ACS Chemistry for Life®

National Meeting, 31 March - 4 April 2019, Orlando, FL
CHED Symposium 1 April 2019
UN Sustainable Development Goals:
Unique Opportunities for the Chemical Enterprise

Systems thinking:
A vital contribution to strengthening the role of chemistry in achieving the UN Sustainable Development Goals

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#ACSorlando

THE KING'S UNIVERSITY

Sustainability

Sustainability

Concerns and concepts

Forestry

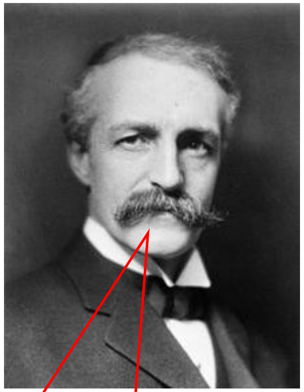
Hans Carl Von Carlowitz
1645–1714

Nachhaltigkeit
Sustainability of forestry

Georg Ludwig Hartig
1764-1837

1795: *Consideration of the needs of future generations*

Gifford Pinchot
1865-1946



Scientific forestry; ‘conservation ethic’ for natural resources

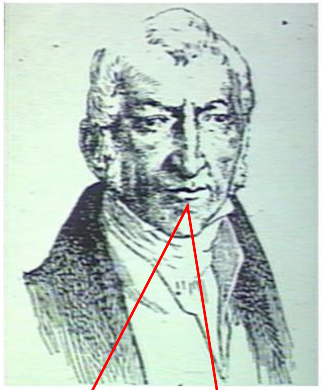
Sustainability

Concerns and concepts

Forestry

Population

Robert Malthus
1766 – 1834



Population growth outstripping rate of increase in agricultural production

Sustainability

Concerns and concepts

Forestry

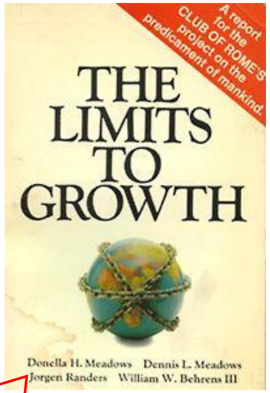
Population

Economics

David Ricardo
1772-1823

John Stuart Mill
1806-1873

Club of Rome
1968-



Scarcity of resources will eventually lead to cessation of economic growth

1972: sustainable world avoiding "overshoot and collapse" of the global system due to interactions between the Earth's and human systems

Sustainability

Concerns and concepts

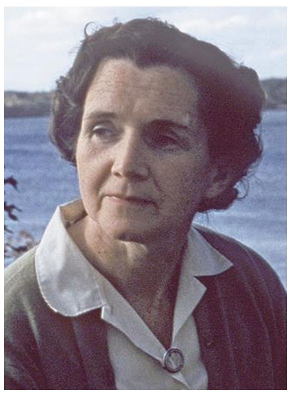
Forestry

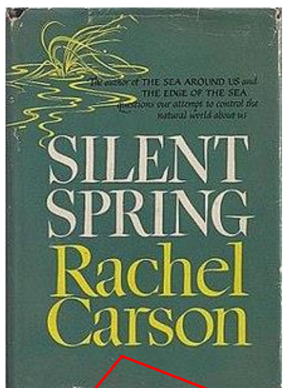
Population

Economics

Pollution

Rachel Carson
1907-1964





1962: ecological damage from pesticide and herbicide use in agriculture

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Concerns and concepts

Forestry

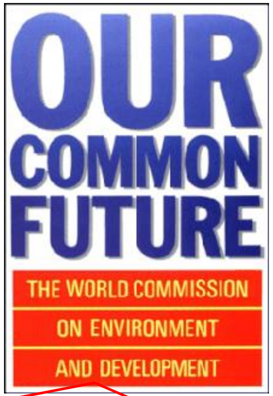
Population

Economics

Pollution

Global politics

Gro Harlem
Brundtland 1939-



1987: Sustainable development *"meets the needs of the present without compromising the ability of future generations to meet their own needs"*

Sustainability

Concerns and concepts

Forestry

Population

Economics

Pollution

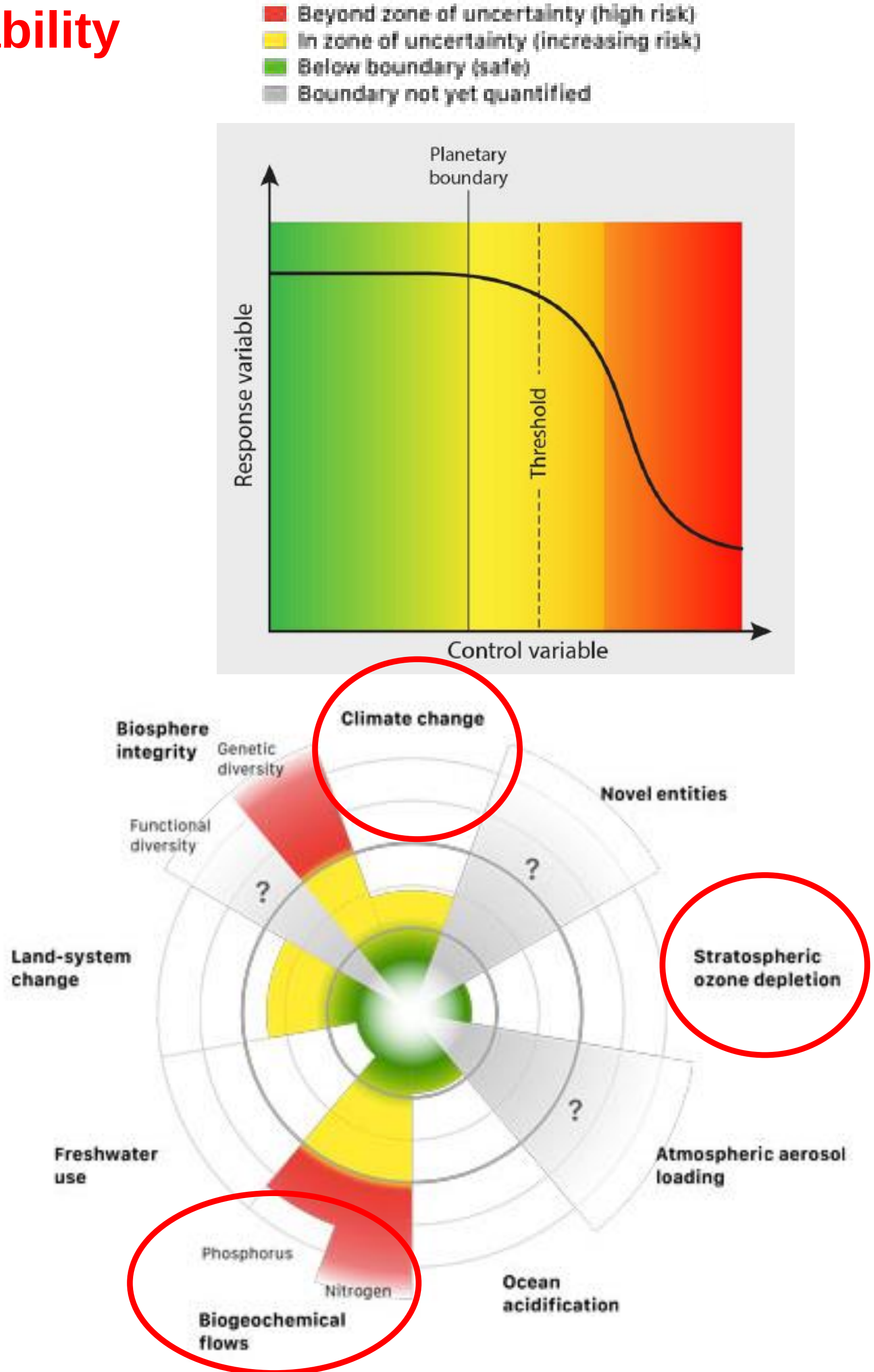
Global politics

Planetary boundaries

Johan Rockström
1965-

Will Steffen
1947-

2009-2015:
Planetary boundaries:
"safe operating space for humanity"



Sustainability

Concerns and concepts

Forestry

Population

Economics

Pollution

Global politics

Planetary boundaries

Anthropocene Epoch

Geological Society of London
1807-

2008: proposal to make ***Anthropocene*** a formal unit of geological epoch divisions

The period during which human activity has been the dominant influence on climate and the environment

Sustainability

Agendas and agreements

1972 UN Conference on the Human Environment, in Stockholm

- a human being's *"fundamental right to ... adequate conditions of life, in an environment of a quality that permits a life of dignity and well-being"*
- responsibility of each State not to cause damage to the environment

Sustainability

Agendas and agreements

1985 Vienna Convention for the Protection of the Ozone Layer

1987 Montreal Protocol on Substances that Deplete the Ozone Layer

1992 UN Conference on Environment and Development (Earth Summit), Rio de Janeiro

Agenda 21 preparing the world for the challenges of the next century

1992 UN Framework Convention on Climate Change (UNFCCC)

2001 Earth Charter

4 pillars + 16 principles

2005 Kyoto Protocol to UNFCCC

Internationally binding emission reduction targets for greenhouse gasses

2005 - 2014 UN Decade for Education for Sustainable Development

2012 Rio+20

Launch of process to develop a set of Sustainable Development Goals (SDGs)

