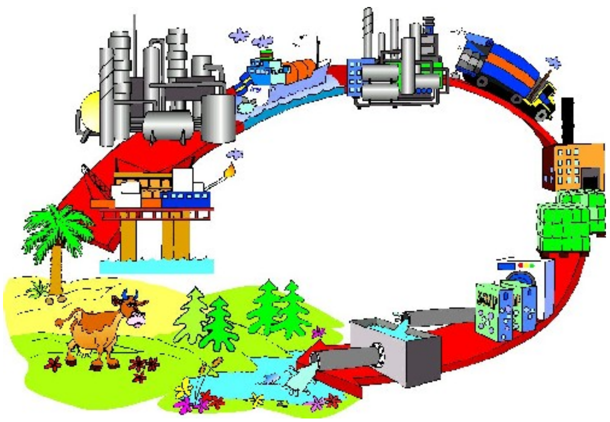
Life cycle analysis (LCA) and sustainability assessment



Richard A. Venditti
Forest Biomaterials
North Carolina State University
Raleigh, NC 27695-8005

Richard_Venditti@ncsu.edu
Go.ncsu.edu/venditti

Tragedy of the Commons

Hardin, G. (1968). "The Tragedy of the Commons". *Science, 12(3859): 1243-1248.*

"Ruin is the destination toward which all men rush, each pursuing his own best interest in a society that believes in the freedom of the commons. Freedom in a commons brings ruin to all."

2

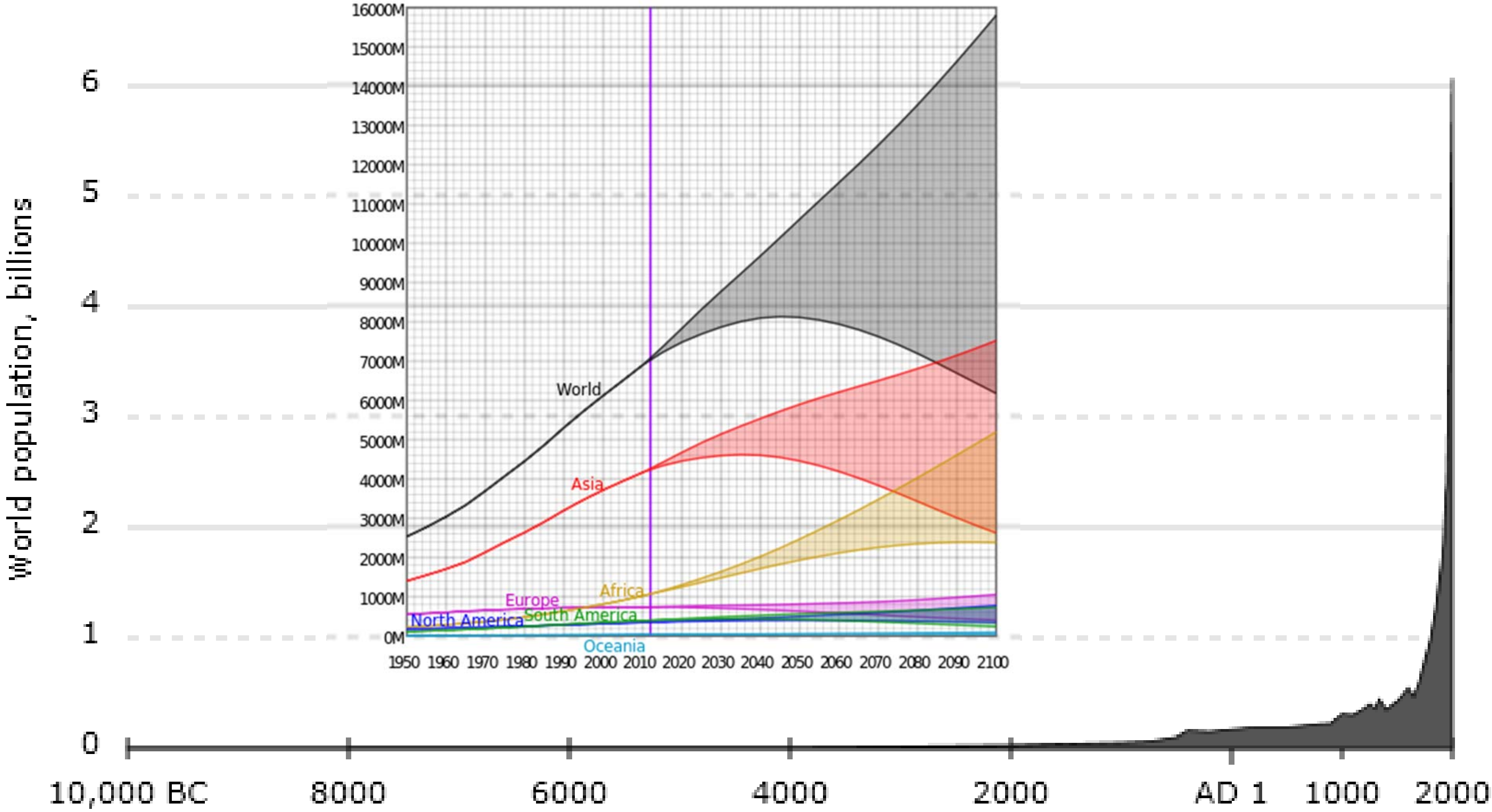
Cuyahoga River

Cuyahoga river in Ohio (runs through Cleveland) caught on fire several times between 1868 and 1969. A catalyst for Clean Water Act of 1972.

November 3, 1952 (Source: U.S. EPA)

Sometime in the 1960s (Source: cleveland.com)

World Population



Wikipedia, World Population

Sustainability?

- How do we supply societies needs without (irreversibly) harming the environment or future generations' ability to meet their needs?
  - **People – Planet - Profit**

- We have many options to meet our demands.

- PAPER OR PLASTIC?

- How to choose the "best" option with respect to environmental concerns?

- Life cycle assessment helps to inform our choices.

What is a Life Cycle Assessment ?

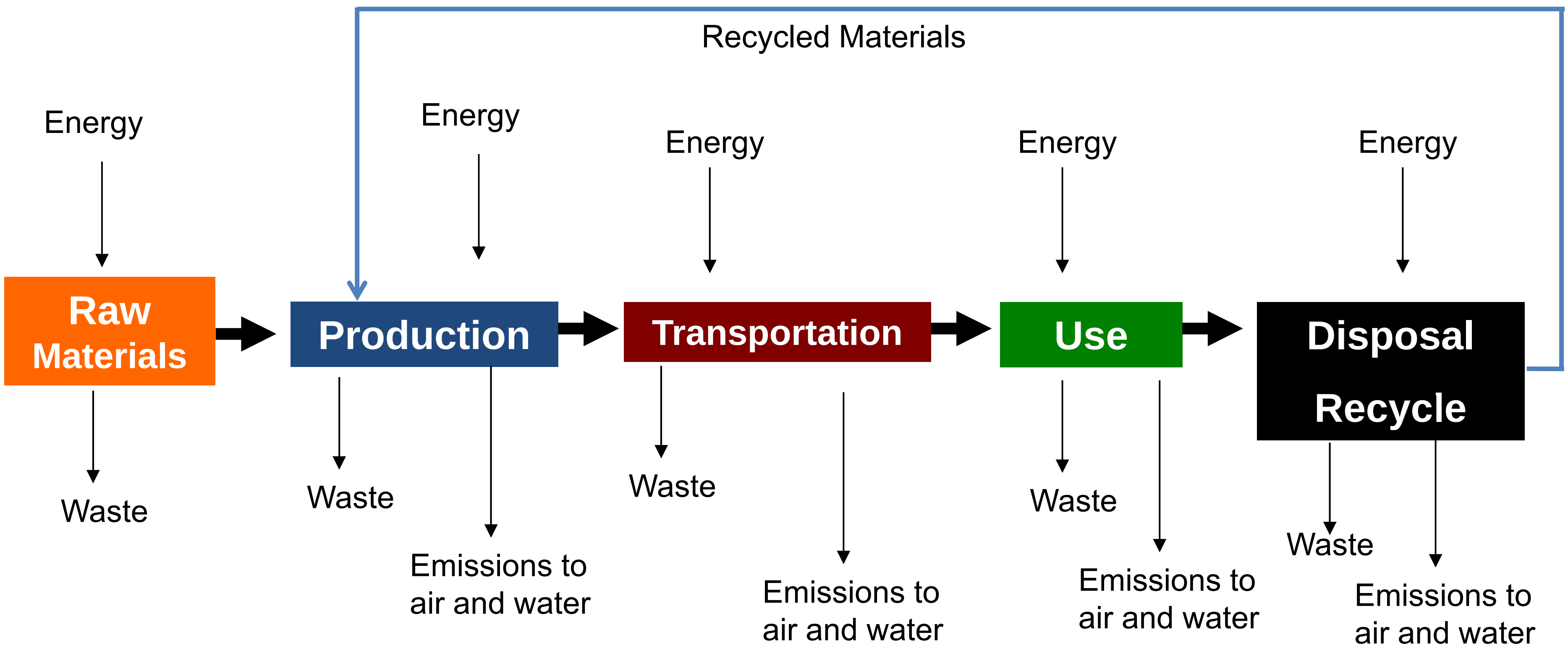
Life Cycle Assessment (LCA) is a tool to assess the potential environmental impacts of products, systems, or services at all stages in their life cycle

The most widely accepted methodology: ISO 14044:2006(E).

Alternative boundaries:

- **Cradle to Gate**: raw materials to finished good (no use or end life considerations)
- **Cradle to Grave**: Considers everything from harvesting materials to the disposal of the finished goods
- **Gate to Gate**: Considers everything from receiving to shipping gate

Life Cycle Stages



LCA: Systems Thinking

- **Systems thinking** is the process of understanding how things influence one another within a whole.

- In nature, systems thinking examples include ecosystems in which various elements such as air, water, movement, plants, and animals work together to survive or perish.

- In organizations, systems consist of people, structures, and processes that work together to make an organization healthy or unhealthy.

