

IRSN

INSTITUT
DE RADIOPROTECTION
ET DE SÛRETÉ NUCLÉAIRE

Faire avancer la sûreté nucléaire

Combined exposures to stable and radioactive substances for ecological risk assessment

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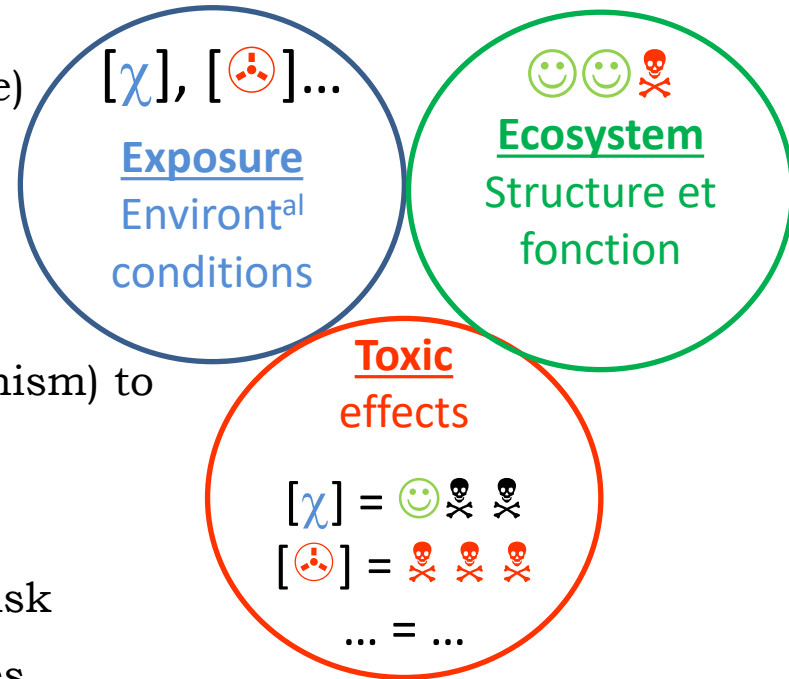
**Research Department on Transfers and Effects of
Radionuclides on ecosystems
IRSN / PSE-ENV / SRTE
Cadarache, France**



Introduction

1

- Exposure in ecosystems: Many substances (stable or radioactive) at potential risk
- Ecotoxicity of substances: approach by 1 (substance, organism) to determine toxic effects
- Protection target for ecological risk assessment: species assemblages, ecosystem structure and function sensitivity to all variables (contaminants and other environmental factors)



1- Introduction

Joint exposure to stable and radioactive substances

Example of stable and radioactive substances present in releases from nuclear fuel cycle facilities

Vandenhove *et al.* (2012) STAR D 4.1

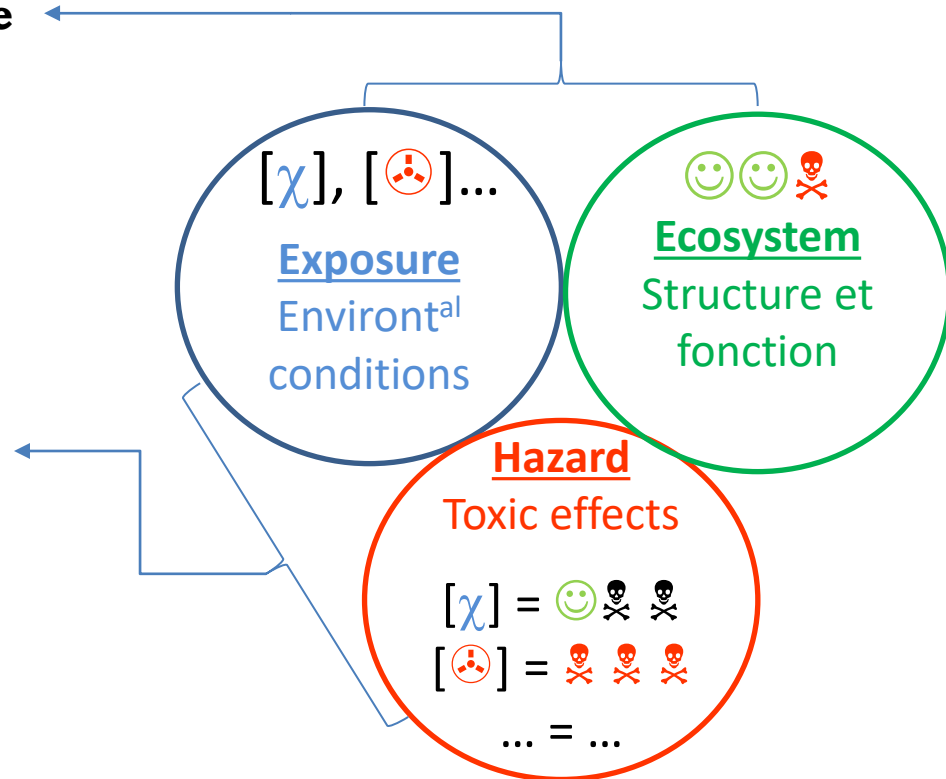
	Substances Stables	Radioactives
U mining (ex. Canada, Germany, Brazil, France)	As, Cd, Cr, Cu, Pb, Zn Ba, Fe, Al, F, Cl	U and daughters
Nuclear Fuel Production	F, NH ₄ , K, SO ₄ , As, Cl, Cr, Cu, Fe, Zn	¹⁴ C, ³ H, ⁹⁹ Tc, α, β
Electric power production	NH ₄ , B, Cu, Zn, LiOH Morpholine, hydrazine ...	^{110m} Ag, ¹⁴ C, ⁵⁸ Co, ^{134/7} Cs, ³ H, ¹³¹ I, ⁵⁴ Mn, ^{124/5} Sb, ^{123m} Te
Spent fuel reprocessing (ex. AREVA-NC La Hague)	TBP, NO ₃ , hydrazine, NH ₄ , SO ₄ , Fe, K, Ba, Al, F, Co, Cd, Ni, Cr, Hg, Pb, Zr	¹⁴ C, ³ H, ⁸⁵ K, ⁶⁰ Co, ^{134/7} Cs, I, ¹⁰⁶ Ru, ⁹⁰ Sr, ⁶⁰ Ni, ²³⁸⁻⁴¹ Pu, ¹⁰⁶ Rh, ¹²⁵ Sb, ²⁴¹ Am, ²²⁴⁴ Cm, U
Waste disposal
NORM (coal, petrol, gaz, minerals extraction...; <i>Hospitals, R&D</i> <i>Accidents</i> <i>Other industries, agriculture, non-point sources...</i>	metals, hydrocarbons...	natural RNs

1- Introduction

Approaches developed at IRSN

Determination of the **ecological structure**
(species assemblages) **and function**
(integrated biomarker response)

Cumulative Risk Assessment (msPAF
approach for the prediction of chronical
impact to aquatic ecosystem)



Cumulative Risk Assessment

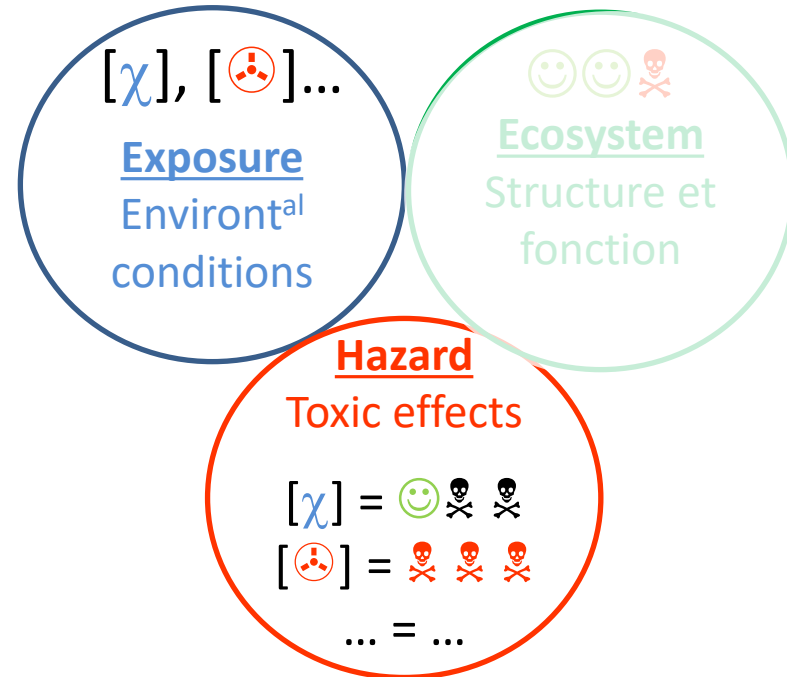
2



Example : routine releases
of NPPs in the Rhône river

Beaumelle et al. (2017), *Environ. Poll.* 231:1421-32

IPOTOMUS project (in progress)

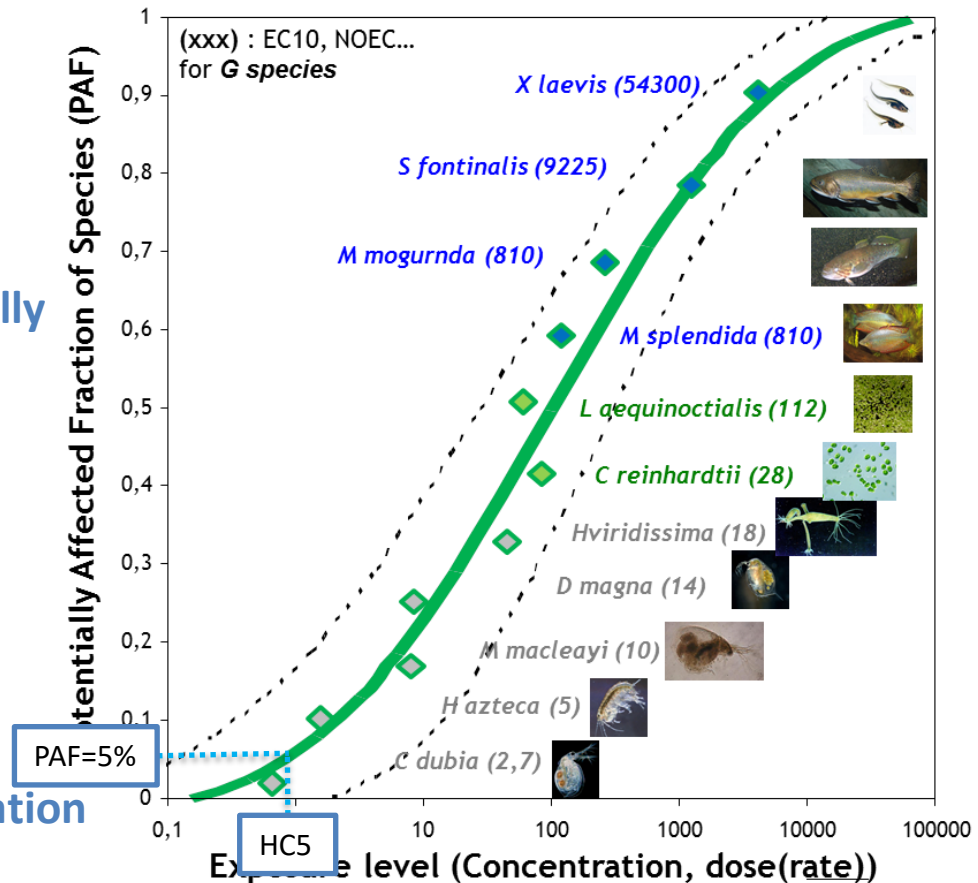


2- Cumulative Risk Assessment

Methods : Species Sensitivity Distribution (SSD)

- **Cumulated Distribution Function (CDF)** of chronic (or acute) ecotoxicological data (NOEC, EC10...) for *all** species
- Expresses the **fraction of species potentially affected (PAF)** by the exposure to a given stressor
- Widely used to account for the **variation in species sensitivity** (De Zwart & Posthuma, 2005)

& to derive **maximum acceptable concentration** of a substance
(e.g. HC5 : Hazardous Concentration that affect 5% of species)



