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for toxic compounds
in the environment

Introduction to Ecotoxicology

linking fundamental science
with environmental risk assessment and management

Ludek Blaha, Jakub Hofman, Klara Hilscherova & co.

european social fund in the czech republic
EUROPEAN UNION
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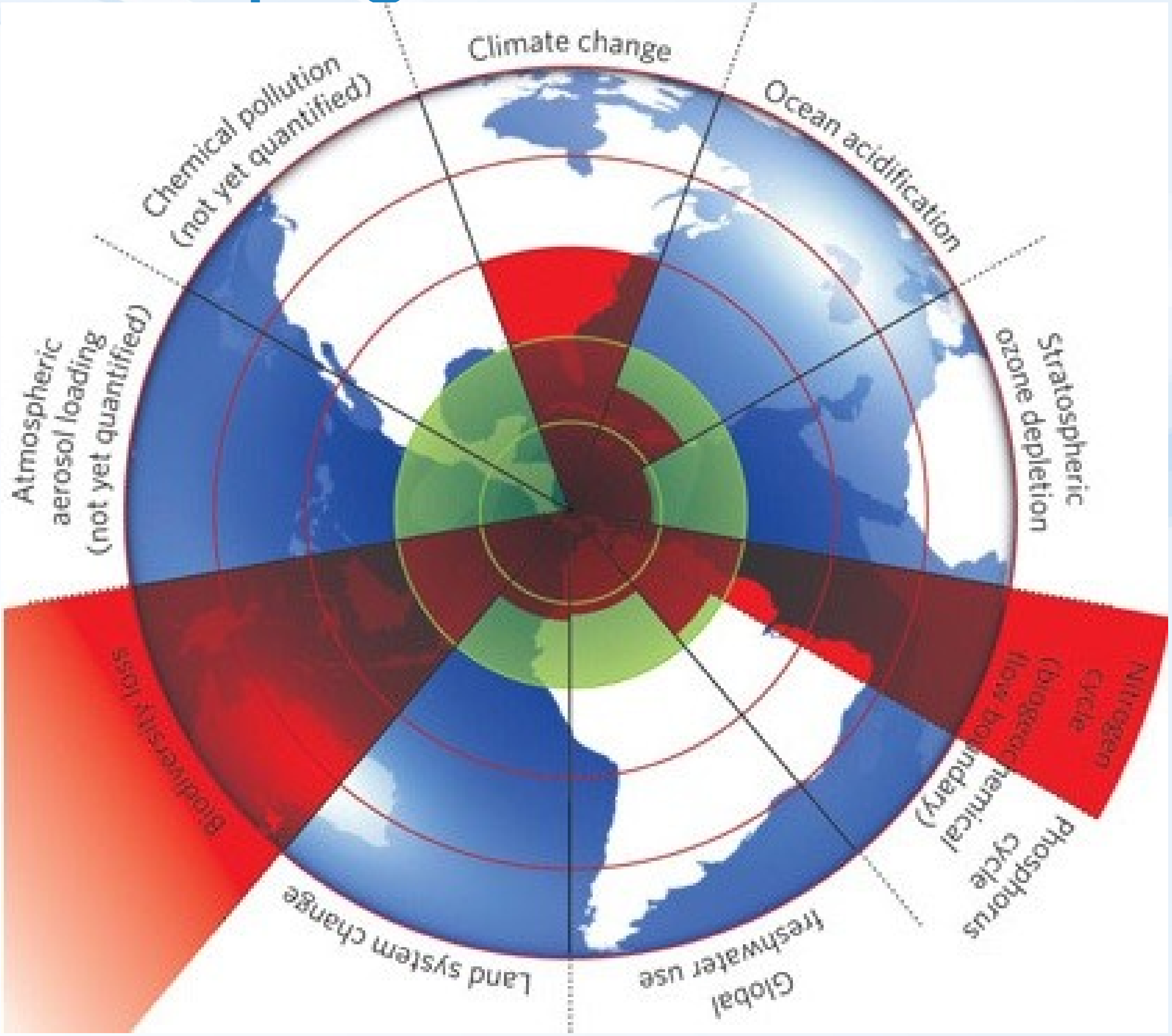
Global anthropogenic threats ?

A safe operating space for humanity & the nine planetary boundaries

Rockstrom et al. 2009
(*Ecology and Society* **14**(2): 32; Nature **461**, 472-475)



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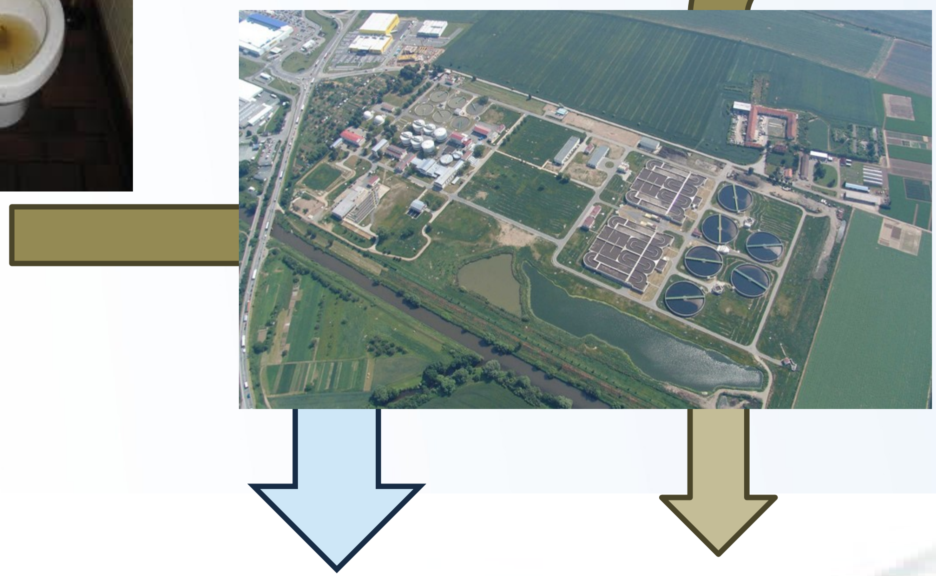
Environmental pollution

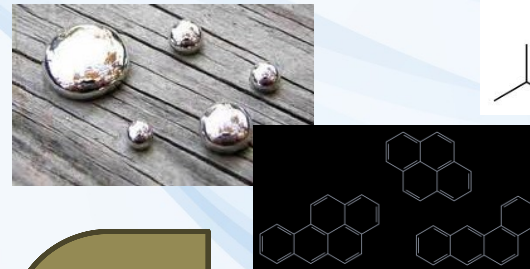
Any examples ???

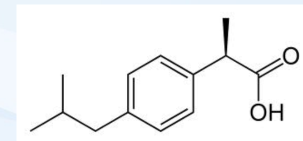
Contamination of water - chemicals ?

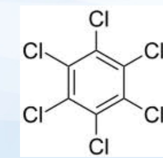
Degradable „nontoxic“
organic material
+ nutrients / fertilizers (N/P)

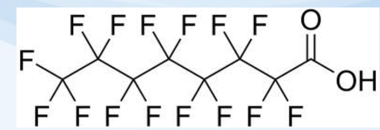


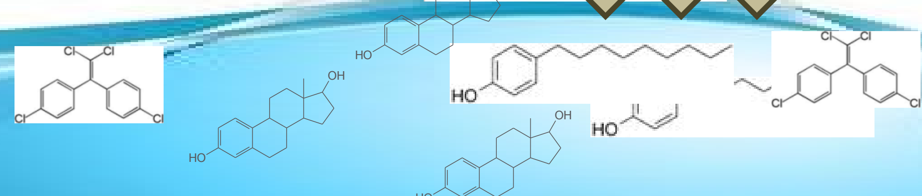
„Other“ chemicals







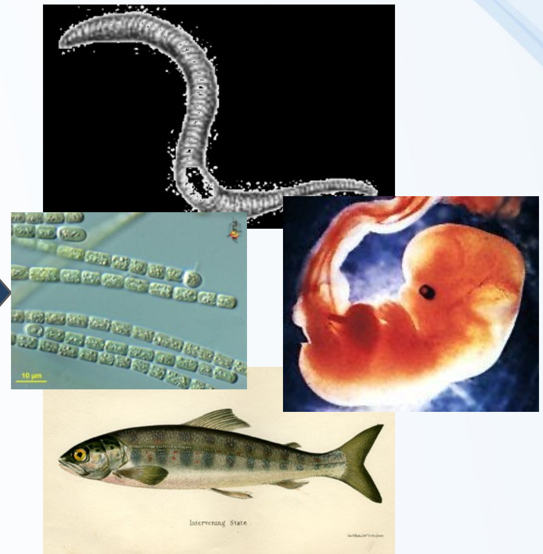




CHEMICAL ENTERS THE ENVIRONMENT

LEVELS, FATE, PROCESSES

Bioavailable fraction



"EXPOSURE"

acute

chronic

CHEMICAL ENTERS THE ORGANISM

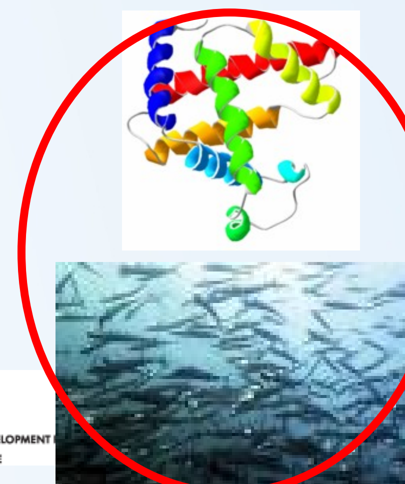
biomonitoring

<u>Toxikokinetics</u>

biotransformation
bioactivation
excretion / sequestration

Target site

"EFFECT"

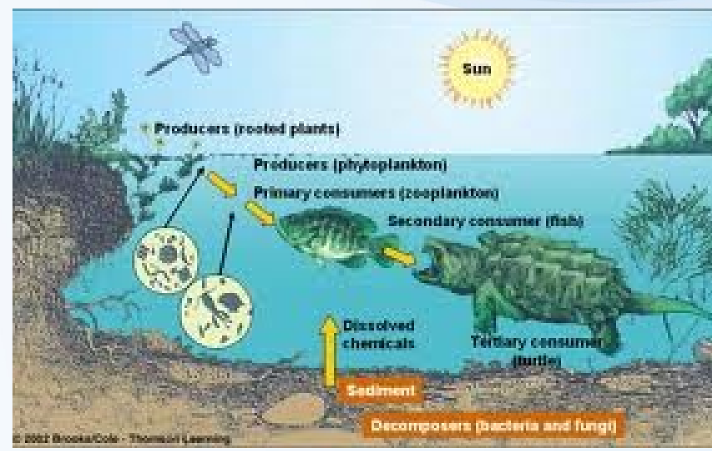


Assessment of chemical hazards

…to…

Humans
(**TOXICOLOGY**)

Other organisms
(**ECO**toxicology)



Chemicals in the environment

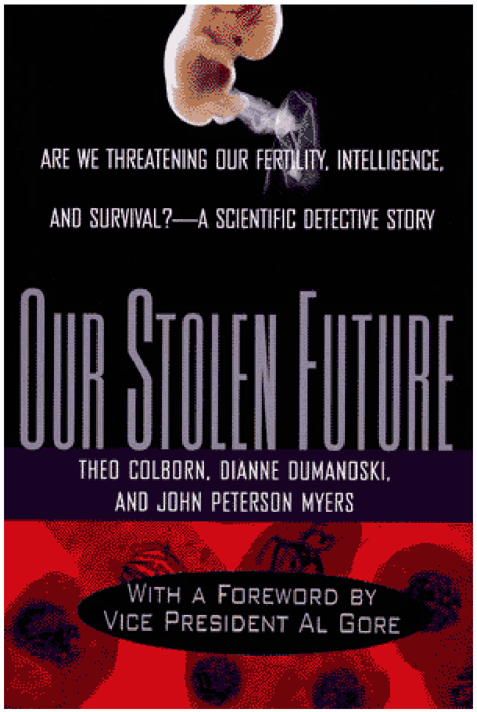
Do you believe that chemicals in products sold to consumers have been proven safe?

Think again

Most chemicals in modern use have simply not been tested for their impacts on human*, even very basic effects.*

… what about the effects in nature, then ?

Chemicals in the environment



- *Rats exposed in the womb* ***to a single low dose of a widespread brominated flame retardant become hyperactive and have decreased sperm counts…***
- *Experiments with dioxin and similar compounds provide support for the assumption that cancer risks mediated by the aryl hydrocarbon receptor are additive. Previously untested for cancer, this assumption underpins a standard way of estimating exposure risks to these compounds. The results reinforce the need to focus health standards on mixtures rather than single compounds.*
- *At exposure levels within the range experienced by the general public, the phthalate* ***DBP*** *reduces expression of genes necessary for testosterone synthesis in fetal rats…*
- ***Eutrophication of frog ponds*** *is linked to epidemics of frog deformities, because it creates conditions that lead to* ***higher rates of parasitic infections of tadpoles****. The parasitic infections in turn disrupt normal development of the tadpoles' limb buds during metamorphosis.*

news@nature.com
The best in science journalism

Published online: 21 October 2005; | doi:10.1038/news051017-16

Pollution makes for more girls

The stress of dirty air skews sex ratios in Sao Paulo.

Erika Check

Toxic fumes favour the fairer sex, a group of researchers in Brazil has found.

Babies born in highly polluted areas are more likely to be girls.

Jorge Hallak and his team at the University of Sao Paulo turned up the surprising result by studying babies born in their city. They divided the metropolis of 17 million people into areas of low, medium and high air pollution, using test results from air-quality monitoring stations. They then studied birth registries of children born from 2001 to 2003.

The team found that 48.3% of babies were female in the least polluted areas, but 49.3% were female in the dirtiest parts of town. After measuring the ratio of boys to girls born in all the areas, they calculated that 1,180 more babies would have been boys in the polluted areas if they had the same sex ratios as the cleaner areas. The team reported their findings on 17 October at the American

Major anthropogenic threats – example: waters

Direct






Indirect

Impacts

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Major impacts

- **Loss of biodiversity**

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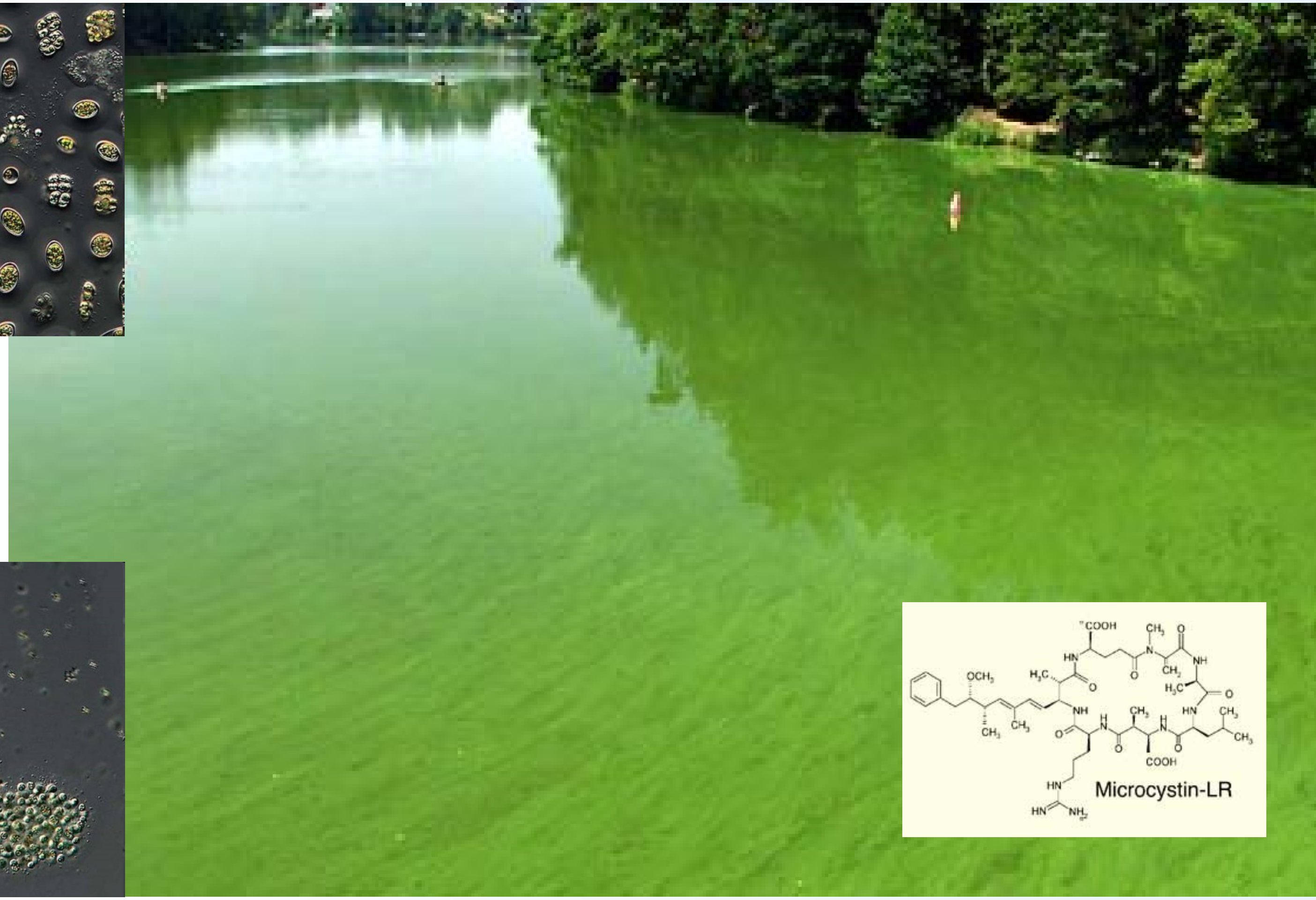
Changes in biodiversity



Changes in biodiversity

NATURE (2012) 482: 20

ATTACK OF THE BLOBS

Blooms of giant Nomura's jellyfish (*Nemopilema nomurai*) have troubled Japanese fishing crews.

