The use of life cycle assessment (LCA) for environmental sustainability assessment of waste water treatment systems

Focus on micropollutant removal and ecotoxicity

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Publication date:
2010

Citation (APA):
Larsen, H. F. (2010). The use of life cycle assessment (LCA) for environmental sustainability assessment of waste water treatment systems: Focus on micropollutant removal and ecotoxicity [Sound/Visual production (digital)]. CRTE scientific group meeting July 6th 2010. Centre de Recherche Public Henri Tudor, Public Research Centre Henri Tudor / CRTE, 66, rue de Luxembourg, (BP 144), L-4002 Esch-sur-Alzette - Luxembourg, 01/01/2010

The use of life cycle assessment (LCA) for environmental sustainability assessment of waste water treatment systems

-focus on micropollutant removal and ecotoxicity

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Quantitative Sustainability Assessment

Presented at: CRTE scientific group meeting
July 6th 2010 Technoport, Luxembourg

(mainly based on research related to NEPTUNE; www.eu-neptune.org)

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Outline

- The environmental sustainability challenge when introducing new waste water treatment technologies (WWTT) for micropollutants removal; avoid sub optimisation
- The principle of avoided against induced impacts
- Characteristics of life cycle assessment (LCA)
- LCA environmental impact profiles: Conventional treatment
- Environmental sustainability assessment: Impact profiles for ozonation and pulverized activated carbon (PAC) addition
- The effect of including more treatment processes and more substances
- Conclusion and further research regarding the cases
- How to include ecotoxicity in life cycle impact assessment (LCIA)
- Two main approaches for effect assessment (PNEC and PAF)
- Extra: Including whole effluent toxicity on estrogenicity in LCIA

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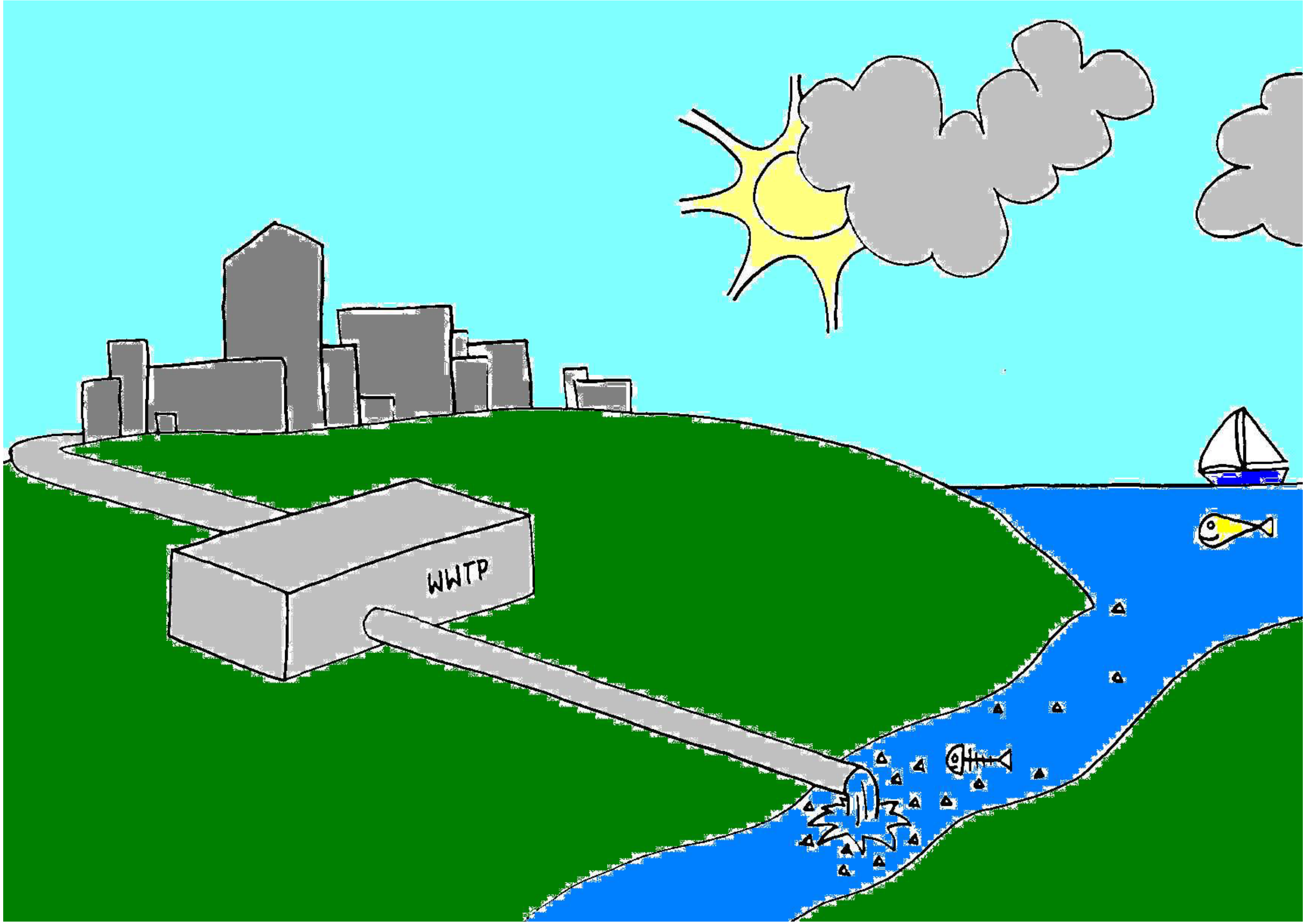

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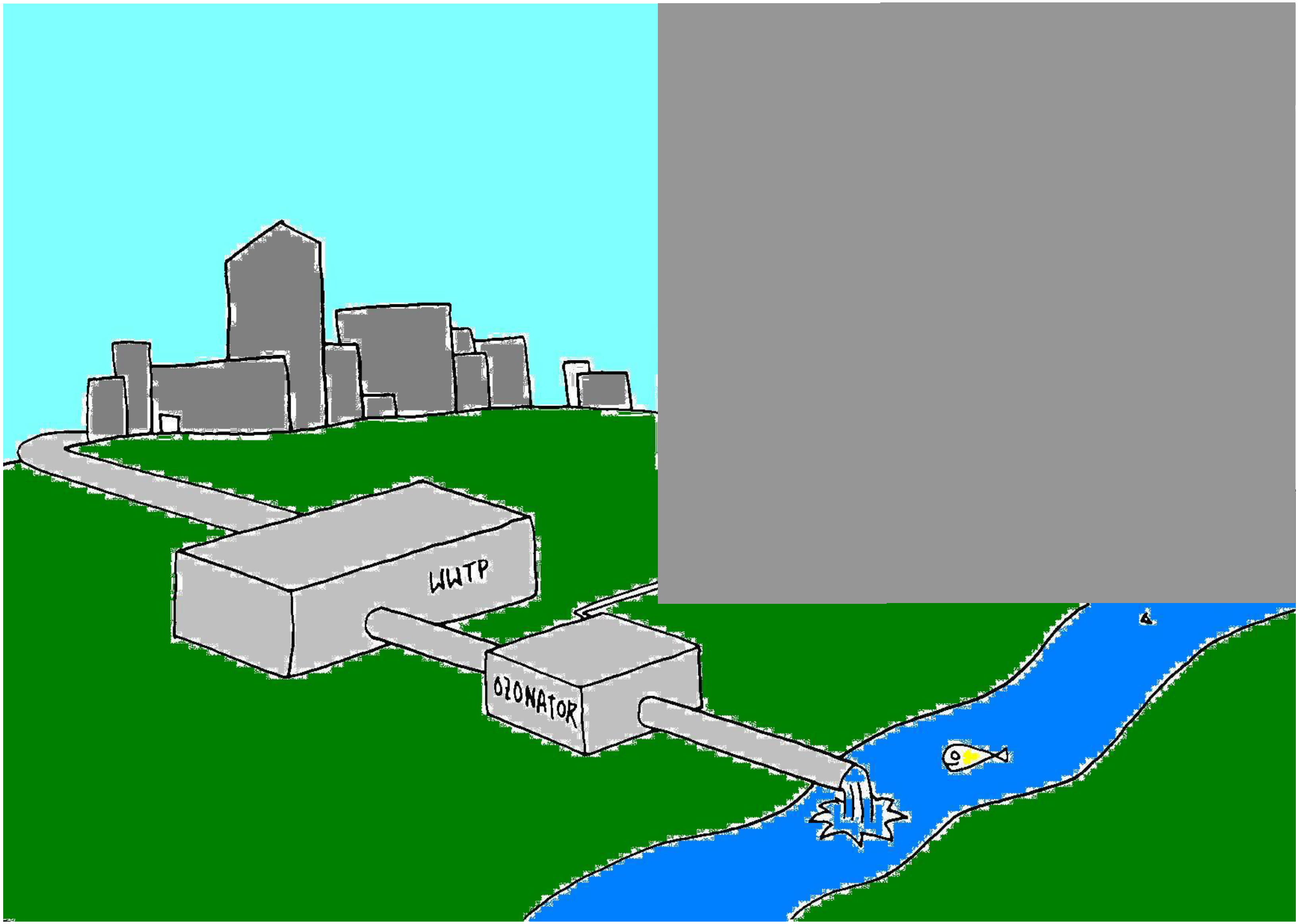

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Avoided against induced impacts

Induced impact:
(impact construction + impact operation + impact disposal)

PLANT CONSTRUCTION
Materials (kg)
Life time of plant (years)

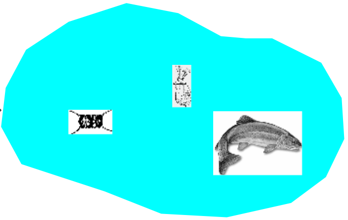
PLANT OPERATION
Energy (kWh/d)
Chemicals (kg/d)
Emissions (kg/d)

PLANT DISPOSAL
Materials (kg)
(disposal ways)

MWWTP → (m^3/d) →

WWTT
Wetlands
Sand filtration
Activated carbon
Ozonation

→ (m^3/d) →



Sludge disposal or handling

INFLUENT

Substance	Concentration (mg/m^3)
4-MBC	23
DEHP	50
Ibuprofen	10
DeBDE	8
Trimethoprim	2
-	-
-	-

EFFLUENT

Substance	Concentration (mg/m^3)
4-MBC	5
DEHP	30
Ibuprofen	2
DeBDE	1
Trimethoprim	1
-	-
-	-

Avoided impact:
(impact influent ÷ impact effluent)

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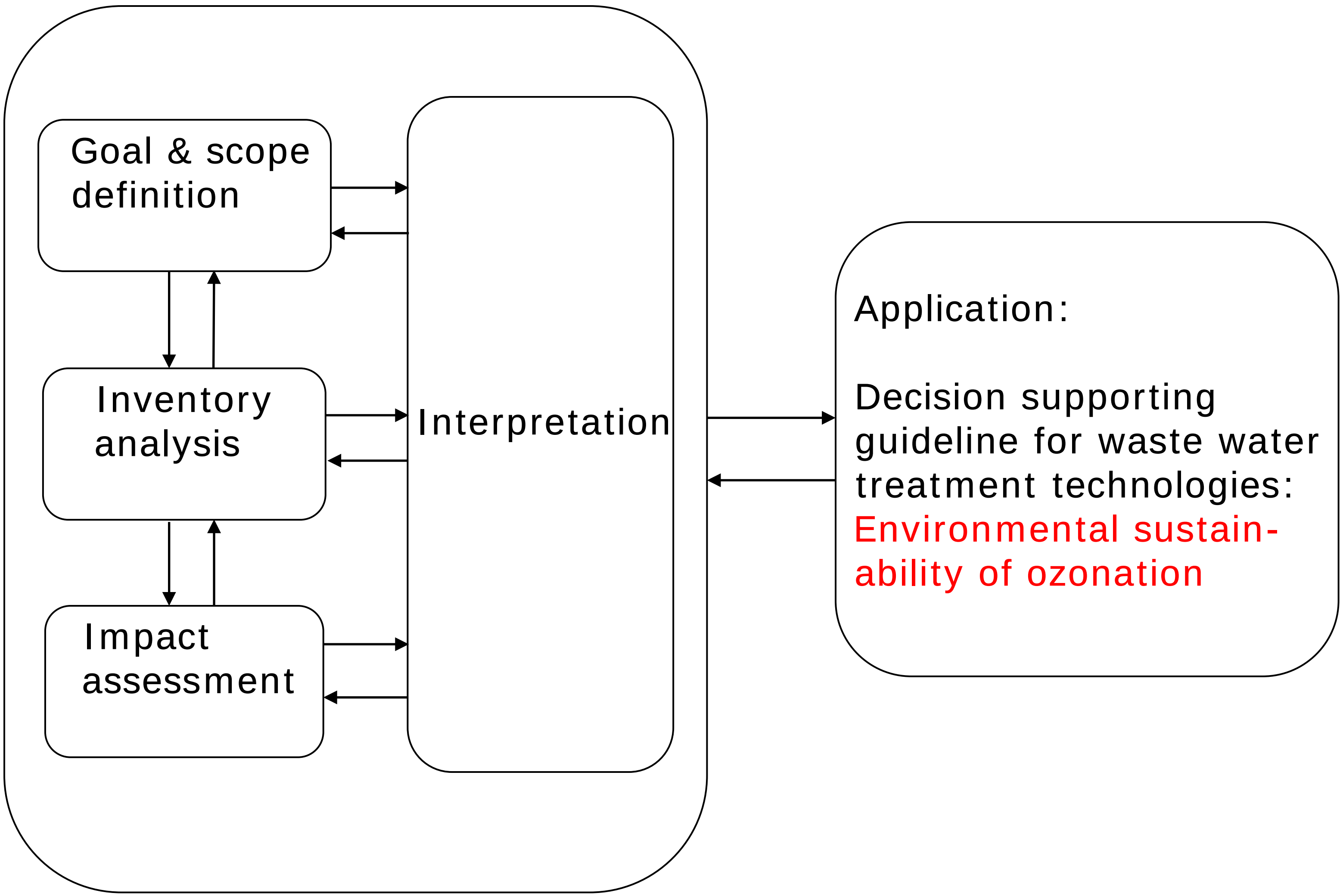
Elements of life cycle assessment (LCA)



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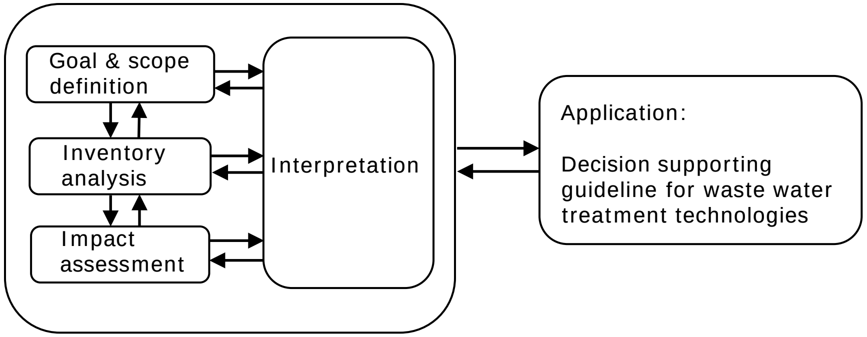
Characteristics of LCA