2015 UN Agenda 2030: SDGs agreed

17 goals and 169 targets

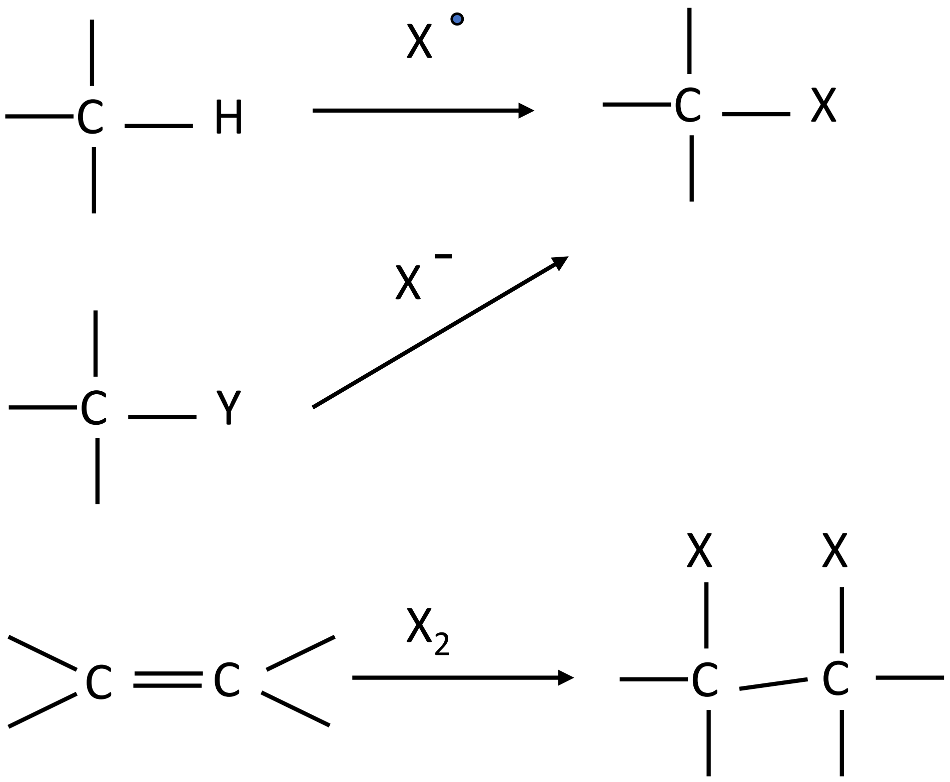
Sustainability

Agendas and agreements

1985 Vienna Convention for the Protection of the Ozone Layer

1987 Montreal Protocol on Substances that Deplete the Ozone Layer

Synthesis of alkyl halides



Sustainability

Agendas and agreements

1985 Vienna Convention for the Protection of the Ozone Layer

1987 Montreal Protocol on Substances that Deplete the Ozone Layer

Synthesis of alkyl halides

Refrigerants

1928 Thomas Midgley improved synthesis of chlorofluorocarbons (CFCs) e.g. CF_2Cl_2 (b.pt. -30^{o}C).

$$2CCl_4 + 3HF \xrightarrow{SbF_3Cl_2} CFCl_3 + CF_2Cl_2 + 3HCl$$

Freon® used in fridges from 1930; by 1960s 'halons' also widely used in aerosol cans and in fire-fighting

1957 Electron capture detector invented by James Lovelock

- Late 1960s, Lovelock first to detect the widespread presence of CFCs in the atmosphere

1974 Mario Molina and Sherwood Rowland (Nobel 1995): photolysis of atmospheric CFCs releases chlorine atoms which break down ozone.

- Since 1970s: 4 % per decade decline in atmospheric O_3 and much larger annual springtime decrease in stratospheric O_3 over S. polar region ('ozone hole' reported in *Nature*, 1985)

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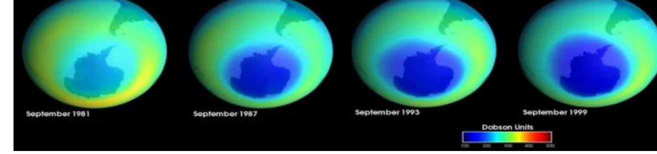


Agendas and agreements

1985 Vienna Convention for the Protection of the Ozone Layer

1987 Montreal Protocol on Substances that Deplete the Ozone Layer

1977 UN Environment Programme: World Plan of Action on the Ozone Layer

1981 Begun: Global Framework Convention on stratospheric ozone protection

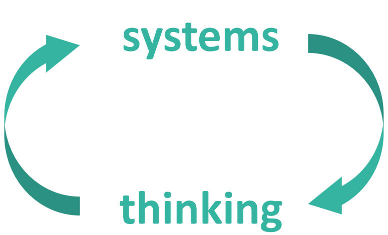
1985 Vienna Convention: Cooperation, but no specific limits on chemicals that deplete the ozone layer.

1987 Montreal Protocol signed; came into force 1 January 1989

- Rapid phasing out CFCs
- Slower phasing out of hydrochlorofluorocarbons (HCFCs), 1996-2030

"**Rearchers… had to bridge traditional scientific disciplines and examine the earth as an interrelated system of physical, chemical, and biological processes occurring on land, in oceans, and in the atmosphere – processes that were themselves influenced by economic, political, and social forces**"

Richard E Benedick (US State Department, Chief US Negotiator on the Montreal Protocol).
www.eoearth.org/view/article/155895/



But: also a failure to apply systems thinking fully:
HCFCs and HFAs are very powerful greenhouse gases
– some hundreds/thousands of times more potent than CO_2

Sustainability

Chemistry's role

Environmental chemistry

19th C	John Tyndall (UK), Svante Arrhenius (Sweden)
	Effects of CO_2 in the atmosphere on temperature
1960s	Courses becoming popular – demand for graduates boosted by the growth in legislation and in regulatory agency action on pollution
1990s	Increasing policy shift from pollution control to pollution prevention
	Scientific focus moving the upstream to consider from the outset how materials would be sourced and handled, how by-products, waste products and end-of use products would be safely managed and disposed of or recycled.

Sustainability

Chemistry's role

Environmental chemistry

Green chemistry

1998 Paul Anastas, John Warner: GC 12 principles

Green Chemistry: Theory and Practice. Oxford University Press: New York 1998

Invention, design and application of chemical products and processes to reduce or to eliminate the use and generation of hazardous substances, and where possible utilize renewable raw materials

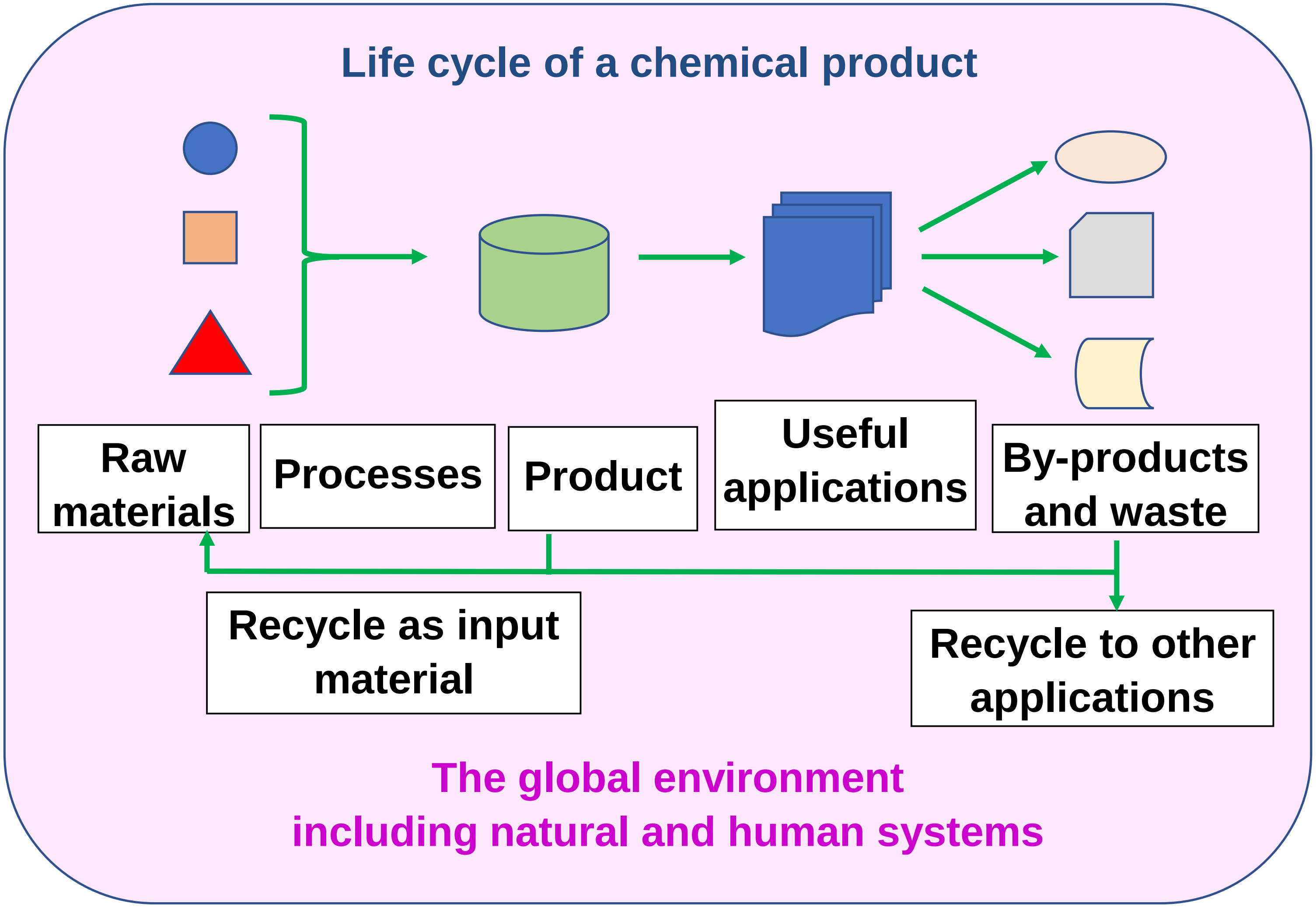
Sustainability

Chemistry's role

Environmental chemistry

Green chemistry

Life-Cycle Assessment



Sustainability

Chemistry's role

Environmental chemistry

Green chemistry

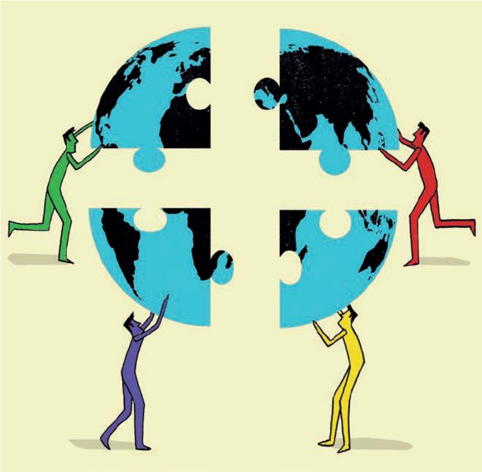
Life-Cycle Assessment

Sustainability science

- interactions between natural and social systems, and how these affect the challenge of sustainability

