Systems Thinking to Educate about the Molecular Basis of Sustainability

50th General Assembly
& 47th IUPAC World Chemistry Congress

"Frontiers in Chemistry: Let's create our Future! 100 years with IUPAC"

Peter Mahaffy

THE KING'S UNIVERSITY

Stephen Matlin

IOCD

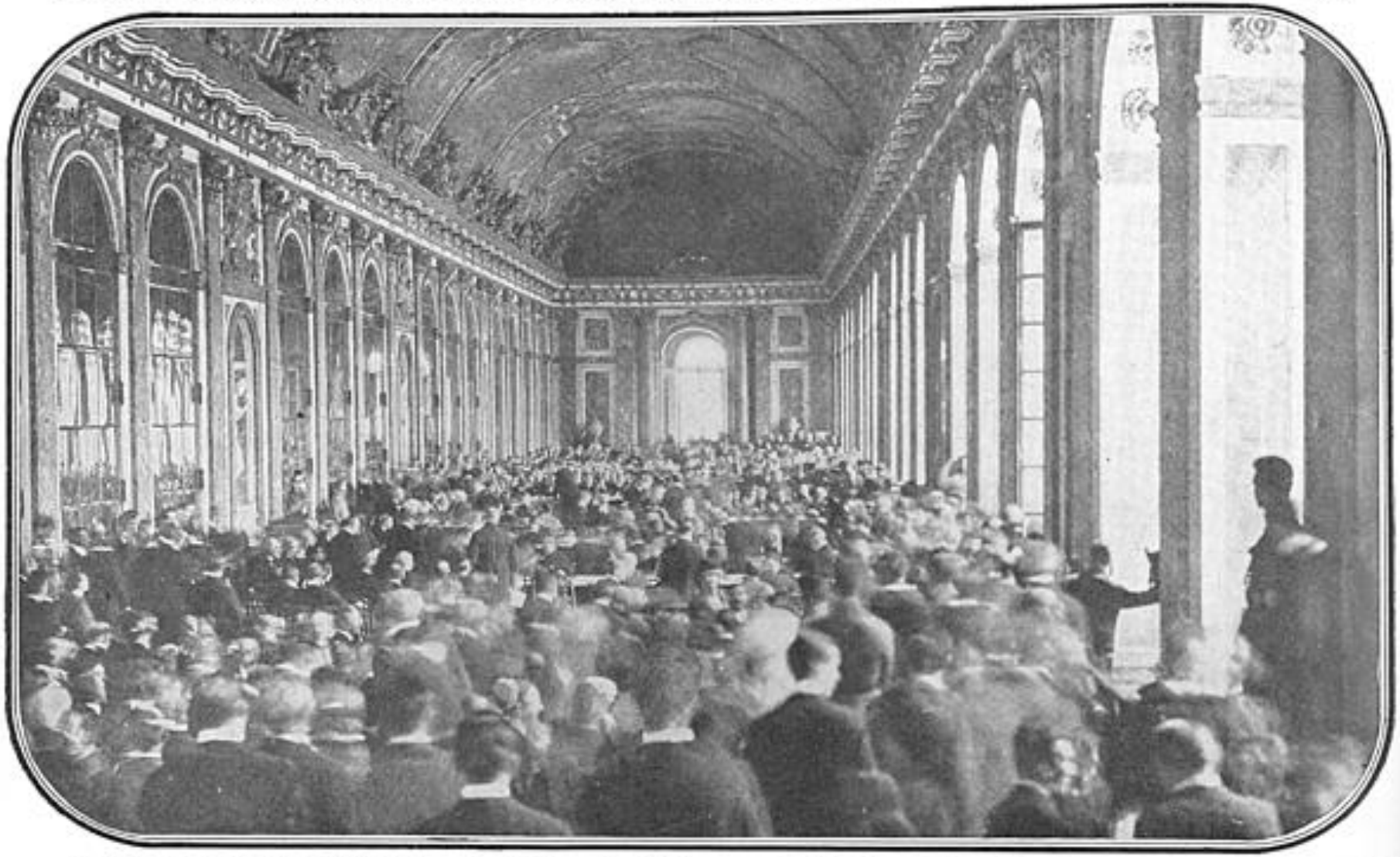
@peter.mahaffy

@iupac #IUPAC2019Paris

IUPAC's World in 1919

The Greatest Moment in History

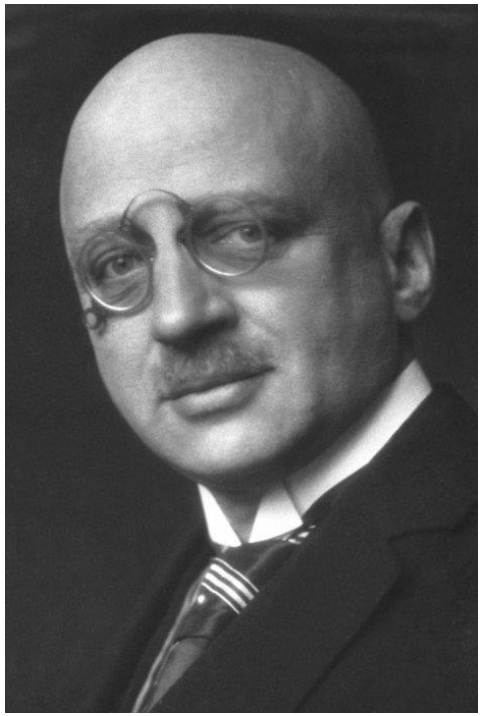
Exclusive Photographs by HELEN JOHNS KIRTLAND and LUCIAN SWIFT KIRTLAND, Leslie's Staff Correspondents



The signing of the Peace Treaty at Versailles on June 28th formally ended the greatest war in the history of the world, and as the German delegates attached their signatures the thoughts of many turned back to the days of 1871 when Bismarck imposed his stern conditions on the French delegates in the same hall.

Versailles/Paris Peace Treaty marking end of "The Chemist's War."

IUPAC's World in 1919



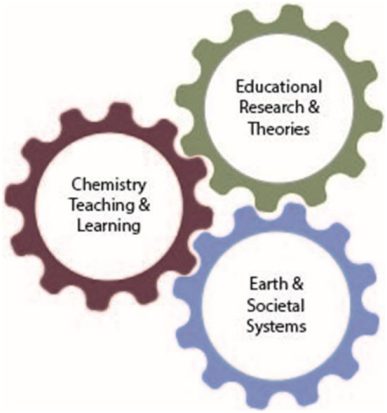
50th General Assembly & 47th IUPAC World Chemistry Congress

"Frontiers in Chemistry: Let's create our Future! 100 years with IUPAC"

IUPAC Mission/Vision (2019)

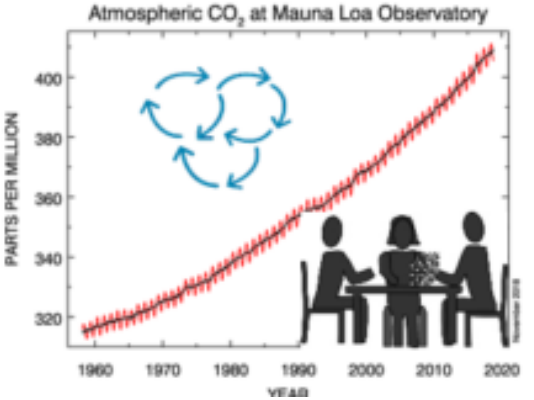
- …Application and communication of chemical knowledge for the benefit of humankind and the world.
- Fostering sustainable development, providing a common language for chemistry, and advocating the free exchange of scientific information.

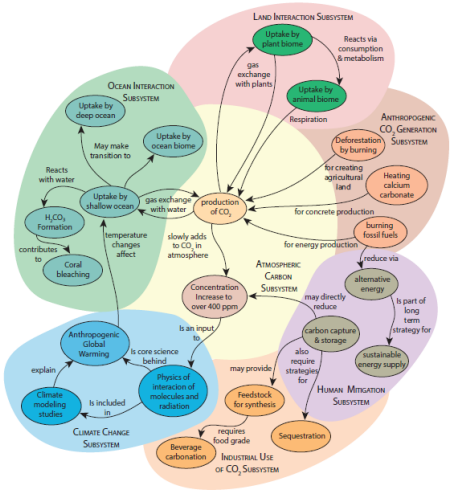
Systems Thinking to Educate about the Molecular Basis of Sustainability



Systems thinking in Chemistry Education

Molecular Basis of Sustainability





ST tools and boundaries: SOCMEs

Next Steps for STICE

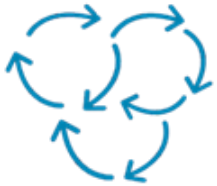
Why Systems Thinking in Chemistry Education?

Complexity requires specialization in the pursuit of discovery as we deepen our understanding of the modern world and create the knowledge needed to resolve current dilemmas and improve the quality of life.

In this process, we continually ***fractionate knowledge****, analyzing the pieces in greater and greater depth. We have trained our 20th century professional quite well in this task— it's a global strength we must sustain— but what additional skill will be demanded of 21st century leaders?*

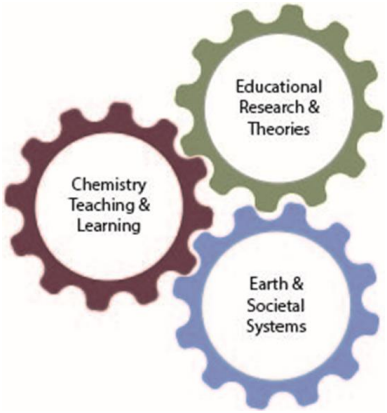
Joseph Bordogna in PKAL, What Works, Vol. I, **1991**

Systems Thinking

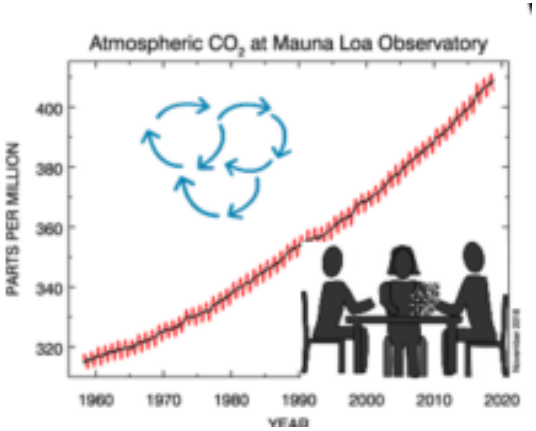


- Systems Thinking*: Use **tools, strategies, and cognitive frameworks** to:
  - Visualize **interconnections and relationships among components** of complex, dynamic systems.
  - Examine how **behavior of the system changes over time**.
  - Understand how **systems-level phenomena emerge** from interactions among the system parts.