- A decision supporting tool
- Focus on services typically represented by a product (the “functional unit”, fu). In this case: Treatment of one cubic meter waste water (all impacts related to this unit)
- Comparative (relative statements). In this case: Comparing induced impacts with avoided impacts regarding ozonation and PAC addition
- Holistic perspective
  - life cycle from cradle to grave
  - all relevant potential environmental impacts or damages to ‘areas of protection’. In this case:
    - Global warming
    - Nutrient enrichment (eutrofication)
    - Acidification
    - Ecotoxicity
    - ……..
- Aggregation over time and space
  - life cycle is global
  - life cycle may span over decades or even centuries

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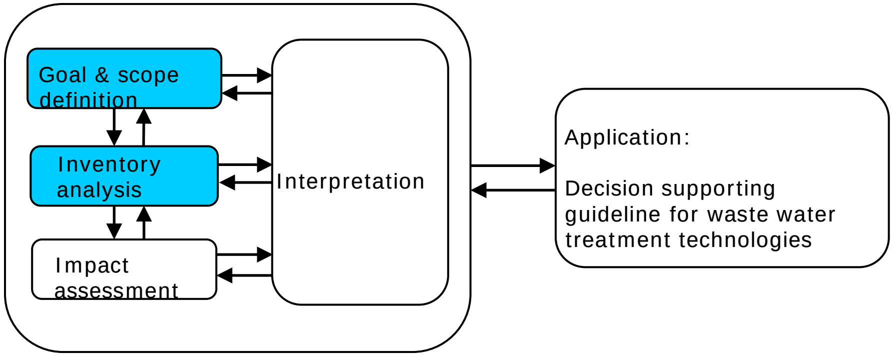
Goal and scope, and inventory



- Goal
  - An assessment of the environmental sustainability of the WWTT
- Scope
  - Comparative LCA: Induced impacts as compared to avoided impacts
  - Functional Unit(s): 1 m^3 secondary MWWTP effluent water with well defined composition as regards content of micropollutants and more
- Inventory
  - collecting in- and output data for all processes

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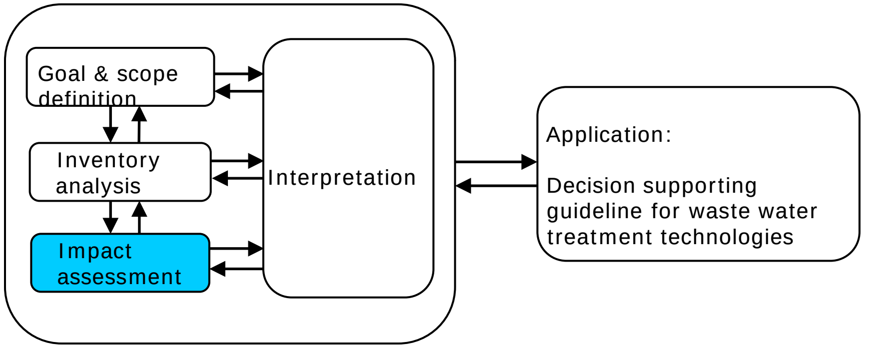
Life cycle impact assessment (LCIA)



Classification: *"What does this emission contribute to?"*

- Assignment of emissions to impact categories according to their potential effects
  - Global warming (e.g. CO_2, CH_4)
  - Acidification (e.g. NO_2, SO_3)
  - Ecotoxicity (e.g. pharmaceuticals, heavy metals)
  - Human toxicity (e.g. benzene, PAH's)
  - ………..

Characterisation: *"How much may it contribute?"*

- Quantification of contributions to the different impact categories by estimating impact potentials, IPs (e.g. multiplying the characterisation factors (CFs) for each chemical by the emitted amount (Q) per functional unit (fu):

$$IP = Q*CF$$

- Example (GWP):

Substance	Q (g/fu)	CF (g CO_2-eq/g)	IP (g CO_2-eq/fu)
Carbon dioxid (CO_2)	250	1	250
Methane (CH_4)	10	25	250
Total			500

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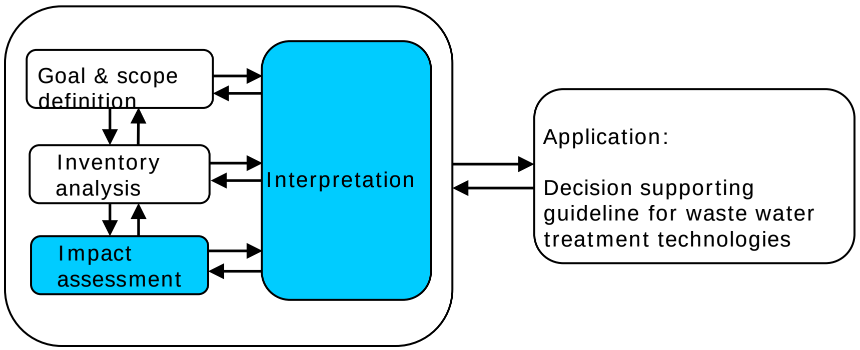
Life cycle impact assessment (LCIA) and interpretation



Normalisation: *"Is that much?"*

- Expression of the impact potentials relative to a reference situation (person-equivalence, PE), e.g. normalisation reference (NR) for GWP: 8,700 kg CO_2-eq/pers/year. The normalised impact potential (nIP):

nIP = IP/NR

Impact category	NR (kg CO_2-eq/pers/year)	IP/fu (kg CO_2-eq/fu)	nIP (mPE/fu)
Global warming (GWP)	8700	0,5	0,057

Valuation: *"Is it important?"*

- Ranking, grouping or assignment of weights (weighting factors, WFs) to the different impact potentials (EDIP: political reduction targets), e.g. for global warming a targeted 10 years reduction of 20% => WF=1/(1-0.2) = 1.3. The weighted impact potential (wIP):

wIP = nIP*WF

Impact category	WF	nIP (mPE/fu)	wIP (mPET/fu)
Global warming (GWP)	1,3	0,057	0,074

Interpretation: *"Which alternative is better and what determines it?"*

- E.g. is ozonation worth it in an environmental sustainability context or should we avoid it?

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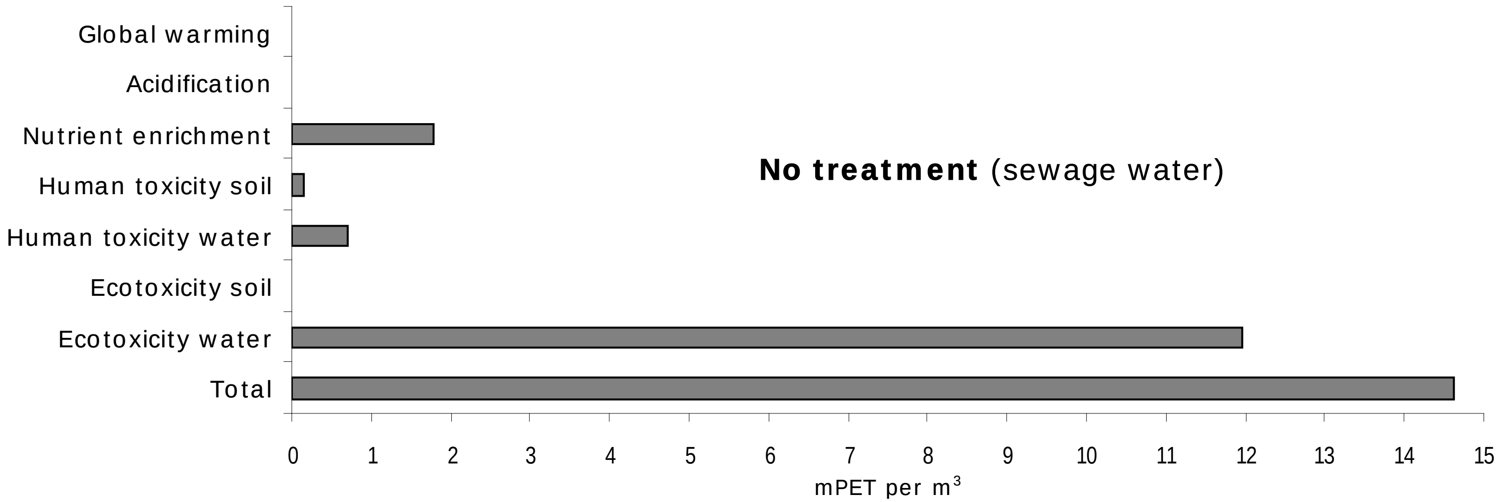
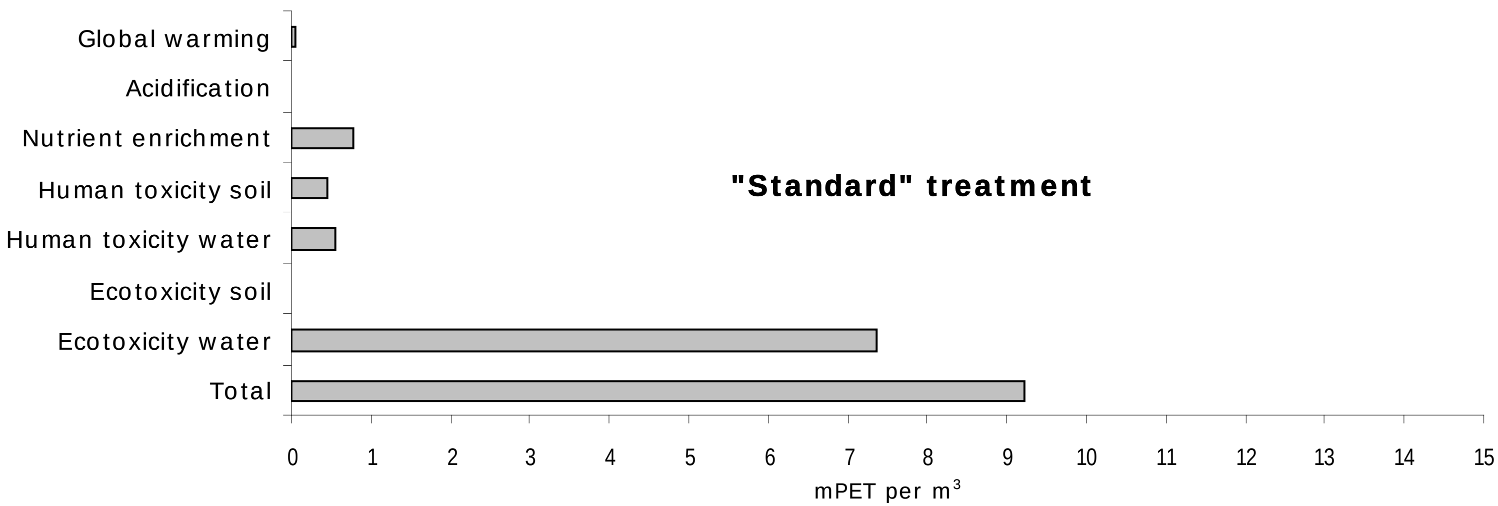
Environmental impact profiles

(25 substances)





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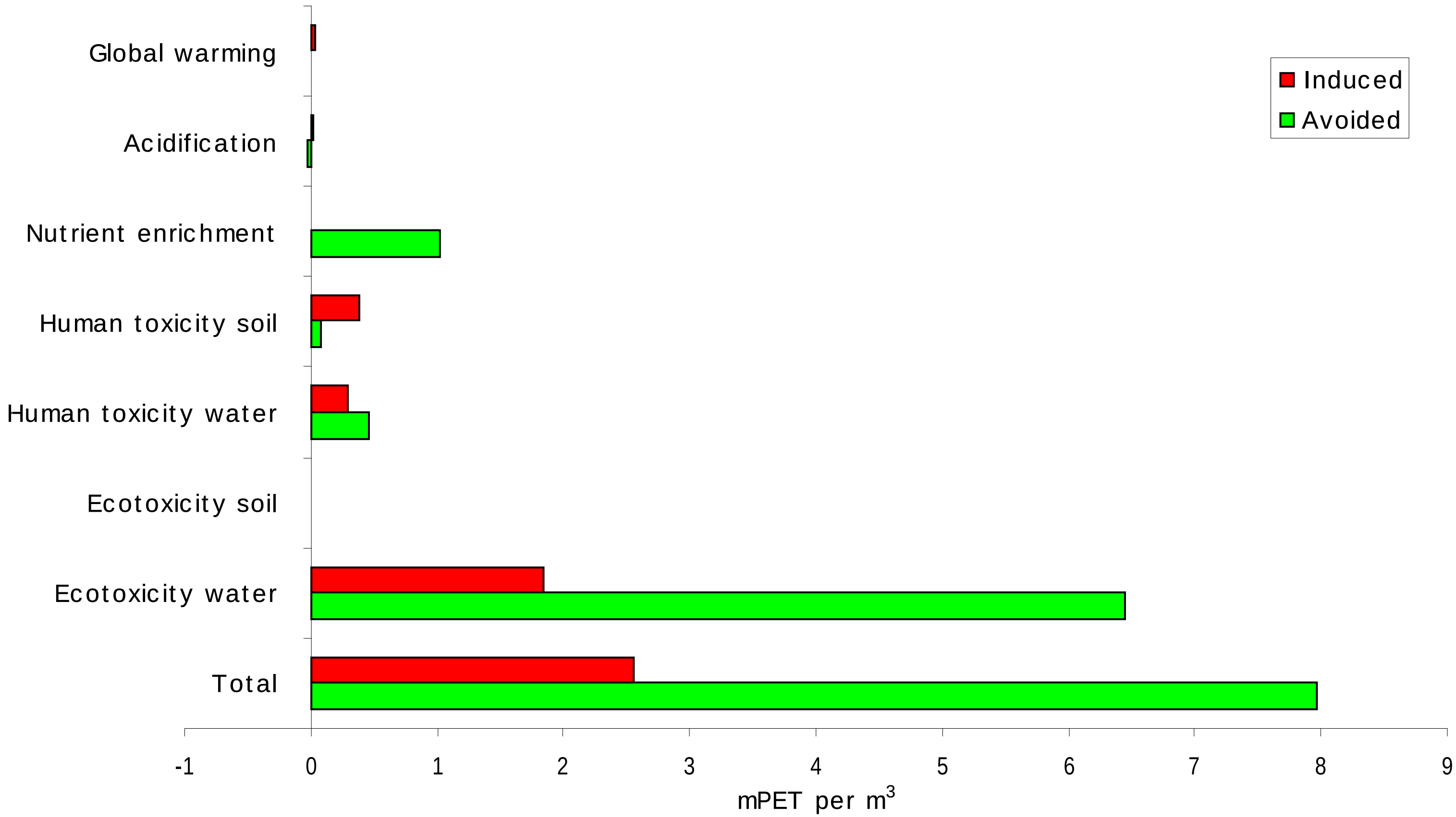
Avoided⇔induced: "Standard" treatment

(25 substances)



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Environmental sustainability assessment

LCA environmental impact profiles for ozonation and pulverized activated carbon (PAC) addition

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Ecotoxicity CFs and characteristics of incoming water (sec. effluent) for ozonation and PAC addition

(functional inventory)

