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7th Summer School on Sustainable Chemistry for Sustainable Development
Institute of Sustainable Chemistry, Leuphana University 12-16 July 2021

Sustainable Chemistry and Agriculture

Wednesday14th July 2021
Concepts of Sustainable Chemistry

Chemistry and agriculture: approaching sustainability using systems thinking

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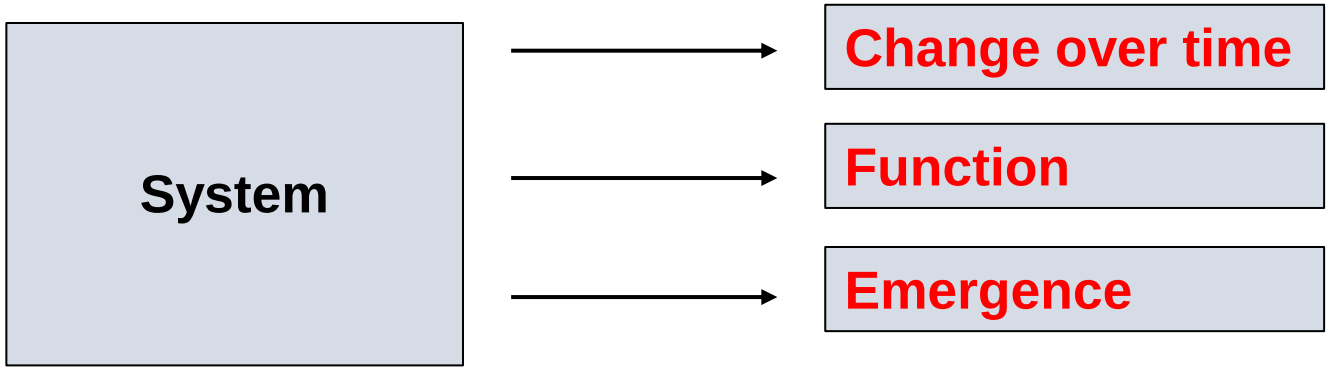
Chemists for Sustainability

International Organization for Chemical Sciences in Development

IOCD

Imperial College
London
Institute of Global Health Innovation



A set of components working together to form a complex whole that produces a function[1]

- Systems have boundaries (open or closed)
- Systems have properties

System/function can be:

Object – e.g. a clock to tell the time
– e.g. an organism that lives

Process – e.g. a company's management system
e.g. a national regulatory system to ensure compliance with standards of quality in food or pharmaceuticals

Emergence:

An overall function or effect that cannot be deduced or produced from the isolated parts separately.

- Time-telling is not a property of individual cogs & springs in a clock
- Life is not a property of individual molecules in a cell

Sustainability:

Sustainability is a property of the whole system

– it is not simply a property of individual elements of the system[2]

[1] D. H. Meadows,. *Thinking in Systems: A Primer.* Earthscan, London 2009. https://wtf.tw/ref/meadows.pdf

[2] F. Ceschin, I. Gaziulusoy. Design Studies 2016, 47, 118-163, https://doi.org/10.1016/j.destud.2016.09.002

Systems Thinking …. Sustainability …. Chemistry… Agriculture

Why use ST?

One of 5 key competencies identified[1] as essential for achieving sustainability
(and connects with the other 4: anticipatory, interpersonal, normative and strategic competences)

- *ST competence is the ability to analyse complex systems across different domains (society, environment, economy, etc.) and across different scales (local to global), thereby considering cascading effects, inertia, feedback loops and other systemic features related to sustainability issues and sustainability problem-solving frameworks.*

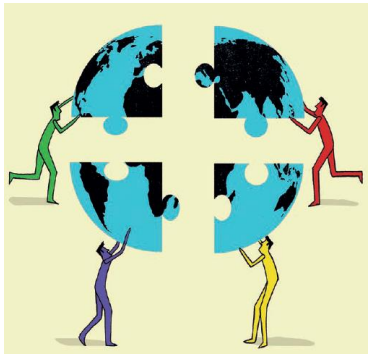
ST core skill: ability to analyse, understand and interpret complex systems.

Value of ST in chemistry?

[1] A. Wiek, L. Withycombe, C.L. Redman. *Sustainability Sci.* 2011, 6, 203–218, https://doi.org/10.1007/s11625-011-0132-6

The chemical sciences have been central to global progress and will be essential to meeting oncoming global challenges – especially sustainable development – with **'one-world' chemistry**[1]

'One-world' chemistry

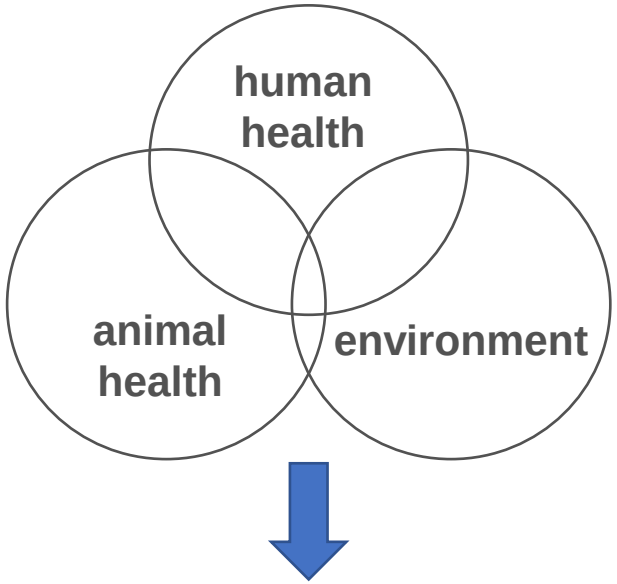


Aims to be:

- A science for the benefit of society
  - Ethical practice
  - Systems thinking
  - Cross-disciplinarity

Recognises:

- Earth is a single system in which the health of human beings, animals and the environment are all strongly interconnected: all three must be taken into account in considering the impacts of chemistry



Implications for chemistry

- Idea of chemistry
- Beyond chemistry in the context of its applications; AND
- Chemistry in the context of its impacts
- Requires:
  - Thinking about systems and how they function and interact
  - Connecting science principles with sustainability goals
  - Using cross-disciplinary approaches

[1] S.A. Matlin, G. Mehta, H. Hopf, A. Krief. *Nature Chemistry* 2016, 8, 393-396, https://doi.org/10.1038/nchem.2498

Systems Thinking …. Sustainability …. Chemistry… Agriculture

Value of ST in chemistry: Involves capacity to see

- chemistry itself as an organized system of materials, processes, and products regulated by physical principles
- how knowledge of chemistry can be leveraged to better understand molecular-level processes in other disciplines
- how chemical processes contribute to and interact with Earth and societal systems to impact planetary sustainability

IUPAC
International Union of Pure and Applied Chemistry

Infusing **S**ystems **T**hinking **i**nto
(Post)-Secondary General **C**hemistry **E**ducation
STICE[1]

Supported by

IOCD
International Organization for Chemical Sciences in Development

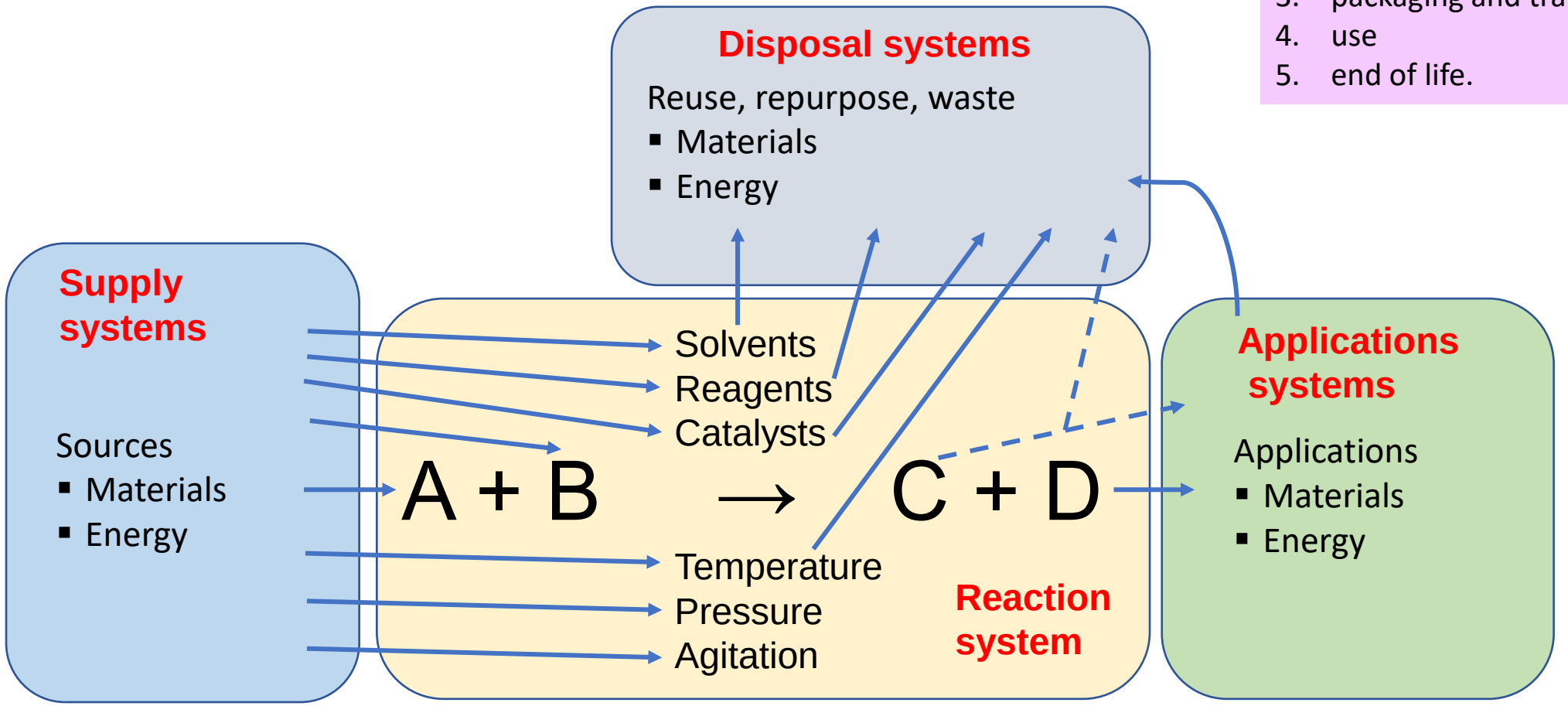
Journal of Chemical Education 2019, vol 96: Special Themed Issue
Reimagining Chemistry Education: Systems Thinking and Green and Sustainable Chemistry[2,3]

Development of a new visualization tool to assist in teaching, learning and practicing ST in chemistry
Systems-Oriented Concept Map Extension ***SOCME***[4]

1 IUPAC Project # 2017-010-1-050 Co-chairs: P.G. Mahaffy, S. A. Matlin https://iupac.org/projects/project-details/?project_nr=2017-010-1-050
2 J. Chem. Educ. 2019, vol 96: https://pubs.acs.org/toc/jceda8/96/12
3 P.G. Mahaffy, S.A. Matlin. Next hundred years: Systems thinking to educate about the molecular basis of sustainability. *L'Actualité Chimique* 2019, 446,47-49. https://www.lactualitechimique.org/Pour-les-cent-ans-a-venir-reflexions-sur-l-enseignement-de-la-chimie-et-la-durabilite
4 P.G. Mahaffy, S.A. Matlin, T.A. Holme, J. MacKellar. *Nature Sustainability* 2019, 2, 362-370, https://doi.org/10.1038/s41893-019-0285-3
K.B. Aubrecht, Y.J. Dori, T.A. Holme, R. Lavi, S.A. Matlin, M. Orgill, H. Skaza-Acosta. *J Chem Educ* 2019, 96, 2888-2900, https://doi.org/10.1021/acs.jchemed.9b00314

"The away myth"
There is no such thing as 'away'. When we throw anything away it must go somewhere.
A. Leonard, A. Conrad. The Story of Stuff, 2010
https://epdf.pub/the-story-of-stuff.html

Life Cycle Assessment
5 main stages, with inputs and outputs, flow-throughs, value losses, and potential gains.
1. materiel extraction
2. manufacturing
3. packaging and transportation
4. use
5. end of life.



