Applying Life Cycle Assessment Tools to Nanomaterials and Nano-enabled Products

NSE NSF Meeting
Washington, DC

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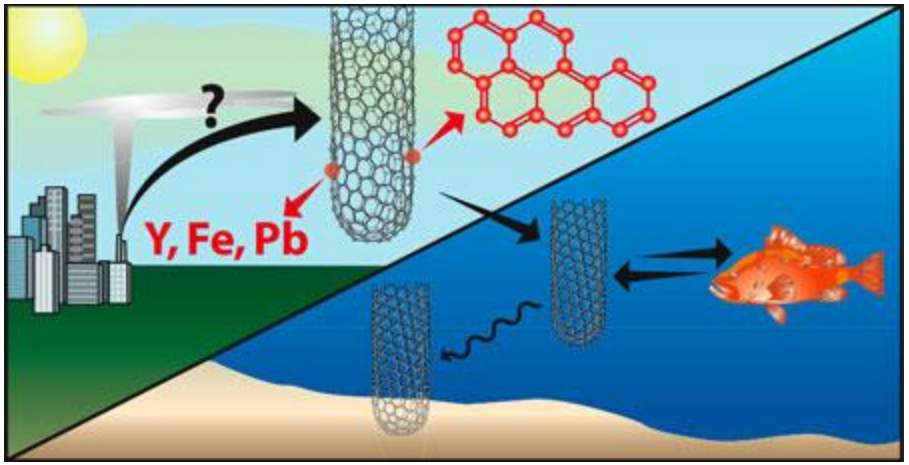
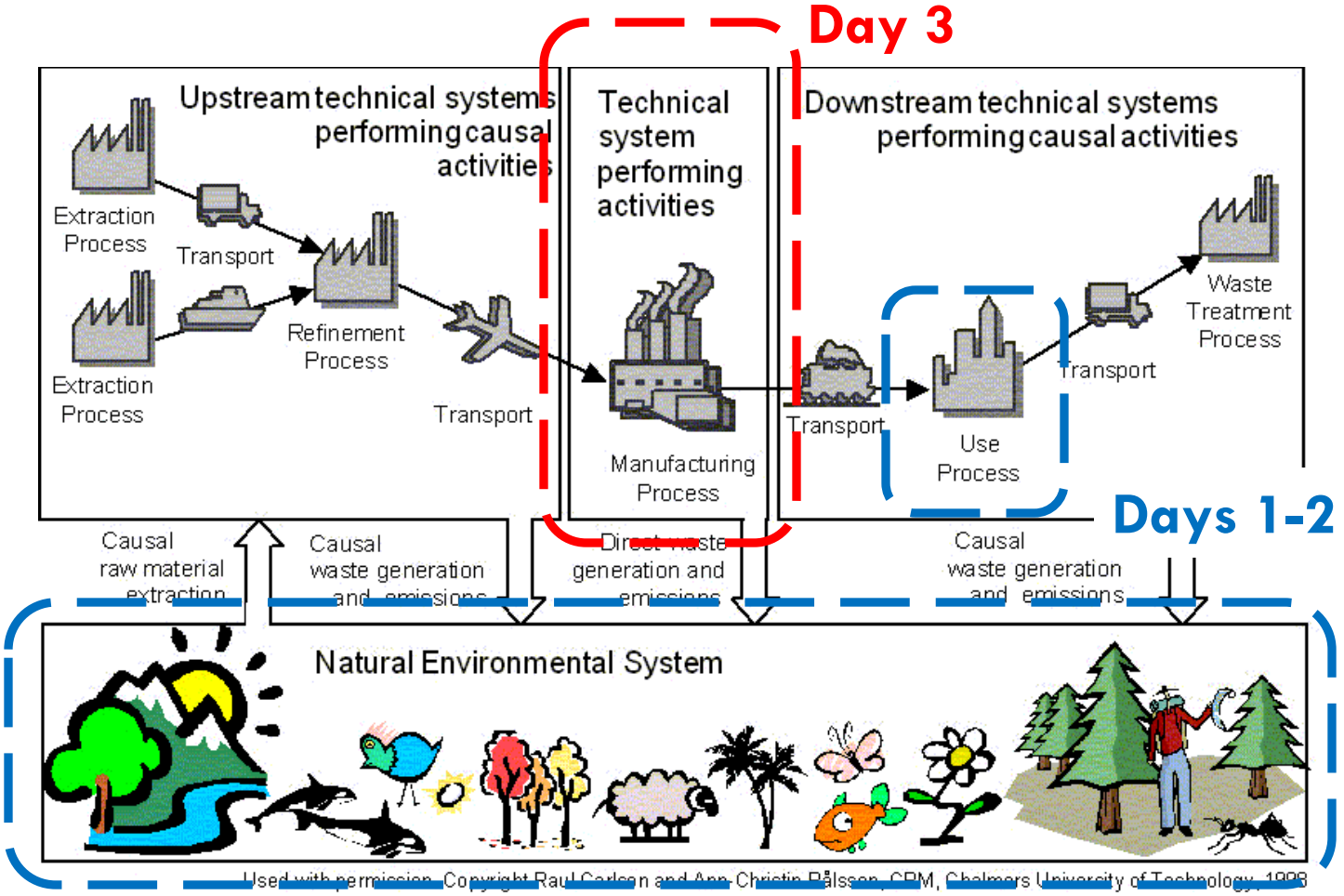
MIT/ Christine Daniloff



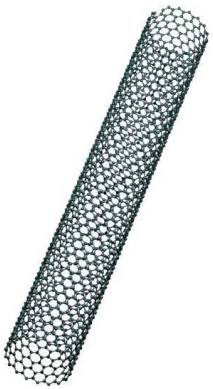
IOP Publishing 2010

Life Cycle Assessment (LCA) of Materials and Products



Components of LC Impact Assessment

$\dot{S}$	$\bar{M}$	$\dot{I}$	$\dot{N}$	$\dot{D}$
Emission flow (n_i) [$kg_{emitted}$/day]	Mass in env. (n_i) [kg]	Intake flow (n_{xr}) [kg_{intake}/day]	Risk flow (n_{ef}) [cases/day]	Damage flow (n_{ef}) [years/day]
$\bar{S}$	$\int \bar{M} dt$	$\bar{I}$	$\bar{N}$	$\bar{D}$
Mass emitted [$kg_{emitted}$]	Time integr. mass [kg·day]	Mass intake [kg_{intake}]	Risk [cases]	Damage [years]



$\overline{FF}$	$\overline{U} \cdot \overline{XF}$	$\overline{EF}$	$\overline{DF}$
$(n_i \times n_i)$	$(n_{xr} \times n_i)$	$(n_{ef} \times n_{xr})$	(n_{ef})
[day]	[1/day]	[cases/kg_{intake}]	[years/case]
Mass / Emission flow	Intake flow / Mass	Risk of incidence / Intake flow	Severity of incidence / Intake flow

$$\overline{iF_{xr}} = \overline{U} \cdot \overline{XF} \cdot \overline{FF} = \frac{\text{Intake flow}}{\text{Emission flow}}$$

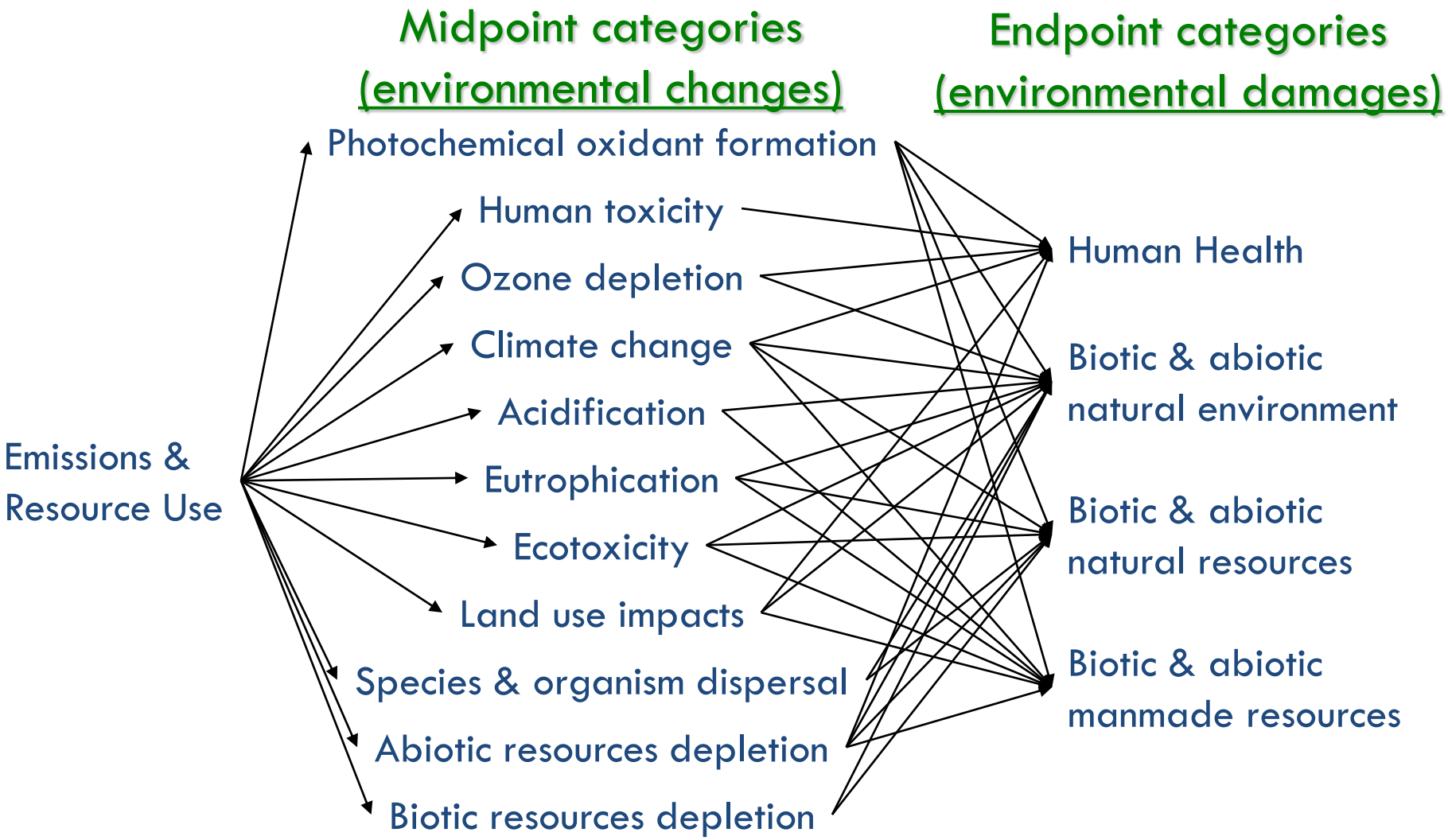
$(n_{xr} \times n_i)$

[$kg_{intake}/kg_{emitted}$]