KYODO/NEWSCOM

increase in the global population of jellyfish — a catch-all term that covers some 2,000 species of true cnidarian jellyfish, ctenophores (or comb jellies) and other floating creatures called tunicates. But many marine biologists are now questioning the idea that jellyfish have started to overrun the oceans.

This week, a group of researchers published preliminary results from what will be the most comprehensive review of jellyfish population data[1]. They say that there is not yet enough evi-

Major impacts

- **Loss of biodiversity**

- **Impairment of ecosystem services**
  - **Unbalanced water cycles**
    - Water scarcity
    - Draughts/floods
  - **Impaired water quality**
    - Drinking waters
    - Bathing waters
    - Toxicants in food chain
  - **Shrinking of food supplies**
    - Direct → lowering fish amounts
    - Indirect → crop yield

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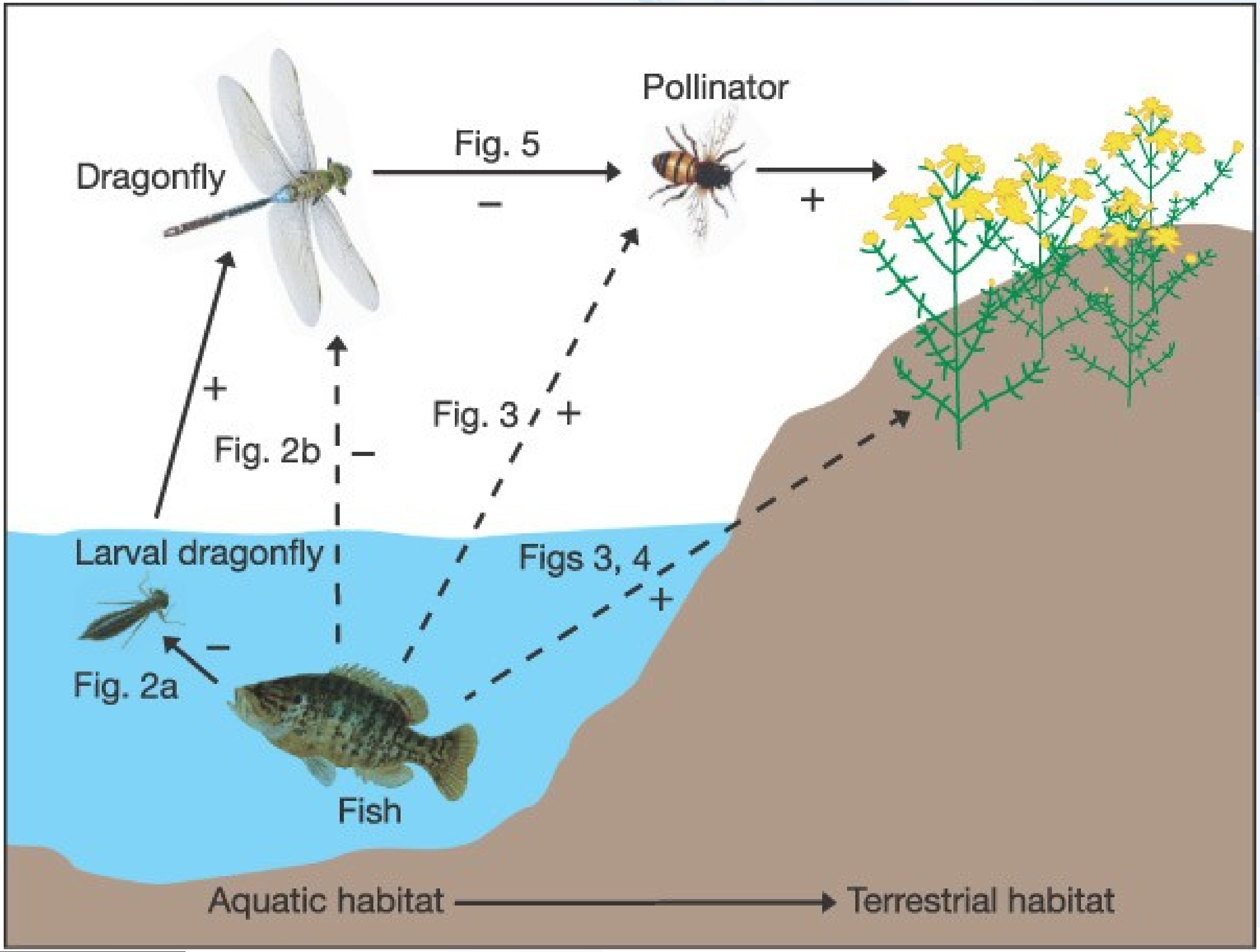
Impacts on fish → decreased crop yields

NATURE (2005) 437: 880



Impacts on biota → global effects

Mixing oceans

→ cooling the atmosphere

[Nature 447, p.522, May 31, 2007]

Marine life supplies up to 50% of the mechanical energy required worldwide to mix waters from the surface to deeper cool layers

[Dewar, Marine Res 64:541 (2006)]

[Katija a Dabiri, Nature 460:624 (2009)]

Ecotoxicology: ecological hierachy

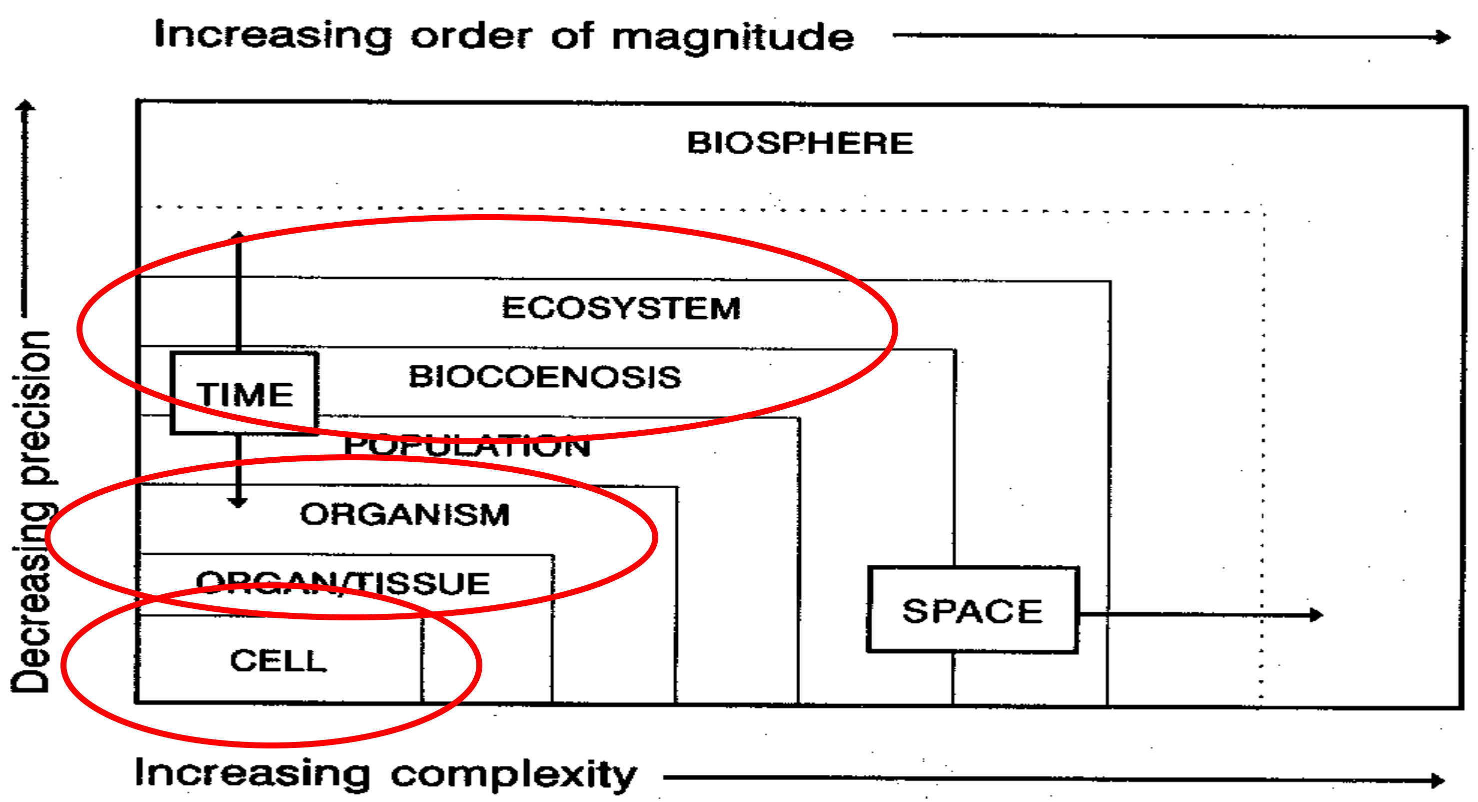


Figure 3.1 Biological levels of organization. The dimensions of time and space are less important for the investigation up to the levels of populations and biocoenoses.

From molecules to ecosystem

… and backwards

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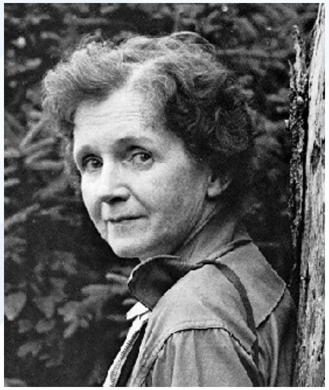

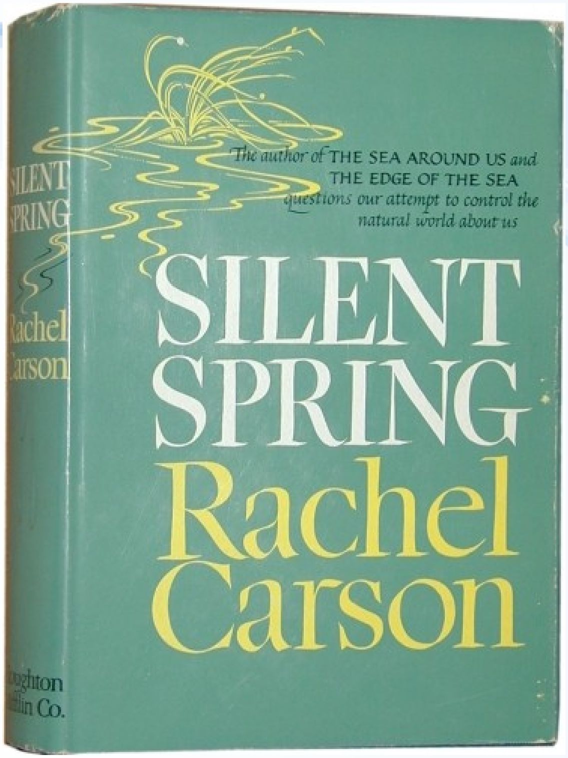

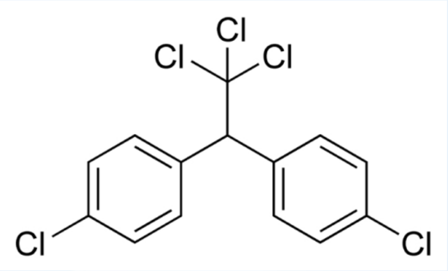

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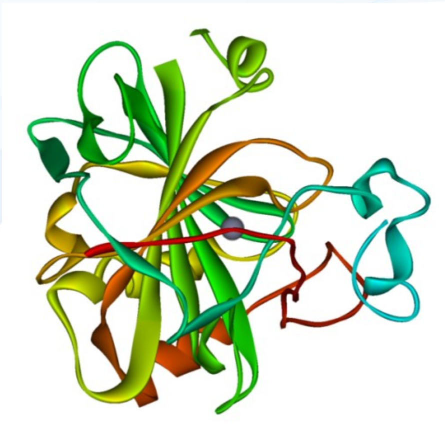
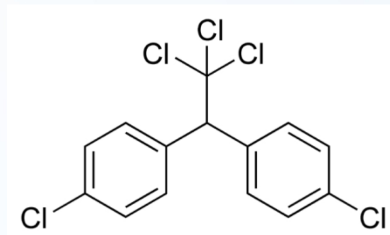
http://www2.ucsc.edu/scpbrg/

Bitman et al. *Science* 1970, 168(3931): 594

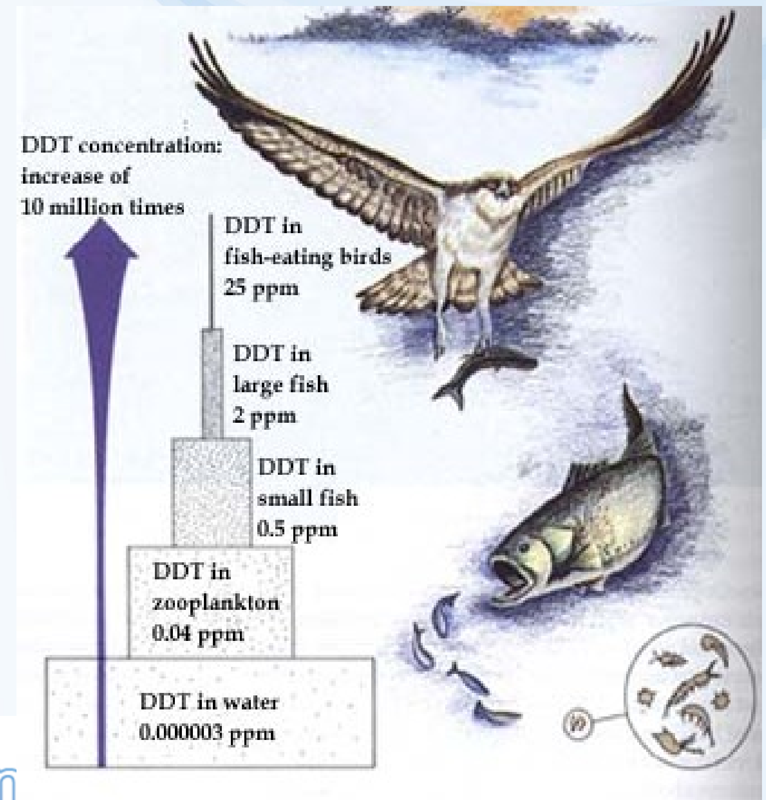


Biochemistry
bird carbonate dehydratase



In situ: bioaccumulation
-> bird population decline

In vivo: shell thinning



ECOTOXICOLOGY by definition

- **Aim:** to maintain the natural structure and function of ecosystems

- **Definitions:**
  - ecotoxicology is concerned with the **toxic effects** of chemical and physical agents on living organisms, especially on populations and communities within defined ecosystems; **it includes the transfer pathways** and their interactions with the environment
  - science of contaminants in the biosphere and their effect on constituents of the biosphere, including humans' (Newman & Unger, 2002)
  - science that provides critical information on effects of toxic compounds on living organisms which **SERVE various practical** aims (environmental protection)