	Inlet conc. (ng/L)	Removal rate (3,2 g O_3/m^3)*	Removal rate (20 g PAC/m^3)	PNEC (µg/L)	Conservative RA based PNEC (µg/L)	CF (m^3/kg)	Conservative CF (m^3/kg)
Atenolol	1600	0,80	n.d.	330		2,99E+03	
Bezafibrat	82	0,62	0,38	2,3		4,35E+05	
Carbamazepin	710	1,00	0,79	2,5	0,5	4,00E+05	2,00E+06
Clarithromycin	170	0,96	0,57	0,31		3,23E+06	
Clindamycin	34	0,95	n.d.	8,5		1,17E+05	
Clofibrinsäure	72	0,66	0,42	25	5	4,07E+04	2,00E+05
Diatrizoate	1800	0,00	0,12	11000		9,09E+01	
Diclofenac	1500	1,00	0,42	100	0,1	1,00E+04	1,00E+07
Erythromycin	99	0,80	0,50	0,20	0,02	5,00E+06	5,00E+07
Ibuprofen	91	0,00	0,21	96	3	5,21E+03	1,67E+05
Iohexol	190	0,00	0,00	7400000		1,36E-01	
Iopamidol	1100	0,24	0,90	380000		2,65E+00	
Iopromid	1800	0,26	0,00	100000		1,00E+01	
Metoprolol	410	0,88	n.d.	76	7,3	1,32E+04	1,37E+05
Naproxen	230	0,99	0,00	190		5,18E+03	
NDMA (N-nitrosodimethylamin)	57	-1,71	n.d.	40		2,50E+04	
Primidon	170	0,62	0,48	1400		6,94E+02	
Propanolol	95	0,90	n.d.	0,050		2,00E+07	
Roxithromycin	50	0,82	0,53	2,8		3,56E+05	
Sotalol	430	0,98	n.d.	300		3,33E+03	
Sulfamethoxazol	500	0,95	0,43	0,59	0,15	1,69E+06	6,67E+06
Trimethoprim	130	0,98	0,50	800		1,25E+03	
(*data on removal rates from MicroPoll; personal communication with Juliane Hollender)							

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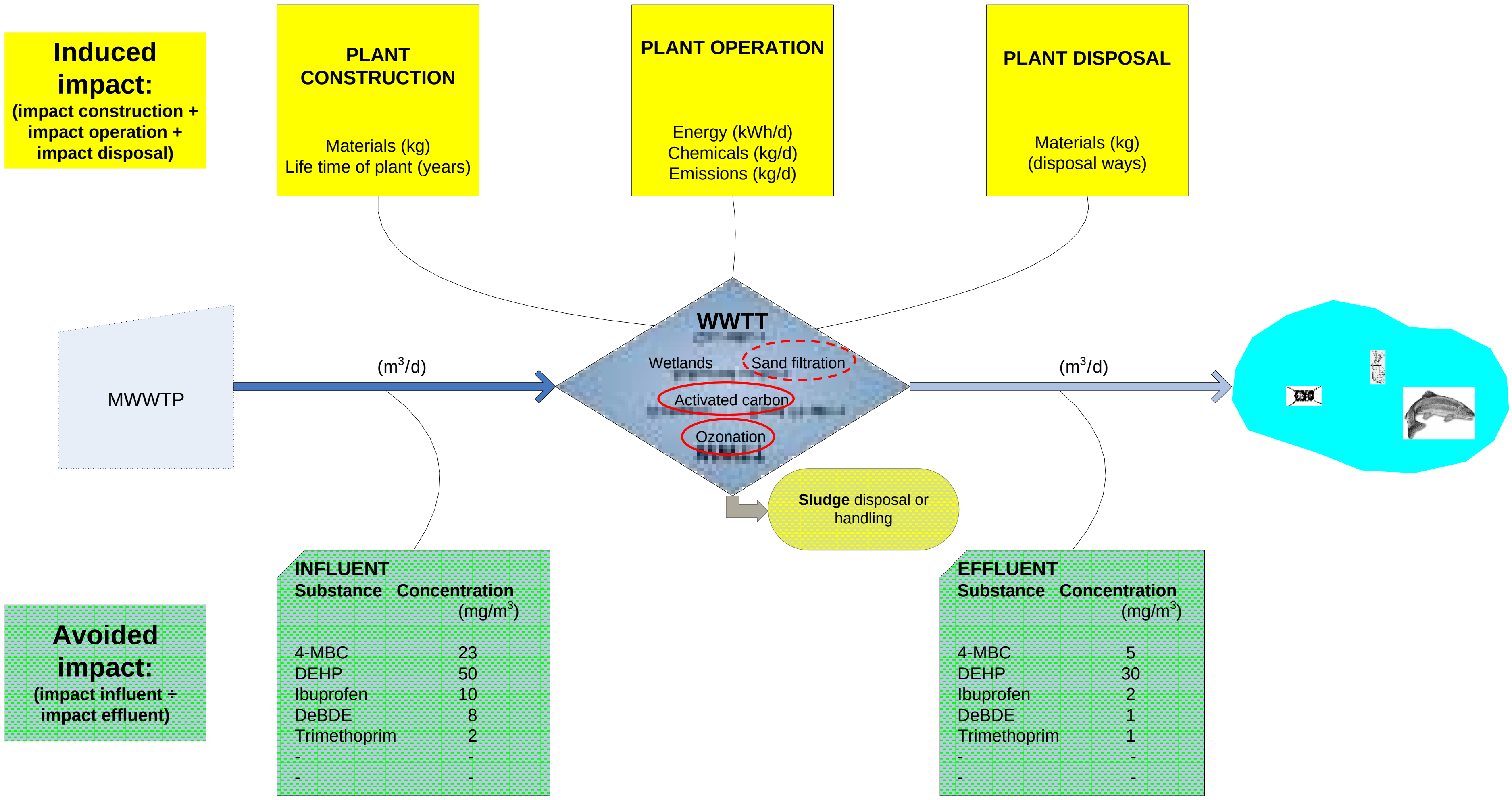
Avoided against induced impacts



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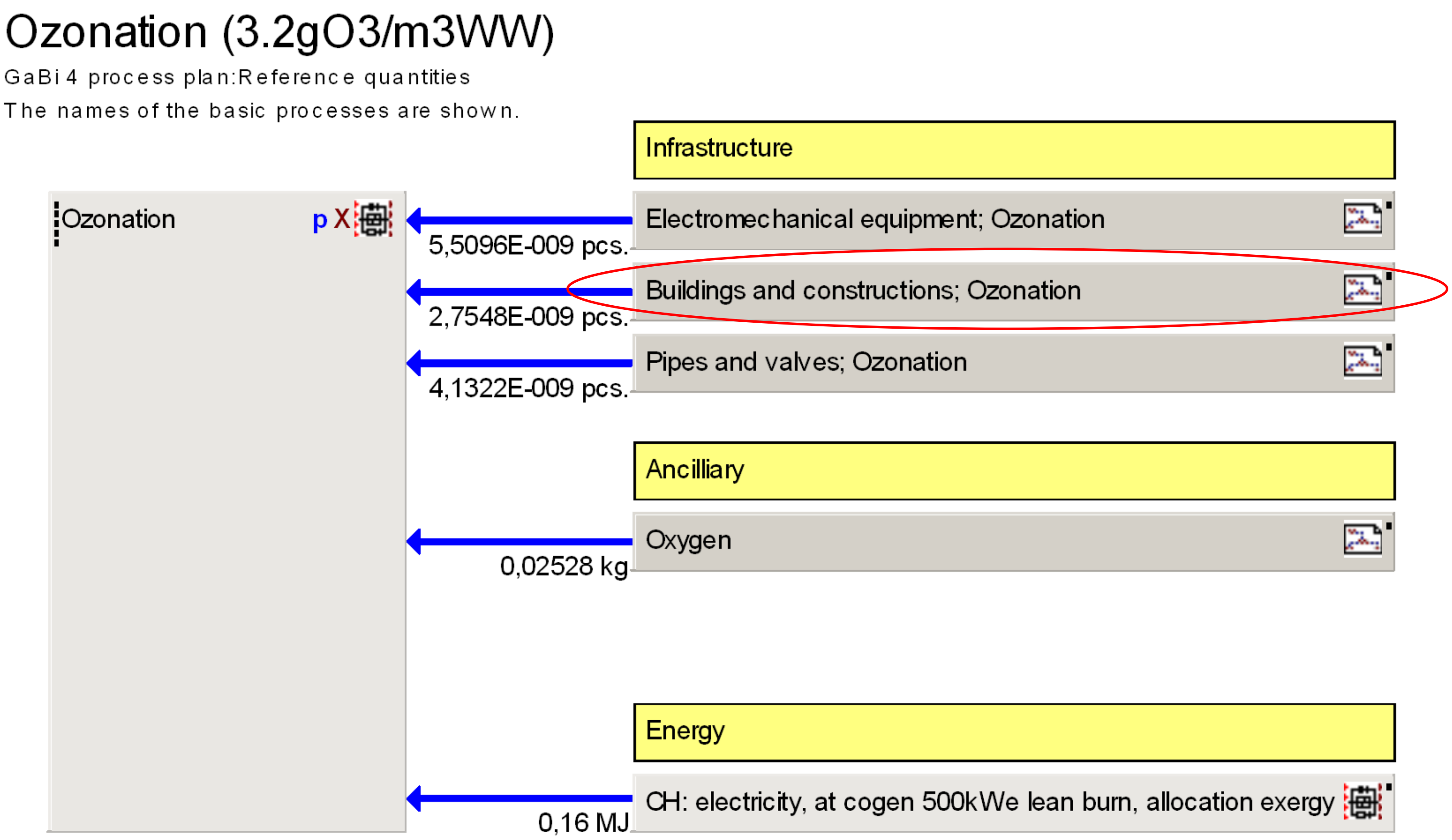
Modelling LCA on ozonation; Main plan
(physical inventory)



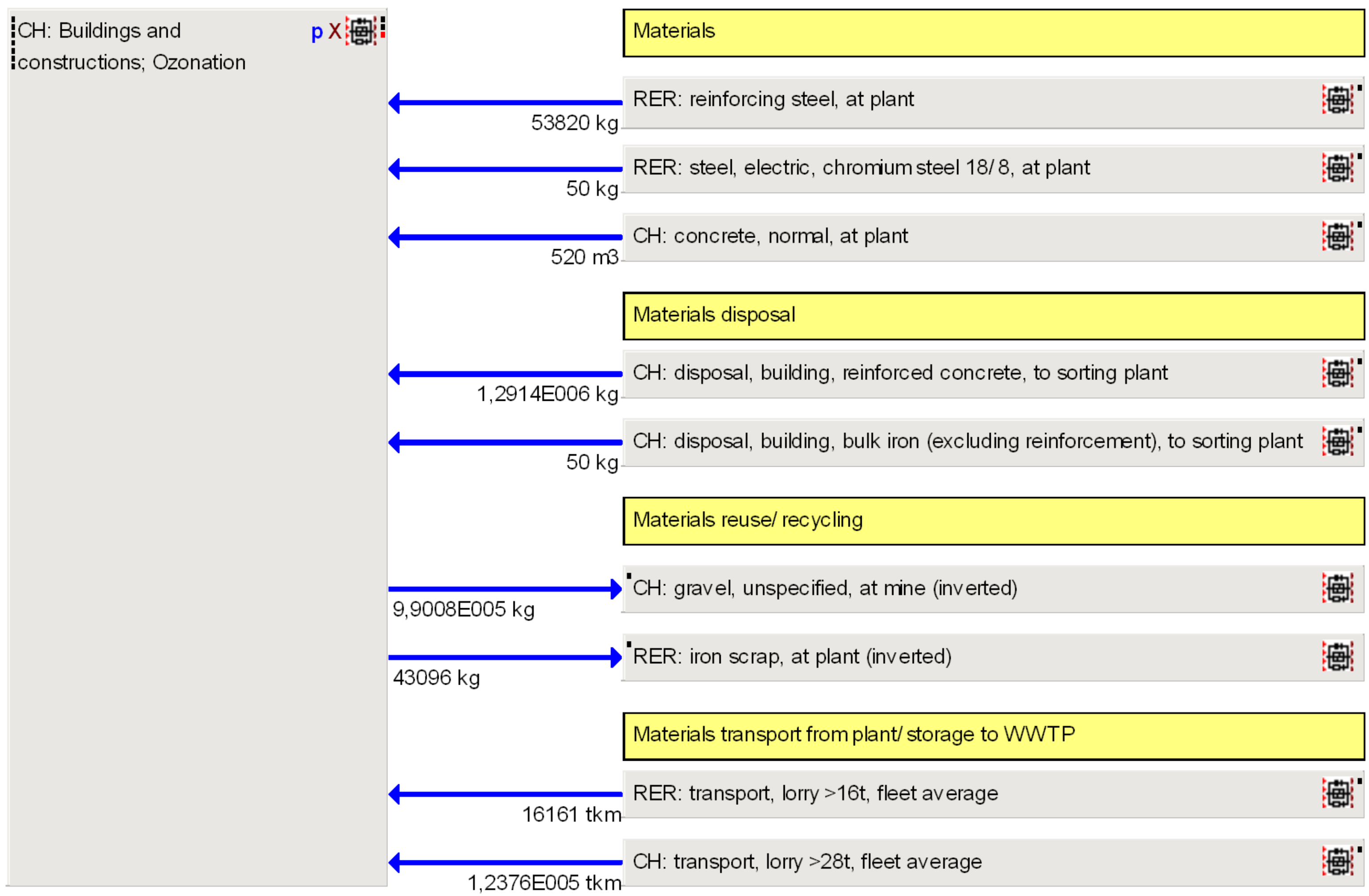
Modelling LCA on ozonation; Sub-plan

(physical inventory)

Buildings and constructions; Ozonation

GaBi 4 process plan:Reference quantities

The names of the basic processes are shown.