USEtox Model

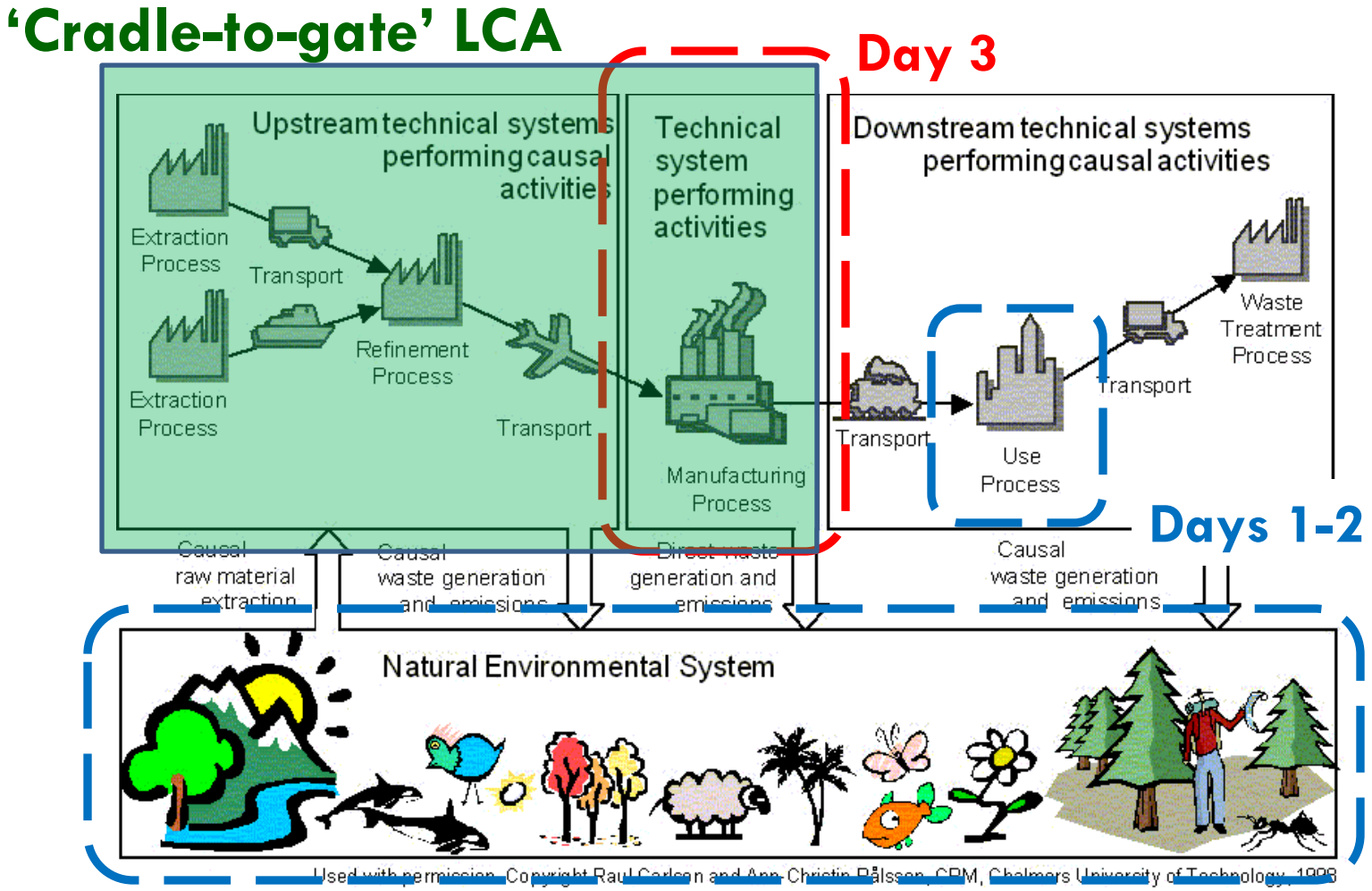
http://www.sciencedirect.com/science/article/pii/S0160412007000098