Ecotoxic effects

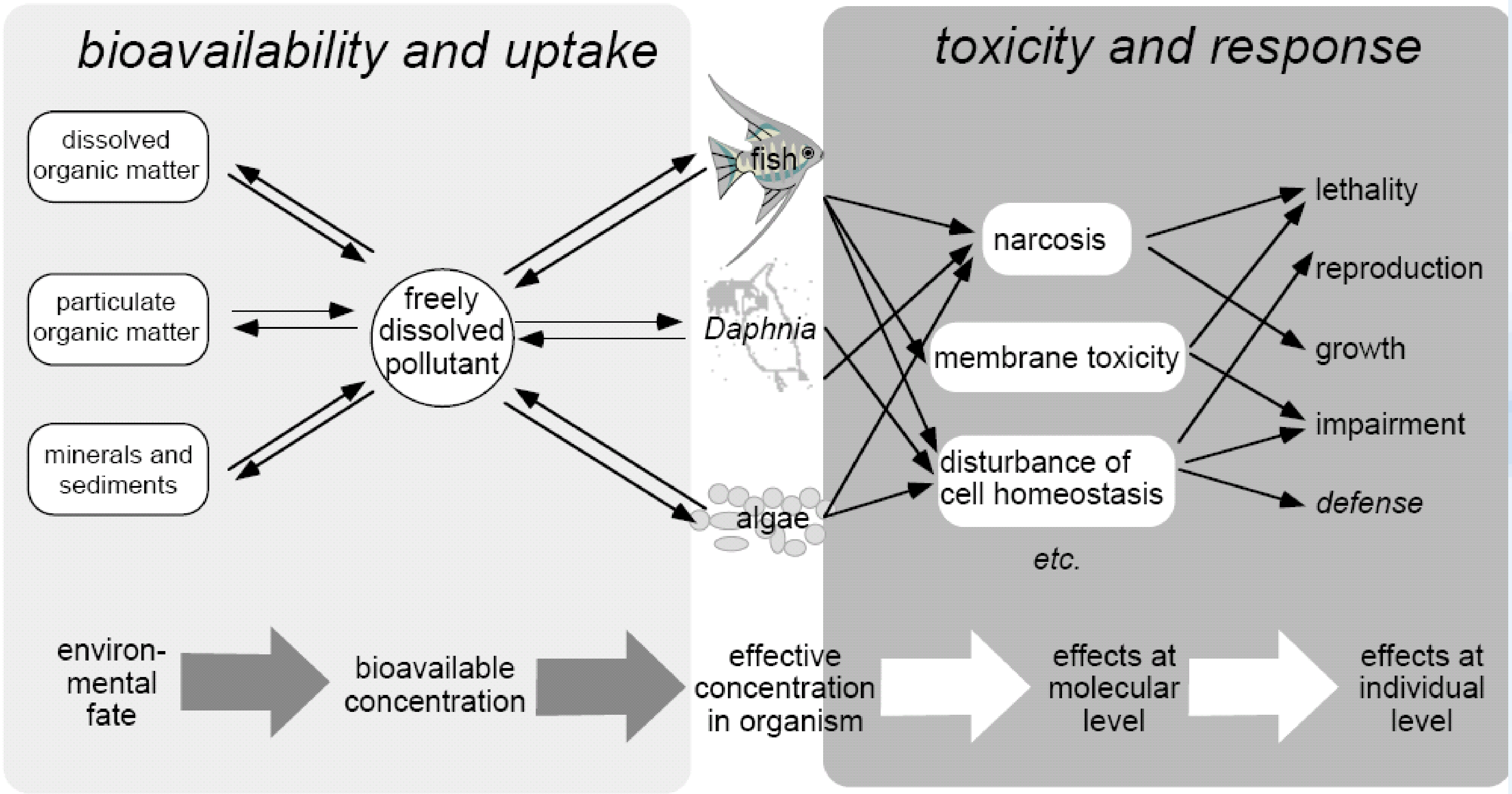
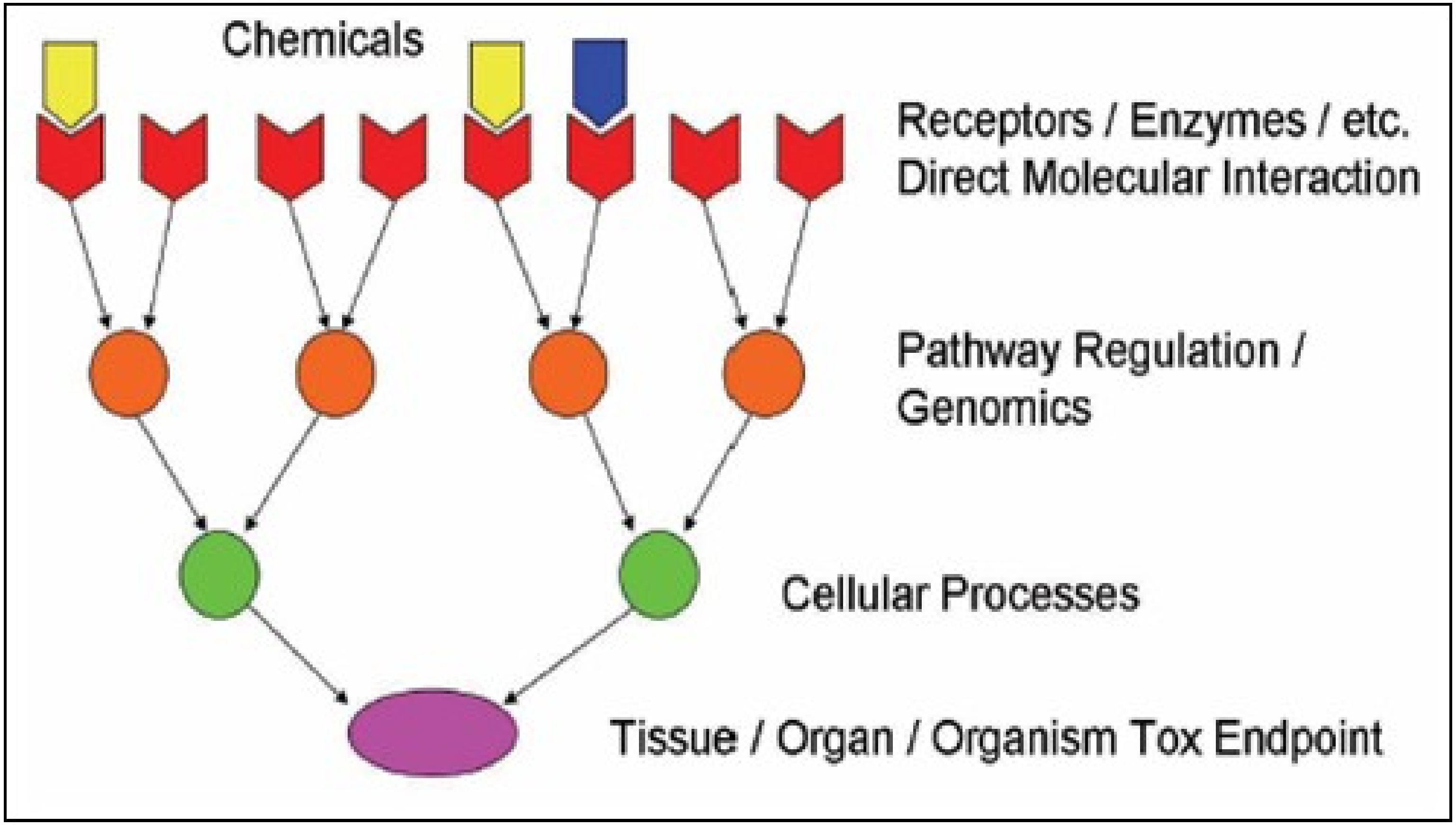


Figure 1 *The effective concentration of a pollutant in an organism (e.g. fish, daphnia, algae) or at the target site inside the organism is the link between the environmental fate of a pollutant and its toxic effect.*

Escher, B. I., Behra, R., Eggen, R. I. L., Fent, K. (1997), "Molecular mechanisms in ecotoxicology: an interplay between environmental chemistry and biology", *Chimia,* **51**, 915-921.

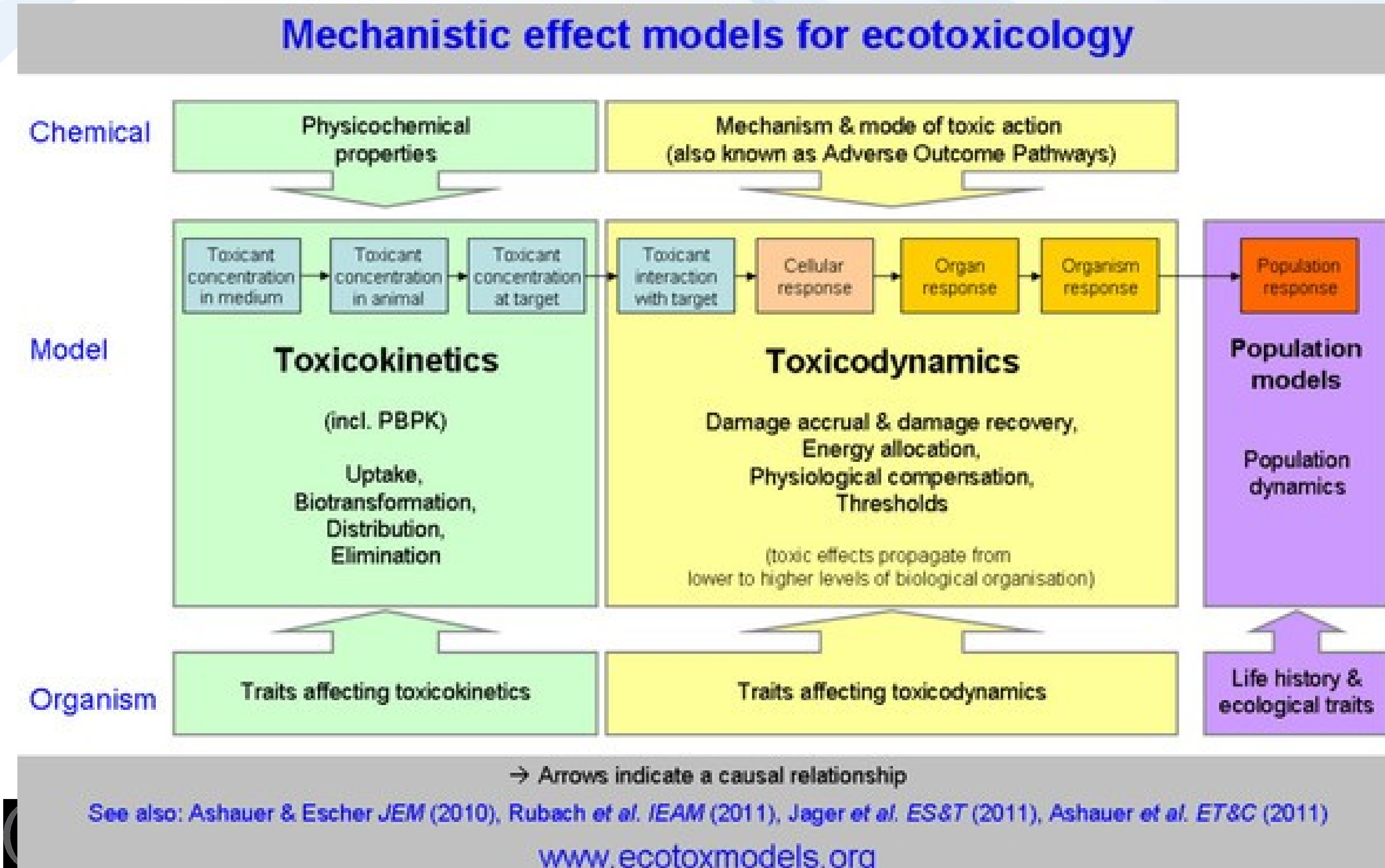
1) From molecules to individuals

MECHANISMS OF TOXICITY



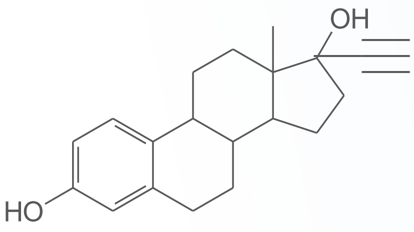
2) From molecules to individuals

ADVERSE OUTCOME PATHWAYS

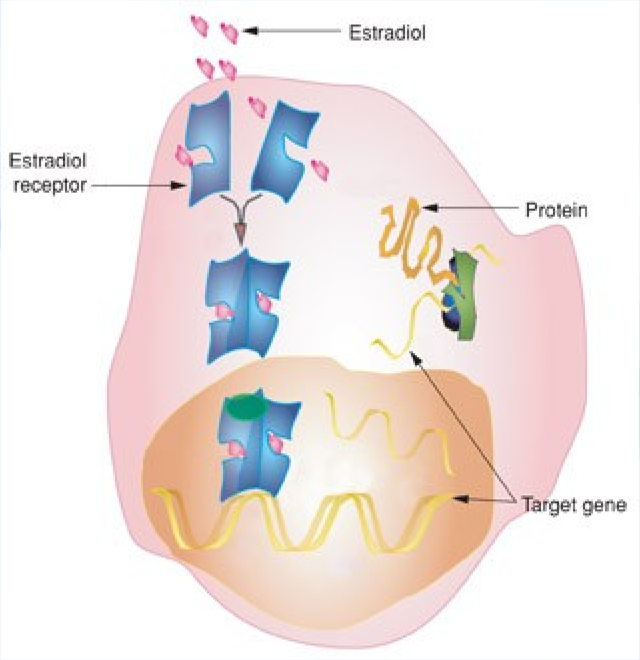


AOP Example: ethinylestradiol

Ethinylestradiol



Binds to ESTROGEN RECEPTOR



Target genes
- Proliferation/Apoptosis (sexual organs)
- Synthesis of egg yolk (fish, amphibia)

Effects
- Females: reproduction regulation
- Males: feminization

(+ *e.g. cancer promotion, development, immunomodulation)*

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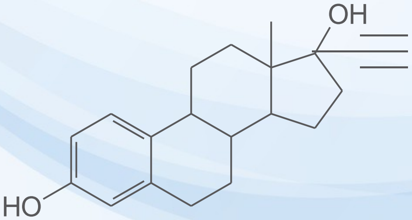
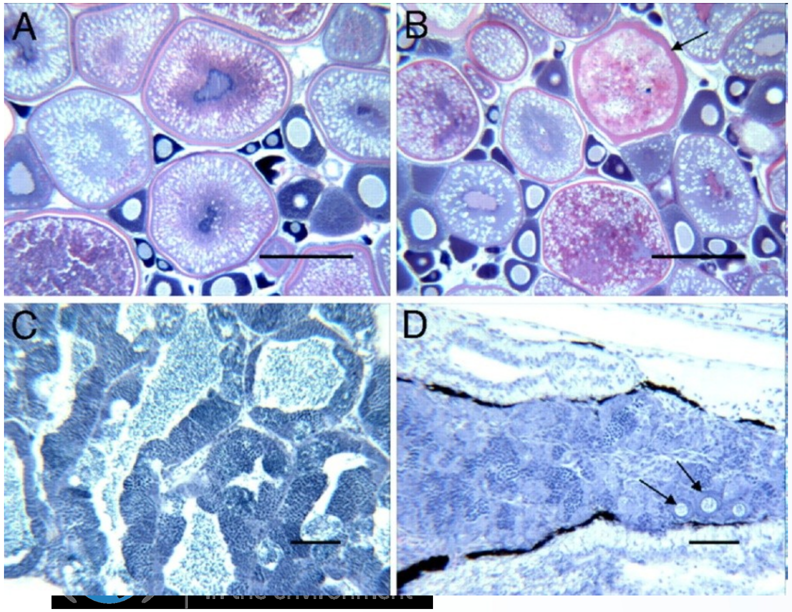
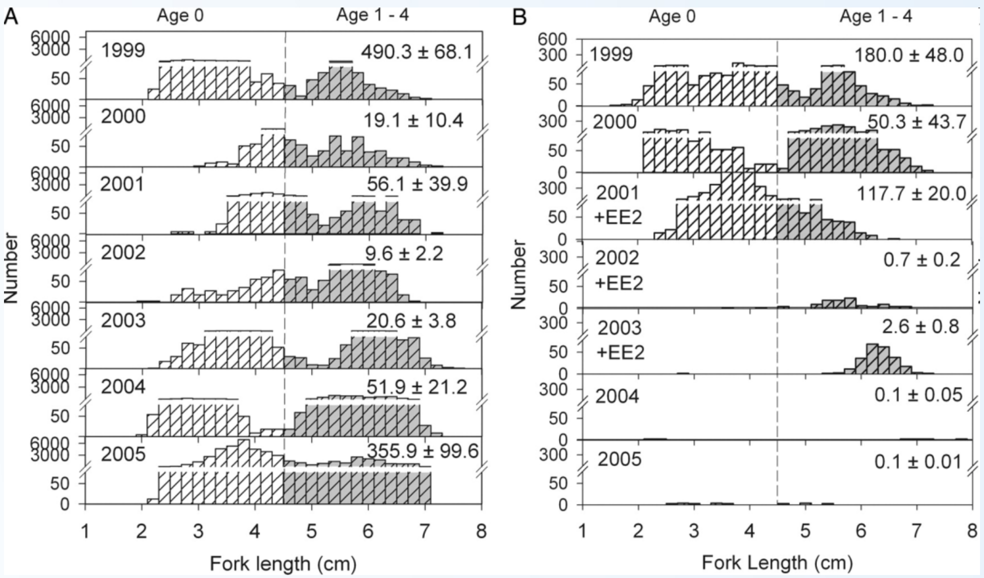
Kidd, K.A. et al. 2007. **Collapse of a fish population** following exposure to **a synthetic estrogen**. *Proceedings of the National Academy of Sciences* 104(21):8897-8901