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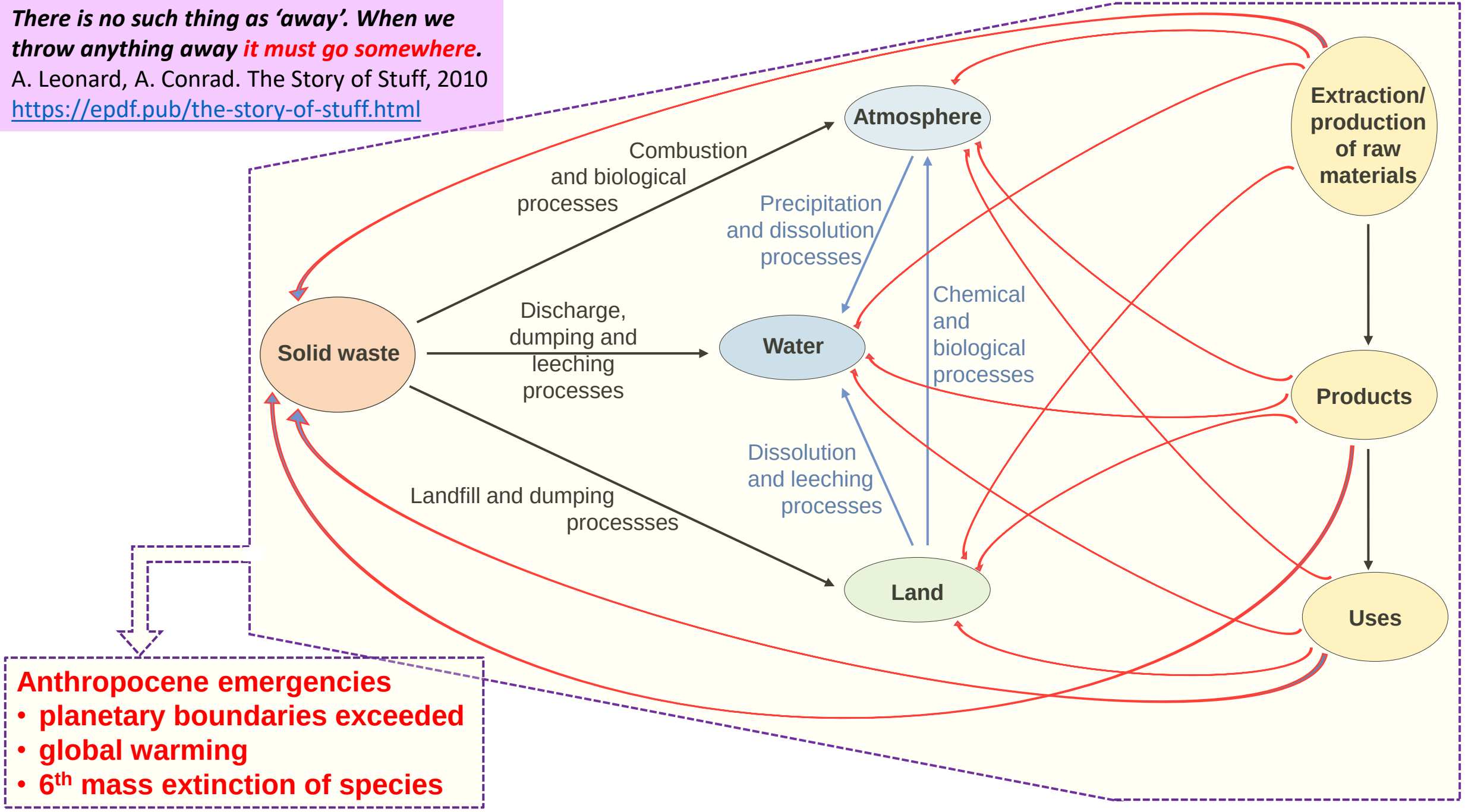

Anthropocene emergencies
- **planetary boundaries exceeded**
- **global warming**
- **6th mass extinction of species**

"The away myth"
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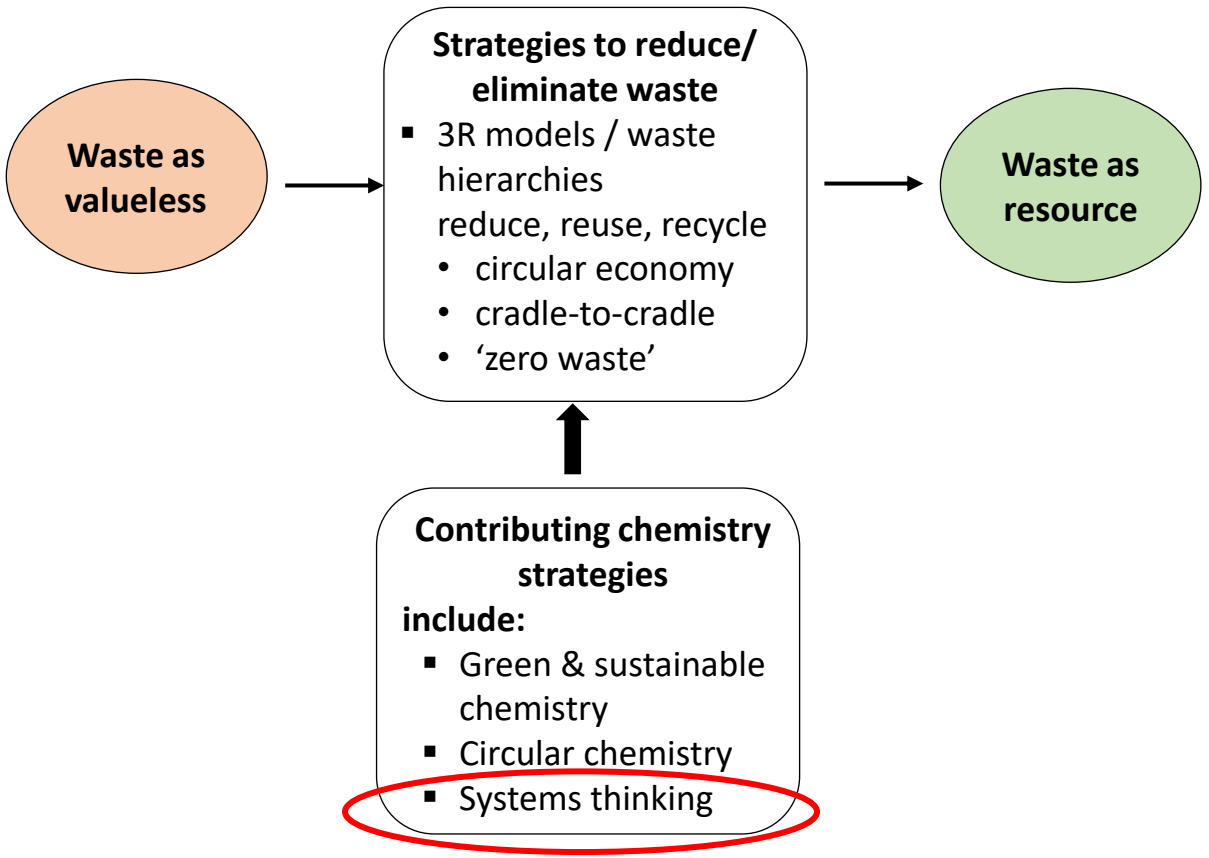
A. Leonard, A. Conrad. The Story of Stuff, 2010
https://epdf.pub/the-story-of-stuff.html

Waste does not exist: there is only post-trash. Hopf et al. *SciDev.Net*, 22 April 2019
https://www.scidev.net/global/environment/opinion/waste-does-not-exist-there-is-only-post-trash.html

Ending the time of waste: Clean up, catch up, smarten up. Matlin et al. *Angle J.*, 1 Nov 2019
http://anglejournal.com/article/2019-11-ending-the-time-of-waste-clean-up-catch-up-smarten-up/

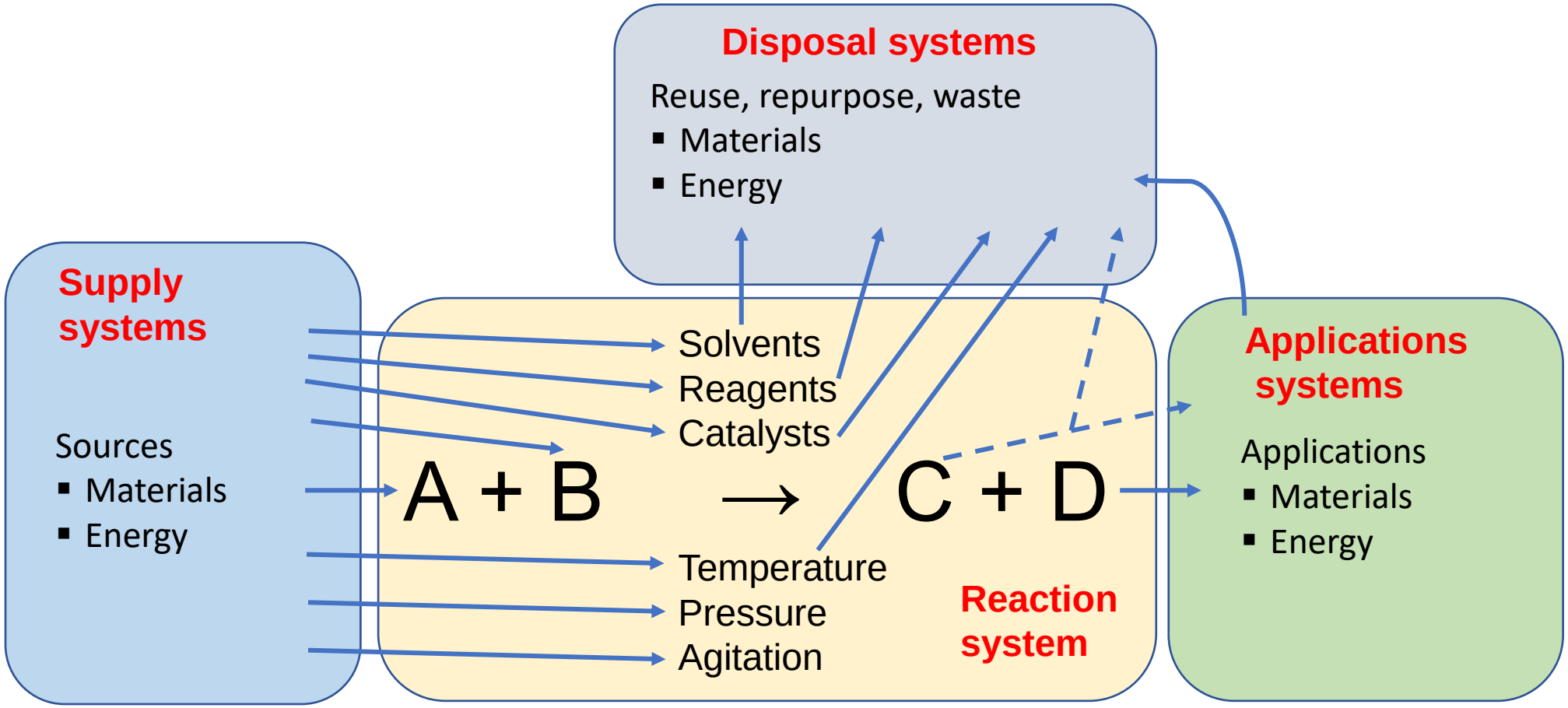


Food waste

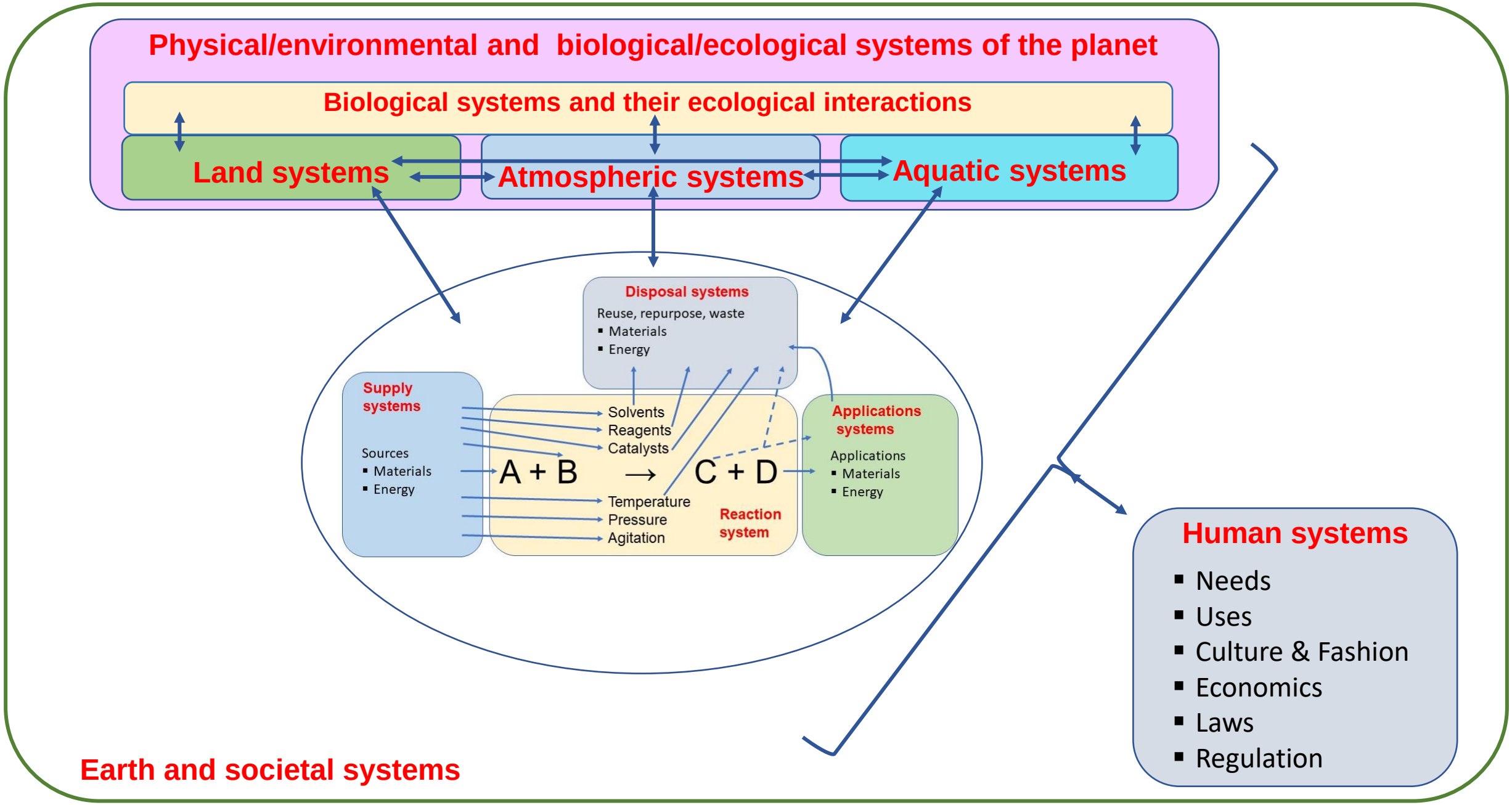
≥A third of all the food produced in the world goes to waste