LMA Bettencourt, B Kaur. PNAS 2011, 108, 19540-19545

Sustainability



Chemistry's role

Environmental chemistry

Green chemistry

Life-Cycle Assessment

Sustainability science

One-World Chemistry

IOCD's 'Chemists for Sustainability' (C4S)

Henning Hopf (Germany), Alain Krief (Tunisia/France), Stephen Matlin (UK) Goverdhan Mehta (India)

2015 Chemistry essential to achieve the SDGs – but must reorient profoundly to do so

Nature Chemistry 2015, 7, 941-943

2016 One-World Chemistry

re-positioning chemistry: a 'sustainability science' for benefit of society

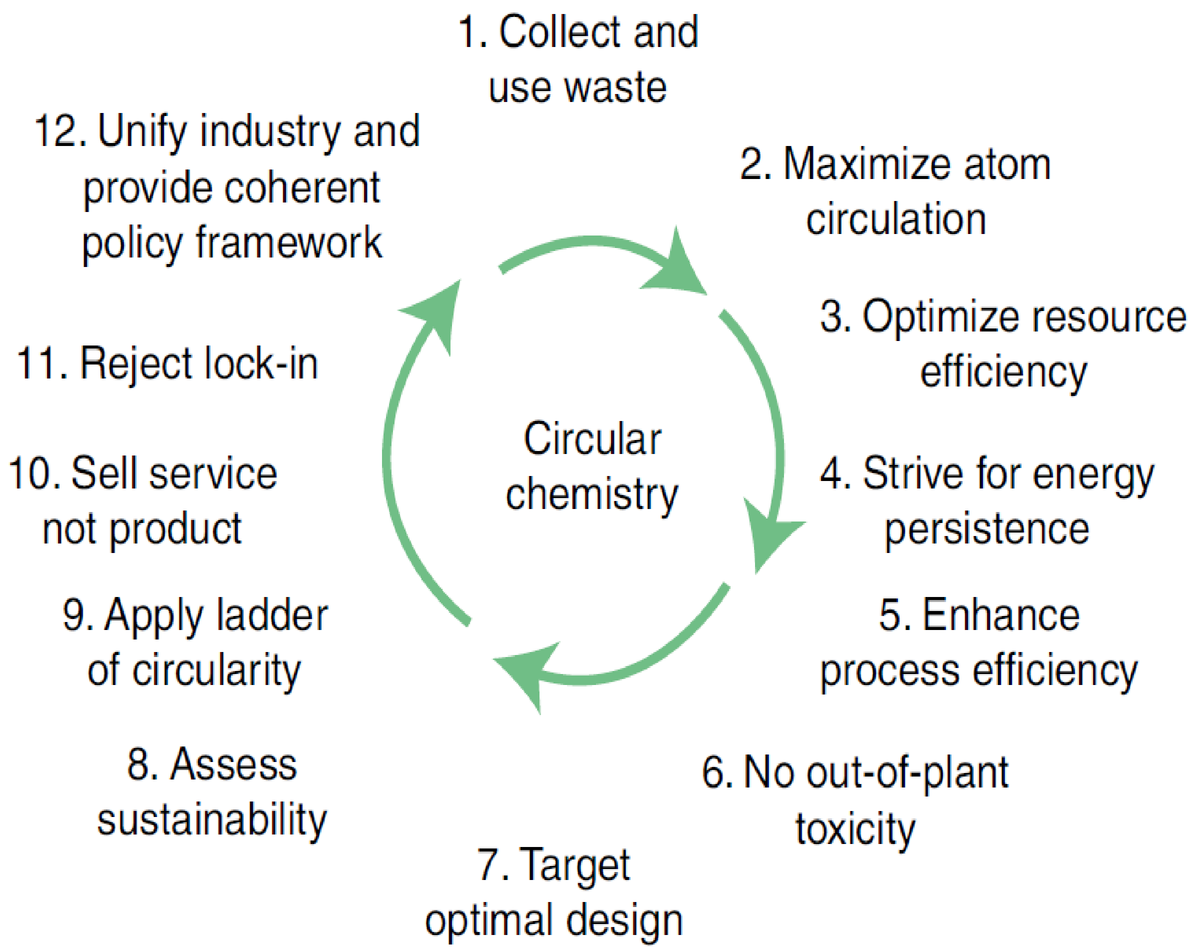
recognising: human, animal, environmental health intimately connected

embracing: **systems thinking** and working across disciplines to tackle contemporary global challenges

Nature Chemistry 2016, 8, 393-396

Sustainability

Circular Chemistry: 12 Principles



T. Keijer, V. Bakker and J. C. Slootweg. Nature Chemistry 2019, 11, 190-195

social, …ntal, financial

- Circular Chemistry

Sustainability

Chemistry's role

Environmental chemistry

Green chemistry

Life-Cycle Assessment

Sustainability science

One-World Chemistry

3Rs Initiative: Reduce, Reuse, Recycle

- Makes extensive use of Life Cycle Assessments
- Cradle-to-cradle
- Circular economy
  - ➢ breaking the global 'take, make, consume and dispose' pattern of growth
    1. controlling finite stocks and balancing renewable resource flows
    2. optimising resource yields by circulating products, components and materials in use at the highest utility at all times
    3. foster systems effectiveness by designing out negative externalities.
  - ➢ Private sector: Triple Bottom Line (John Elkington, 1994): social, environmental, financial
  - ➢ Circular Chemistry

Reduce

Recycle

Reuse

3Rs logo

USA: Earth Day

22 April 1970

Sustainability

Chemistry's role

Environmental chemistry

Green chemistry

Life-Cycle Assessment

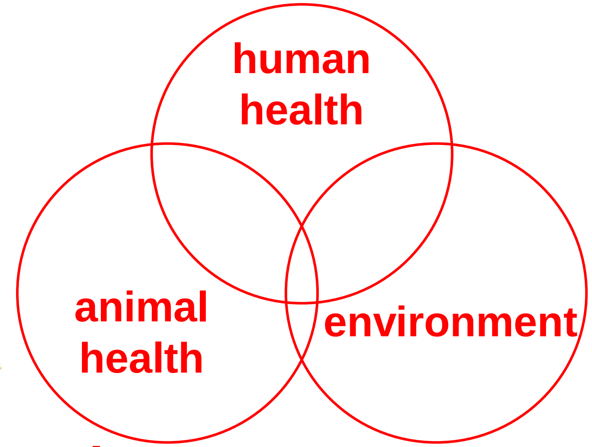
Sustainability science

One-World Chemistry

3Rs Initiative: Reduce, Reuse, Recycle

- Cradle-to-cradle
- Circular Economy
  - ➢ Circular Chemistry

Sustainability



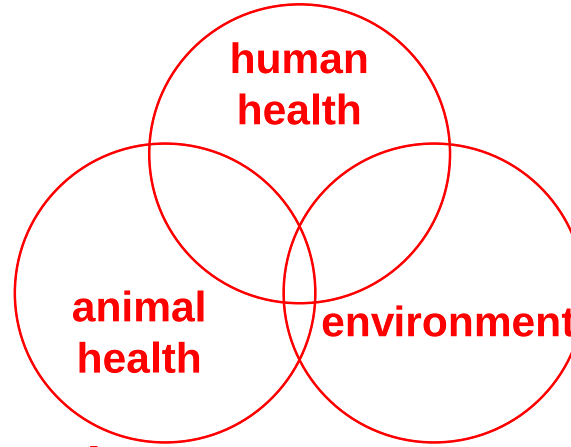
Key linkages in concepts and approaches

- All recognize interdependence between human activity, human and animal health and the biological and physical environments of the planet.
- The problems of sustainability cannot be solved without major inputs from chemistry: understanding of the ***molecular basis of sustainability****
  - Green chemistry through **design** –chemists can no longer plead ignorance of or ambivalence to the consequences of their science: they possess ultimate responsibility for consequences in the design.
  - *"By understanding that many of our environmental concerns are derived from molecular characteristics, we as chemists can realize that many of the solutions are, potentially, also molecular."*

  * P. Anastas, J. B. Zimmerman. The Molecular Basis of Sustainability. *Chem* 2016, 1, 10-12
- Potential solutions through prevention, mitigation, clean-up, recycling, etc.

➢ ***Systems thinking can be seen as the interconnecting thread that runs through and unites all these approaches to sustainability*.**

Sustainability



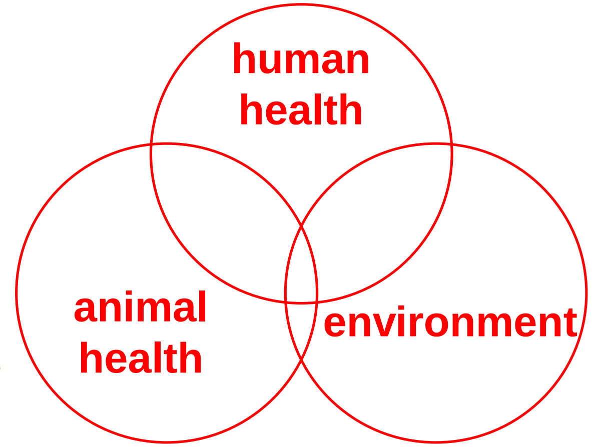
Key linkages in concepts and approaches

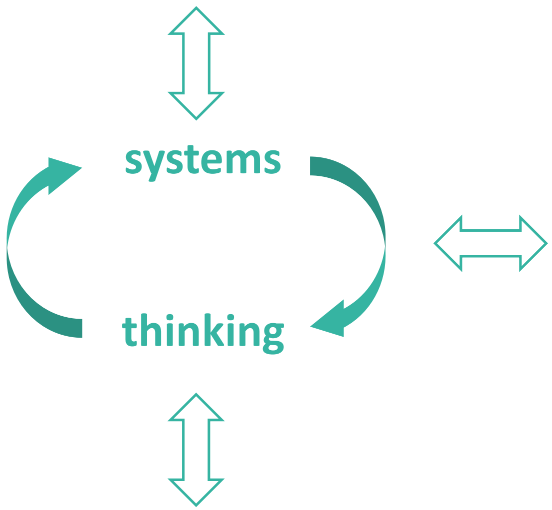
- All recognize interdependence between human activity, human and animal health and the biological and physical environments of the planet.
- The problems of sustainability cannot be solved without major inputs from chemistry: understanding of the ***molecular basis of sustainability****
  - "*the ways 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.*"
    - reflects central role for chemistry in analyzing, synthesizing, and transforming the material basis of society
    - establishes need for both the practice of chemistry and education in and about chemistry to address sustainability of earth and societal systems.

