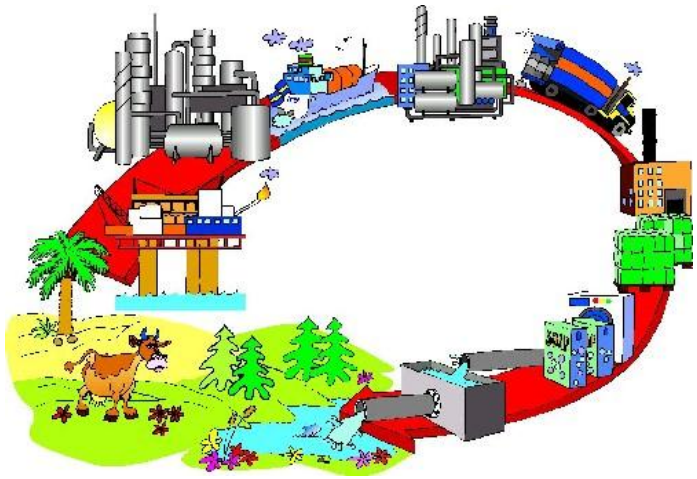
Environmental Life Cycle Assessment
PSE 476/WPS 576/WPS 595-005

Lecture 11: TRACI Impact Assessment Method

Richard Venditti



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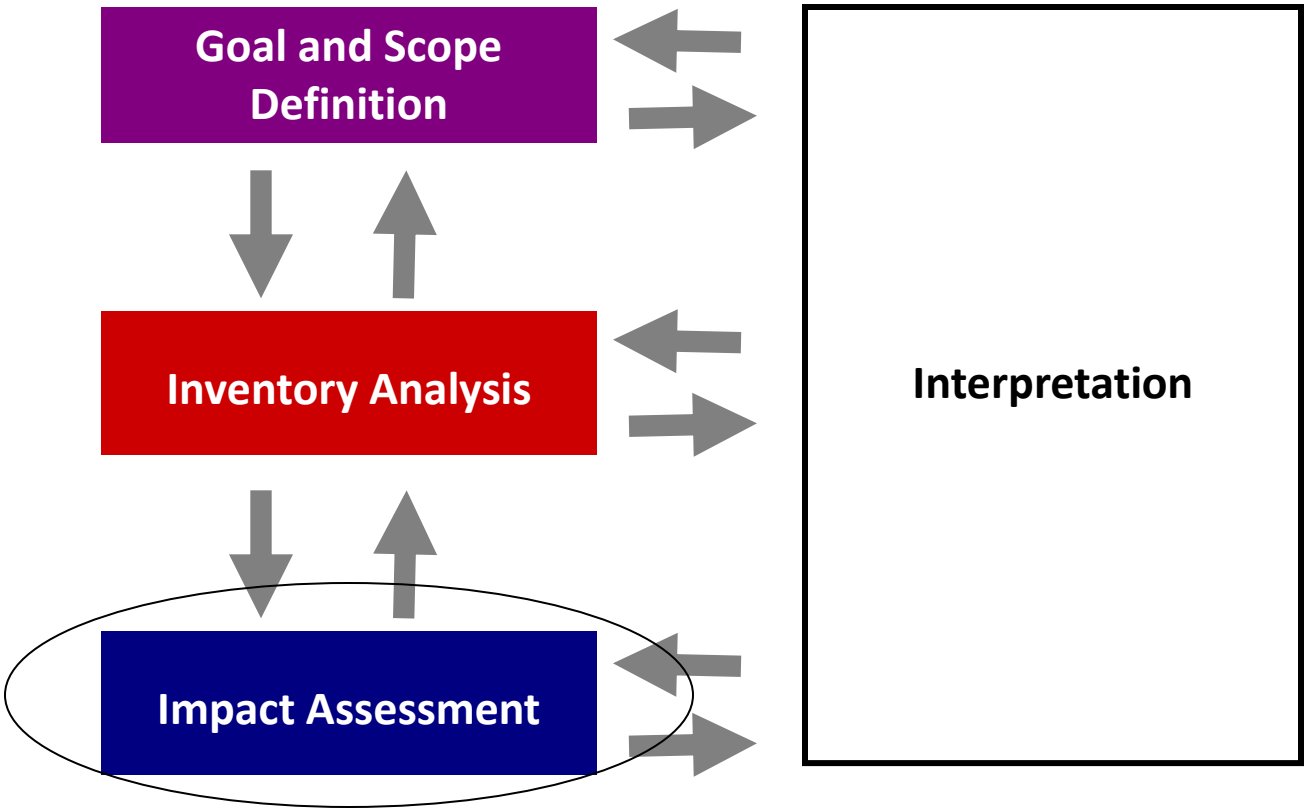
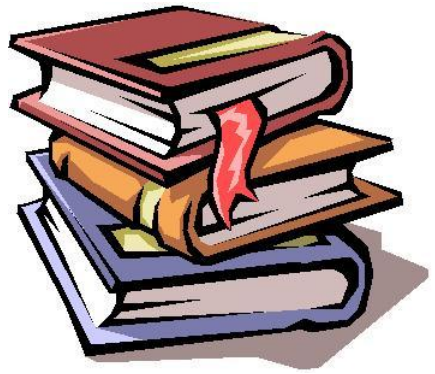
Important Aspects of Life Cycle Assessment



Impact Assessment

Definition:

Phase of life cycle assessment aimed at understanding and evaluating the magnitude and significance of the potential environmental impacts for a product system throughout its life cycle of the product [ISO 14044:2006E].



Impact Assessment: ISO Standard

- Overall steps for LCA are defined in ISO 14044

- Mandatory elements for an impact assessment
  - Selection of impact categories
  - Assignment of inventory analysis results to impact categories (classification)
  - Calculation of impact category indicator results (characterization)

- Optional elements
  - Calculation of the magnitude of category indicators (normalization), to show the significance of the calculated impact category result to the overall environmental problem
  - Grouping and ranking of the impact categories
  - Weighting of the impact categories (may not be used if competing products are compared and presented to public)

TRACI:

the tool for the reduction and assessment of chemical

and other environmental impacts

References for this presentation:

- If a reference does not appear on a slide, the following sources were used:
- Tool for the Reduction and Assessment of Chemical and other Environmental Impacts (TRACI) Software Name and Version Number: TRACI version 2.1 USER'S MANUAL Software Baseline Documentation Number S-10637-CP-2-0, August 24, 2012.
- TRACI 2.0: the tool for the reduction and assessment of chemical and other environmental impacts 2.0, Jane Bare, Clean Techn Environ Policy, DOI 10.1007/s10098-010-0338-9, January 21, 2011.
- **TRACI:** The Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts, *Jane C. Bare, Gregory A. Norris, David W. Pennington,a nd Thomas McKone, Journal of Industrial Ecology, 6(3-4), 2003.*

TRACI:

- Mid point impact assessment model
- Takes life cycle inventory data and predicts environmental impacts
- developed for sustainability metrics, life cycle impact assessment, industrial ecology, and process design impact assessment for developing increasingly sustainable products, processes, facilities, companies, and communities.
- all of these applications require quantitative data to guide decision making which impacts the current and future generations.

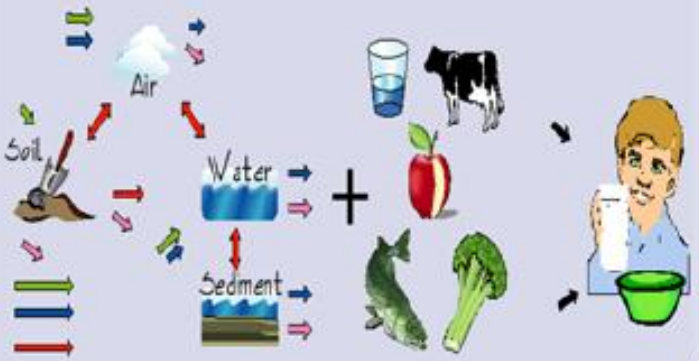
Latest version:

- Software Name and Version Number: TRACI version 2.1
- Software Baseline Documentation Number S-10637-CP-2-0
- As of: 7/24/2012
- This presentation was developed 11/20/12.