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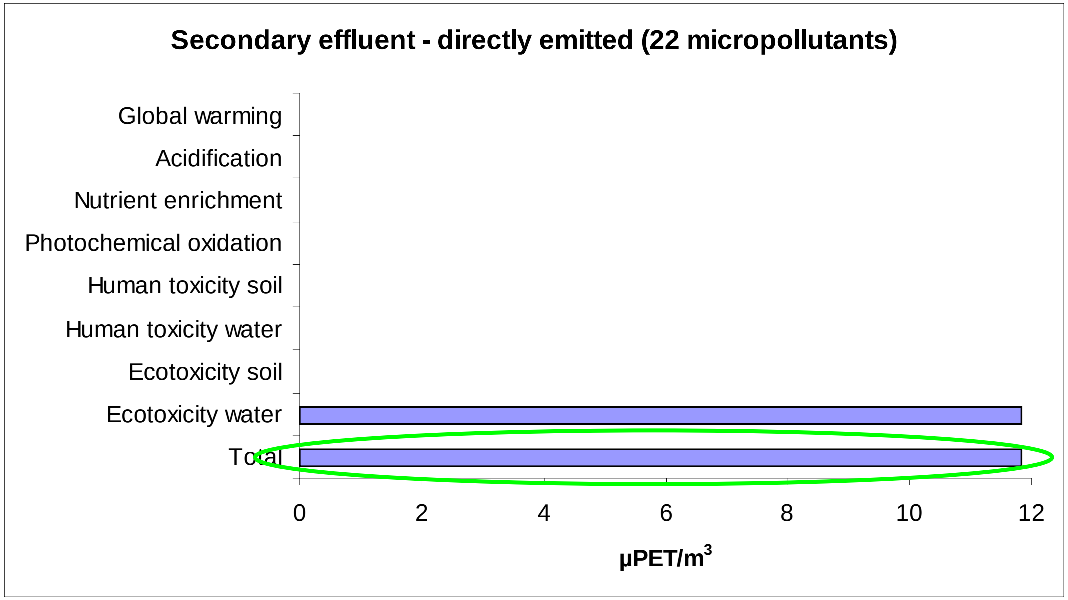
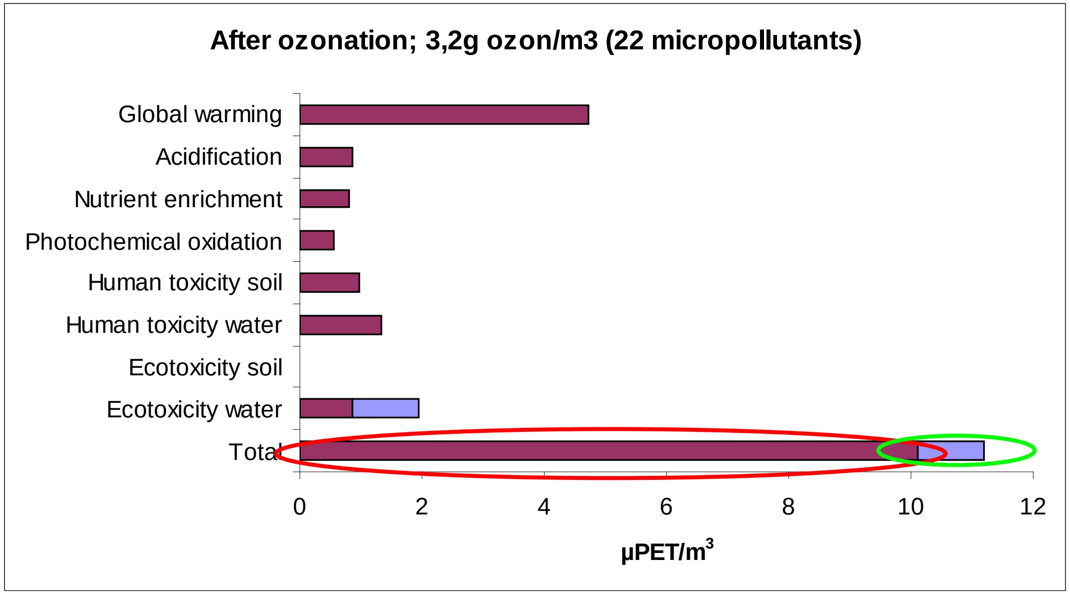
LCA impact profiles

(weighting factor = 1 for all impact categories)
(non-conservative ecotox CFs)





Avoided: 10,7 µPET/m3

Induced: 10,1 µPET/m3

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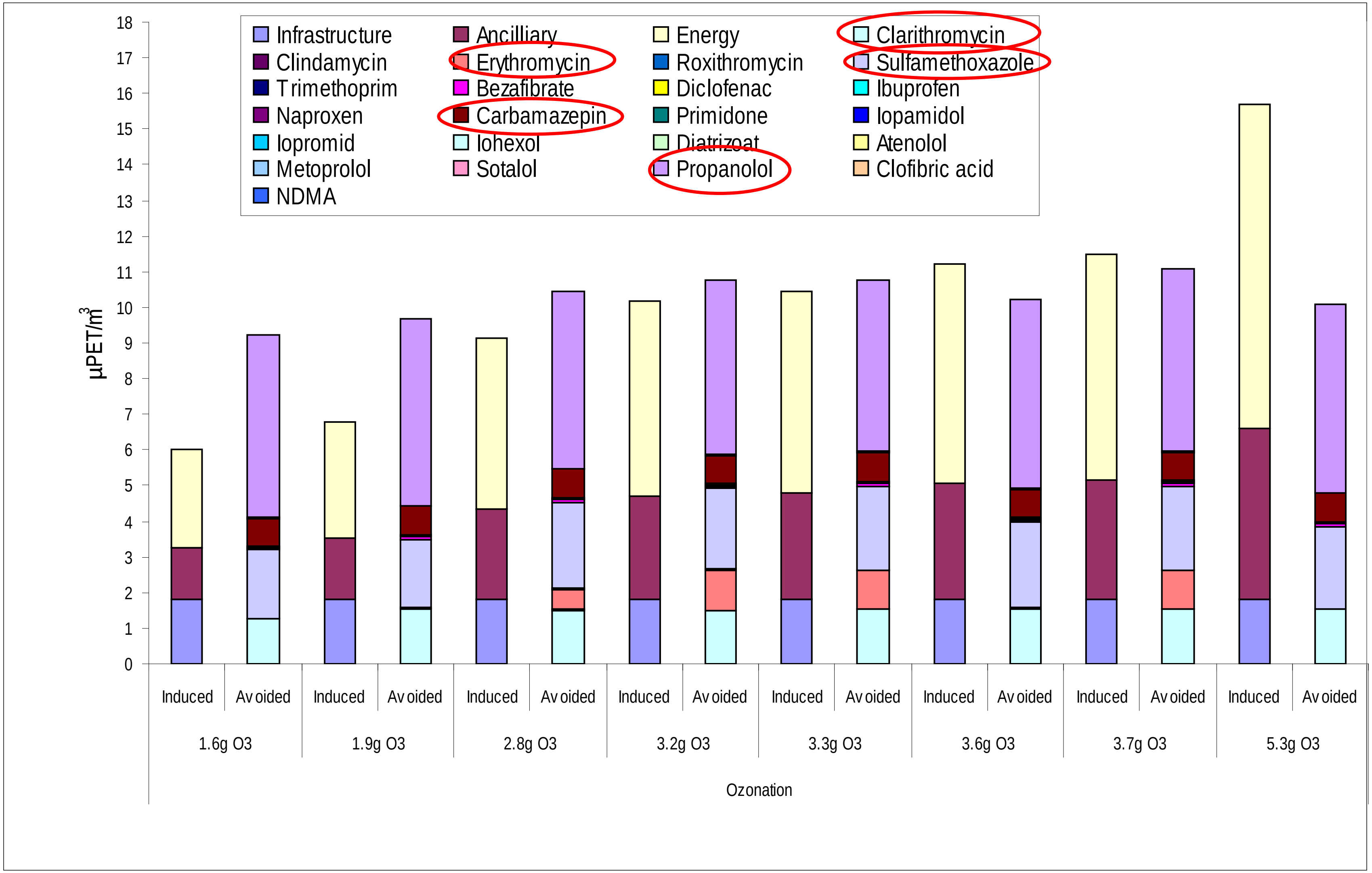
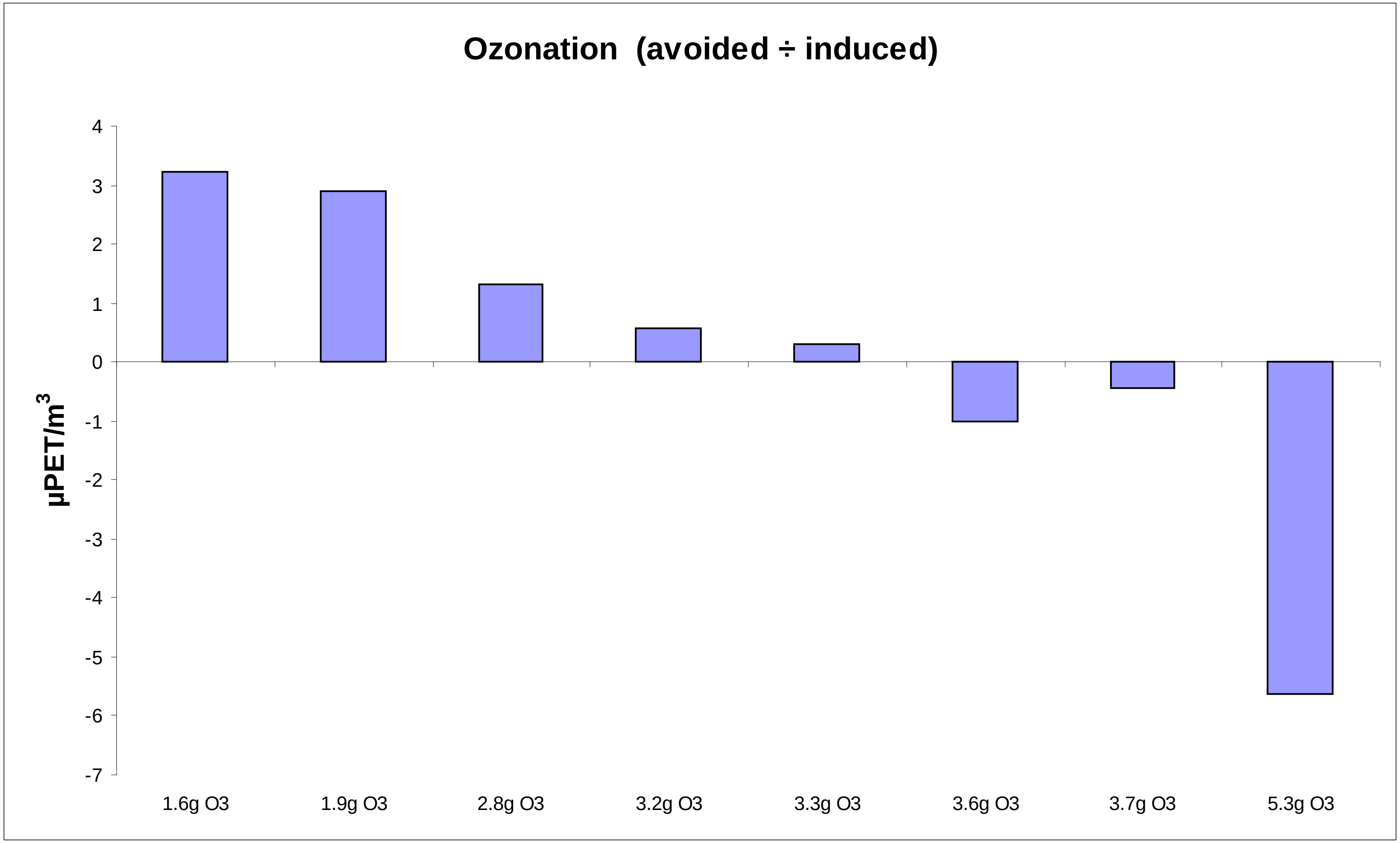
Environmental sustainability profiles; ozonation

(22 micropollutants; weighting factor = 1 for all impact categories)



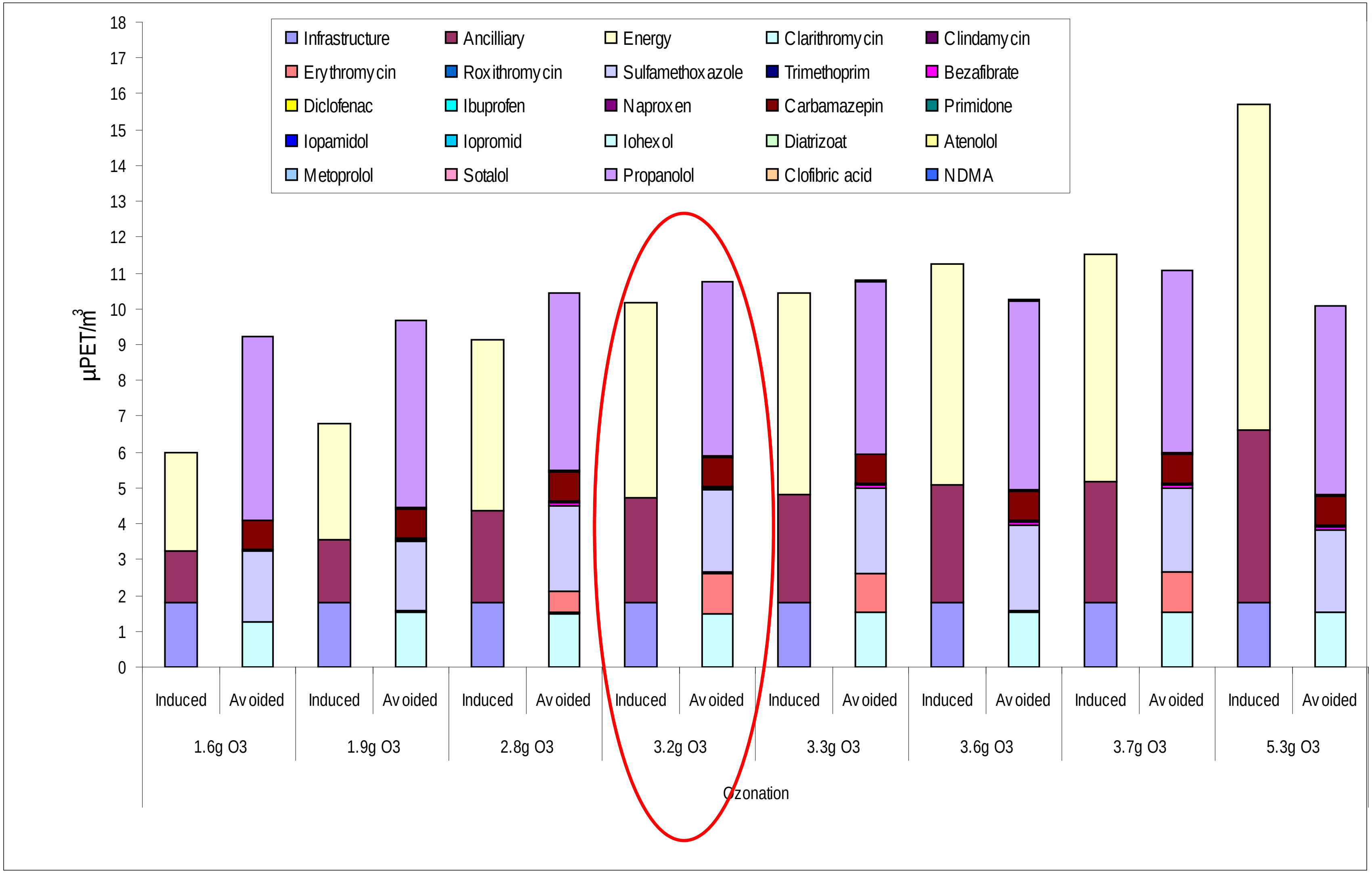
Environmental sustainability profiles; ozonation

(22 micropollutants; weighting factor = 1 for all impact categories)



Environmental sustainability profiles; ozonation

(22 micropollutants; weighting factor = 1 for all impact categories)