*P.G. Mahaffy, S.A. Matlin, T.A. Holmes, J. MacKellar, *Nature Sustainability*, 2019, in press.

- ***Systems thinking can be seen as the interconnecting thread that runs through and unites all these approaches to sustainability***.

Sustainability





Practice
- Green chemistry
- Sustainability chemistry
- 3Rs/Circular chemistry

Education
- Systems Thinking in Chemistry Education - STICE

Systems Thinking in Chemistry Education - STICE

Why STICE?

ST core skill: ability to understand and interpret complex systems. Involves capacity to examine

- interconnections and relationships between the parts in the system
- behavior that changes over time
- how systems-level phenomena emerge from interactions between the system's parts.

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.

International Union of Pure and Applied Chemistry

Infusing Systems Thinking into (Post)-Secondary General Chemistry Education STICE

Chemistry Teaching & Learning
Educational Research & Theories
Earth & Societal Systems

Systems Thinking in Chemistry Education
An IUPAC Project

Supported by

International Organization for Chemical Sciences in Development (IOCD)

IUPAC Project # 2017-010-1-050

- Help students move from fragmented knowledge of chemical reactions and processes to a more holistic view, equipping them to better address emerging global challenges through chemistry education
- Develop learning objectives, and perhaps a tool kit, to help educators infuse systems thinking into (general) chemistry courses
- Identify barriers and develop strategies to guide the use of learning objectives based on ST in the design of curriculum and selection of engaging pedagogies
- Disseminate outcomes for both the chemistry education and broader science communities

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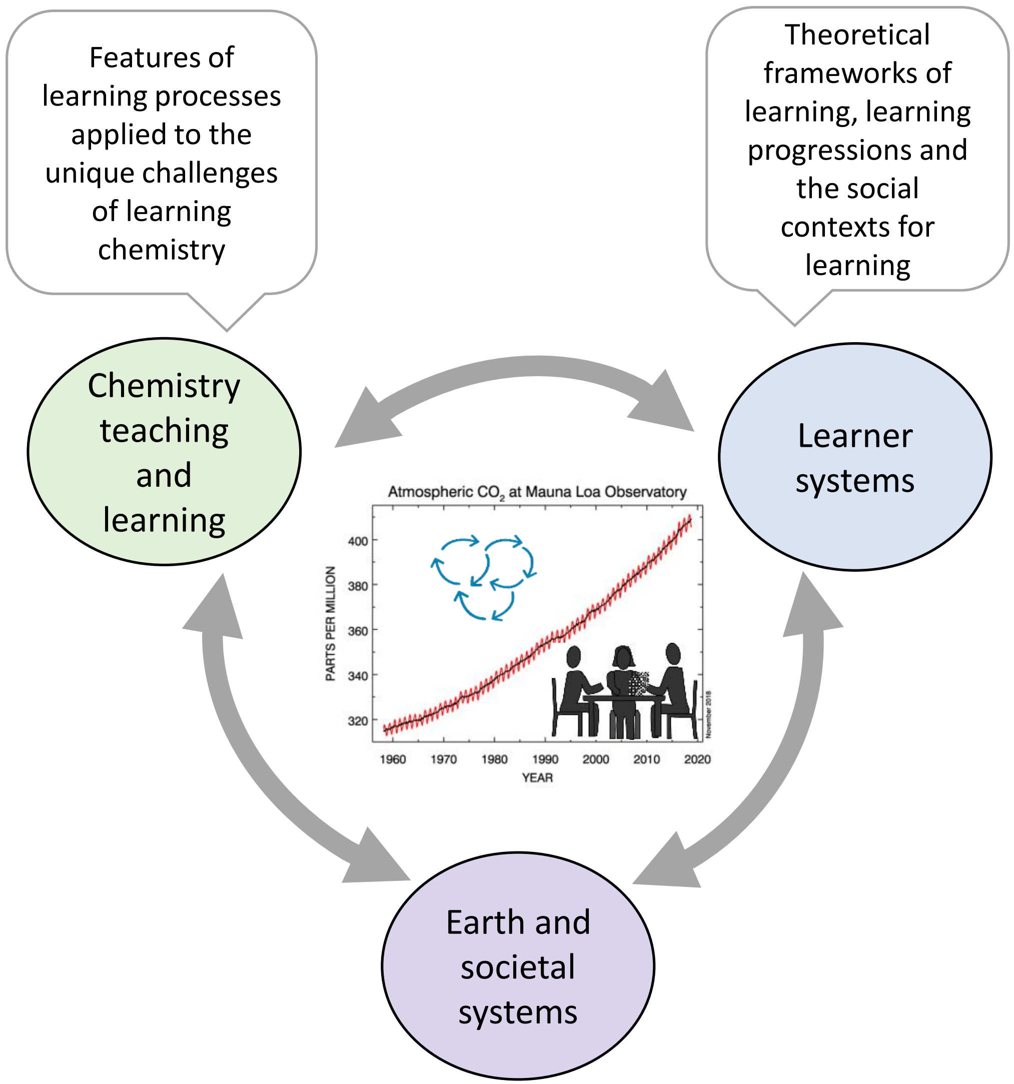

Elements that orient chemistry education toward meeting societal and environmental needs

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**

JOURNAL OF CHEMICAL EDUCATION

News and Announcements

Cite This: *J. Chem. Educ.* 2018, 95, 1689–1691

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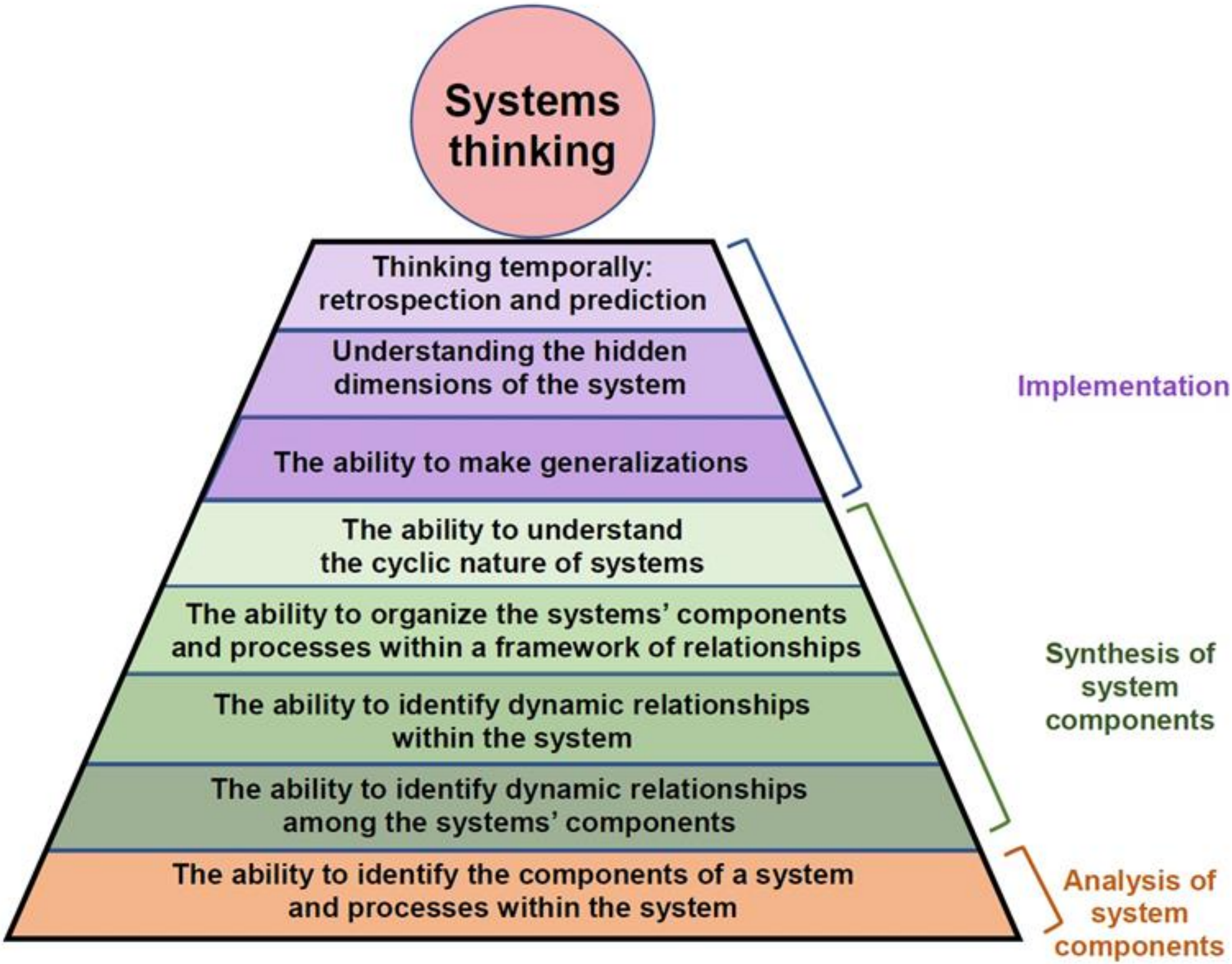
ABSTRACT: The *Journal of Chemical Education* announces a call for papers for an upcoming special issue on Reimagining Chemistry Education: Systems Thinking, and Green and Sustainable Chemistry.

