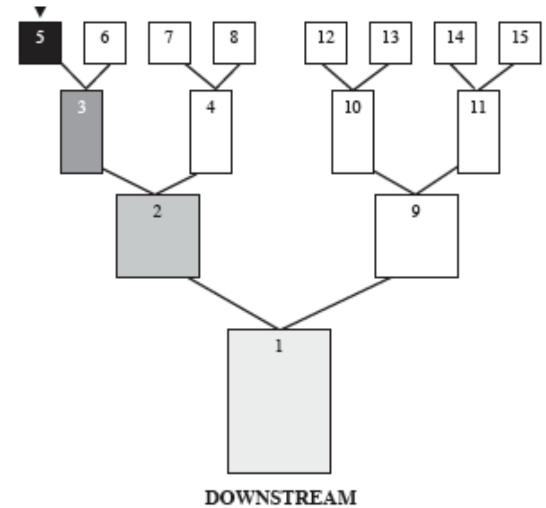


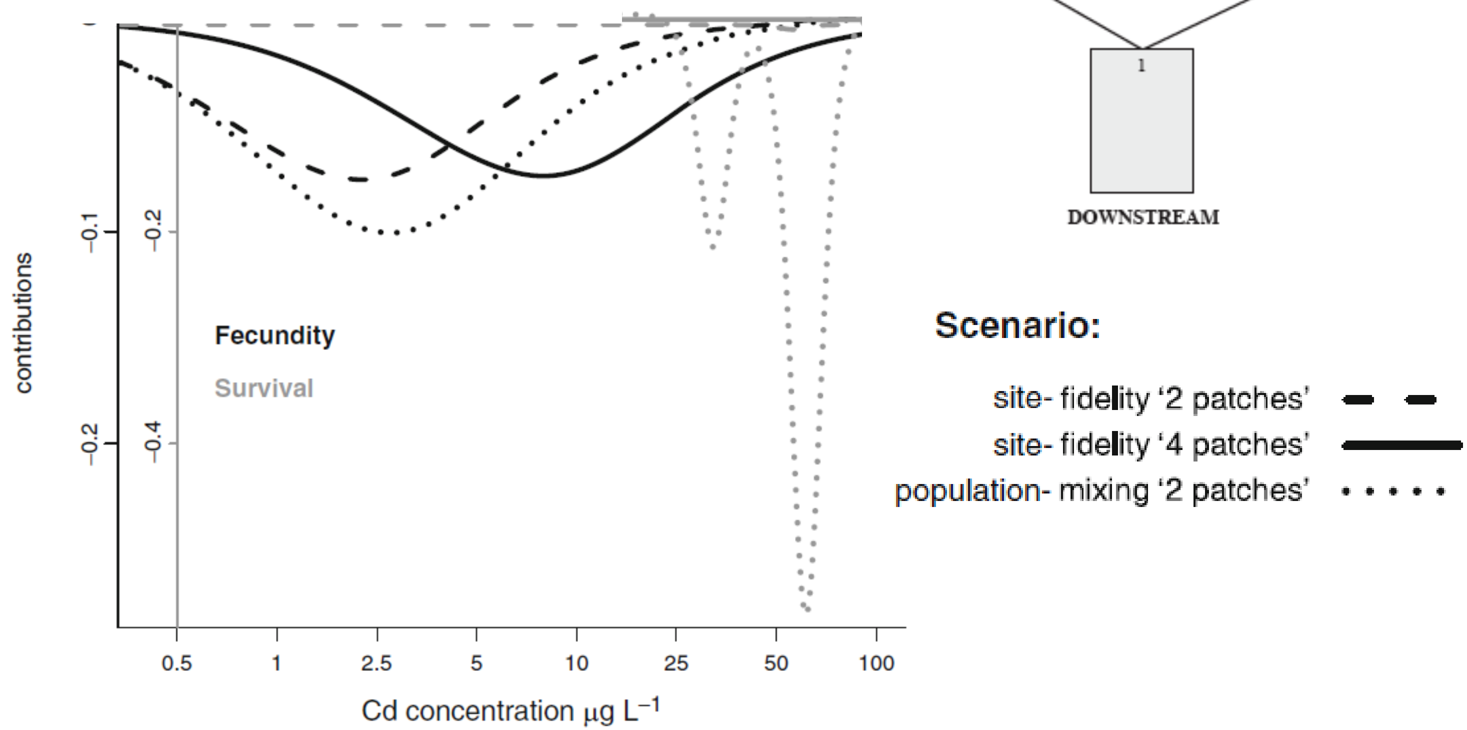


Perturbation analysis

$$\frac{\partial\lambda}{\partial(\log\ c)} = \sum_{x,y} \frac{\partial\lambda}{\partial l_{xy}} \frac{\partial l_{xy}}{\partial(\log\ c)}$$

$$\chi f = \sum_j \chi f_j \quad \text{and} \quad \chi s_i = \sum_j \chi s_{(i,j)}$$