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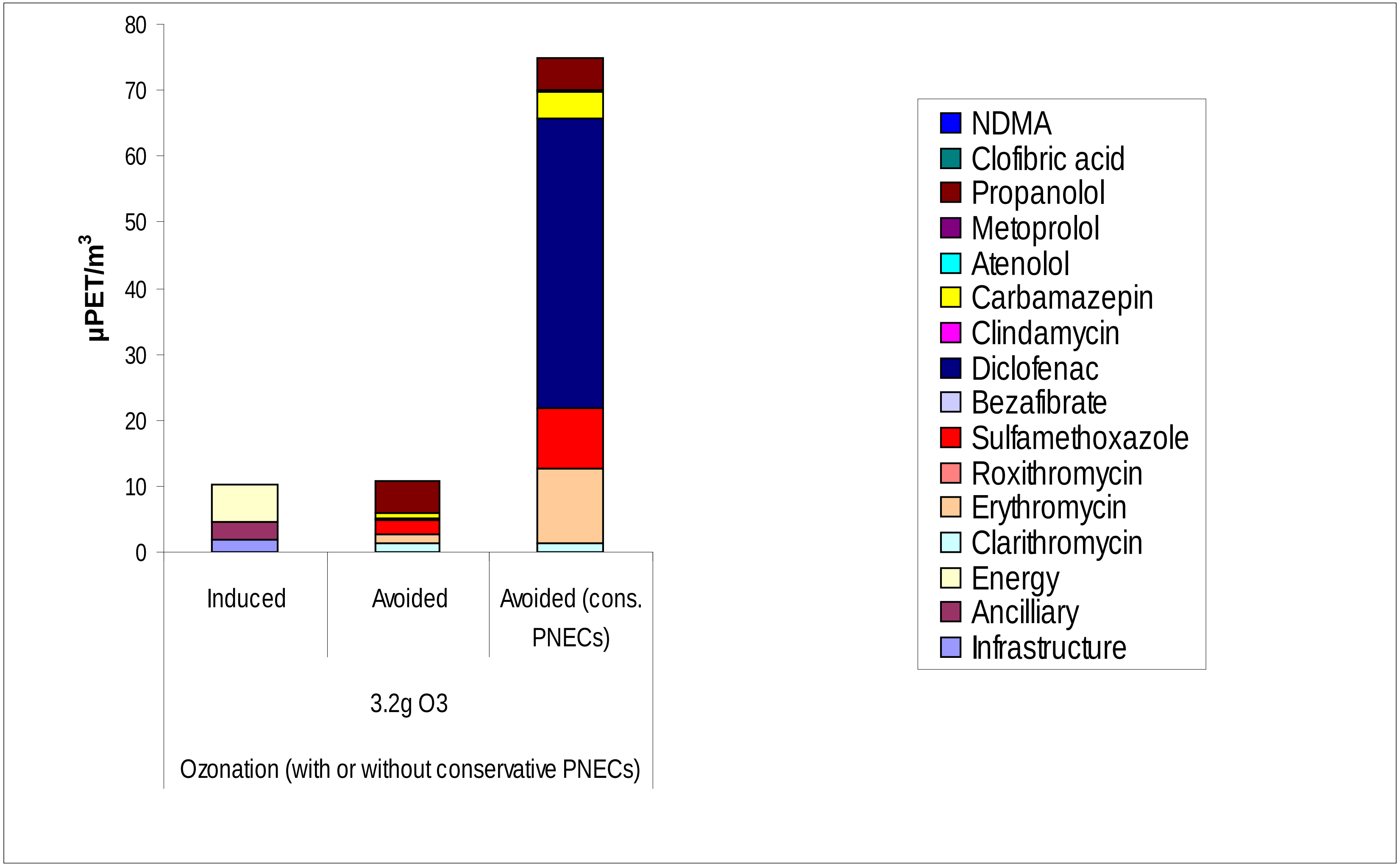
Environmental sustainability profiles; ozonation

(22 micropollutants (only significant ones shown); weighting factor = 1 for all impact categories)



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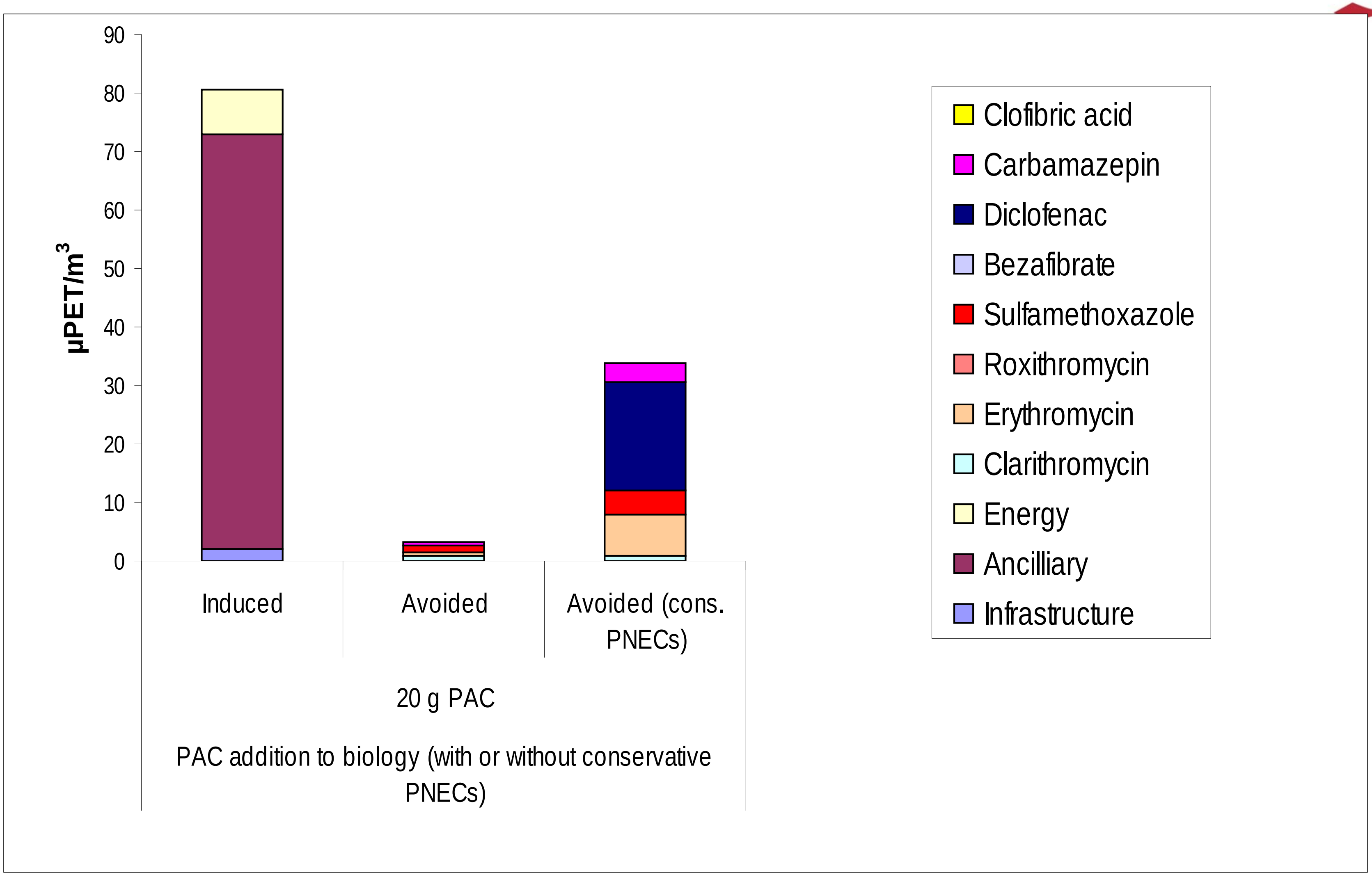
Environmental sustainability profiles; PAC addition to biology

(16 micropollutants (only significant ones shown); weighting factor = 1 for all impact categories)



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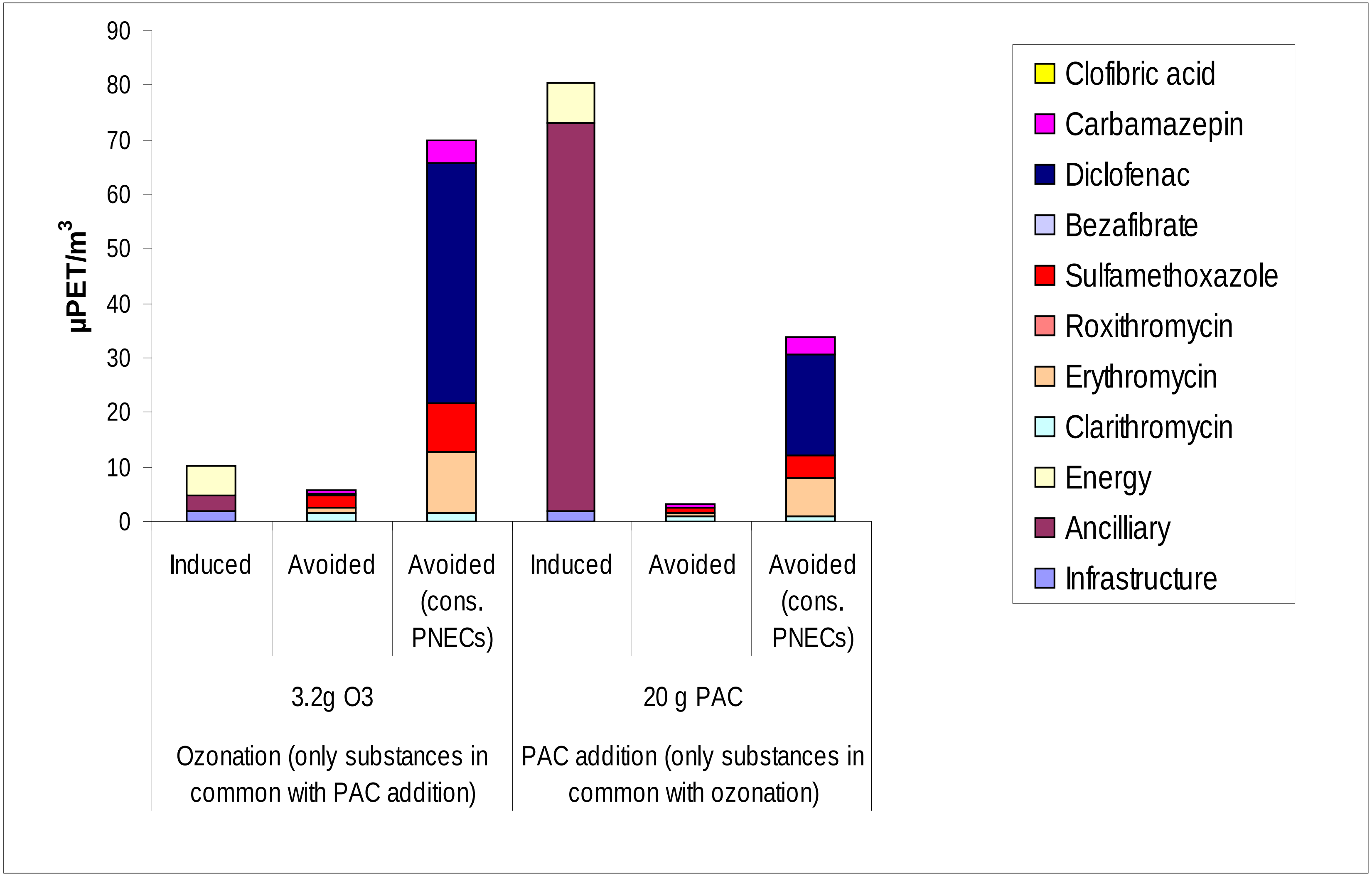
Environmental sustainability profiles; Ozonation as compared to PAC addition to biology

(16 micropollutants (only significant ones shown); weighting factor = 1 for all impact categories)



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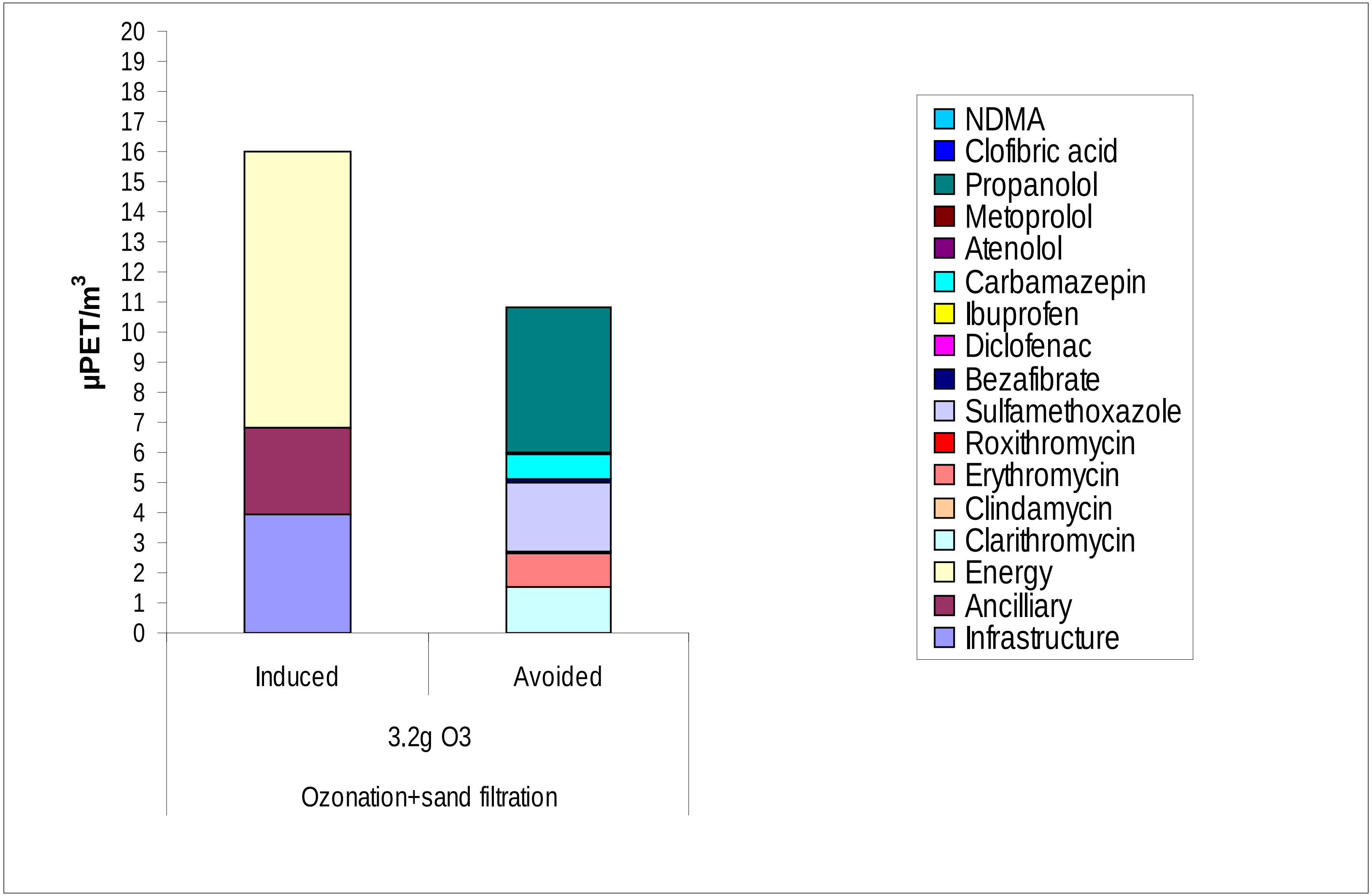
Environmental sustainability profiles; ozonation + sand filtration