*Orgill, M.K.; York, S.; Mackellar, J. An introduction to systems thinking for the chemistry education community, *J Chem. Educ.* **ASAP - 2019,** *Special Issue on Systems Thinking and Green & Sustainable Chemistry*



Systems thinking in Chemistry Education



International Union of Pure and Applied Chemistry

Systems Thinking in Chemistry Education (STICE)
An IUPAC Project

How might systems thinking apply to Chem Ed, and how can that help the next generation address emerging global challenges?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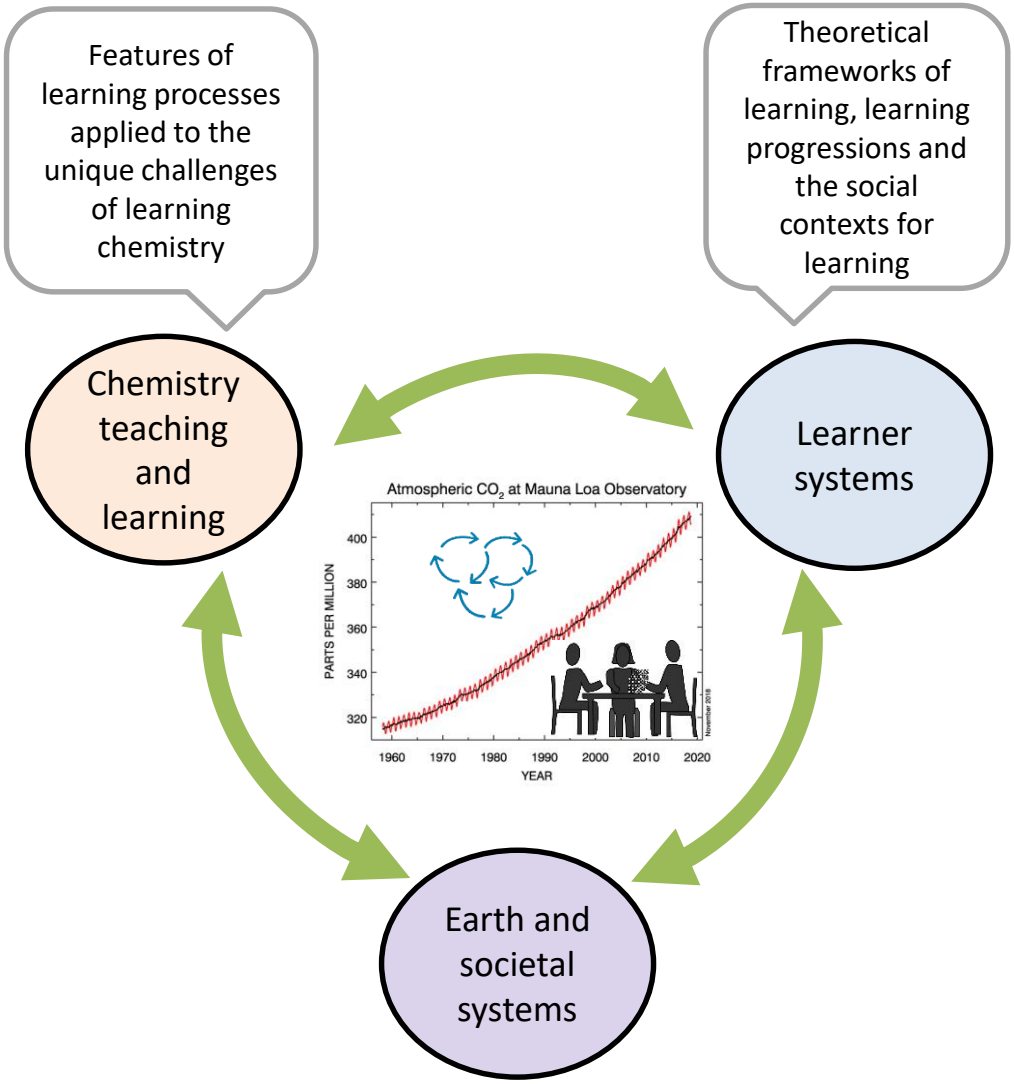

Framework for Systems Thinking in Chemistry Education

Mahaffy, Matlin, Krief, Hopf, Meta, *"Reorienting Chemistry Education through Systems Thinking"*

nature REVIEWS CHEMISTRY

(2018) VOLUME 2 | ARTICLE NUMBER 0126 | **1**

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News and Announcements

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Journal of Chemical Education Call for Papers—Special Issue on Reimagining Chemistry Education: Systems Thinking, and Green and Sustainable Chemistry

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ABSTRACT: The *Journal of Chemical Education* announces a call for papers for an upcoming special issue on Reimagining Chemistry Education: Systems Thinking, and Green and Sustainable Chemistry.

KEYWORDS: *High School/Introductory Chemistry, First-Year Undergraduate/General, Upper-Division Undergraduate, Curriculum, Environmental Chemistry, Interdisciplinary/Multidisciplinary, Problem Solving/Decision Making, Green Chemistry, Learning Theories, Student-Centered Learning, Systems Thinking, Sustainability*

Tom Holme
Associate Editor
J. Chem. Educ.

Systems Thinking in Chemistry Education (STICE) Progress to Date

- STICE - Definition, purpose, preliminary framework
- Review of ST in other STEM fields
- Challenges of dealing with complexity
- ST skills and competencies
- ST tools and visualizations
- ST to address global challenges – the molecular basis of sustainability
- Learning frameworks to guide use of STICE
- ST and educational standards related to chemistry

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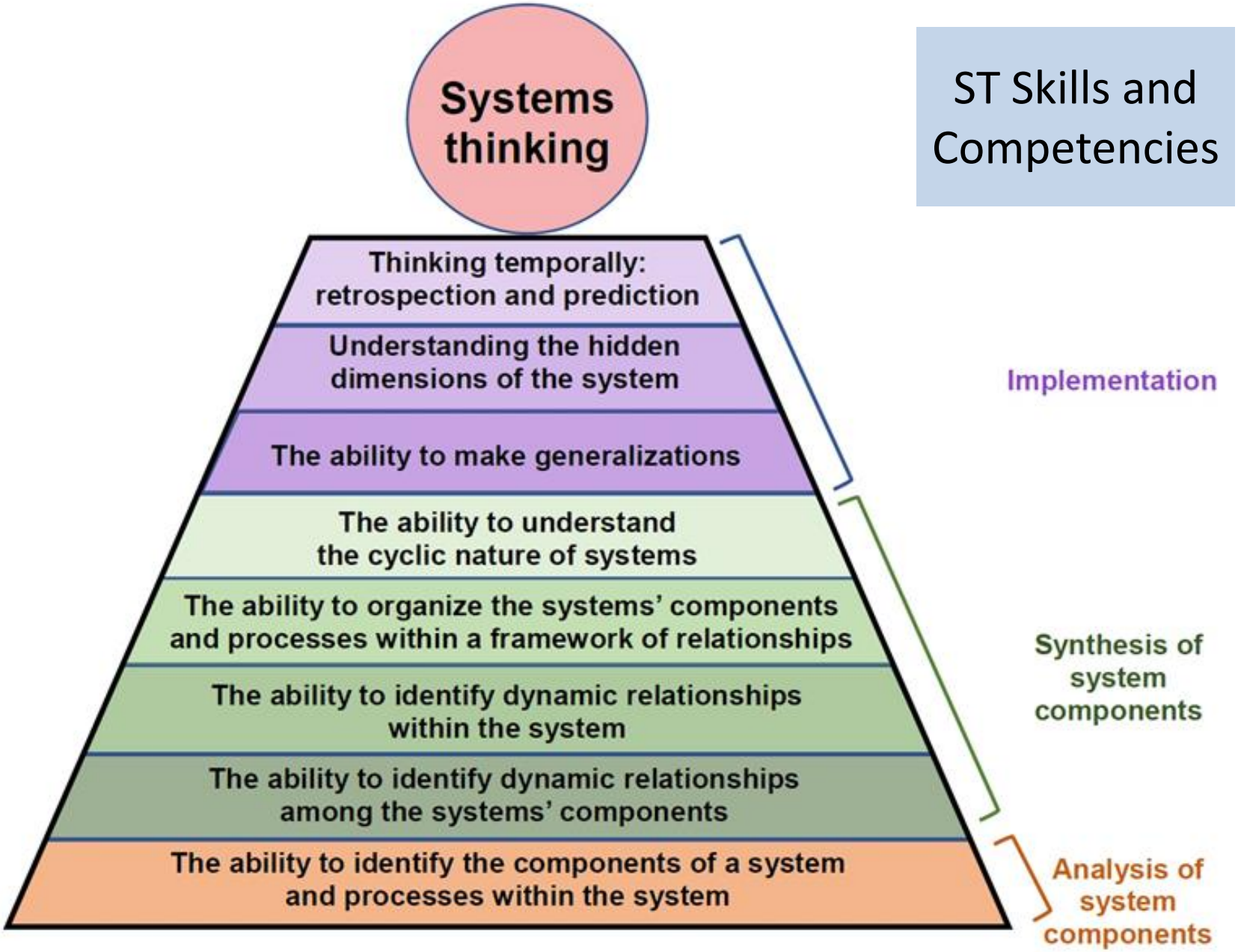
ST Skills and Competencies



Orgill, M.K.; York, S.; Mackellar, J. An introduction to systems thinking for the chemistry education community. *J Chem. Educ.* **ASAP - 2019, *Special Issue on Systems Thinking and Green & Sustainable Chemistry.*

Systems thinking in Chemistry Education

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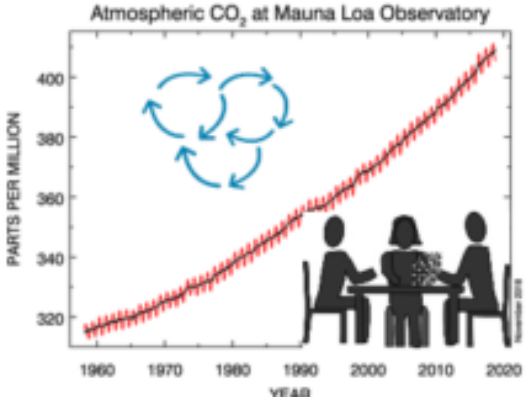
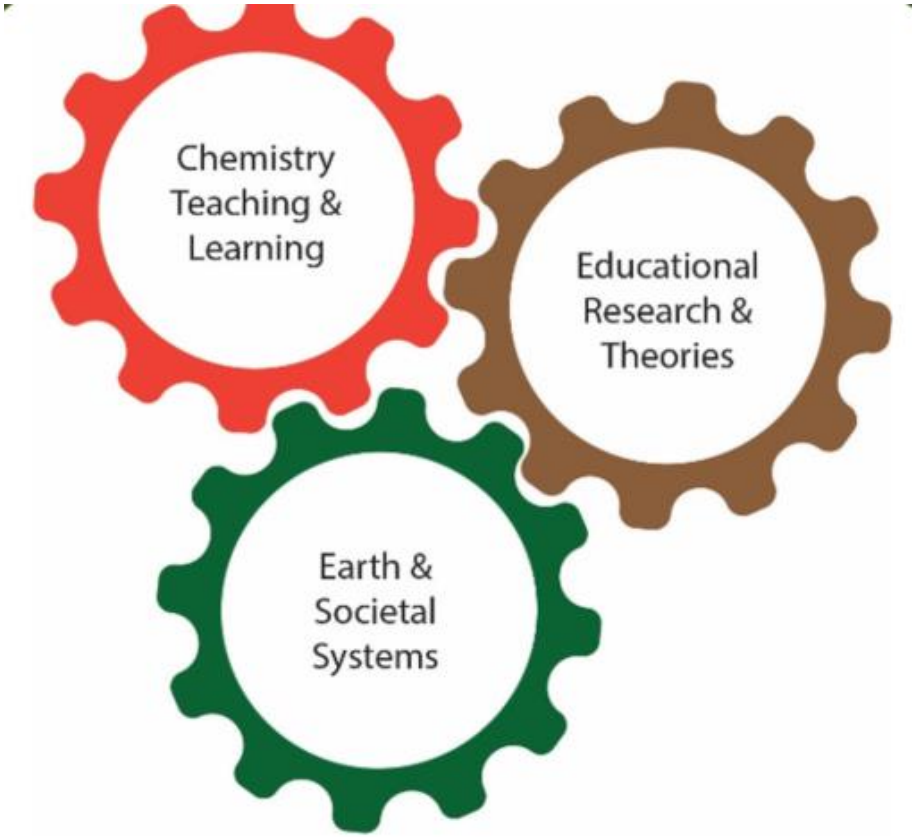
Molecular Basis of Sustainability



ST tools and boundaries: SOCMEs

Next Steps for STICE



Earth and Societal Systems Node – Steering Group

- Tom Holme, Iowa State University
- Jennifer MacKellar and David Constable, Green Chemistry Institute, ACS
- Peter Mahaffy, King's University
- Stephen Matlin, Imperial College

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The molecular basis of sustainability

Many environmental issues have molecular considerations

Anastas, P. T., Zimmerman, J. B. The molecular basis of sustainability. *Chem* **2016,** *1*, 10–12

nature chemistry

The molecular basis of sustainability

- The flow of material and energy is integral to all aspects of society and the environment.
- Chemistry understands and <u>controls</u> matter through activities to analyze, synthesize, and transform substances.
- Chemistry and chemistry education have a special responsibility to address the sustainability of earth and societal systems.
- <u>Molecular basis of sustainability</u>: "*The ways in which the material basis of society and economy underlie considerations of how present and future generations can live within the limits of the natural world.*"
- MBOS: Crucial, but largely invisible aspect of sustainability