- Identification of key parameters:

  age-class / toxicological effect / spatial location and behaviour

→ **Population pathways** of contaminant effect

Life history influence : *Example 3 variability in aquatic invertebrates*

R. Coulaud

Between species variability **&** ***Seasonal variability***

1 cm

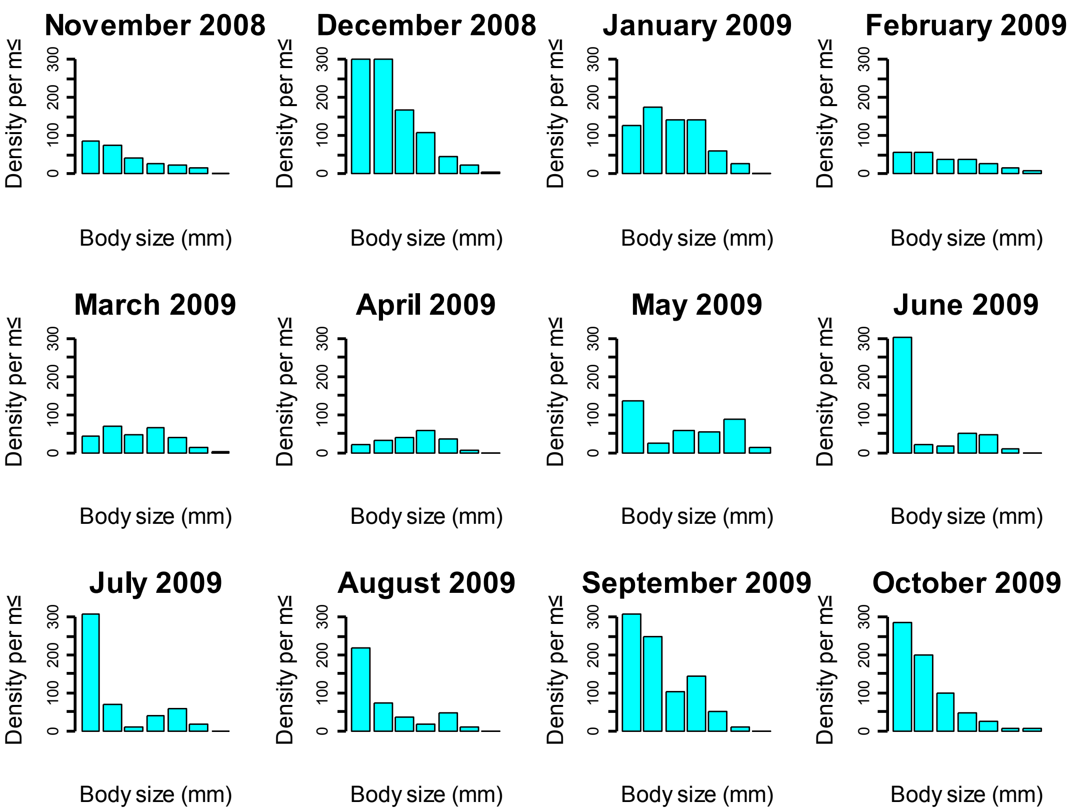
- *Gammarus fossarum* (Crustacean Amphipod):
  - widespread and abundant in Europe
  - known to be sensitive to a large range of stressors
  - **currently used in ecotoxicological tests**
  - important food resource in freshwater communities
  - **major role** in the leaf litter breakdown process

5 mm

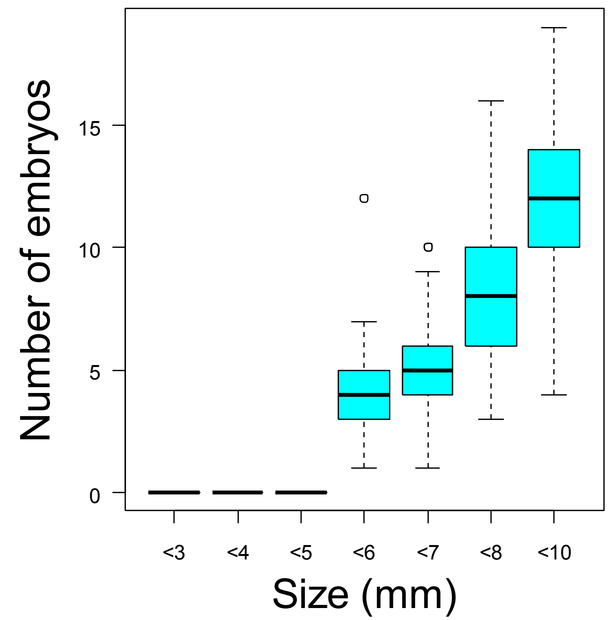
- *Potamopyrgus antipodarum* (Mollusk Gastropod):
  - widespread and abundant in Europe
  - known to be sensitive to a large range of stressors
  - parthenogenetic reproduction
  - invasive species