Inventory of Stressors
Chemical Emissions
Fossil Fuel Use
Land Use
Water Use

Impact Categories
Ozone Depletion
Global Warming
Acidification
Eutrophication
Smog Formation
Human Health
  Particulate
  Cancer
  Noncancer
Ecotoxicity
Fossil Fuel Use
Land Use
Water Use

Characterization (e.g., Human Health Noncancer)



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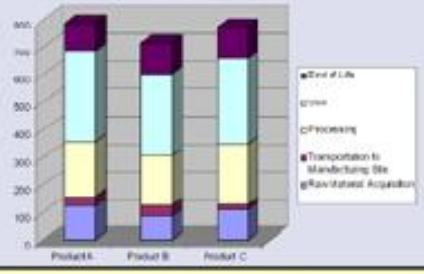
Ozone Depletion
Global Warming
Human Health Noncancer



TRACI

Tool for the Reduction and Assessment of Chemical and other environmental Impacts

Media (compartments) considered for each impact category

Impact category	Media
Ozone depletion	Air
Global climate	Air
Acidification	Air
Eutrophication	Air, water
Smog formation	Air
Human health criteria	Air
Human health cancer	Urban air, nonurban air, freshwater, seawater, natural soil, agricultural soil
Human health noncancer	Urban air, nonurban air, freshwater, seawater, natural soil, agricultural soil
Ecotoxicity	Urban air, nonurban air, freshwater, seawater, natural soil, agricultural soil

Human health criteria: particulate matter.
Smog formation: photochemical smog formation, ground level ozone.

Cause-Effect Chain Selection

Table 1 Cause-effect chain selection

Impact category	*Midpoint level selected*	*Level of site specificity selected*	*Possible endpoints*
Ozone depletion	Potential to destroy ozone based on chemical's reactivity and lifetime	Global	Skin cancer, cataracts, material damage, immune-system suppression, crop damage, other plant and animal effects
Global warming	Potential global warming based on chemical's radiative forcing and lifetime	Global	Malaria, coastal area damage, agricultural effects, forest damage, plant and animal effects
Acidification	Potential to cause wet or dry acid deposition	U.S., east or west of the Mississippi River, U.S. census regions, states	Plant, animal, and ecosystem effects, damage to buildings
Eutrophication	Potential to cause eutrophication	U.S., east or west of the Mississippi River, U.S. census regions, states	Plant, animal and ecosystem effects, odors and recreational effects, human health impacts
Photochemical smog	Potential to cause photochemical smog	U.S., east or west of the Mississippi River, U.S. census regions, state	Human mortality, asthma effects, plant effects

Cause-Effect Chain Selection

Table 1 Cause-effect chain selection

Impact category	*Midpoint level selected*	*Level of site specificity selected*	*Possible endpoints*
Ecotoxicity	Potential of a chemical released into an evaluative environment to cause ecological harm	U.S	Plant, animal, and ecosystem effects
Human health: criteria air pollutants	Exposure to elevated particulate matter less than 2.5μm	U.S., east or west of the Mississippi River, U.S. census regions, states	Disability-adjusted life-years (DALYs), toxicological human health effects
Human health: cancer	Potential of a chemical released into an evaluative environment to cause human cancer effects	U.S.	Variety of specific human cancer effects
Human health: noncancer	Potential of a chemical released into an evaluative environment to cause human noncancer effects	U.S.	Variety of specific human toxicological noncancer effects
Fossil fuel	Potential to lead to the reduction of the availability of low cost/energy fossil fuel supplies	Global	Fossil fuel shortages leading to use of other energy sources, which may lead to other environmental or economic effects
Land use	Proxy indicator expressing potential damage to threatened and endangered species	U.S., east or west of the Mississippi River, U.S. census regions, state, county	Effects on threatened and endangered species (as defined by proxy indicator)
Water use	Not characterized at this time		Water shortages leading to agricultural, human, plant, and animal effects

Impact Categories that are not included:

- Odor
- Noise
- Radiation
- Waste heat
- Accidents
- Land (in the future)
- Water (in the future)
- Others? _____

LCA activities that are not included:

- Normalization
- Weighting
- Single Score

Basic tenant of the life cycle assessment estimation:

- Environmental impact is the product of
  - the amount of the chemical emission or resource used (the environmental stressor)
  - the estimated potency (potential for damage) of the stressor.
- Reflects relative potency of the environmental stressors at a common midpoint within the cause-effect chain

Impact Categories: non-site specific

- I_i= the potential impact of all chemicals (x) for a specific impact category of concern (i)
- CF^i_{xm} = the characterization factor of chemical (x) emitted to media (m) for impact category (i)
- M_{xm} = the mass of chemical (x) emitted to media (m)

$$I^i = \sum_{xm} CF^i_{xm} * M_{xm}$$

Impact Categories: site specific :

- I_i = the potential impact of all chemicals (x) for a specific impact category of concern (i)
- F^i_{xms} = the fate of chemical (x) emitted to media (m) at site (s) for impact category
- P^i_{xms} = the potency of chemical (x) emitted to media (m) at site (s) for impact category (i)
- M_{xms} = the mass of chemical (x) emitted to media (m) at site (s).

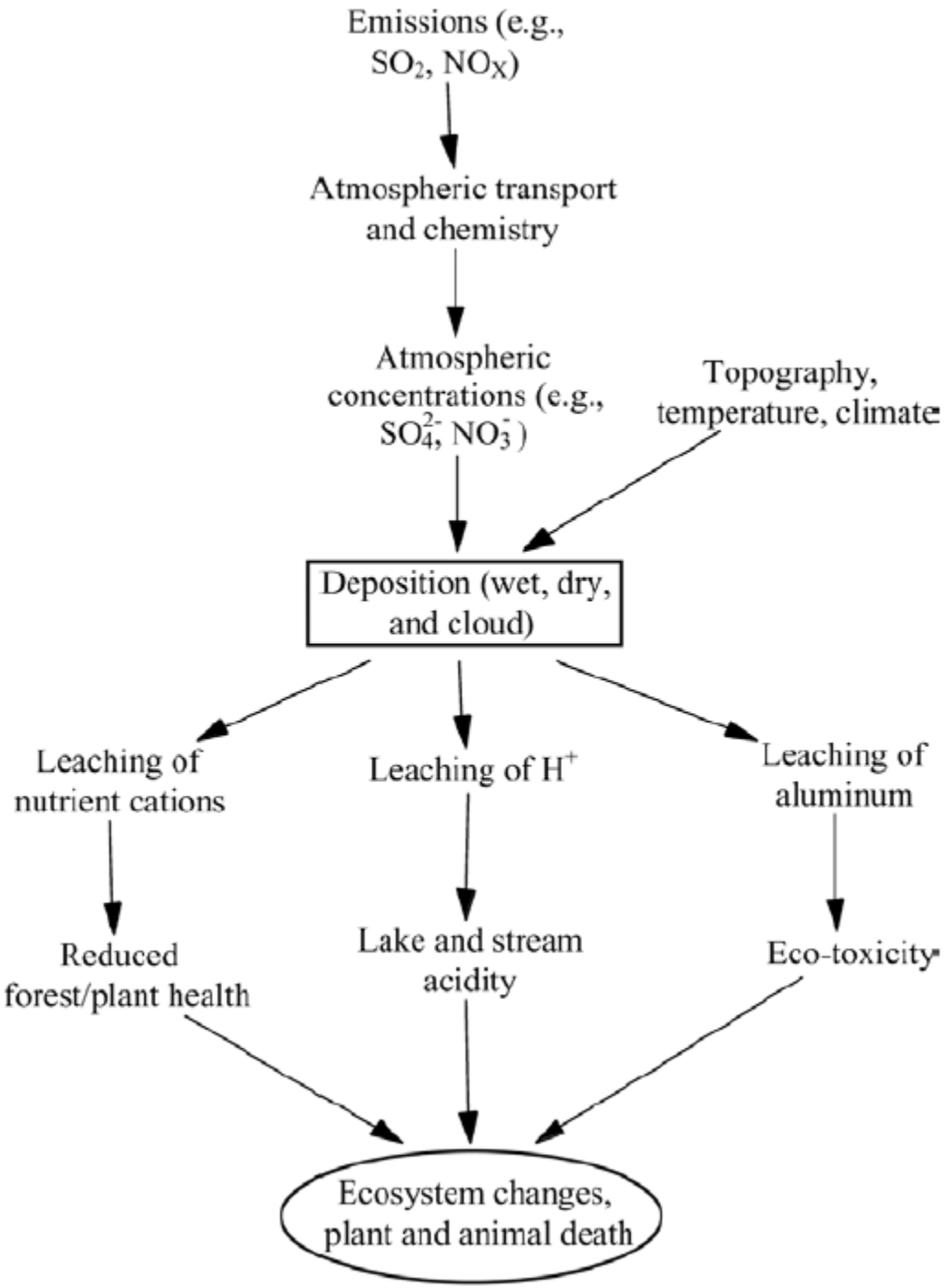
$$I^i = \sum_s \sum_x \sum_m F^i_{xms} P^i_{xms} M_{xms}$$