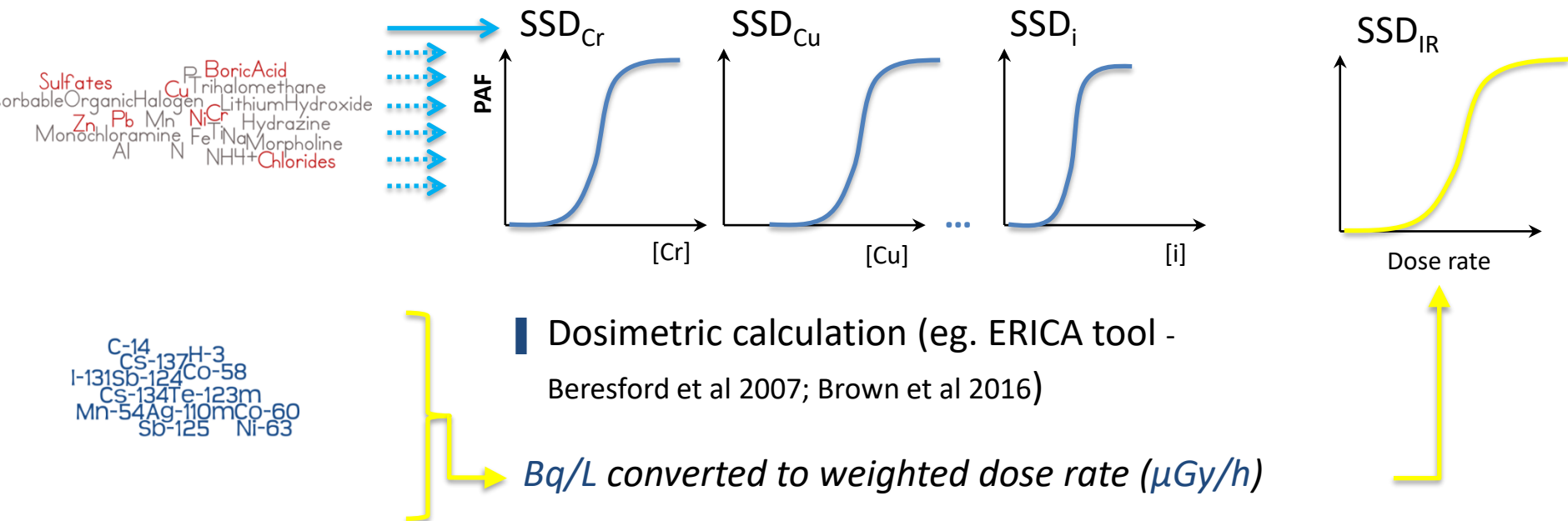
➔ **Consistent benchmark derivation for substances**

2- Cumulative Risk Assessment

Methods : Multi-Substances SSDs (msPAF)

SSDs recommended to provide an **integrated indicator** of the potential ecological risk of a mixtures: **msPAF** (multi-substance Potentially Affected Fraction of species)
(De Zwart and Posthuma, 2005)

SSD derivation: every stable substance ionizing radiation



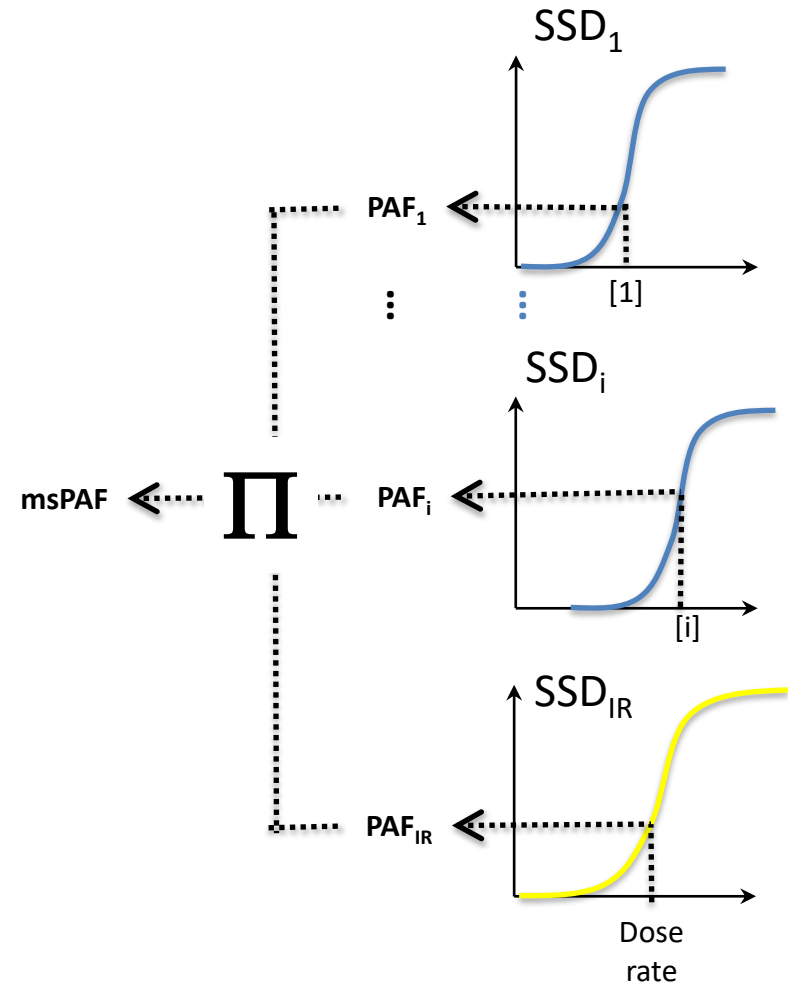
2- Cumulative Risk Assessment

Methods : SSDs combination (1/2)

Independent Action (IA)

- stressors considered independently
- PAF calculation for each stressor
- msPAF computed as following :

$$msPAF_{IA} = 1 - \prod_{i=1}^n (1 - PAF_i)$$



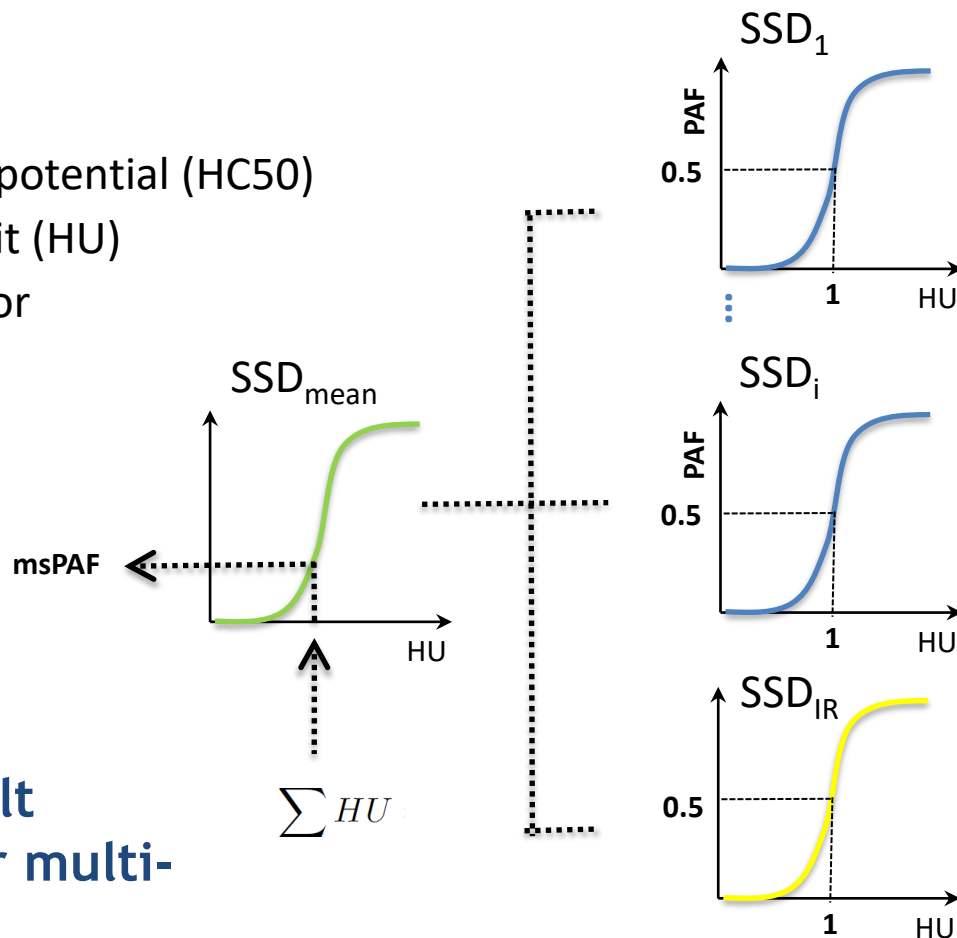
2- Cumulative Risk Assessment

Methods : SSDs combination (2/2)

Concentration Addition (CA)

- all SSDs normalized to their toxic potential (HC50)
- exposure expressed as Hazard unit (HU)
- 1 single average SSD for all stressor
- msPAF computed as following :

$$\sum HU = \sum_{i=1}^n \frac{C_i}{HC50_i}$$



➔ recommended as the default (conservative) approach for multi-substance Risk Assessment

(Backaus et al., 2000)

2- Cumulative Risk Assessment

Case study : NPPs routine releases

Rhône river catchment
(SE France)



4 NPPs

Bugey

4x900 MW
130-457 m³/s

St Alban

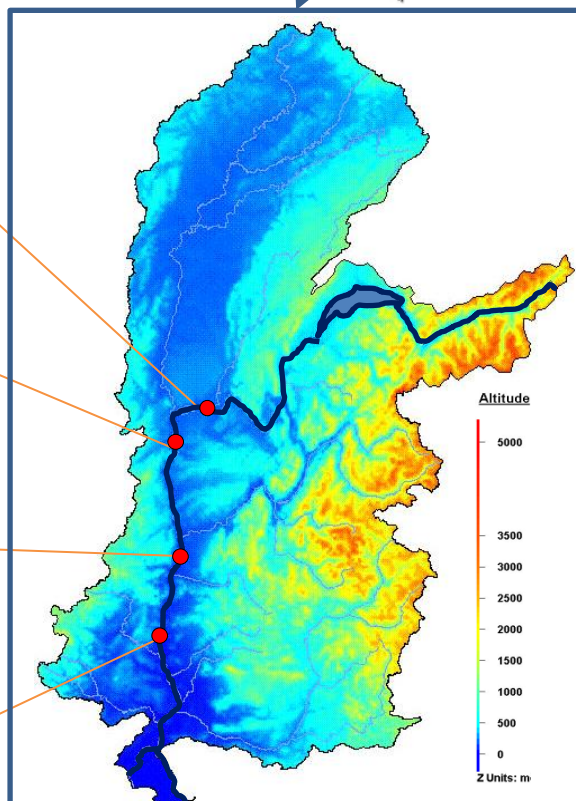
2x1300 MW
255-1040 m³/s

Cruas

4x900 MW
400-1500 m³/s

Tricastin

4x900 MW
300-1500 m³/s



Annual released quantities (Q_i)
under normal operating conditions

(EDF, 2013)

Q _i (kg or GBq)	Bugey	Tricastin	Cruas	St-Alban	
Cr			1		stable substances
Cu	17	2	15 100	1	
Ni			1		
Pb		1	1		
Zn	7	9	6 600	4	
Boric acid	9 000	9 050	13 700	3 730	
Chlorides	44 200	13 900		33 000	
Sulfates	142 000	98 000	3 967 000		
Ag-110m	0.47	0.05	0.13	0.01	radioactive substances
C-14	38.00	45.00	47.00	31.00	
Co-58	0.45	0.06	0.13	0.04	
Co-60	0.10	0.16	0.18	0.07	
Cs-134	0.02	0.03	0.04	0.01	
Cs-137	0.02	0.04	0.04	0.01	
H-3	44 300.00	51 300.00	58 300.00	55 600.00	
I-131	0.02	0.03	0.03	0.01	
Mn-54	0.02	0.04	0.04	0.01	
Ni-63	0.13	0.07	0.19	0.14	
Sb-124	0.05	0.03	0.03	0.01	
Sb-125	0.08	0.09	0.09	0.03	
Te-123m	0.01	0.04	0.04	0.01	

2- Cumulative Risk Assessment

Case study : NPPs routine liquid releases

average annual conc. (C_i) ←

4 NPP considered

2 dilution scenarios

- mean flow rate
- minimum flow rate

$$C_i = \frac{Q_i F_{rel}}{V_{tot} F_{riv}}$$

C_i	concentration/activity in river (Bq/L)
Q_i	cumulated annual release (Bq or kg)
V_{tot}	volume of liquid effuents (L)
F_{rel}	flow rate of the releases (m ³ /s)
F_{riv}	flow rate of the Rhône river (m ³ /s)

➔ 8 contrasted scenarios
(dilution, mixture composition)