Demographic survey based on monthly population census

Densities & size- structure



Fertility



Demographic survey based on monthly population census

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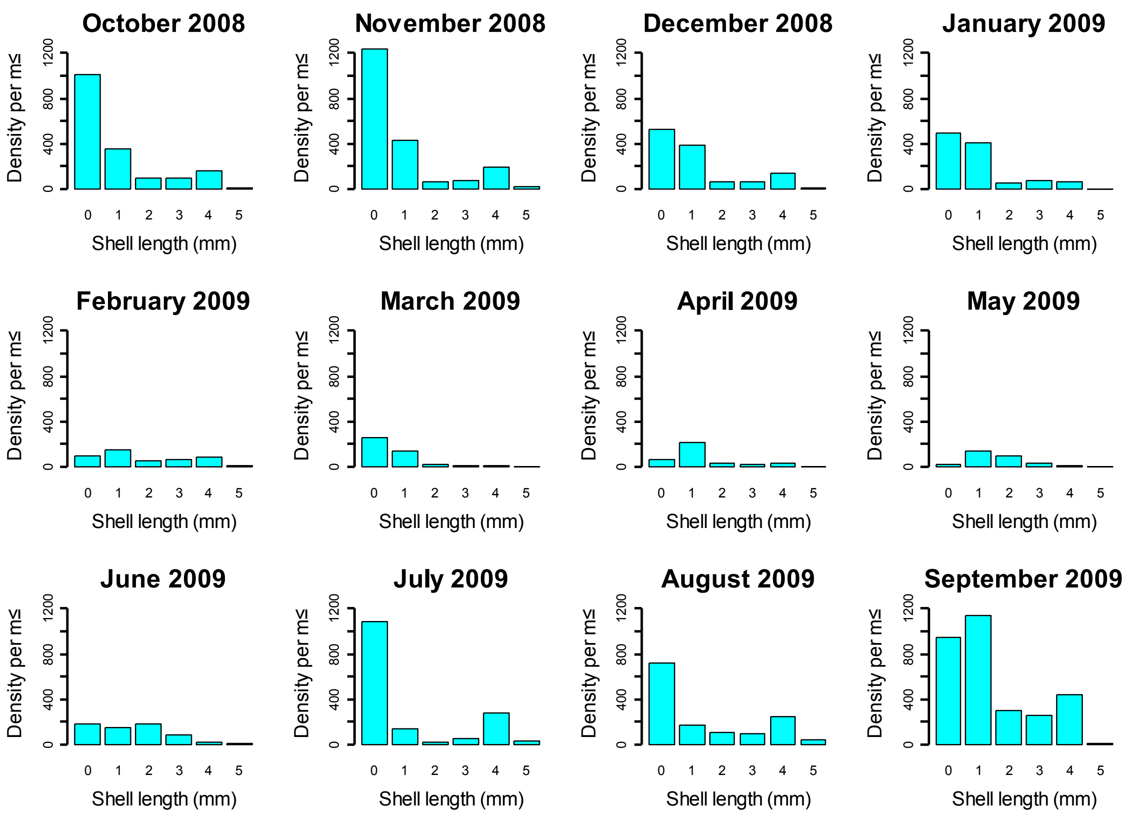
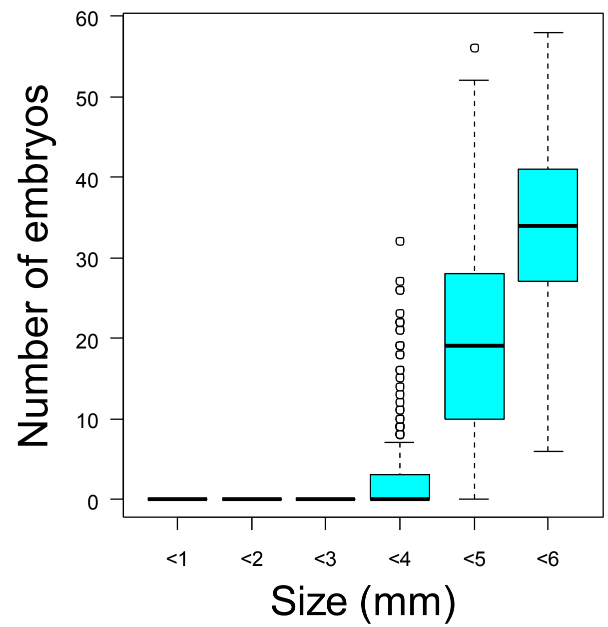
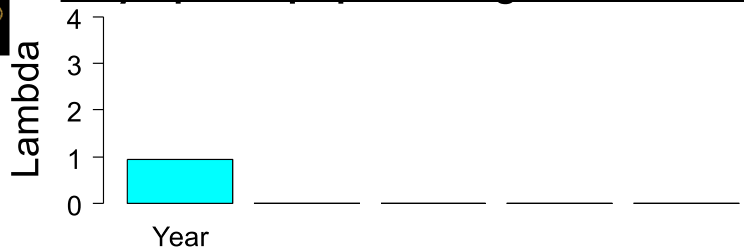