- Lost nutrition
- Decomposing in landfills releases CH_4. Total carbon footprint of food produced but not eaten = to 3.3 bn tonnes/year CO_2 - the world's third-largest aggregate source of GHGs.[1]
- Chemistry contributions help limit post-harvest food losses and/or capture value, including:
  - control of chemical environments for storage and ripening
  - inhibition of decay processes
  - Packagings, refrigerants to preserve quality and extend shelf life
  - energy-generating incineration or biogas production

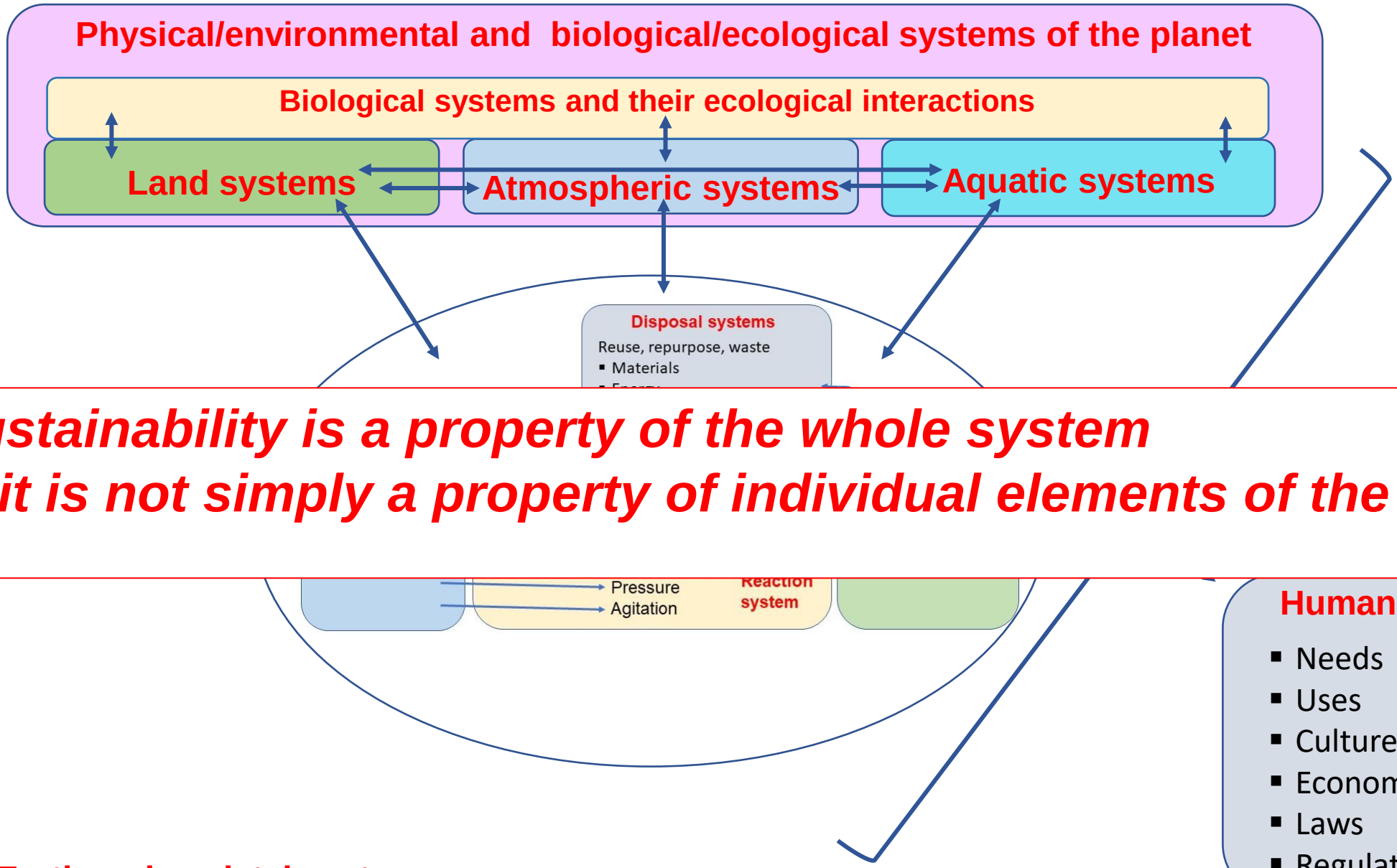
[1] *Food wastage footprint: Impact on natural Resources.* Food and Agriculture Organization, Rome **2013**, ISBN 978-92-5-107752-8. http://www.fao.org/news/story/en/item/196402/icode/


Disposal systems
Reuse, repurpose, waste
Materials
Energy
Supply systems
Sources
Materials
Energy
Solvents
Reagents
Catalysts
A + B
C + D
Temperature
Pressure
Agitation
Reaction system
Applications systems
Applications
Materials
Energy

Production and consumption in the context of Earth and societal systems



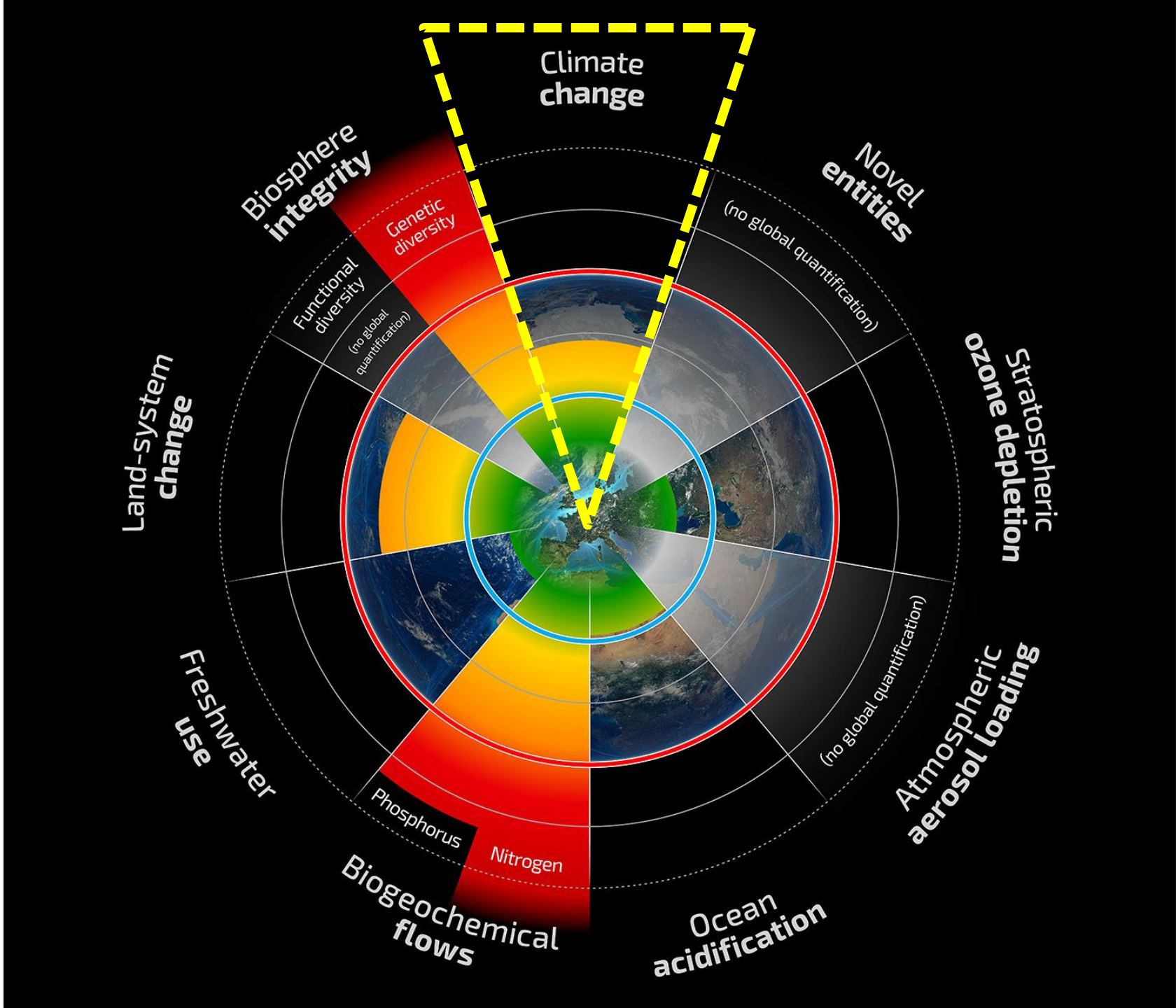
Production and consumption in the context of Earth and societal systems



Sustainability is a property of the whole system
– it is not simply a property of individual elements of the system

Planetary Boundaries Framework

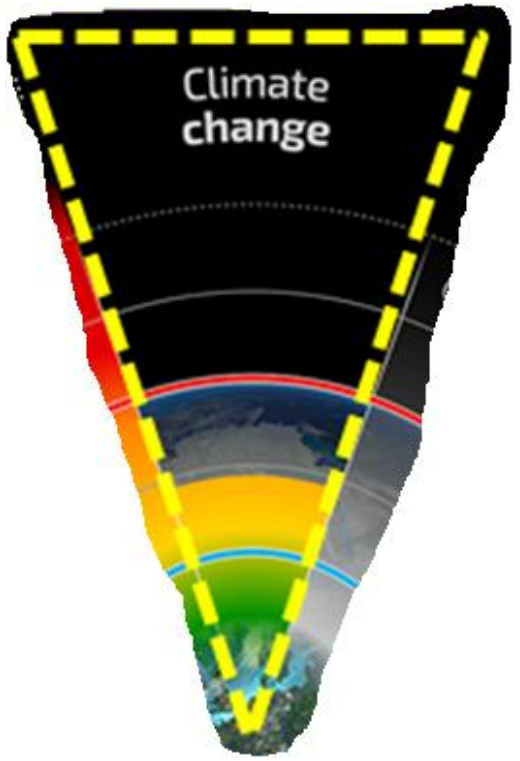
- 9 PBs identified that help define the stability and resilience of our planetary environment
- To date, for 7 of the PBs, control variables have been identified and quantified that indicate whether that Earth system process is still in a **safe operating zone (below the planetary boundary - green)**, a **zone of increasing risk (yellow)**, or a **zone of high risk (red)** as a result of human activity.
- Most of the control variables measuring the state of each Earth system are directly related to the production and measurement of chemical substances in the atmosphere, hydrosphere or lithosphere.



J.Rockström, W. Steffen et al.