Acidification

- Acidification is the increasing concentration of hydrogen ion [H+] within a local environment.
  - Acids (e.g., nitric acid and sulfuric acid)
  - Other substances that increase aciditiy by chemical/biological events (e.g., ammonia)
  - By natural circumstances such as the change in soil concentrations because of the growth of local plant species.
- Acidifying substances are often air emissions, which may travel for hundreds of miles prior to wet deposition as acid rain, fog, or snow or dry deposition as dust or smoke particulate matter on the soil or water.
- Sulfur dioxide and nitrogen oxides from fossil fuel combustion have been the largest contributors to acidification.
- Substances which cause acidification can cause damage to
  - lakes, streams, rivers, and various plants and animals.
  - building materials, paints, and other human-built structures,

Acidification

- In these type of figures, the rectangle identifies the midpoint indicator and the oval indicates the endpoints



Acidification

- TRACI is not site-specific in acidification , thus not sensitive to
  - the local buffering capacity,
  - the local plant and animal species
  - the existing acidity within the environment
- These site effects may be important and should be acknowledged in an LCA

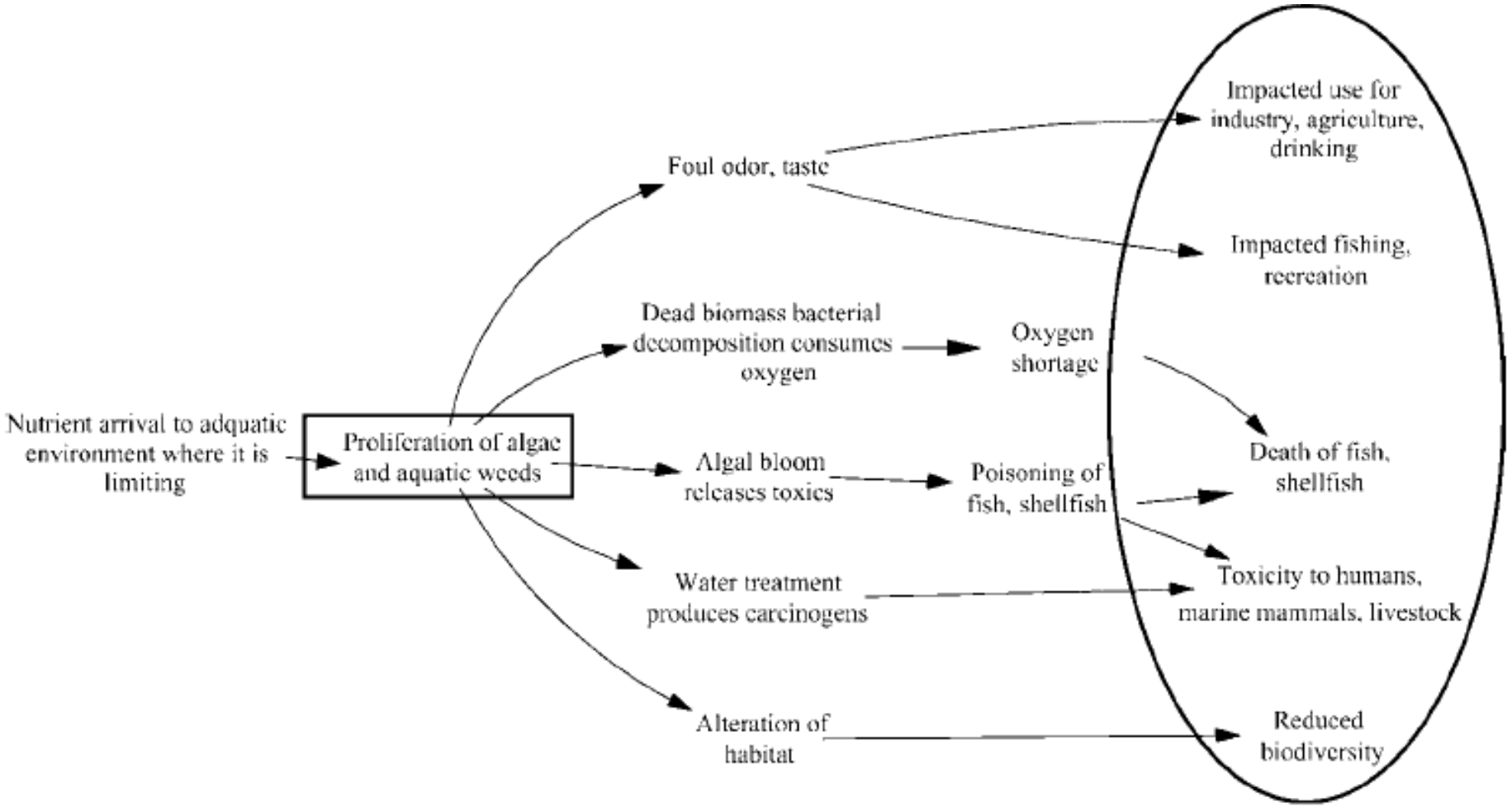
Eutrophication

- The ‘enrichment of an aquatic ecosystem with nutrients (nitrates, phosphates) that accelerate biological productivity (growth of algae and weeds) and an undesirable accumulation of algal biomass’

- *Eutrophication is responsible for 60% of the impaired river reaches in the US, most widespread pollution problem in estuaries*

- Although nitrogen and phosphorus are important parts of fertilization of agricultural lands/vegetation, excessive releases may provide undesired effects on the waterways in which they travel.
- While phosphorus usually has a more negative impact on freshwater lakes and streams nitrogen is often more detrimental to coastal environments

Eutrophication



Eutrophication

- Some of the major substances which have a role in this impact category are difficult to characterize including emissions from:
  - wastewater treatment plants,
  - Decaying plant life
  - pulp and paper mills,
  - food processing plants,
  - fertilizers used in agricultural, commercial, and individual household locations.