Multiple Categories of Environmental & Health Impacts

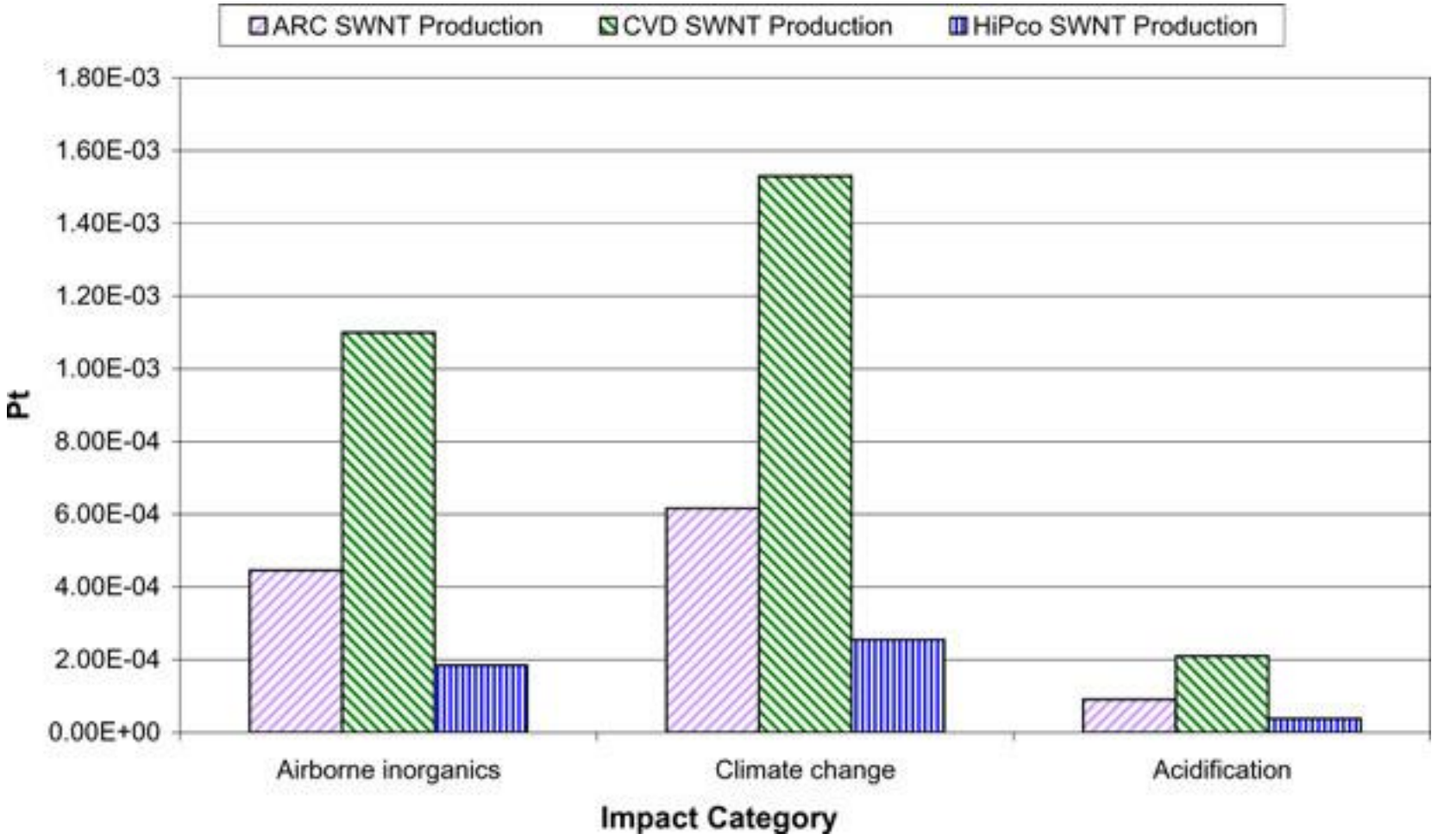


Int J of LCA 9(6) 2004

Life Cycle Assessment (LCA) of Materials and Products

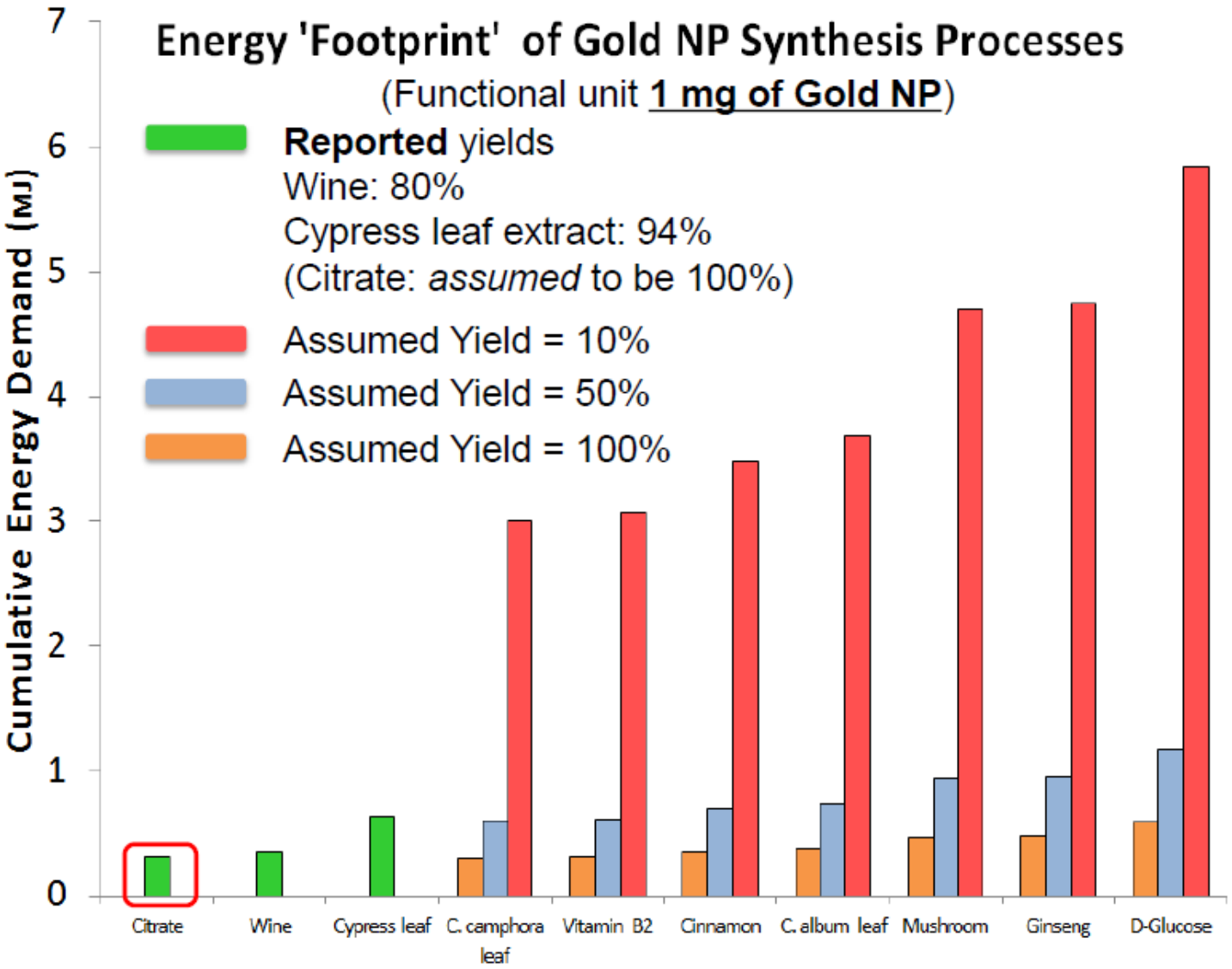


Reveals Differences Among Synthesis Techniques



Healy *et al.* (2008). *Journal of Industrial Ecology*

Reveals Differences Among Reaction Chemistries



Pati *et al.* (2013). *Sustainable Nanotechnology Organization Meeting;* San Diego, CA

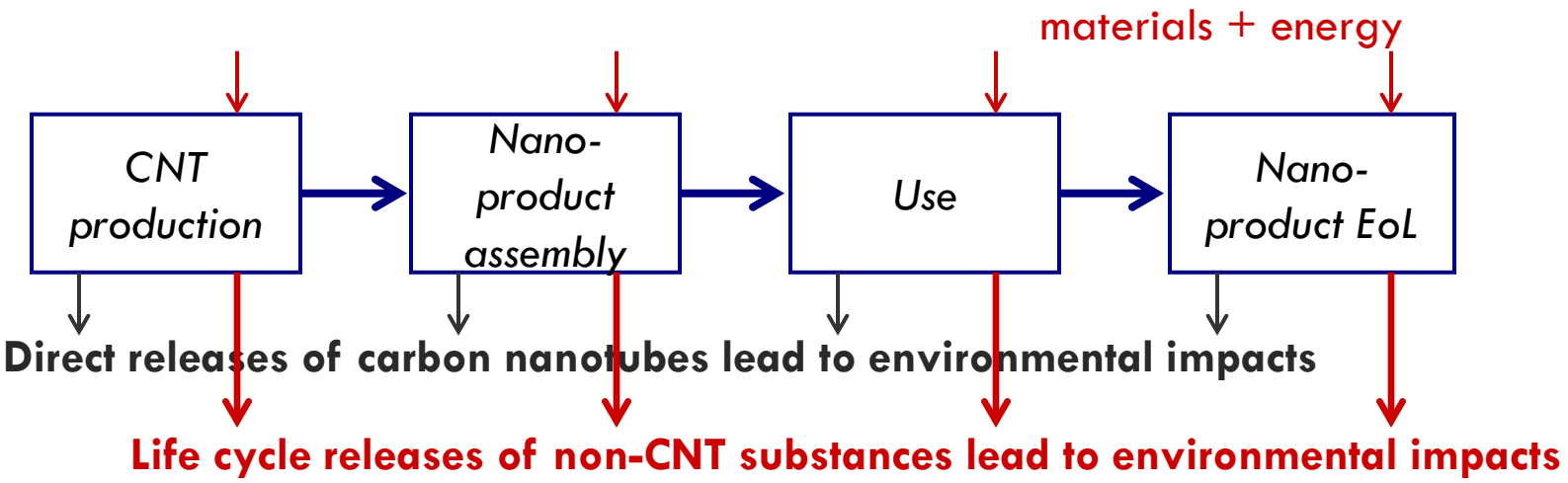
Challenges and Opportunities in Nano LCA

- Linking Production, Fate, Exposure, and Effect data together to create full cradle-to-grave LCA

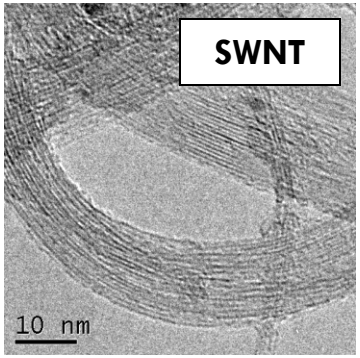
- Impacts of ENMs *in relation to* nano-enabled products

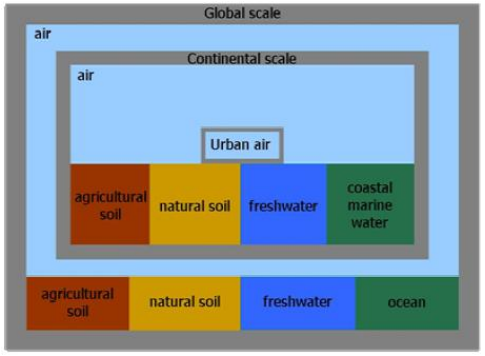
- Including impacts *and* benefits of ENM use in LCA models