5 ng/L (!)
7 years



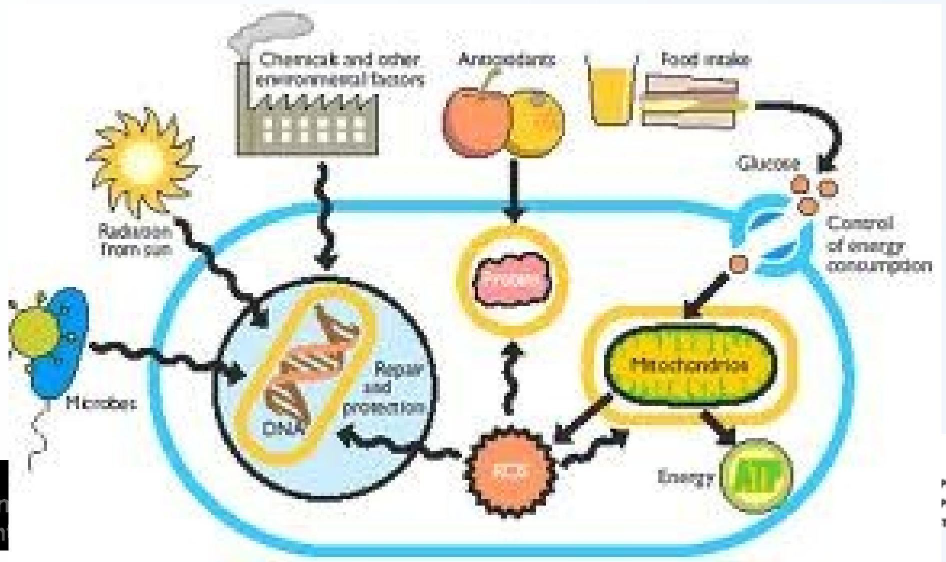


Controls **+Ethinylestradiol**



Effects at different levels

- **Molecular**
  - Nonspecific effects
    - Hydrophobic interactions with phospholipid membranes (baseline = narcotic toxicity)
    - Direct reactivity: electrophilic compounds → nucleophilic organism (e.g. oxidation of PROTEINS, lipids (membranes), DNA …)
  - Specific effects
    - Activation of ER, AR and other „nuclear receptors“
    - Inhibition of enzymes (e.g. CN- inhibits hemes in mitochondria/hemoglobin)
    - Neurotoxicity in nontarget organisms (e.g. Insecticides)



Effects at different levels

- **Cellular**
  - Effects on structure
  - Effects on metabolism (maintenance)
  - Effects on regulation

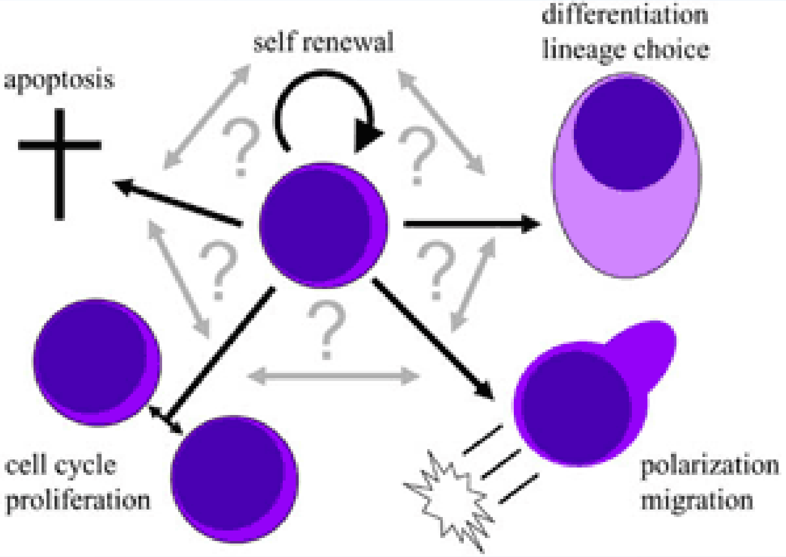
→Changes in functions (e.g. Ethinylestradiol)

→Repair, survival, growth

→Death (apoptosis or necrosis)

→Proliferation

→Differentiation



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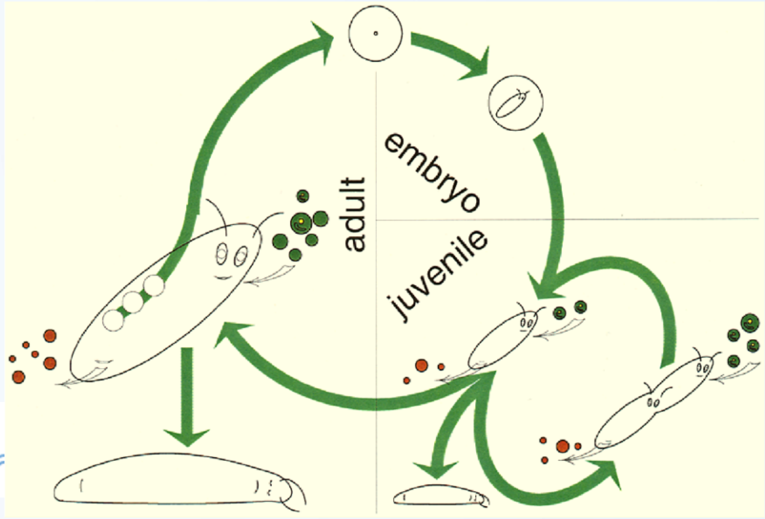
Effects at different levels

- **Organism**
  - Effects on structure
  - Effects on metabolism (maintenance)
  - Effects on regulation

→Changes in functions (e.g. Ethinylestradiol)
→Repair, survival, growth
→Death
→Proliferation = **Reproduction**
→Differentiation = **Evolution**



Effects at different levels

- **Population**

  (… all the organisms that both belong to the same group or species (i.e. can sexually reproduce) and live in the same time within the same geographical area)

  - Effects on structure
    - elderly vs. young, males vs. females
  - Effects on maintenance & growth
    - Natality, mortality, reproduction fitness

Effects at different levels

- **Community & Ecosystem**

  (… a group of interacting living organisms sharing a populated environment)

  - Effects on structure
    - Loss of species, loss of biodiversity
  - Effects on functioning
    - (including „ecosystem functions“)

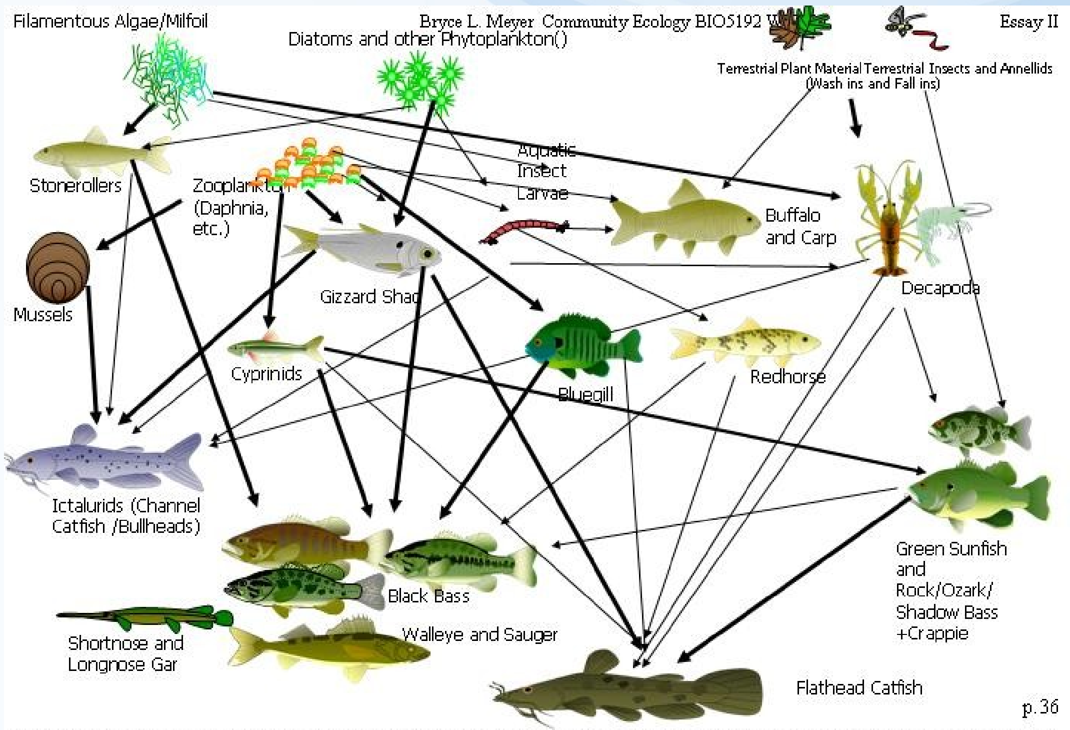


Figure #31: Simplified Food Web (Source Down) similar to warm water lower end of river before entry into Mississippi River System or impoundment. The Flathead acts as a super predator when present as large speciemens, and many predators such as walleyes and Gars compete for minnows and shad. Channel Catfish also appear and prey upon mussels and other invertebrates.

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(Eco)toxicology – science of „doses“

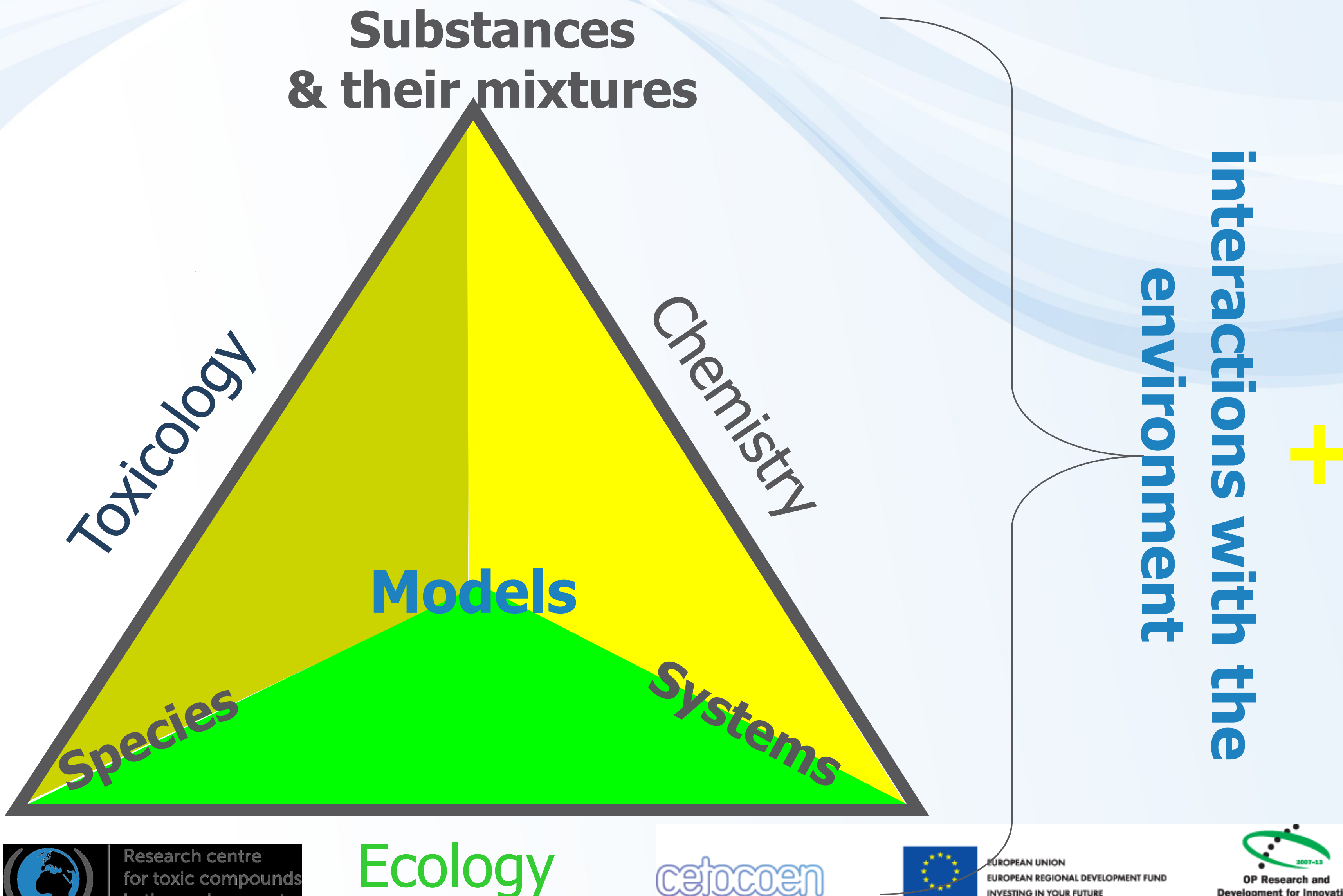
Paracelsus (1493 - 1541)

‘What is there which is not a poison?