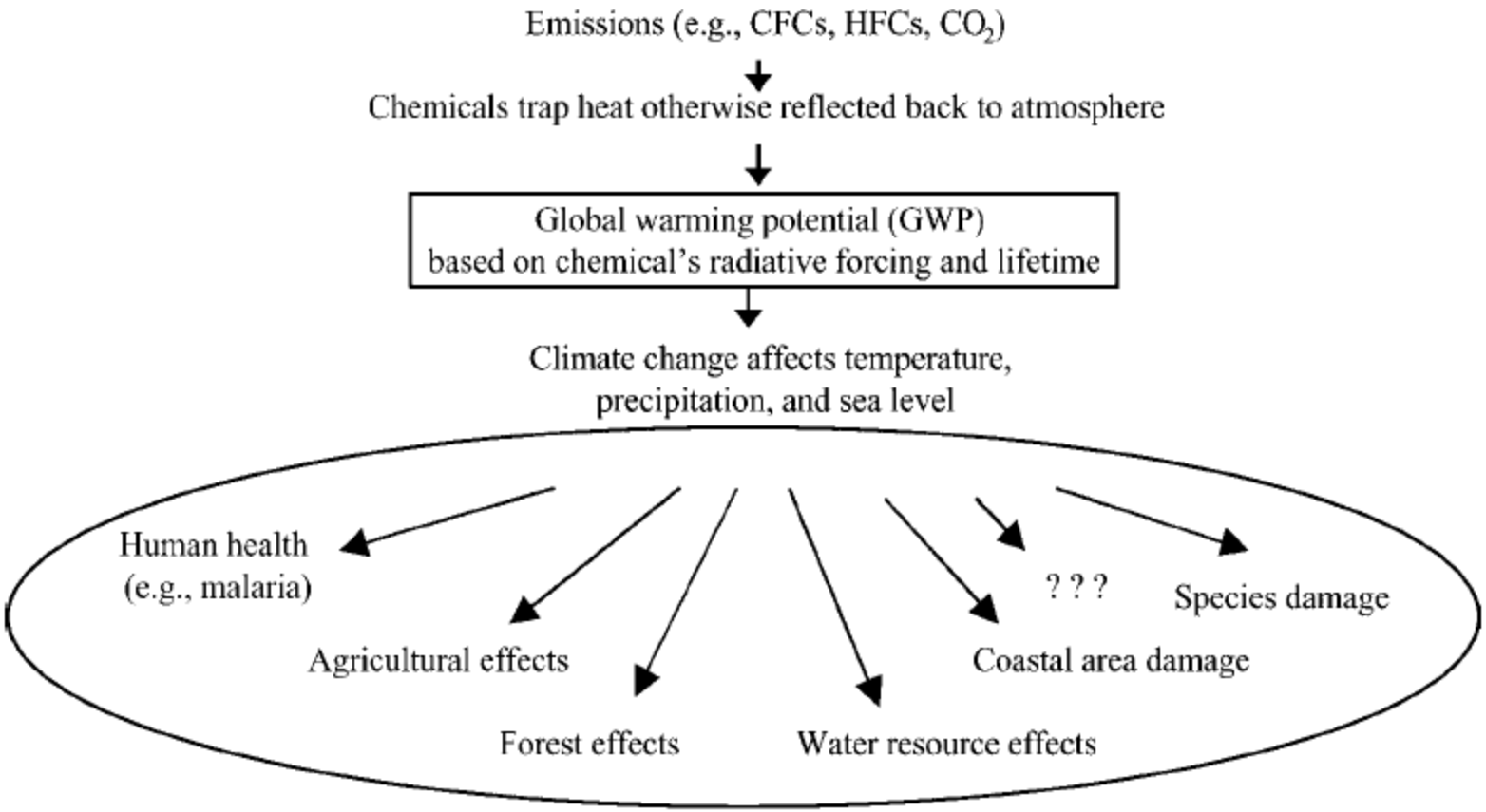
Eutrophication

- The majority of fertilizer (when utilized correctly) is a product and provides the benefits for which it was purchased.
    - the portion of the application that achieved its aim of fertilizing fields considered to be the useful product
- However, depending on the slope of the fields, the precipitation, and volatilization of the fertilizer, some of this product may go beyond the original intended boundaries and cause unintended consequences downstream.
  - *unintended consequences considered to be the emission*

Climate Change (Global Warming)

- Global warming is an average increase in the temperature of the atmosphere near the Earth's surface and in the troposphere, which can contribute to changes in global climate patterns.
- Global warming can occur from both natural and human activities.
- During the past 200 years,
  - the sources of GHG's have increased (mostly caused from the increased combustion of fossil fuels
  - the sinks have decreased (e.g.,deforestation and land use changes).

Climate Change (Global Warming)



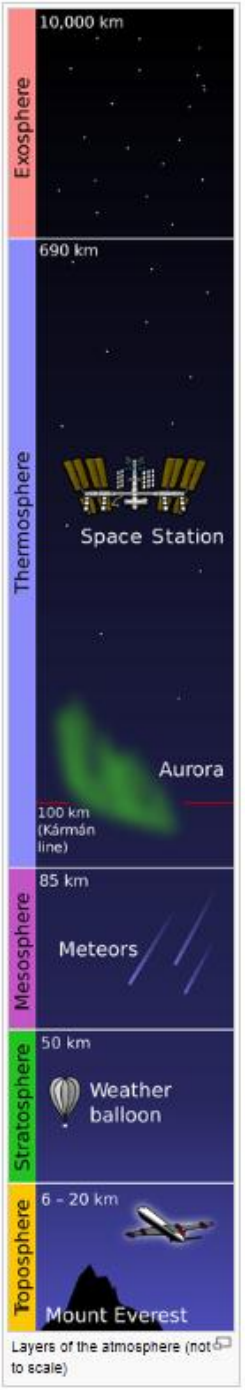
Climate Change (Global Warming)

- Global Warming Index = $\Sigma_i e_i \times GWP_i$
- e_i emission in kg
- GWP_i global warming potential of substance i

Ozone depletion

- Ozone (O_3) within the stratosphere provides protection from radiation
- Decreases in this O_3 can lead to skin cancers and cataracts in humans
- This O_3 has been documented to have effects on crops, other plants, marine life, and human-built materials.
- Substances reported and linked to decreasing the stratospheric O_3 level:
  - Chlorofluorocarbons (CFCs) which are used as refrigerants
  - foam blowing agents
  - solvents
  - halons such as used as fire extinguishing agents

- Ozone Depletion Index = $\Sigma_i\ e_i \times ODP_i$
- e_i emission in kg
- ODP_i ozone depletion potential of substance i



Layers of the atmosphere (not to scale)