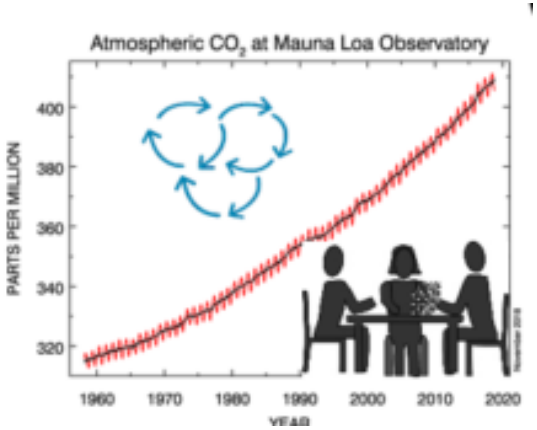
Many environmental issues have molecular considerations

Matlin, Mehta, Hopf, Krief, "One-world chemistry and systems thinking," (2016), 8, 393-398.

nature chemistry

Mahaffy, Matlin, Holme, MacKellar, *"Systems Thinking for Education about the Molecular Basis of Sustainability," (2019), 2, 362–370.*

nature sustainability



Molecular Basis of Sustainability

Molecular Basis of Sustainability

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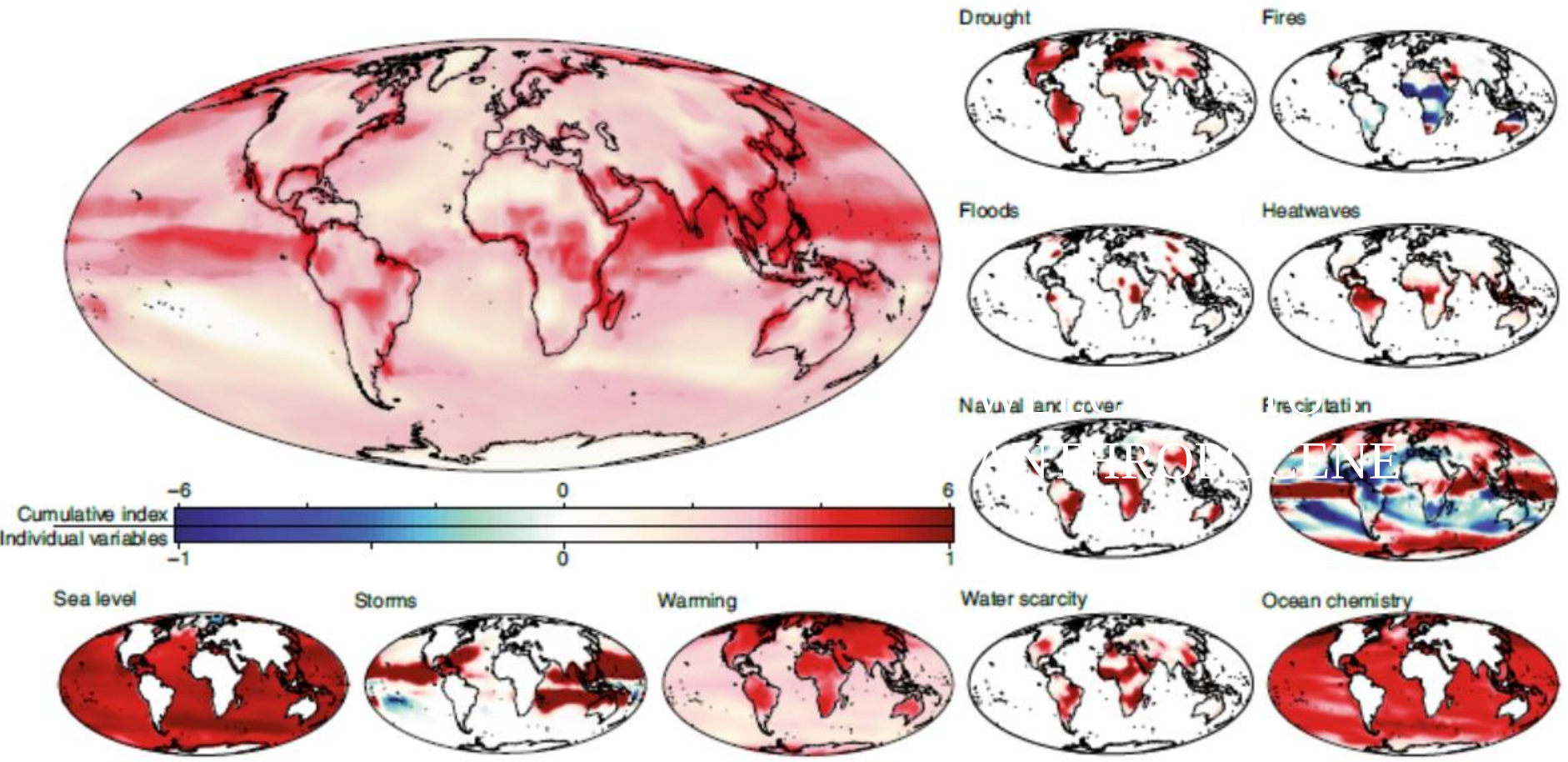
World is 'on notice' as major UN report shows one million species face extinction

There is more CO2 in the atmosphere today than any point since the evolution of humans

nature climate change

REVIEW ARTICLE

https://doi.org/10.1038/s41558-018-0315-6



467 traceable pathways for impacts on human health, water, food, economy, infrastructure and security by multiple climate hazards

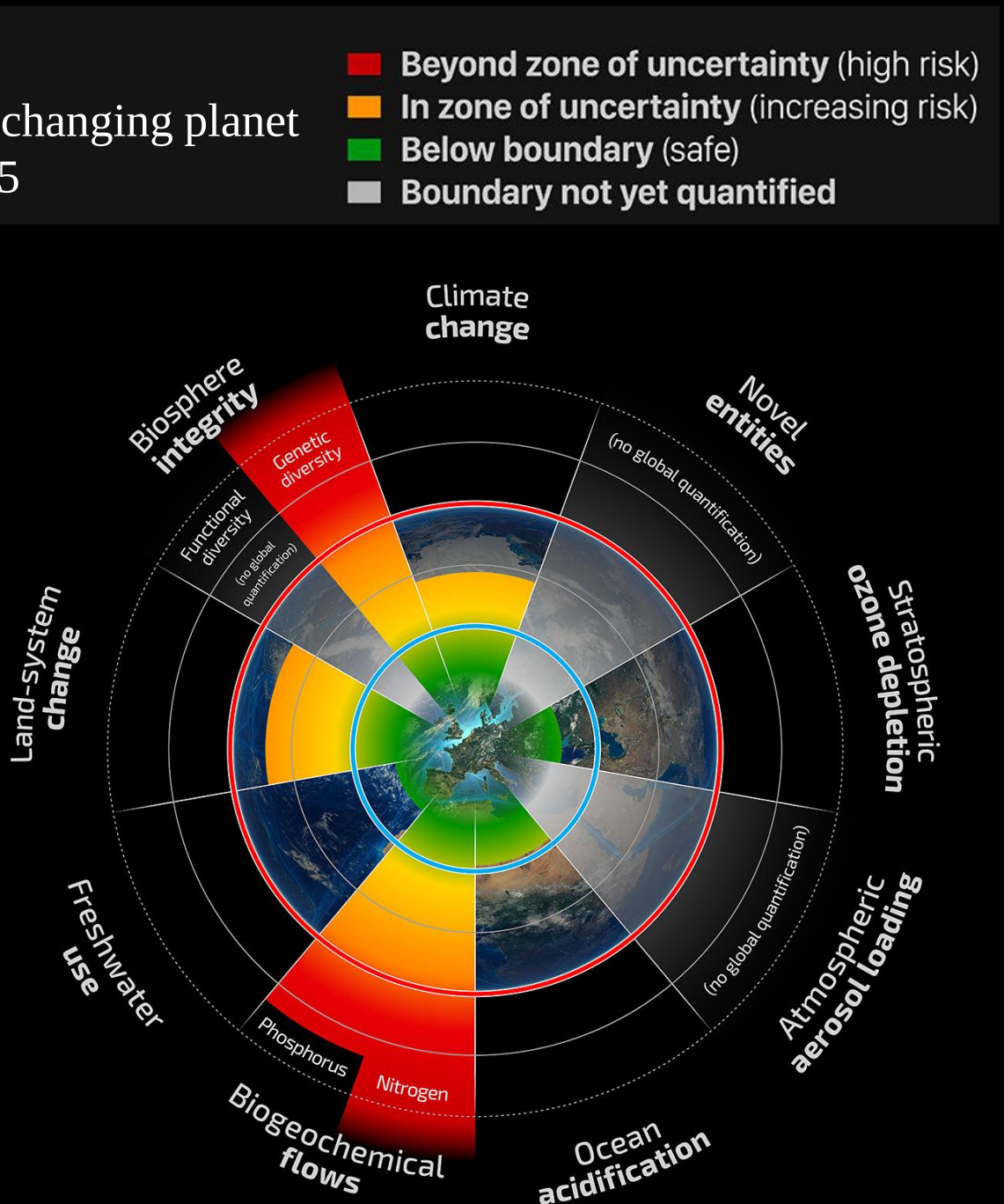
The molecular basis of sustainability

Two global sustainability agendas

169 targets require strategies based on consideration of systems rooted in the flow of materials and energy: Fundamental chemistry at the heart

Planetary boundaries

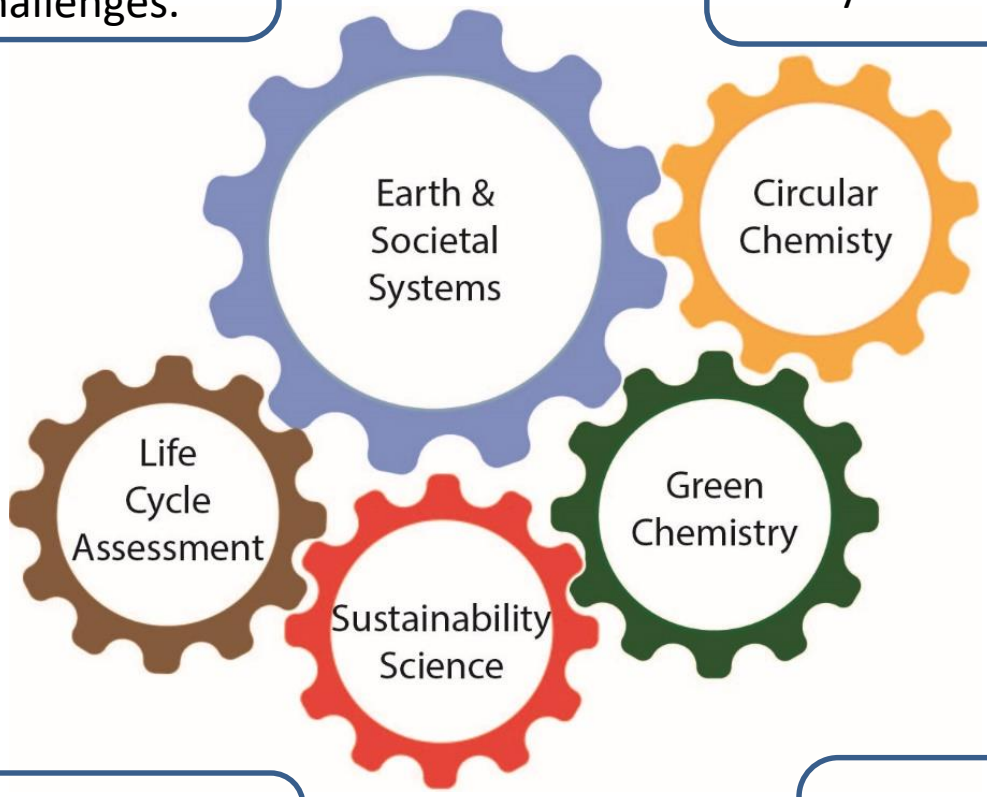
Guiding human development on a changing planet
Steffen et. al. Science, Jan 16, 2015



Two core boundaries—climate change and biosphere integrity—have been identified, each of which has the potential on its own to drive the Earth System into a new state should they be substantially and persistently transgressed.

Recognize the **material basis of society** as a core element in sustainability challenges.