„Cause-effect paradigm“

- *All things are poison and nothing without poison.*
- *Solely the dose determines that a thing is not a poison.*

ECOTOXICOLOGY – a synthetic science



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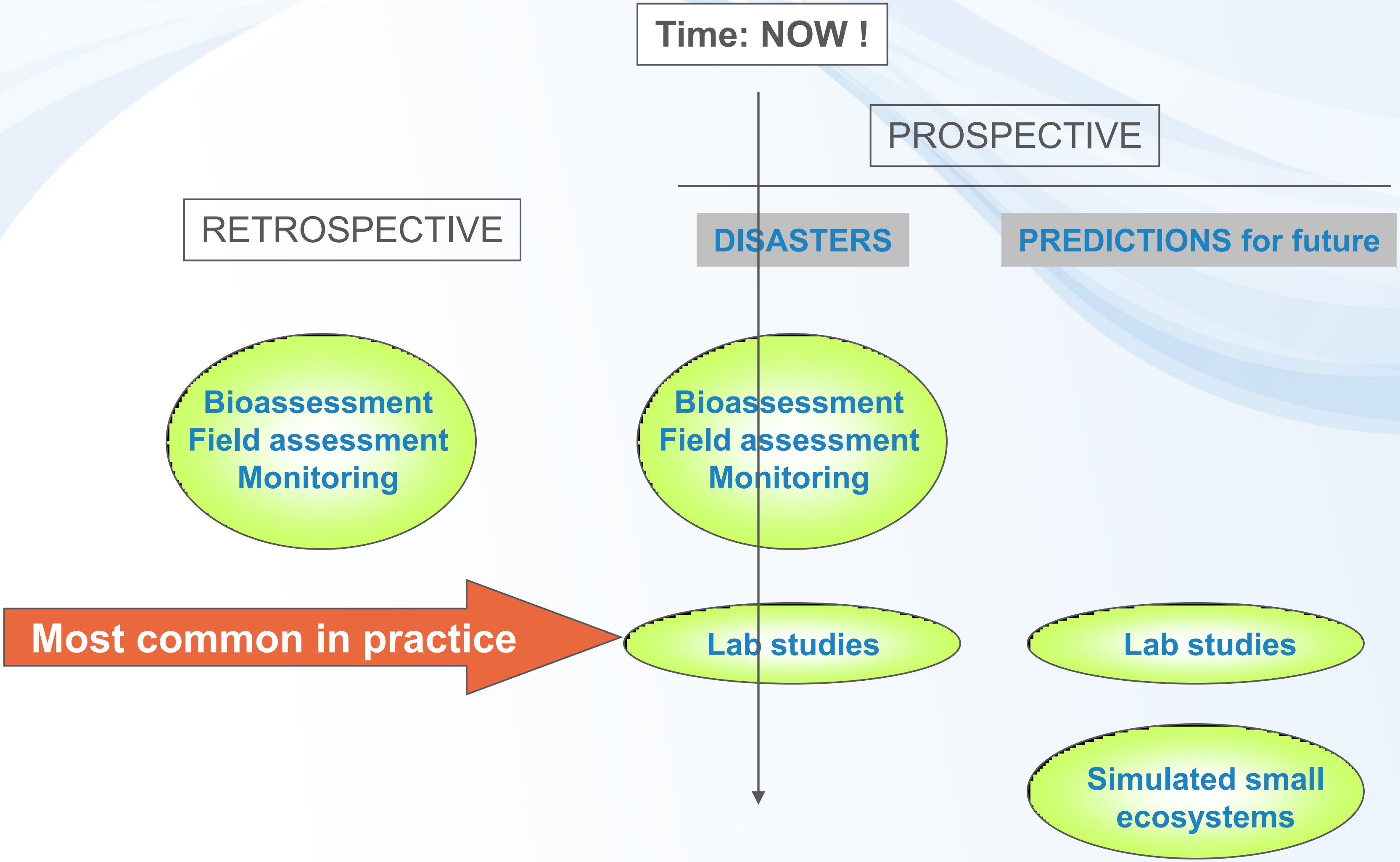
Ecotoxicology – ultimate goal ?

To identify (or predict) safe vs hazardous levels

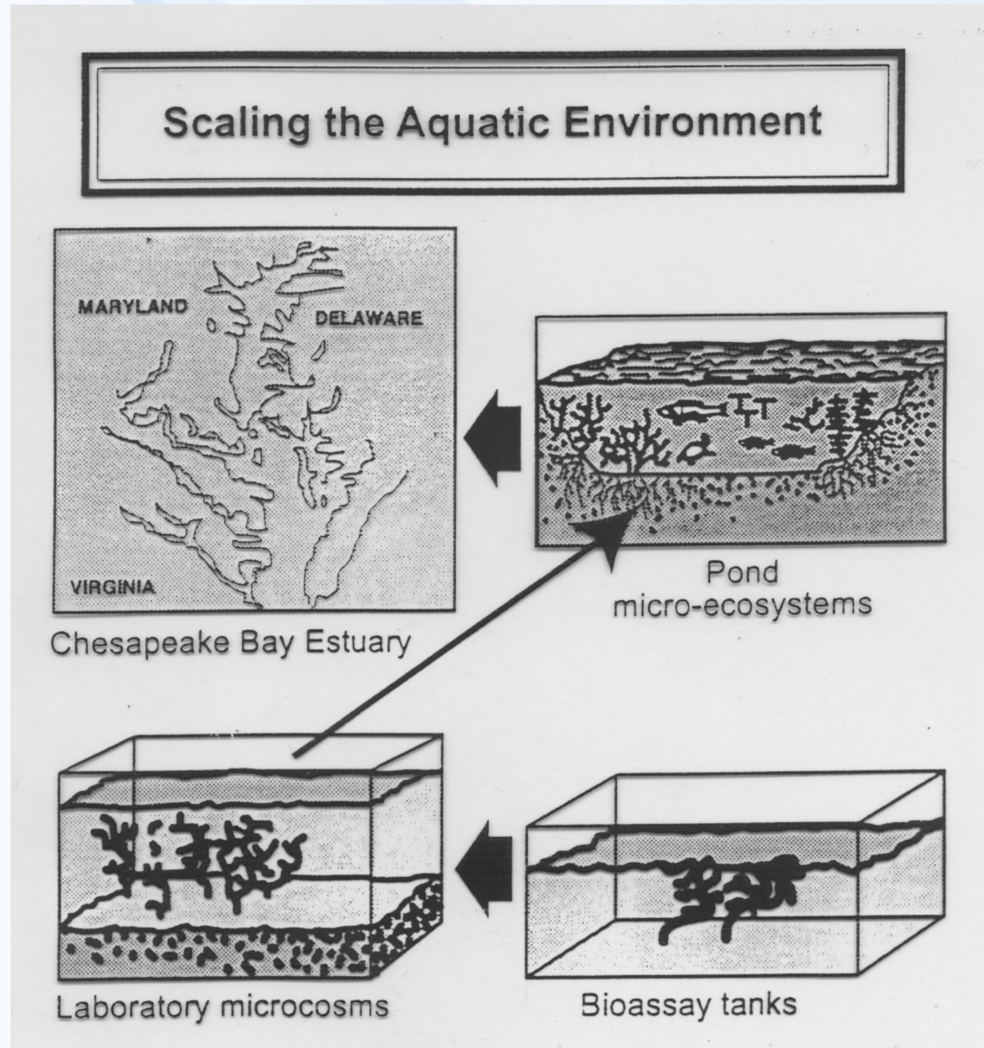
Ecotoxicology: problems and approaches



Testing ecotoxicity – basics

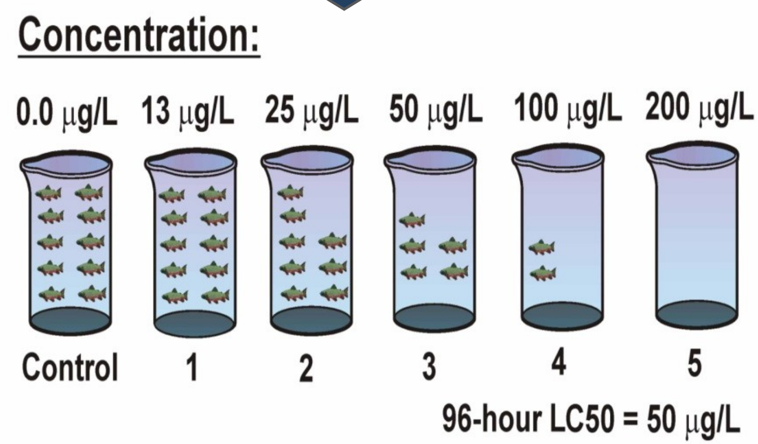
Bioassays
- single / multiple species
- acute / chronic effects
- standardized (practical)
  vs. experimental (research)

Simulation of the ecosystem
- major **trophic levels**
  - producers
  - consumers
  - decomposers



Ecotoxicology methods 1) - standardized assays

Cu addition



Effect concentrations expressed in total/dissolved Cu

??? Safe concentrations ???

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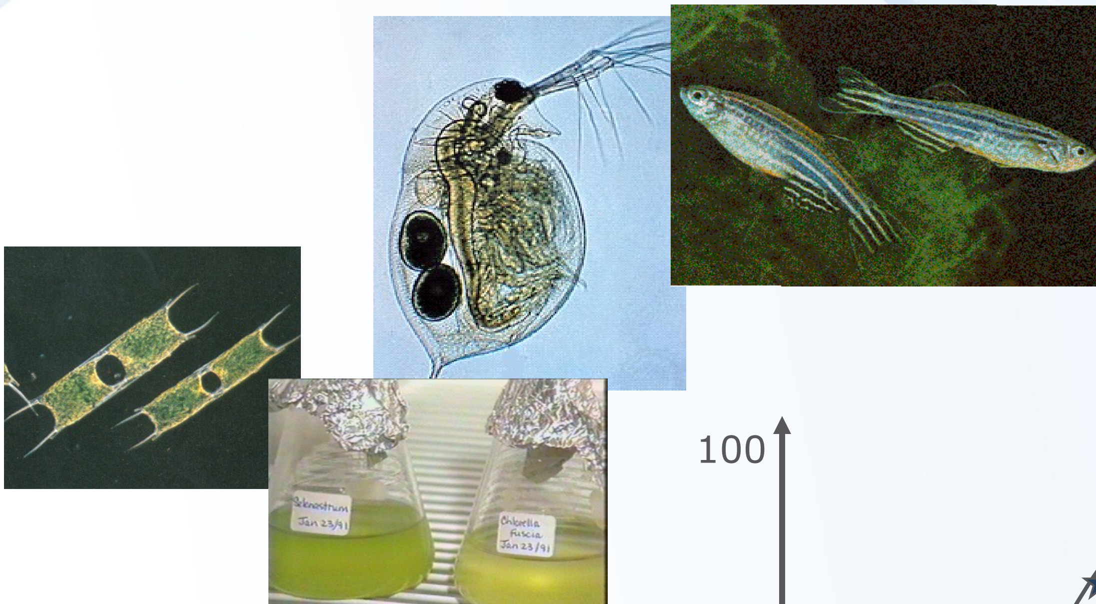
Laboratory ecotoxicology – data and results



Threshold:

No Observed Effect Concentration (NOEC)

Ecotoxicology – methods 2: Micro & Mesocosms

Expensive & time consuming *(e.g. Pesticide testing)*
Variable results (natural variability …)
Higher ecological relevancy

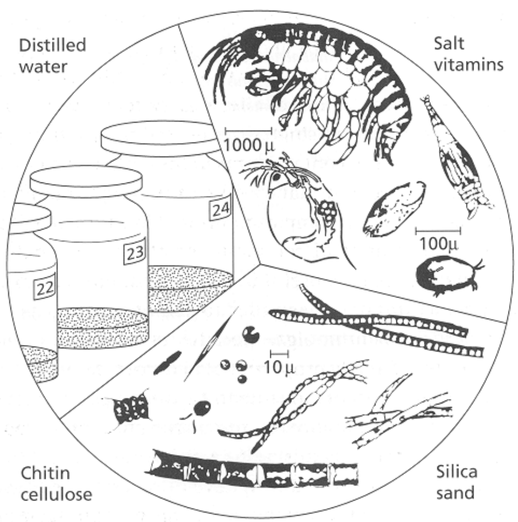
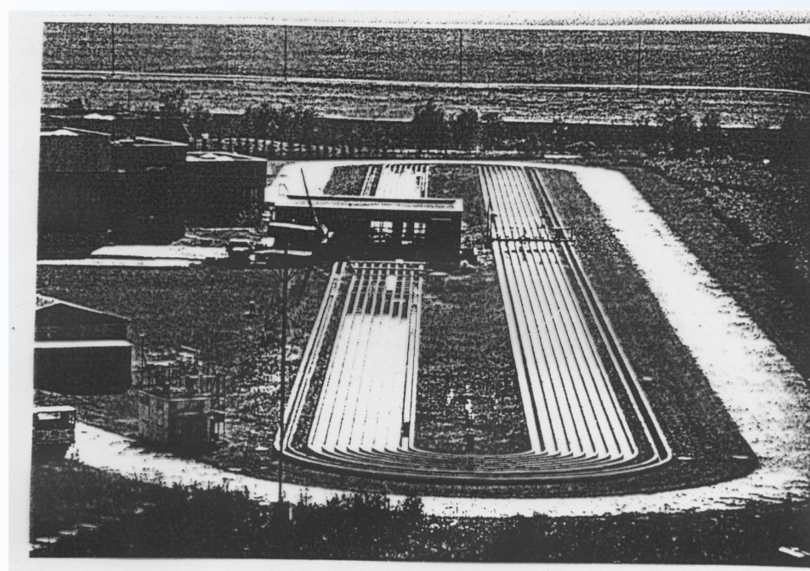


Fig. 5.2 Components of a standardized aquatic microcosm.



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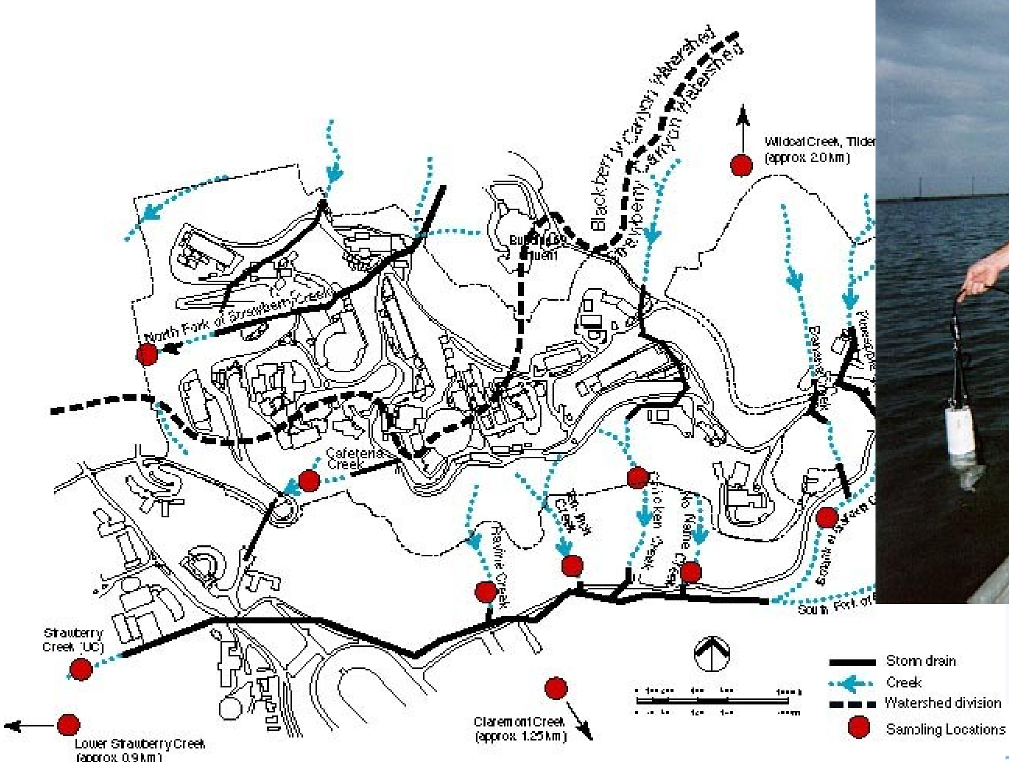
Ecotoxicology – methods 3: Field assessment / biomonitoring

- complex issue (geology, climate, chemistry, biology ..)
  Ecotoxicology mixes with Ecology
- comparing „contaminated“
  with „control“ sites



Notes on practical testing

- Testing chemicals
  - Traditional / bioassays developed to assess **individual chemicals**
  - Advantage: Standardized approaches
  - Disadvantage: Limited ecological relevance
    - often **acute** tests only
    - „too standardized…“ (? Less representative ?)
    - does not assess/consider bioavailability
    - no consideration of mixture effects
    - no consideration of specific modes of action
    - no consideration of ecological situation

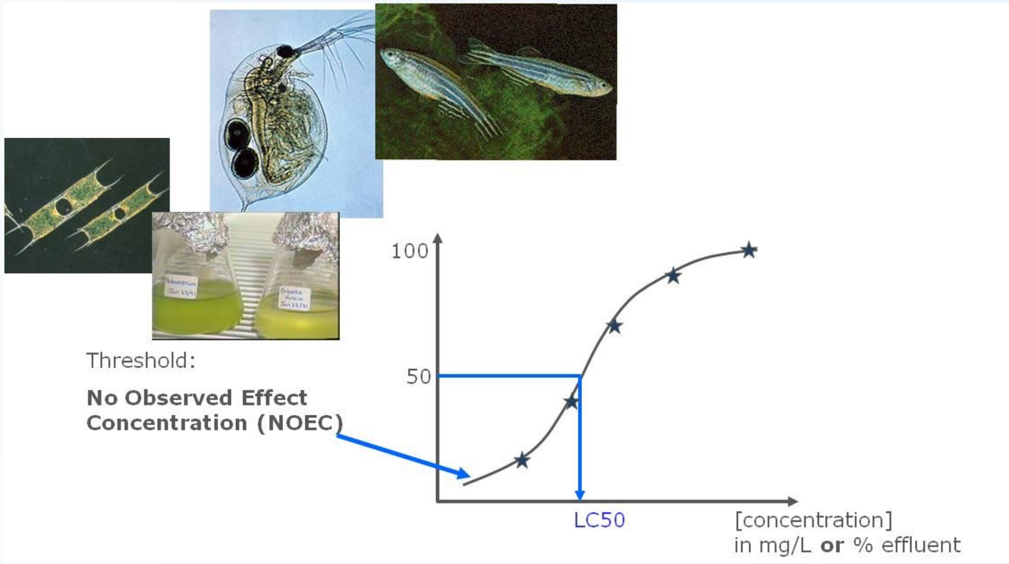
- Example: Acute (96h) fish toxicity assay with ethanol
  - No deaths (but fish are passive – slow swimming) → OK ?
  - Real life: easy prey → population decline