Ozone depletion

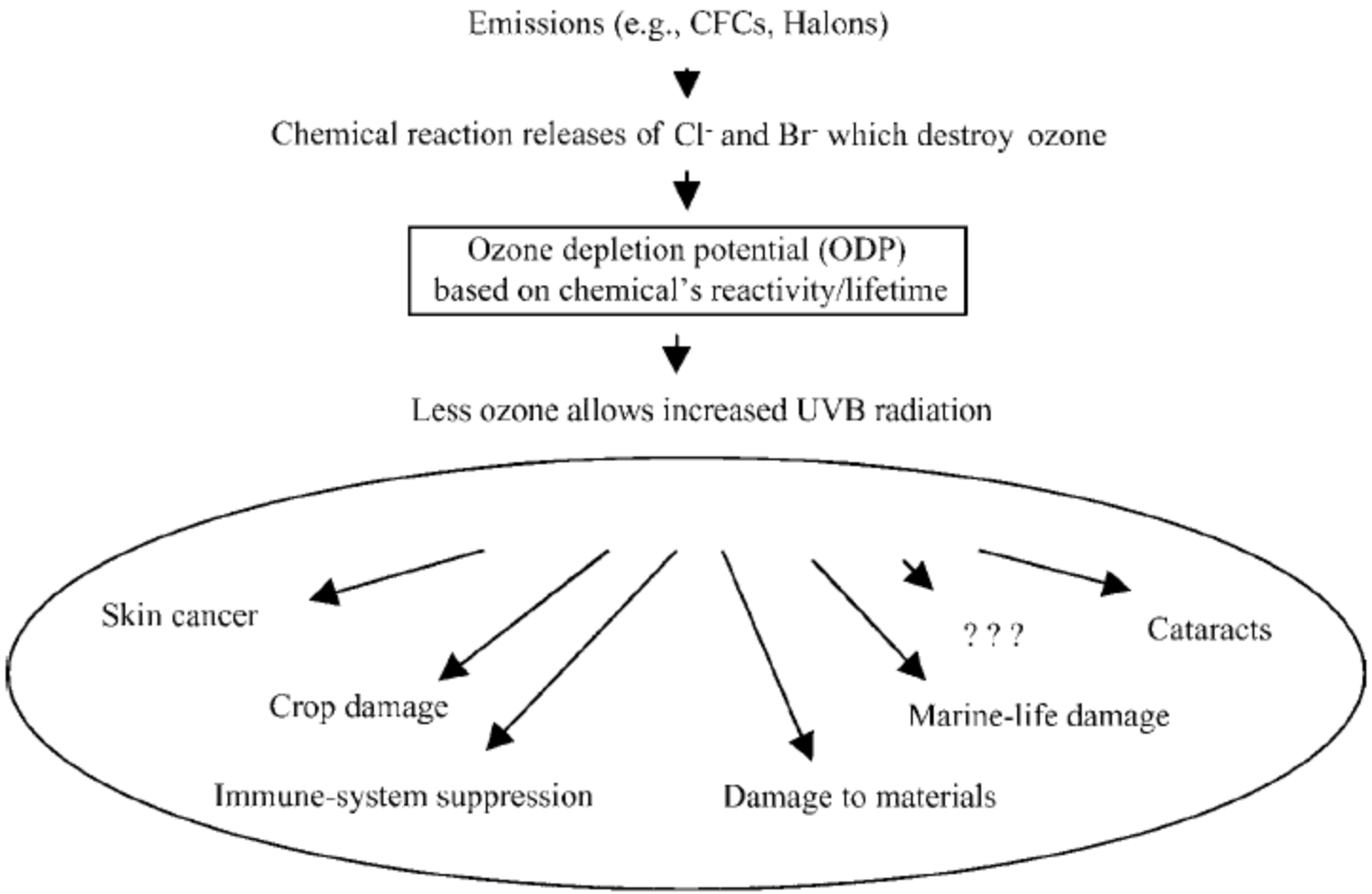


Figure 2 Ozone depletion midpoint/endpoint modeling. The rectangle indicates the midpoint and the oval indicates the endpoints.

Ozone depletion

- Over 20 years ago, the US signed the Montreal Protocol to reduce CFC production
- US later implemented even more stringent reductions which have led to a complete end of production of CFCs (by 1996) and halons (by 1994).
- Levels of total inorganic chlorine have been declining since 1998
- Recovery of the ozone layer is expected in about 50 years

The human health criteria pollutants category

- The Clean Air Act requires EPA to set National Ambient Air Quality Standards for six common air pollutants (also known as "criteria pollutants"):
  - particle pollution (often referred to as particulate matter),
  - ground-level ozone,
  - carbon monoxide,
  - sulfur oxides,
  - nitrogen oxides,
  - and lead.
- These pollutants can harm human health and the environment, and cause property damage.
- Of the six pollutants, particle pollution and ground-level ozone are the most widespread health threats.
- EPA calls these pollutants "criteria" air pollutants because it regulates them by developing human health-based and/or environmentally-based criteria (science-based guidelines) for setting permissible levels
- http://www.epa.gov/air/criteria.html

TRACI: The human health criteria pollutants category (particulates)

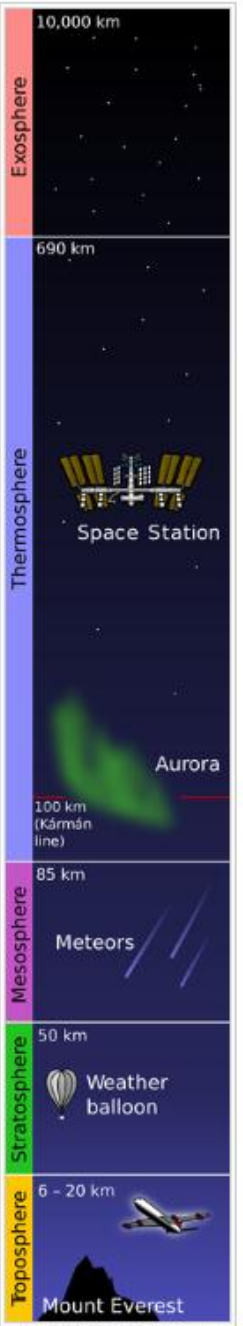
- Particulate matter (primary particulates) and precursors to particulates (secondary particulates).
- Particulate matter is a collection of small particles in ambient air, and can cause negative human health effects including respiratory illness and death
- The most common precursors to secondary particulates are sulfur dioxide (SO_2) and nitrogen oxides(NO_x).
- Common sources:
  - fossil fuel combustion
  - wood combustion
  - dust particles from roads and fields

The human health criteria pollutants category (particulates)

- Particulate matter is divided into two major groups of concern:
  - ‘‘inhalable coarse particles’’ between 2.5 and 10 μm in diameter, like dust from roadways,
  - ‘‘fine particles’’ which are smaller than or equal to 2.5 μm in diameter, often the products of combustion
- Sensitive populations such as children, the elderly, and people with asthma are more susceptible to experiencing higher consequences
- Although national US standards have existed since 1971, even more stringent standards were placed in 2006