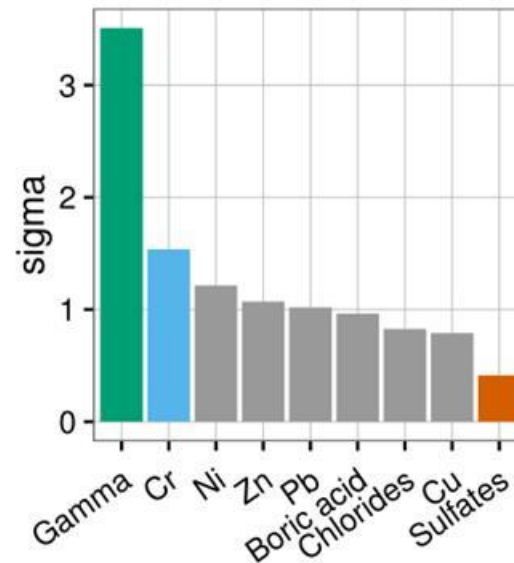
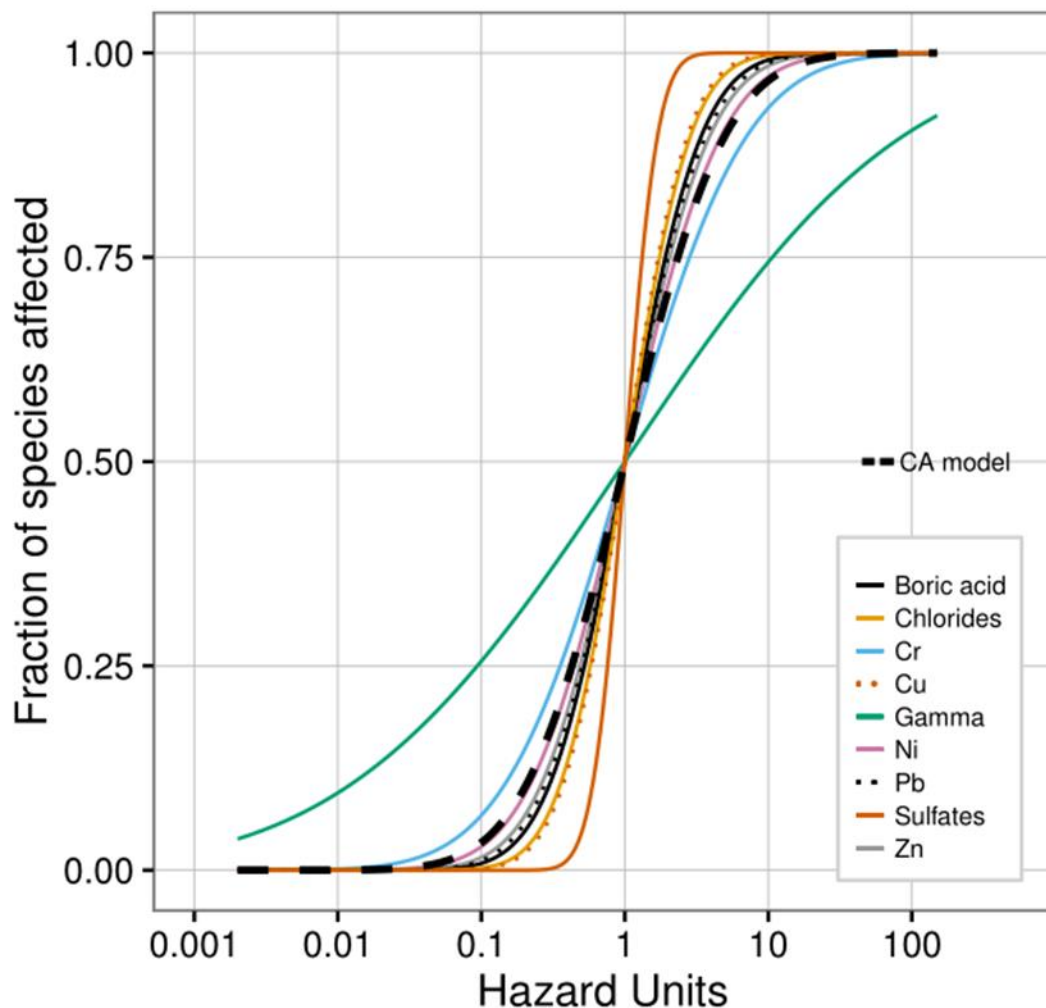
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under normal operating conditions

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2- Cumulative Risk Assessment

Average SSD derivation (for CA approach)



Statistically relevant groups = similar slopes (Bartlett test)

➔ 3 msPAF calculations

CA

Conc. Addition

IA

Independent Action

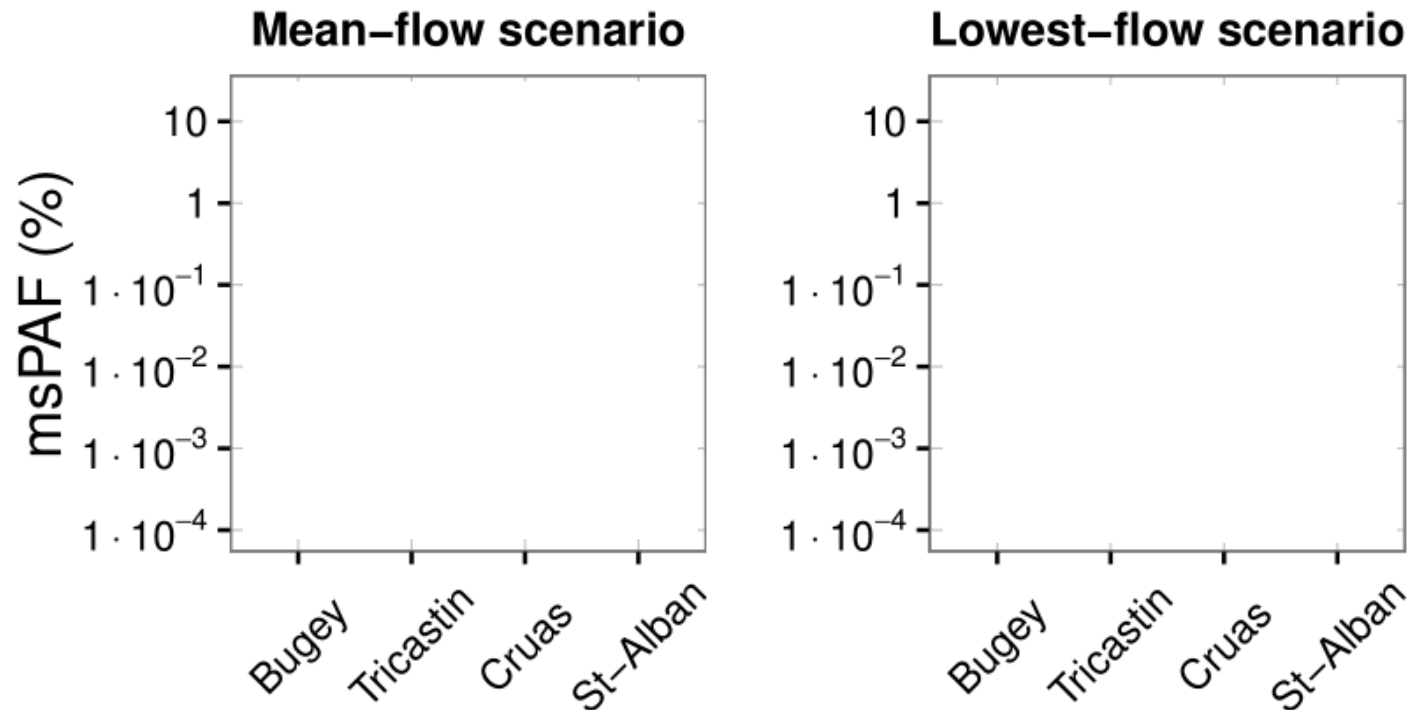
CA&IA

4 CA groups, then IA

2- Cumulative Risk Assessment

msPAF calculation results

msPAFs associated with different release scenarios using



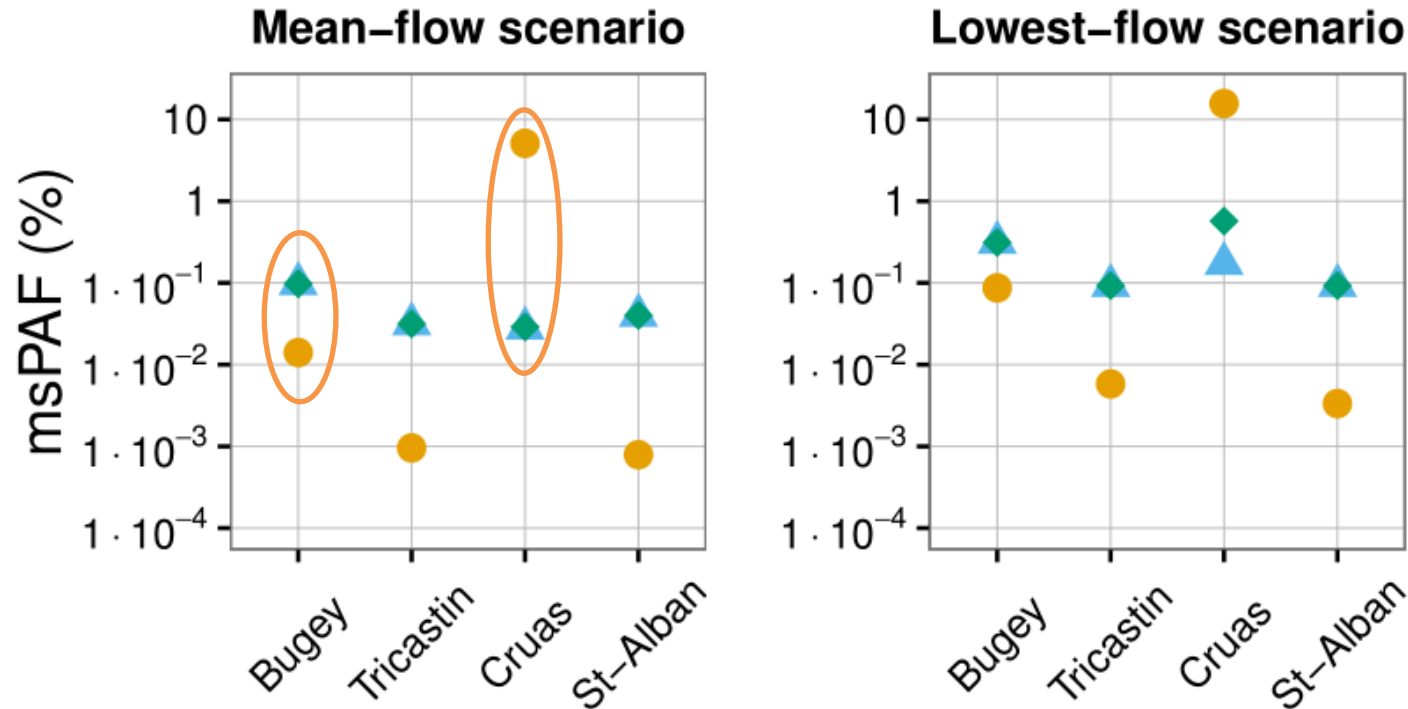
- very low risk level : $msPAF \ll 5\%$ except 1 case (Cruas with CA)
- No difference between CA and CAIA
- Surprisingly, CA not always conservative due to the differences in SSD slopes

➔ Use of both concepts (CA and IA) to provide a “prediction window”

2- Cumulative Risk Assessment

msPAF calculation results

msPAFs associated with different release scenarios using



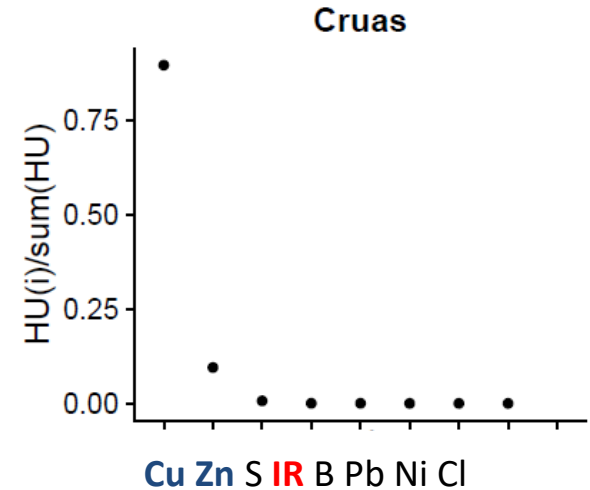
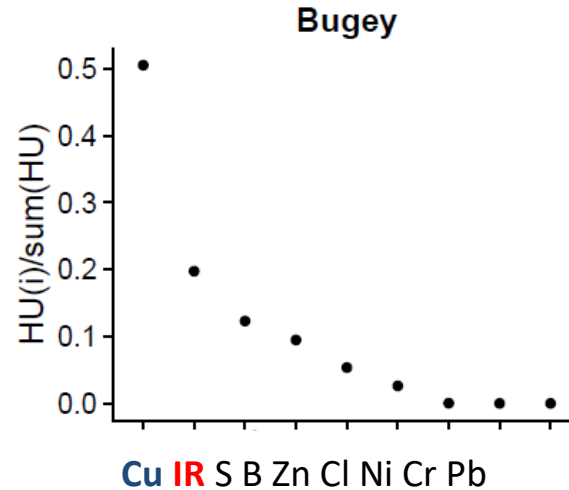
➔ **Contribution of the different stressors to the overall msPAF ?**
eg. contrasted cases of Bugey and Cruas (mean flow)

2- Cumulative Risk Assessment

Stressors combination and ranking

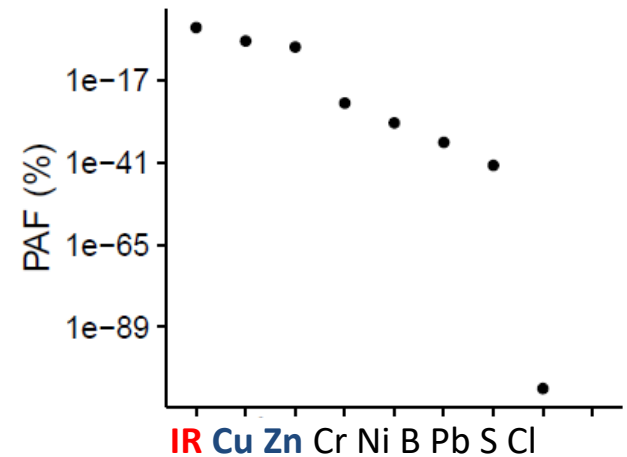
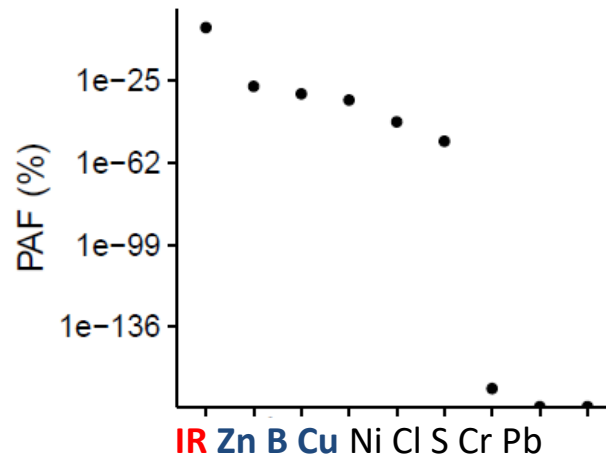
- Concentration Addition

$$HU_i = \frac{C_i}{HC_{50i}}$$



- ▲ Independant Action

individual PAF for each stressor/group



➔ Different ranking as a function of the considered model (CA or IA)