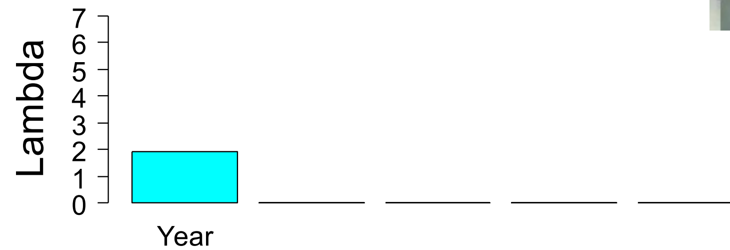
Fertility



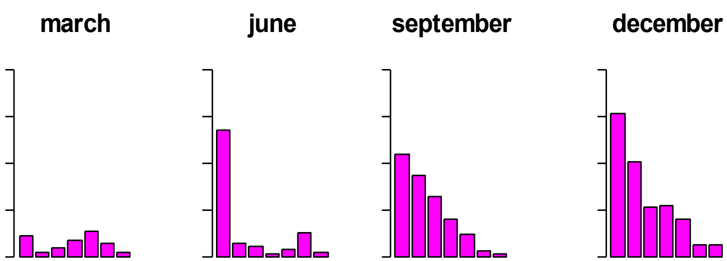
→ Calibration of size-structured population models