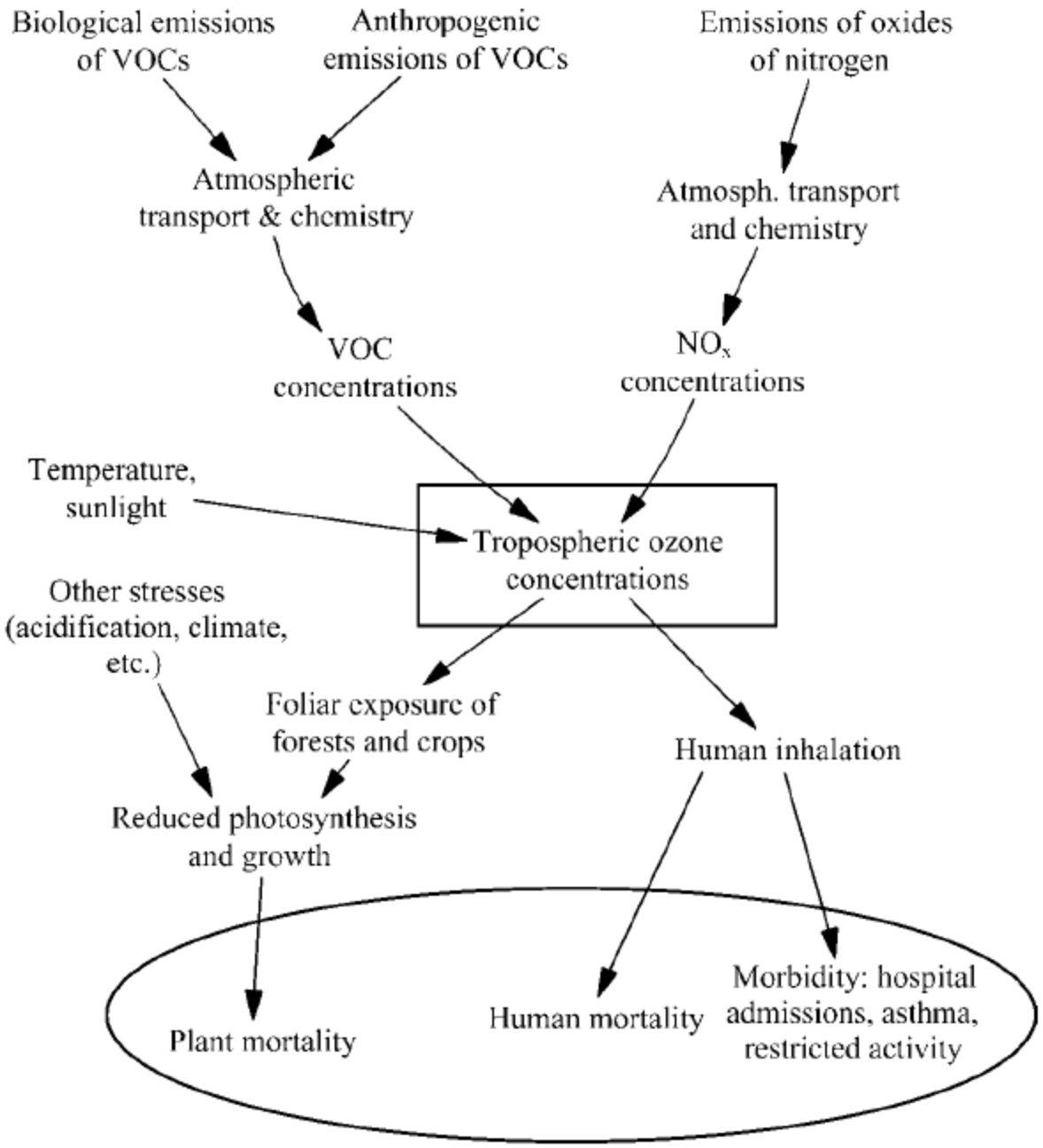
Photochemical smog formation

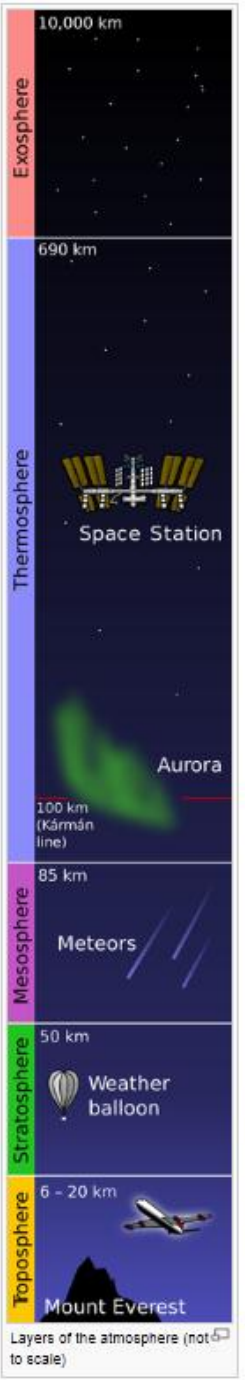
- Ground-level (troposphere) ozone created by various chemical reactions, between nitrogen oxides (NO_x) and volatile organic compounds (VOCs) in sunlight.
- Human health effects result in a variety of respiratory issues including increasing symptoms of bronchitis, asthma, and emphysema.
- Permanent lung damage may result from prolonged exposure to ozone.
- Ecological impacts include damage to various ecosystems and crop damage.
- The primary sources of ozone precursors:
  - motor vehicles
  - electric power utilities
  - industrial facilities



Layers of the atmosphere (not to scale)

Photochemical smog formation





Human health cancer, non-cancer, and ecotoxicity

- Based on the USEtox model
- USEtox is developed with two spatial scales: continental and global. (and is international)
- The environmental compartments (media) within the continental scale includes:
  - urban air
  - rural air
  - agricultural soil
  - industrial soil
  - freshwater
  - coastal marine water
- USEtox includes inhalation, ingestion of drinking water, produce, meat, milk, and freshwater and marine fish.

Human health cancer, non-cancer, and ecotoxicity

Characterisation

- how much does the emission contribute?

Quantitatively determine the impact score per environmental category

$$IS = \sum_i \sum_x CF_{x,i} \cdot m_{x,i}$$

IS = impact score
CF = characterisation factor
m = life cycle emission
x = substance type
i = compartment type

a Characterisation Factor is a quantitative representation of the (relative) hazardousness of a specific emission
expressed in absolute metric or relative to a reference substance
e.g. the human toxicity characterisation factor of benzene is 300 CTU

USEtox™

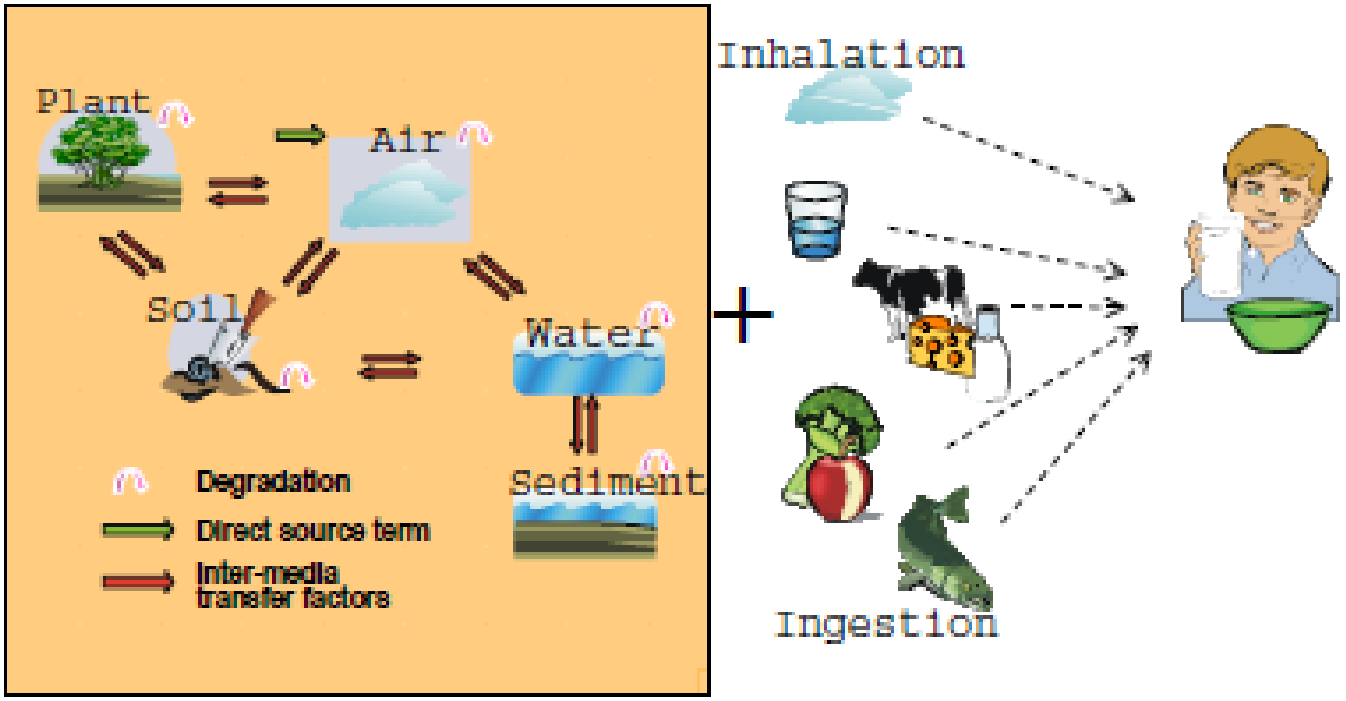
Chemical fate

- The environmental fate of chemicals describes the processes by which chemicals move and are transformed in the environment.
- Environmental fate processes that should be addressed include:
  - persistence in air, water, and soil
  - reactivity and degradation
  - migration in groundwater
  - removal from effluents by standard waste water treatment methods
  - bioaccumulation in aquatic or terrestrial organisms