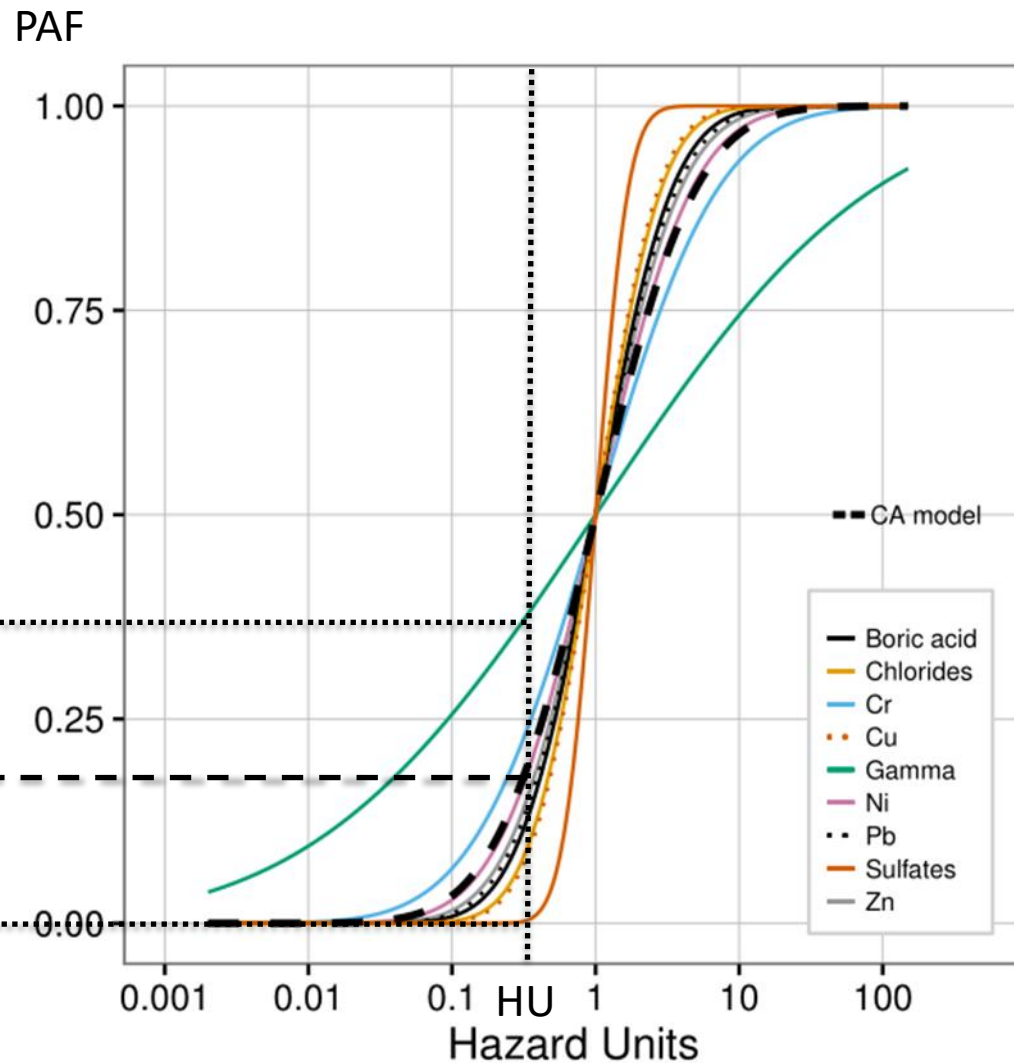
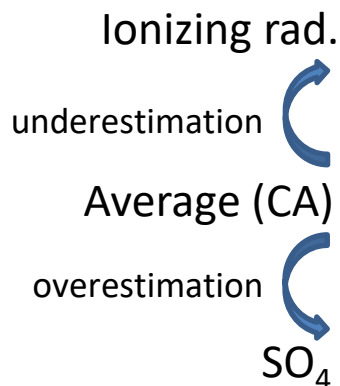
2- Cumulative Risk Assessment

Conclusion (1/2)

Very different SSD shapes (ionising radiation vs. stable chemicals)

CA is not the most conservative

→ Considering both CA and IA mixture models to provide a prediction window



2- Cumulative Risk Assessment

Conclusion (2/2)

- **Negligible overall potential ecological risk** in the context of routine effluents releases in aquatic ecosystems (except msPAF exceeding 5% in 1 case)

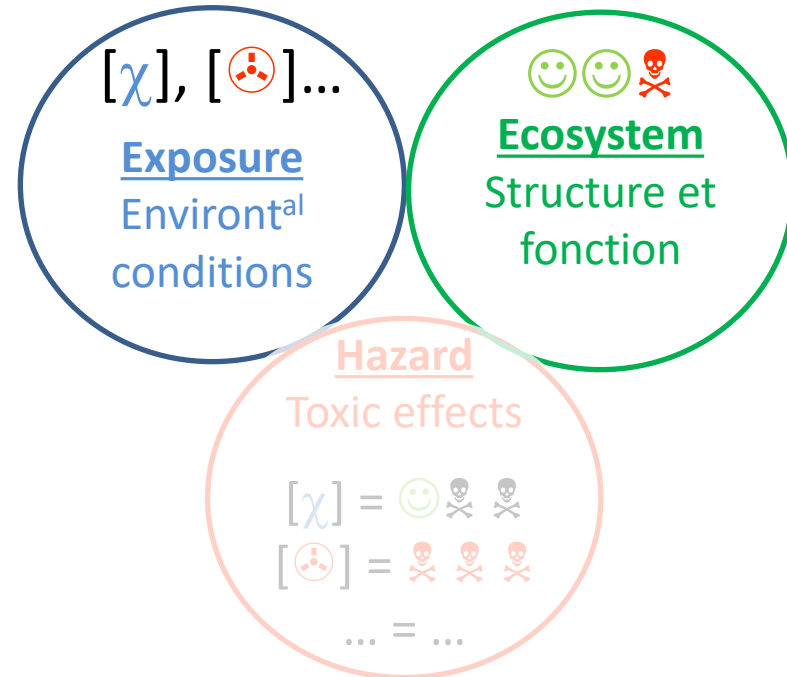
- msPAF **does not provides directly information about the contribution / ranking** of each stressor
 - ionizing radiation dominates the contribution to PAF (IA)
 - stable chemicals (mainly Cu, Zn) dominates contribution to HU (CA)

- Main limitations (and perspectives)
 - **Unsufficient ecotoxicity datasets** for some substances cannot allow a robust SSDs derivation (only 8 among 22 stable chemicals considered)
 - ➔ In progress (**Ipotomus Project**): use of monitoring data (chemical, radioactive) and the Δ PAF approach (> chemicals considered: 84 among 1046)
 - **Limited ecological relevance** (needs validation with field data)
 - Do not consider **realistic exposure conditions** (bioavailability, competitions...)
 - Do not consider **potential interactions** (synergism, antagonism)

Mixture Exposure and Ecological status



Example : releases from former U mines in France

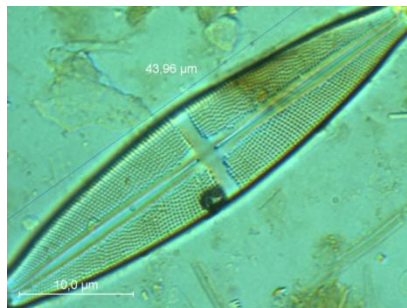
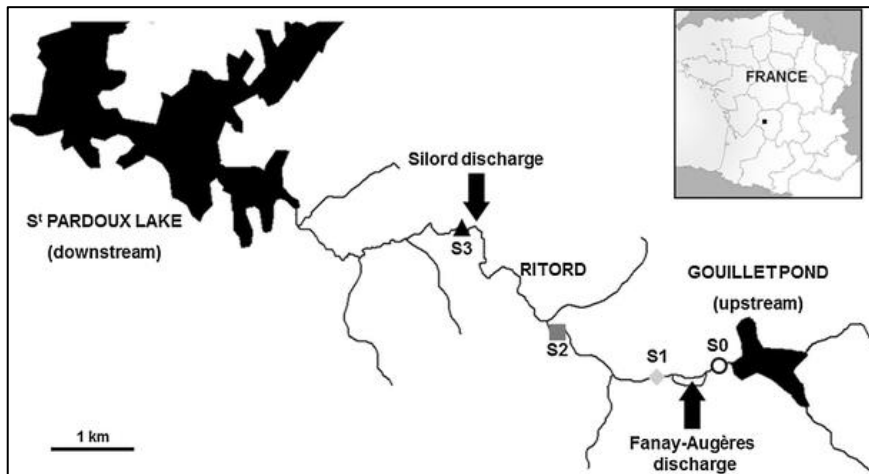


3- Mixture exposure and diatom community diversity

Example : Ritord, releases from former uranium mine sites

Herlory et al. (2013) *Ecotoxicology*

- Objective: to determine the **diversity and quality of species assemblages**
- Methodology: **Benthic diatoms** (community distribution and ecological preferences)
- Data set: **7-month monitoring** (July-January), monthly sampling
 - environmental conditions, contaminants
 - biomass, photosynthesis, specific composition of diatom assemblages



3- Mixture exposure and diatom community diversity

Example : Ritord, releases from former uranium mine sites

▪ Environnemental conditions

T°, pH, conductivity, O₂, ORP (redox)

Nutrients (Si, NO₂, NH₄, NO₃, SO₄, Cl)

Carbon inorg. (TIC) et organique (TOC)

Cations (Ca, K, Mg, Na)

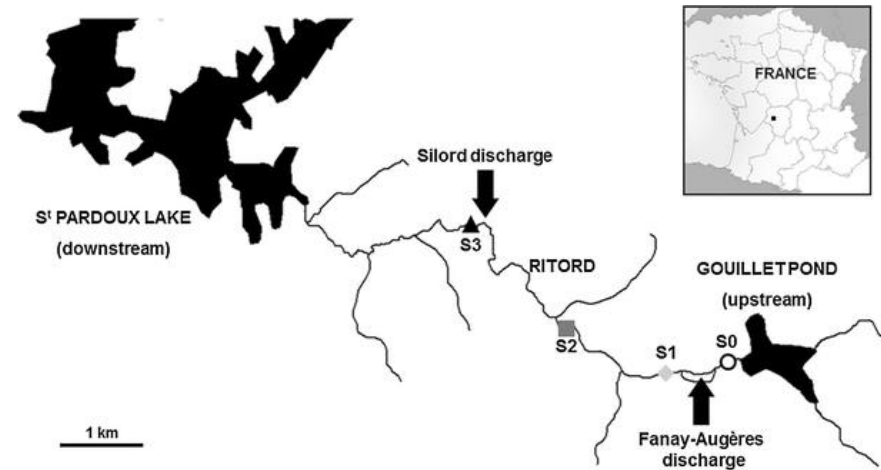
Metals diss and bioacc (U, Al, Ba, Fe, Mn)

▪ Specific composition of diatom assemblies



→ Specific identification and abundance (microscopy after cleaning)

Herlory et al. (2013) *Ecotoxicology*



12km (1m prof.), BV 17km²
connects 2 ponds (Gouillet → St Pardoux)

7 former mines, collect and treatment of effluents (Fanay-Augères, Silord) : BaCl₂ (²²⁶Ra↓), Al₂(SO₄)₃ (Fe, U ↓)

4 stations :