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*

Framework for Systems Thinking in Chemistry Education

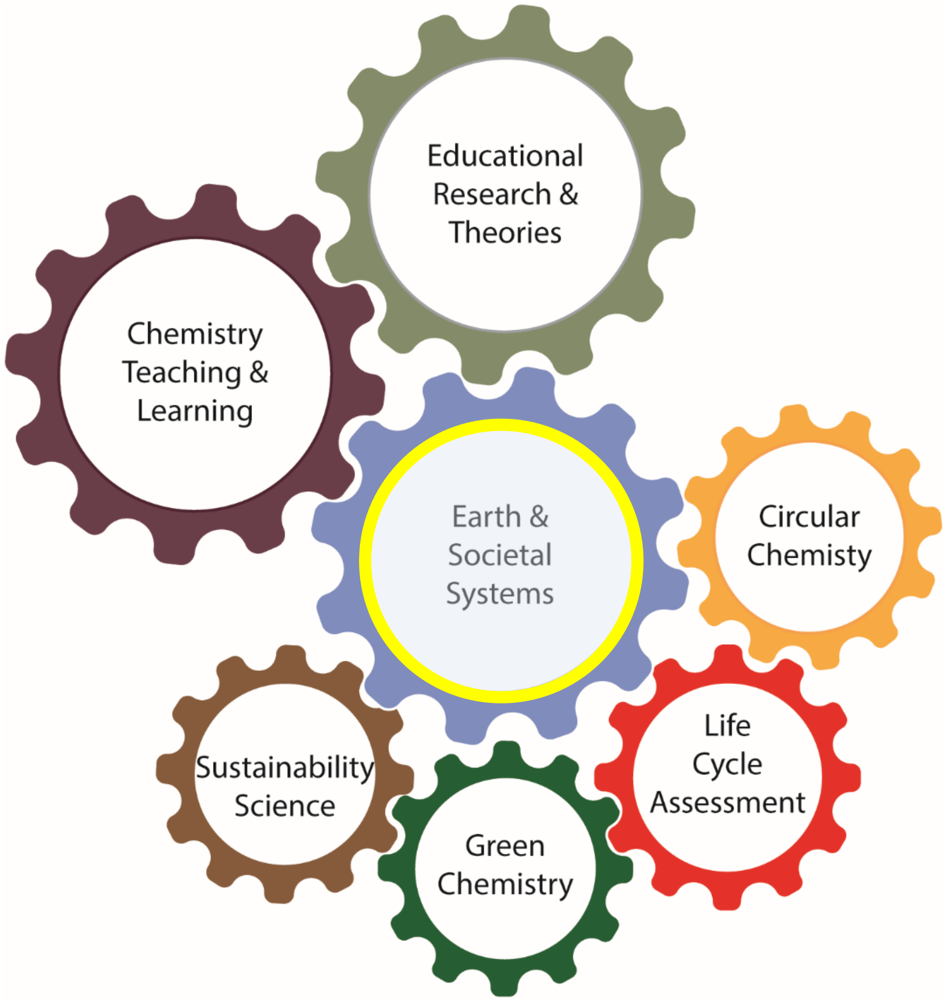
Mahaffy, Matlin, Krief, Hopf, Meta, *"Reorienting Chemistry Education through Systems Thinking"* nature REVIEWS CHEMISTRY

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



Orgill, York & MacKellar, J Chem Educ. submitted, 2019, from information by Assaraf & Orion, 2010

Systems thinking to address emerging global challenges

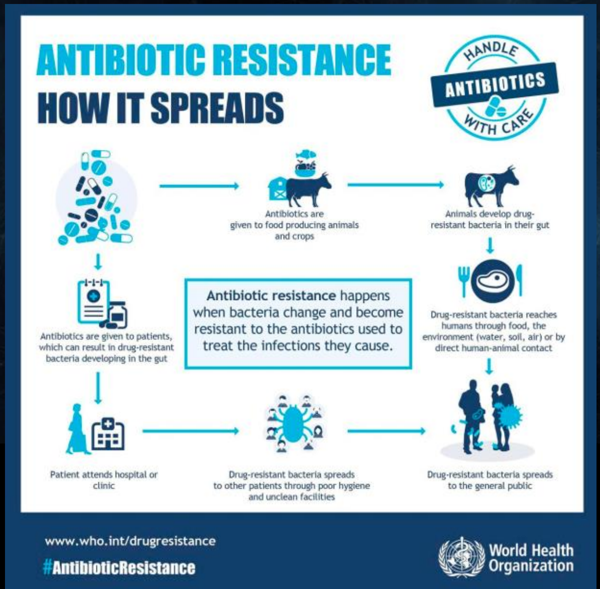


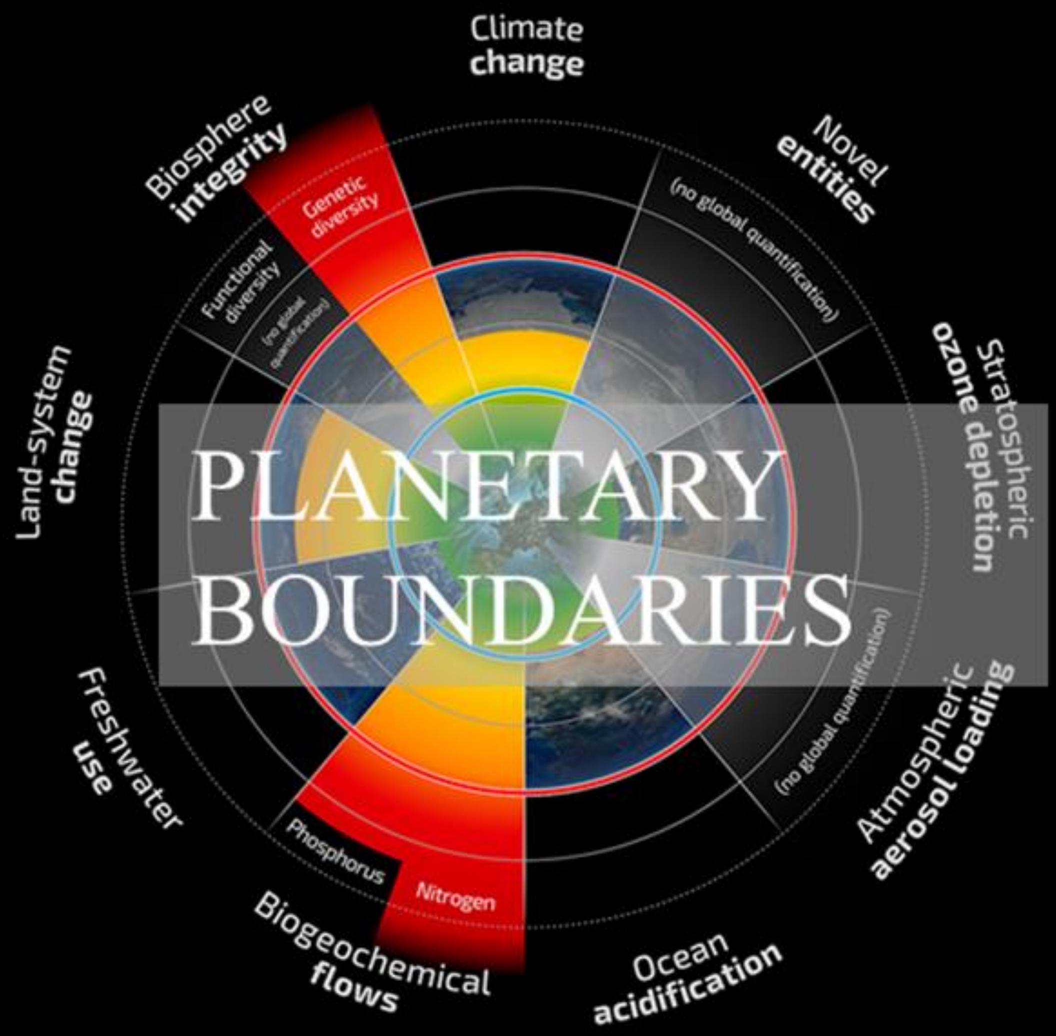
Earth and Societal Systems Node – Steering Group

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

Quality of life for many humans has been profoundly improved by the many applications of chemistry