Linking Production, Fate, Exposure and Effect: Life Cycle Ecotoxicity of SWNTs

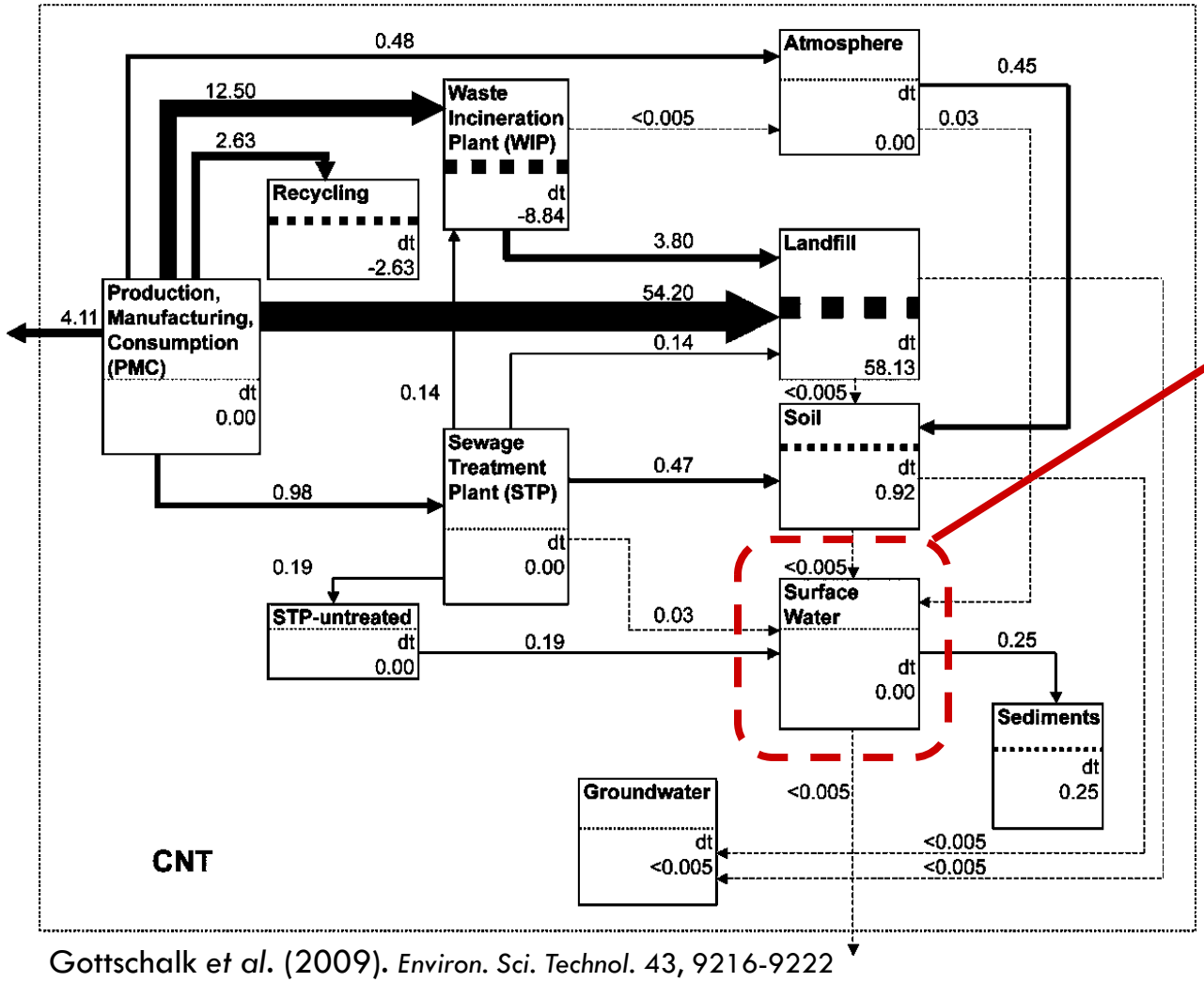


- Adapt consensus USEtox impact assessment model for SWNTs to include colloidal processes
- Only consider freshwater ecotoxicity





Fate and Transport (FF) and Exposure (XF)



Gottschalk *et al.* (2009). *Environ. Sci. Technol.* 43, 9216-9222

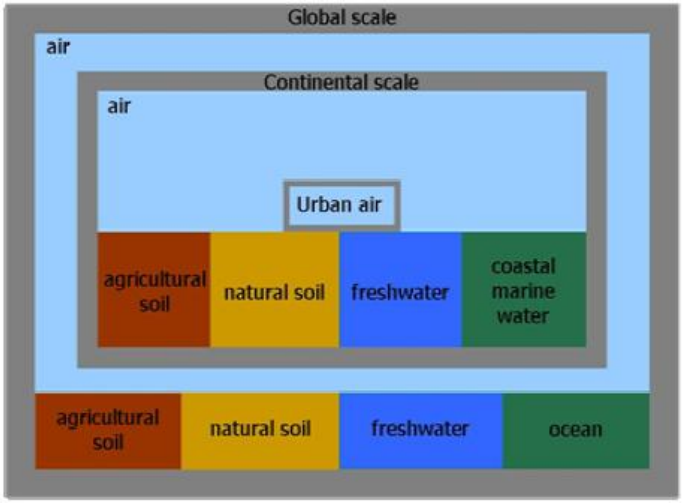
Worst Case Scenario
100% release;
All CNTs stable in water column

Realistic Scenario
Modeled concentrations based on fate and transport parameter estimates

Effect Factor (EF)

Ecotoxicity of CNT Production Emissions

- Toxicity factors have already been calculated for many organic and inorganic chemicals (~3200)
- Some chemicals have group toxicity factors, and required disaggregation (such as PAHs)

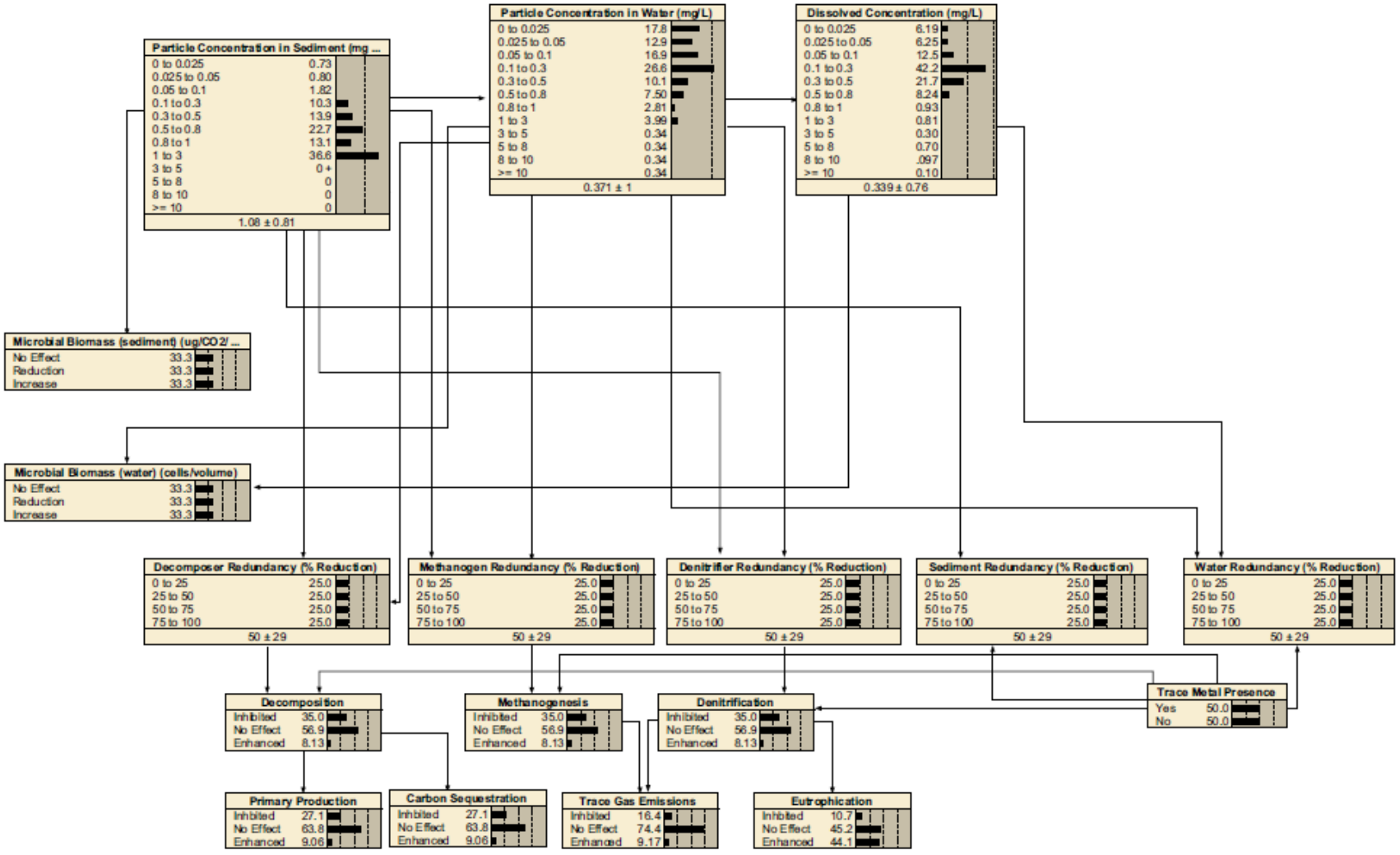


Rosenbaum et al., *IntJLCA* **2008**
USEtox™ User Manual v1.01, Feb **2010**

Ecotoxicity of CNTs themselves

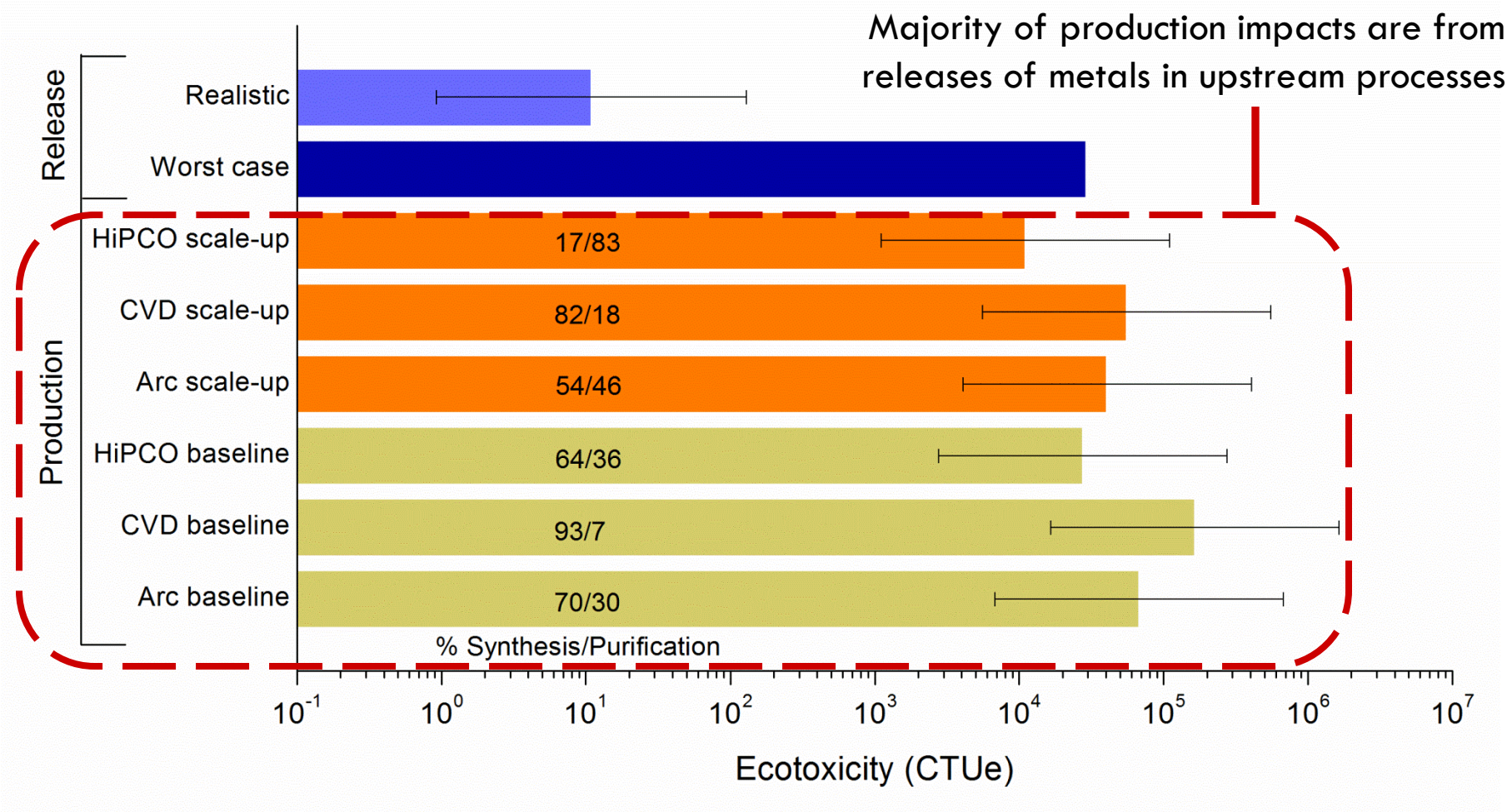
- Adapt USETox model for CNTs
  - Incorporate Aggregation and settling processes
- Single-species toxicological data *(priority on chronic EC50 measurements)*
  - Bacteria, Protozoa, Copepods, Algae, Hydra, Daphnia, Fish