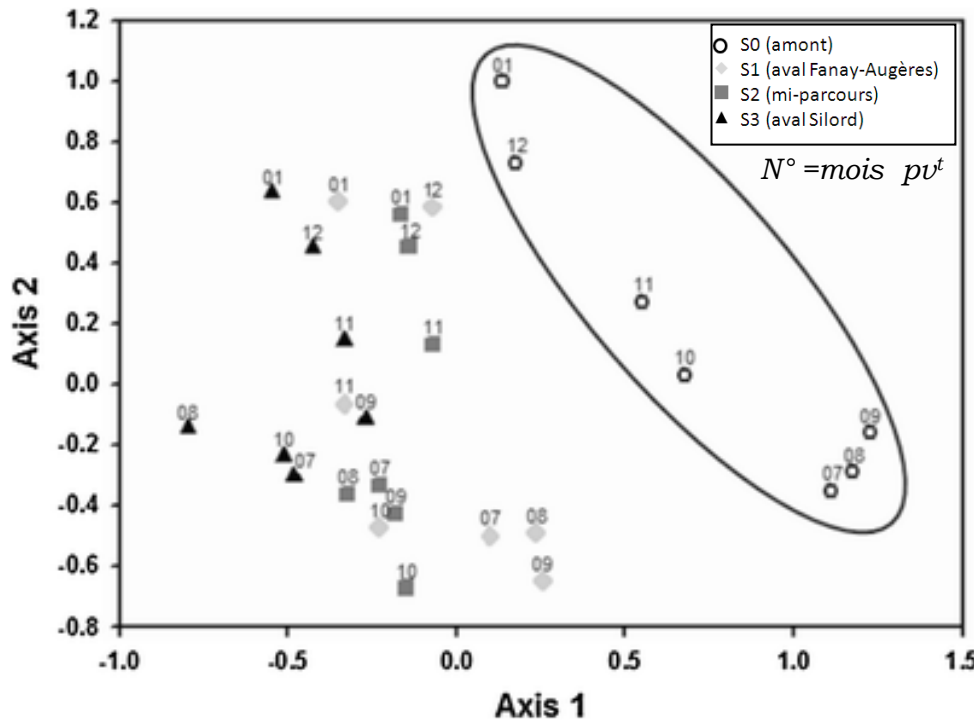
- | | |
|---|------------------------|
| ○ | S0 (upstream) |
| ◇ | S1 (downs. Fanay) |
| ■ | S2 (mid-course) |
| ▲ | S3 (downstream Silord) |

3- Mixture exposure and diatom community diversity

Example : Ritord, releases from former uranium mine sites

Herlory et al. (2013) Ecotoxicology

■ Environnemental conditions



Axis 1		Axis 2	
Variable	ρ_s	Variable	ρ_s
Al accumulated	-0.82	TIC	-0.85
Cl	-0.77	Conductivity	-0.83
pH	-0.67	Temperature	-0.79
Ba accumulated	-0.59	O ₂ dissolved	0.44
Mn accumulated	-0.46	Stream water flow	0.64
Na	-0.45	ORP	0.82
Ba dissolved	-0.41		
U dissolved	-0.39		
NH ₄	0.62		
Fe dissolved	0.65		
Fe accumulated	0.77		

NMDS (Non-metric multidimensional scaling)

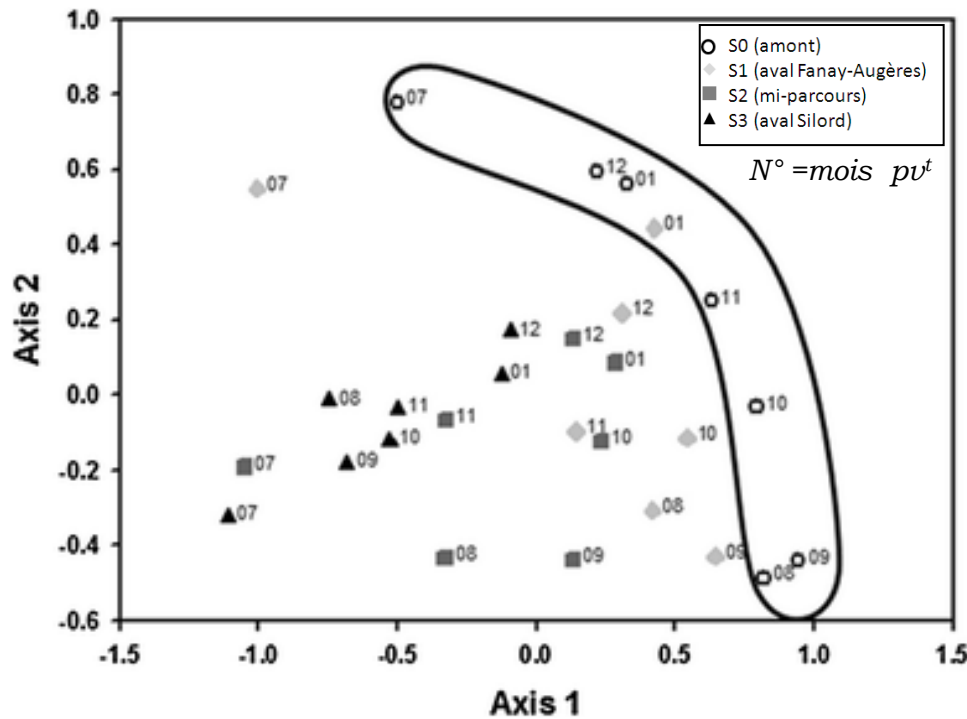
ρ_s : corrélation de Spearman (rang) entre les coordonnées de l'échantillon et les variables

- **S0 (upstream) significantly different** from other stations (PERMANOVA)
- Effect of **contamination (Axis 1)**: U and treatment effect (Ba, Al, Mn, pH)
- **'Season' effect (Axis 2)**: ICT, Cond, redox, T °, flux, O₂

3- Mixture exposure and diatom community diversity

Example : Ritord, releases from former uranium mine sites

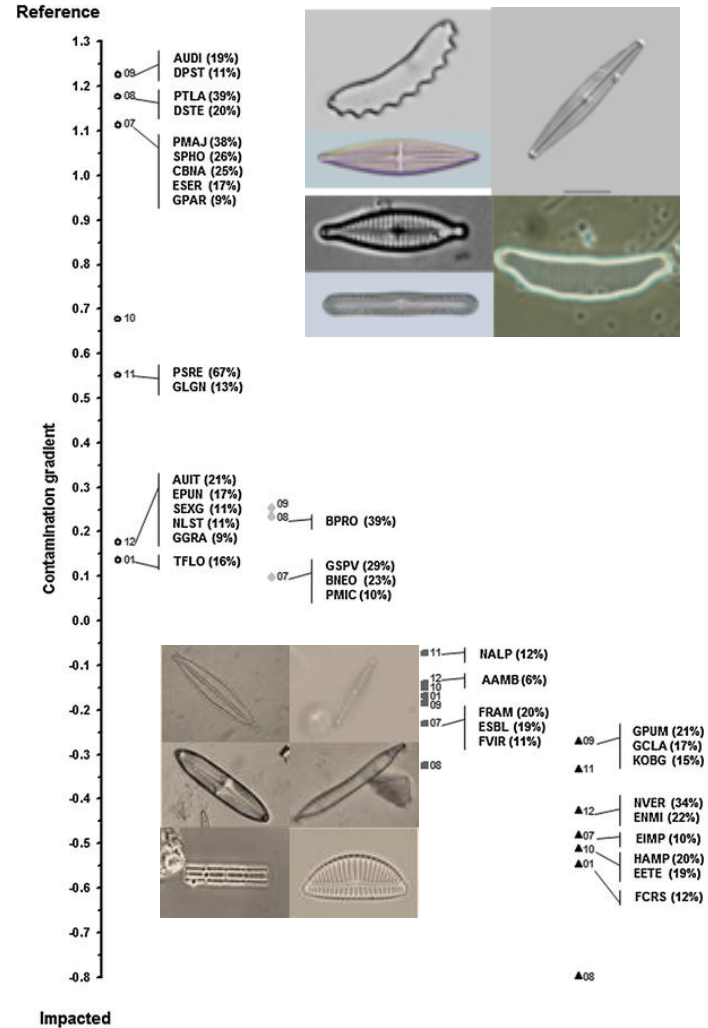
■ Diatom Species composition



■ **No effect on specific wealth** ($S = 55$ to 74), diversity ($H' = 2,5$ to $3,2$), biomass or photosynthesis

■ **Differences in community composition** (S0 differ from other stations, "indicator species")

Herlory et al. (2013) Ecotoxicology



3- Mixture exposure and diatom community diversity

Example : Ritord, releases from former uranium mine sites

- Diatom community composition differences attributed to the variables characterizing the **effluents 'as a whole'**
- **U, but also** Cl, Ba, Al, Mn ...
- Role of uranium vs. other environmental variables on Diatom community composition ?
- Interactions between substances?
- Actual exposure and bioavailability conditions (pH changes, conductivity, redox ...)?

ρ_S : Spearman correlation (rank) between similarity matrices 'Specified composition' and 'Environmental conditions'

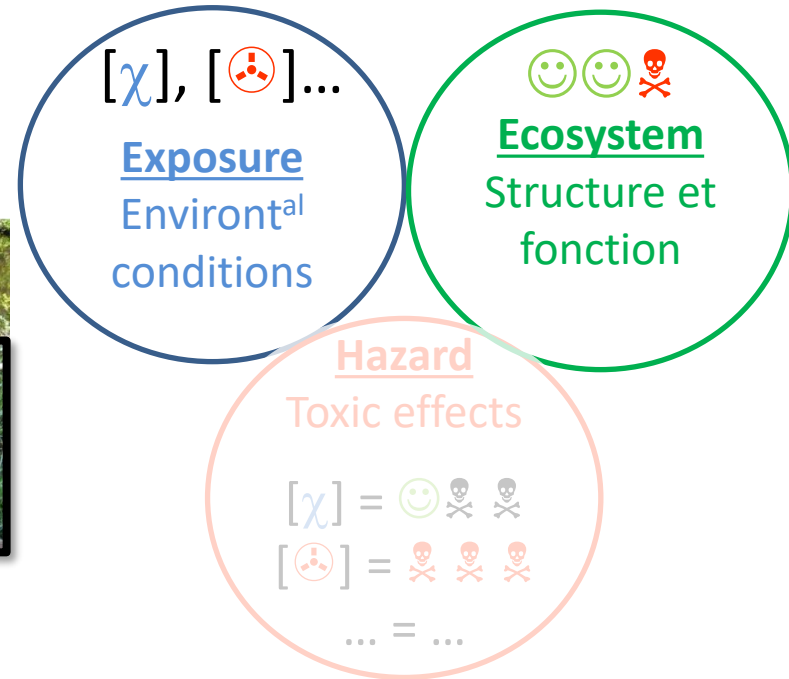
Herlory et al. (2013) Ecotoxicology

Variable	ρ_S
<i>Corrélations individuelles</i>	
Cl	0.466***
<u>U</u> _{diss}	0.377***
Ba _{diss}	0.321***
ORP (redox)	0.294***
Conductivity	0.273**
Al _{acc}	0.258**
Mn _{diss}	0.270**
Ba _{acc}	0.250**
TIC	0.151**
Na	0.165**
Fe _{acc}	0.249**
NH ₄	0.176**
Temperature	0.168*
Mn _{acc}	0.188*
Fe _{diss}	0.211*
pH	0.165*
Flow	0.088*
TOC, SPM, O ₂ , Al	NS

BIO-ENV procedure, (Clarke and Ainsworth, 1993)

*** $p \leq 0.001$; ** $p \leq 0.01$; * $p \leq 0.05$

Mixture Exposure and Ecological status



Other examples on fish :

Integrated Biomarker Response
 Approach

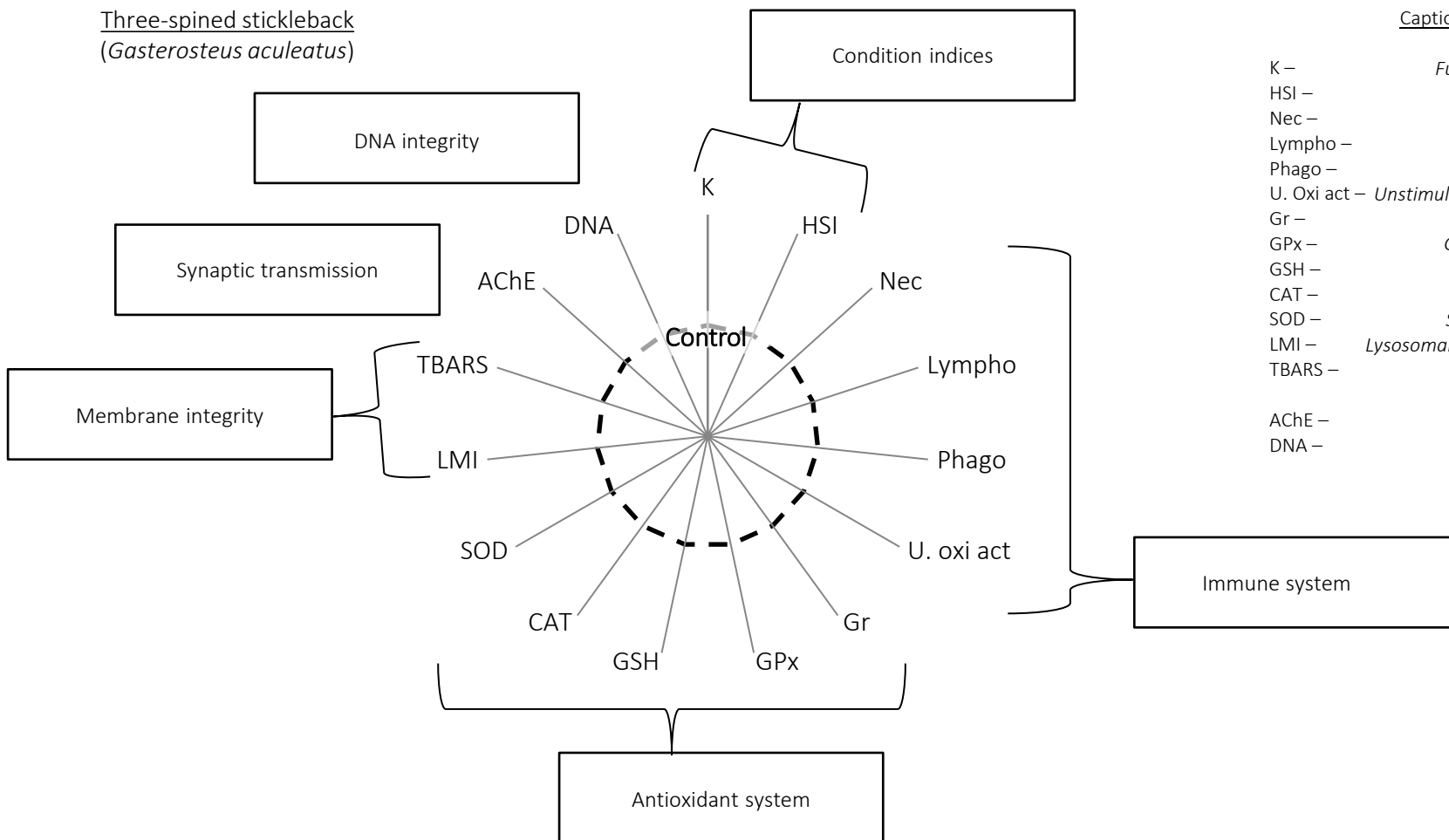
3- Integrated Biomarker Response approach