Yet multiple challenges for earth and its people are emerging



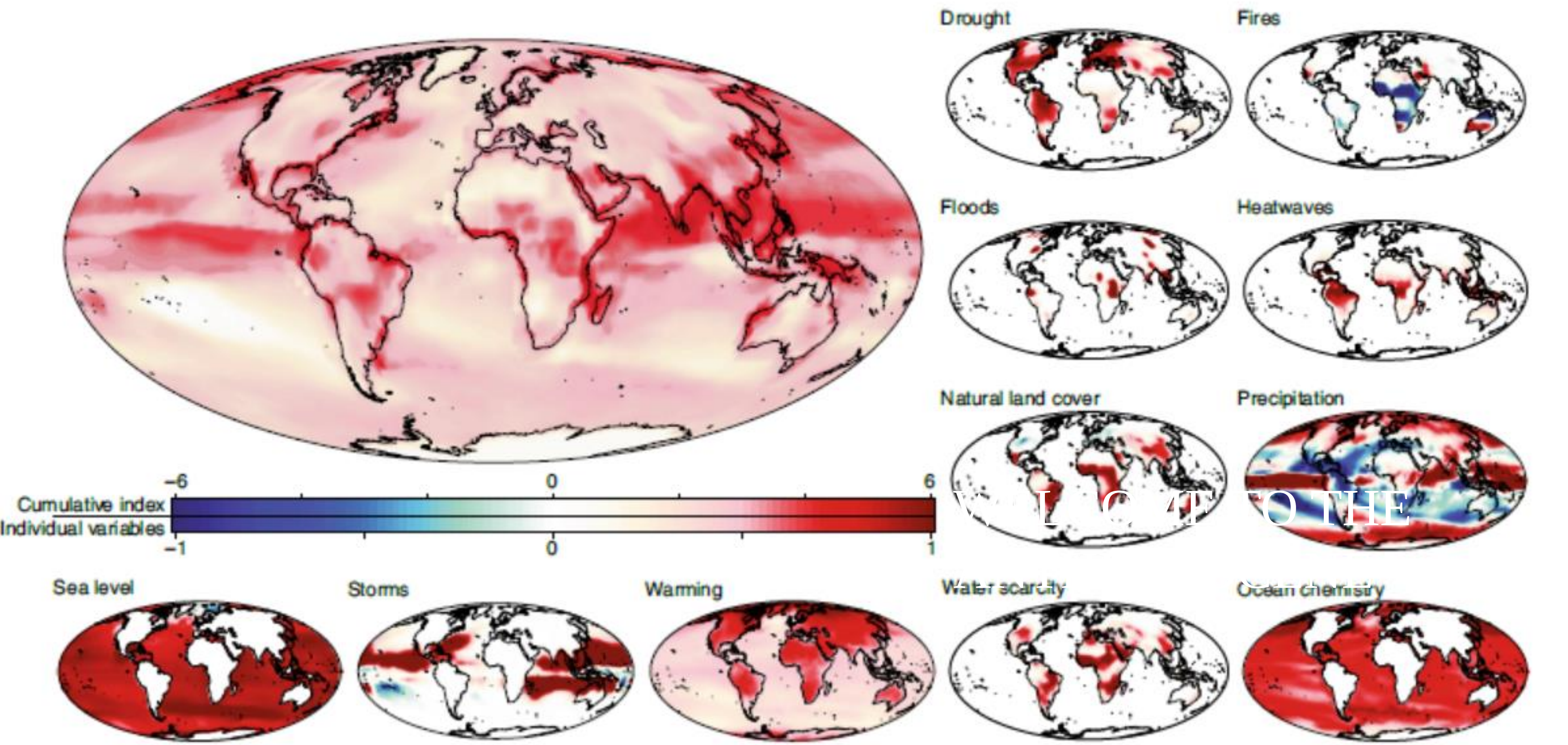


Stockhomresilience.org

nature climate change

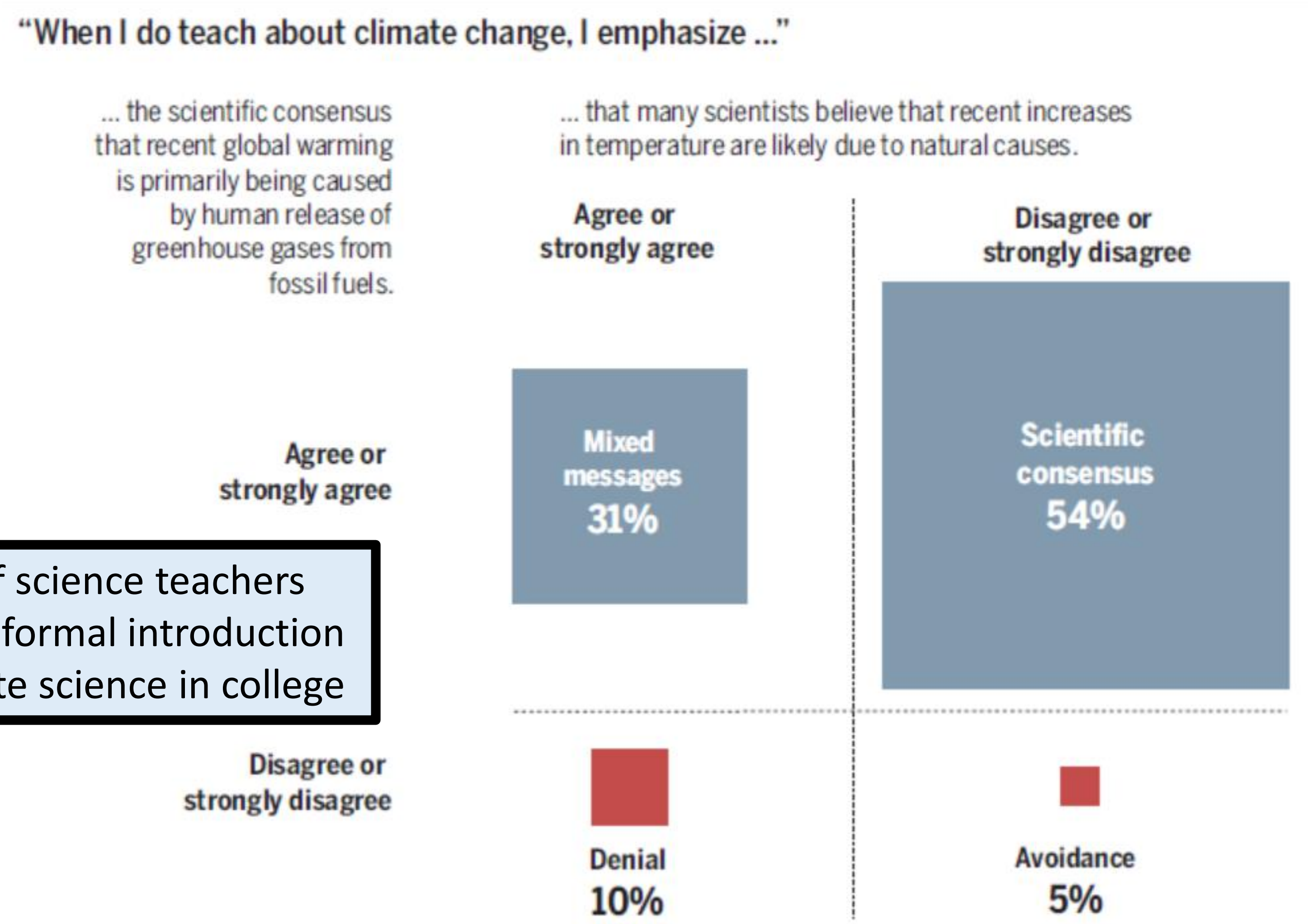
REVIEW ARTICLE

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



Do students leave gateway science courses knowing how their knowledge of chemistry can help to understand and meet multiple emerging global challenges, like climate change?

K-12 STEM coverage of climate change



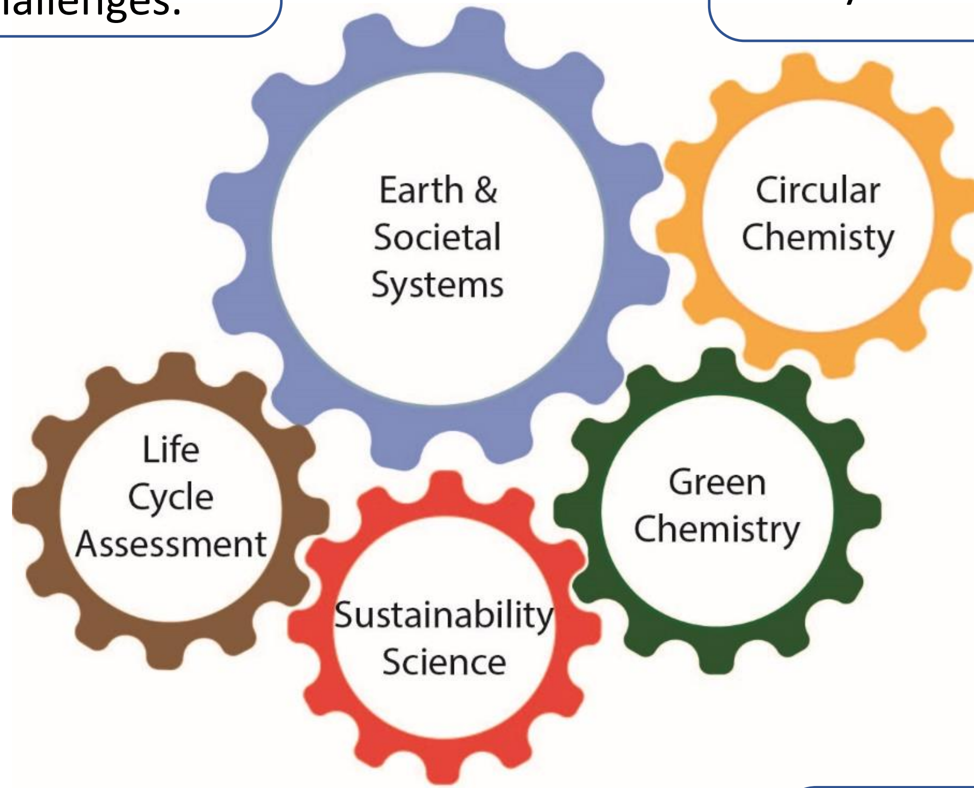
Teachers' emphasis. Teachers reported emphasis on causes of global warming, among those devoting an hour or more to the topic (see SM for details on calculation).

< 50% of science teachers had any formal introduction to climate science in college