Bayesian Modeling of ENM Fate and Effect



Money *et al.* (2012). *Sci Total Environ* 426, 436-445

CNT Ecotoxicity Production vs Releases



Eckelman *et al.* (2012). *Environ Sci Technol* 46, 2902-2910

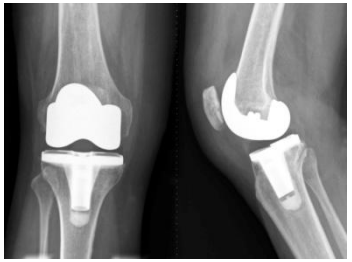
Moving Toward Product-Level LCA of Impacts



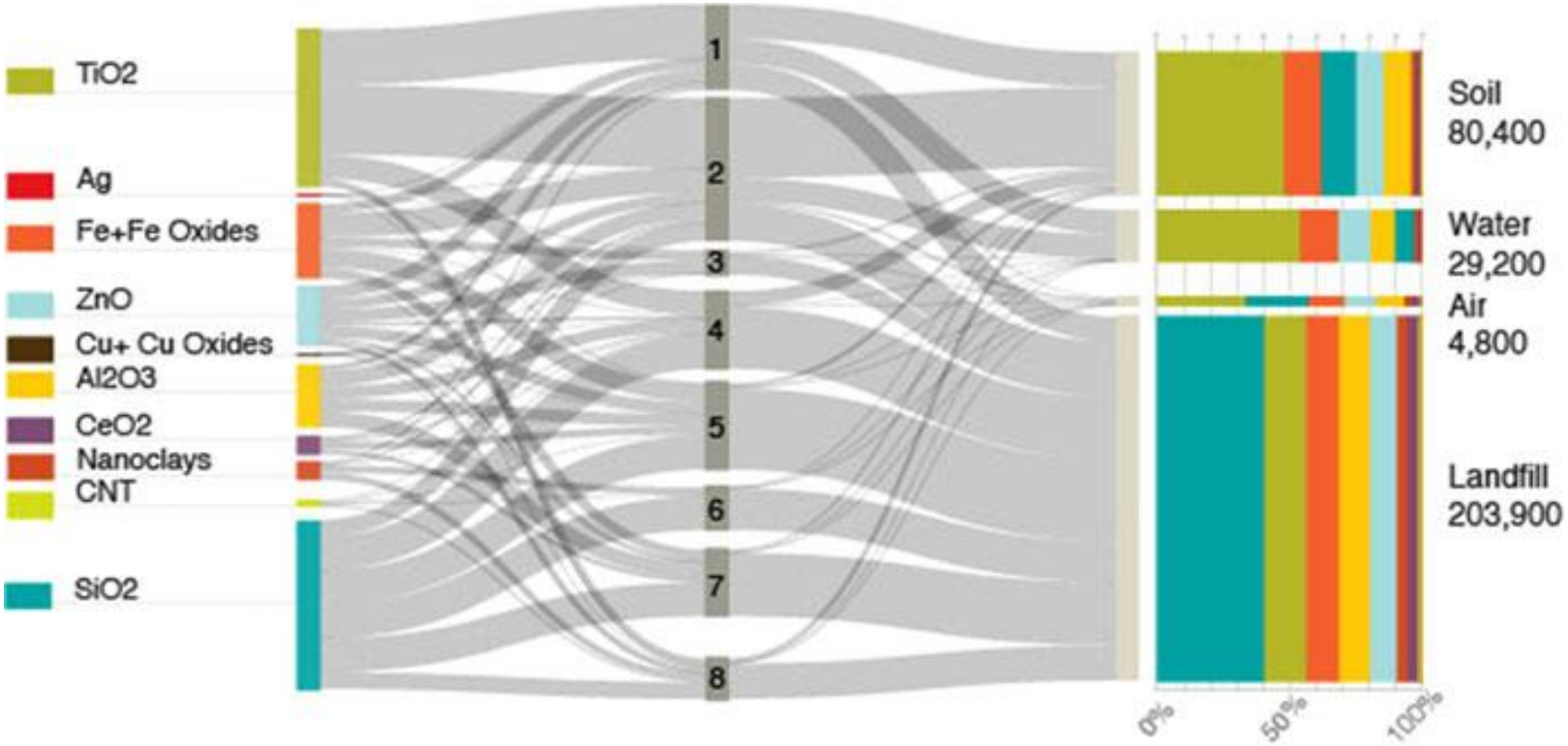








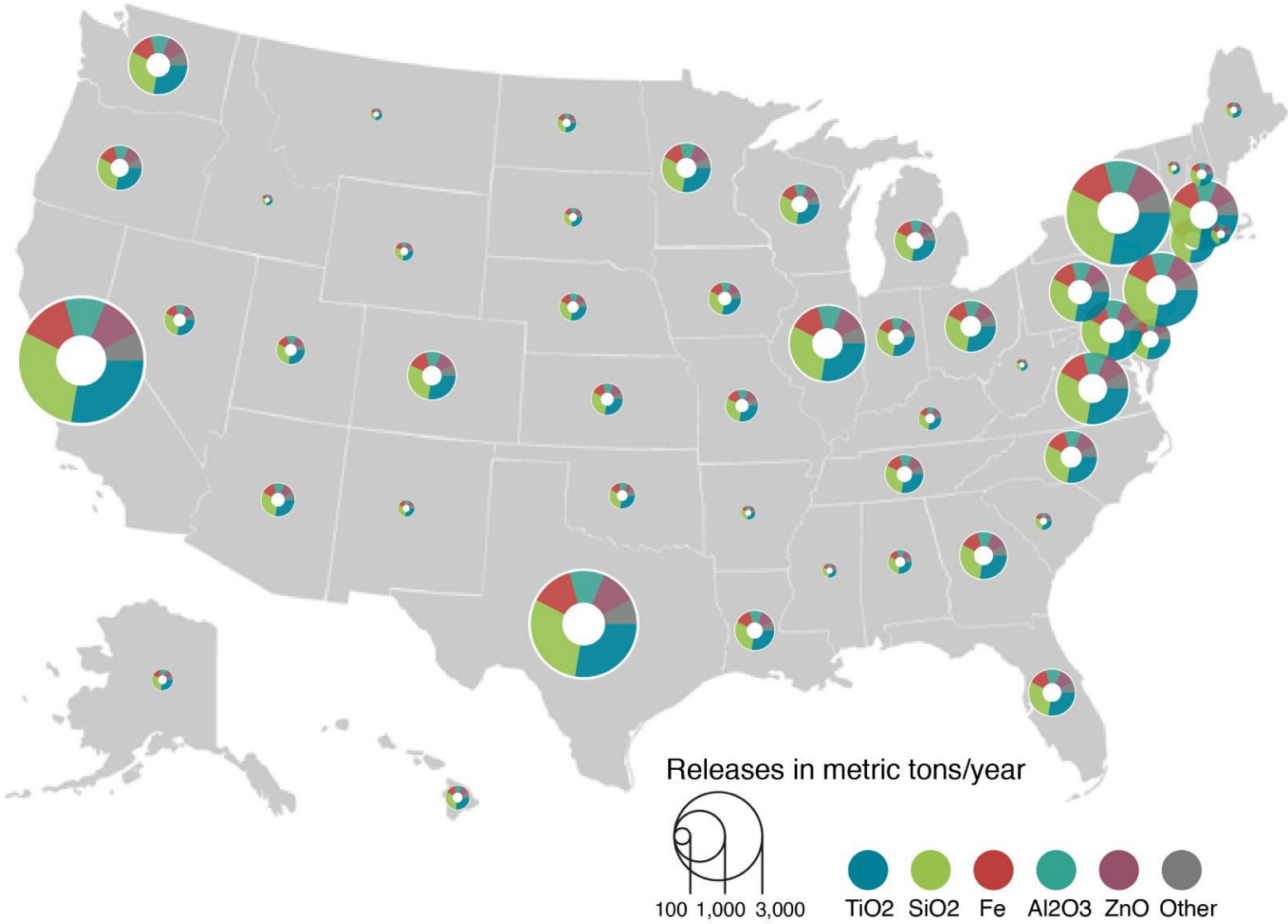

Global Releases of ENMs – What and Where?