Shape the **practice of chemistry** by sustainability science



Educate about the ***molecular basis of sustainability** using **systems thinking**

Reorient **chemistry education** to address the sustainability of earth and societal systems

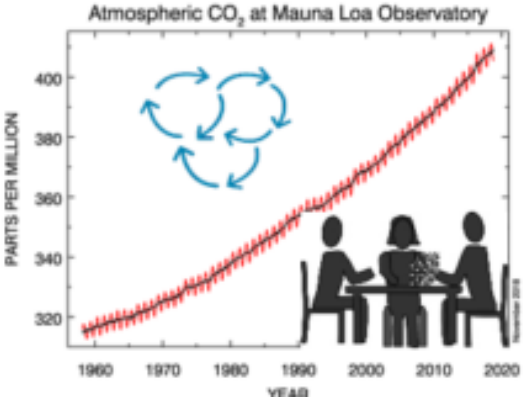
**The ways in which the material basis of our society and economy underlie considerations of how present and future generations can live within the limits of the natural world*

Mahaffy, Matlin, Holme, MacKellar, *"Systems Thinking for Education about the Molecular Basis of Sustainability,"* (2019), 2, 362–370.

nature sustainability

Systems thinking in Chemistry Education

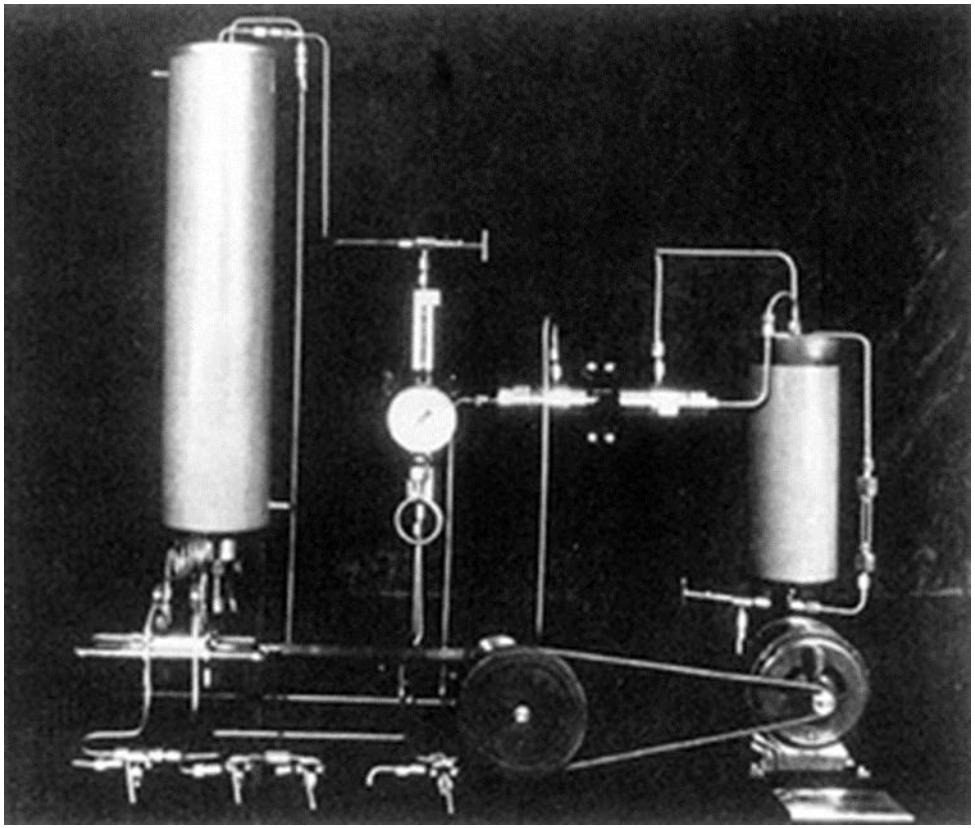
Molecular Basis of Sustainability



Next Steps for STICE

ST tools and boundaries: SOCMEs

The most important technological invention of the 20th Century?



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

Haber-Bosch Process

The most important technological invention of the 20th Century?

"When you travel in Hunan or Jiangsu, through the Nile Delta or the manicured landscapes of Java, remember that the children running around or leading docile water buffalo got their body proteins via the urea their parents spread on the fields, from the Haber–Bosch synthesis of ammonia. Without this, 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

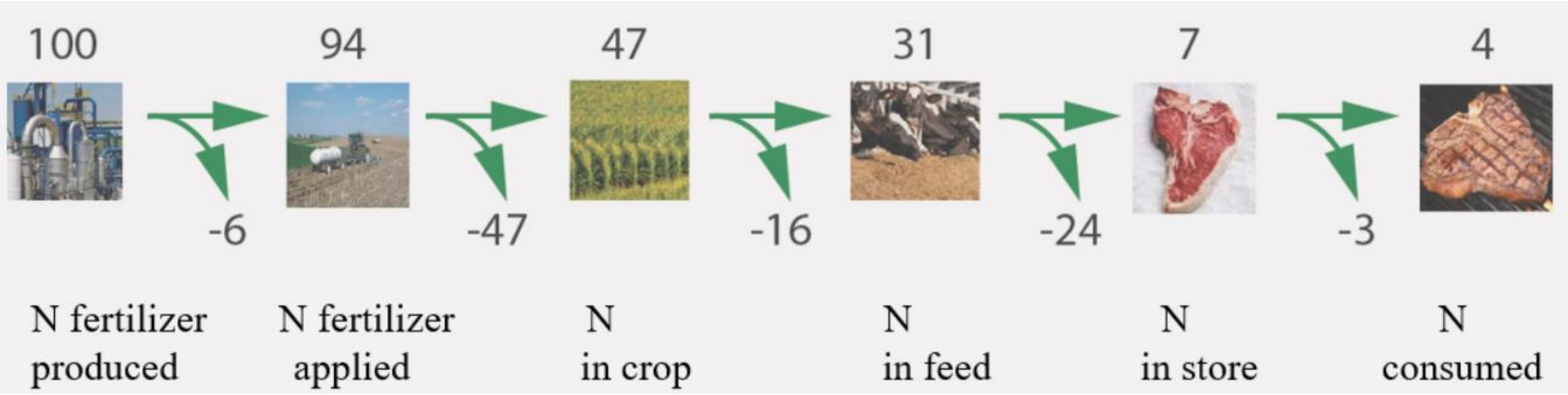
University of Manitoba

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

V Smil, Nature 1999, 400, 415

Yet, a Failure of Systems Thinking in Chem?

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



Mahaffy, Bucat, Tasker, et. al, *Chemistry: Human Activity, Chemical Reactivity*, Nelson/Cengage, 2015, adapted from J. N. Galloway & E. B. Cowling, 31, Ambio, March 2002

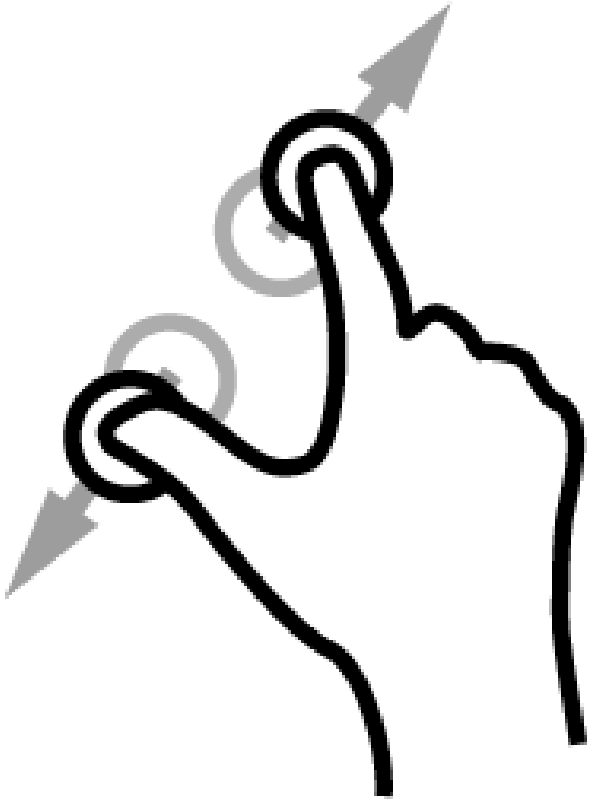
And a Failure of Systems Thinking in Chem Ed?

- Texts show ammonia synthesis in equilibrium chapter, often with a (sanitized) sidebar on Haber, Nobel laureate
- Classroom treatment and assessment focuses on mathematical calculations related to changing concentrations and pressures (ICE tables?)
- No connection usually made between this chemical reaction and either the survival of 40% of our planet's human beings or the threat to our planetary boundaries of our massive fixed nitrogen footprint.

Fritz Haber was a German chemist who received the Nobel Prize in Chemistry in 1918 for his invention of the Haber-Bosch process, the method used in industry to synthesize ammonia from nitrogen and hydrogen gases.

7
N
Nitrogen
14.007

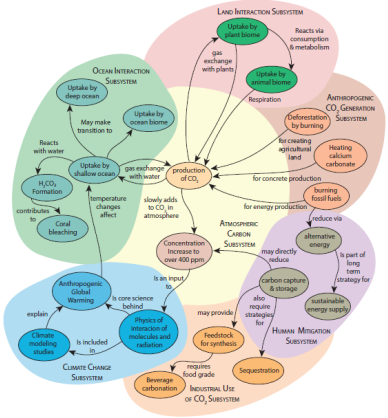
How might this change with a systems thinking framework?



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

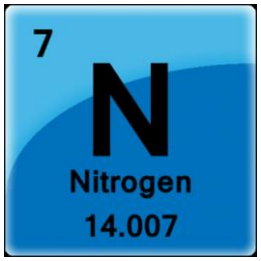
Systems-Oriented Concept Map Extensions (SOCMEs)

- Tools to visualize the interconnections among system components
- Set boundaries of focus, based on Learning Outcomes (LO) for a topic, course or program
- Can facilitate seeing emergent behavior and change over time and cause-effect relationships

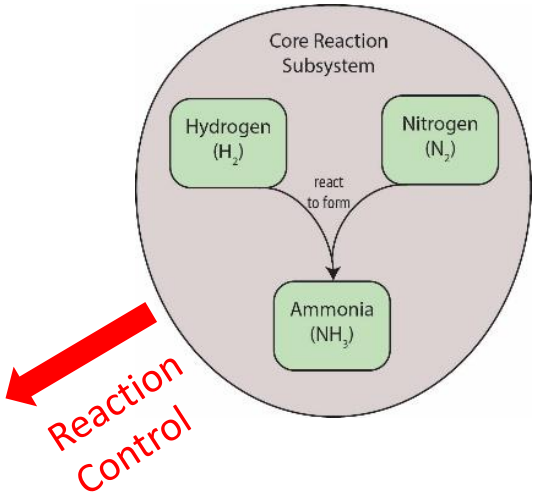


SOCME

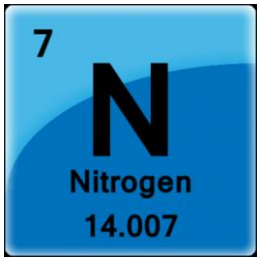
Tom Holme
Iowa State



System-Oriented Concept Map Extension (SOCME):
Choosing the system boundaries to extend the picture to the level desired



Kinetics: Requires a catalyst and T above 350 °C to form NH_3 at a practical rate.