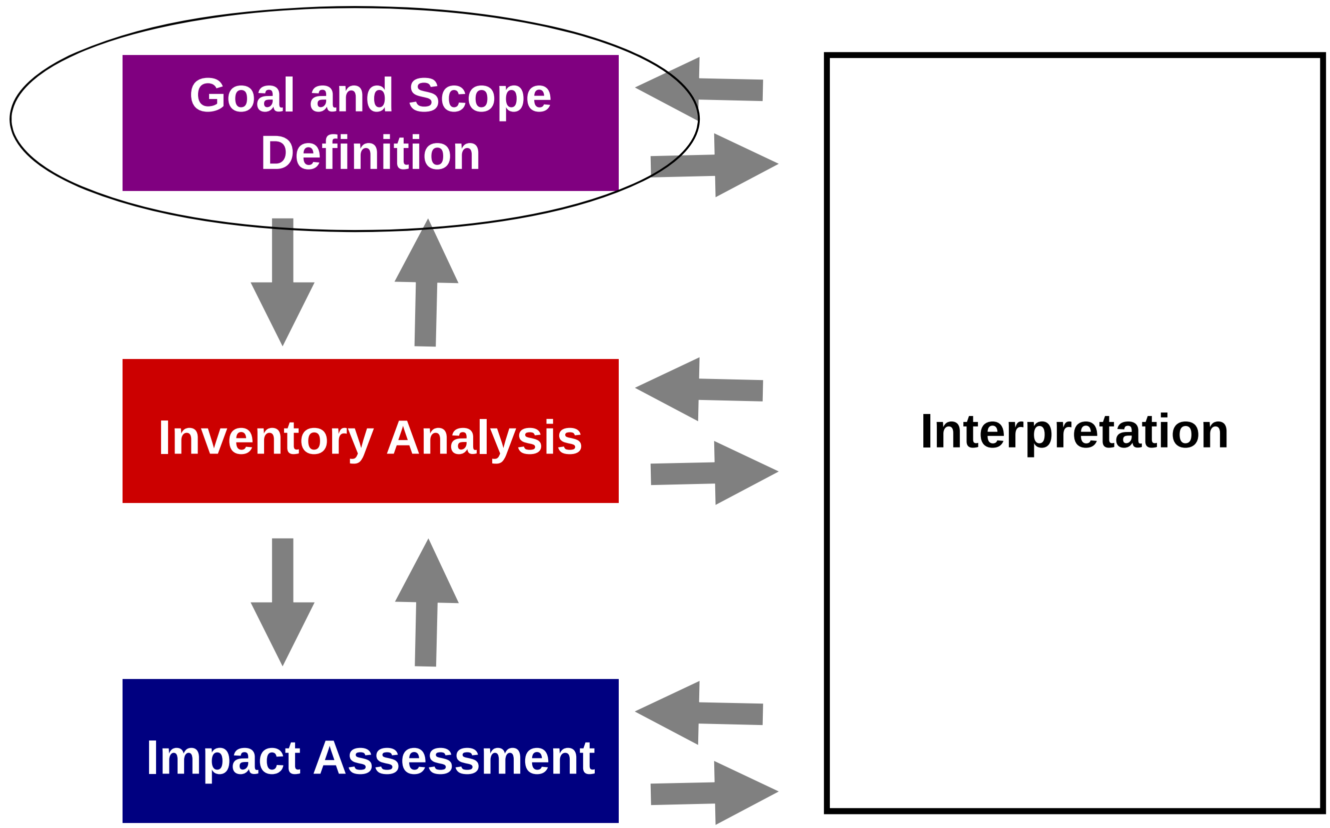
- Systems Thinking has been defined as an approach to problem solving, by viewing "problems" within the context of an overall system, rather than reacting to specific parts, outcomes or events and potentially contributing to further development of unintended consequences. (Wikepedia)

Interpretation: Systems Thinking: Unintended Consequences

- For example, in the manufacturing of a metal alloy,
  - one can use a different alloy to reduce GHG emissions during processing
  - however, that might cause carcinogens from the process to go up,
  - that might cause pollution prevention equipment to be considered,
  - that might require more electricity,
  - that might increase GHG emissions

- For example, in emerging countries it was considered to promote electric bikes instead of old cars to reduce pollution
  - bikes are more power efficient and could lead to a lower GHG per mile of transport
  - however, young people like the electric bikes
  - many more electric bikes were put in use than cars taken out of service,
  - the electric bikes need to be charged with electricity that comes from inefficient coal power plants
  - Net GHG emissions went up

Important Aspects of Life Cycle Assessment, ISO 14044:2006(E).



Goal definition

- Goal of study should unambiguously state (ISO 14044: 2006E):
  - The intended application
  - Reasons for carrying out the study
  - Intended audience (who will the LCA be communicated to?)
  - Whether the results are intended to be used in **comparative assertions** intended for the public
    - **Comparative assertion:** environmental claim regarding the superiority or equivalence of one product versus a competing product that performs the same function.

Scope definition

- Scope definition must be in accordance with the goal definition
- Scope definition should consider and clearly describe (ISO 14044: 2006E):
  - The product system studied
  - The functions of the product(s) studied
  - **The functional unit**
  - The system boundary
  - Allocation procedures
  - LCIA methodology and types of impacts
  - Interpretation to be used
  - Data requirements
  - Assumptions
  - Value choices and optional elements
  - Limitations
  - Data quality requirements
  - Type of critical review, if any
  - Type and format of the report required for the study

  - temporal scope
  - technological scope
  - allocation or system equivalency

Functional Unit and Reference Flows

- **Functional unit:** Quantified performance of a product system for use as a reference unit (ISO 14044: 2006E)
- **Reference flow:** measure of the outputs from processes in a given product system required to fulfill the function expressed by the functional unit

Time, gloss, color, opacity,

Functional Unit and Reference Flows

- Example: We are critically evaluating the environmental impact of lipstick.

- What is the functional unit?

- What is the reference flow?

Functional Unit and Reference Flows

- Example: We are critically evaluating the environmental LCA of students having breakfast. We believe there are two options that we would like to study:
  - A bowl of cereal
  - A traditional eggs and meat breakfast

- What is the functional unit?

- What are the reference flow(s)?

System Boundary (subjective)

- Which unit processes are included in the LCA
- Must be consistent with the goal
- Deletion of a life cycle stage, process, inputs or outputs only permitted if it does not significantly affect the overall conclusions
- Any decision to omit must be justified

- Ideally, the system boundary so that inputs and outputs are all elementary flows (exchanges with nature) and product flows

Refs: ISO 14044: 2006E

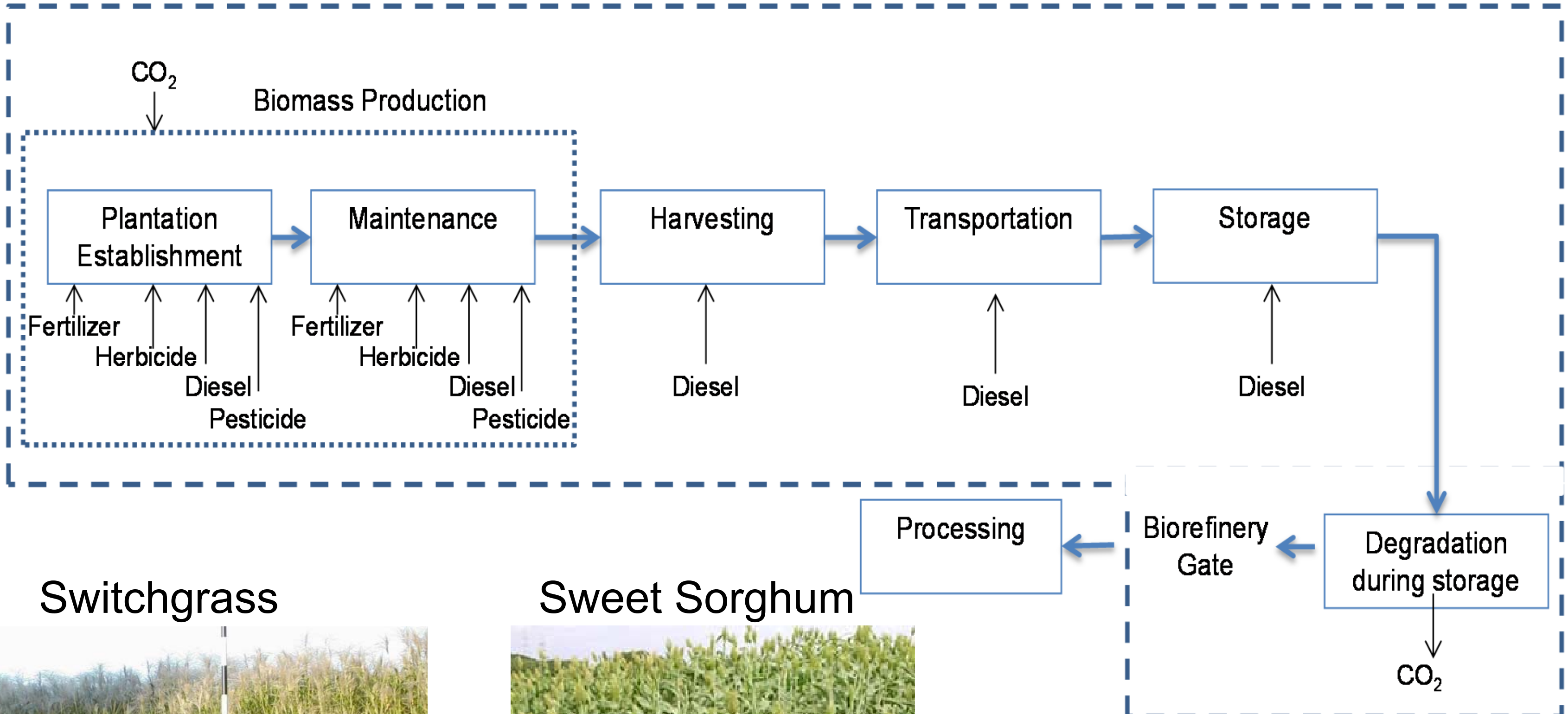
System Boundary

- Cut off criteria: specification of the amount of material or energy flow or the level of environmental significance associated with unit processes or product system to be excluded from the study
  - Mass, all the inputs that contribute less than X% to the total mass input of the product system
  - Energy, all the inputs that contribute less than X% to the total energy input of the product system
  - Environmental significance, any input that contributes less than X% of a the environmental significance of a specially selected environmentally relevant individual data

- Similar criteria for outputs

Refs: ISO 14044: 2006E

System Boundaries:
Switchgrass & Sweet Sorghum



Switchgrass

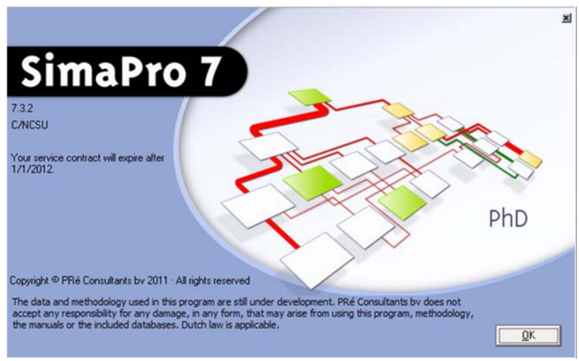
Sweet Sorghum

Scope: Data Collection Methods

Literature

Measurements

LCA Software

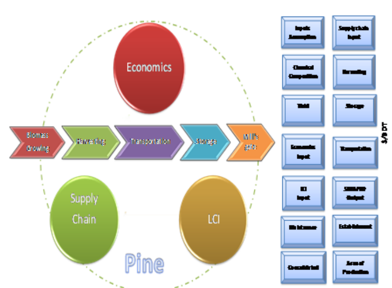


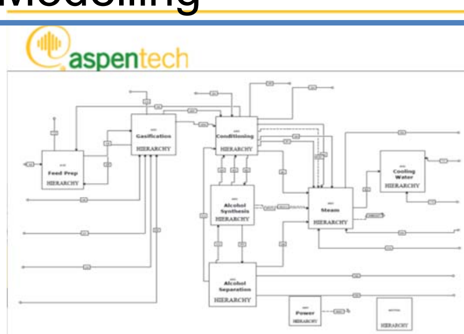
Databases

ecoinvent Centre

U.S. Life Cycle Inventory Database

Process Modelling





Allocation Methods in LCA:

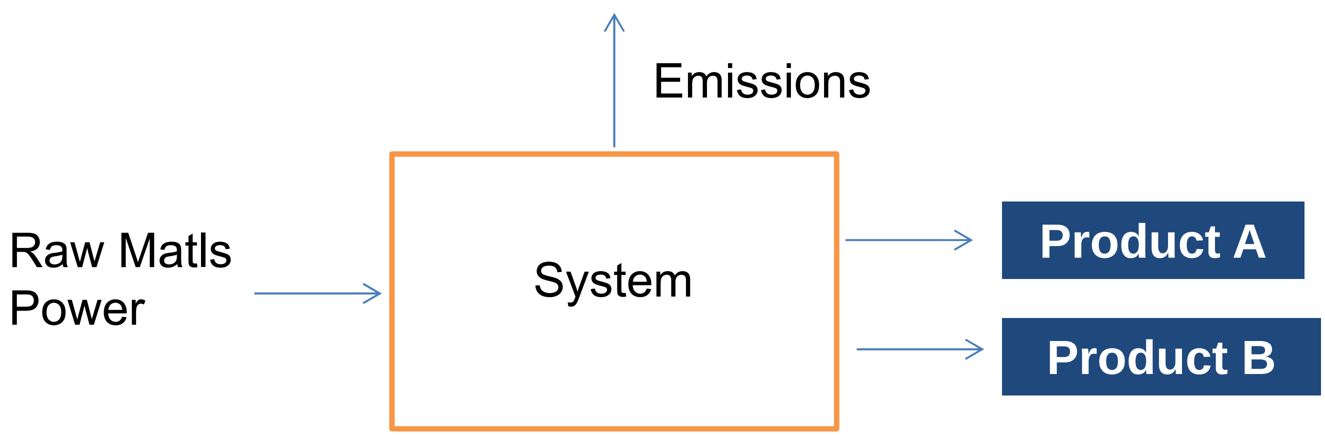
- **Allocation:** partitioning the input and output flows of a process or a product system between the product system under study and one or more of the other product systems
- **Controversial:**
  - **ISO methods recommend that allocation is**
  - **avoided 1st,**
  - **determined by a physical relationship 2nd,**
  - **or by a non-physical relationship 3rd**

Allocation Methods in LCA:

- **ISO does not provide allocation rules, practitioner must decide the rules and justify their use**
- **ISO requests that the sensitivity of the LCA results are evaluated with respect to the allocation methods**
- **Bottom line: allocation method can determine which related product in a life cycle is preferred**
- **Most common situations:**
  - **Co-products**
  - **Recycling**

Allocation Issues: Co-products:

- **Co-products Allocation: a single process produces multiple products,**
  - **Burdens can be partitioned by separating the system, mass flows, monetary values….**
  - **Must use process/product knowledge to determine partioning method**



Allocation Issues: Co-products:

- **What are the co-products for a cow?**

- **How should the burdens be allocated?**

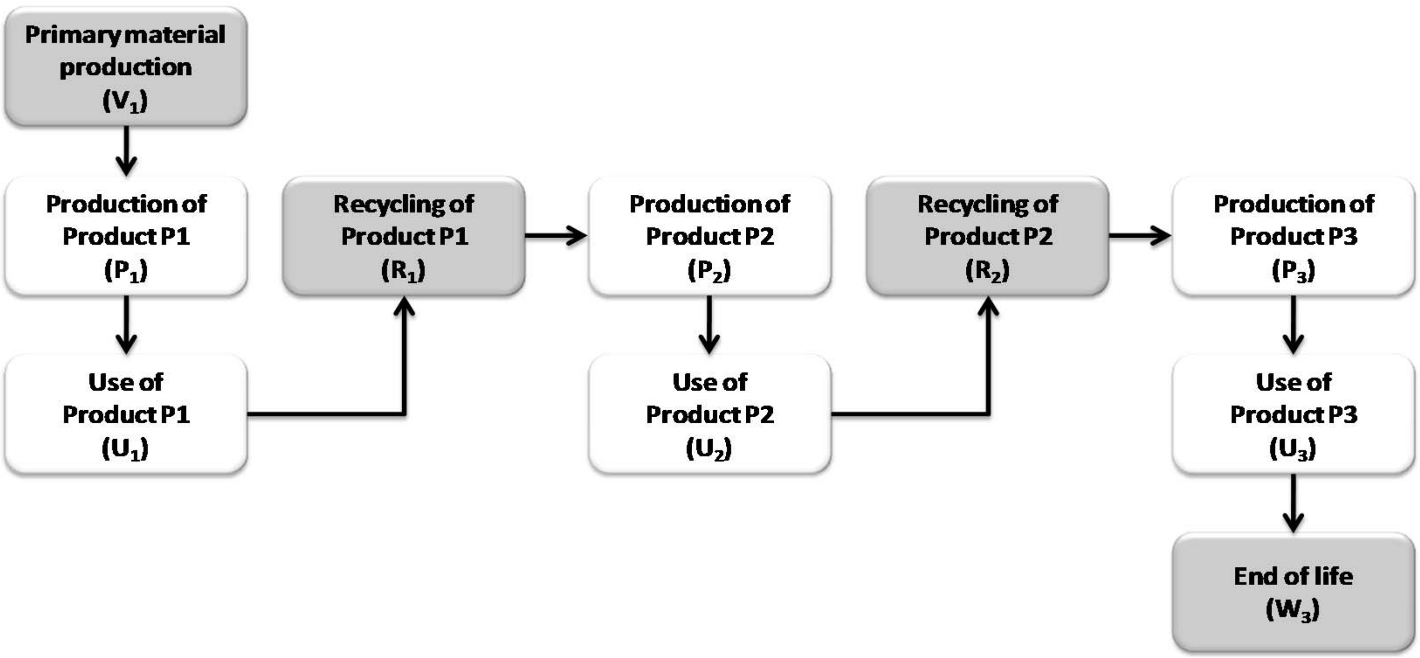
Allocation Issues: Co-products:

- What are the co-products for paper?

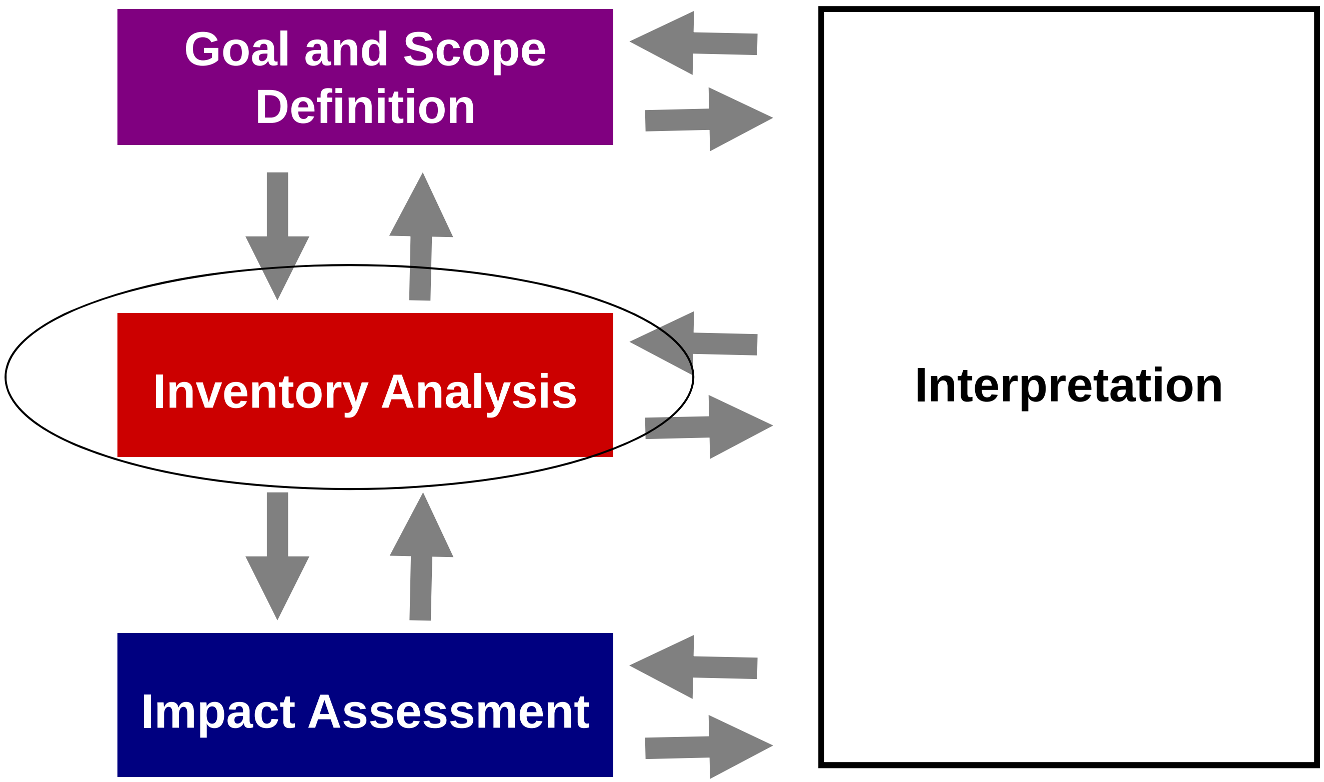
- How should the burdens be allocated?

Allocation Issues: Recycling

- **Recycling Allocation: a virgin product is recycled or re-used in a subsequent life**
  - **There exists operations that are required by the virgin and the recycled products (shared operations)**
  - **Example shared operations: virgin raw material production, final disposal**
  - **Many ways to allocate the burdens of the common operations**
  - **Controversial**



Important Aspects of Life Cycle Assessment



Life Cycle Inventory Analysis(LCI):

- **Life cycle inventory analysis**: Phase of the life cycle assessment involving the compilation and the quantification of inputs and outputs for a product throughout its life cycle [ISO 14044:2006(E)]
- "an inventory analysis means to construct a flow model of a technical system."
- "environmentally indifferent flows such as diffuse heat and emissions of water vapour as a combustion product are not modelled" HHGLCA, 2004.
- A pertinent mass and energy balance….