1. Cosmetics	48,000	5. Electronics & Optics	48,700
2. Coatings, Paints, & Pigments	80,500	6. Automotive	23,500
3. Medical	13,400	7. Catalysts	37,500
4. Energy & Environment	43,700	8. Other	22,900

Keller *et al.* (2013). *J Nanoparticle Research* 15, 1692

Geospatially Resolved ENM emissions



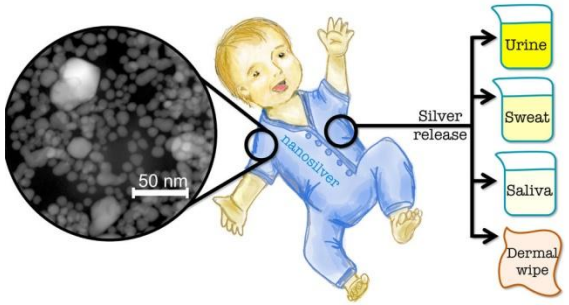
Keller and Lazareva. *ES&T Letters 5*; **DOI:** 10.1021/ez400106t

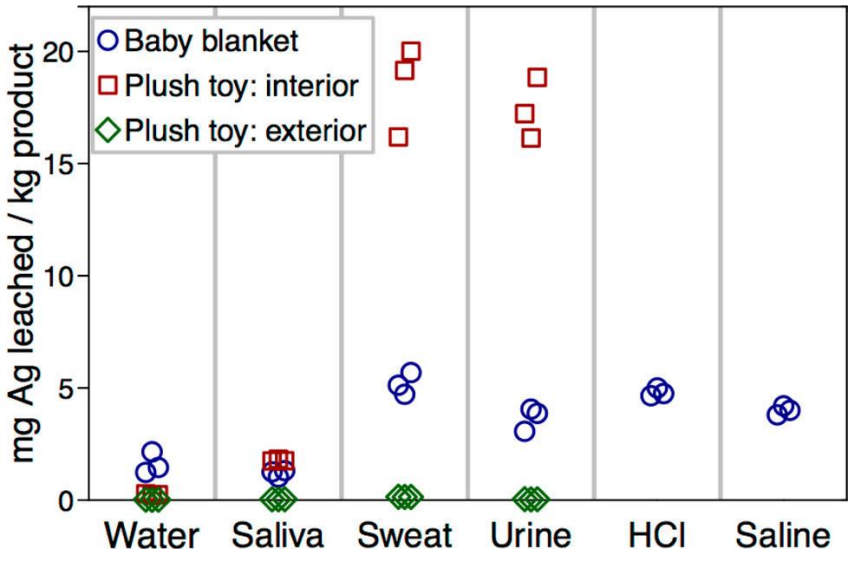
Environmental Science & Technology

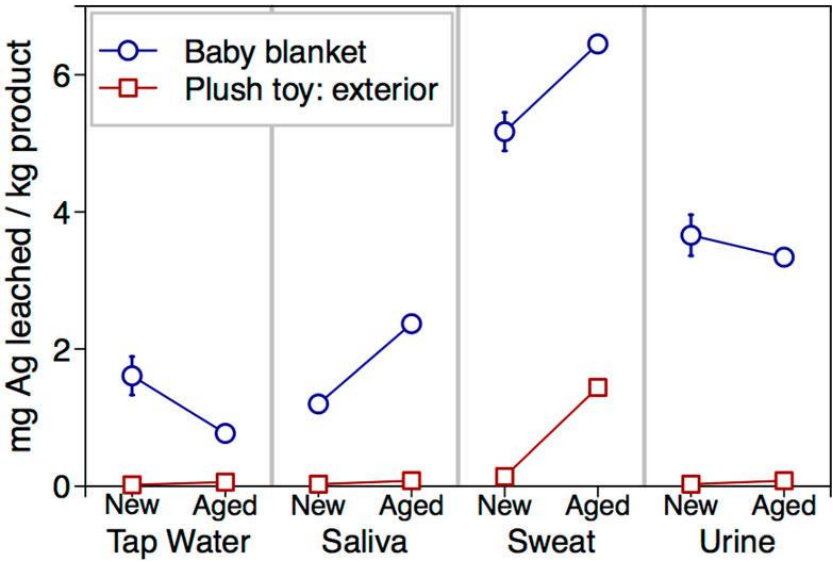
Release of Silver from Nanotechnology-Based Consumer Products for Children

Marina E. Quadros,*[,†,∥] Raymond Pierson, IV,[†] Nicolle S. Tulve,[‡] Robert Willis,[‡] Kim Rogers,[‡] Treye A. Thomas,[§] and Linsey C. Marr[†]

- What about direct exposure routes for ENM emissions to vulnerable population?
- How does the age of the product affect ENM emissions?







Size, Form, Matrix, etc. Important for LC Results

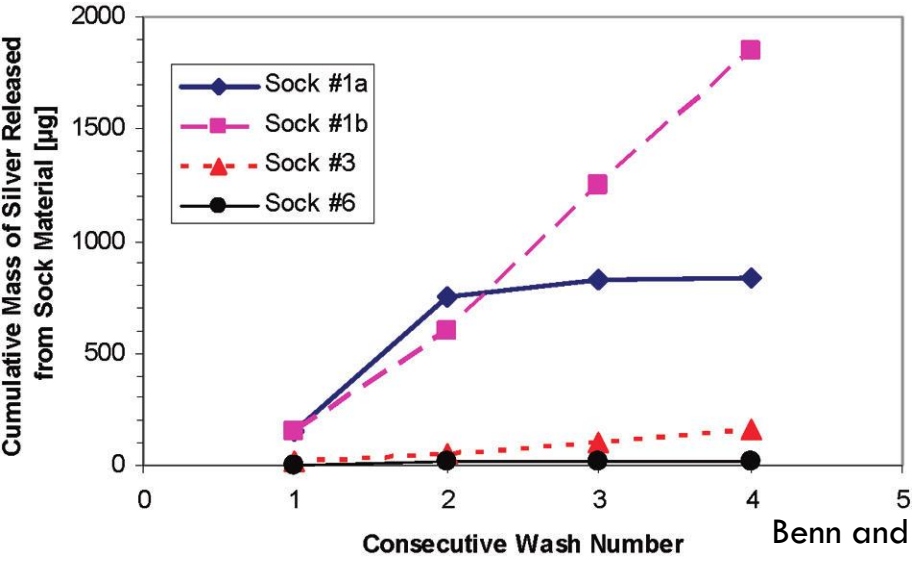
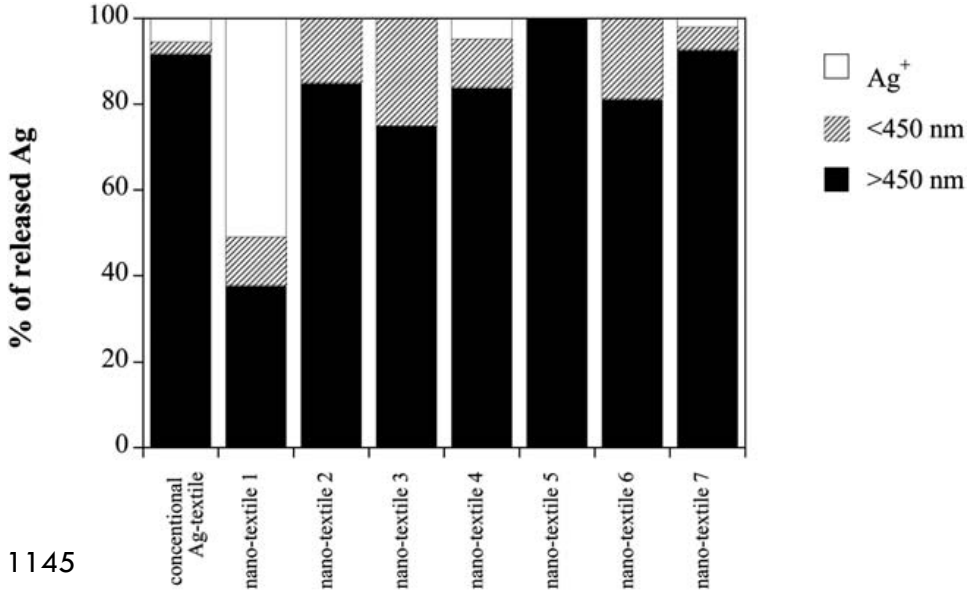


TABLE 2. Nanoparticle and Ion Separation for Silver in 1-hr

sock ID	total silver in wash water (µg)
1b, first 1-hr wash	145
1b, second 1-hr wash	275
1b, third 1-hr wash	600
3, first 1-hr wash	80
3, second 1-hr wash	160
3, third 1-hr wash	150

Benn and Westerhoff (2008) *Environ Sci Technol.* 42, 4133-4139



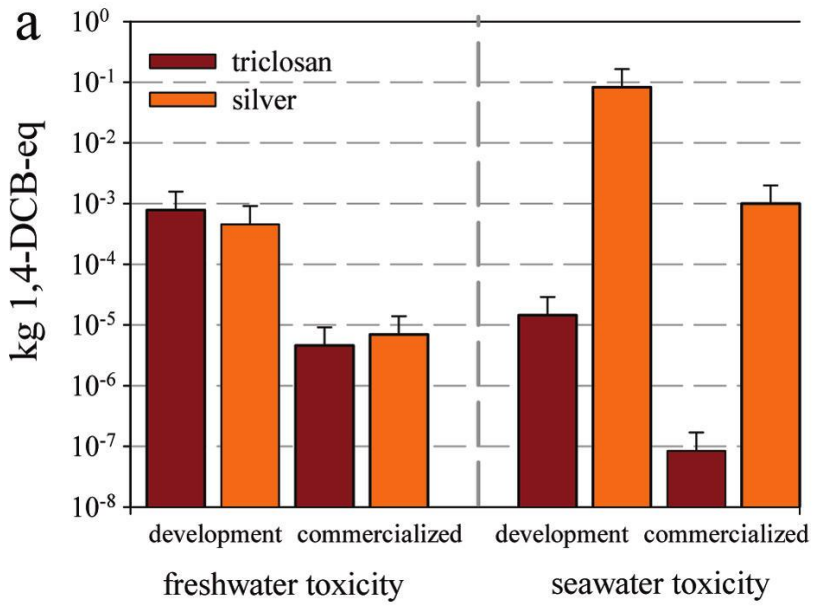
Gottschalk and Nowack (2009) *J Environ Monit.* 13, 1145