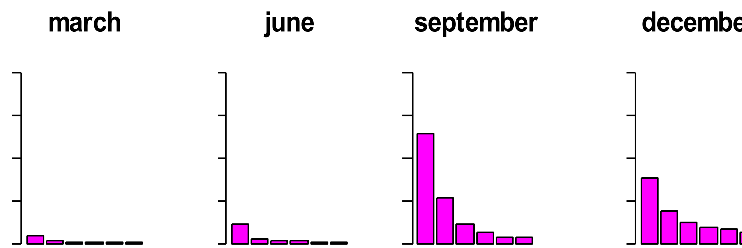
- **Asymptotic population growth rate**



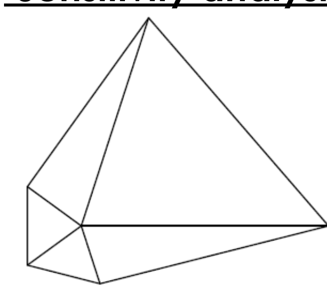


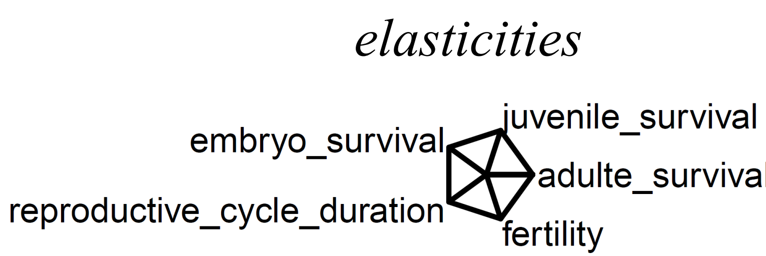
- **Stable size distributions**

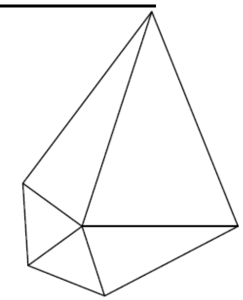




- **Sensitivity analysis**

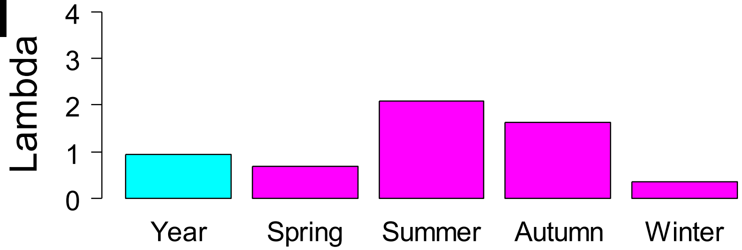


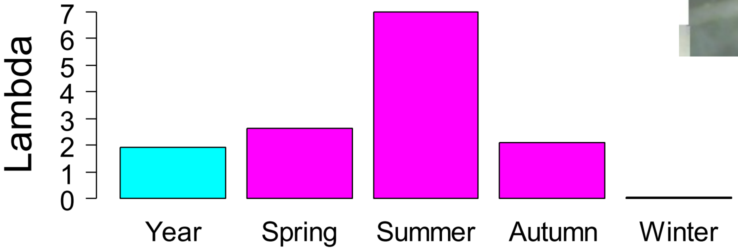




Seasonal variability

- **Asymptotic population growth rate**





Seasonal variability

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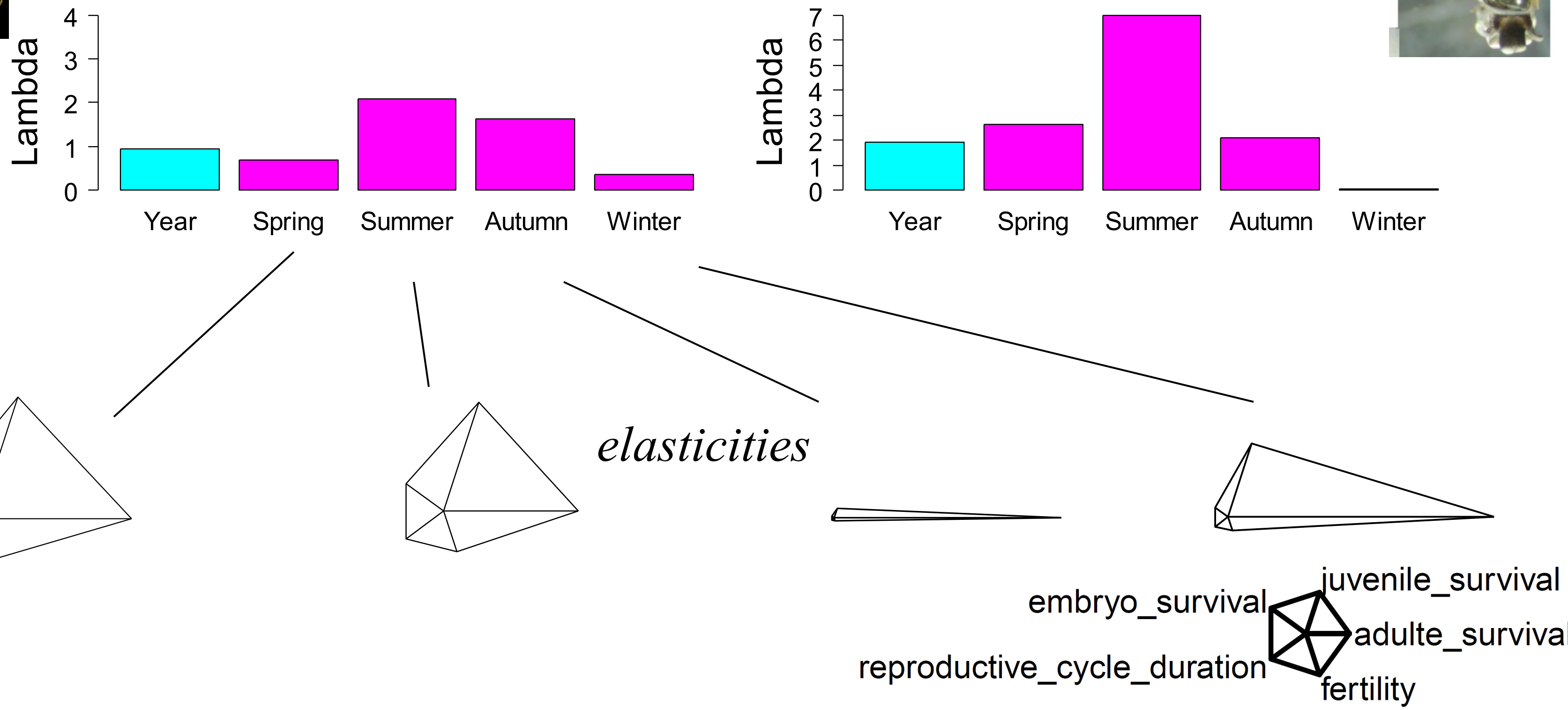


• Population modeling allows to **mechanistically understand** how **between-species** and **seasonal variability** in life history could influence the **population response to toxic stressors**.

• **Exposure variability** (*e.g.* seasonal pulses of agricultural pesticides) can be considered at the population level by considering **seasonal variability** in this **mechanistic** population modeling.

What is the potential added value of matrix population models in ERA ?

Identification of population pathways of contaminant effect

In diagnostic context:

• Understanding the link between (observed or potential) toxicological effects and obsevred impacts on communities in the field.

• Selection of biomarkers and bioassays predictive of population effects

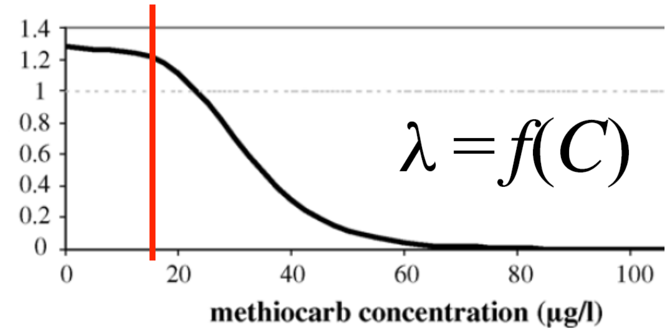
In predictive ERA: *from lab bioassays to the protection of populations*

Improvement of safety factors ?

• The bad use : NEC population

less protective

predictive models ?



• The good use: deciphering important pathways

selection of toxicological markers / effect on population fitness

one fundamental question: environmental canalization ?

Matrix population modeling asks future questions for ecotoxicology

Question 1: variability of life histories at low phylogenetic levels ?

• ERA: screening approach to take into account the biodiversity

→ choice of model species

variability in toxicological sensitivities

Modes of action of toxic

(insecticides, endocrine disruptors,

photosynthetis inhibitors, …)

at large phylogenetic scale

Matrix population modeling asks future questions for ecotoxicology

Question 1: variability of life histories at low phylogenetical levels ?