- *Nature* **2009**, 461, 472-475, https://doi.org/10.1038/461472a.
- *Science* **2015**, 347 (6223), 736−747, https://doi.org/10.1126/science.1259855

[1] https://www.climate.gov/news-features/understanding-climate/climate-change-atmospheric-carbon-dioxide



Planetary boundary

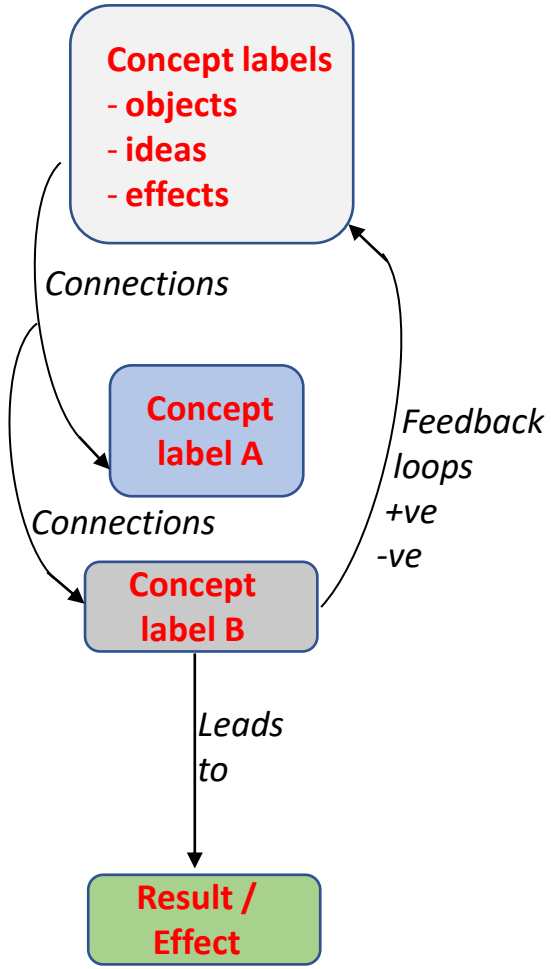
Threshold

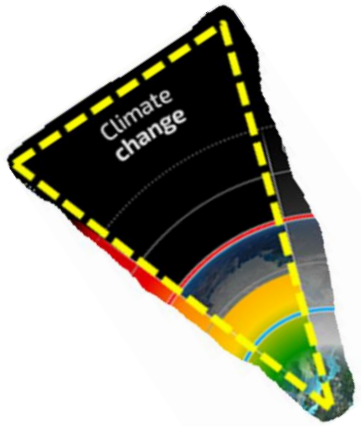
Variable Indicator measured	Below boundary (safe)	In zone of uncertainty	Beyond zone of uncertainty (increasing risk) (High risk)	Planetary boundary	Value of indicator (2015)
Climate change **Atmospheric CO_2 conc^n**				350 ppm	398.5 ppm

2019
409.8 ppm

- highest in at least the last 800,000 years[1]

Concept map





Biogeochemical flow CO_2

The most important technological invention of the 20th Century?

$$N_2(g) + 3H_2(g) \rightleftharpoons 2NH_3(g)$$

Haber-Bosch Process

- **NH_3 plant produces 1,000-3,000 t/day**
- **World production 2017 c. 175 Mt**
- **c. 85% used in agriculture**

Without the N fertilizers spread on the fields, from the Haber-Bosch synthesis of ammonia, almost two-fifths of the world's population would not be here - and our dependence will only increase as the global count moves from six to nine or ten billion people.

Vaclav Smil, *Nature* **1999,** *400*, 415

The most important technological invention of the 20th Century?

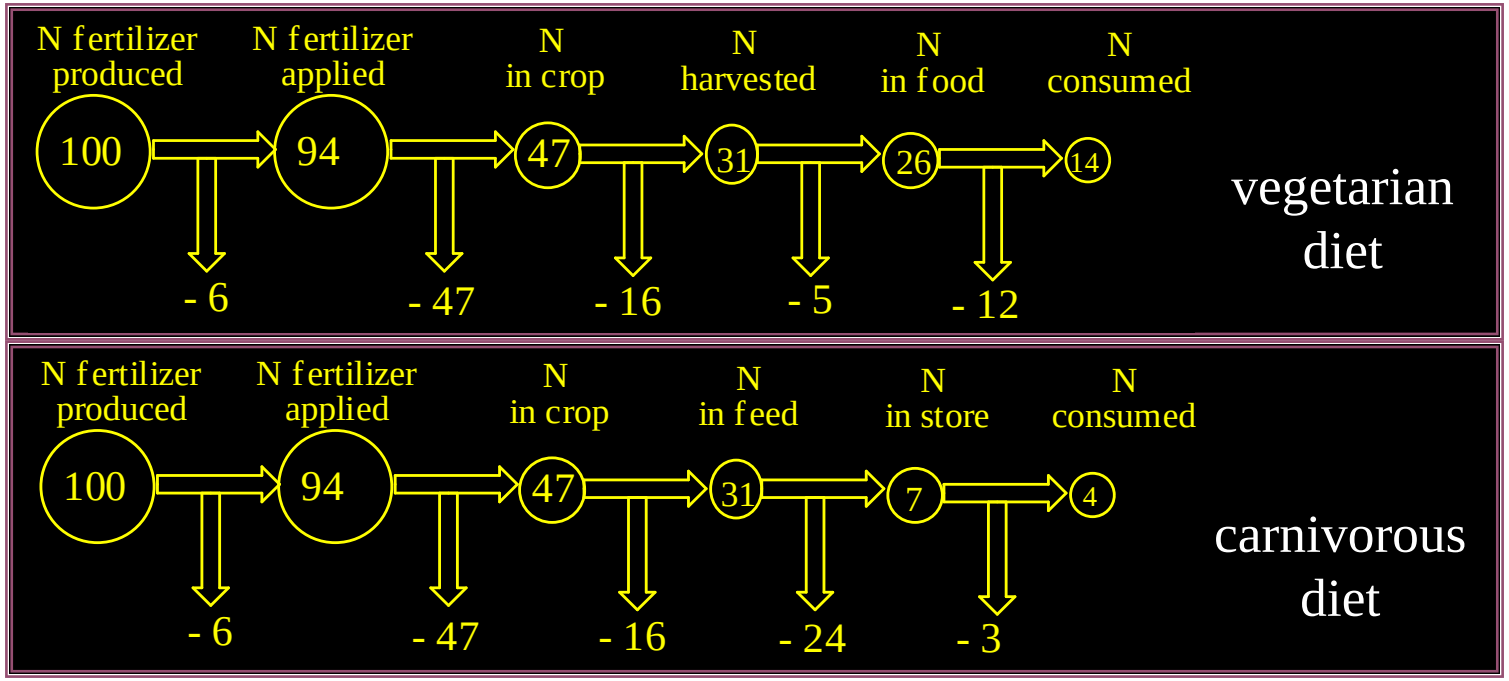
$$N_2(g) + 3H_2(g) \rightleftharpoons 2NH_3(g)$$

Equilibrium process; but multiple passes give **97% overall conversion**

Feeding the world *("making bread from air")*…
…yet, a failure of systems thinking in chemistry?

Making and using N fertilizer

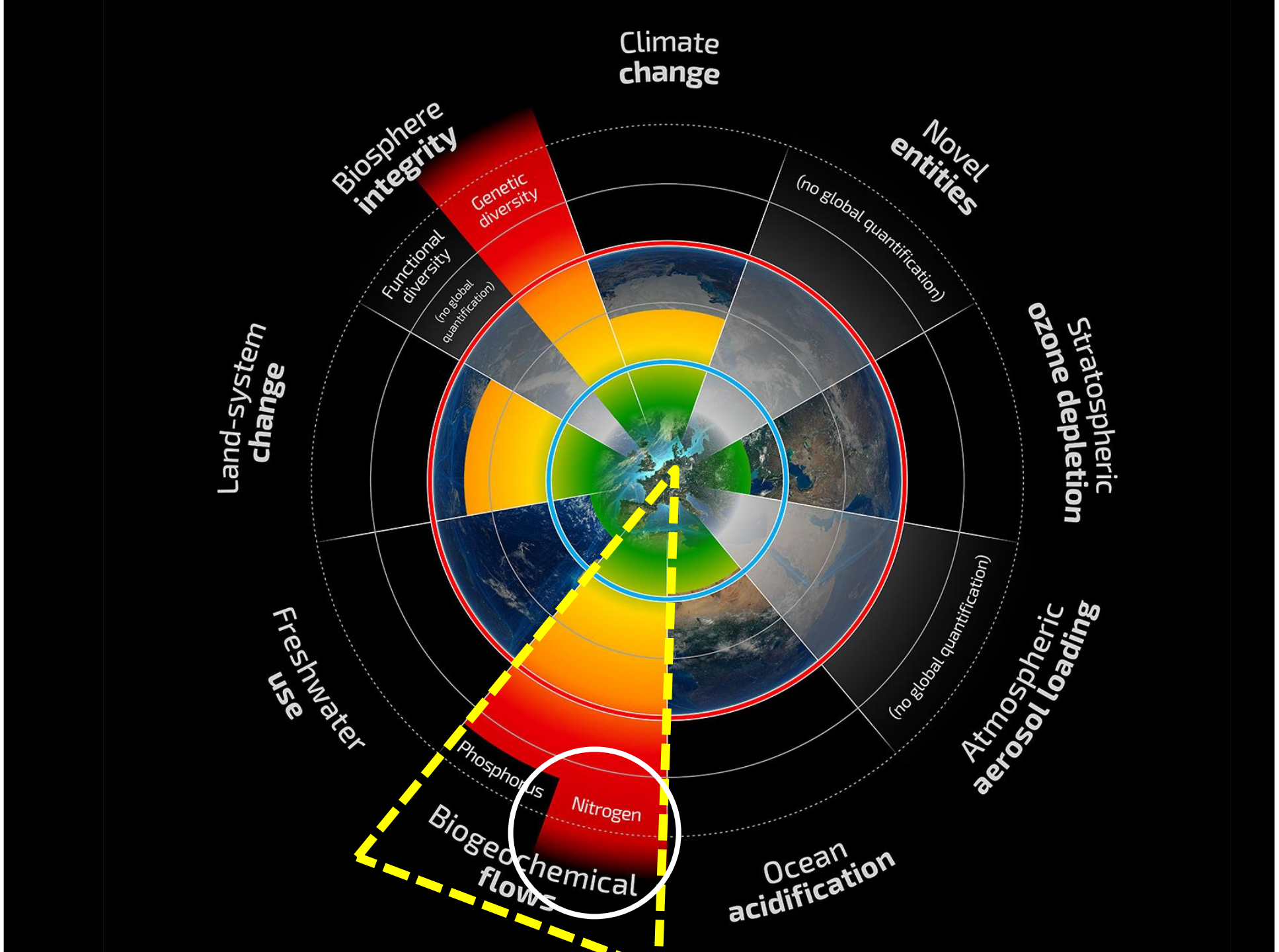
- High demand for energy / high production of CO_2
  1.8% of global fossil fuel consumption in 2017 / 1-2% of global warming
- Wasteful of N



Large biogeochemical flow of reactive N **Nr**

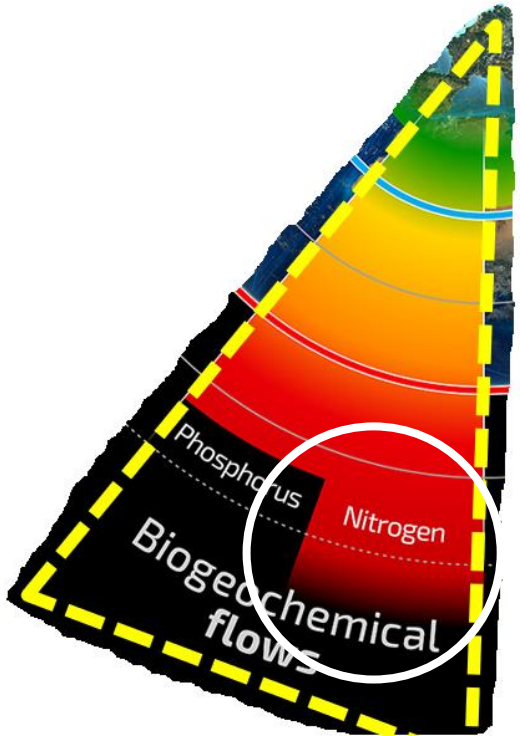
Mahaffy et. al, *Chemistry: Human Activity, Chemical Reactivity*, Nelson/Cengage, 2015

- Damaging to environment
  Air, land, oceans


Climate change
Novel entities
Stratospheric ozone depletion
Atmospheric aerosol loading
Ocean acidification
Biogeochemical flows
Freshwater use
Land-system change
Biosphere integrity
Genetic diversity
Functional diversity
(no global quantification)
(no global quantification)
(no global quantification)
Nitrogen
Phosphorus