Notes on practical testing

- Testing toxicity of natural **contaminated matrices**
  - Rather new in ecotoxicology – many open challenges
    - Whole effluent toxicity testing (WET)
    - Contact soil toxicity assays
  - More complex and more complicated
    - „cause-effects“ often not clear
      - Natural variability in matrices
      - Algal tests - nutrients (Nitrogen, Phosporus) >> Toxic compounds

Ecotoxicology in current practice

- Most legislations on chemicals)
  (e.g. REACH, Pharmaceuticals, Pesticides)
  have very simple (basic) requirements
  - EC50 from acute toxicity
  - Of 3 basic assays
    - Algae
    - Daphnia
    - Fish



Ecotox database:
www.epa.gov/ecotox

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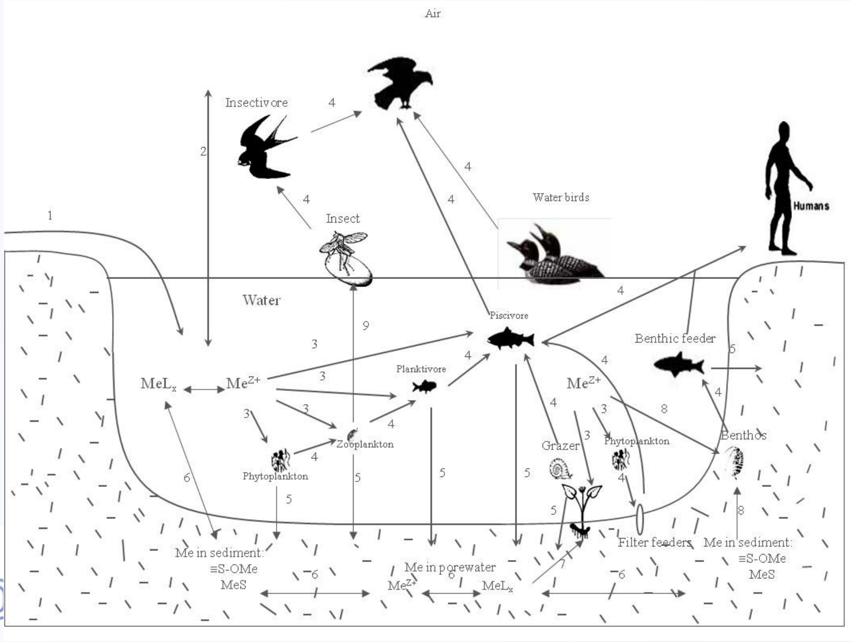
Ecotoxicology in current practice

- How to extrapolate 3 (or few more) EC50 values to get legally binding safe concentration, which is protecting virtually all organisms?

PNEC (Predicted No Effect Concentration)

EQS(Environmental Quality Standard)



Extrapolation approaches

Ecotoxicological data

Assessment / Extrapolation factors

Data	Assessment factor
L(E)C50 short-term toxicity tests	1000
NOEC for 1 long-term toxicity test	100
NOEC for additional long-term toxicity tests of 2 trophic levels	50
NOEC for additional long-term toxicity tests of 3 species of 3 trophic levels	10

PNEC

Extrapolation approaches

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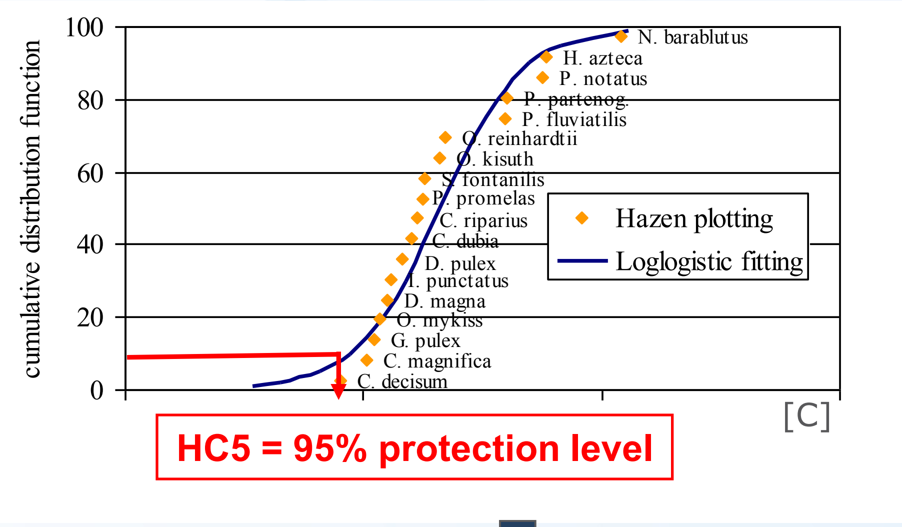
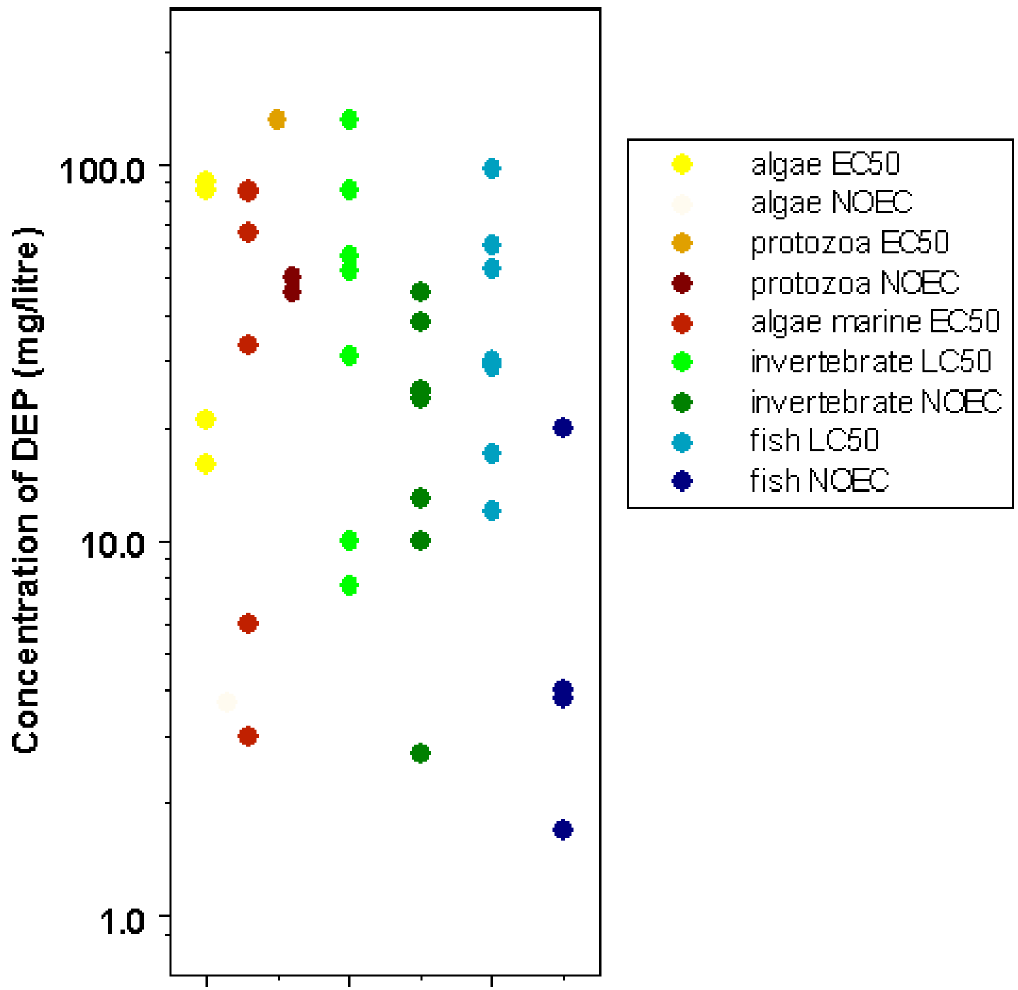
Species sensitivity distribution (SSD)



PNEC

Species Sensitivity Distribution

EC50 values for Diethylphthalate



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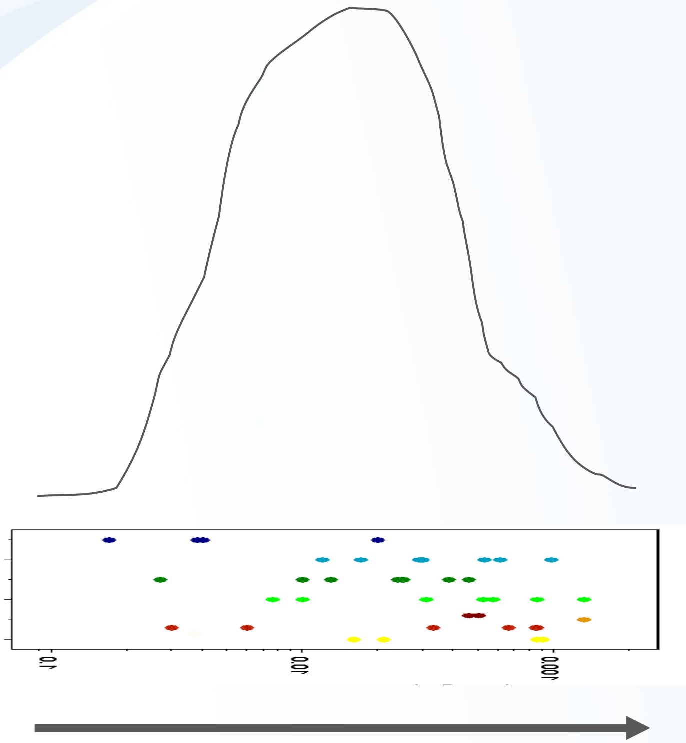
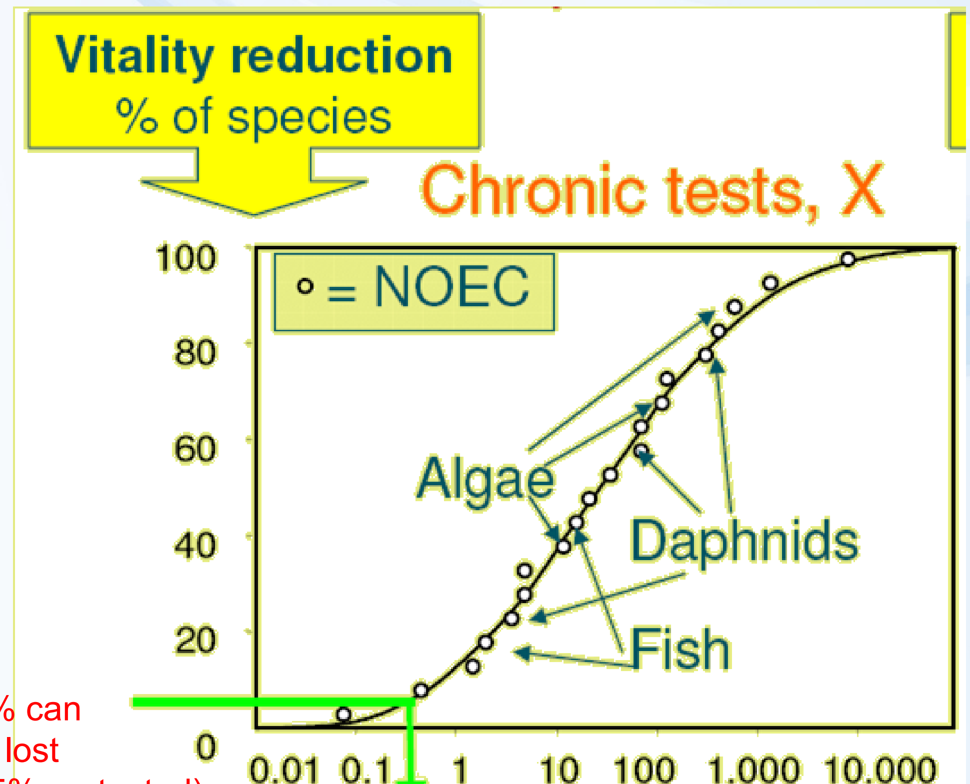
Species Sensitivity Distribution

Frequency of EC50 values



Increasing concentration

Cummulative distribution of EC50 values



5 % can be lost (95% protected)

Safe concentration

Ecotoxicology

WHAT IS IT GOOD FOR ?

SOLVING PRACTICAL PROBLEMS

Environmental policy: Limitations of sources and effects

Starting point:

Prevention and **reduction of environmental load**

Source-directed policy

Source-directed measures

Limits

Starting point:

Prevention of adverse effects

Effect-directed policy

Effect-directed measures

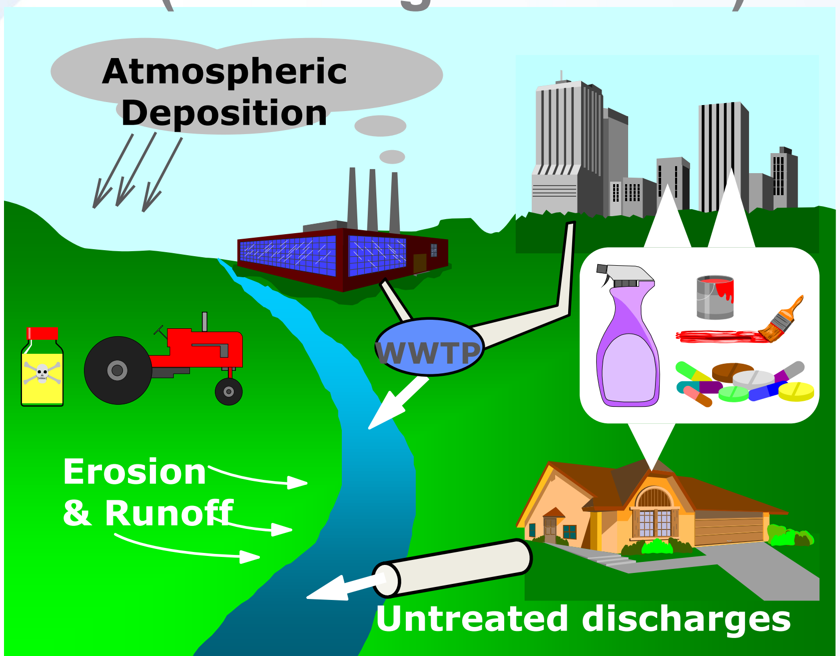
EQS

(Env. Quality Standards)

Cause – effect → Risk assessment

Exposure

(resulting from load)



Effects

(what exposures cause effects ?)