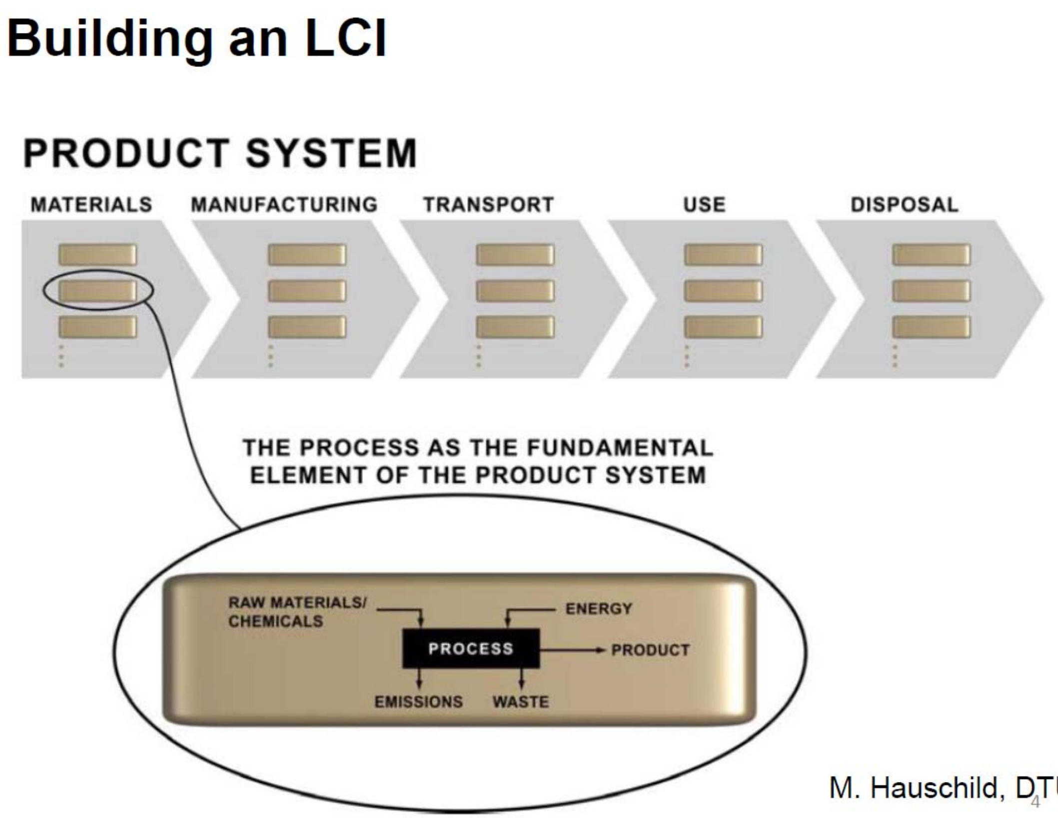
Data Collection

- One of the most time consuming activities in a LCA
- Garbage in, garbage out
- Main data:
  - Input flows of raw materials and energy
  - Other "inputs" such as land use, type of energy source
  - Product output flows
  - Emissions to air, water and land and other environmental impacts (eg., noise)
  - Data to describe processes
    - Example: production efficiencies, equipment, useful lifetimes of products, travel distances…
- Should also have data to guide allocation

HHGLCA, 2004.

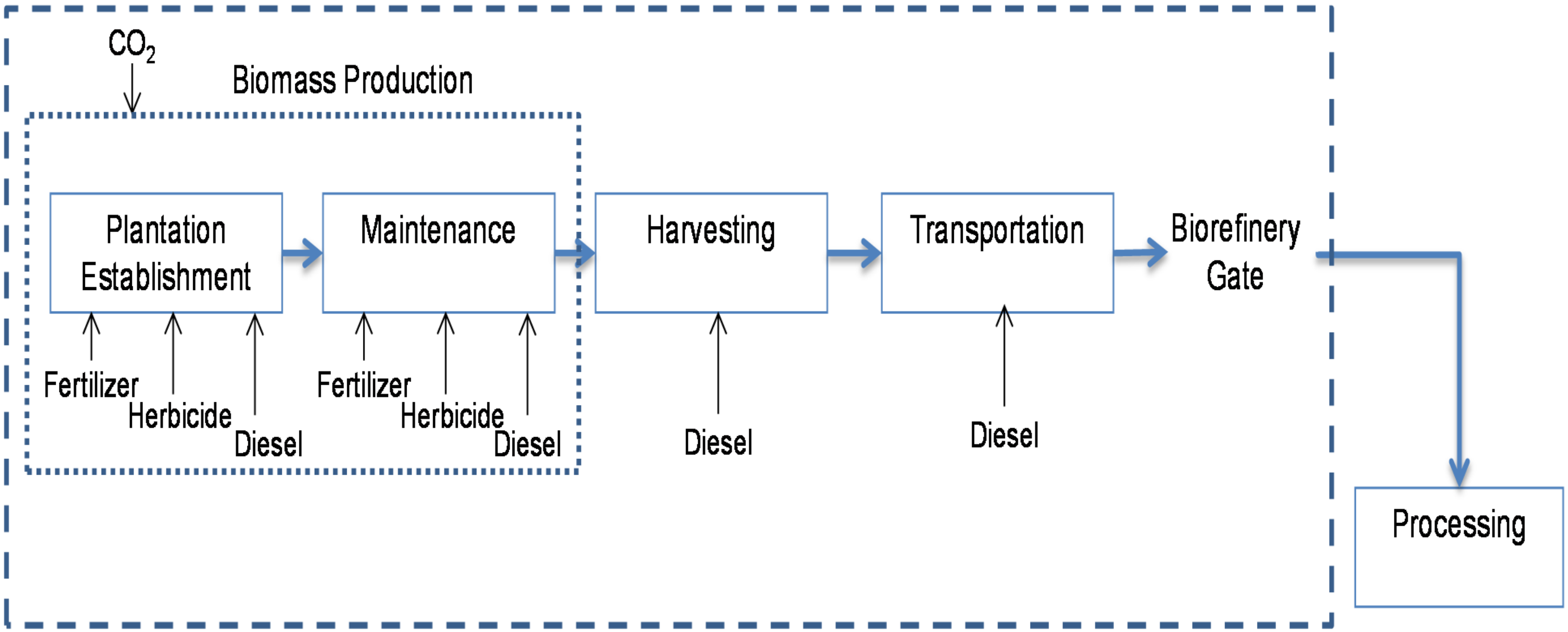
Life Cycle Inventory (LCI):

- **Definition of the process**
- **Definition of all mass and energy inputs to the process**
- **Defining all flows from the “technosphere” into and out of the surrounding environment, called elementary flows**



M. Hauschild, DTU

LCI Example
Biomass (Wood) Production

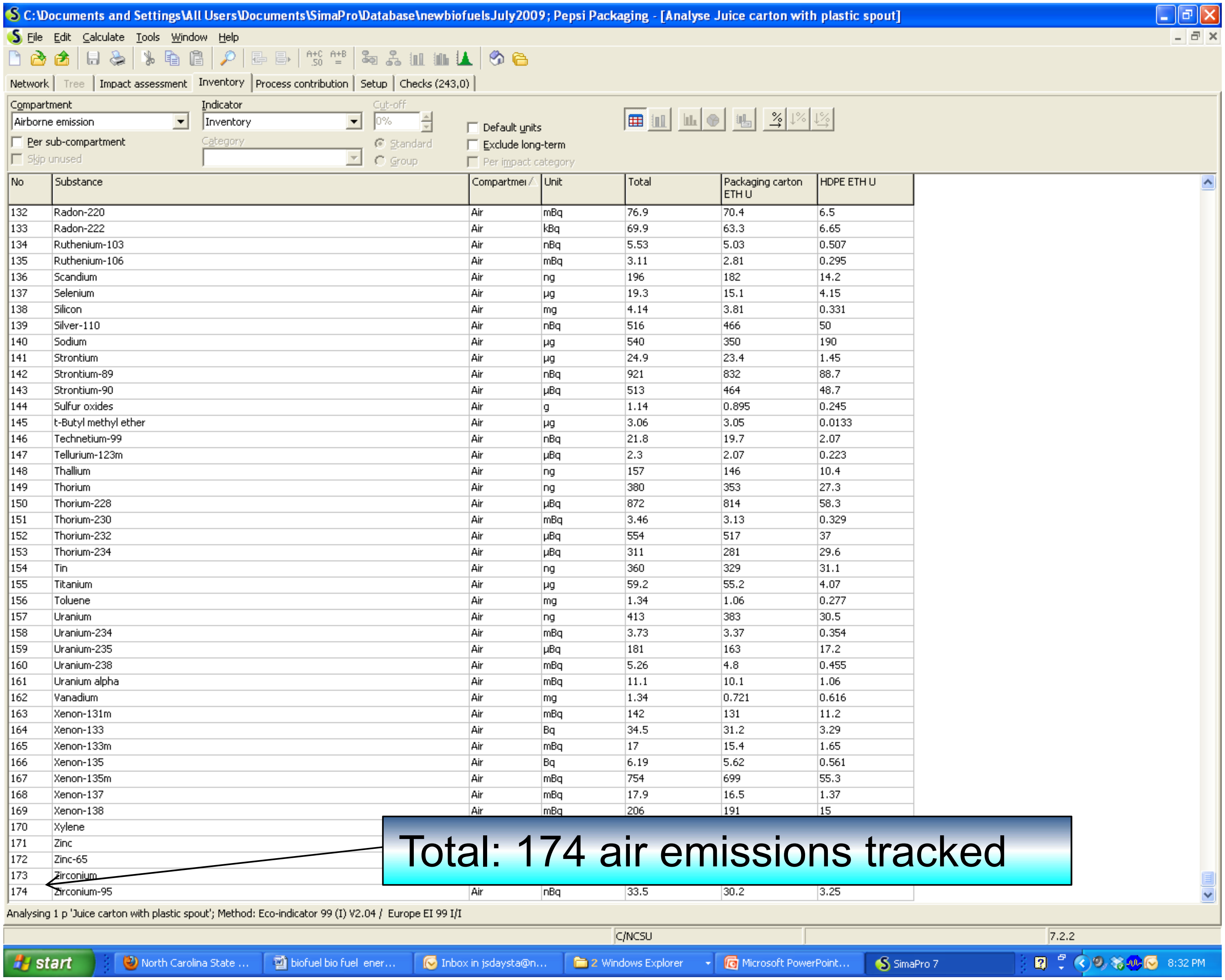


Life Cycle Inventory
Feedstock Production For Biofuels

	Loblolly Pine			Eucalyptus			Unmanaged Hardwood			Forest Residues			Switchgrass			Sweet Sorghum		
Productivity level	L	M	H	L	M	H	L	M	H	L	M	H	L	M	H	L	M	H
	Liter per dry ton			Liter per dry ton			Liter per dry ton			Liter per dry ton			Liter per dry ton			Liter per dry ton		
Fuel consumption, collection	-	-	-	-	-	-	-	-	-	0.05	0.04	0.03	-	-	-	-	-	-
Plantation establishment and maintenance, diesel	0.86	0.65	0.52	2.47	1.85	1.48	-	-	-	0.61	0.45	0.36	-	-	-	-	-	-
Plantation establishment and maintenance, gasoline	0.04	0.03	0.03	0.12	0.09	0.07	-	-	-	8.0	6.0	4.8	3.93	2.95	2.36	-	-	-
Harvesting, diesel	10.1	7.58	6.06	10.1	7.58	6.06	10.1	7.6	6.1	-	-	-	6.02	4.51	3.61	4.13	3.1	2.48
Storage													0.6	0.6	0.6	0.84	0.84	0.84
	Dry ton*km			Dry ton*km			Dry ton*km			Dry ton*km			Dry ton*km			Dry ton*km		
Transportation forest to facility	79	69	62	78	67	60	219	190	170	327	283	253	-	-	-			
Transportation farm to storage	-	-	-	-	-	-	-	-	-	-	-	-	51	44	39	175	152	136
Transportation storage to facility	-	-	-	-	-	-	-	-	-	-	-	-	9.5	9.5	9.5	31	31	31
Fertilizer	kg per Dry Ton			kg per Dry Ton			kg per Dry Ton			kg per Dry Ton			kg per Dry Ton			kg per Dry Ton		
UREA	2.1	1.6	1.3	2.9	2.2	1.7	-	-	-	0.13	0.1	0.08	-	-	-			
Phosphorus	-	-	-	-	-	-	-	-	-	-	-	-	1.6	1.2	0.96	3.43	2.57	2.06
Potassium	-	-	-	-	-	-	-	-	-	-	-	-	15.83	11.88	9.5	1.7	1.27	1.02
Lime	-	-	-	-	-	-	-	-	-	-	-	-	62.28	46.71	37.37	-	-	-
Nitrogen	-	-	-	-	-	-	-	-	-	-	-	-	8.47	6.36	5.08	-	-	-
Herbicide	kg per Dry Ton			kg per Dry Ton			kg per Dry Ton			kg per Dry Ton			kg per Dry Ton			kg per Dry Ton		
General herbicide, glyphosate	0.03	0.01	0.01	0.08	0.04	0.03	-	-	-	0.002	0.001	0.001	-	-	-	-	-	-
Pursuit	-	-	-	-	-	-	-	-	-	-	-	-	2.36	1.77	1.41	-	-	-
MSO	-	-	-	-	-	-	-	-	-	-	-	-	3.31	2.48	1.99	-	-	-
2,4	-	-	-	-	-	-	-	-	-	-	-	-	1.14	0.85	0.68	-	-	-
Alzarine 90 DF	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0.19	0.14	0.11
Dipel ES	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0.2	0.15	0.12