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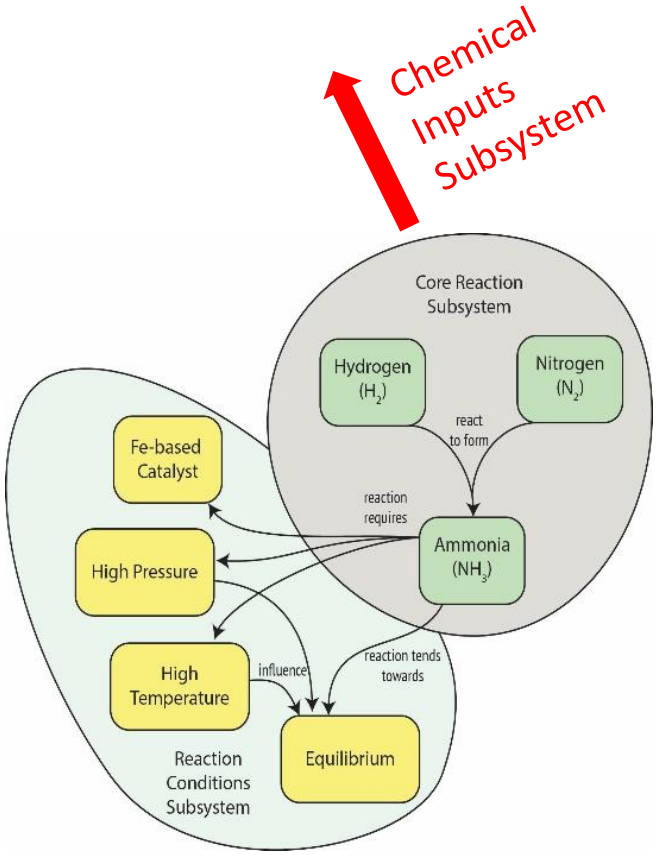
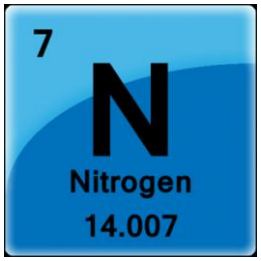
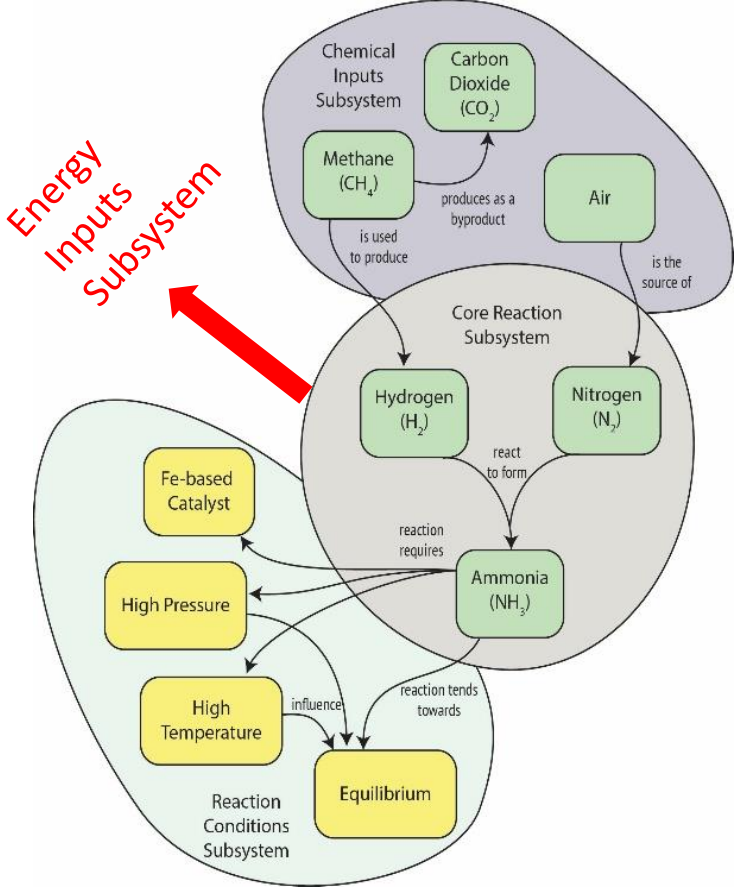




Marc Whalen
Dalhousie Univ., Canada



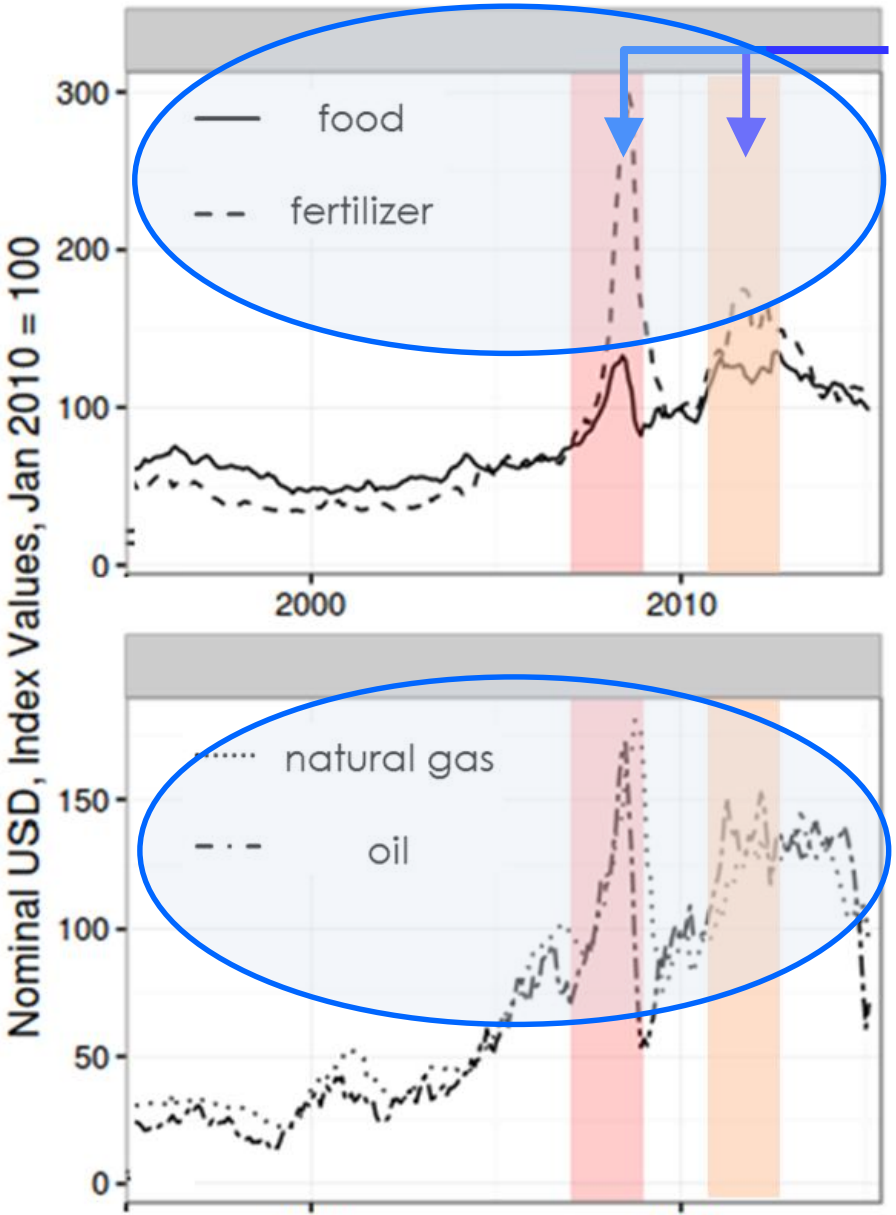
H_2 starts from CH_4 (steam reforming/ water-gas shift)
To produce 1 kg NH_3

- 3 kg CH_4 is consumed
- 3.5 kg CO_2 is formed

80% of the cost of NH_3 is the cost of natural gas

Haber-Bosch Process uses ~ 2% of total annual energy supply

Food and Energy Systems: Natural Gas, Fertilizer and Food Prices are Connected



price spikes 2008 & 2011

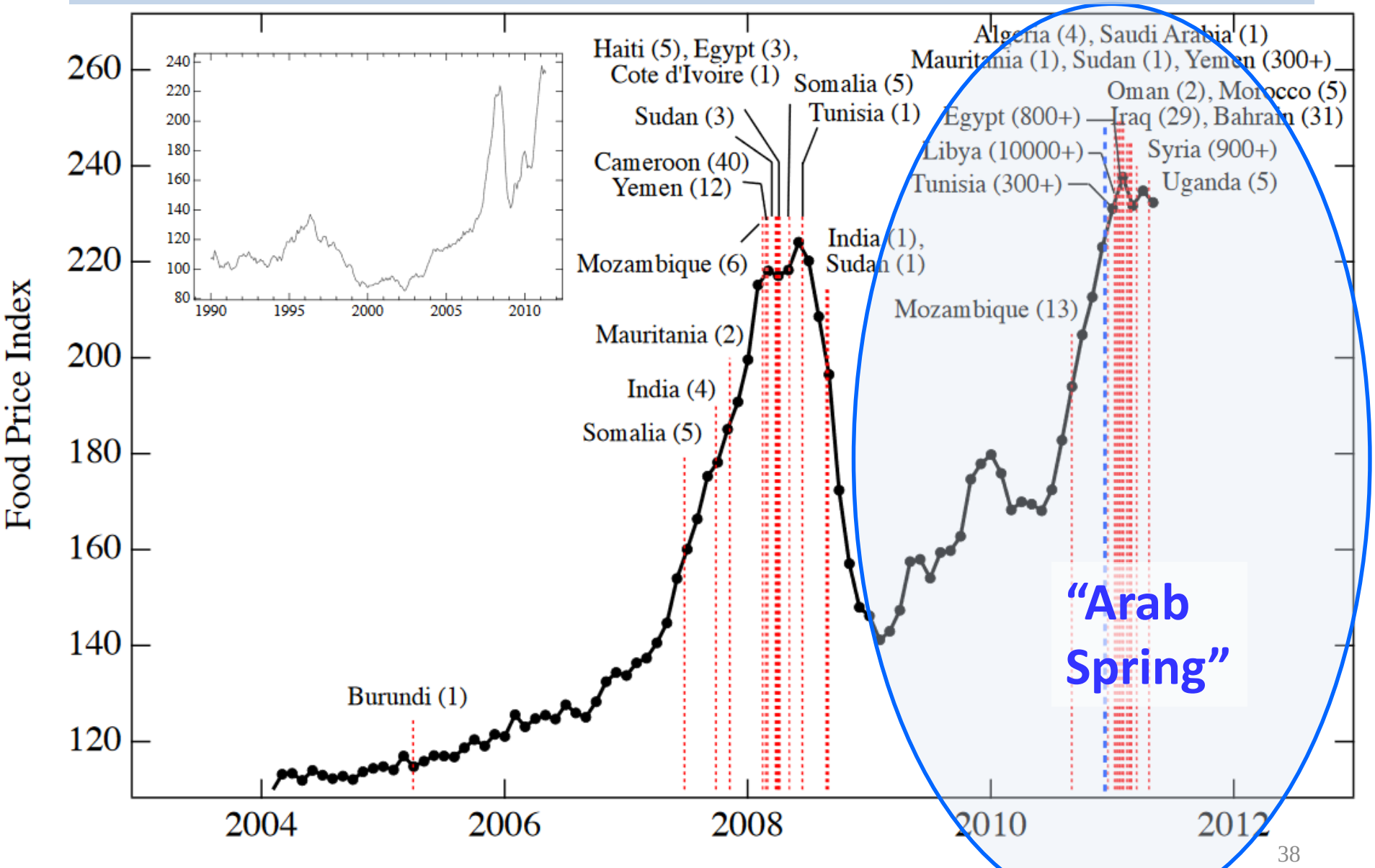
- Nitrogen fertilizers are the highest single operating cost for U.S. farmers
- U.S. produced 40% of the world's corn in 2008.