Predicted Environmental Concentration (PEC)

effective concentrations (PNEC)

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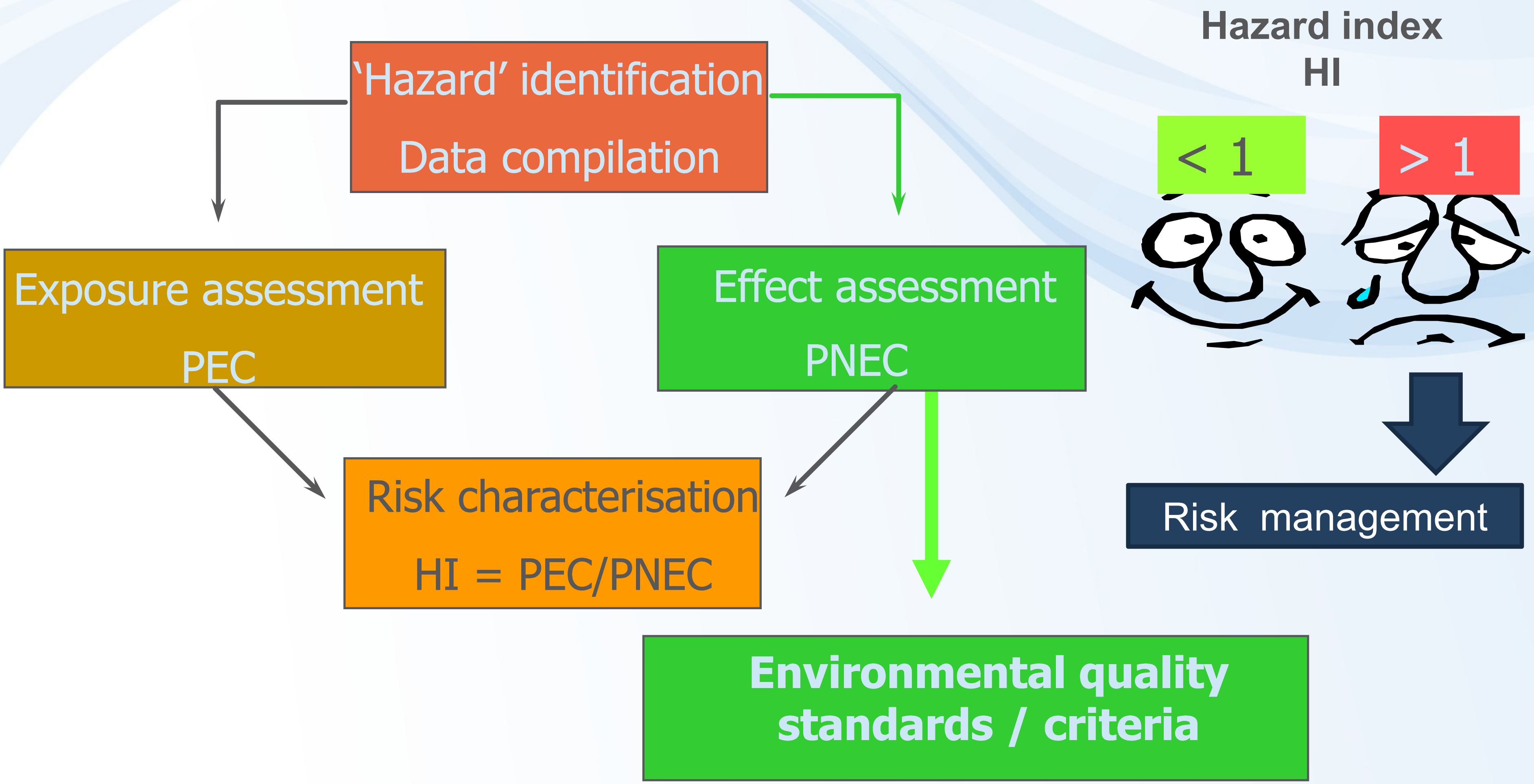
Risk assessment & management



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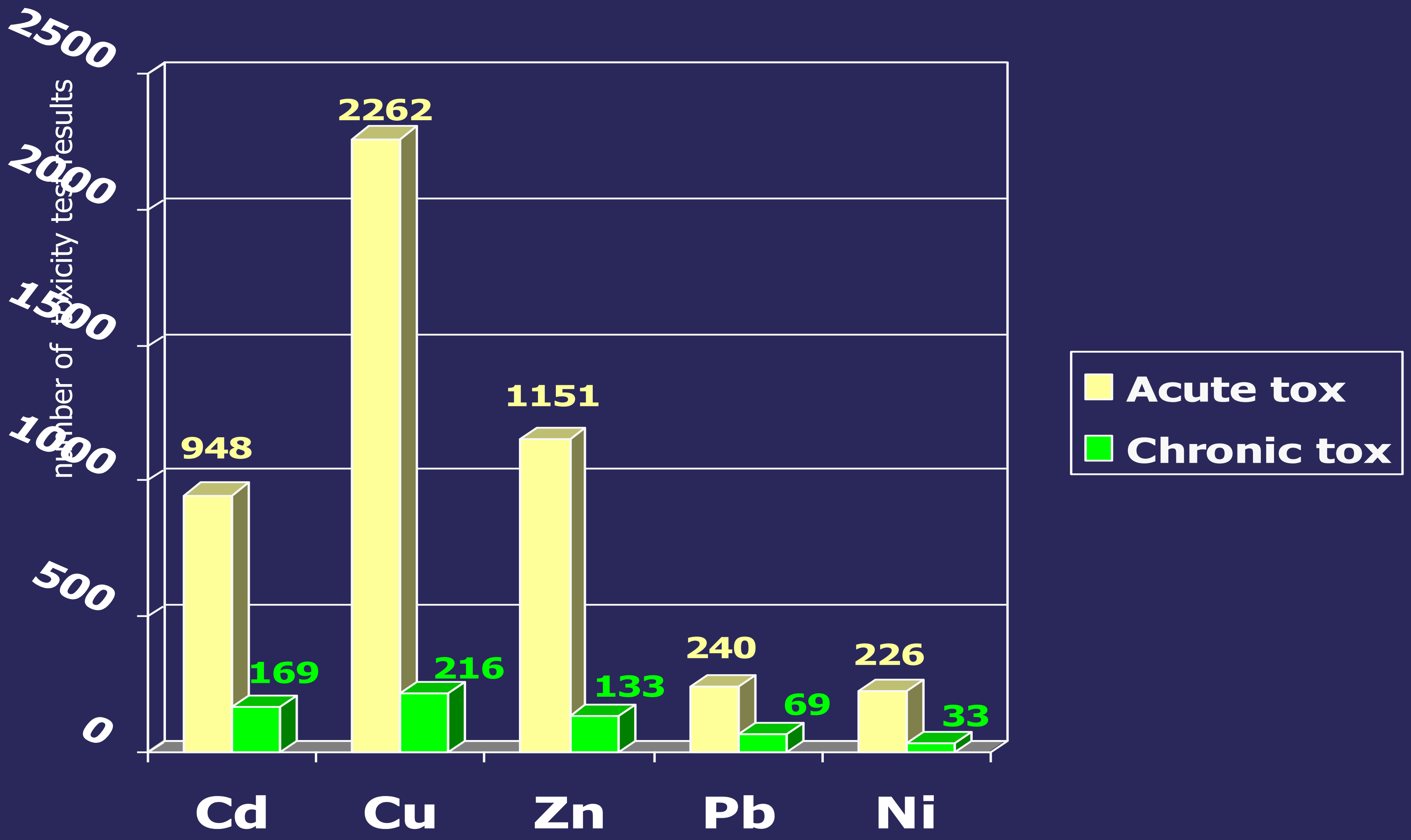
UNCERTAINITIES
& challenges in ecotoxicology

... stay cautious and critical

1) Data availability



2) Bioavailability

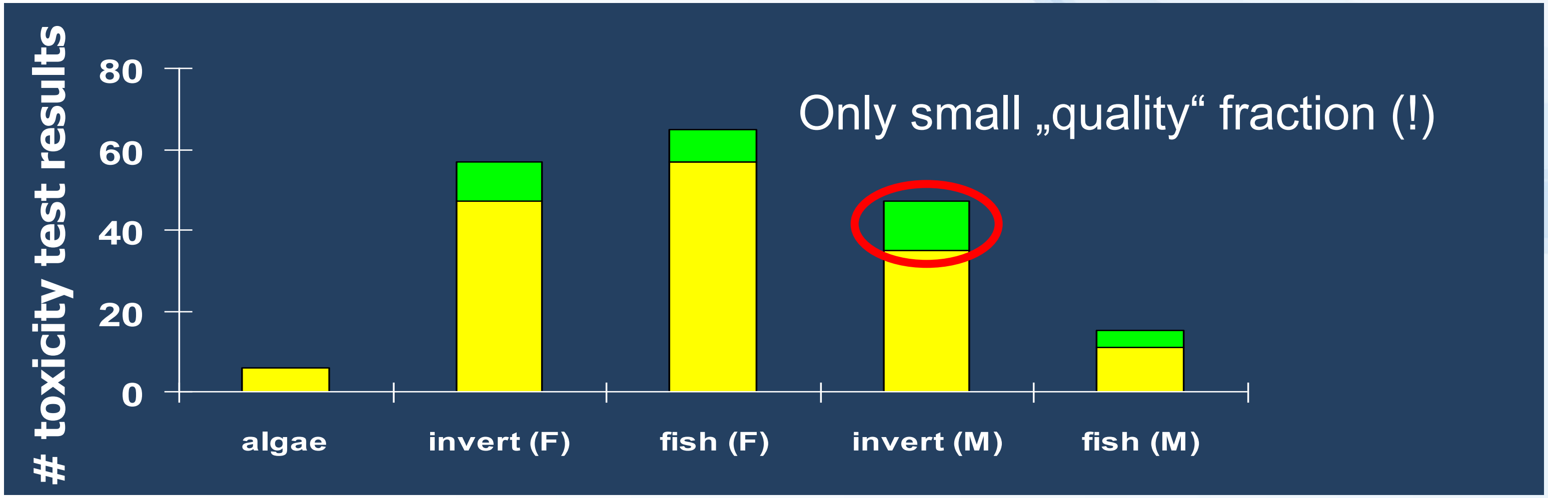
EQC expressed as total concentrations do not reflect the true environmental risk

➔ **Bioavailability** of chemicals depends on number of factors:

- physico-chemical
  - pH, hardness, alkalinity, DOM concentration / quality
- biological factors:
  - species, uptake route, physiological regulation

3) Data quality

Quality and relevance of the (scientific) data used for EQC derivation of metals, in most cases, POOR !



- Literature search: 156 data points
- Application of QC/QA and acceptance criteria [measured, pH and Hum (F), salinity (M)]

➔ 34 data points (22 %) used in risk assessment

4) „Real ecotoxicology“ needed

1) Use non-standardized organisms

- Laboratory - aquatic snails, chironomids, soil organisms …
- Natural – sample natural organisms and test ecotoxicity immediately

2) Assess parameters important for populations

- Reproduction
- Life cycle effects (including early life stages)

3) Consider natural situations

- Addapt test conditions (temperature?, water hardness? …)
- Simulate real exposures (e.g. peaks during pesticide spraying)

4) „Real ecotoxicology“ needed

4) Work on development of models – answer difficult questions ?

- AOPs (?)
- E.g. ecological impacts of pharmaceuticals ?

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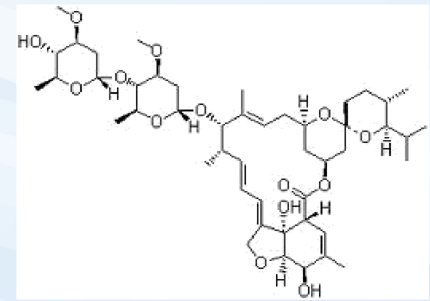

Example - antiparasitic ivermectin

- Used (for example) 2-times per season per sheep/cow
- Kills 100% parasites in sheep
- Released in dung - kills 80% larvae of dung flies
- High concentrations in dung (released 2 days post application)
- Fairly persistent in the soil (half-life 30 days)
- May be washed into adjacent streams (highly toxic to water insects)

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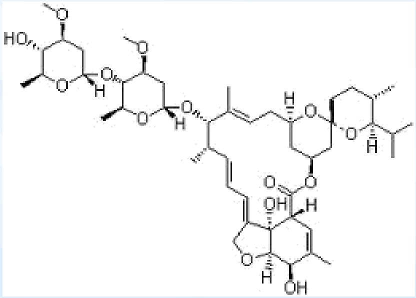
- E.g. ecological impacts of pharmaceuticals ?



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- **What are the indirect impacts on soil biota ?**
  - Soil texture and quality ? Will plants grow on the pastures ?
- **Any impacts on bats, birds?**
  - Dung flies and aquatic invertebrates serve as food

Practical example for ecotoxicologist

European strategy how to deal with chemicals

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EU and risk assessment

- **± 40 Directives** or Regulations concerning the evaluation and management of the dangers/risks associated with chemical substances
  - Regulation EEC 793/93 –**Existing substances**
  - Dir. 67/548/EEC – **New substances**
  - Dir. 98/8/EC – Biocides / Plant Protection Products
  - Further Directives – E.R.A. of new pharmaceuticals

Existing substances

- 100196 substances in EINECS
- 2747 HPVCs (High Production Volume Chemicals)
  - 14% minimum data-set (base-set)
  - 65% less than base-set
  - 21% no toxicity data
- Various priority lists
  - Aquatic hazard (EU Water framework directive)
  - Endocrine disruptors
  - ….

REACH
Registration, Evaluation and Authorisation of Chemicals

- 27-2-2001: White Paper on the Strategy for Future Chemicals Policy
- 23-10-2003: Commission's proposal REACH
- December 2008: Pre-registration mandatory (all chemicals in EU must be registered at ECHA

European Chemicals Agency (http://echa.europa.eu)

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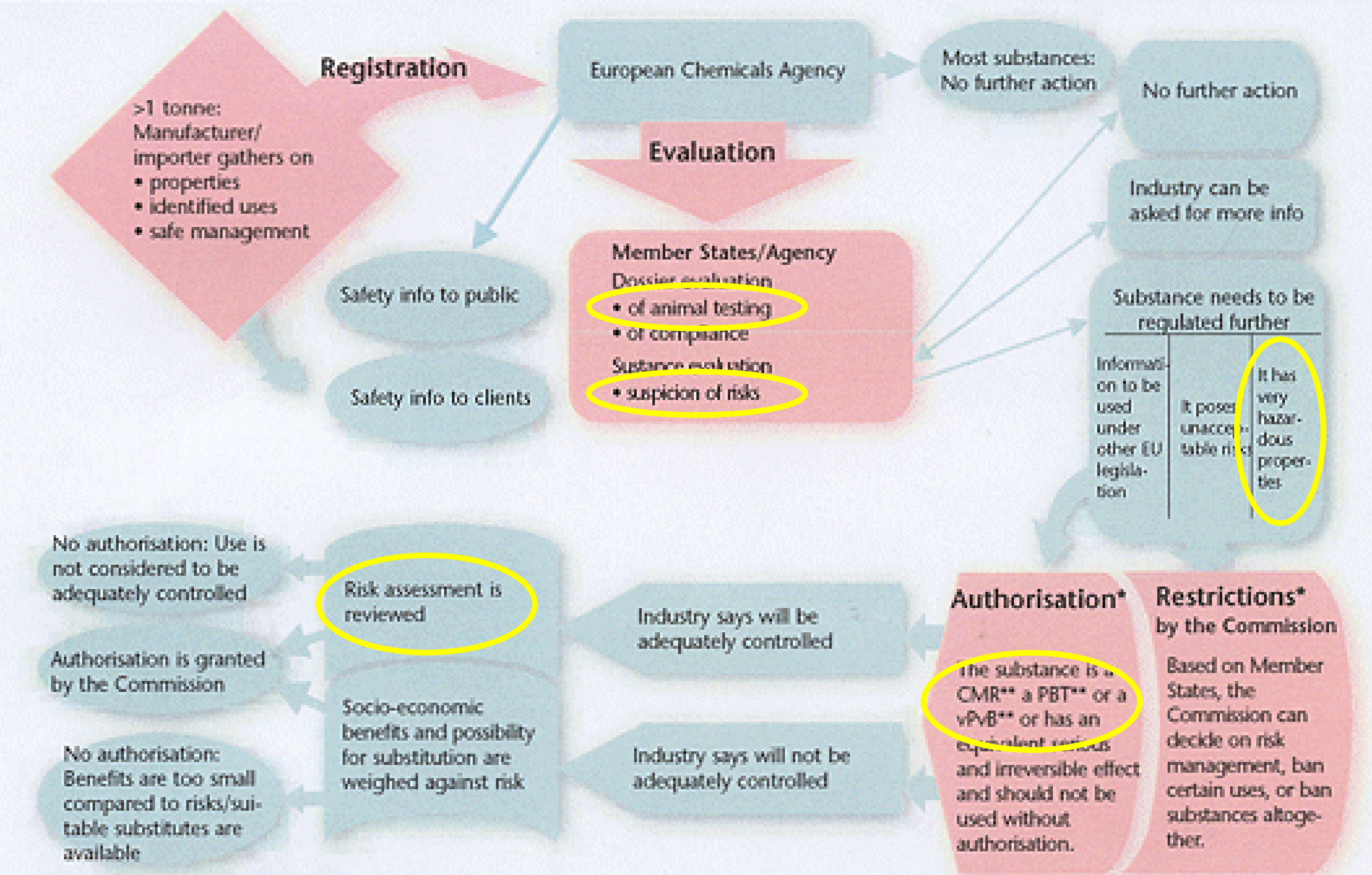
REACH : Registration, Evaluation and Authorisation of CHemicals



* Substances do not have to be registered or evaluated to be placed under authorisation or restriction. They can be identified in other ways.