- ERA: screening approach to take into account the biodiversity

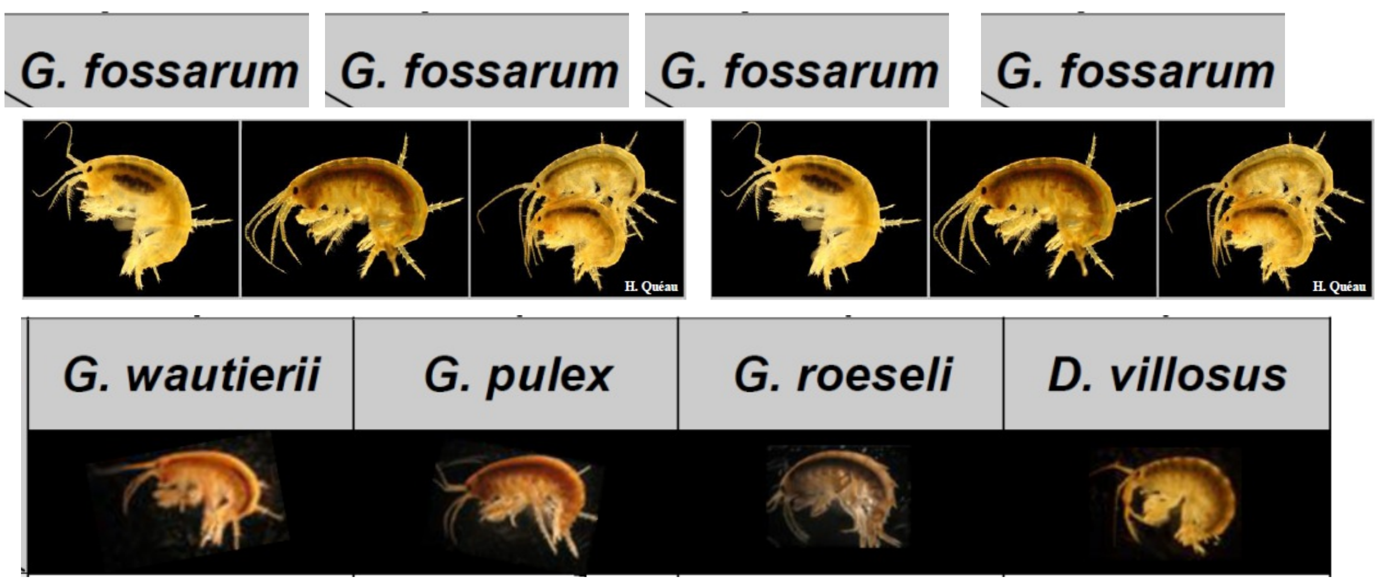
→ choice of model species

variability in toxicological sensitivities

variability in life histories:

at low phylogenetic scales (within species or gender)

Should we take into account these levels of variability in ERA ?



Question 2: adaptation of life histories to contamination ?

Life histories can rapidly evolve in response to environmental changes (genetic adaptation)

SCIENCE VOL 312 9 JUNE 2006

Adaptive animals. The Yukon red squirrel (*Tamiascurus hudsonicus*) (**left**), the pitcher-plant mosquito (*Wyeomyia smithii*, shown descending into its carnivorous host, *Sarracenia purpurea*) (**middle**), and the European blackcap (*Sylvia atricapilla*) (**right**) show genetically based shifts in the timing of their seasonal reproduction, dormancy, or migration during recent, rapid climate warming.

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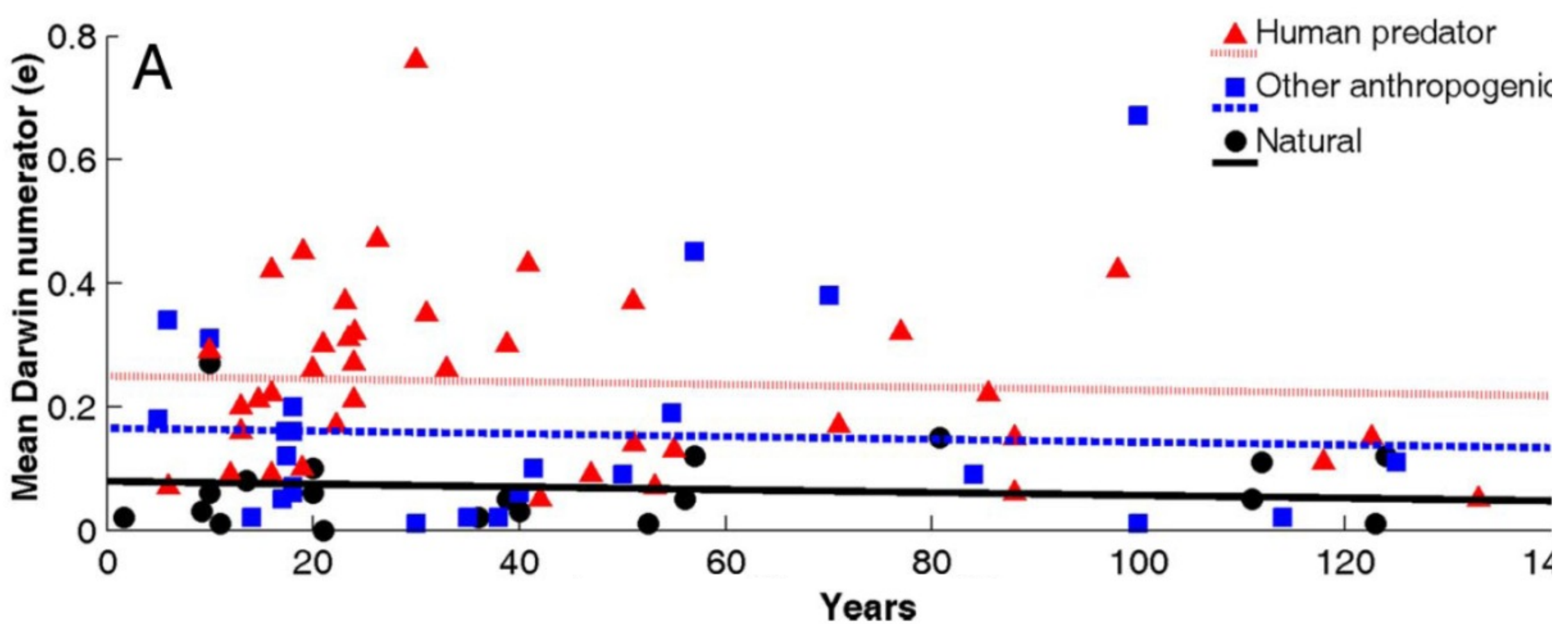
Human predators outpace other agents of trait change in the wild