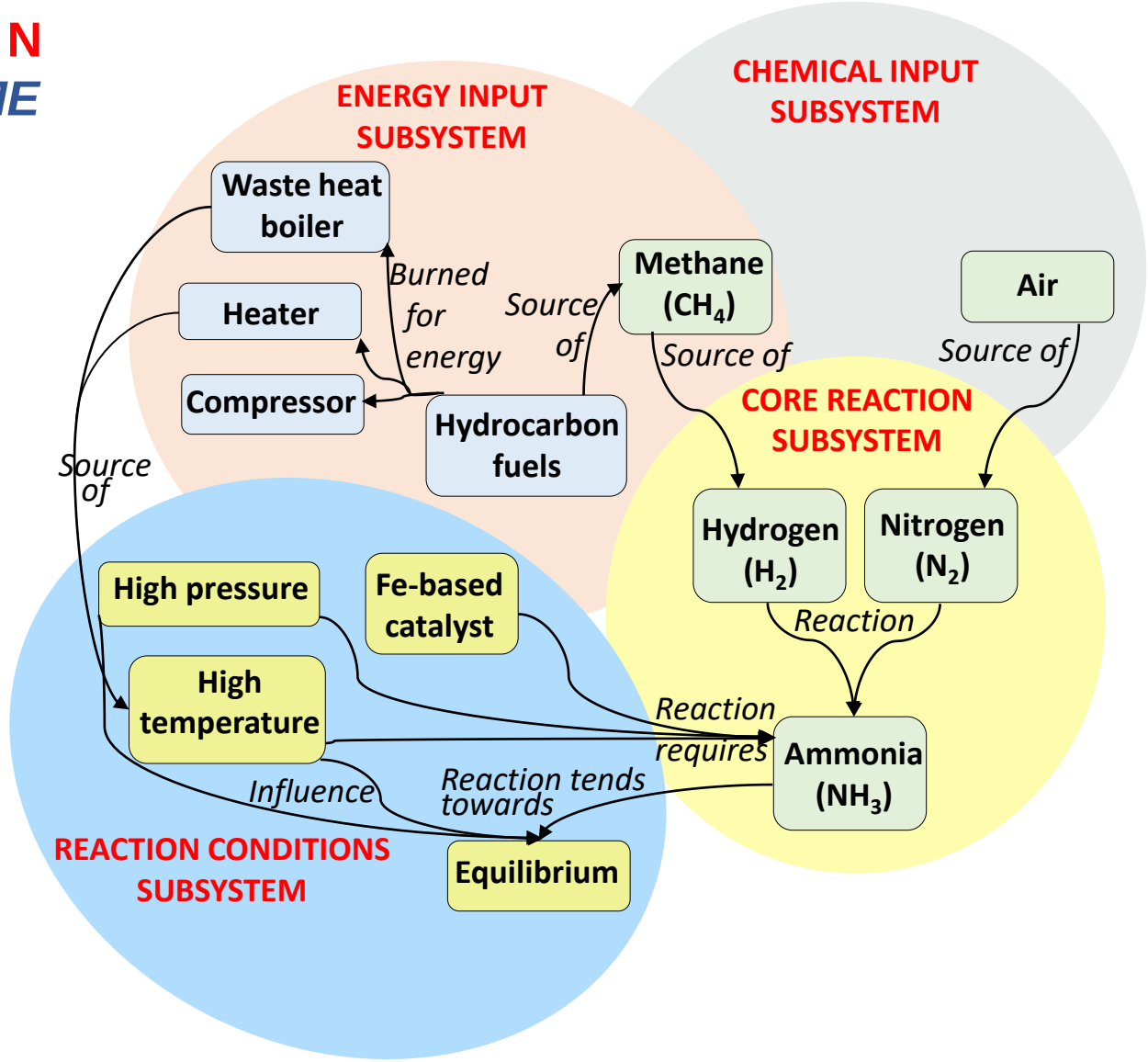
Planetary boundary Threshold

Variable Indicator measured	Below boundary (safe)	In zone of uncertainty	Beyond zone of uncertainty (increasing risk) (High risk)	Planetary boundary	Value of indicator (2015)
Biogeochem. flow: Nr Industrial & intentional biological N fixation				62 Tg / y	150 Tg / y



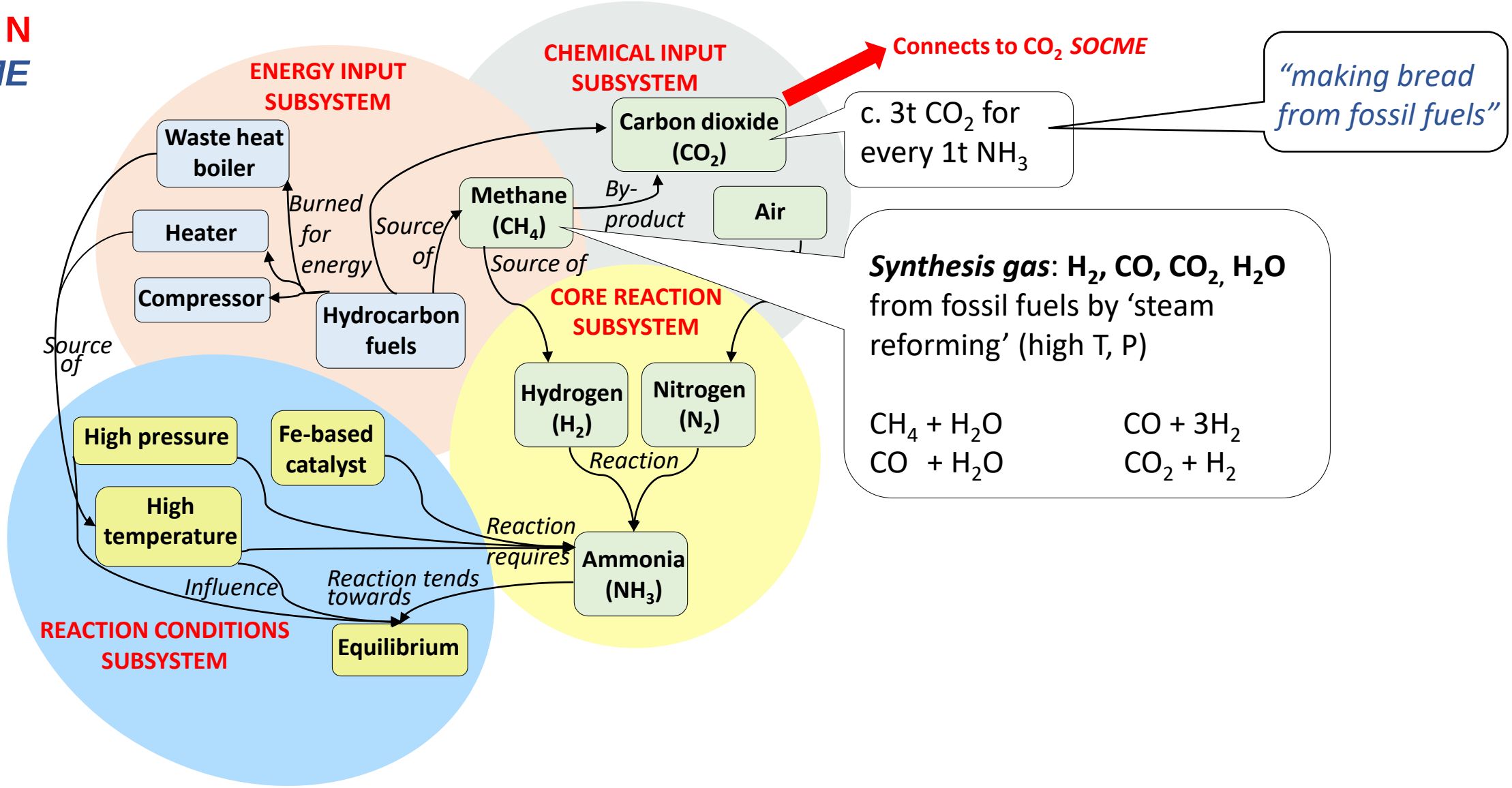
Reactive N

Nr *SOCME*



Reactive N

Nr *SOCME*



c. 3t CO_2 for every 1t NH_3

"making bread from fossil fuels"

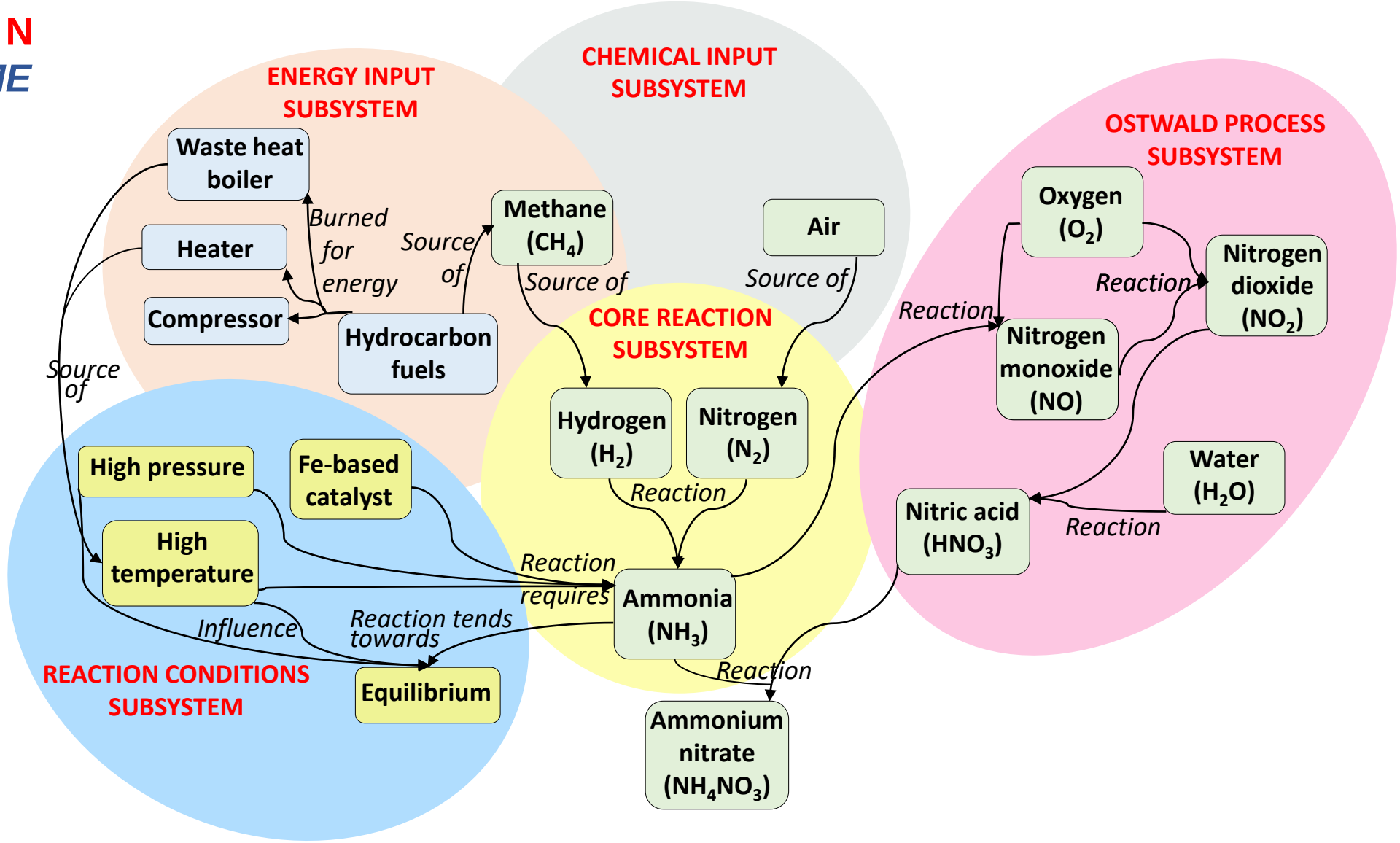
Synthesis gas: **H_2, CO, CO_2, H_2O** from fossil fuels by 'steam reforming' (high T, P)