  - http://www.epa.gov/dfe/pubs/tools/ctsa/ch5/mod5-3.pdf

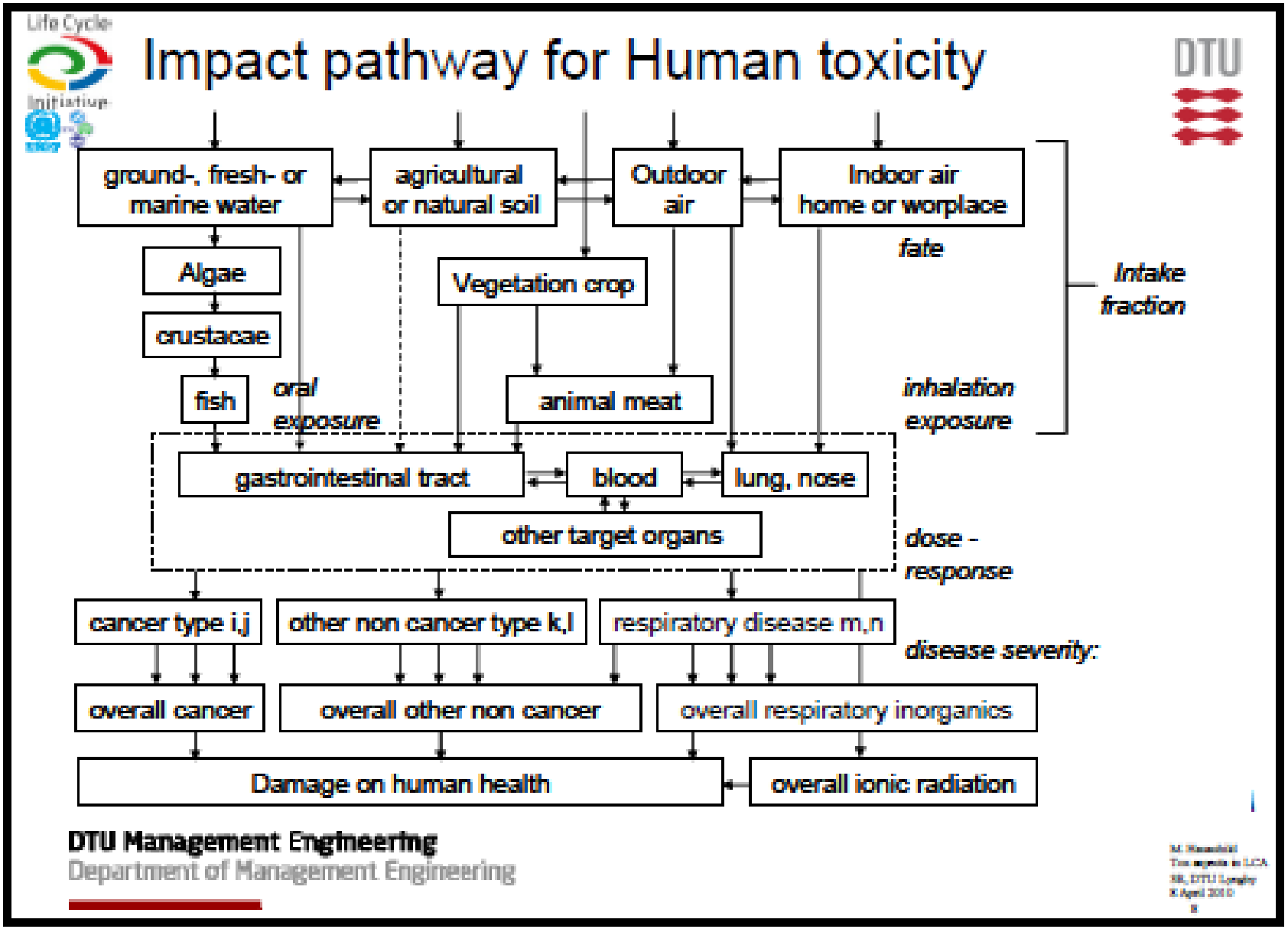
Human health cancer, non-cancer, and ecotoxicity

What is chemical fate
Role of fate models in LCA

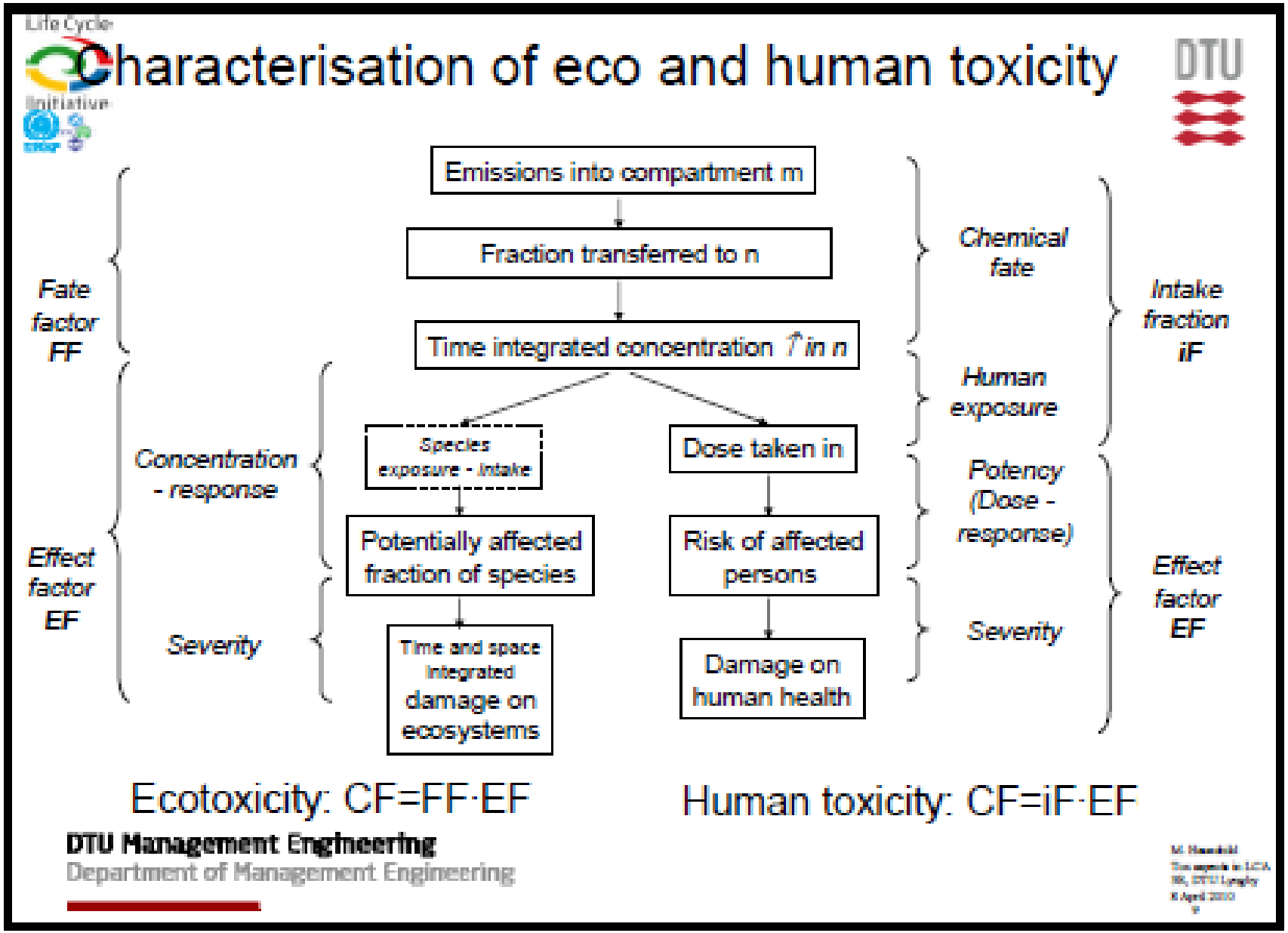


Environmental distribution of chemical – resulting human exposure

Human health cancer, non-cancer, and ecotoxicity



Human health cancer, non-cancer, and ecotoxicity



Resource Depletion: fossil fuel use.