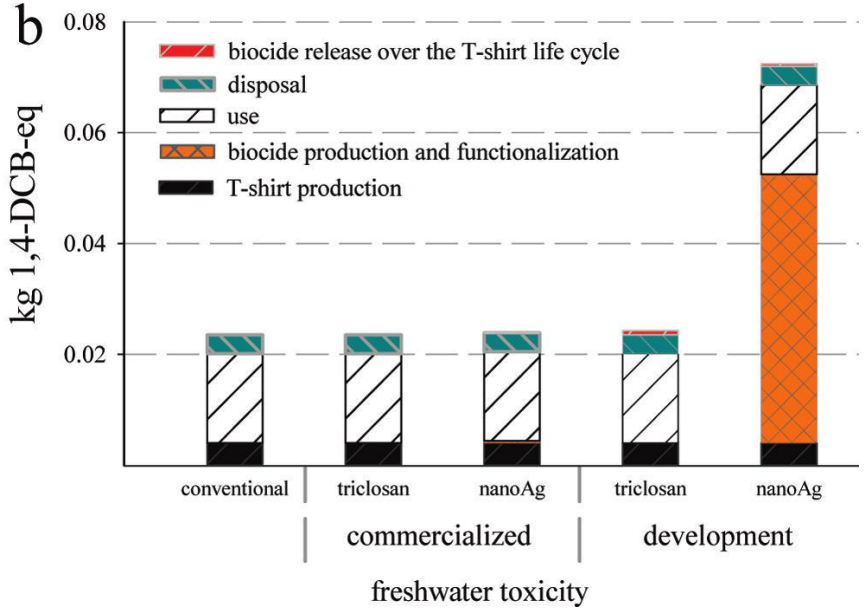
Environmental Science & Technology

Prospective Environmental Life Cycle Assessment of Nanosilver T-Shirts

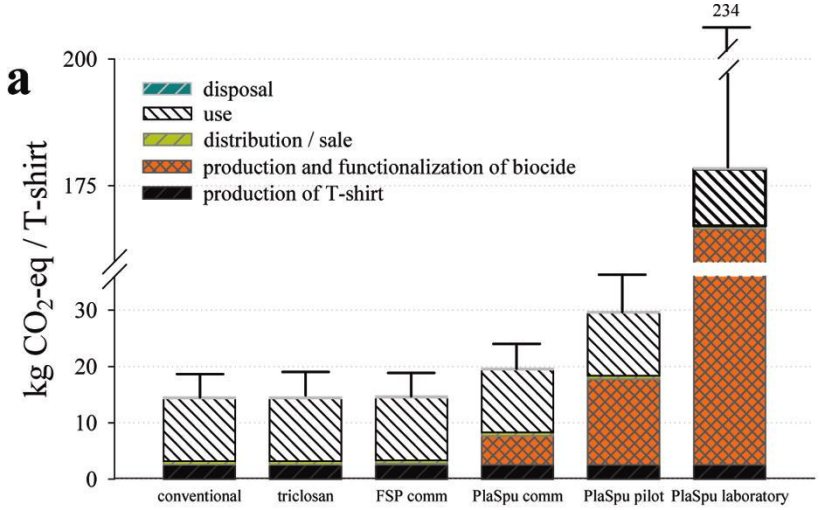
Tobias Walser,[*,†] Evangelia Demou,[†,‡] Daniel J. Lang,[§,∥] and Stefanie Hellweg[†]

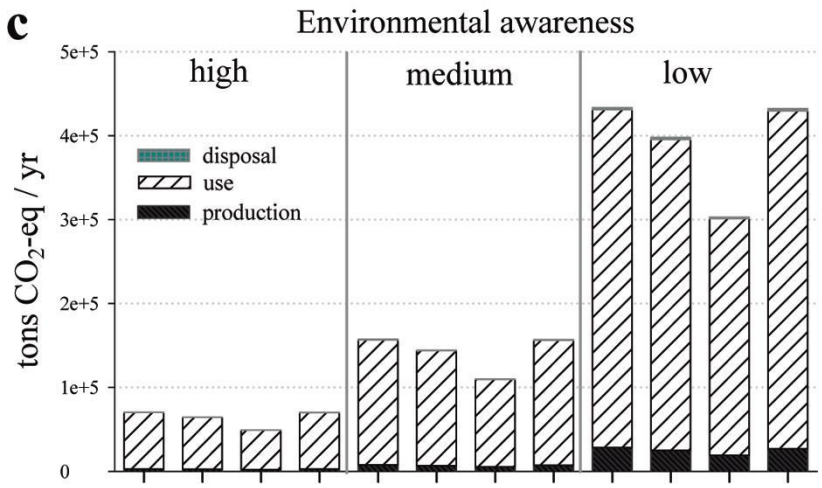
- Compares antimicrobial treatments on a LC basis
- Full cradle-to-grave assessment including production and processes

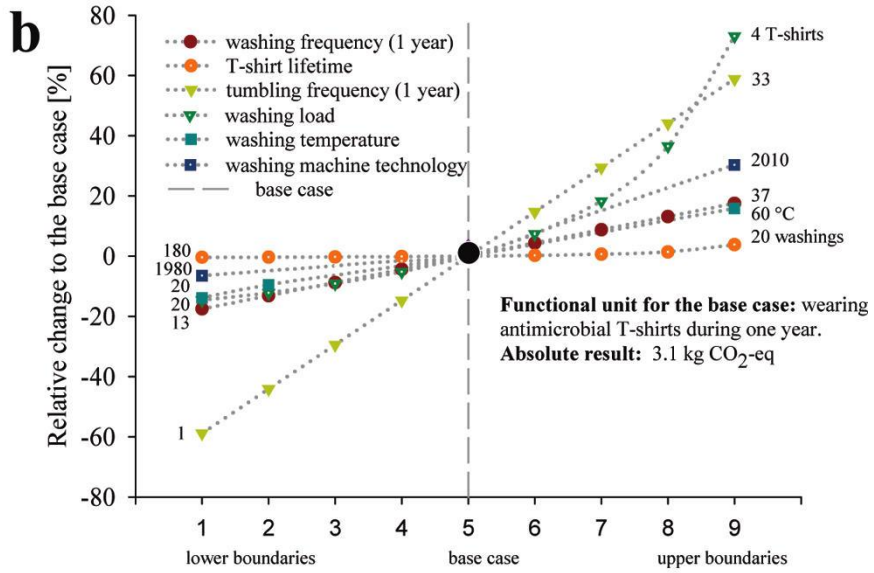




Behavior and Use Patterns are Critical







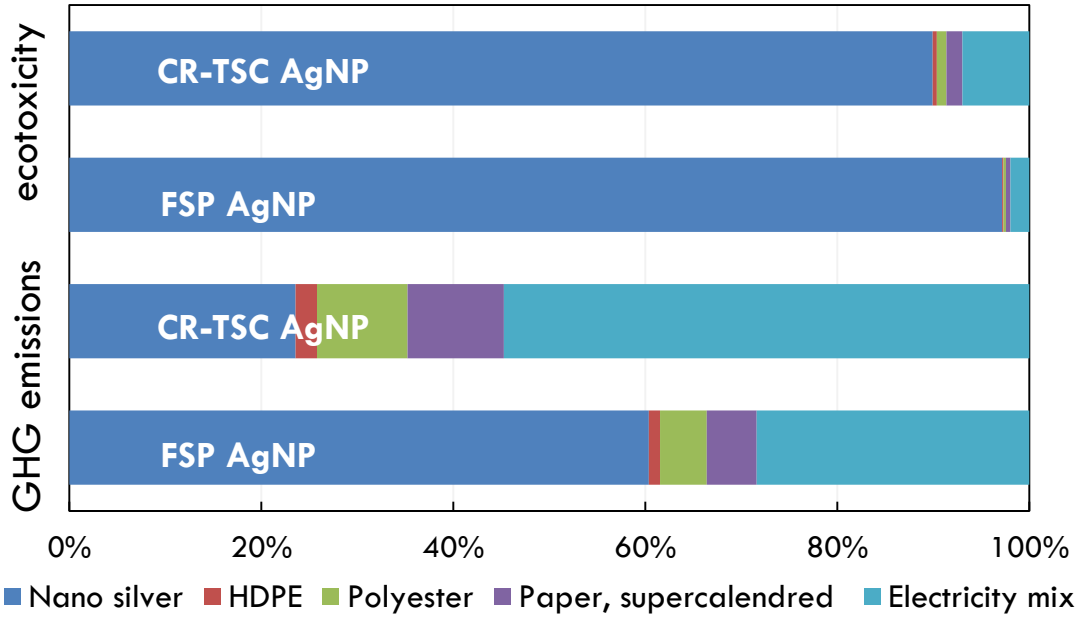
parameter	1	2	3	4	base case	6	7	8	9
washing frequency (year $^{-1}$)	13	16	19	22	**25**	28	31	34	37
T-shirt lifetime (washings)	180	160	140	120	**100**	80	60	40	20
tumbling frequency (year^{-1})	1	5	9	13	**17**	21	25	29	33
washing load (T-shirts)	20	18	16	14	**12**	10	8	6	4
washing temperature (°C)	20	30			**40**				60
machine technology (year)	1980				**2000**				2010