H. Gnutzmann et al. *SSRN Electronic Journal* (September 2016).

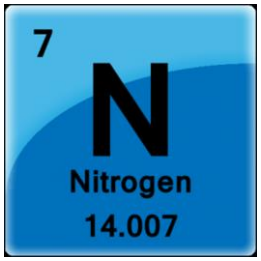
W. Huang, USDA 2007.www.ers.usda.gov/publications/wrs0702/

S. Mueller et al. *Biomass and Bioenergy* **2011**, 35, 1623-32.

Food Security and Political Unrest:
2008 and 2011 price spikes (red)



M. Lagi, et al. *SSRN*, 2011. http://www.fao.org/worldfoodsituation/foodpricesindex/en/



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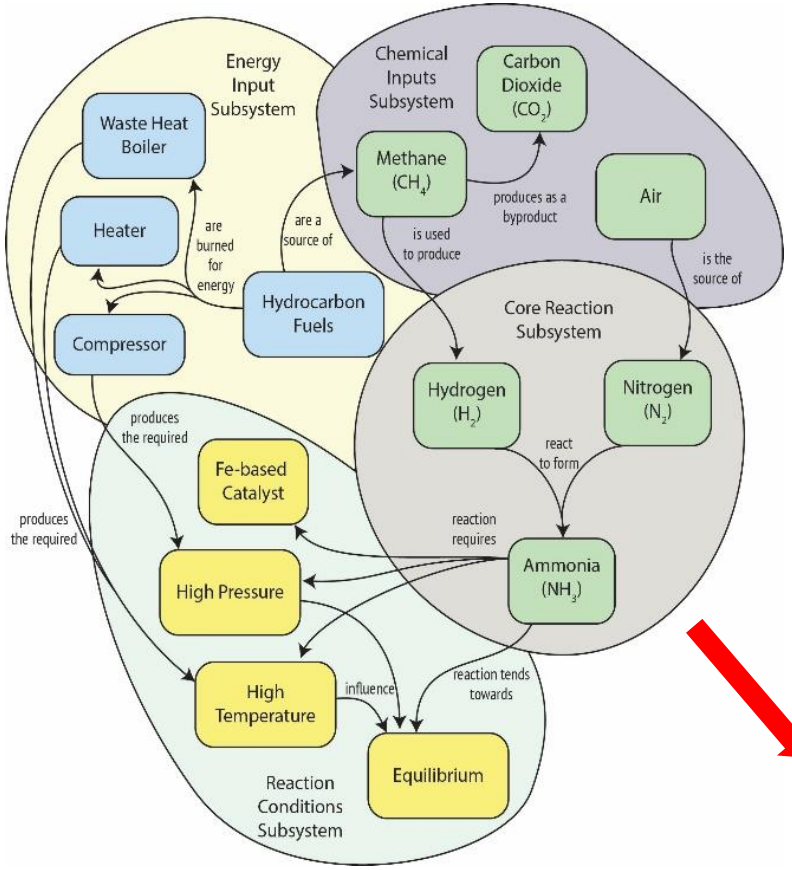
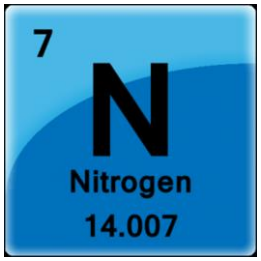


Oswald Process (HNO_3) Subsystem



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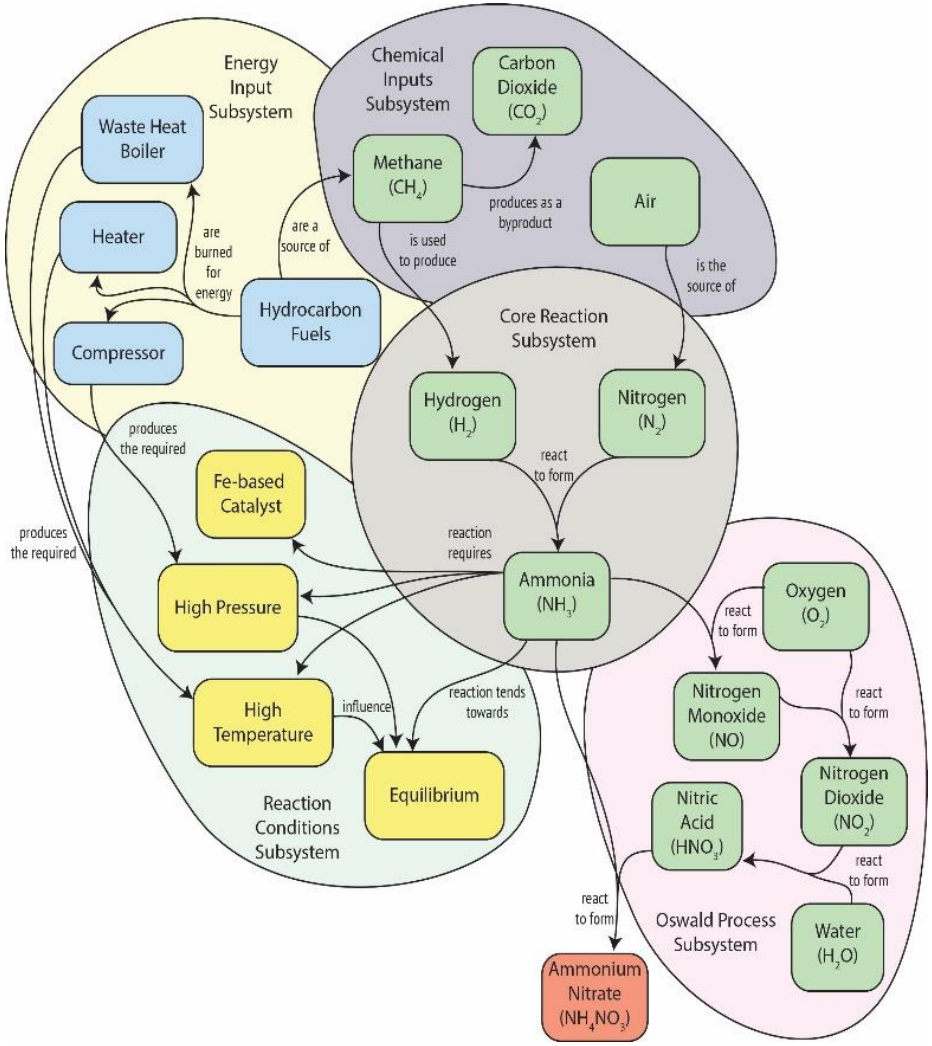
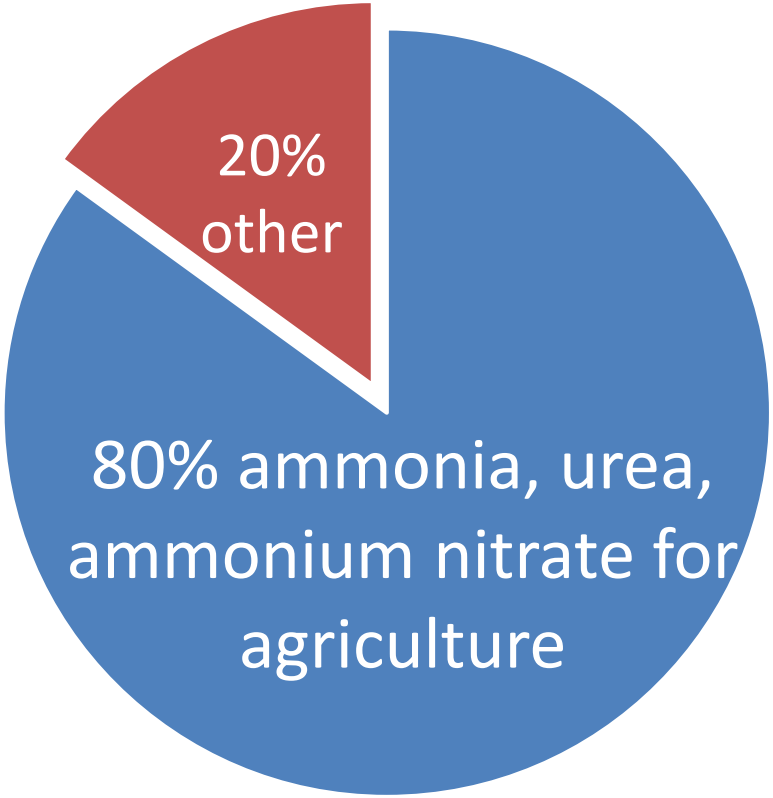


Intended Uses Subsystem

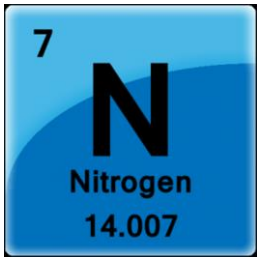
180 million tons NH_3 produced globally in 2018

Uses



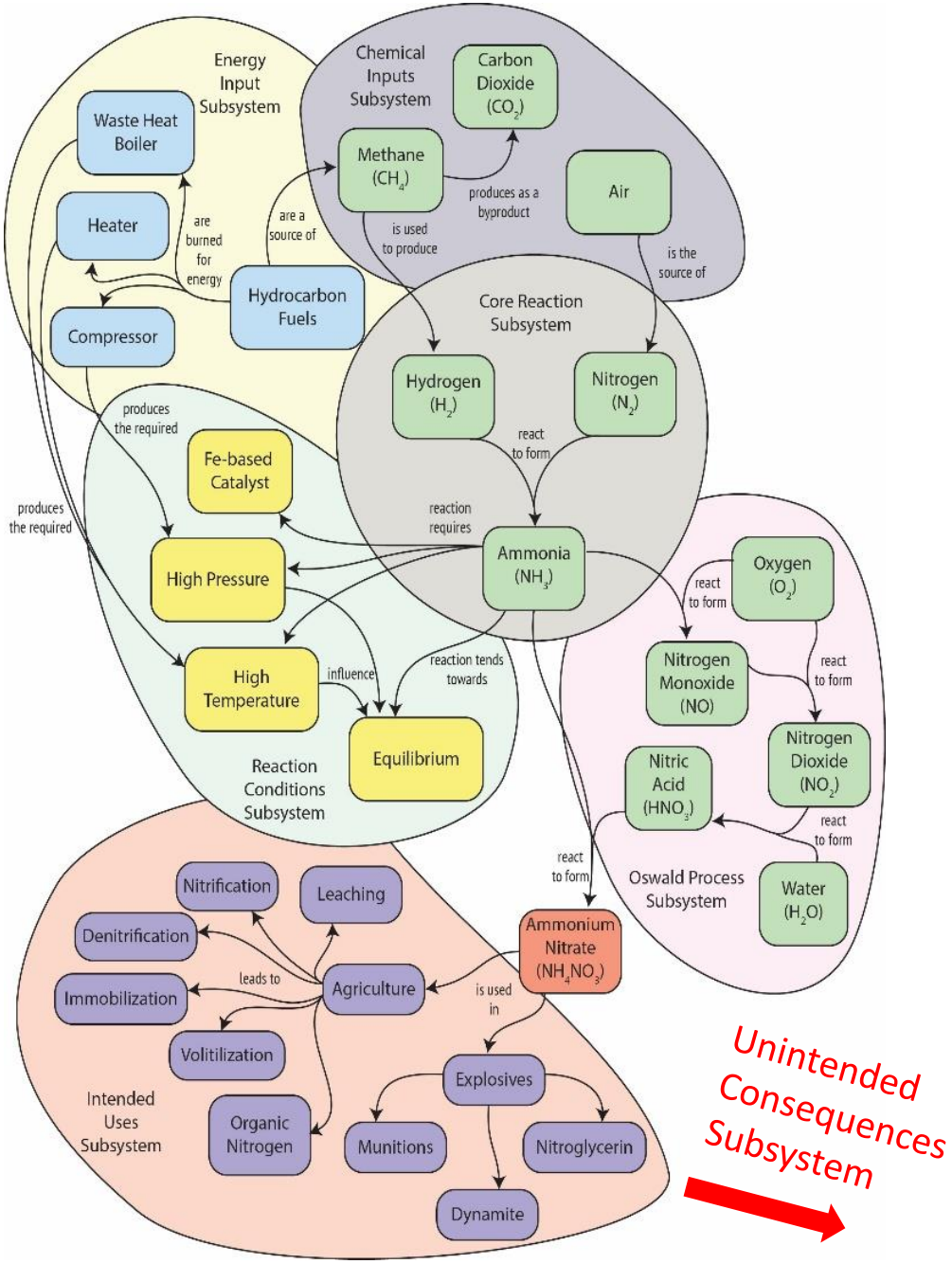
Industrial fertilizers to increase crop yields for globally traded food commodities (corn, rice, wheat).