Putzer, McCaffery, et al., Science, 2016, VOL 351 ISSUE 6274

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

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

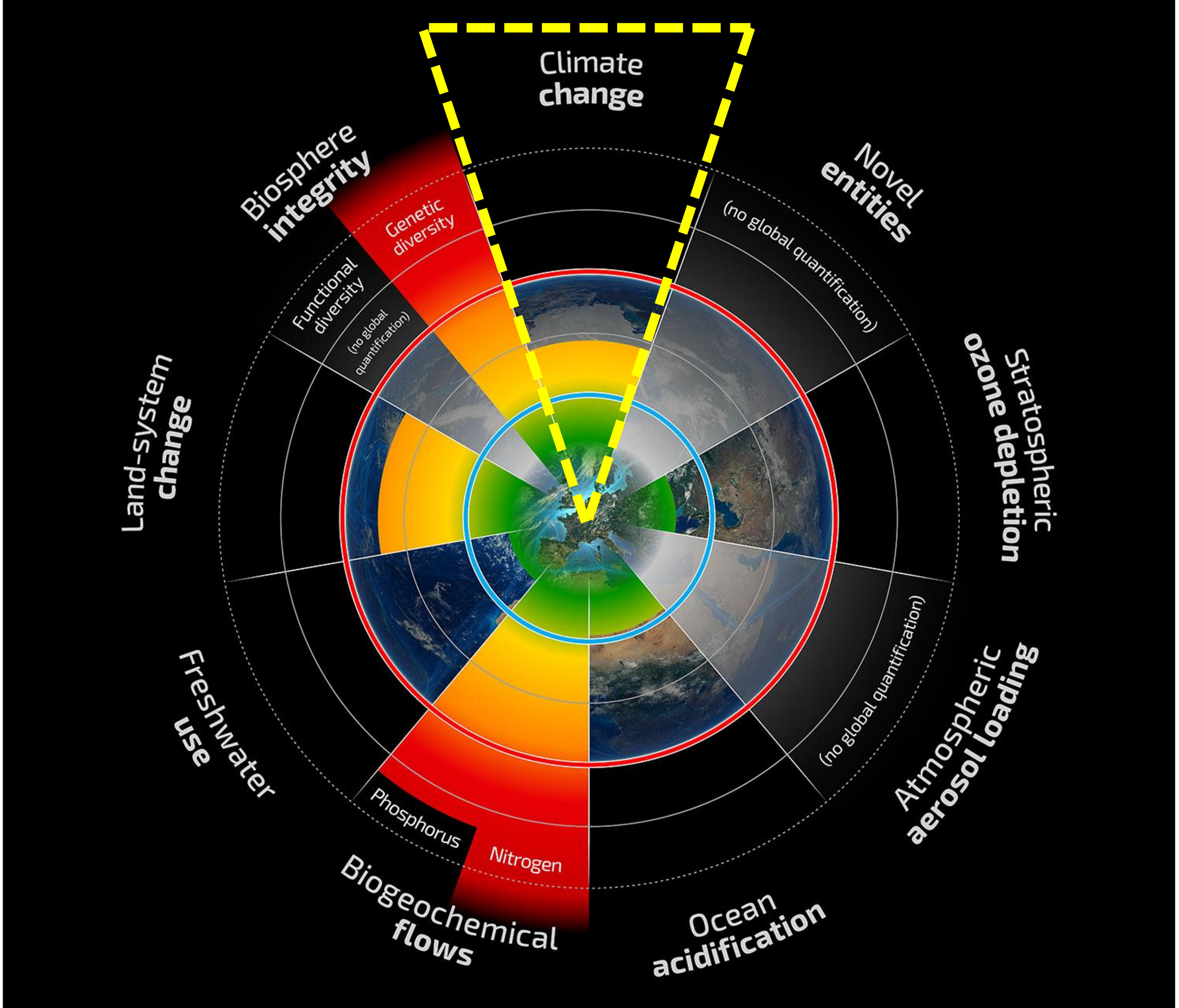


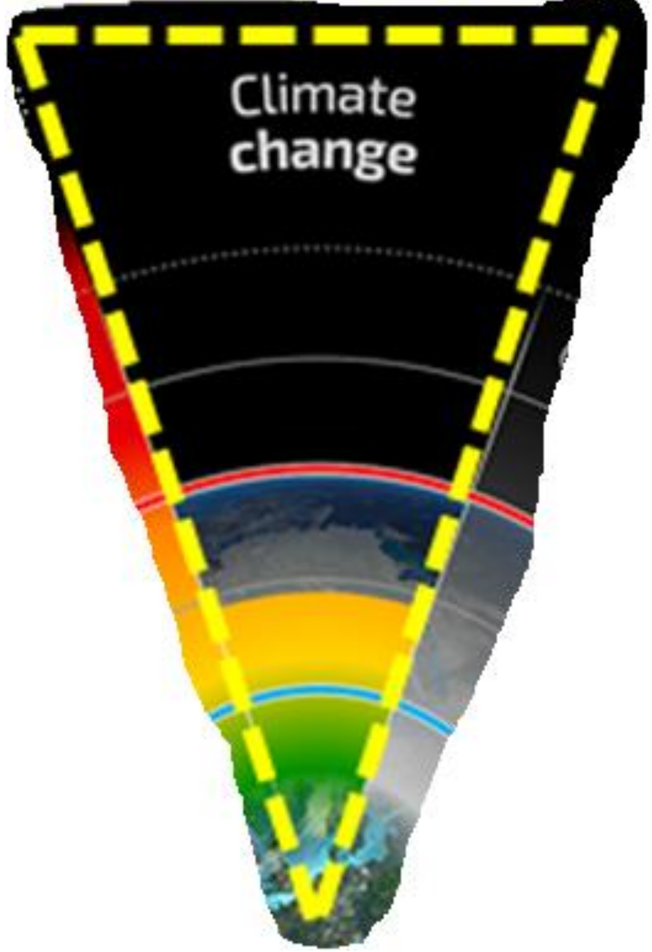
Reorient **chemistry education** to address the sustainability of earth and societal systems

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

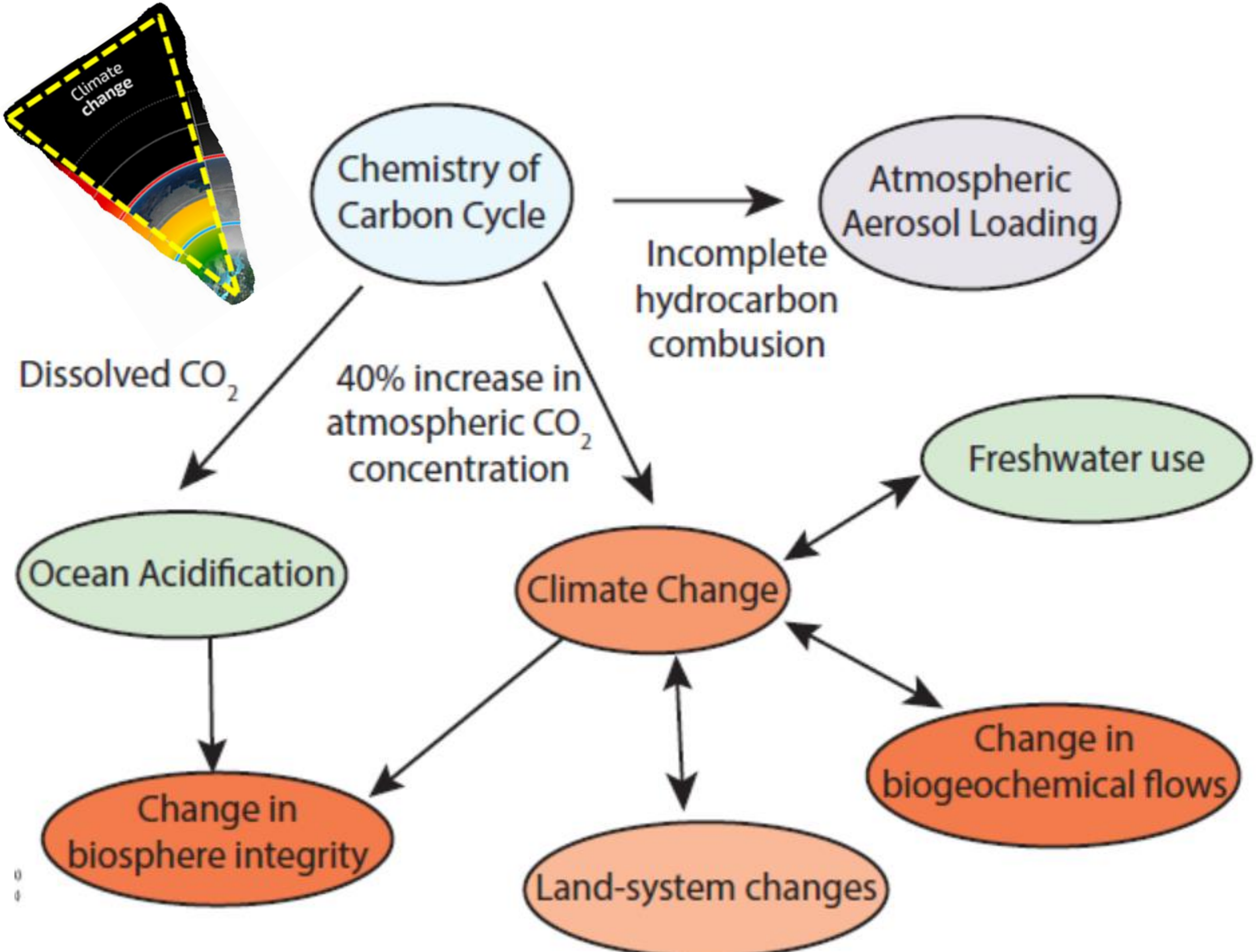
Mahaffy, Matlin, Holme, MacKellar, *"Systems Thinking for Education about the Molecular Basis of Sustainability," 2019, in press.*

nature sustainability


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



Control variable(s)	Planetary boundary (zone of uncertainty)	Current value of control variable
Atmospheric CO_2 concentration, ppm	350 ppm CO_2 (350-450 ppm)	396.5 ppm CO_2
Energy imbalance at top-of-atmosphere, W m^{-2}	Energy imbalance: +1.0 W m^{-2} (+1.0-1.5 W m^{-2})	2.3 W m^{-2} (1.1-3.3 W m^{-2})