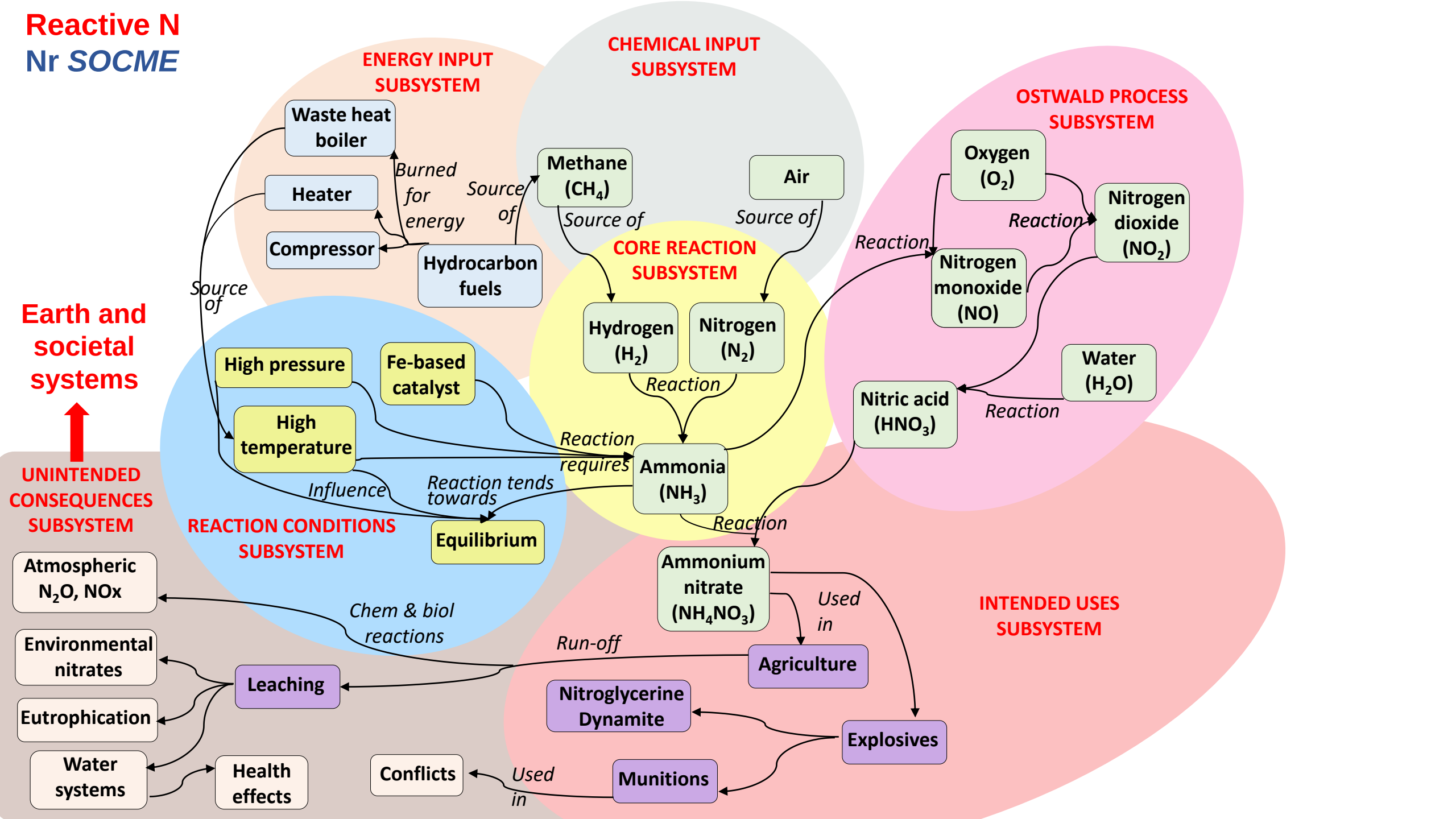
$CH_4 + H_2O$ $\quad$ $CO + 3H_2$

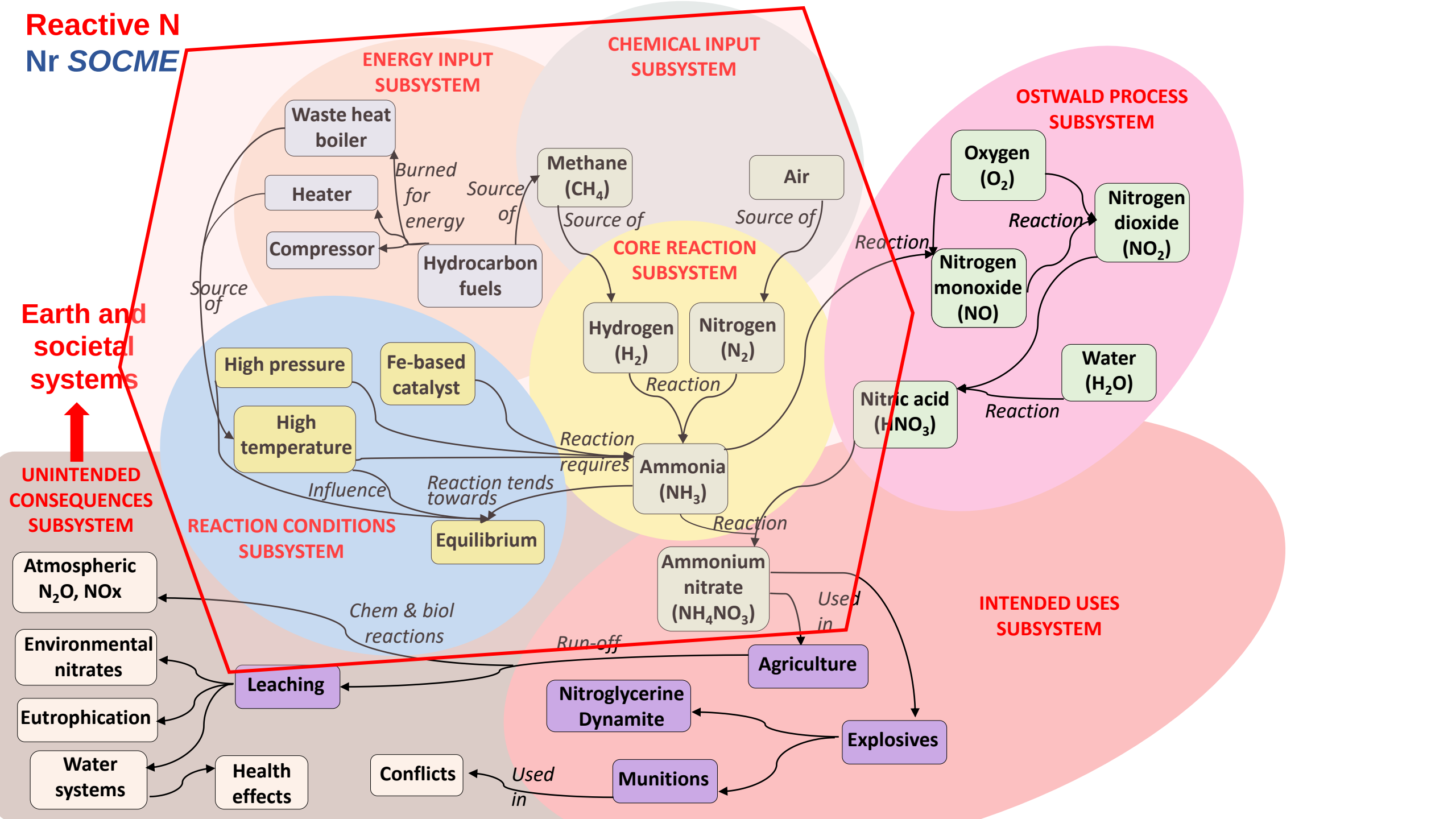
$CO + H_2O$ $\quad$ $CO_2 + H_2$

Reactive N

Nr *SOCME*




Reactive N
Nr SOCME
Earth and societal systems
ENERGY INPUT SUBSYSTEM
CHEMICAL INPUT SUBSYSTEM
OSTWALD PROCESS SUBSYSTEM
CORE REACTION SUBSYSTEM
REACTION CONDITIONS SUBSYSTEM
UNINTENDED CONSEQUENCES SUBSYSTEM
INTENDED USES SUBSYSTEM
Waste heat boiler
Heater
Compressor
Hydrocarbon fuels
Burned for energy
Source of
Methane (CH_4)
Air
Source of
Source of
Oxygen (O_2)
Nitrogen dioxide (NO_2)
Reaction
Reaction
Nitrogen monoxide (NO)
Hydrogen (H_2)
Nitrogen (N_2)
Reaction
Water (H_2O)
Nitric acid (HNO_3)
Reaction
High pressure
Fe-based catalyst
High temperature
Reaction requires
Ammonia (NH_3)
Influence
Reaction tends towards
Equilibrium
Reaction
Ammonium nitrate (NH_4NO_3)
Used in
Agriculture
Run-off
Chem & biol reactions
Atmospheric N_2O, NOx
Environmental nitrates
Leaching
Eutrophication
Water systems
Health effects
Nitroglycerine Dynamite
Explosives
Munitions
Used in
Conflicts


Reactive N
Nr SOCME
Earth and societal systems
ENERGY INPUT SUBSYSTEM
CHEMICAL INPUT SUBSYSTEM
OSTWALD PROCESS SUBSYSTEM
CORE REACTION SUBSYSTEM
REACTION CONDITIONS SUBSYSTEM
UNINTENDED CONSEQUENCES SUBSYSTEM
INTENDED USES SUBSYSTEM
Waste heat boiler
Heater
Compressor
Hydrocarbon fuels
Burned for energy
Source of
Methane (CH_4)
Air
Source of
Source of
Oxygen (O_2)
Nitrogen dioxide (NO_2)
Reaction
Nitrogen monoxide (NO)
Reaction
Hydrogen (H_2)
Nitrogen (N_2)
Reaction
Water (H_2O)
Nitric acid (HNO_3)
Reaction
High pressure
Fe-based catalyst
High temperature
Reaction requires
Ammonia (NH_3)
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Equilibrium
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Used in
Agriculture
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Run-off
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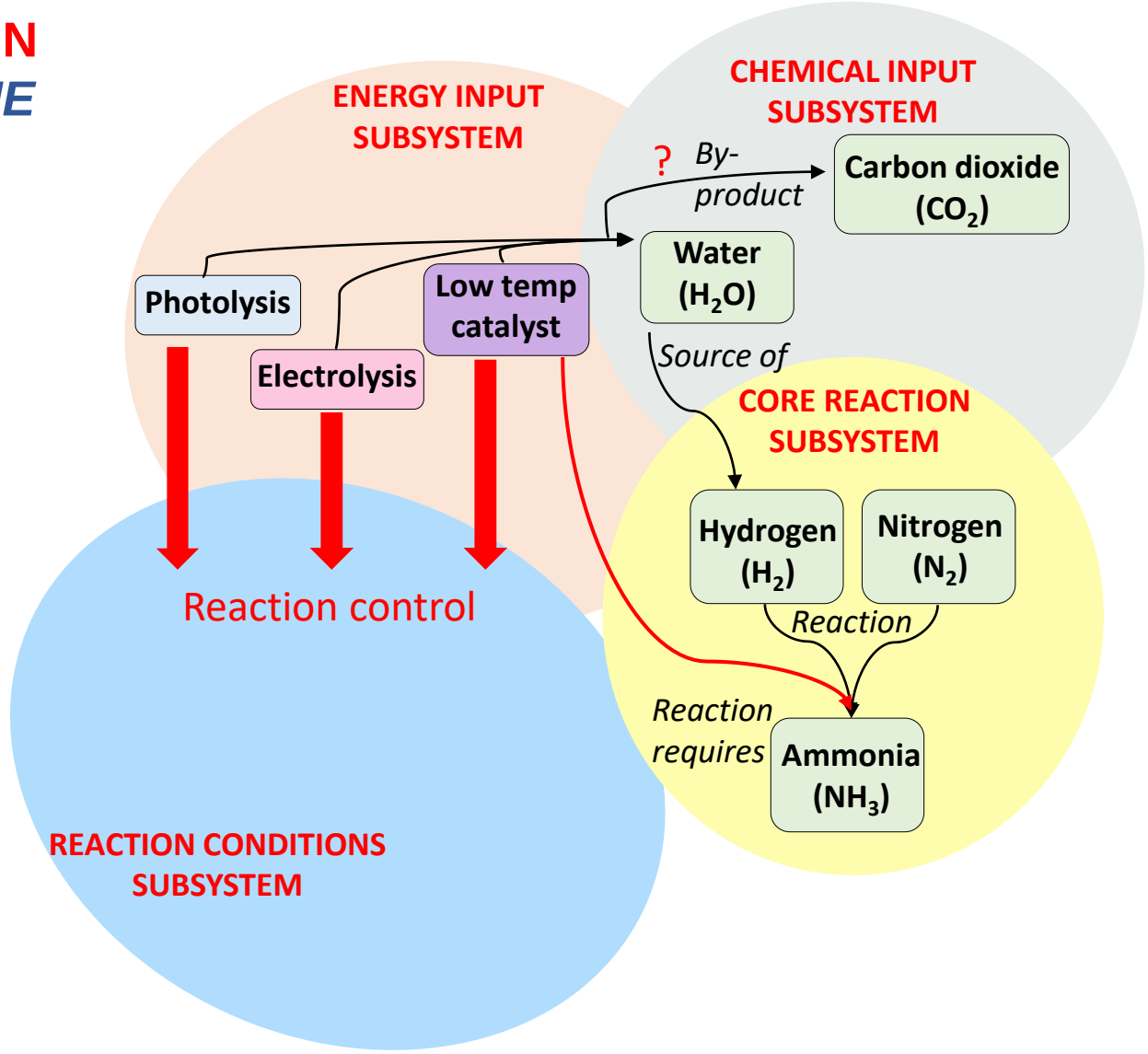
Atmospheric N_2O, NOx
Environmental nitrates
Eutrophication
Water systems
Health effects
Nitroglycerine Dynamite
Explosives
Munitions
Used in
Conflicts