Responses on stickleback health



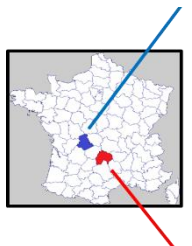
**Le Guernic et al. (2016),
Ecotoxicology 25(8):1478-99**

Three-spined stickleback
(*Gasterosteus aculeatus*)



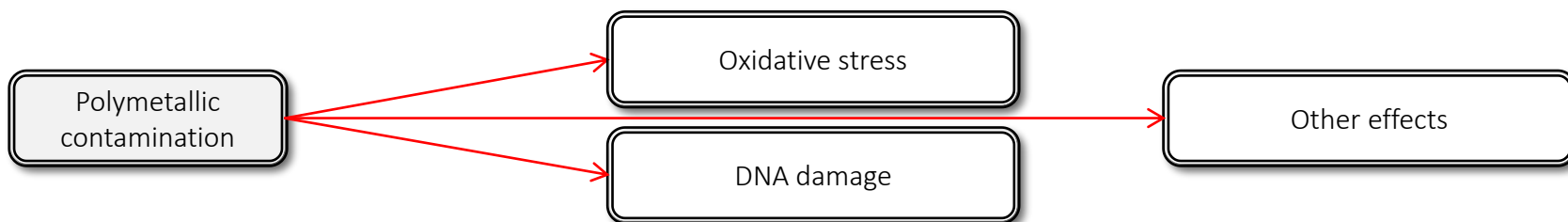
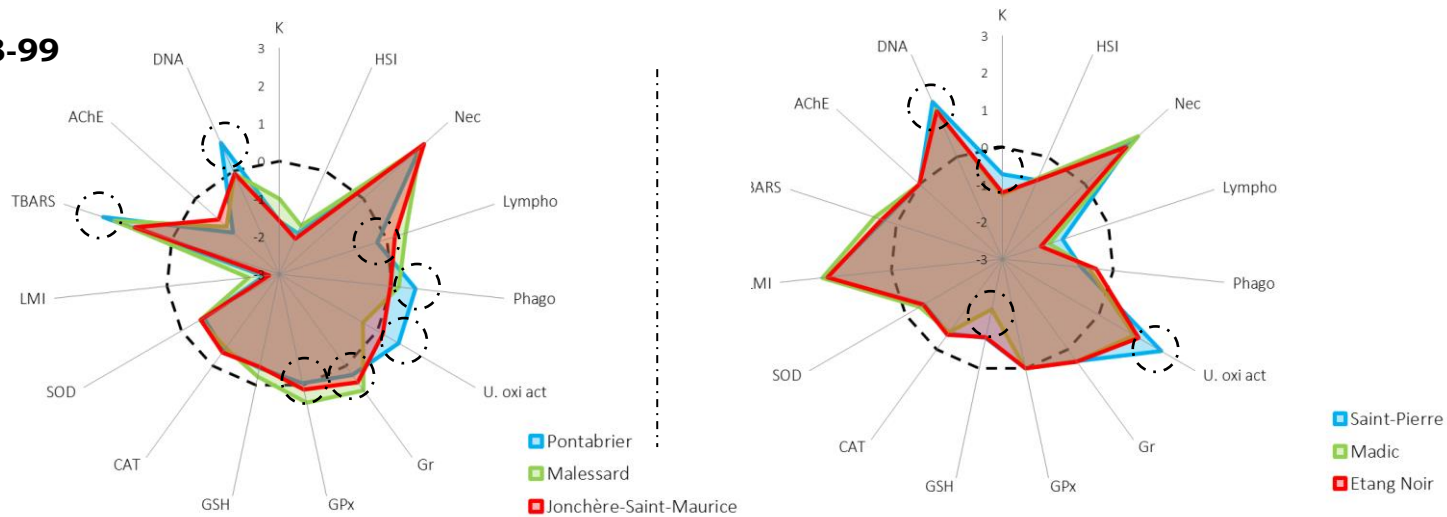
3- Integrated Biomarker Response approach

Responses on stickleback health



		U	Al	Fe	Mn	Ba
		µg/L				
Haute Vienne	Pontabrier	23.5	82.7	263.6	52.2	18.5
	Malessard	0.3	44.9	82.0	16.1	6.4
	JSM	0.1	48.7	396.6	27.1	22.1
Cantal	Saint-Pierre	5.9	44.1	165.7	218.1	16.5
	Madic	0.1	137.0	466.4	44.3	40.5
	Etang Noir	0.2	202.2	295.0	28.7	21.2

Le Guernic et al. (2016),
Ecotoxicology 25(8):1478-99



3- Integrated Biomarker Response approach

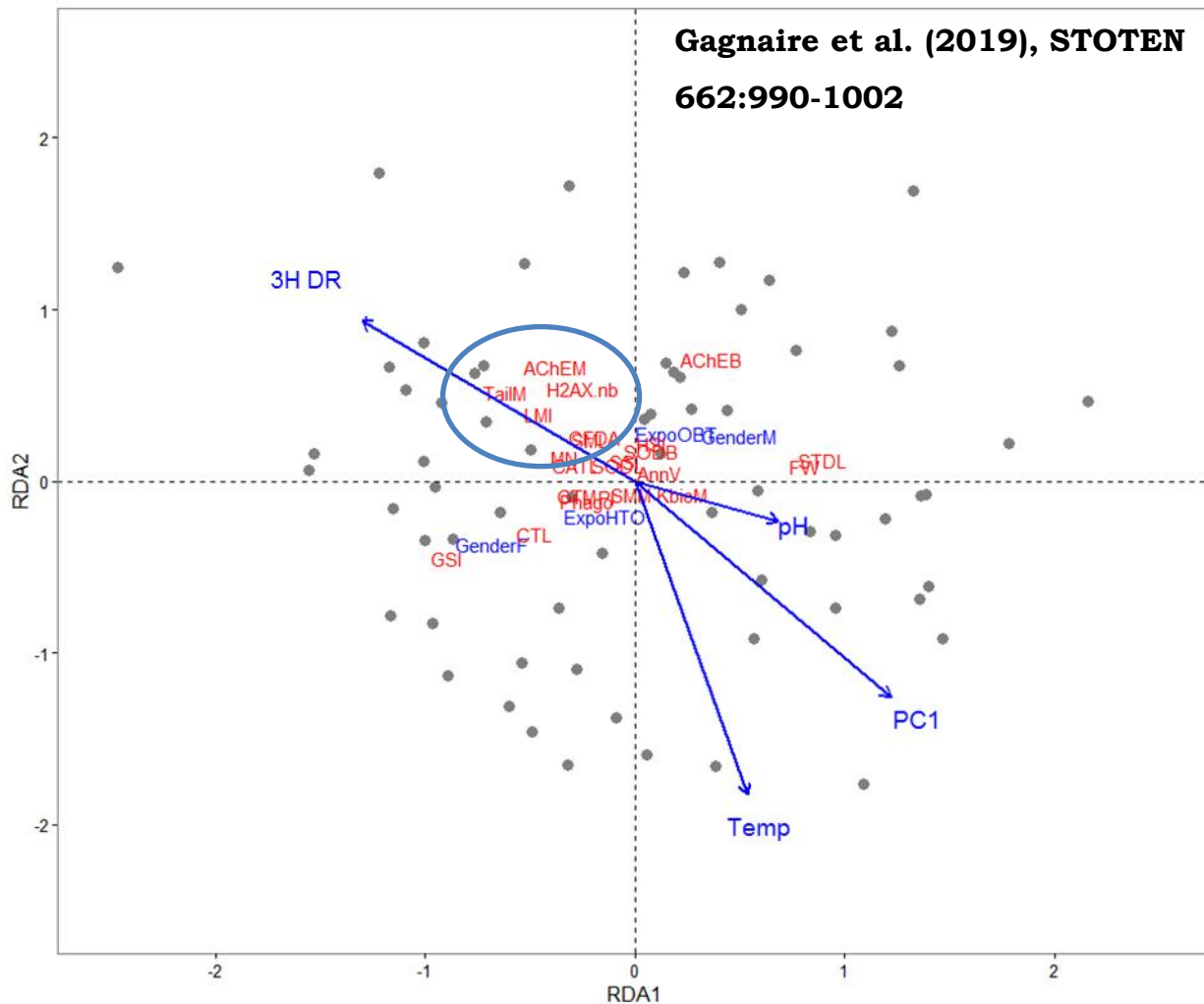
Responses on fathead minnow



[Tritium] from 4 to 12000 Bq/L (max=0.15 μ Gy/h) - Chalk River Laboratory (CNL)
60 days contamination + 60 days depuration

Fathead minnow
(*Pimephales promelas*)

- Redundancy Discriminant Analysis (RDA) with all biomarkers data
→ Positive correlation of responses (LMI, μ N, comet, H2AX, muscle AChE, SOD, CAT, fatty acids) with tritium exposure (despite very low dose-rate estimates)
- Lower correlation (few biomarkers) linked with metals (PC1)



- Provides relevant (and direct) information on structure and/or function of communities/organisms

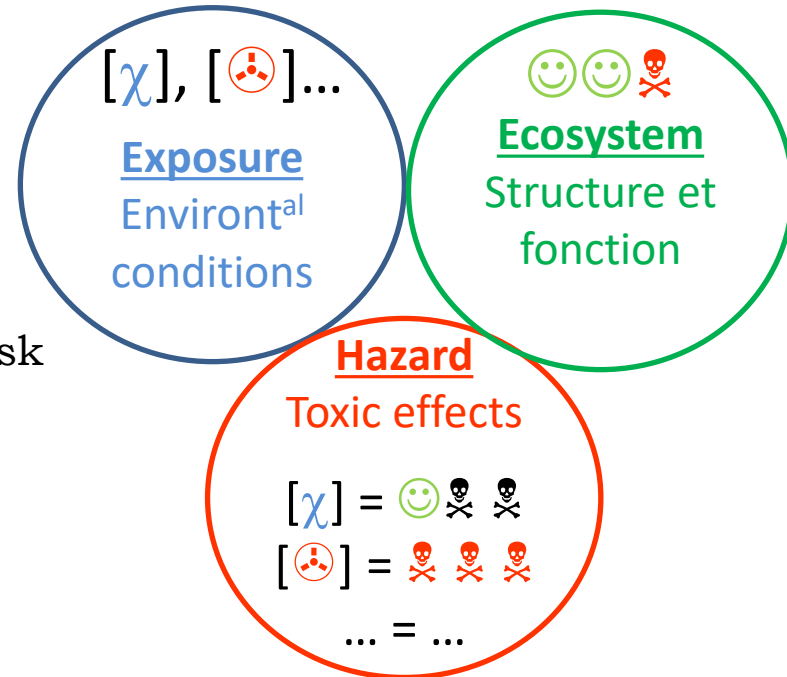
- However, results interpretation is not straightforward:
 - how to identify the contribution of stressors?
presented examples (former U mines, 3H contamination):
ionizing radiation may not be the main stressor

 - How to link changes (diversity, biomarkers...) with ecological consequences?

How to go beyond a descriptive approach?



- Exposure in ecosystems:
 - Chemical speciation?
 - Bioavailability?
- Protection target for ecological risk assessment:
 - Relevancy of the SSD?
- Ecotoxicity of substances in mixture:
 - CA or IA?
 - Interactions between substances?