** Can cause cancer or mutations, or is toxic to reproduction; or is persistent, bio-accumulative and toxic, or very persistent and very bio-accumulative.

REACH: aims & timing

- **Major goals**
  - Protection of man and the environment
  - Increase competiveness of EU chemical industry
  - Increase transparency
  - Avoid fragmentation of market
  - Integration with international policies
  - Reduction use of test animals

- **Approach**
  - Industry is responsible – provides data

- **30000 existing substances**
  - 0-3 year (2010): all HPVC and CMR substances (~ 3000)
  - 4-6 year (2013): all 100-1000 t/y substances
  - 7-11 year (2018´): all 10-100 and 1-10 t/y substances

REACH: data type?

- **Physico-chemical properties, e.g.:**
  - Vapour pressure, boiling point, Kow,…
- **Human toxicology, e.g.:**
  - Acute and chronic toxicity, skin irritation, carcinogenity,…
- **Environment/ Ecotoxicological information, e.g.:**
  - Acute and/or chronic toxicity for aquatic organisms, biodegradation, …

REACH: situation 2010

- Original plan (2007-2010)
  - R.A. for ~ 3000 HPVC and CMRs

  - Situation 2010
    - ~ 200 substances RA status
    - ~ 150 draft RA reports
    - ~ 50 final RA reports

REACH: how many substances

Table 6. Estimated testing needs (% of total number of substances)

Endpoint	Minimum	Average	Maximum
6.3 Skin sensitisation	7486 (25.5)	10293 (35.1)	13728 (46.8)
6.2 Eye irritation (incl. *in vivo*)	5923 (20.1)	6910 (23.5)	8182 (27.9)
6.4.4 *In vivo* mutagenicity study	6580 (22.4)	6580 (22.4)	6580 (22.4)
7.1.2 Growth inhibition algae	2638 (9.0)	5277 (18.0)	11466 (39.1)
7.1.4 Active sludge respiration test	4616 (15.7)	4616 (15.7)	4616 (15.7)
7.1.1 Short-term *Daphnia* toxicity	2321 (7.9)	4096 (14.0)	8798 (30.0)
6.1 Skin irritation/corrosion (incl. *in vivo*)	1974 (6.7)	3949 (13.4)	5817 (19.9)
7.2.2.1 Hydrolysis	2691 (9.2)	3425 (11.7)	4518 (15.4)
6.4.1 Gene mutation study in bacteria	875 (3.0)	2916 (9.9)	6424 (21.9)
6.4.2 Cytogenicity study in mammalian cells	875 (3.0)	2916 (9.9)	6424 (21.9)
6.7.2 Development toxicity study	2408 (8.2)	2893 (9.9)	3711 (12.6)
7.2.1.1 Ready biodegradability test	1574 (5.4)	2624 (8.9)	5752 (19.6)
6.7.3 Two-generation reproduction toxicity	1665 (5.7)	2135 (7.3)	2699 (9.2)

REACH: testing

Classification categories	Test requirements in REACH			
	>1t		>10t	>100t
	New or prioritised substance			
Reproductive toxicity (a generation test)	no	no	no	no
Chronic toxicity and cancer	no	no	no	(yes)
90-day study	no	no	no	(yes)
28-day study	no	no	(yes)	yes
Acute toxicity (a second route of exposure)	no	no	yes	yes
Acute toxicity	no	yes	yes	yes
Skin allergy	no	yes	yes	yes
Skin and eye irritation	no	yes	yes	yes
Mutageneicity (in vitro)	no	yes	yes	yes
Further ecotoxicity studies (incl long term tests)	no	no	no	yes
Acute toxicity: fish	no	no	yes	yes
Acute toxicity: algae	no	yes	yes	yes
Acute toxicity: Daphnia	no	yes	yes	yes
Biotic degradation	no	yes	yes	yes

REACH: costs

	>1t/y	>10t/y	>100t/y	>1000t/y	Total
Registration costs	€ 100 mn	€ 100 mn	€ 100 mn	€ 200 mn	**€ 500 million**
Testing costs	€ 150 mn	€ 300 mn	€ 350 mn	€ 450 mn	**€ 1250 million**
Safety data sheet costs					**€ 250 million**
Authorisation procedures					**€ 100 million**
Reduced costs for new substances below 1t etc.					**(benefit of € 100 million)**
Total testing and registration costs					**€ 2, 000 million**
Agency fees (paid by chemicals sector)					**€ 300 million**
Total costs (including Agency fees)					**€ 2, 300 million**

REACH: testing costs

Table 8. Estimated testing costs for most costly endpoints (Million EURO)

Endpoint	Minimum	Average	Maximum
6.7.2 Development toxicity study	396	476	611
6.7.3 Two-generation reproduction toxicity	293	376	475
6.4.4 *In vivo* mutagenicity study	129	129	129
6.6.2 Sub-chronic toxicity	76	111	210
6.6.3 Long-term repeated dose toxicity study (incl. 6.9 Carcinogenicity study)	44	52	73
6.6.1 Short-term repeated dose toxicity study	13	49	189
6.4.2 Cytogenicity study in mammalian cells	16	52	116
6.3 Skin sensitisation	29	40	54
7.2.1.1 Ready biodegradability test	19	32	71
7.3.2 Accumulation	14	28	67
7.1.2 Growth inhibition algae	13	26	57
6.7.1 Development toxicity screening	12	26	101
7.2.2.1 Hydrolysis	16	21	28

REACH: test and cost reduction?

MODELS,

QSAR

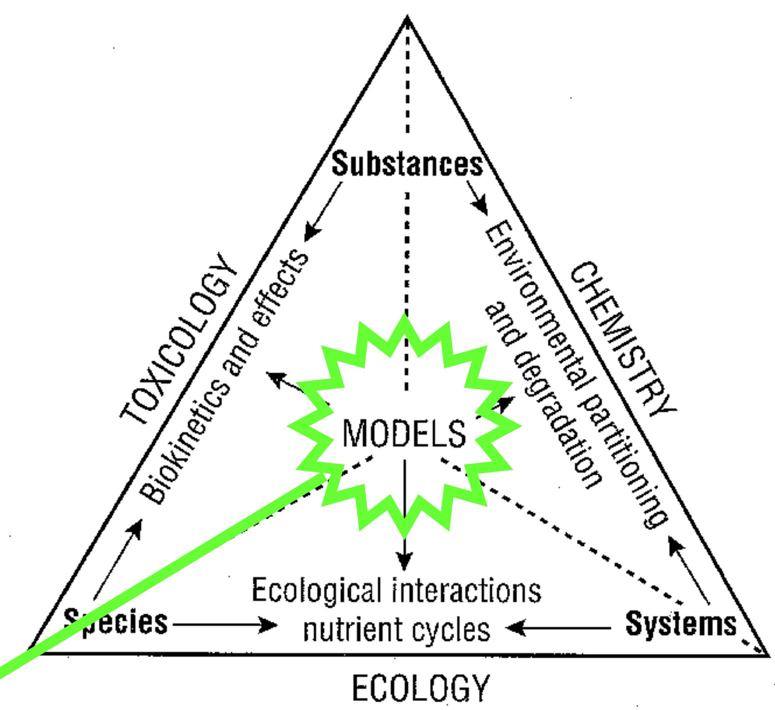


Figure 6.1. Ecotoxicology is a multi-disciplinary study into the toxic effects of substances on species in complex systems [1].

REACH: implications

- Total: 2,8 to 5,6 billion €

- Industry pays
- Test costs (50-60% of total cost):
  - 86% for HH tests
  - 14% for environment tests
  - 0% for analyses
- Manpower and expertise?
  - Tests
  - Risk assessments
  - Evaluations

- Financial and time pressure:
  danger for ‘hazard-based’ instead of ‘risk-based’ approach

Risks of chemicals: a balancing act ….

between perception, uncertainties, science and pragmatism?

Final considerations

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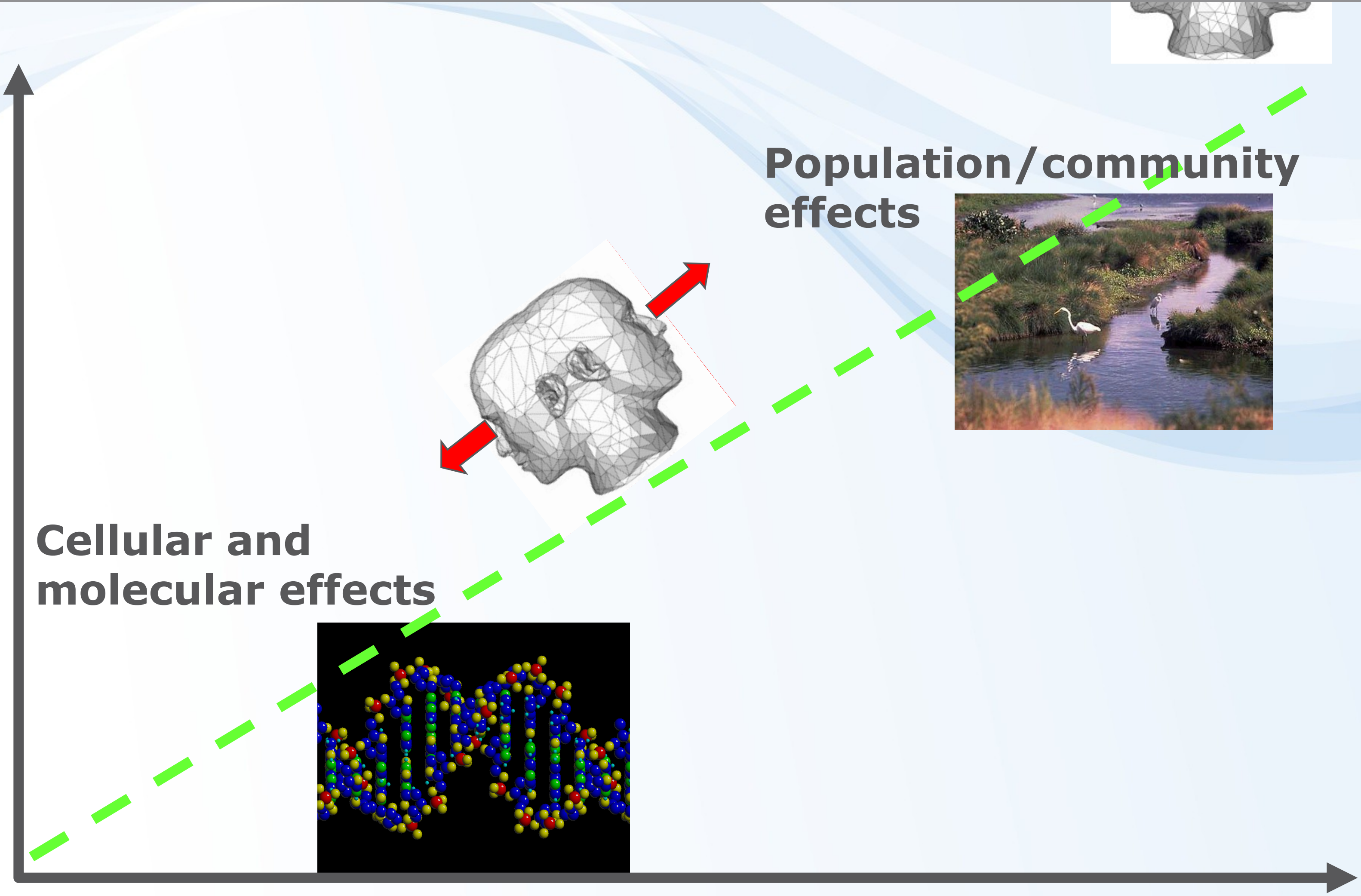
Ecological risks of chemicals



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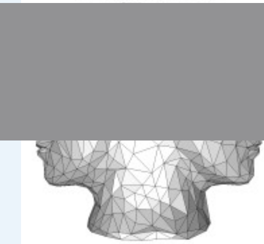
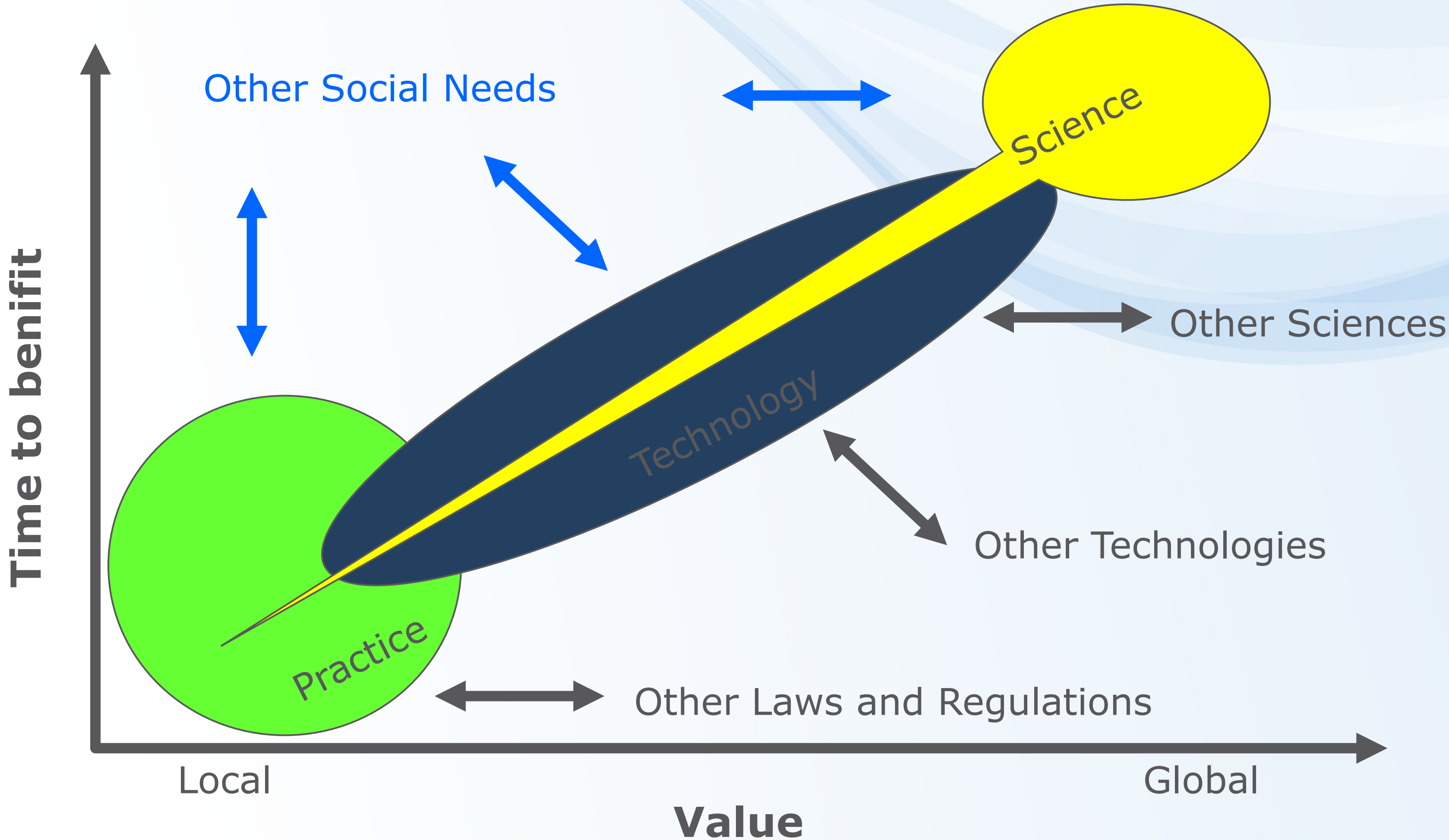
Risks vs. Benefits





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Society a balancing act …

Scientist

Closing remarks

- Ecotoxicology is exciting **science**!
- Interface: science and society
- Many opportunities
- Science is a hard work

  10% inspiration and 90% „perspiration“
- Be creative: move frontiers
- Keep the purpose in mind
- Be critical: do not accept perceptions as facts
- Speak up: you have something to say!

Introduction to ecotoxicology

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