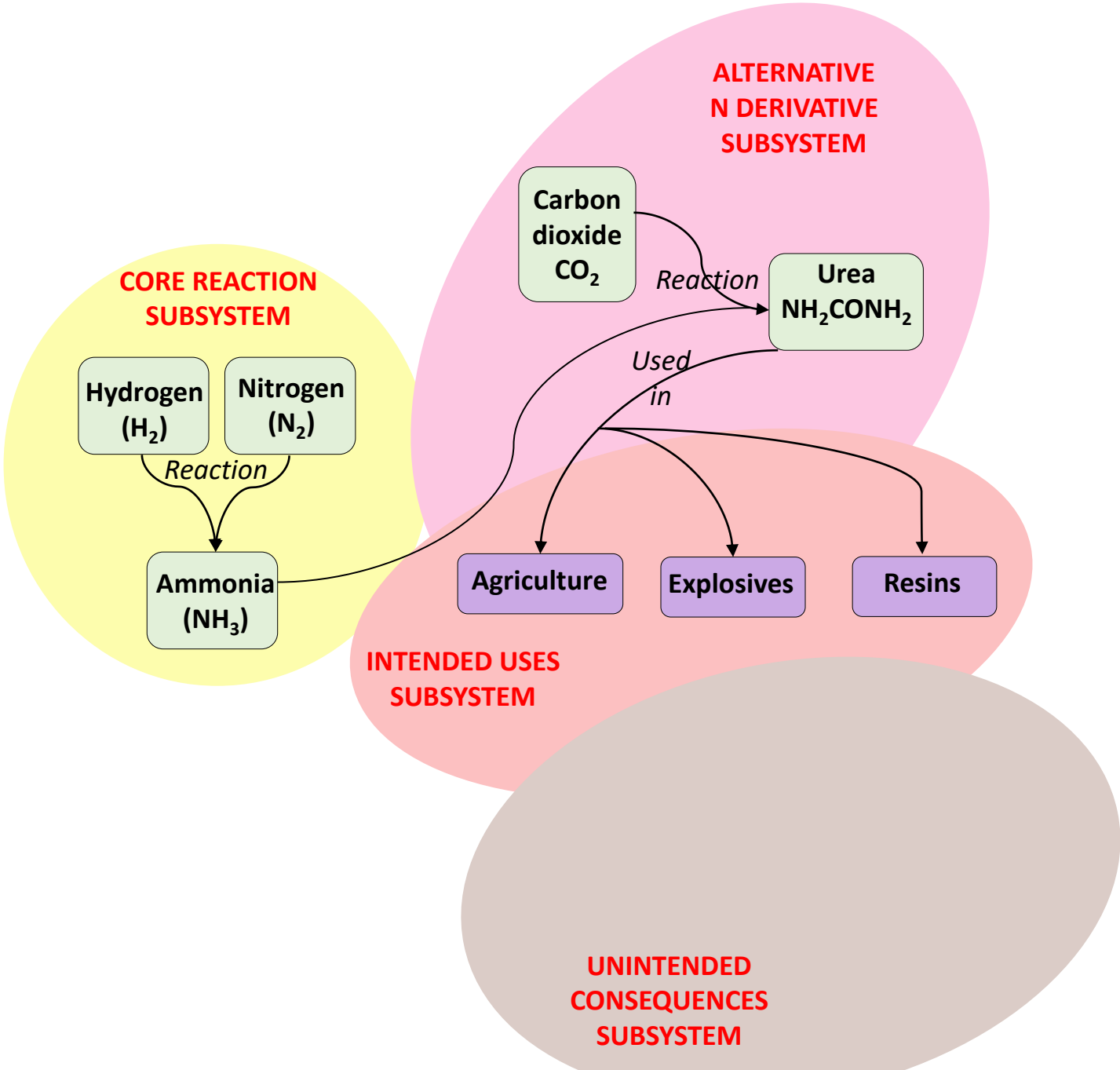
Reactive N

Nr *SOCME*



Reactive N

Nr *SOCME*



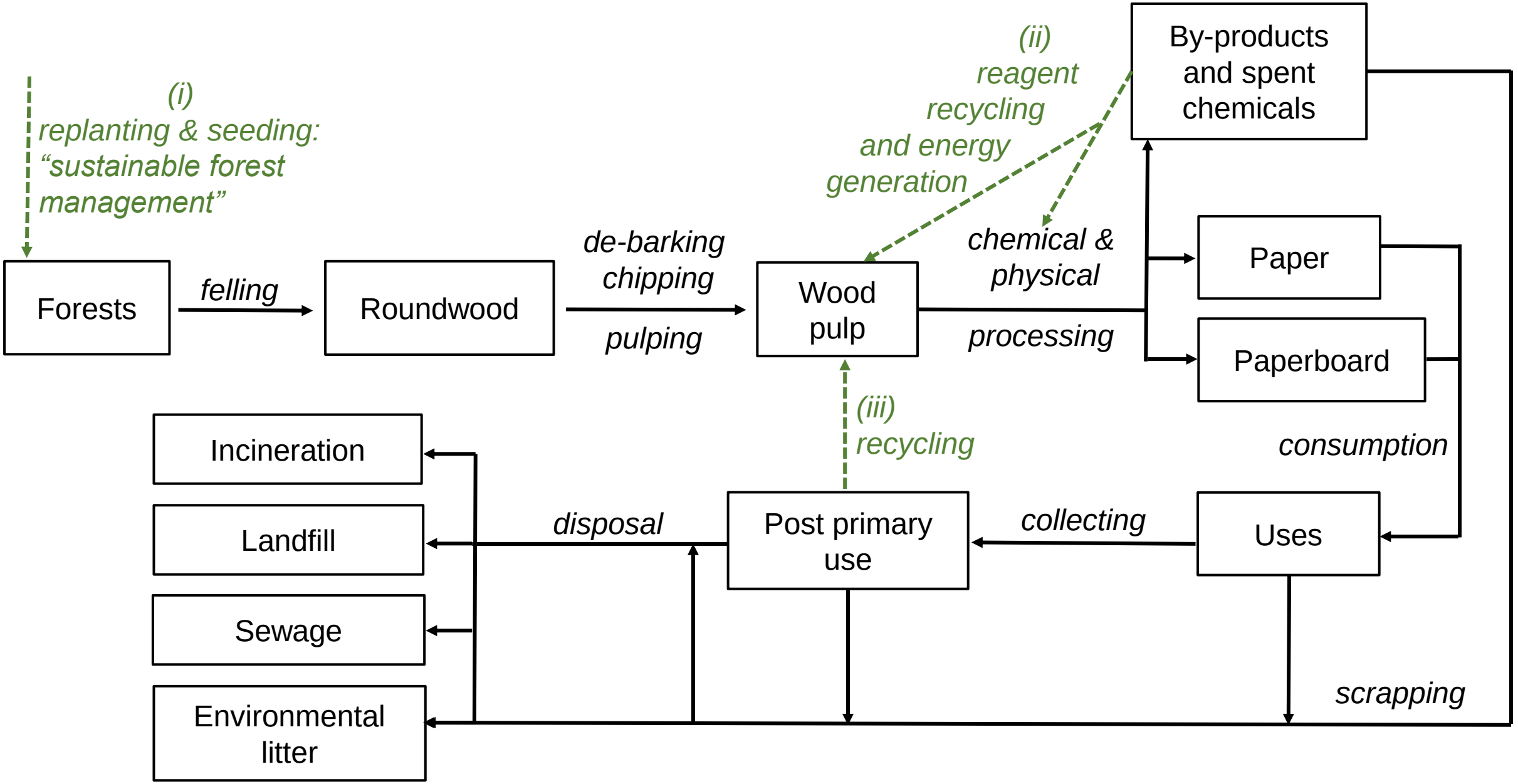
Paper and paperboard: products of wood pulp[1]

"Paper is one of the few truly sustainable products."
"The myth that paper is bad for the environment"
Two Sides, 2020
https://www.twosides.info/sustainable-products/

"Paper is one of the few products which is completely sustainable." FESPA, 2018
https://www.fespa.com/en/news-media/features/sustainability-and-paper-what-are-your-options

- Based on wood: natural, renewable
- Growing trees absorb atmospheric CO_2 and the C is stored in paper & paperboard throughout their lifetimes
- The wood pulp industry very efficiently recycles the chemicals it uses
- Using 1 T of [brand] 100% recycled paper instead of virgin fibre paper saves equivalent of 1,231 kg landfill, 3,794 kWh electricity, 29,800 l water, 2,000 kg wood and 295 kg CO_2 and greenhouse gases

[1] S.A. Matlin, K. Kümmerer, P.G. Mahaffy. *Mapping complex cross-system sustainability effects: the sustainability of paper and paperboard.* In: E. Michalopoulou, T. Stanmore, L. Ma. N. Jester, E.D. Shallcross, E. Atkins, W. Leal Filho (eds), *Sustainability and complexity: towards a post-disciplinary approach.* World Sustainability Series, Springer, 2021, submitted.

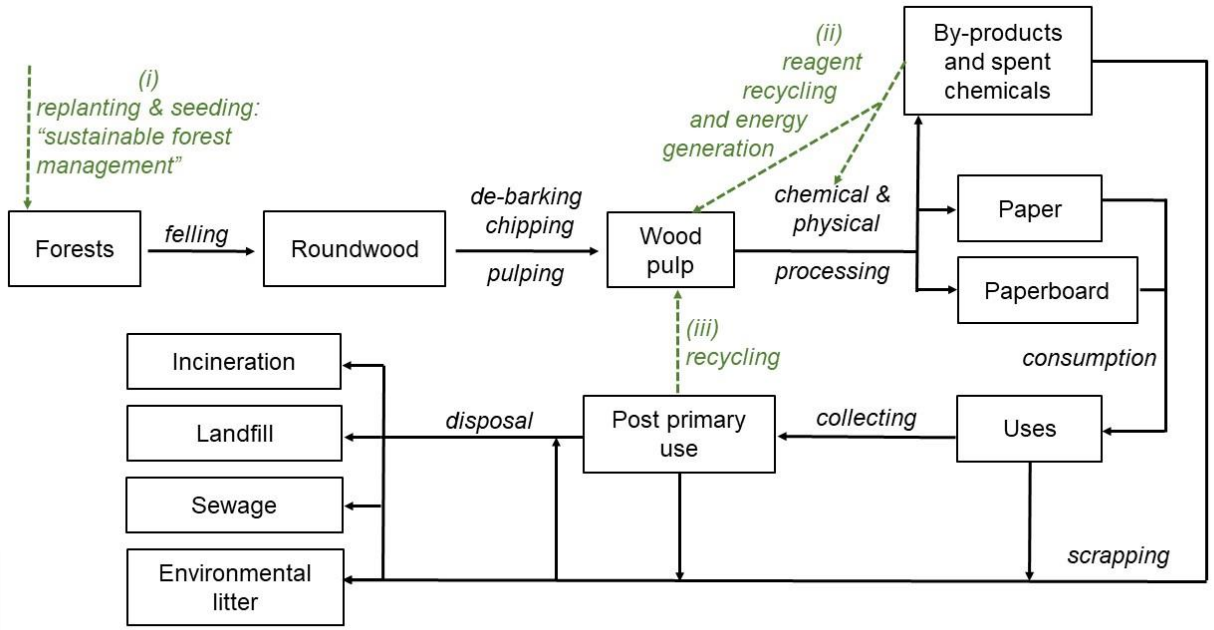

(i)
replanting & seeding:
"sustainable forest
management"
(ii)
reagent
recycling
and energy
generation
By-products
and spent
chemicals
Forests
felling
Roundwood
de-barking
chipping
pulping
Wood
pulp
chemical &
physical
processing
Paper
Paperboard
(iii)
recycling
consumption
Incineration
Landfill
Sewage
Environmental
litter
disposal
Post primary
use
collecting
Uses
scrapping