Note: 500,000 BDT/year, 10% covered area

Air Emissions Inventory: Example

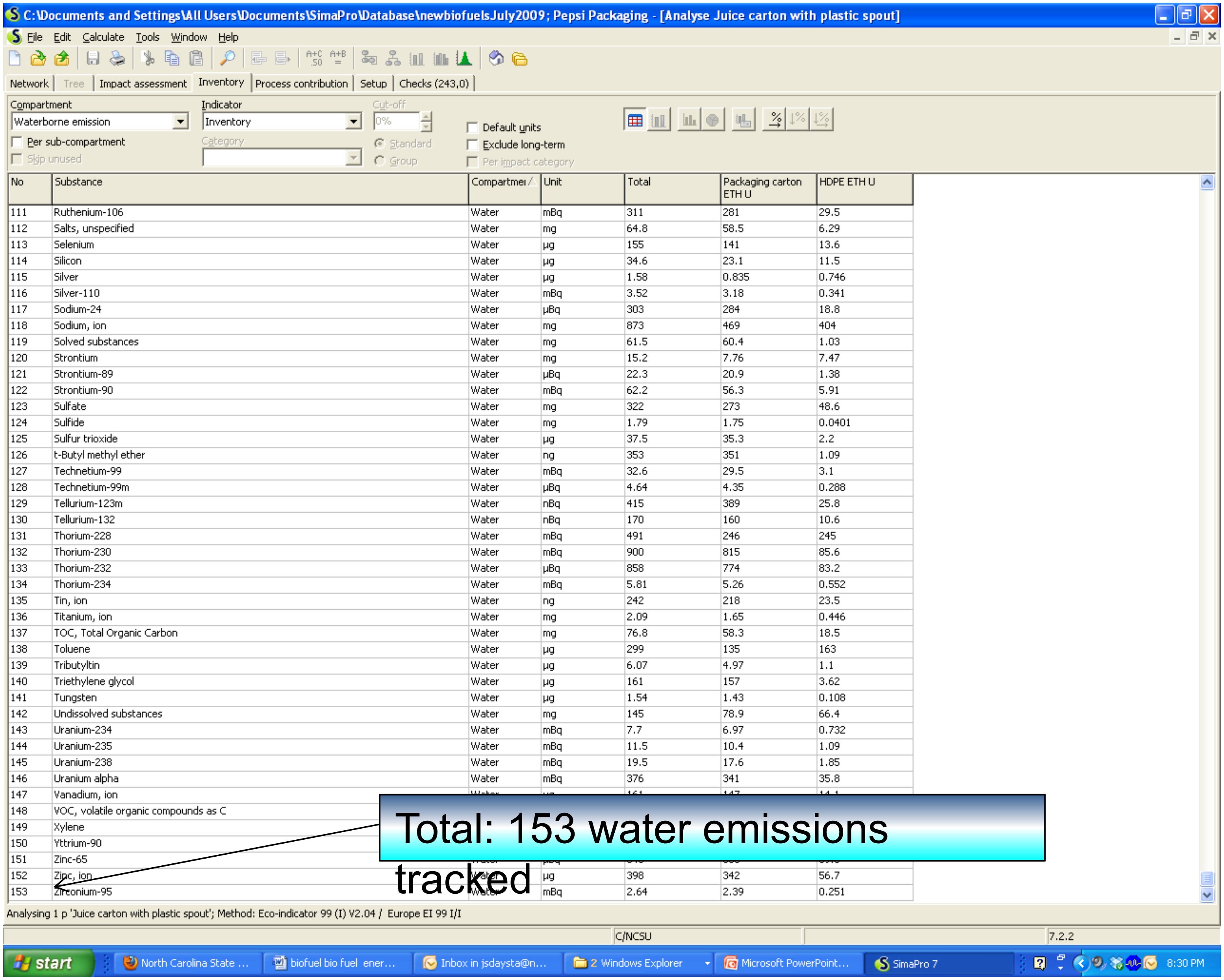


No	Substance	Compartment	Unit	Total	Packaging carton ETH U	HDPE ETH U
132	Radon-220	Air	mBq	76.9	70.4	6.5
133	Radon-222	Air	kBq	69.9	63.3	6.65
134	Ruthenium-103	Air	nBq	5.53	5.03	0.507
135	Ruthenium-106	Air	mBq	3.11	2.81	0.295
136	Scandium	Air	ng	196	182	14.2
137	Selenium	Air	µg	19.3	15.1	4.15
138	Silicon	Air	mg	4.14	3.81	0.331
139	Silver-110	Air	nBq	516	466	50
140	Sodium	Air	µg	540	350	190
141	Strontium	Air	µg	24.9	23.4	1.45
142	Strontium-89	Air	nBq	921	832	88.7
143	Strontium-90	Air	µBq	513	464	48.7
144	Sulfur oxides	Air	g	1.14	0.895	0.245
145	t-Butyl methyl ether	Air	µg	3.06	3.05	0.0133
146	Technetium-99	Air	nBq	21.8	19.7	2.07
147	Tellurium-123m	Air	µBq	2.3	2.07	0.223
148	Thallium	Air	ng	157	146	10.4
149	Thorium	Air	ng	380	353	27.3
150	Thorium-228	Air	µBq	872	814	58.3
151	Thorium-230	Air	mBq	3.46	3.13	0.329
152	Thorium-232	Air	µBq	554	517	37
153	Thorium-234	Air	µBq	311	281	29.6
154	Tin	Air	ng	360	329	31.1
155	Titanium	Air	µg	59.2	55.2	4.07
156	Toluene	Air	mg	1.34	1.06	0.277
157	Uranium	Air	ng	413	383	30.5
158	Uranium-234	Air	mBq	3.73	3.37	0.354
159	Uranium-235	Air	µBq	181	163	17.2
160	Uranium-238	Air	mBq	5.26	4.8	0.455
161	Uranium alpha	Air	mBq	11.1	10.1	1.06
162	Vanadium	Air	mg	1.34	0.721	0.616
163	Xenon-131m	Air	mBq	142	131	11.2
164	Xenon-133	Air	Bq	34.5	31.2	3.29
165	Xenon-133m	Air	mBq	17	15.4	1.65
166	Xenon-135	Air	Bq	6.19	5.62	0.561
167	Xenon-135m	Air	mBq	754	699	55.3
168	Xenon-137	Air	mBq	17.9	16.5	1.37
169	Xenon-138	Air	mBq	206	191	15
170	Xylene					
171	Zinc					
172	Zinc-65					
173	Zirconium					
174	Zirconium-95	Air	nBq	33.5	30.2	3.25

Analysing 1 p 'Juice carton with plastic spout'; Method: Eco-indicator 99 (I) V2.04 / Europe EI 99 I/I

Total: 174 air emissions tracked

Water Emissions Inventory: Example



No	Substance	Compartment	Unit	Total	Packaging carton ETH U	HDPE ETH U
111	Ruthenium-106	Water	mBq	311	281	29.5
112	Salts, unspecified	Water	mg	64.8	58.5	6.29
113	Selenium	Water	µg	155	141	13.6
114	Silicon	Water	µg	34.6	23.1	11.5
115	Silver	Water	µg	1.58	0.835	0.746
116	Silver-110	Water	mBq	3.52	3.18	0.341
117	Sodium-24	Water	µBq	303	284	18.8
118	Sodium, ion	Water	mg	873	469	404
119	Solved substances	Water	mg	61.5	60.4	1.03
120	Strontium	Water	mg	15.2	7.76	7.47
121	Strontium-89	Water	µBq	22.3	20.9	1.38
122	Strontium-90	Water	mBq	62.2	56.3	5.91
123	Sulfate	Water	mg	322	273	48.6
124	Sulfide	Water	mg	1.79	1.75	0.0401
125	Sulfur trioxide	Water	µg	37.5	35.3	2.2
126	t-Butyl methyl ether	Water	ng	353	351	1.09
127	Technetium-99	Water	mBq	32.6	29.5	3.1
128	Technetium-99m	Water	µBq	4.64	4.35	0.288
129	Tellurium-123m	Water	nBq	415	389	25.8
130	Tellurium-132	Water	nBq	170	160	10.6
131	Thorium-228	Water	mBq	491	246	245
132	Thorium-230	Water	mBq	900	815	85.6
133	Thorium-232	Water	µBq	858	774	83.2
134	Thorium-234	Water	mBq	5.81	5.26	0.552
135	Tin, ion	Water	ng	242	218	23.5
136	Titanium, ion	Water	mg	2.09	1.65	0.446
137	TOC, Total Organic Carbon	Water	mg	76.8	58.3	18.5
138	Toluene	Water	µg	299	135	163
139	Tributyltin	Water	µg	6.07	4.97	1.1
140	Triethylene glycol	Water	µg	161	157	3.62
141	Tungsten	Water	µg	1.54	1.43	0.108
142	Undissolved substances	Water	mg	145	78.9	66.4
143	Uranium-234	Water	mBq	7.7	6.97	0.732
144	Uranium-235	Water	mBq	11.5	10.4	1.09
145	Uranium-238	Water	mBq	19.5	17.6	1.85
146	Uranium alpha	Water	mBq	376	341	35.8
147	Vanadium, ion	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
148	VOC, volatile organic compounds as C	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
149	Xylene	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
150	Yttrium-90	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
151	Zinc-65	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
152	Zinc, ion	Water	µg	398	342	56.7
153	Zirconium-95	Water	mBq	2.64	2.39	0.251

Analysing 1 p 'Juice carton with plastic spout'; Method: Eco-indicator 99 (I) V2.04 / Europe EI 99 I/I