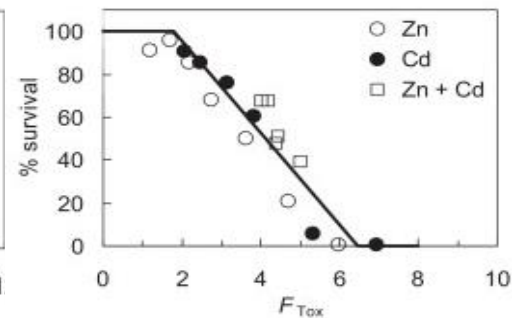
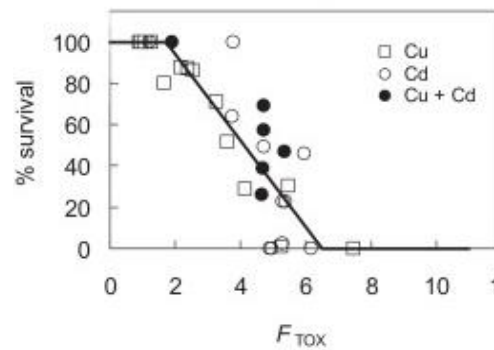
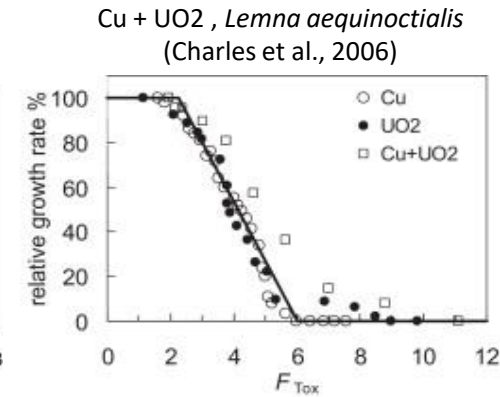
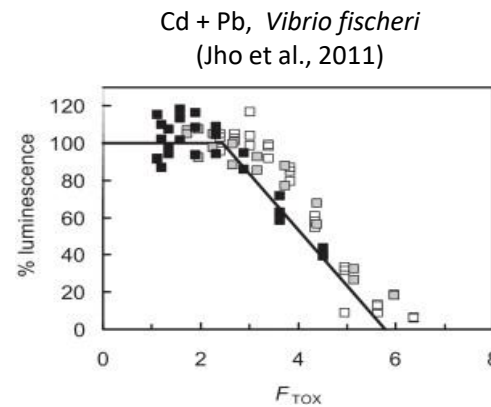


4- Beyond a descriptive approach

Exposure : Speciation and Bioavailability

Tipping & Lofst (2013) Aquat Tox 142-3:114

- Generalization of BLM approach : WHAM-FTOX
- metal-organism binding on non-specific sites; analogy with humic acids (WHAM)
- Advantage: model already parameterized and thermodynamically coherent



Toxic Function:

$$F_{TOX} = \sum \alpha_M v_m$$

α_M : quantité de métal M accumulé ($mmol.g^{-1}$)

v_M : coefficient de toxicité

Toxic Response:

$$TR = \frac{F_{TOX} - F_{TOX,LT}}{F_{TOX,UT} - F_{TOX,LT}}$$

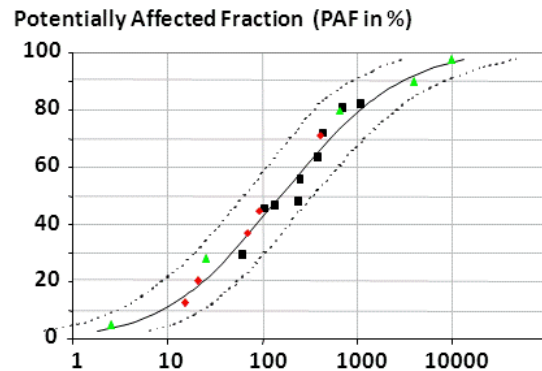
$F_{TOX,LT}$: lower threshold (pas d'effet)

$F_{TOX,UT}$: upper threshold (effet maximum)

4- Beyond a descriptive approach

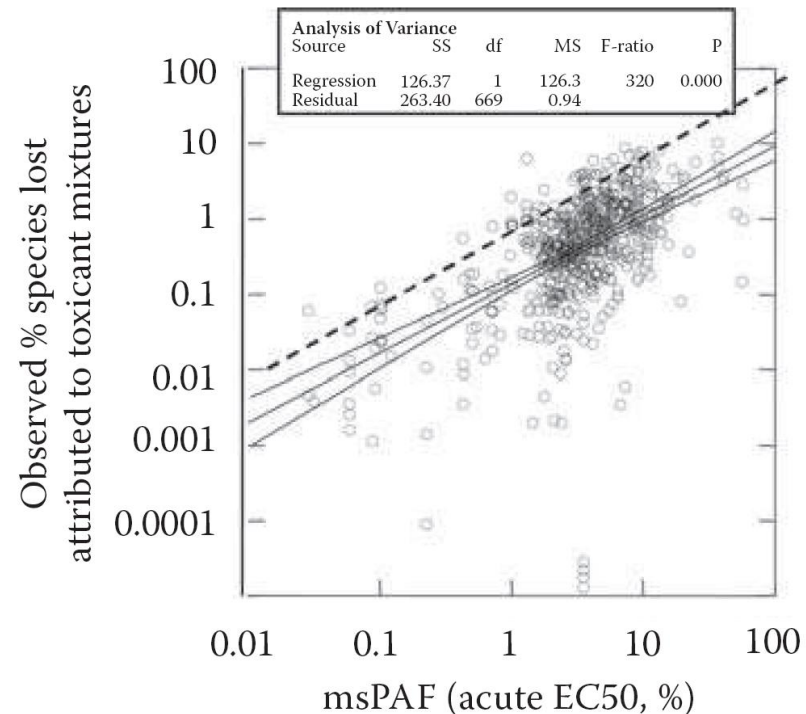
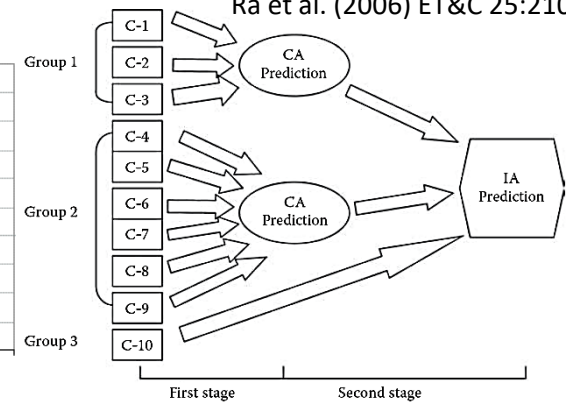
SSD and msPAF: Integrated Approach for Ecological Risk Assessment

- Prediction of effects from laboratory data base (SSD)
 - Measurement of the contamination pressure (Cd, Cu, Pb, Ni, Zn, ammonium, triclosan, ...)
 - Bioavailability (available fraction, hardness correction)
- Mixed mixture model (CA ou IA)
- Fish species diversity (espèces de poissons, 700 sites, Ohio)
- msPAF vs. species abundance correlation (GLM)



Posthuma & de Zwart (2006) ET&C 25:1105

Ra et al. (2006) ET&C 25:2107



4- Beyond a descriptive approach

Ecotoxicity: Interactions between stable and radioactive substances

- 16 reported studies (binary mixtures, 11 organisms)
- 13 Negative Interactions
 - U + Se, Cd
 - γ + Cd, Pb, Al
- 10 Positive Interactions
 - β + Cu
 - γ + Cd, Hg
 - γ + organiques
 - Pu + γ , Amiante, Be
- Exploratory studies (partial experimental design: doses, ratios, effect types considered)
- Not very informative about the mechanisms (toxicico-kinetic and toxic-dynamic interaction)

from Vanhoudt *et al.* (2012) *Env Poll* 168:177

	RN	Ch.	-	=	+	
U + métaux/métalloïdes						
<i>Lemna aequinoctialis</i>	U	Cu	X			Charles <i>et al.</i> (2006)
<i>Arabidopsis thaliana</i>	U	Cd			X	Vanhoudt <i>et al.</i> (2010)
<i>Caenorhabditis elegans</i>	U	Cd	X			Margerit <i>et al.</i> (in prep)
<i>Daphnia magna</i>	U	Se	X			Zeman <i>et al.</i> (2007)
Rayonnement + métaux						
<i>Chlamydomonas reinhardtii</i>	H-3	Cu			X	Réty <i>et al.</i> (2012)
<i>Hordeum vulgare</i>	Cs-137	Cd	X	X	X	Geras'kin <i>et al.</i> (2005)
<i>Souris</i>	X-ray	Cd	X		X	Michel & Fritz-Niggli (1986)
<i>Salmo salar</i>	Gamma-rays	Cd			X	Mothersill <i>et al.</i> (2007)
<i>Salmo salar</i>	Co-60	Cd	X			Salbu <i>et al.</i> (2008)
<i>Salmo salar</i>	Co-60	Cd	X			Olsvik <i>et al.</i> (2010)
<i>Oryzias latipes</i>	Cs-137	Cd			X	Shimada <i>et al.</i> (1985)
<i>Souris</i>	X-ray	Cd	X			Michel & Balla (1987)
<i>Hordeum vulgare</i>	Cs-137	Pb	X	X		Geras'kin <i>et al.</i> (2005)
<i>Salmo salar</i>	Gamma-rays	Al			X	Mothersill <i>et al.</i> (2007)
<i>Salmo salar</i>	Co-60	Al			X	Salbu <i>et al.</i> (2008)
<i>Salmo salar</i>	Co-60	Al	X			Olsvik <i>et al.</i> (2010)
<i>Oryzias latipes</i>	Cs-137	As			X	Shimada <i>et al.</i> (1985)
<i>Souris</i>	X-ray	Hg			X	Michel & Balla (1987)
Rayonnement + organiques						
<i>Hordeum vulgare</i>	Cs-137	2,4-D	X	X		Geras'kin <i>et al.</i> (2005)
<i>Tradescantia</i>	X-ray	PDA	X		X	Xiao & Ichikawa (1998)
<i>Tradescantia</i>	X-ray	DMN	X	X	X	Xiao & Ichikawa (1998)
<i>Oryzias latipes</i>	Cs-137	Cycloheximide			X	Shimada <i>et al.</i> (1985)
Pu en mélange						
<i>Rat</i>	X-ray	Pu-239		X	X	Ballou <i>et al.</i> (1962)
<i>Rat</i>	Pu-239	Amiante		X		Sanders (1975)
<i>Rat</i>	Pu-239	Be			X	Finch <i>et al.</i> (1991)

4- Beyond a descriptive approach

Ecotoxicity: Interactions between stable and radioactive substances

Conclusions from WP4 (2015)

STRATEGY FOR ALLIED RADIOECOLOGY

- **general pattern of the combined effects of $^{238}\text{UxCd}$ and $^{137}\text{mCsCd}$ across species**
→ needed to examine a wide a range of endpoints, timepoints and exposure conditions (bioavailability, bioaccumulation)

→ consistent with the use of SSDs derivations?

- **some interactions were explained (mainly antagonistic) by bioavailability and toxicokinetics (rarely toxicodynamic processes)**
→ needs robust exposure characterization (speciation, bioavailability & bioacc.)
→ toxicokinetic/dynamics (eg. DEBtox) helps for an overall conclusion

→ no evidence of large (but some) synergism: additivity assumption sufficient?

- **we used huge, but mainly 'bioassay-derived' experimental designs**
→ robust but low sensitive species, endpoints, timepoints (=high exposure needed)
- **need more ecological and biological realism to identify interactions!**

→ interactions & mode of action at cell/molecular level?

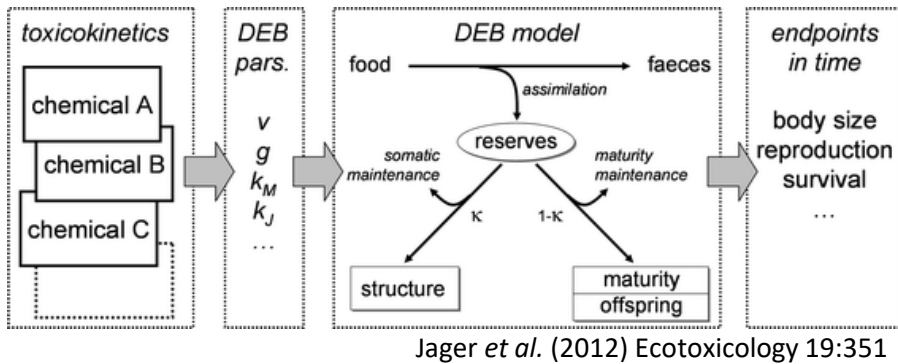
→ interactions at low doses and effect?

→ interactions at higher level (populations) and long-term (trans-generational)?

4- Beyond a descriptive approach

Ecotoxicity: Interactions between stable and radioactive substances

DEBtox: Toxicokinetic & dynamic model



- antagonism: at toxicokinetic or toxicodynamic level?