ATMOSPHERIC SYSTEM

LAND SYSTEM

AQUATIC SYSTEM

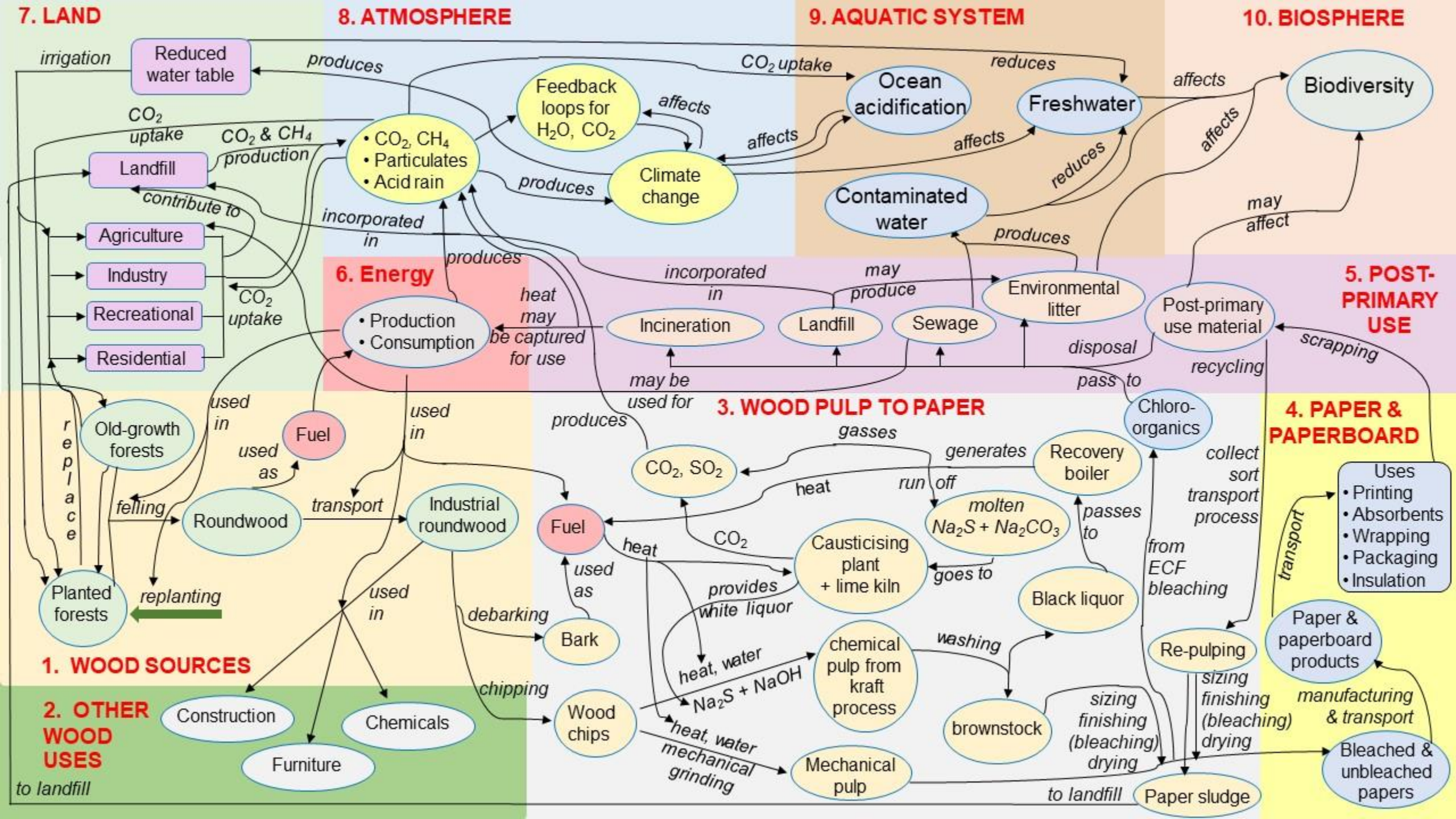
ENERGY INPUT SYSTEM

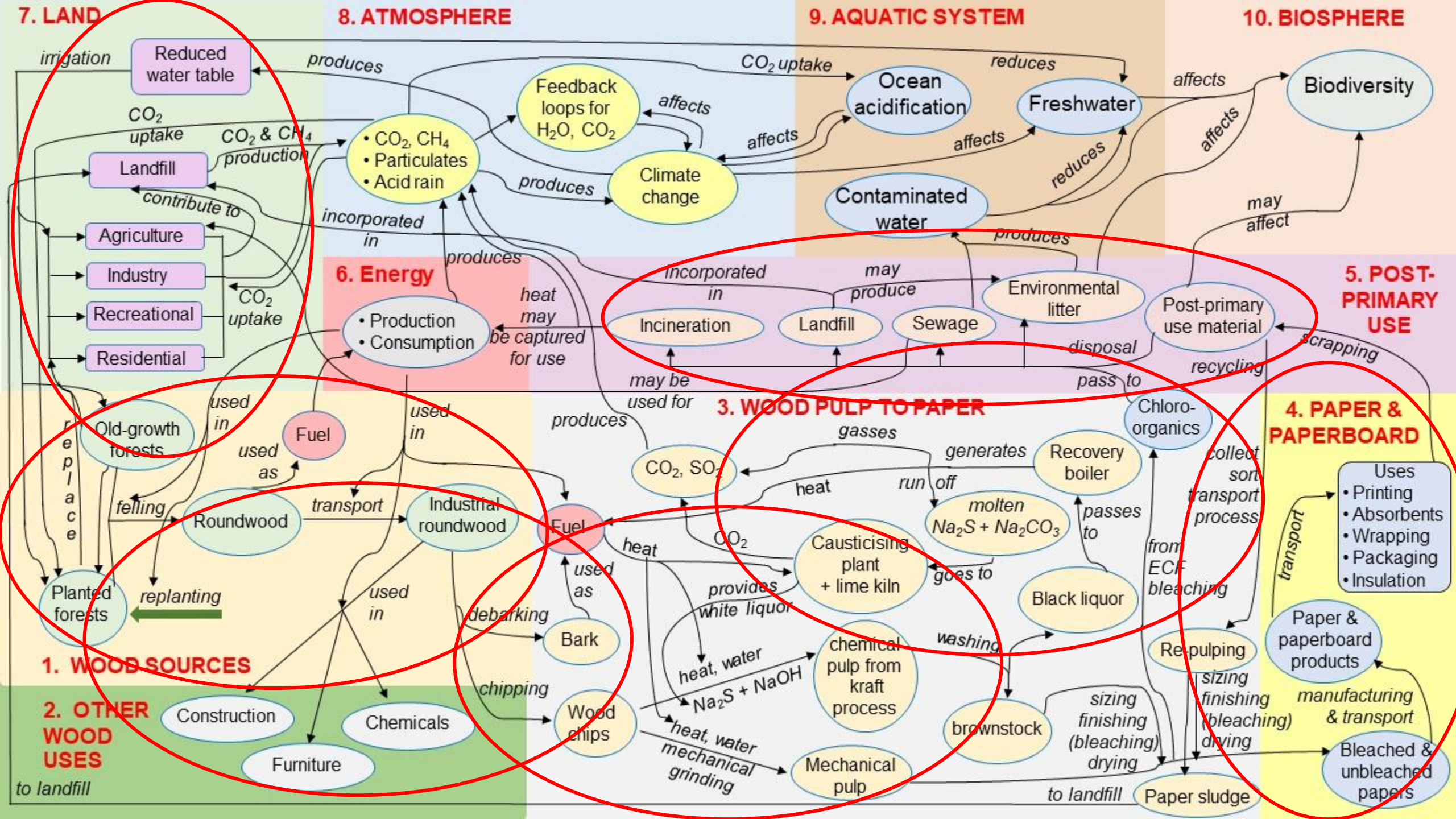


BIOLOGICAL & ECOLOGICAL SYSTEMS

MATERIAL INPUT SYSTEM

HUMAN SYSTEM


7. LAND
8. ATMOSPHERE
9. AQUATIC SYSTEM
10. BIOSPHERE
irrigation
Reduced water table
produces
CO_2 uptake
reduces
Ocean acidification
Freshwater
affects
Biodiversity
Feedback loops for H_2O, CO_2
affects
CO_2 uptake
CO_2 & CH_4 production
• CO_2, CH_4
• Particulates
• Acid rain
affects
affects
affects
reduces
affects
Landfill
Climate change
produces
Contaminated water
contribute to
incorporated in
may affect
produces
Agriculture
Industry
Recreational
Residential
CO_2 uptake
6. Energy
produces
heat may be captured for use
• Production
• Consumption
incorporated in
may produce
Incineration
Landfill
Sewage
Environmental litter
Post-primary use material
5. POST-PRIMARY USE
disposal
recycling
scrapping
may be used for
pass to
Chloro-organics
3. WOOD PULP TO PAPER
4. PAPER & PAPERBOARD
used in
used as
Fuel
used in
produces
gasses
generates
Recovery boiler
collect sort transport process
replace
Old-growth forests
felling
Roundwood
transport
Industrial roundwood
CO_2, SO_2
heat
run off
molten Na_2S + Na_2CO_3
passes to
Uses
• Printing
• Absorbents
• Wrapping
• Packaging
• Insulation
transport
Fuel
heat
CO_2
Causticising plant + lime kiln
goes to
Black liquor
from ECF bleaching
used as
provides white liquor
Planted forests
replanting
used in
debarking
Bark
heat, water
Na_2S + NaOH
chemical pulp from kraft process
washing
Re-pulping
Paper & paperboard products
1. WOOD SOURCES
chipping
Wood chips
heat, water
mechanical grinding
Mechanical pulp
brownstock
sizing
finishing
(bleaching)
drying
manufacturing & transport
2. OTHER WOOD USES
Construction
Chemicals
Furniture
to landfill
to landfill
Paper sludge
Bleached & unbleached papers


7. LAND
8. ATMOSPHERE
9. AQUATIC SYSTEM
10. BIOSPHERE
irrigation
Reduced water table
produces
CO_2 uptake
reduces
Ocean acidification
Freshwater
affects
Biodiversity
CO_2 uptake
CO_2 & CH_4 production
Landfill
• CO_2, CH_4
• Particulates
• Acid rain
Feedback loops for H_2O, CO_2
affects
affects
affects
affects
reduces
affects
Climate change
produces
Contaminated water
contribute to
incorporated in
may affect
Agriculture
Industry
Recreational
Residential
CO_2 uptake
produces
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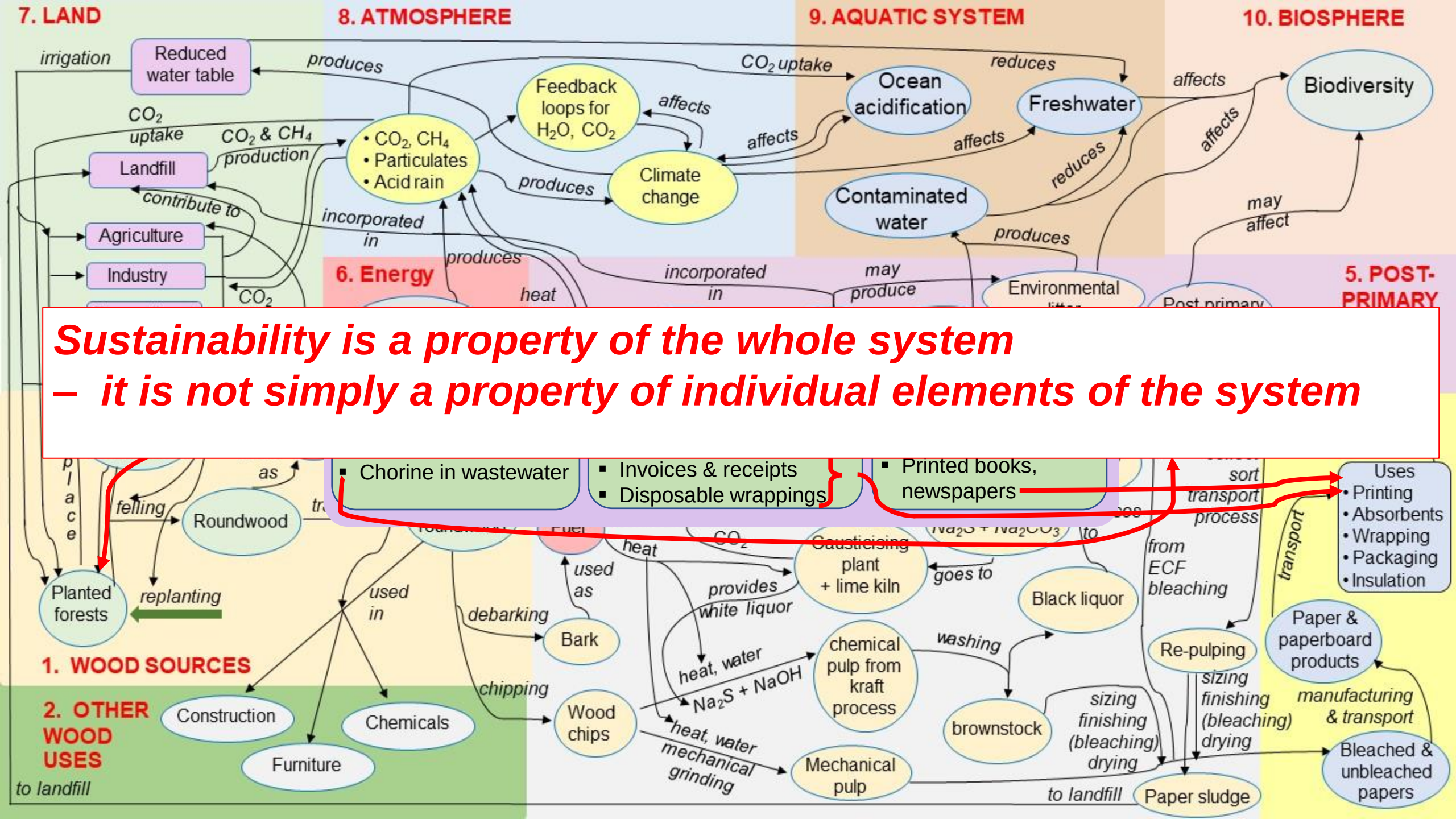
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Industry
produces
6. Energy
heat
incorporated in
may produce
Environmental
5. POST-PRIMARY
CO_2
Sustainability is a property of the whole system
– it is not simply a property of individual elements of the system
▪ Chorine in wastewater
▪ Invoices & receipts
▪ Disposable wrappings
▪ Printed books, newspapers
sort
transport
process
Uses
• Printing
• Absorbents
• Wrapping
• Packaging
• Insulation
transport
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Thank you

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