Walser *et al.* (2012). *Env Sci Technol* 45, 4570-4576

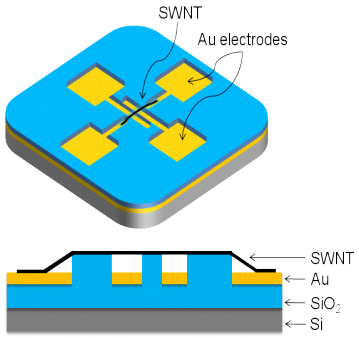
AgNPs in Medical Textiles

- Influence of silver compared to bandage production and medical waste incineration

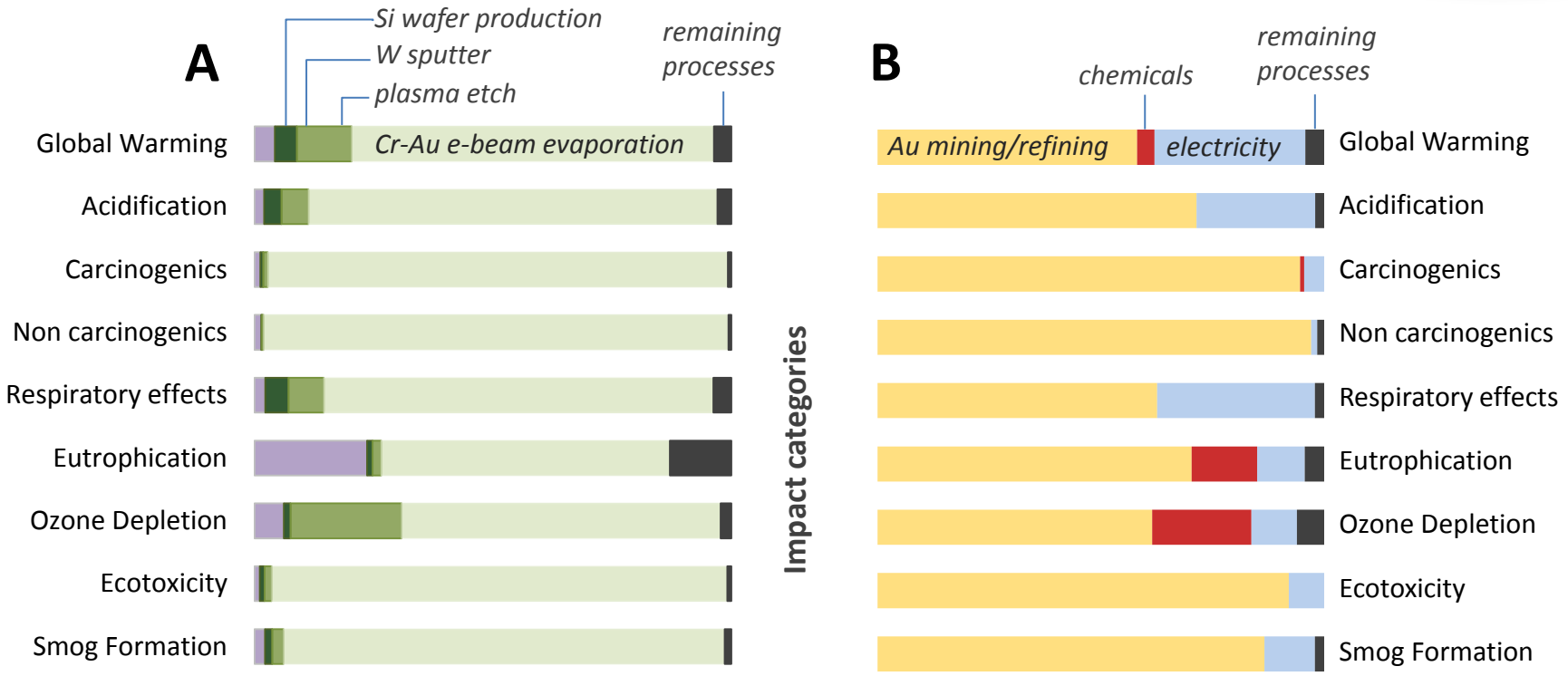
silver nanoparticles for medicine



Pourzahedi and Eckelman, *Sustainable Nanotechnology Organization Meeting;* San Diego, CA



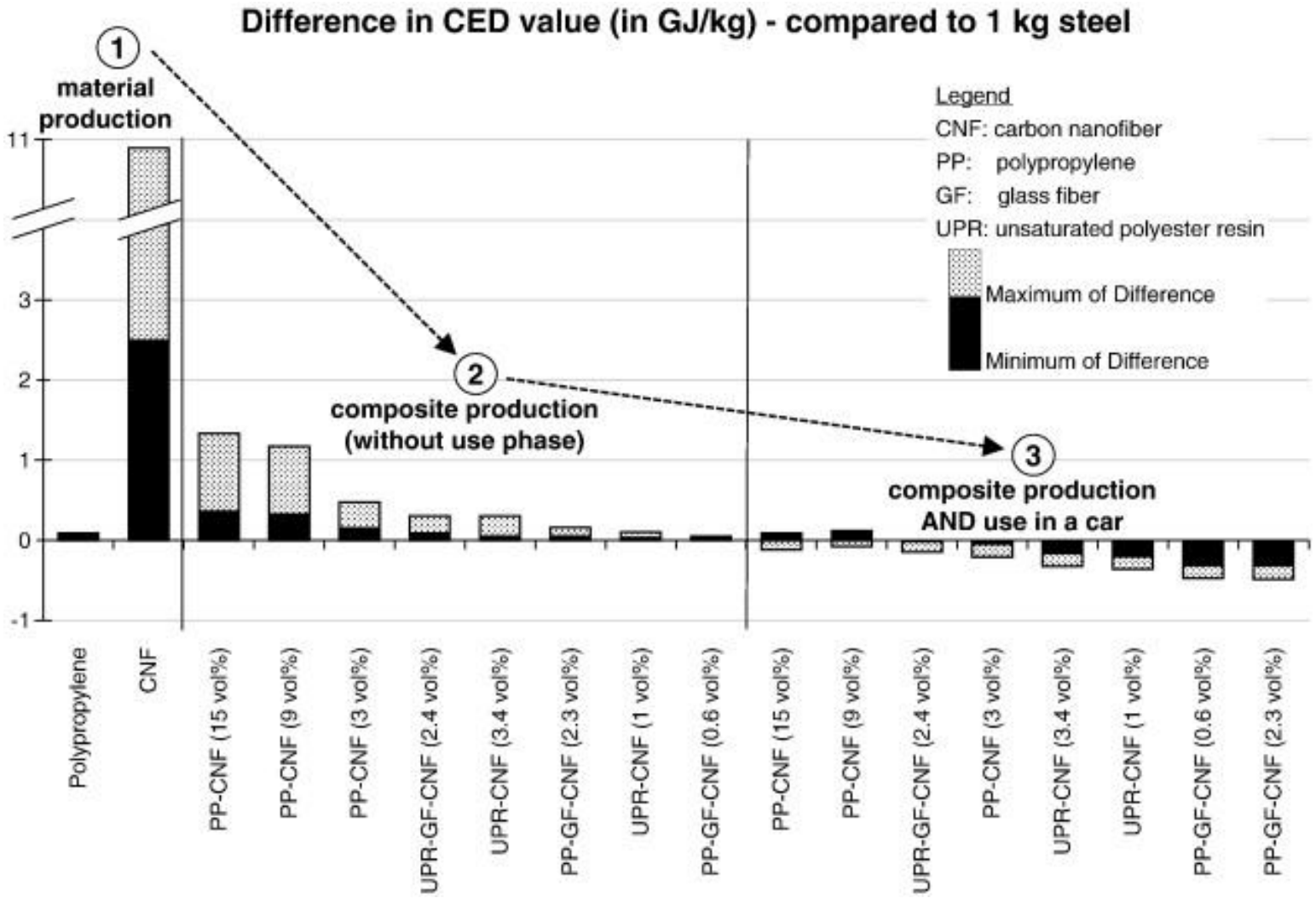
Nano Impacts vs Nano Benefits



Dahlben *et al.* (2013) *Environ. Sci. Technol.* 47, 8471-8478

CNTs are insignificant: <0.0000000000001% of impacts

Incorporating the Use Phase – Quantifying Benefits



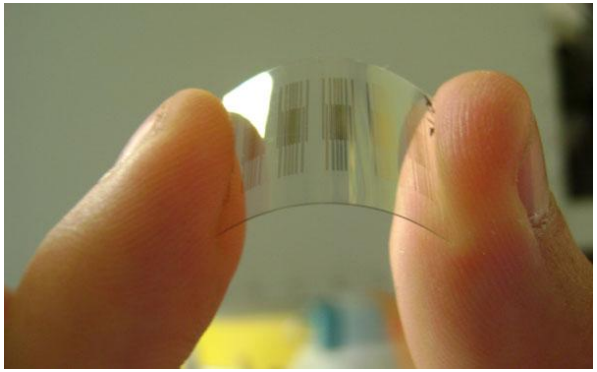
Hischier and Walser (2012) *Sci Total Environ.* 425, 271-282

Moving Towards Incorporating Econ/Environ. Benefits of Nano in LCAs of Nano-Enabled Products

Metallic NPs




Carbonaceous Nanomaterials


Chemical Sensors


Li-ion Batteries


EMI Shielding

Concluding Challenges and Acknowledgements

- What level of detail of fate, transport, exposure, and effect is appropriate or possible in LCA?
- Need information on ENMs as they are emitted from nano-enabled products, directly to consumers?
- How to model LC benefits of nano env. Applications?
- Should indirect toxicity impacts be relevant for the question 'Is this ENM *safe*?'

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Scalable NanoMfg
EEC-0832785