- Non-site specific recommendation for fossil fuel use characterization
- Solid and liquid fuels are not perfect substitutes
- Depletion of coal ≠ depletion of petroleum
- Scenarios developed to replace current energy sources

- Amount of energy to make the replacement fuel minus the energy to make the conventional fuel is called the “increase in energy input requirements per unit of consumption of fuel i”, N_i (a characterization factor)

- F_i is the consumption of fuel i per unit product
- Fossil fuel index = = $\Sigma_i N_i \times F_i$

Resource Depletion: land use, and water use.

- land and water not yet incorporated
- Future use recommendations are expected to be site-specific due to
  - high variability in water availability
  - unique properties of location, meteorology, and existing ecosystems

Impact Category Headings

- Impact Category Headings
- CAS # - Chemical Abstract Services Number
- Substance Name – Substances Name (may include categories)
- Alternate Substance Name – Limited Alternatives are available
- Global Warming Air (kg CO2 eq/kg substance) = Global Warming Potentials for Air Emissions
- Acidification Air (kg SO2 eq/kg substance) = Acidification Potentials for Air Emissions
- Acidification Water (kg SO2 eq/kg substance) = Acidification Potentials for Water Emissions
- HH Particulate Air (PM2.5eq/kg substance) = Human Health Particulate (and secondary particulate matter precursors) Potentials for Air Emissions
- Eutrophication Air (kg N eq/kg substance) = Eutrophication Potentials for Air Emissions
- Eutrophication Water (kg N eq/kg substance) = Eutrophication Potentials for Water Emissions
- Ozone Depletion Air (kg CFC-11 eq/kg substance) = Ozone Depletion Potentials for Air Emissions
- Smog Air (kg O3 eq/kg substance) = Smog Formation Potentials for Air Emissions

- Ecotox CF (CTUeco/kg), Em.airU, freshwater = Freshwater Ecotoxicity Potentials for Urban Air Emissions
- Ecotox CF (CTUeco/kg), Em. airC, freshwater = Freshwater Ecotoxicity Potentials for Rural Air Emissions
- Ecotox CF (CTUeco/kg), Em. Fr.waterC, freshwater = Freshwater Ecotoxicity Potentials for Freshwater Emissions
- Ecotox CF (CTUeco/kg), Em. seawaterC, freshwater = Freshwater Ecotoxicity Potentials for Seawater Emissions
- Ecotox CF (CTUeco/kg), Em. Nat.soilC, freshwater = Freshwater Ecotoxicity Potentials for Natural Soil Emissions
- Ecotox CF (CTUeco/kg), Em. Agr.soilC, freshwater = Freshwater Ecotoxicity Potentials for Agricultural Soil Emissions

- CF Flag Ecotox = Characterization Factor Flag for Ecotoxicity Potentials

- Human health CF (CTUcancer/kg), Emission to urban air, cancer = Human health Cancer Potentials for Urban Air Emissions
- Human health CF (CTUnoncancer/kg), Emission to urban air, non-canc. = Human health Non-cancer Potentials for Urban Air Emissions
- Human health CF (CTUcancer/kg), Emission to cont. rural air, cancer = Human health Cancer Potentials for Rural Air Emissions
- Human health CF (CTUnoncancer/kg), Emission to cont. rural air, non-canc. = Human health Non-cancer Potentials for Rural Air Emissions
- Human health CF (CTUcancer/kg), Emission to cont. freshwater, cancer = Human health Cancer Potentials for Freshwater Emissions
- Human health CF (CTUnoncancer/kg), Emission to cont. freshwater, non-canc. = Human health Non-cancer Potentials for Freshwater Air Emissions
- Human health CF (CTUcancer/kg), Emission to cont. sea water, cancer = Human health Cancer Potentials for Sea water Emissions
- Human health CF (CTUnoncancer/kg), Emission to cont. sea water, non-canc. = Human health Non-cancer Potentials for Sea water Emissions
- Human health CF (CTUcancer/kg), Emission to cont. natural soil, cancer = Human health Cancer Potentials for Natural Soil Emissions
- Human health CF (CTUnoncancer/kg), Emission to cont. natural soil, non-canc. = Human health Non-cancer Potentials for Natural Soil Emissions
- Human health CF (CTUcancer/kg), Emission to cont. agric. soil, cancer = Human health Cancer Potentials for Agricultural Soil Emissions
- Human health CF (CTUnoncancer/kg), Emission to cont. agric. soil, non-canc. = Human health Non-cancer Potentials for Agricultural Soil Emissions

- CF Flag HH carcinogenic = Characterization Factor Flag for Human Health Carcinogenic Potentials
- CF Flag HH non-carcinogenic = Characterization Factor Flag for Human Health Non-carcinogenic Potentials

Acronymns:

- CTU – Comparative Toxicity Unit
- DOE – Department of Energy
- EPA – Environmental Protection Agency
- GWP – Global Warming Potential
- ISO - International Organization of Standardization
- LCA – Life Cycle Assessment
- LCIA – Life Cycle Impact Assessment
- NEI – National Emissions Inventory
- NIST – National Institute of Standards and Technology
- NRMRL – National Risk Management Research Laboratory
- ODP – Ozone Depletion Potential
- ORD – Office of Research and Development
- PM – Particulate Matter
- STD – Sustainable Technology Division
- TRACI – Tool for the Reduction and Assessment of Chemical and other environmental Impacts
- TRI – Toxics Release Inventory
- US – United States
- USETOX –model developed under UNEP-SETAC Life Cycle Initiative

Example using TRACI 2.1

- To calculate the score for each individual impact category, multiply the mass of the substance (kg) emitted in the given compartment (e.g., urban air, agricultural soil) with the characterization factor for that substance in each impact category.

Example 1

- Assume the emissions include the following.
- Halon-1301 = 2 kg emissions to air
- Which has a GWP for air = 7140,
- And an ODP for air = 16.
- Would yield the following scores
- For GWP = 2 kg * 7140 kg CO2 eq / kg substance = 14,280 kg CO2 eq
- For ODP = 2 kg * 16 kg CFC-11 eq / kg substance = 32 kg CFC-11 eq

Example 2

- Similarly, the cancer and non-cancer categories are treated as independent impact categories and should not be aggregated. The media emissions can be aggregated however.

- Assume the emissions include the following.

- **Benzene = 5 kg emissions to rural air**
- Which has a Smog Potential for air = 0.72 O3 eq / kg substance,
- And an Ecotoxicity Potential for rural air = 0.064 CTUeco / kg substance,
- And a Human health Cancer Potential to rural air = 1.2 E-07 CTUcancer / kg substance
- And a Human health Noncancer Potential to rural air = 3.0 E-08 CTUnoncancer / kg substance

- **And Benzene = 10 kg emissions to freshwater**
- And an Ecotoxicity Potential for freshwater = 66 CTUeco / kg substance,
- And a Human health Cancer Potential to freshwater = 2.4 E-07 CTUcancer / kg substance
- And a Human health Noncancer Potential to freshwater = 6.1 E-08 CTUnoncancer / kg substance

Example 2

- The above two emissions of benzene would yield the following scores.
- For Smog = 5 kg * 0.72 ozone eq / kg substance = 3.6 ozone eq
- For Ecotoxicity = (5 kg * 0.064 CTUeco / kg substance) + (10 kg * 66 CTUeco / kg substance) = 660 CTUeco
- For Human Health Cancer = (5 kg * 1.2 E-07 CTUcancer / kg substance) + (10 kg * 2.4 E-07 CTUcancer / kg substance) = 3.0 E-06 CTUcancer
- For Human Health Noncancer = (5 kg * 3.0 E-08 CTUnoncancer / kg substance) + (10 kg * 6.1 E-08 CTUnoncancer / kg substance) = 7.6 E-7 CTUnoncancer

Summary:

- Life cycle assessment
- TRACI
- Stressors
- TRACI Impact Categories
- Characterization
- Media-Compartments
- Cause-effect chain
- Midpoint indicators
- Endpoint indicators
- Optional assessment activities: normalization, weighting, single score
- Potency
- Non-site specific
- Site specific
- USEtox
- Fate factor
- Effect factor
- Intake factor