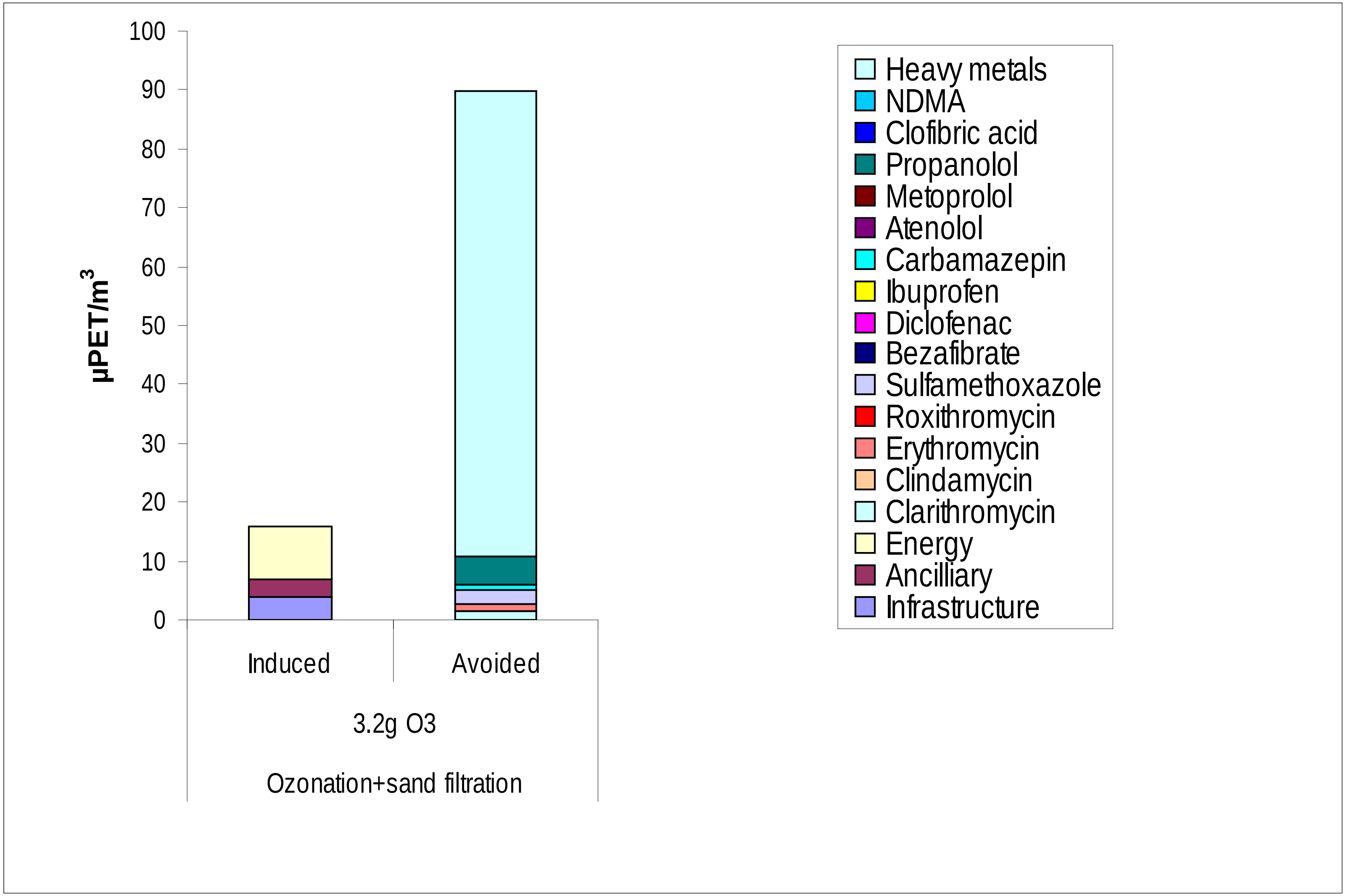
removal of aldehydes and WET **(22 micropollutants, (only significant ones shown)**
(weighting factor = 1 for all impact categories)



Environmental sustainability profiles; ozonation + sand filtration

(Including removal of metals in sand filter)

(31 micropollutants (only significant ones shown); weighting factor = 1 for all impact categories)



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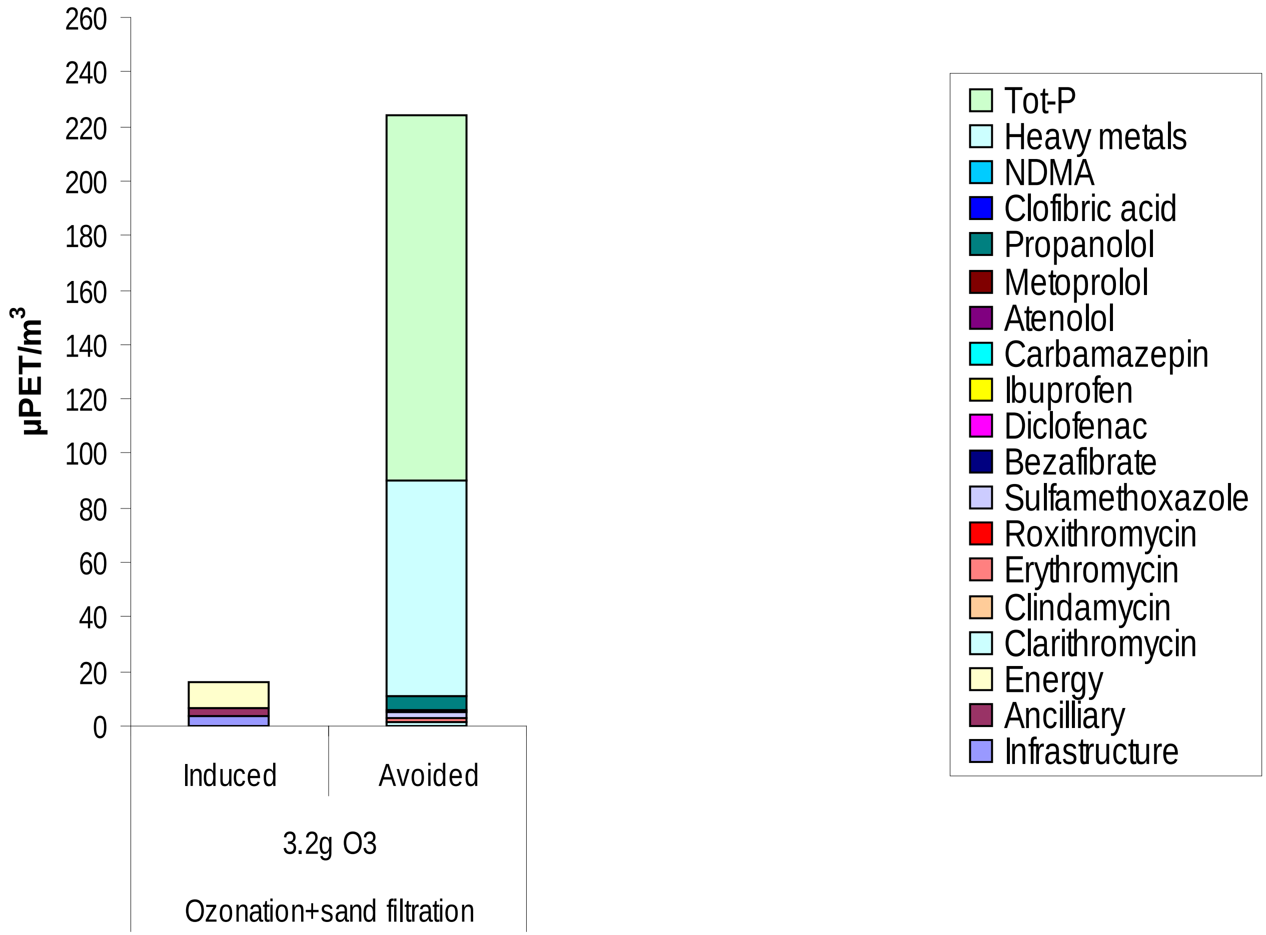
Environmental sustainability profiles; ozonation + sand filtration
(including both metal and phosphorus removal)

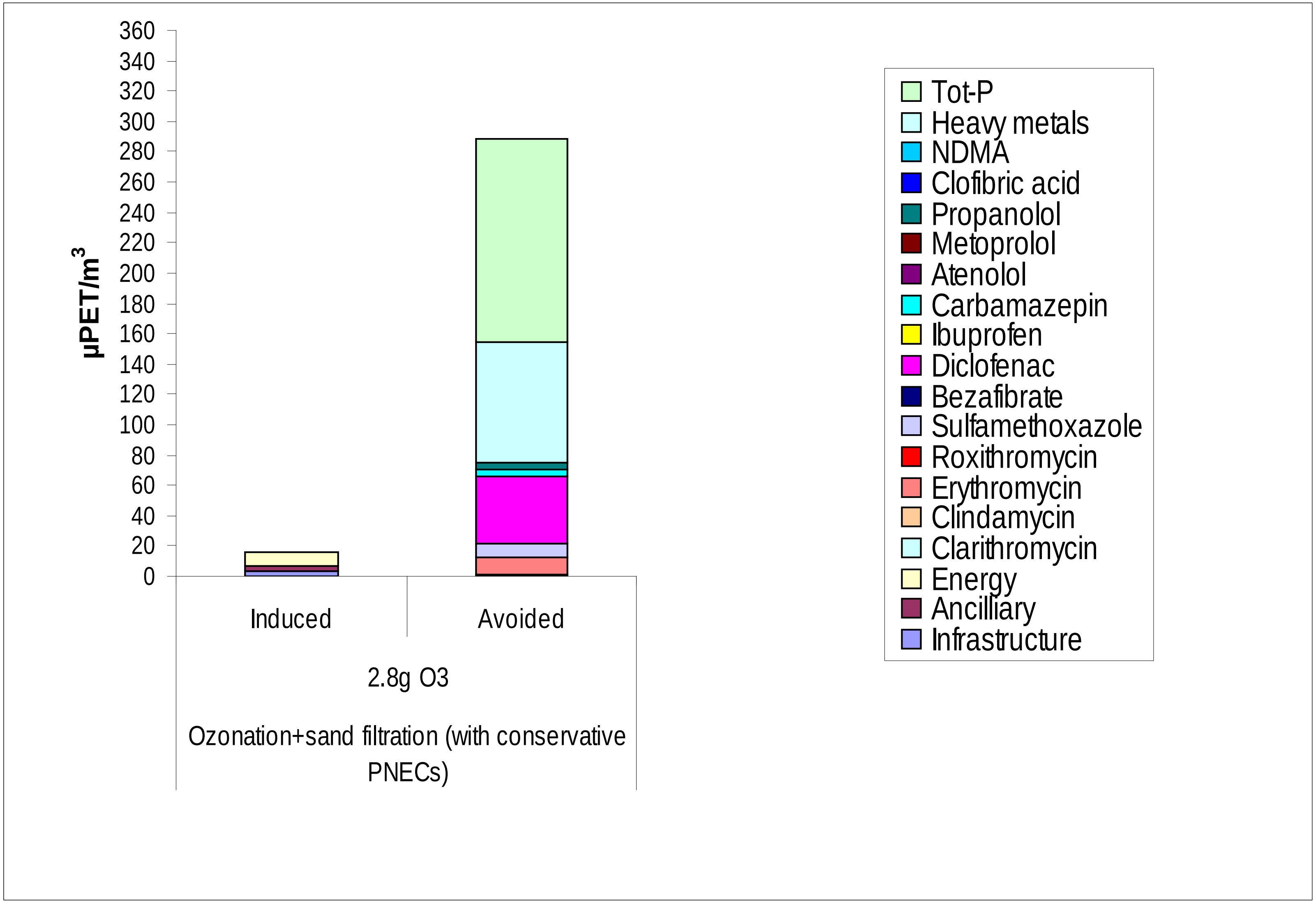
(31 micropollutants + P (only significant ones shown); weighting factor = 1 for all impact categories)

	Secondary effluent	After sandfiltration	Removal rate
Tot-P (mg/l)	0,8	0,3	0,625



Environmental sustainability profiles; ozonation + sand filtration

(31 micropollutants + P (only significant ones shown); weighting factor = 1 for all impact categories) (including CFs based on conservative PNECs)



Cases: Conclusions and further research

Conclusions

- ✓ Based on the given assumptions and scoping results indicate that ozonation used for removal of organic micropollutants most probably is environmentally sustainable, i.e. avoided potential impacts are higher than induced potential impacts
- ✓ The environmental sustainability profile for PAC addition to biology is far from as good as for ozonation. However, by including more micropollutants in the analysis it might improve significantly
- ✓ Including sand filtration (removal of heavy metals and tot-P) - and hereby solving a problem with whole effluent toxicity and aldehydes regarding ozonation - significantly improves the sustainability profile
- ✓ Focusing on global warming a weighting factor of at least 20 – 40 is needed in order to reach a break-even between induced and avoided impacts for ozonation combined with sand filtration

Improvements/further research

- ❖ Including more micropollutants
- ❖ Including new methodology on the ecotoxicity impact category (average toxicity, PAF)
- ❖ Including economy (cost-efficiency)
- ❖ Sustainability approach (avoided - induced) also relevant for treatment of drinking water – but more focus on human health (e.g. Softening: Carries, osteosarkom…)

The impact category on aquatic ecotoxicity

How to include aquatic ecotoxicity in LCIA – two approaches: PNEC and PAF

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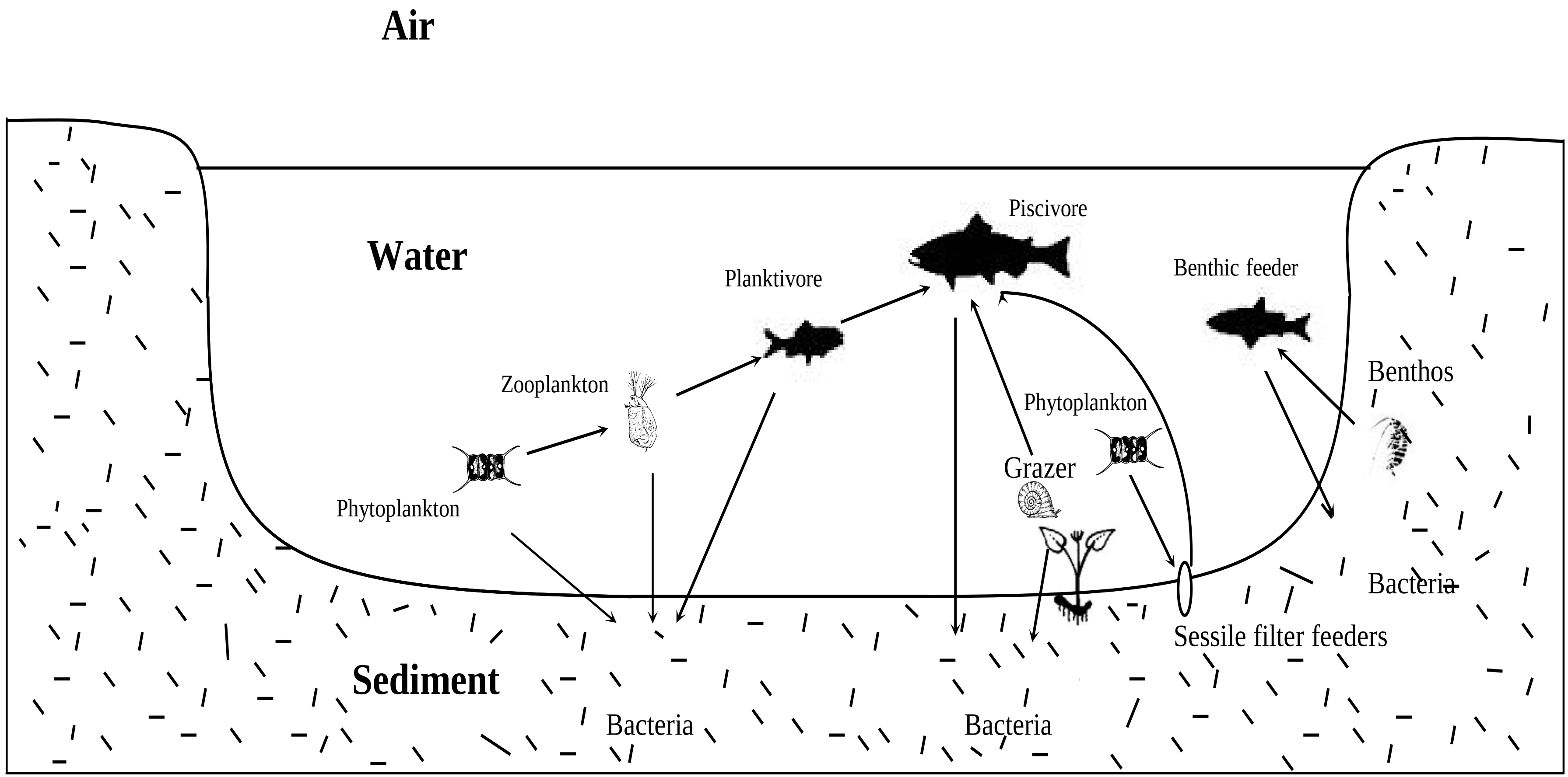
Ecotoxicity/ecosystems
What is it we want to protect?