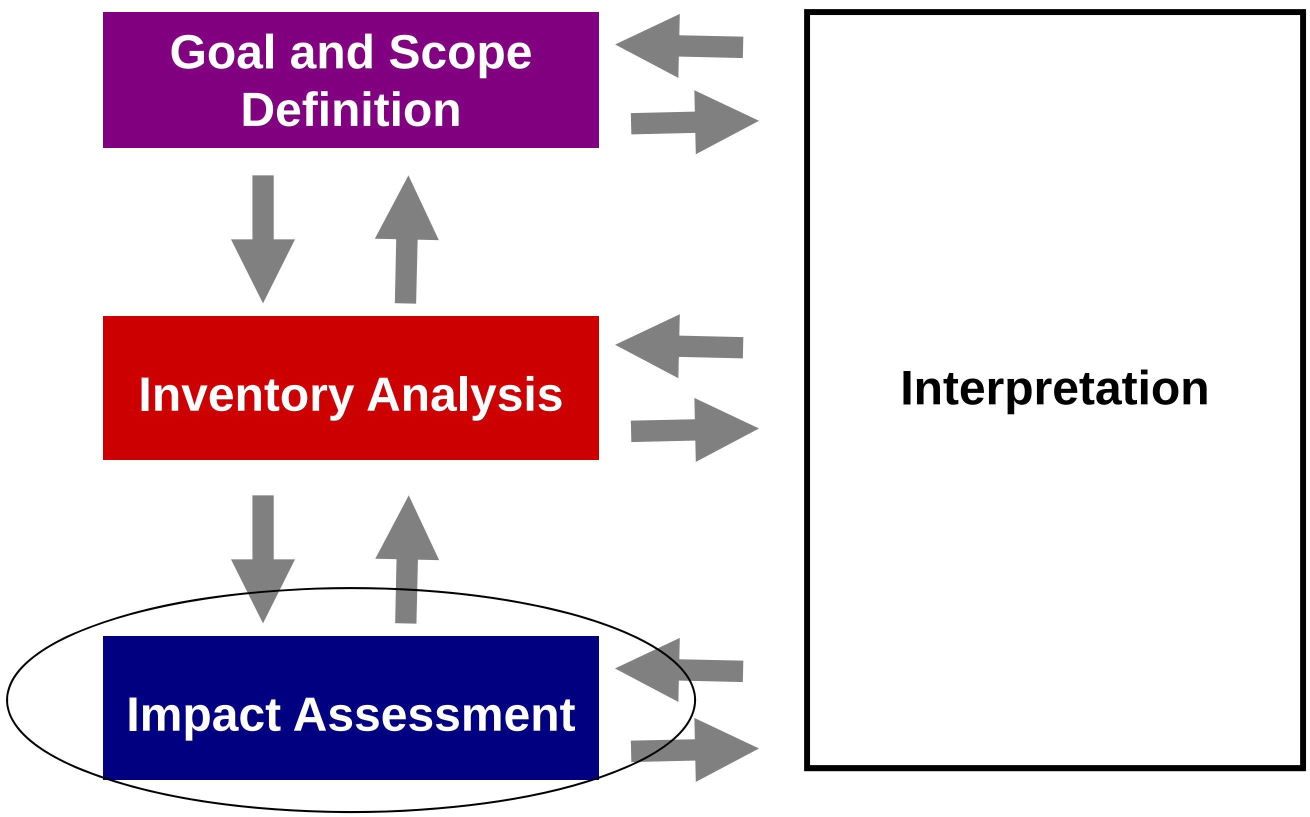
C/NCSU 7.2.2

Total: 153 water emissions tracked

Life Cycle Inventory:

- **We will do a gate to gate inventory analysis of making a mop.**
  - **What are the raw materials input?**
  - **What kinds of energy input?**
  - **What are the emissions?**
  - **What are the products?**
  - **What are the wastes?**

Important Aspects of Life Cycle Assessment

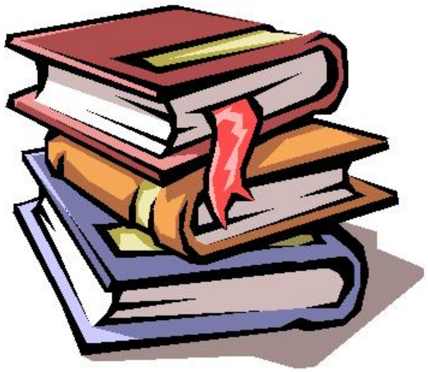


Impact Assessment

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].

It is used to ensure that projects, programs and policies are economically viable, socially equitable and environmentally sustainable. (cbd.int/impact)



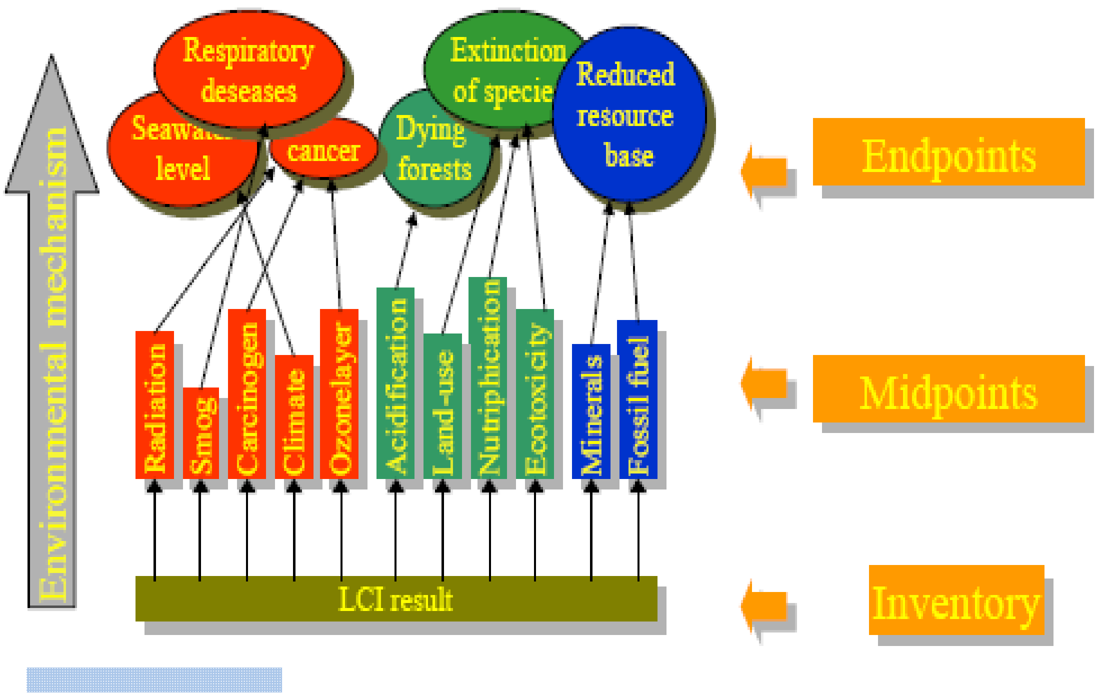
Impact Assessment: What Needs to be Included?

- Ecological Systems Degradation
- Resource Depletion
- Human Health & Welfare

Impact Assessment: ISO Standard

- Some assessments use midpoints, other use endpoints.

• LC Inventory Results: flows of mass or energy	Most certain
• Midpoints: examples: radiation, smog, ozone layer….	Less certain
• Endpoints: **Human health, ecosystems, resources**	Even less certain



Impact Assessment: ISO Standard

- Overall steps for LCA are defined in ISO 14044: 2006(E)
- 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)

Impact Assessment:
Selection of Impact Categories

• TRACI, The Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts, Environmental Protection Agency:

- Global Warming
- Acidification
- Human health: Carcinogenics
- Human Health: Non carcinogenics
- Human Health: Particulates
- Eutrophication
- Ozone Depletion
- Ecotoxicity
- Smog Formation
- Fossil Fuel Use

Impact Assessment:
Selection of Impact Categories

- Some things are not included in TRACI:
  - Odor
  - Noise
  - Radiation
  - Waste heat
  - Accidents
  - Land (in the future)
  - Water (in the future)
  - Others? ____________________

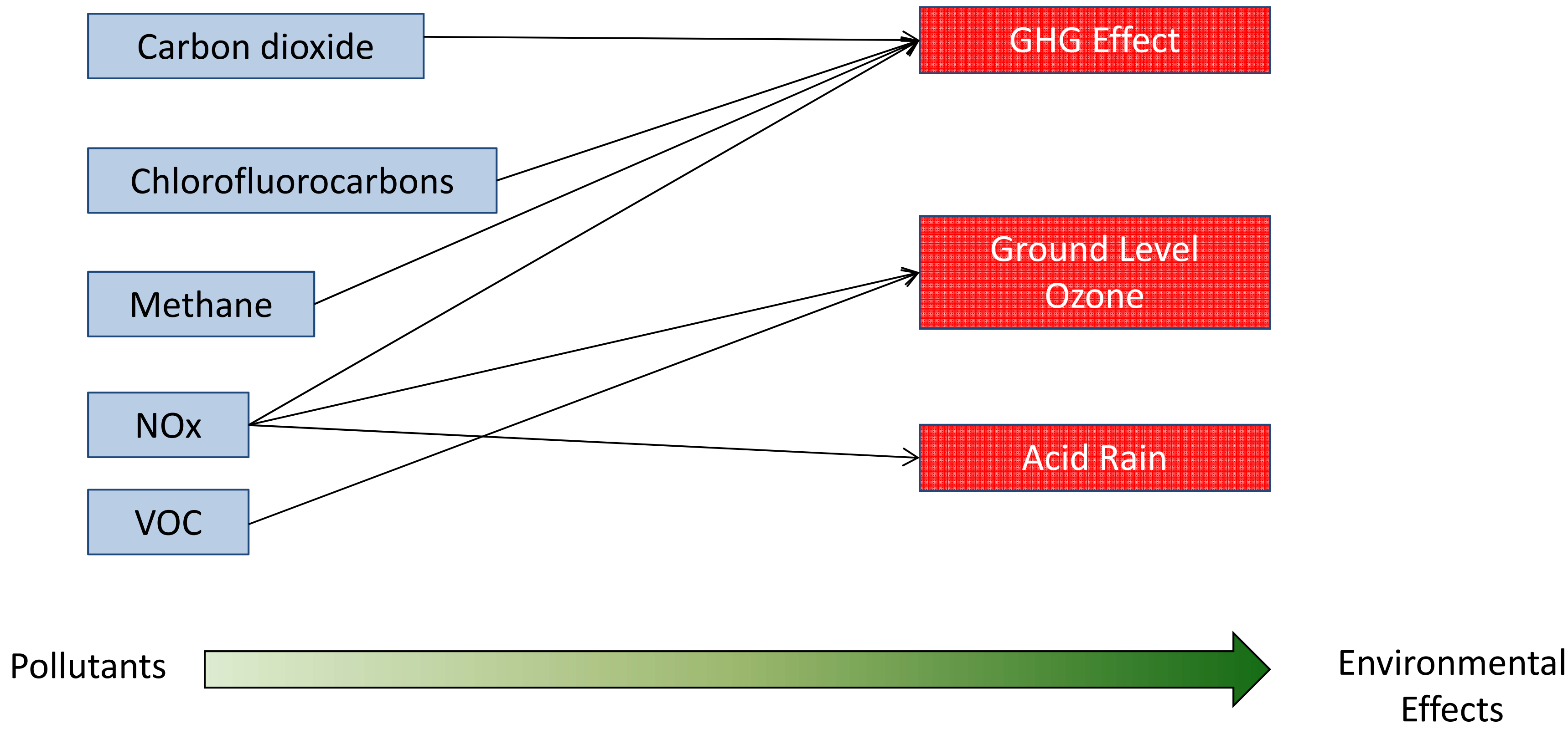
Carbon Footprint: Impact Assessment Method

- **Partial life cycle analysis**

- **Historicially**: the total set of greenhouse gas (GHG) emissions caused by an organization, event, product or person (UK Carbon Trust, 2009)
- **Practically:** A measure of the total amount of carbon dioxide (CO_2) and methane (CH_4) emissions of a defined population, system or activity, considering all relevant sources, sinks and storage within the spatial and temporal boundary of the population, system or activity of interest. Calculated as carbon dioxide equivalent (CO_2e) using the relevant 100-year global warming potential (GWP100) (Wright et al, Carbon Mgmt, 2011)