Measured data

● Cd

- explained by an interaction in the media ($\downarrow [Cd]_{available}$ with U)

DEBtox prediction

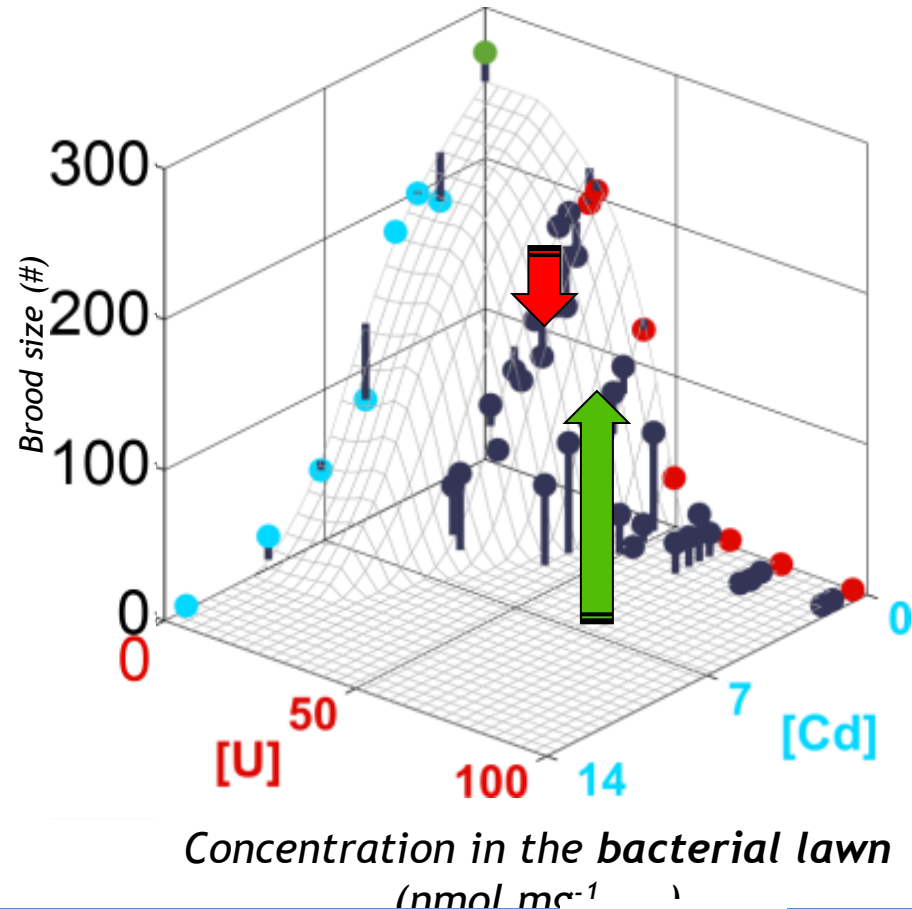
Synergism

→ overall conclusion (timepoints, endpoints) = additivity (slight synergism at low effect)

Antagonism

ex. Toxicity of U+Cd to *C. elegans*

DEBtox of individual substance (U and Cd) + use of additivity model (ex. IA, 11-day)



4- Beyond a descriptive approach

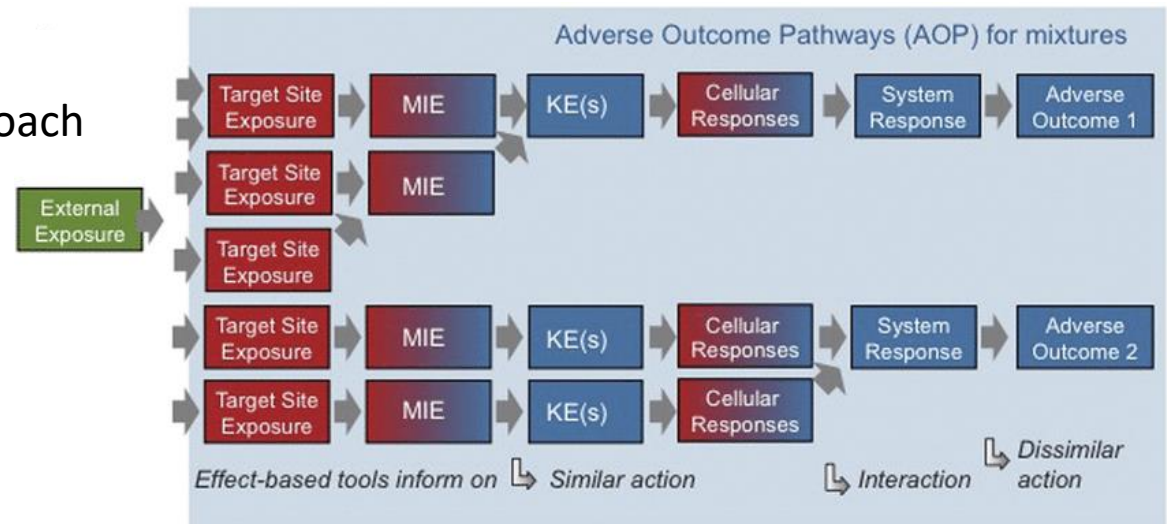
Strong potential of AOP approaches

'Extension' of the DEBtox approach

➔ From linear AOPs to AOP networks

Usefulness :

- **Low doses:** undetectable individual exposure / effect levels. combined exposure with detectable answers
- Identification of the **main risk factors** in the exposome
- **Cause and effect relationships:** Similar AOs may be triggered by different MIEs (affect jointly the same KE)
limitation: complex interactions (eg, complex role of low-dose mixtures in carcinogenesis) - Goodson et al., 2015)

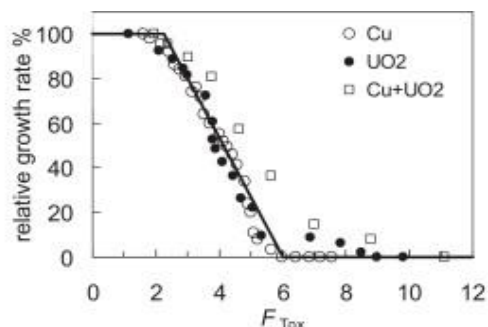


Escher et al. (2017)

Conclusion / Take home message (1/3)

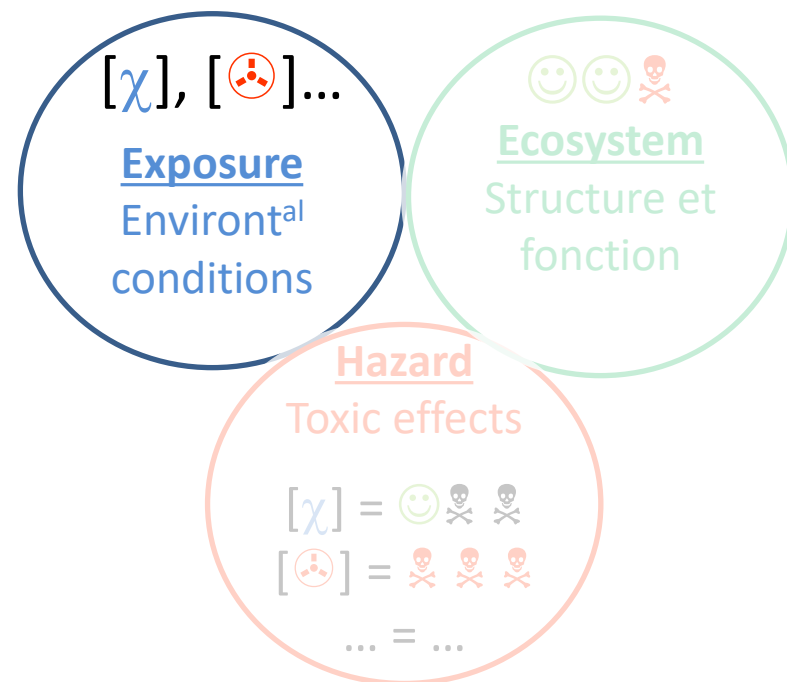
- **Ecosystem Exposure**

- Generalization of the BLM approach to consider interactions in the medium (speciation) and bioavailability (eg WHAM-Ftox)



Tipping & Lofst (2013) Aquat Tox 142-3:114

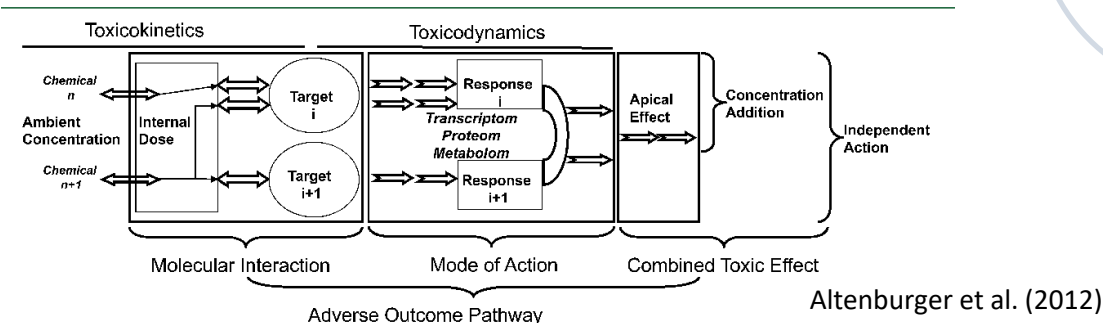
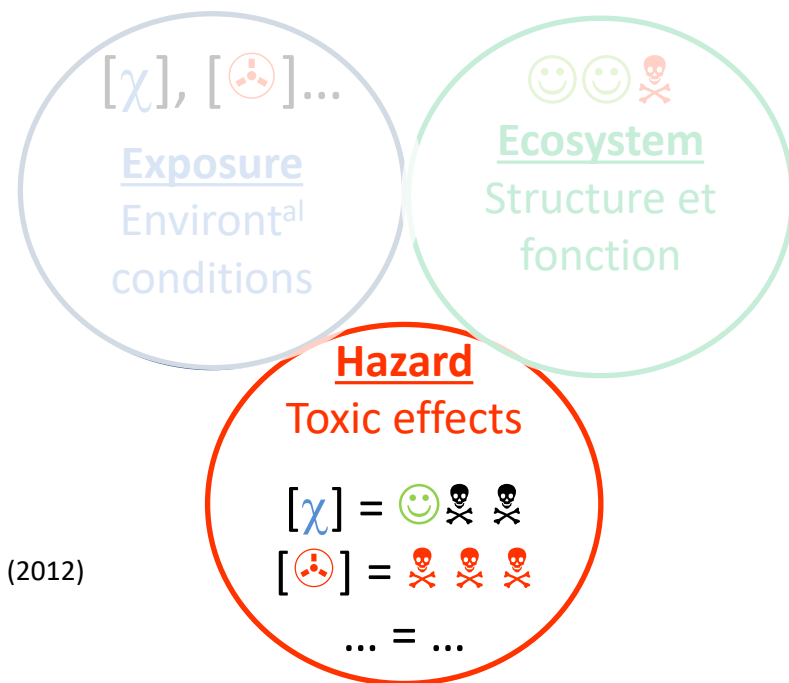
- Co-exposure with organic substances?
- integration of other stress factors (temperature, biotope changes, UVs...)?



Conclusion / Take home message (2/3)

- **Ecotoxicity**

- Explicit modeling coupling toxicokinetic and dynamic (eg DEBtox, AOP) to generalize the observations (mixtures, species, exposure)



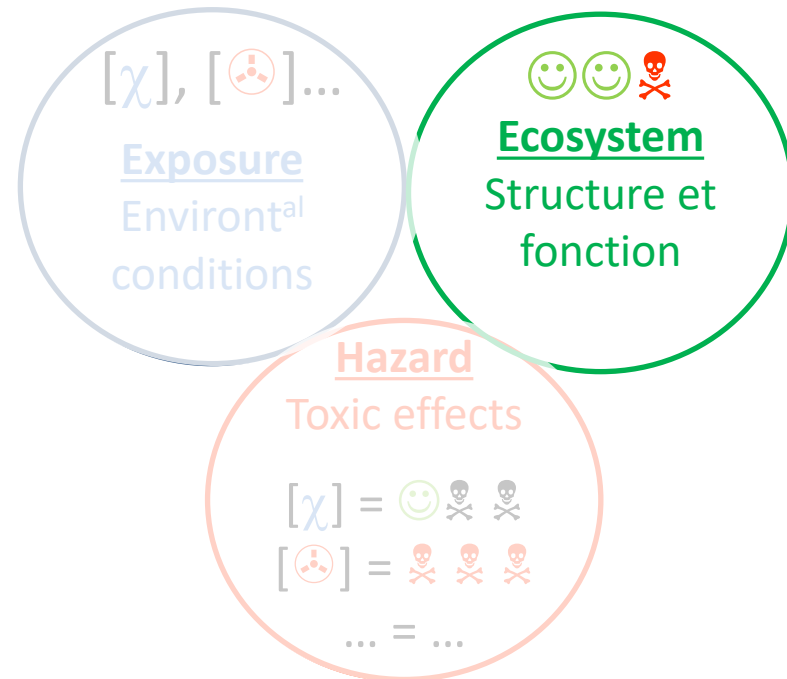
- **Experimental evidences of interactions**

Synergisms and/or Antagonisms may be explained (at least partially) with mechanistic approaches

interactions at different steps from exposure, initial events up to Adverse Outcomes

Conclusion / Take home message (3/3)

- **Ecological Risk Analysis** needs a better prognostic power.
 - May be (partly) solved by a **proper exposure characterisation** (eg. taking into account bioavailability,... exposome) and description of *interactions* (TDTK models such as DEBtox; AOP)
 - **msPAF** (based on SSD) seems to be satisfactory to describe the response of communities, by taking into account bioavailability, modes of action (CA / IA) and lack of specific interaction
 - However, the **real ecological status** under mixture stress **needs more field survey** of ecologically-relevant endpoints (communities structure and function)



Combined exposures to stable and radioactive substances for ecological risk assessment

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