Adapted/modified from Chapman et al. (2003), with permission

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Characteristics and constraints of ecotoxicity impact assessment in LCIA

- A general condition for the LCIA models is that the impact potentials must be additive (e.g. critical dilution volume, PAF).
- In contrast to (tiered) risk assessment (RA) the impact potentials shall be a best estimate, i.e. not a conservative estimate.
- In LCIA we assess potential impacts not actual impacts
- Emission of a toxicant mapped in a life-cycle inventory (LCI) is regarded as a single pulse without time duration, and therefore time and space are integrated in the assessment giving further restrictions to the modelling.
- In ordinary LCAs the location of the processes which release toxicants to the environment is usually not precisely known, and therefore site-specific models cannot easily be used. Most often we have to rely on large-scale averages of environmental conditions.
- The large number of substances covered by an LCI calls for a model that relies on relatively few input data in order to make the data gathering feasible.
- The availability of ecotoxicological effect data for the majority of chemicals on the market puts severe restrictions on the data demand of the effect model.

Ecotoxicity characterisation factors (CFs)

- As for all the other impact categories (global warming etc.) the impact potential (IP) for ecotoxicity is estimated in the following way:

IP = Q*CF   nIP = IP/NR (normalised)   wIP = nIP*WF (weighted)

- The normalisation reference (NR) and the weighting factor (WF) are estimated according to the same principles as for other impact categories
- The critical parameter here is the characterisation factor, CF
- The CF for ecotoxicity (m^3 per kg or PAF per kg) for a given substance is estimated as:

$$CF = EEI \cdot \text{Fate-factor}$$

- **EEI** is the ecotoxicity effect indicator (m^3/kg or PAF · m^3/kg)
- The 'Fate-factor' may be expressed as a change in concentration (kg/m^3) of the substance in a model compartment (unit world, multi media model, as in USEtox) or semi-quantitatively and dimensionless by use of key property parameters (distribution factors, biodegradation factors), e.g. for the EDIP method:

$$\text{Fate-factor} = f \cdot BIO$$

f is a distribution factor (Henrys law constant, K_{oc}, atmospheric DT50)
BIO is a biodegradation factor (aquatic readily and inherent biodegradation, or aquatic or soil DT50)

Two main approaches for estimating the ecotoxicity effect indicator, EEI

- Assessment Factor based approaches (PNEC); *No effect based (e.g. EDIP97, CML2002):*

$$\mathrm{EEI} = \frac{1}{\mathrm{PNEC}}$$

- Species Sensitivity Distribution (SSD) or PAF based approaches; *Effect based*, average approach (e.g. EDIP200X, USEtox)

$$\mathrm{EEI} = \frac{\mathrm{PAF} = 0.5}{\mathrm{HC}_{50}} = \frac{0.5}{\mathrm{HC}_{50}}$$

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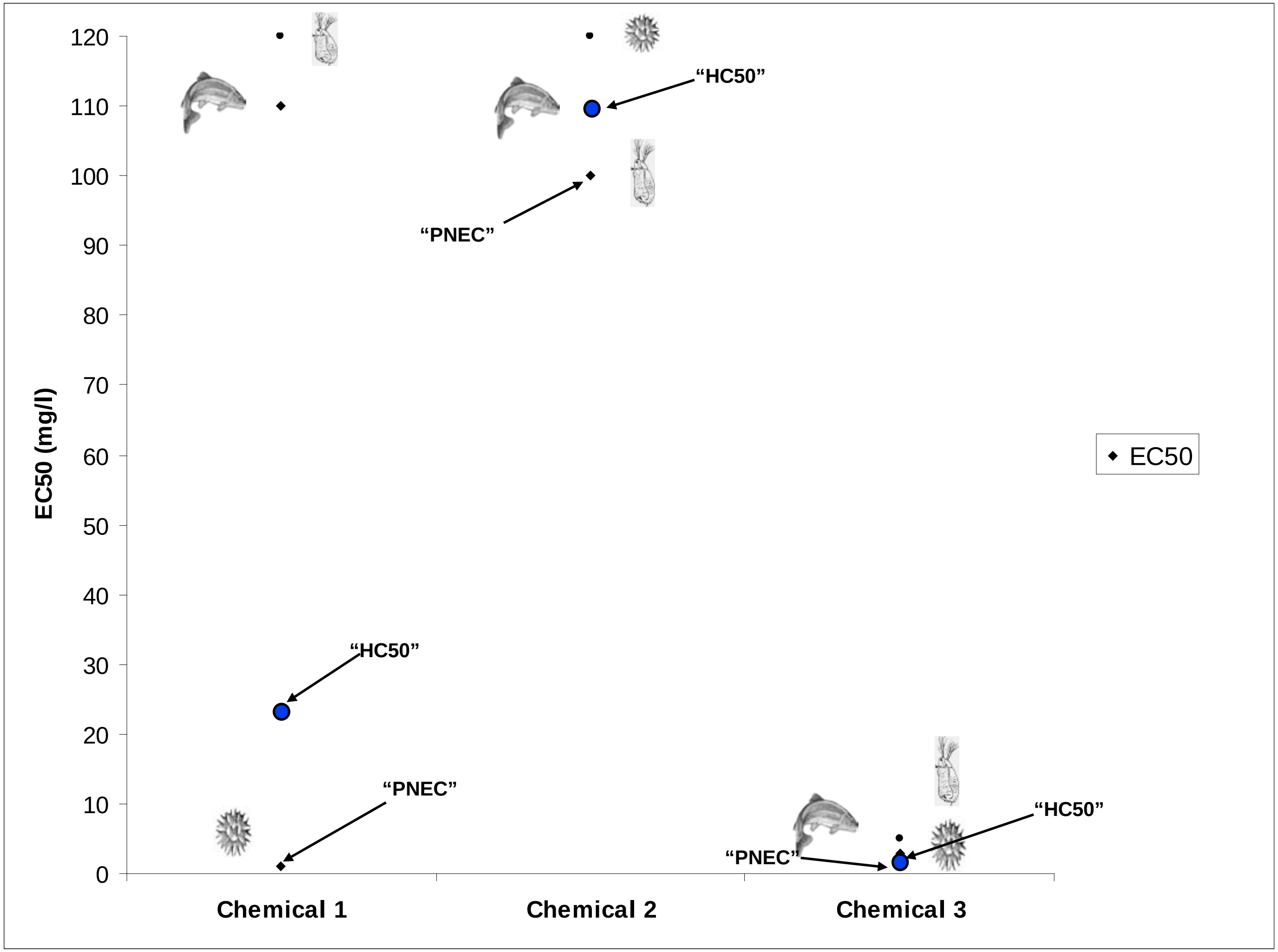
PNEC (low. EC50) as opposed to HC50 (geo. mean)



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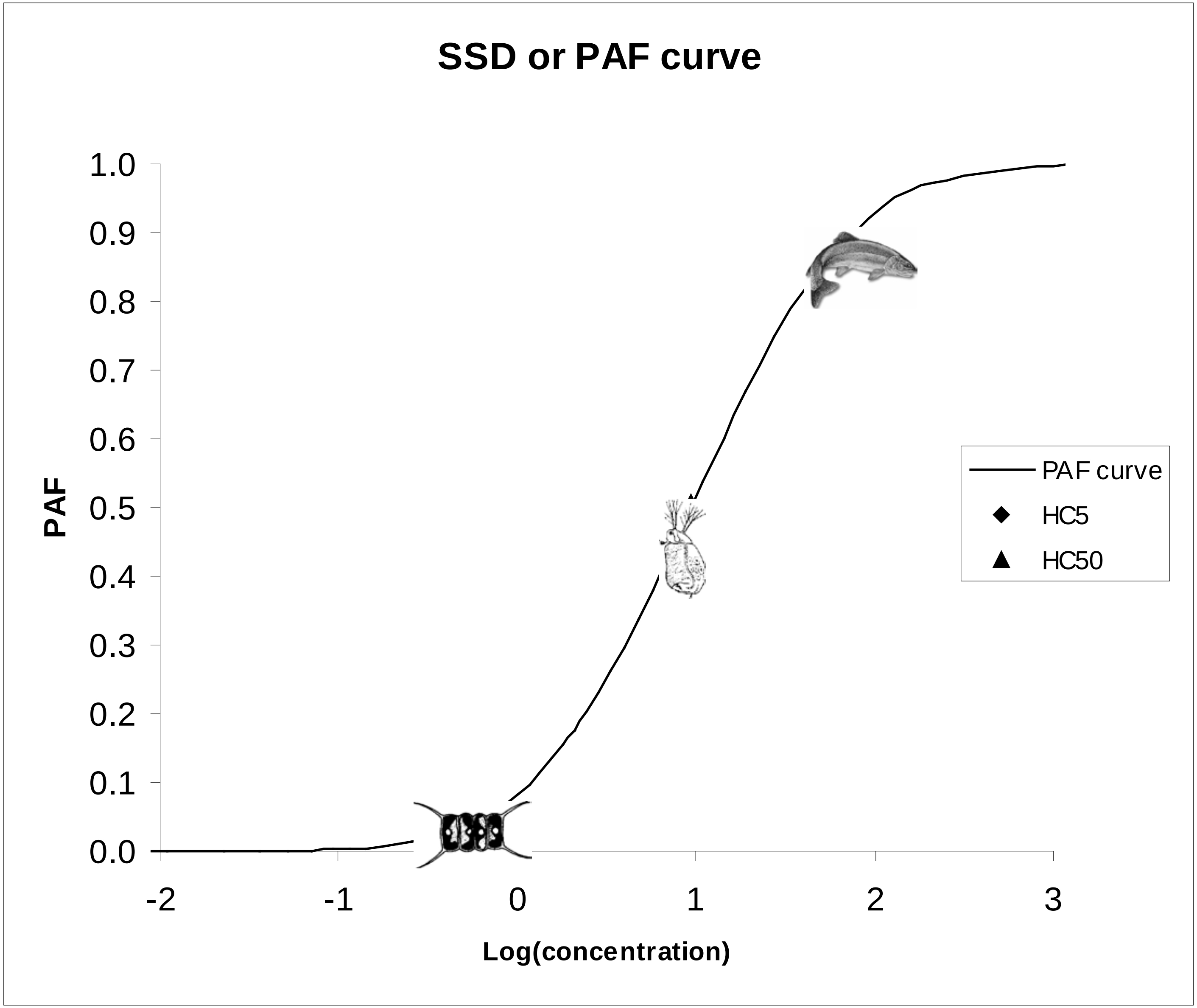
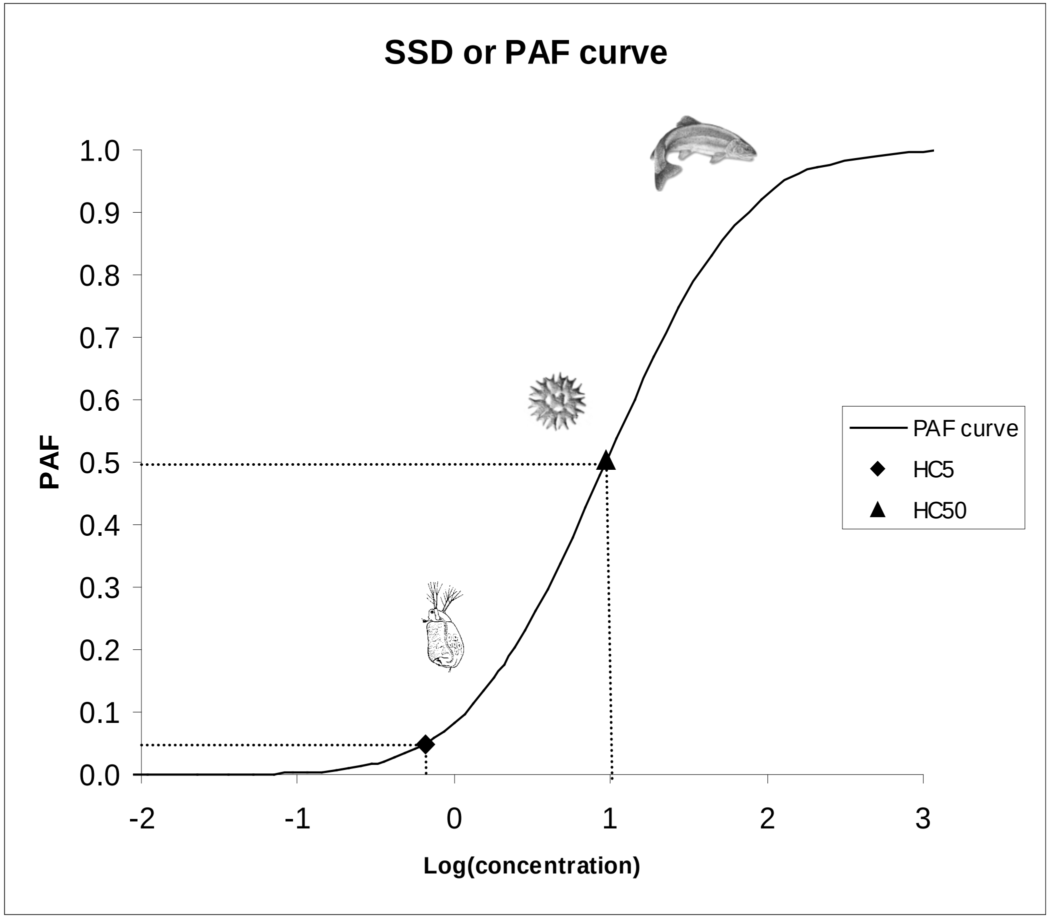
Potentially affected fraction of species (PAF) approach



Species Sensitivity Distribution

Potentially Affected Fraction of species (PAF)



$$\mathrm{PAF} = \frac{1}{1 + e^{-(\log C - \alpha)/\beta}}$$

Where:

C is the concentration

α is the location parameter = logHC50

$$\log HC50 = \frac{1}{n_s} \cdot \sum_s \log EC50_s$$

β is the scale parameter:

$$\hat{\beta} = \frac{\sqrt{3}}{\pi} \cdot \sigma$$

σ is the standard deviation

Pros and cons for the 0.5/HC50 approach
(as opposed to the PNEC approach)

PROS

- The risk of bias from the laboratory test set-up is low compared to a no-effect based indicator (PNEC), where the highest tested concentration, which is not statistically different in toxicity from the control concentration, is typically reported.
- The use of a value which is estimated and placed in the centre of the concentration response curve (i.e. HC50) gives the lowest uncertainty.
- The quantification of damage in terms of potential loss of species is possible (at least in theory).