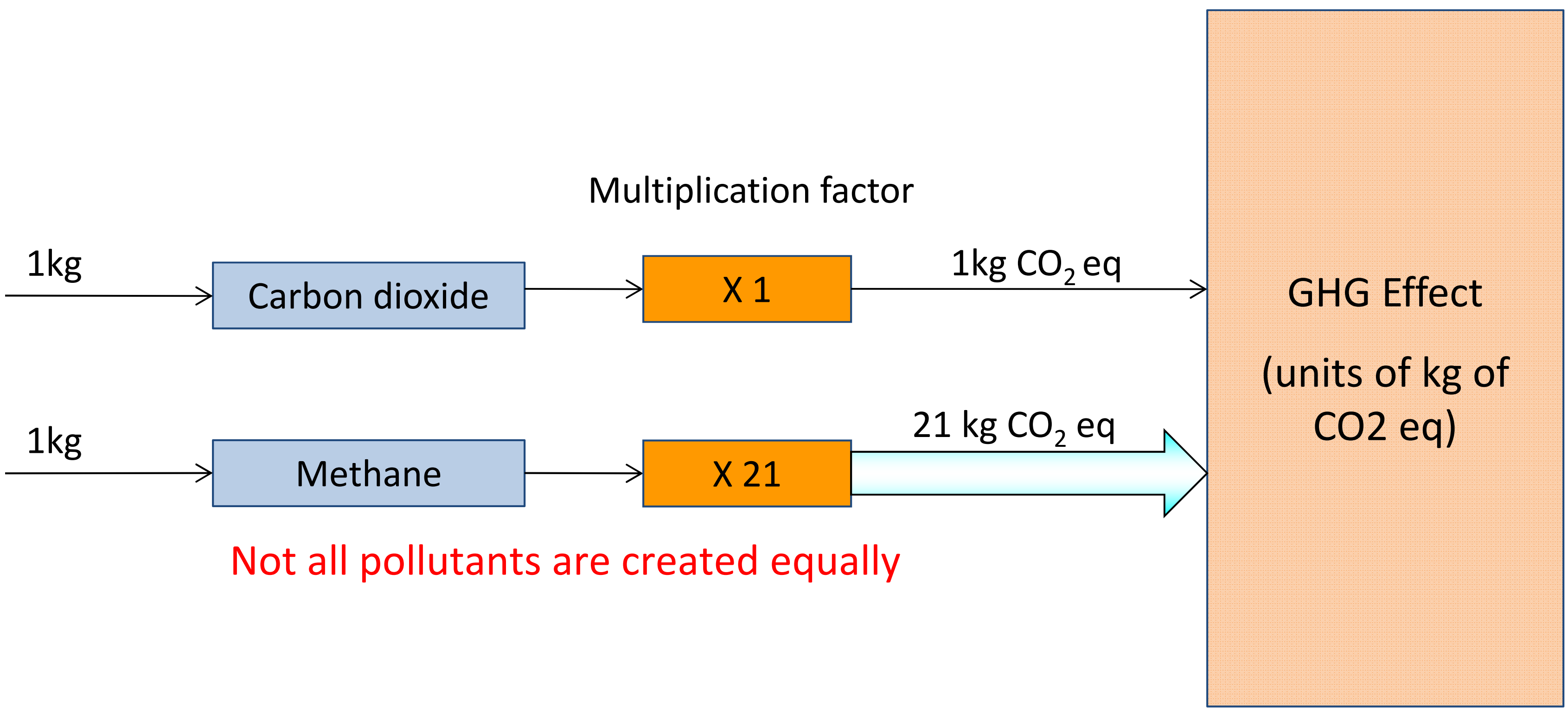
Impact Assessment: Classification

From Life cycle inventory:



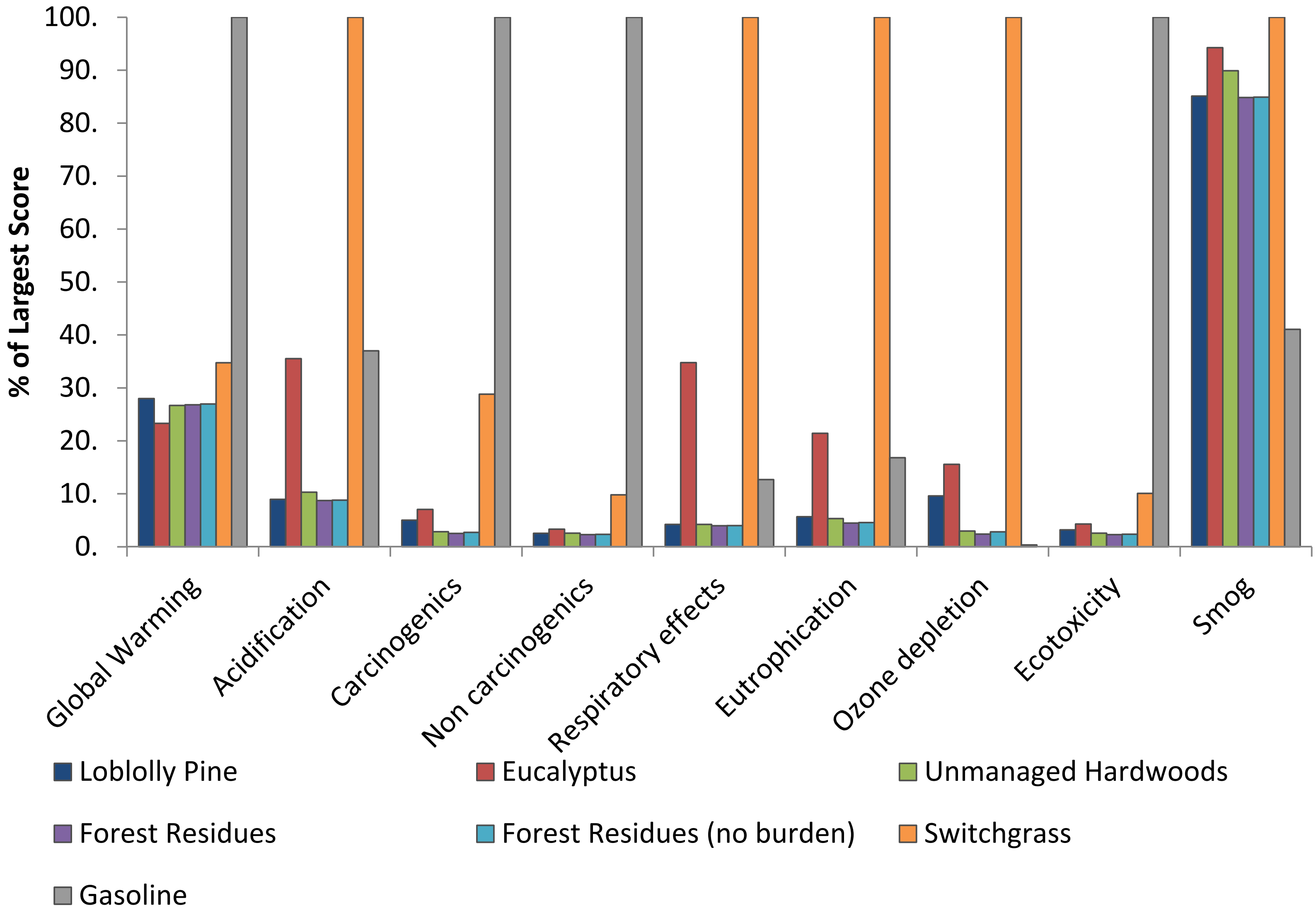
- Classification sorts pollutants according to the effects they have on the environment

Impact Assessment: Characterization



Reference: http://www.epa.gov/RDEE/energy-resources/calculator.html#results

Cradle to Grave: TRACI Impacts: Gasoline and Biofuels



Optional items in life cycle assesment (not often done)

- Normalization of each category, how much does this process contribute to an environmental issue relative to a reference
  - Process emits 20 units of CO_2 (Global warming potential)
  - Country emits 2,000,000 units of CO_2 (Global warming potential)
  - Normalized impact =20/2,000,000= .00001 normalized (Global warming potential)

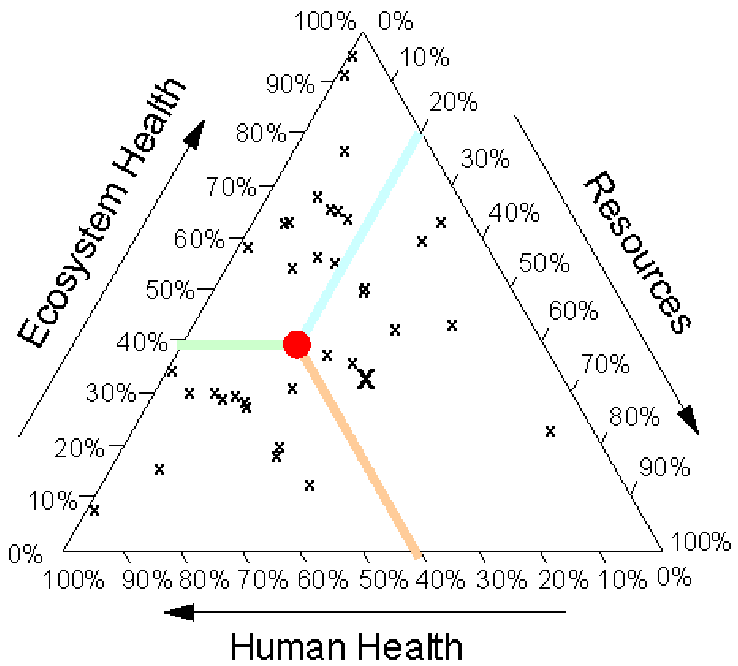
- Weighting, how important is one environmental impact category relative to another
  - "I think human health cancer is twice as bad as fossil fuel depletion"

- Single score: add up the normalized and weighted values of all impact categories
  - "Product A has a single score less than Product B"