Chris T. Darimont[a,b,1], Stephanie M. Carlson[c], Michael T. Kinnison[d], Paul C. Paquet[e], Thomas E. Reimchen[a], and Christopher C. Wilmers[b]



Question 2: adaptation of life histories to contamination ?

Evolutionary changes of life histories ignored in ecotoxicology.

Yet:

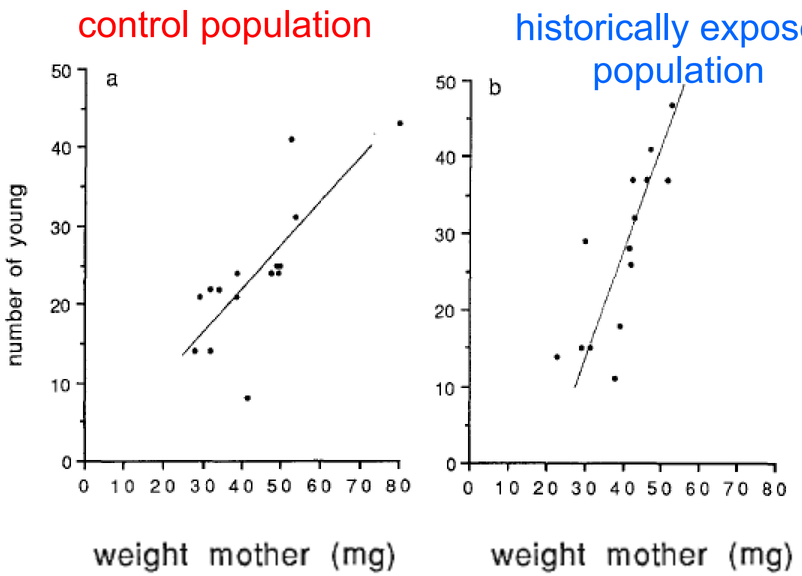
Oecologia (1993) 96:316–323

Oecologia

Early reproduction and increased reproductive allocation in metal-adapted populations of the terrestrial isopod *Porcellio scaber*

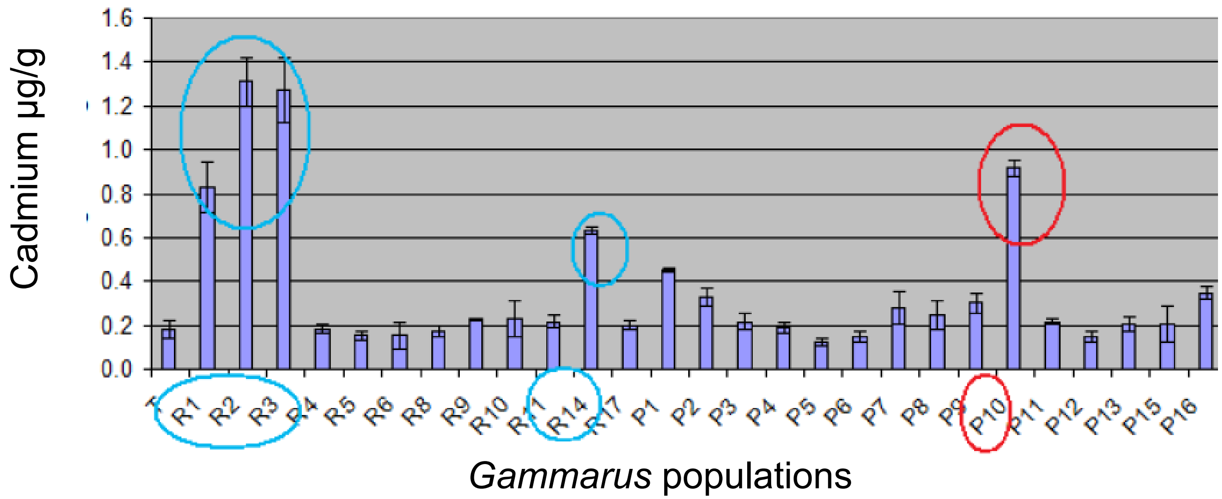
M.H. Donker[1], C. Zonneveld[2], N.M. van Straalen[1]

F1



Question 2: adaptation of life histories to contamination ?