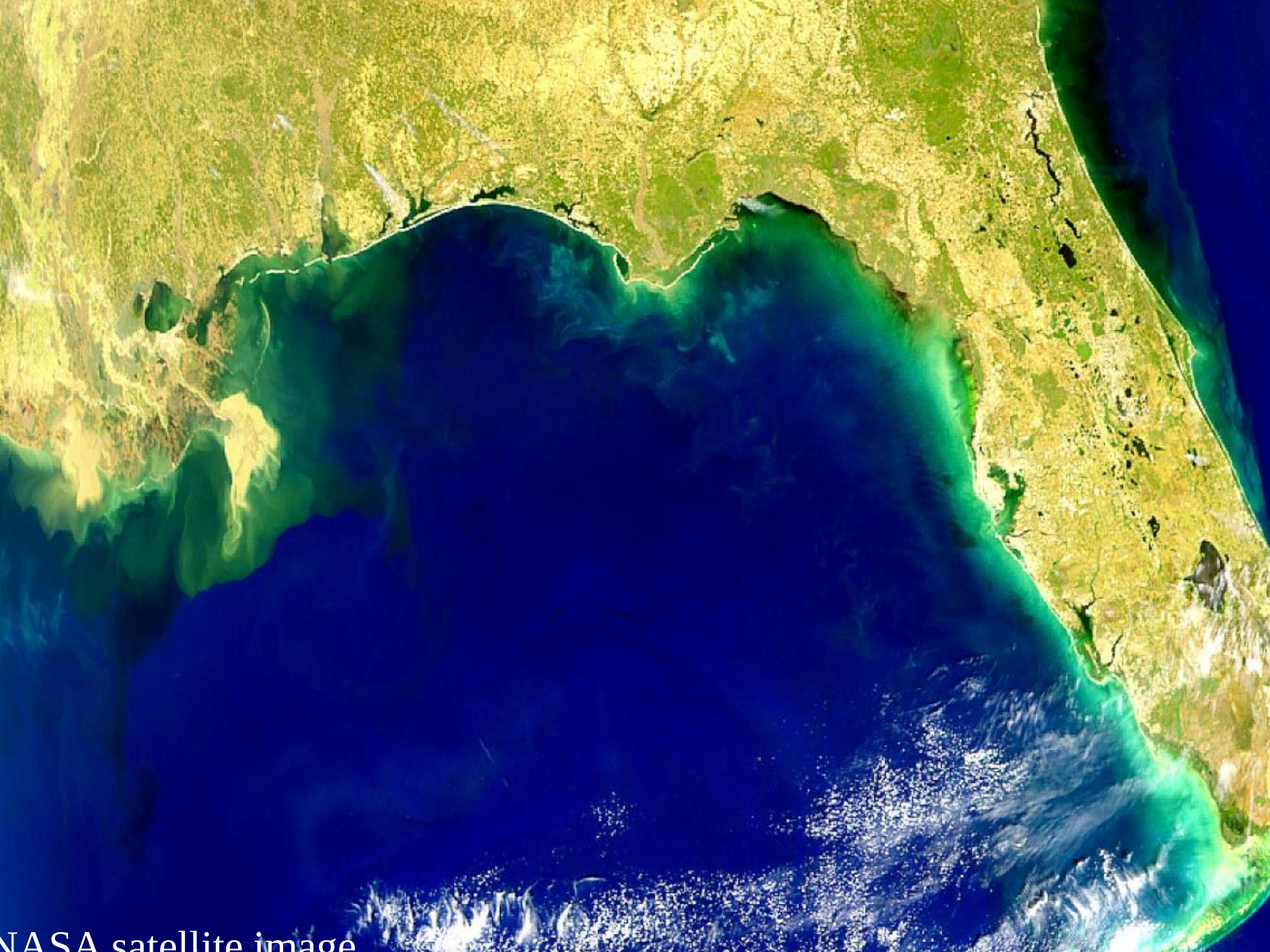
Food and Agriculture Organisation of the United Nations (FAO), 2019. http://www.fao.org/3/a-i4324e.pdf



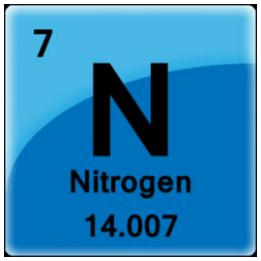
System-Oriented Concept Map Extension (SOCME):