Impact Assessment: Weighting

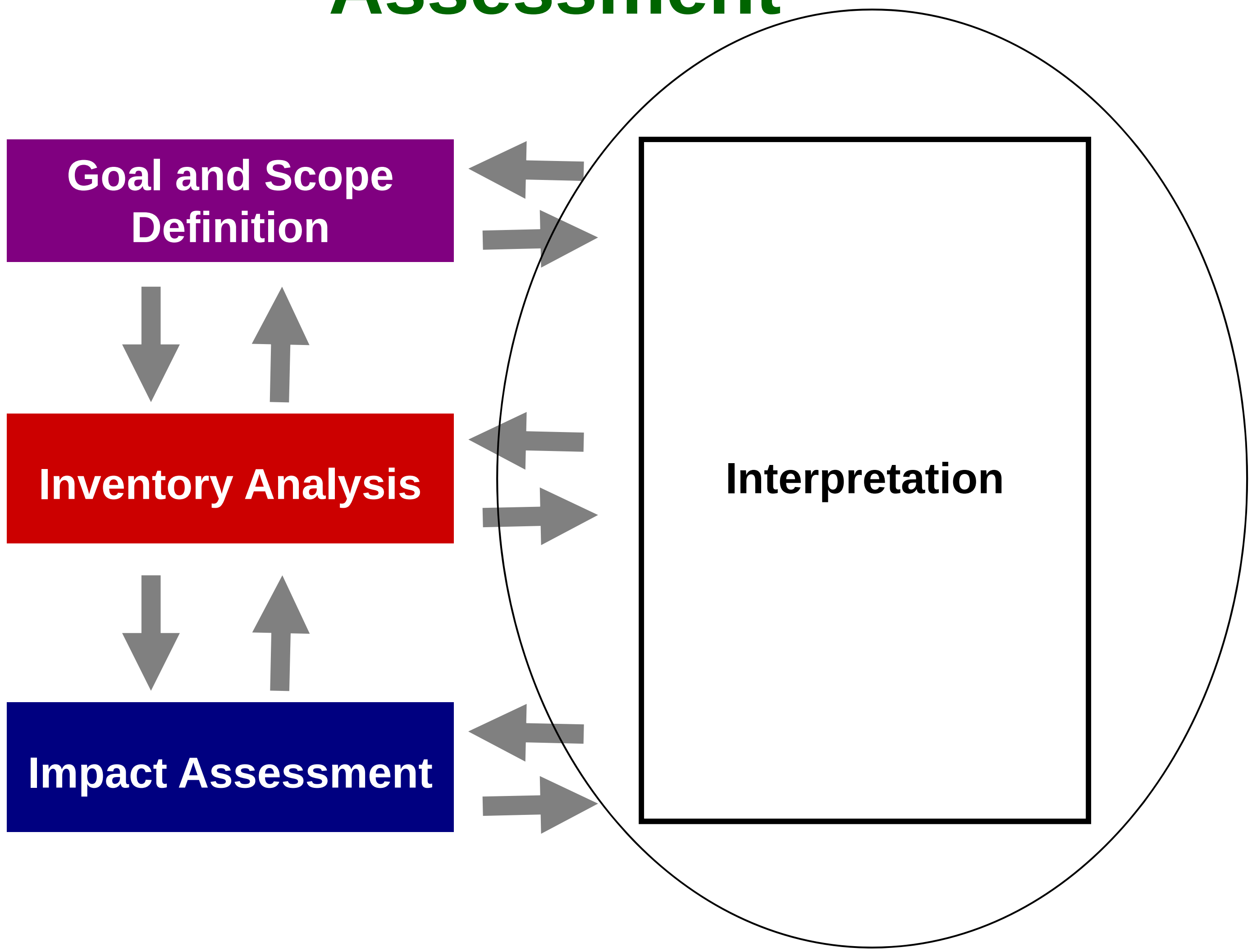
- Weighting relates the relative importance of impact categories
- Eco-Indicator 99
  - Questionnaire sent to 365 Swiss LCA interest groups
  - Panel members ranked and weighted three damage categories
- SUBJECTIVE: Red Dot indicates the weighting for Eco Indicator 99

Impact Category	Mean	Rounded	St. Deviation	Median
Human Health	36%	40%	19%	33%
Ecosystem Quality	43%	40%	20%	33%
Resources	21%	20%	14%	23%



[Mettier 1999] Mettier T.: Der Vergleich von Schutzguetern - Ausgewaehlte Resultate einer Panel-Befragung. In: Hofstetter P., Mettier T., Tietje O. (eds.), *Ansaetze zum Vergleich von Umweltschaeden, Nachbearbeitung des 9. Diskussionsforums Oekobilanzen vom 4. Dezember 1998*, ETH Zürich, Switzerland, 1999

Important Aspects of Life Cycle Assessment



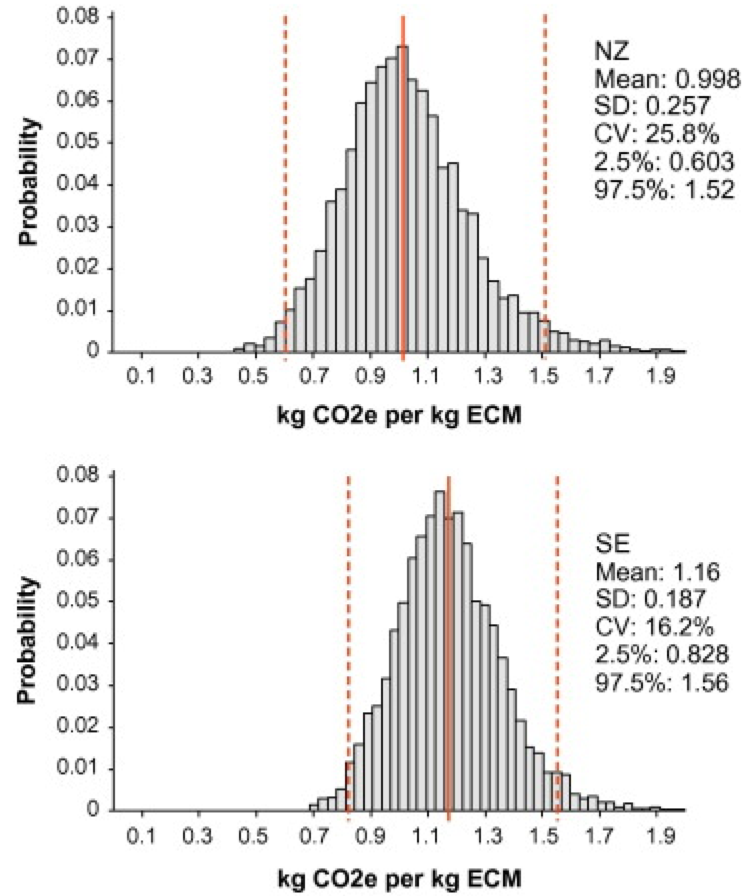
Interpretation: ISO Standard

- Overall steps for LCA are defined in ISO 14044: 2006(E)

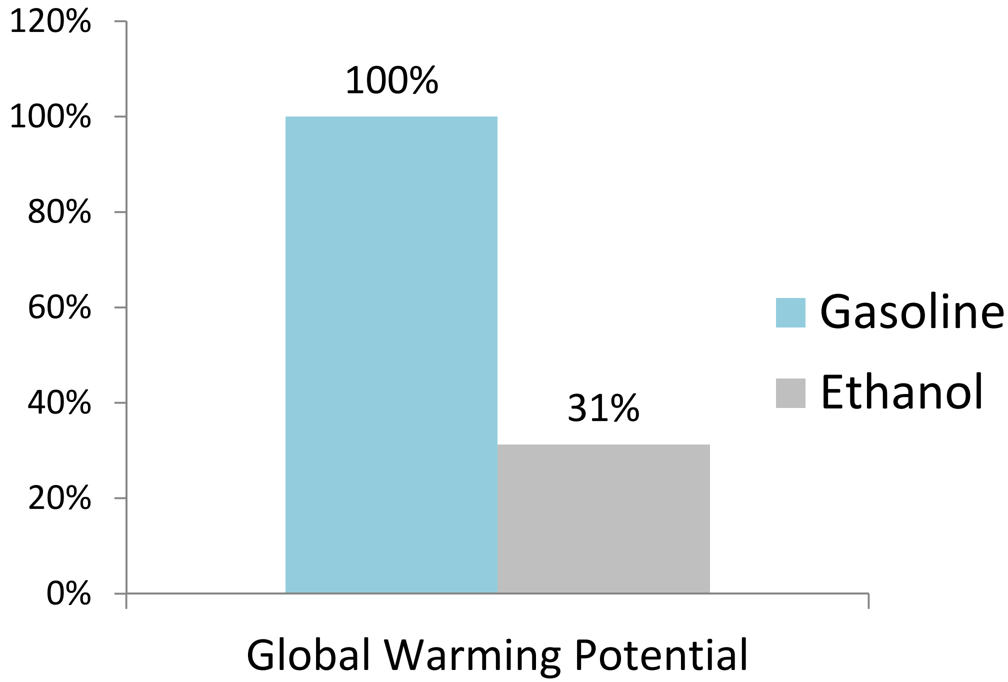
- 1. Should identify the significant issues based on the inventory and assessment phases of the LCA
- 2. The interpretation should conduct these checks
  - Completeness check
    - Is relevant data present?
  - Sensitivity check
    - How sensitive are the LCA results to an assumption? To test: make a change to the assumption and recalculate the LCA results.
  - Consistency check
    - Did the LCA abide by the stated goals and scope
- 3. Include conclusions, limitations and recommendations

Uncertainty Analysis

- Monte Carlo Simulation
  - Data uncertainty
  - Model uncertainty
- Probability of lower environmental impacts
- Agricultural Vs. forest feedstocks



Conclusion Example:
Thermochemical Conversion of Biomass to Ethanol:
69% reduction in GHG



Lifecycle GHG Thresholds Specified in EISA (percent reduction from 2005 baseline)	
Renewable fuel	20%
Advanced biofuel	50%
Biomass-based diesel	50%
Cellulosic biofuel	60%

Summary

Life Cycle Assessment (LCA) is a tool to assess the potential environmental impacts of products, systems, or services at all stages in their life cycle [ISO 14044: 2006(E)].

Avoid unintended consequences with systems thinking

The major parts of an LCA:

- Goal and Scope
- LC Inventory: mass and energy balances
- Impact Assessment
- Analysis and Interpretation

Impact Assessment: identifying the future potential consequences of a current or proposed action

LCA studies have many components that are subjective (beware):

- Choice of boundaries
- Choice of allocation methods
- Valuation of impact categories

Questions???

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 acidity 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,

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

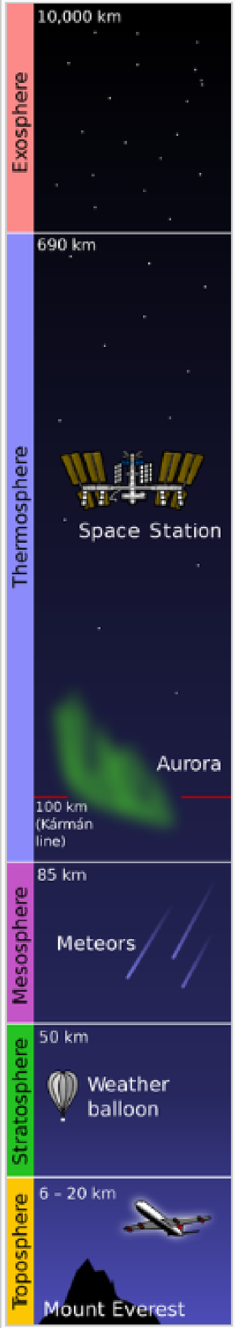
Climate Change (Global Warming)

- 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).

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



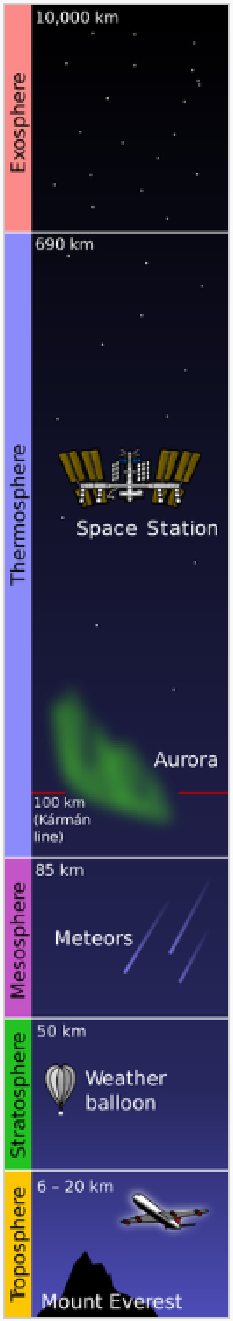
Layers of the atmosphere (not to scale)

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

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)

Human health cancer, Human health 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.

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