Evolutionary changes of life histories in contaminated environments



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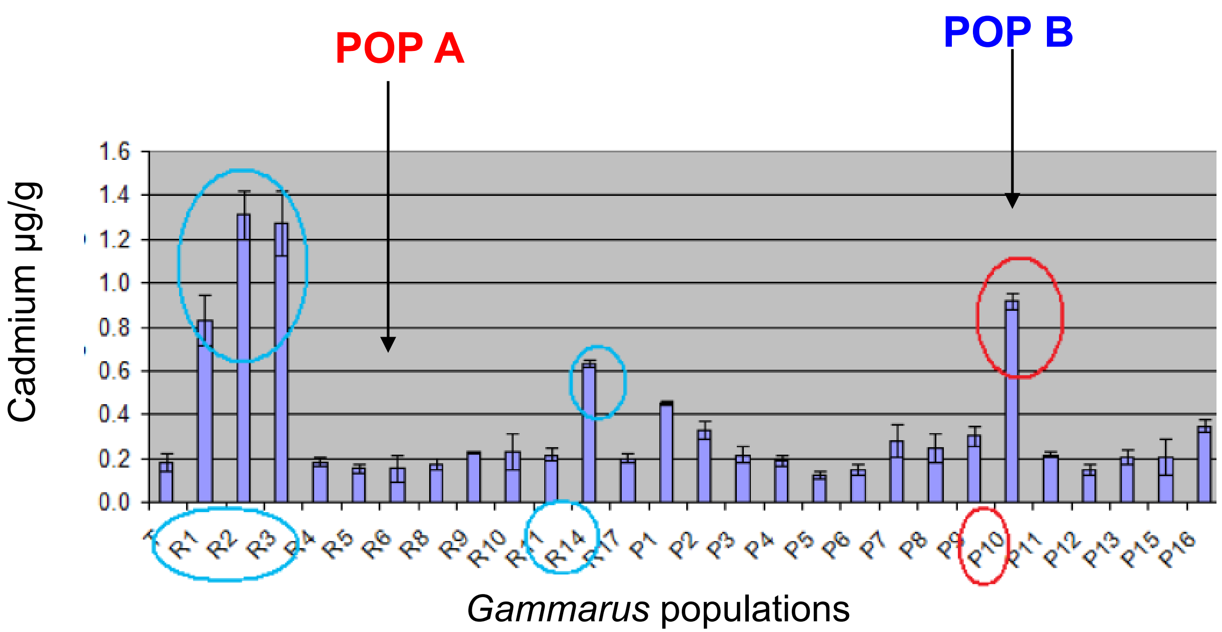


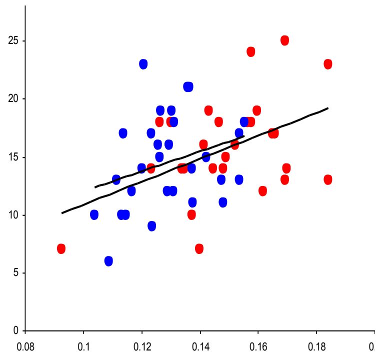
Detection of toxicological effects in population B (survival).

Question 2: adaptation of life histories to contamination ?

Evolutionary changes of life histories in contaminated environments

clutch size

fertility

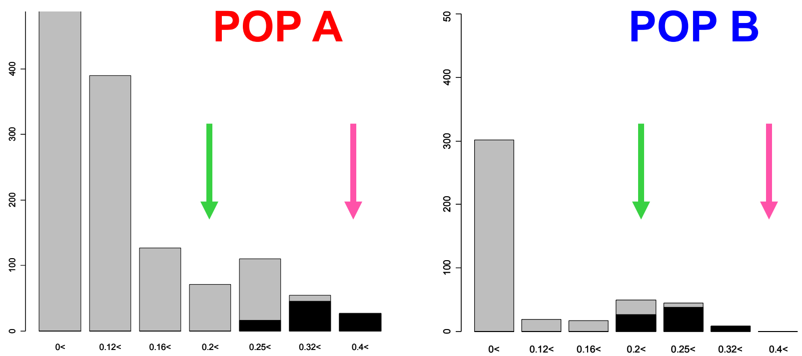


size

size structure (females)

■ reproductive

density

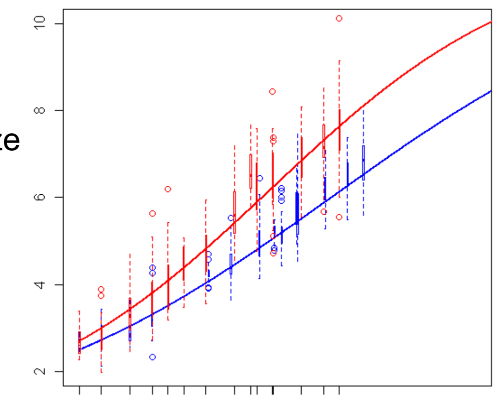


size class   size class

size at maturity A 5.8 mm   B 4.8 mm

growth

size



age

→Adaptation of life cycle to the environmental constraints ???

→Matrix population models

MERCI

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Staff:
H Quéau

and Semovi organizers

Arnaud Chaumot

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Cemagref Lyon

Cemagref
Science, water & land management