Choosing the system boundaries to extend the picture to the level desired

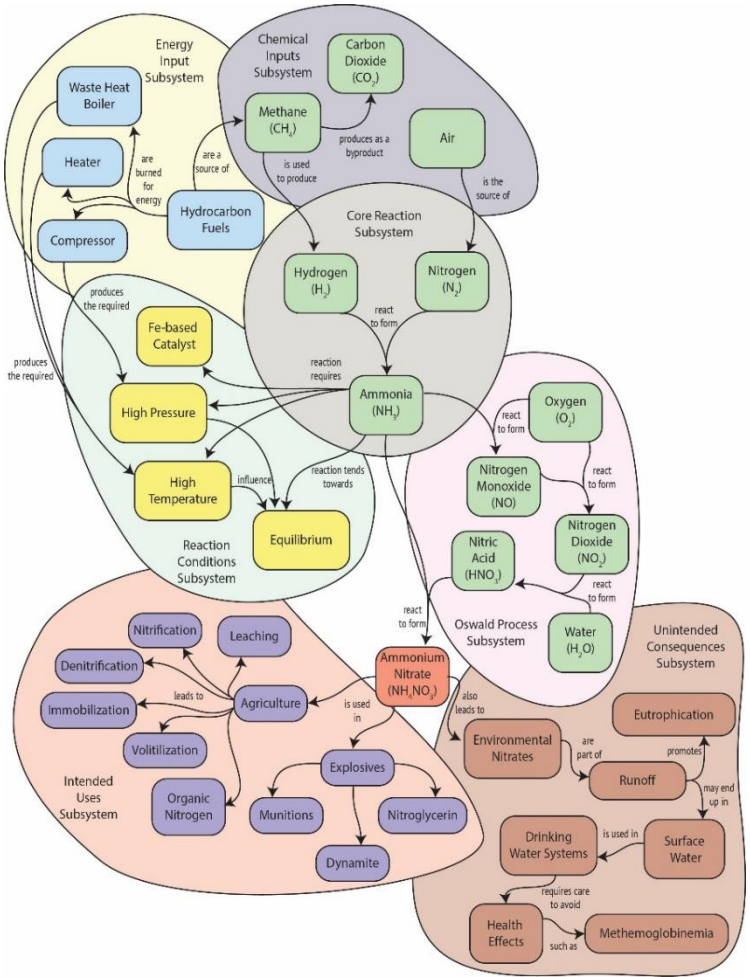


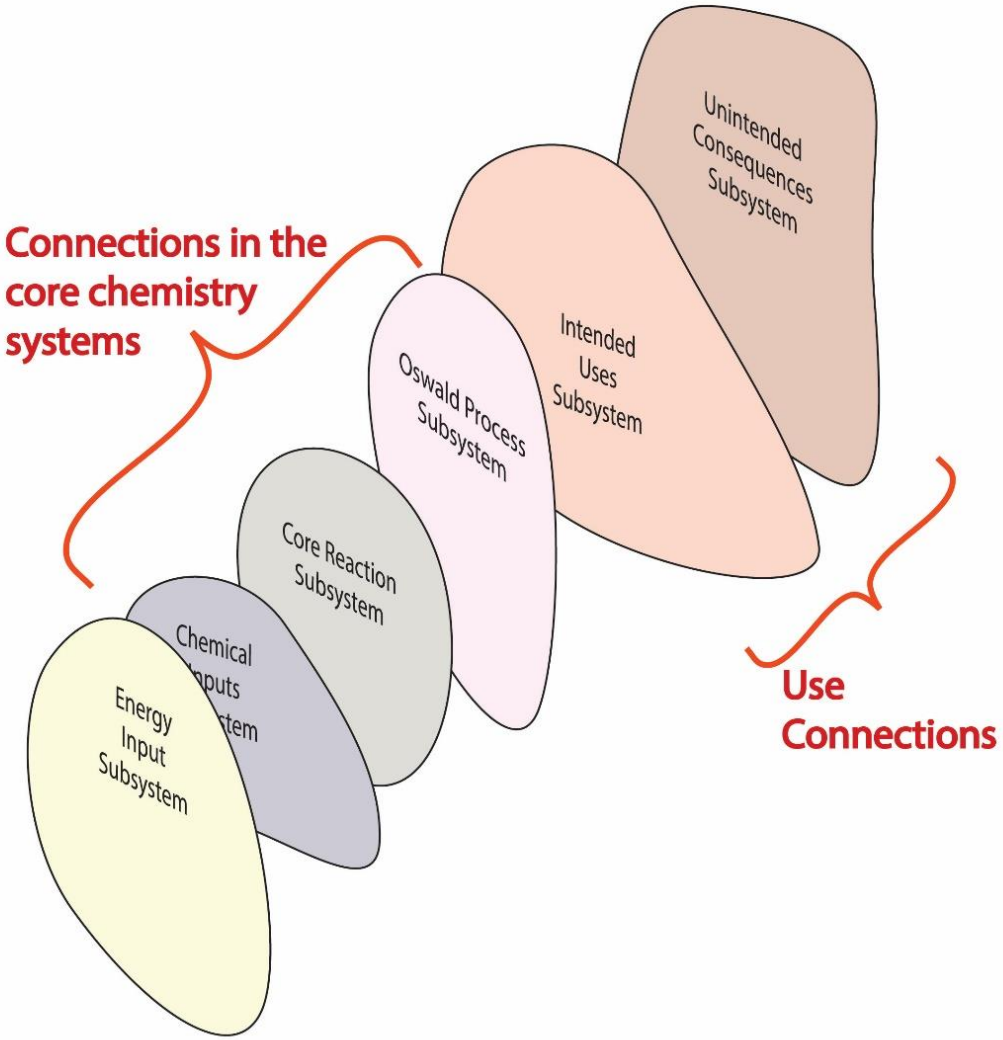


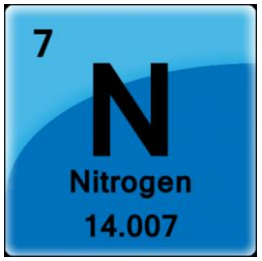
NASA satellite image



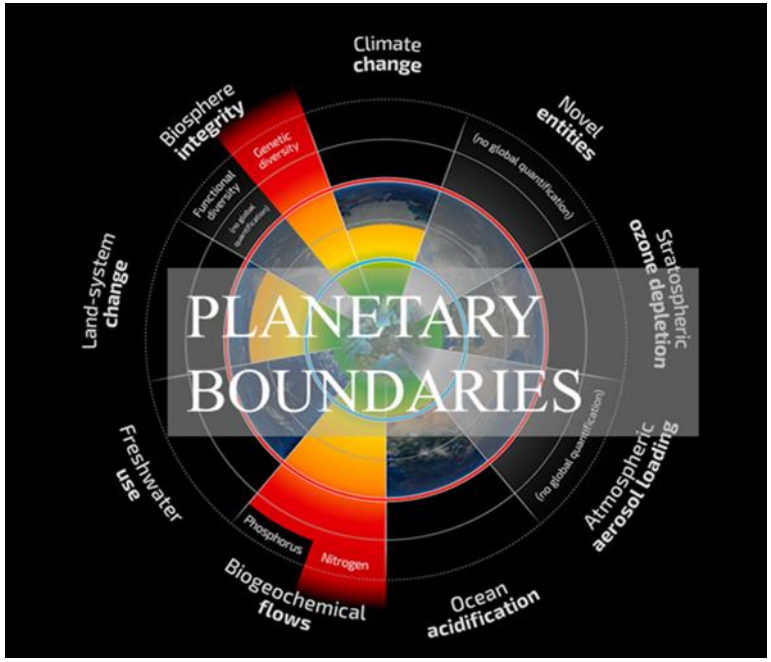
Sub-system connections

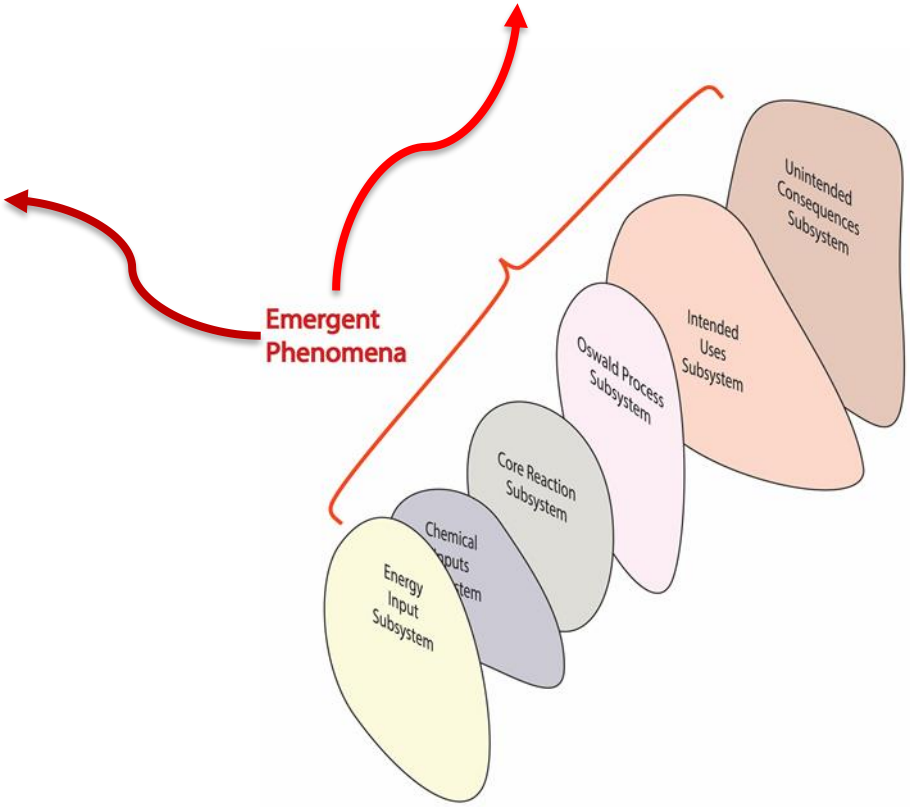






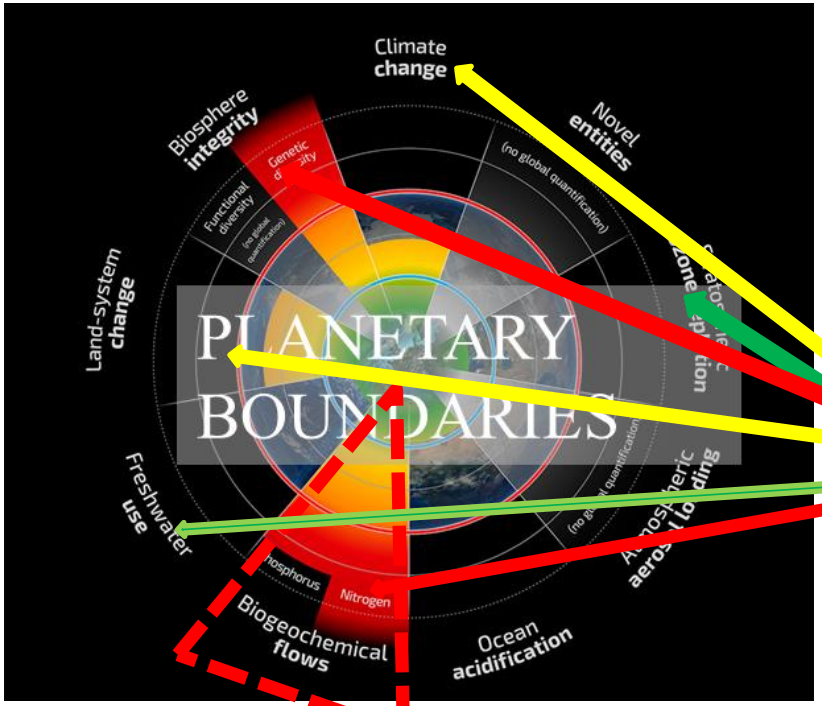
Emergent phenomena

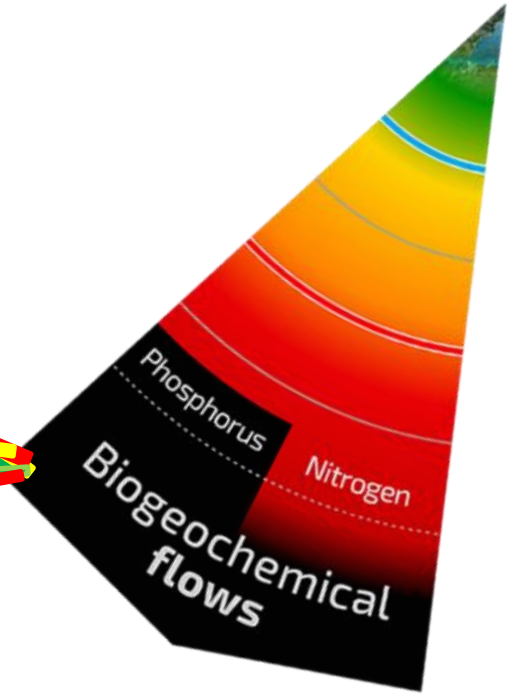




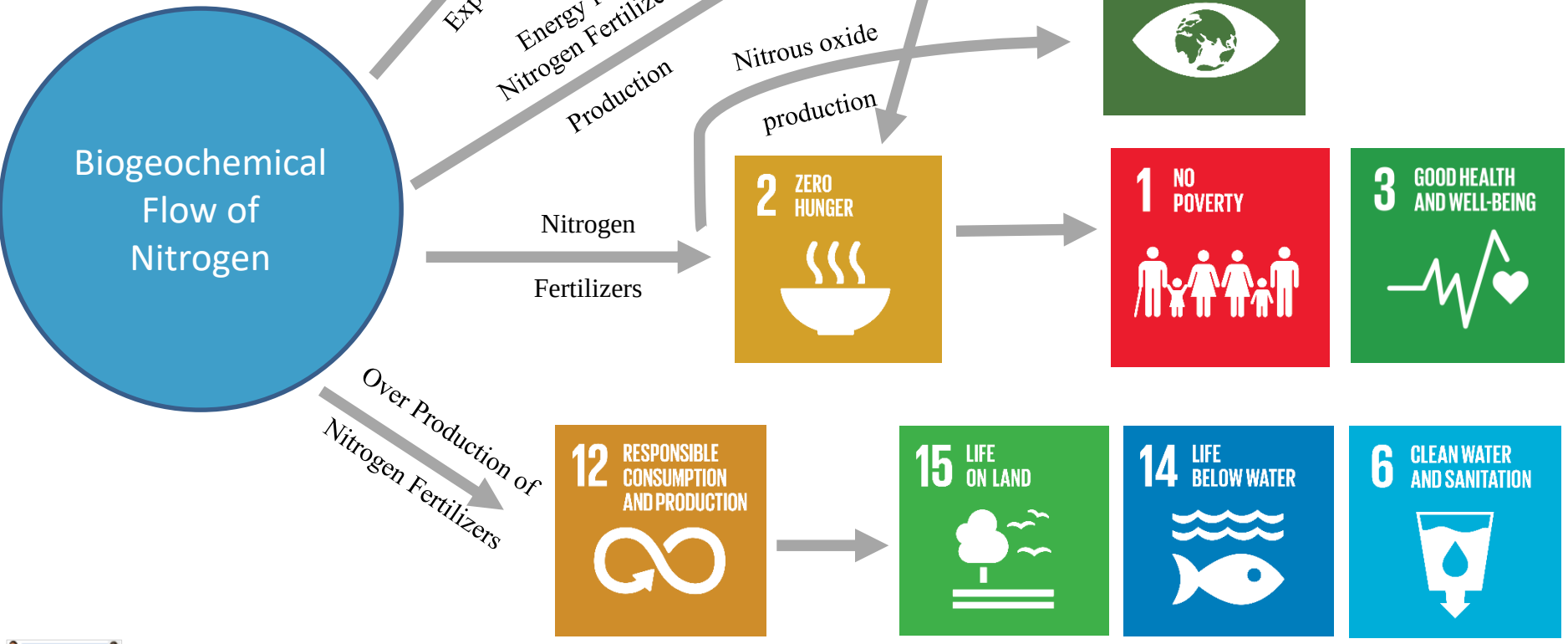
7
N
Nitrogen
14.007

Nitrogen and its Compounds





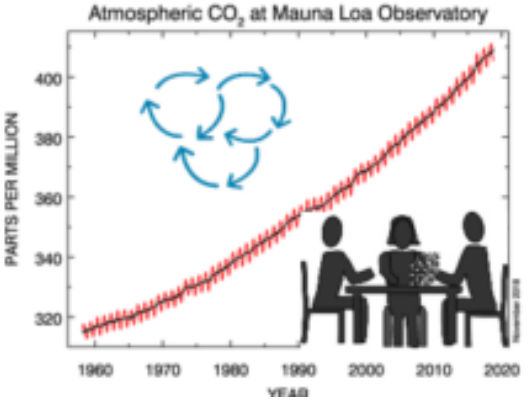
Control variable(s)	Planetary boundary (zone of uncertainty)	Current value of control variable
N Global: Industrial and intentional biological fixation of N	62 Tg N yr^{-1} (62–82 Tg N yr^{-1}). Boundary acts as a global 'valve' limiting introduction of new reactive N to Earth System, but regional distribution of fertilizer N is critical for impacts.	~150 Tg N yr^{-1}



Mahaffy, Matlin, Holme, MacKellar, *"Systems Thinking for Education about the Molecular Basis of Sustainability," (2019), 2, 362–370.* nature sustainability

Systems thinking in Chemistry Education

Molecular Basis of Sustainability



ST tools and boundaries: SOCMEs

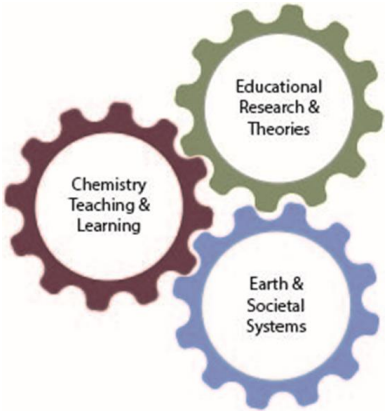
Next Steps for STICE

STICE Future Directions

- Resourcing chemistry educators and students
  - Learning theories perspective
  - Connection to curriculum and program standards
  - Define & explore STICE-related learning outcomes (LO)
  - Develop activities and assessments aligned with STICE LO
  - Develop, pilot, implement, and sustainably scale educator training opportunities.
  - Open access virtual user community
- Chemistry Education research related to STICE
  - Cognitive, affective aspects, assessment
- Examining who stands to benefit from a STICE approach

Follow-on IUPAC STICE Project

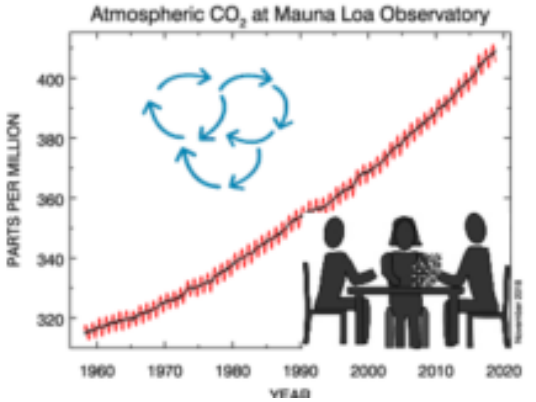
- Consensus of project committee - we should propose to IUPAC a STICE V2.0
- IUPAC is the right framework to bring a global group of chemistry education thought leaders together.
- Other partners will be needed to resource the project (IOCD, UNESCO, European framework, etc.)
- Some members of the project group will provide continuity, new members from within and outside of IUPAC CCE will be sought.
- Please let us know if you have an interest in participating. Peter.Mahaffy@kingsu.ca, Stephen.matlin@gmail.com

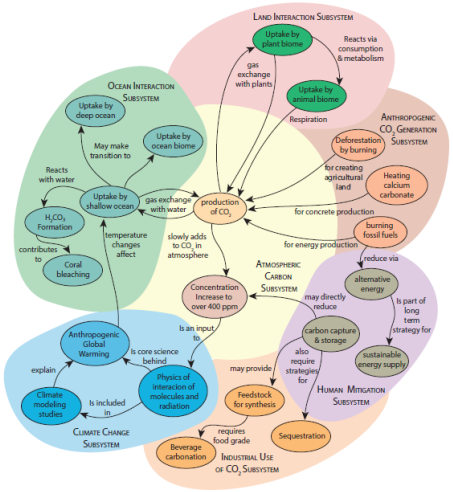


Systems thinking in Chemistry Education

IUPAC

Molecular Basis of Sustainability





ST tools and boundaries: SOCMEs

Next Steps for STICE

Acknowledgements

- IUPAC World Chemistry Congress Organizing Committee
- IUPAC STICE Project steering group and ESS Node

Thank You!

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