CONS

- The focus is shifted away from protection of the function and structure of ecosystems.
- The importance of very sensitive species may be neglected.

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Examples of existing approaches for ecotoxicity effect factors

Criteria	PNEC-based approaches				PAF-based approaches		
	AF-based PNEC (only acute data)	AF-based PNEC (only chronic data)	AF- based PNEC (chronic (preferred) and acute data)	SSD-based PNEC ($HC5_{NOEC}$)	'Marginal PAF increase' (fixed β value)	Average PAF increase, HC5 (fixed β value)	Average PAF increase, HC50
Compatibility	+	++	+(+)	++	++	++	+++
Environmental relevance	+	+++	++(+)	+++	+++	+++	+++
Reproducibility	++	+(+)	+(+)	++(+)	+++	++(+)	+++
Transparency	++++	+++(+)	+++(+)	++	+(+)	+(+)	+(+)
Low data demand	++++	+++	+++(+)	++	+	++	++
High data availability	++++	++	++++	+(+)	+	+(+)	+(+)
Spatial differentiation possible	+	+(+)	+	++	+++	++ [a]	+(+)
Quantification of uncertainty included	+	+	+	++ [c]	++ [c]	++ [c]	++++ [b]

++++: Very high degree of fulfilment
+++: High degree of fulfilment
++: Moderate degree of fulfilment
+: Low degree of fulfilment

a: β not fixed
b: Implemented in AMI (Payet 2004, 2005)
c: Not implemented but possible

(Larsen and Hauschild 2007; Int J LCA 12 (1) 24-33)

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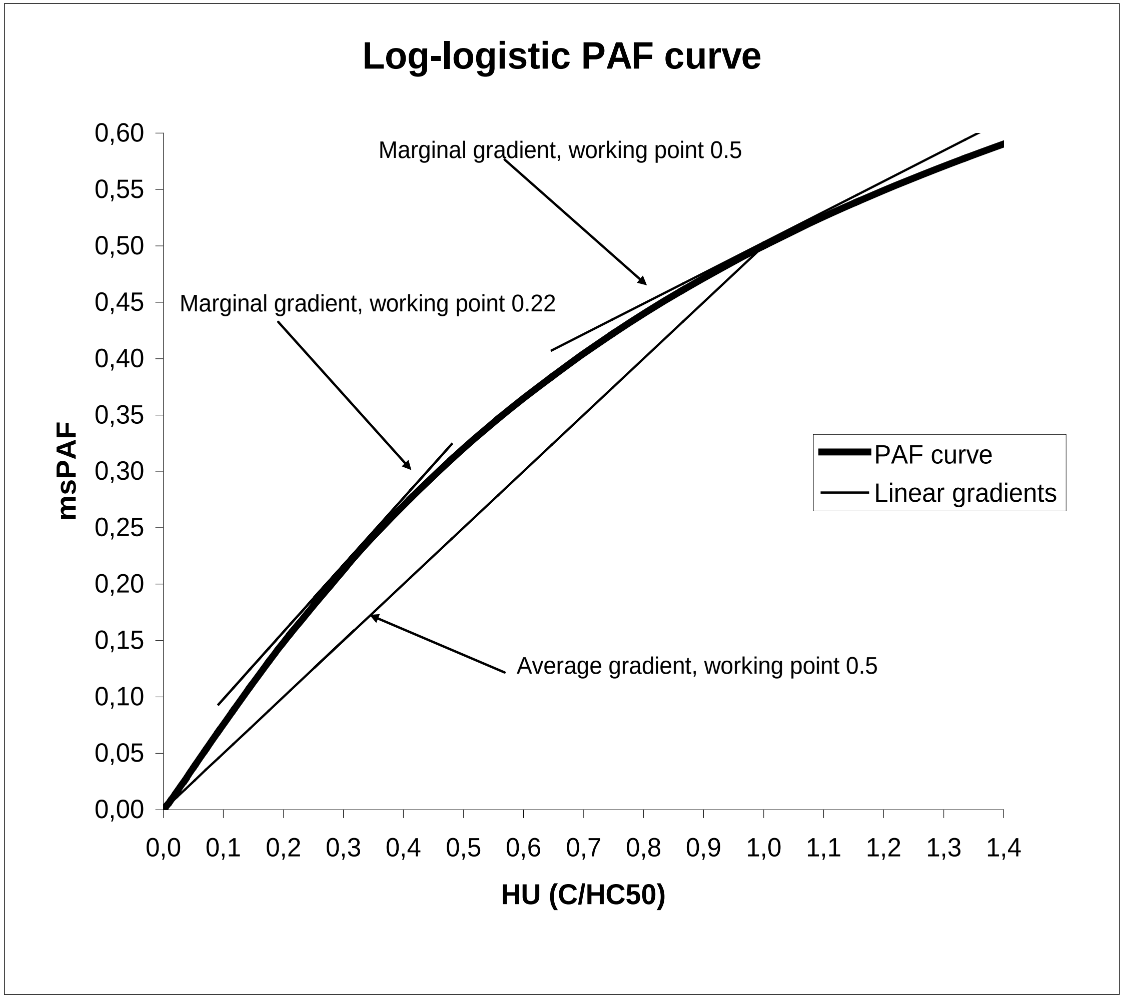
Different linear gradients and working points



(Larsen and Hauschild 2007; Int J LCA 12 (1) 24-33)

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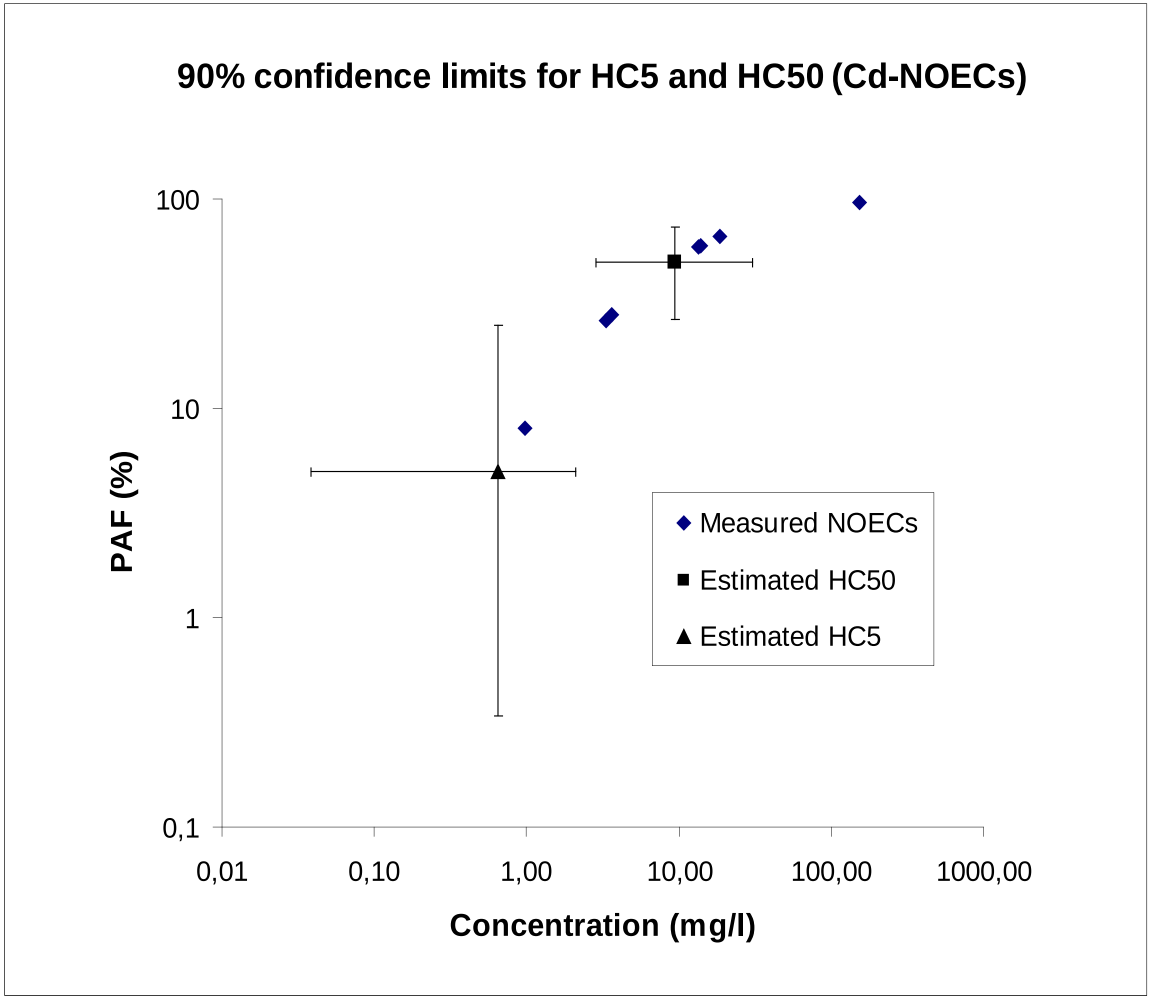
Different uncertainties for HC50 and HC5



(Larsen and Hauschild 2007; Int J LCA 12 (1) 24-33)/Straalen & Denneman 1989)

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Example on special LCIA methodology developed within Neptune

Including WET tests on estrogenicity in LCIA

Challenges regarding including WET in life cycle impact assessment (LCIA)

- Unequal data availability resulting in possible bias of the LCA results
- Lack of fate data, i.e. persistence, distribution among environmental compartments

Single substance approach: ECF = f*BIO*1/PNEC (EDIP97)

- If "f" and BIO is not known two ways may be possible regarding WWTPs
  - Acute freshwater WET
  - Current exposure chronic freshwater WET
- No WET tests for acute toxicity are explicitly included in the NEPTUNE test program
- Almost all ecotoxicity test results in Neptune are only expressed in nominal scale (yes/no regarding statistical difference)
- However, the results of the yeast screening tests for (anti-) estrogenicity (YES), (anti-) androgenicity (YAS) are expressed in equivalents of a known relevant endocrine disruptor regarding the endpoint
- Preliminary methodology on how to include WET in LCIA regarding estrogenicity and the novel impact category "Current exposure chronic freshwater WET" have therefore been developed

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Relative estrogenic potencies (REP) from YES studies, and PNECs for some known estrogenic substances

Substance	YES (REP)	PNEC (ng/L)
Estradiol (E2)	1	2.4 [b]; 0.5 [c]
Estrone (E1)	0.38 [a]	3.6 [d]
	0.29 [e]	
	0.18 [h]	
Ethynylestradiol (EE2)	1.19 [a]	0.06 [b]; 0.03 [c]
	0.88 [e]	
	0.7 [f]	
	0.79 [h]	
Estriol (E3)	2.4E-3 [a]	670 [d]
Nonylphenol	2.5E-5 [a]	330 [b]; 3.3 [c]
	7.2E-7 [f]	
Bisphenol A	1.1E-4 [a]	0.8 [c]

[a] Rutishauser et al. (2004) [b] Clauson-Kaas et al. (2006) [c] Environmental Quality Standard (EQS) from Moltmann et al. (2007) [d] This study: Based on NOEC values of 36 ng/L (estrone) and 6700 ng/L (estriol) regarding the end-point sex ratio and reported in DRP from OECD (2004) [e] Stuer-Lauridsen et al. 2005 [f] Folmar et al. (2002) [g] Based on *in vivo* male fish VTG production study: Folmar et al. (2002) [h] Calculated on basis of data in Schultis and Metzger (2004)

YES test equivalents (EEQs) and "occurrence weighted 1/PNEC-values" for the anticipated average waste water effluent composition

EDS*	REP	Anticipated occurrence (ng/L)**	YES (ng EEQ/L)	PNEC (ng/L)***	1/PNEC (L/ng)	Weighted 1/PNEC
E1	0.38	10	3.8	3.6	0.28	2.8
E2	1	1.5	1.5	2.4	0.42	0.63
EE2	1.19	0.5	0.6	0.06	17	8.3
E3	0.0024	1.4	0.0034	670	0.0015	0.0021
Total			**5.9**			**11.7**

* Endocrine Disrupting Substance. These four assumed to dominate estrogenicity of municipal waste water

** Based on recently published review paper including average WWTP effluent concentrations for a high number of WWTPs/studies (Miege et al. 2009). Median effluent concentrations within the ranges found in other studies not included in the review like the Danish survey of estrogenic activity including Danish WWTPs (Stuer-Lauridsen et al. 2005).

*** PNEC values based on end point: sex ratio

The "Current exposure chronic freshwater WET" ecotoxicity characterisation factor (ECF) for estrogenicity

- The total weighted 1/PNEC-value of 11.7 may be divided by the total YES response of 5.9 ng EEQ/L leading to an effect indicator value of 2.0 L/ng EEQ for the YES test.
- This figure equals an average weighted "PNEC" value of 0.5 ng EEQ/L (as comparison the "PNEC" value for EE2 is 0.6 ng EEQ/L)
- The "Current exposure chronic freshwater WET" ecotoxicity characterisation factor (ECF) for estrogenicity becomes:

$$ECF\ (WET_{YES}) = f*BIO*1/PNEC = 1/PNEC = 2.0\ L/ng\ EEQ = 2{,}000{,}000\ m3/g\ EEQ$$

- Using the alternative and lower PNEC values reported (instead of the sex ratio based) does only increase the ECF (WET_{YES}) by a factor of 1.9
- If also the REPs used are substituted with the lowest ones reported the factor is increased to 3
- Even by increasing the anticipated concentration of EE2 (the most potent one) to the max. value observed in effluent from WWTPs (according to the review by Miege et al. 2009), i.e. 5 ng EE2/L, the ECF (WET_{YES}) becomes 7.7 E6 instead of 2.0E6, that is only a factor of below 4 in difference

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Use, concerns and further developments on how to include WET in LCIA

- It must be stressed that the developed ECF (WET_{YES}) is only a preliminary proxy and until it have been tested and further analyzed it is recommended to use the single substance approach instead whenever possible

- If, however, we try to use it as a substitute for single substances in the estimations of the impact potential on ecotoxicity of EDS we will for example for an incoming concentration of 2 ng EEQ/L and a removal rate of 70 – 80% (ozonation or PAC) get a contribution of 10 µ PET/m3 in avoided impact. This is a significant contribution.

- One of the main problems with using an characterization factor like the developed ECF (WET_{YES}) is that it is based on test results from *in vitro* tests and many studies have shown that prediction of *in vivo* test response (e.g. VTG production) on the basis of *in vitro* test results (e.g. YES) is extremely difficult (Aerni et al. 2004, Folmer et al. 2002)

- Investigating the possibilities and consequences of including anti-YAS WET test results (units of flutamide-eqv.) in the LCIA characterization of the end-point feminization (related to population sex ratio) could be a future way of further elaboration on the issue of including WET in LCIA.

References/Further information

- Neptune: www.eu-neptune.org (D4.1, D4.2 and D4.3)
- USEtox: www.usetox.org (LCIA on ecotox and human tox)
- Larsen HF, Hauschild M (2007). GM-troph: A low data demand ecotoxicity effect indicator for use in LCIA. *Int J LCA 12(2) 79-91.*
- Larsen HF, Hauschild M (2007). Evaluation of Ecotoxicity Effect Indicators for Use in LCIA. *Int J LCA 12(1) 24-33 (Erratum for p. 32 in: Int J LCA 12(2) 92).*

Thank you for your attention

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