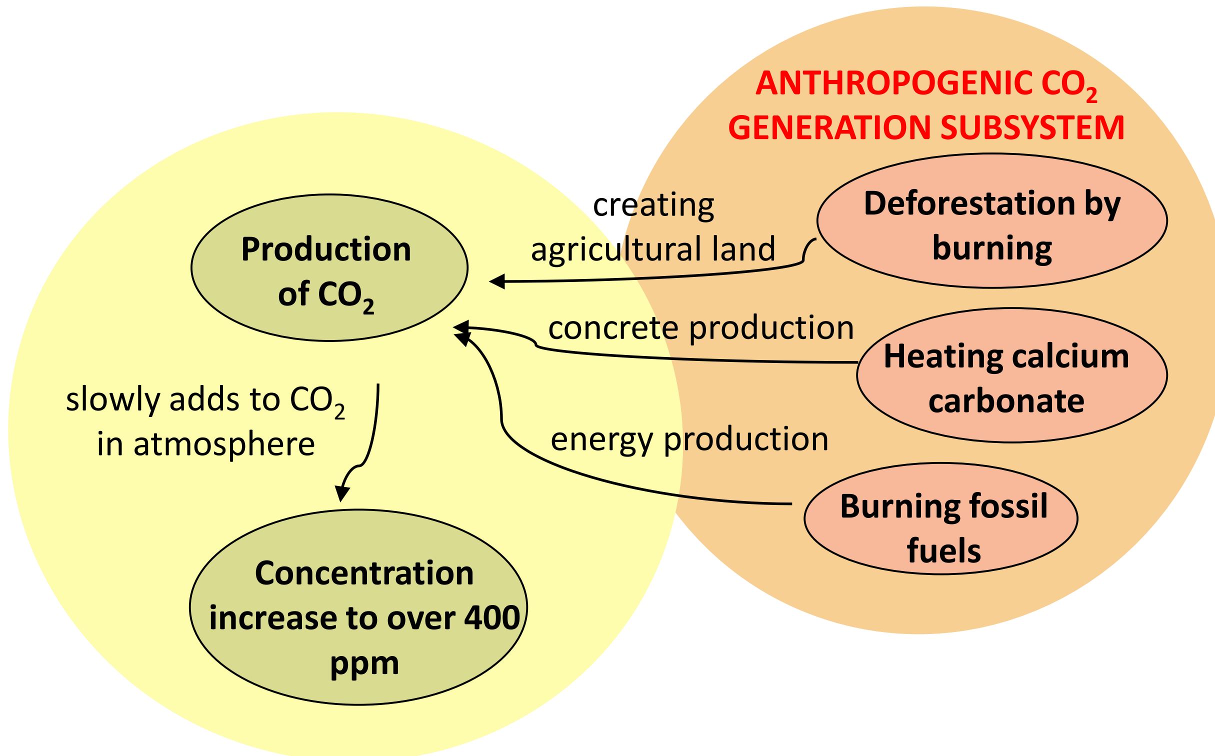


Climate change
Chemistry of Carbon Cycle
Atmospheric Aerosol Loading
Incomplete hydrocarbon combustion
Dissolved CO_2
40% increase in atmospheric CO_2 concentration
Freshwater use
Ocean Acidification
Climate Change
Change in biogeochemical flows
Change in biosphere integrity
Land-system changes

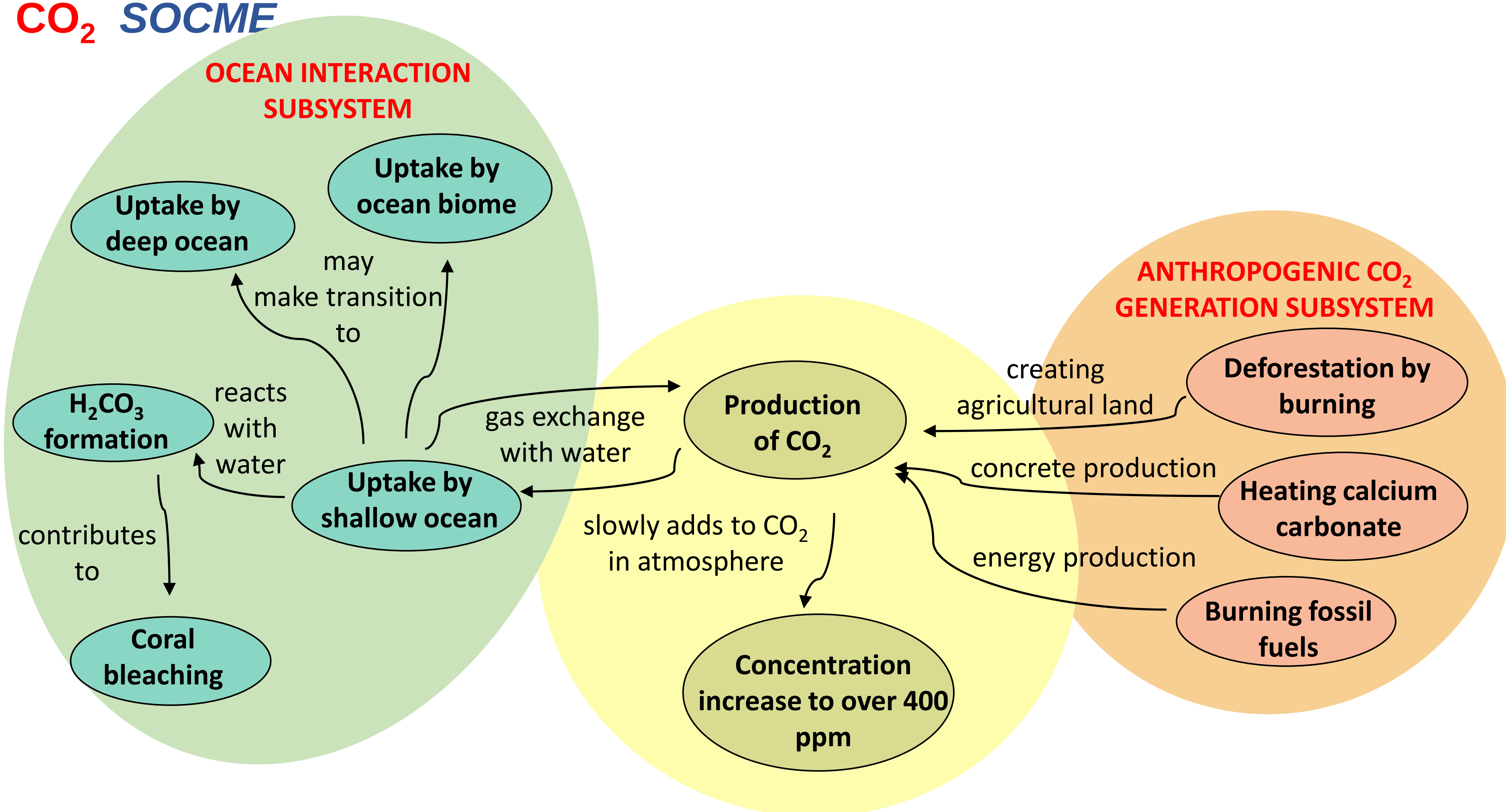
CO_2 *SOCME*

Systems-oriented concept map extension

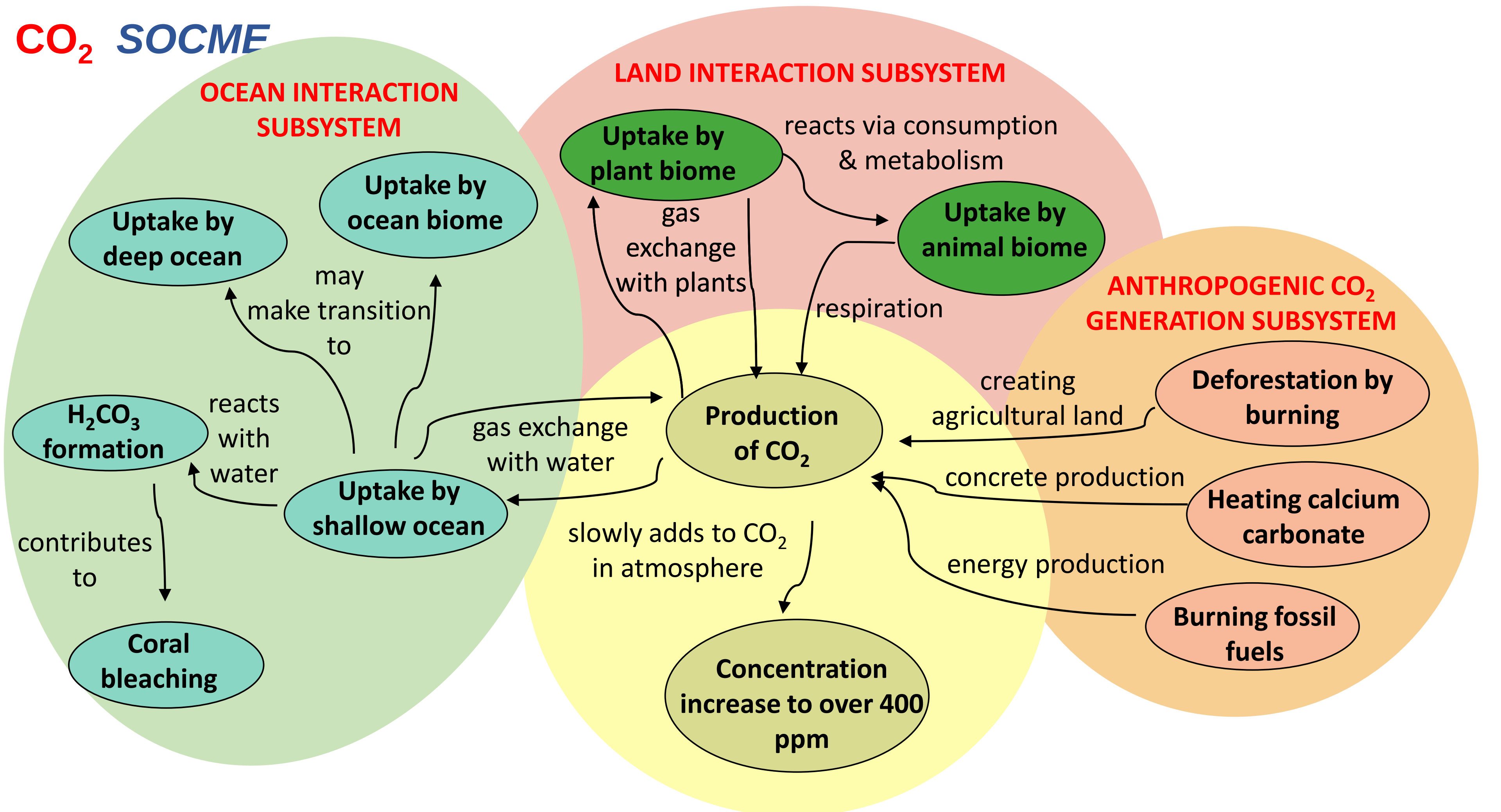
P.G. Mahaffy, S.A. Matlin, T.A. Holmes, J. MacKellar, *Nature Sustainability*, 2019, in press.



CO_2 *SOCME*



OCEAN INTERACTION SUBSYSTEM
Uptake by ocean biome
Uptake by deep ocean
may make transition to
H_2CO_3 formation
reacts with water
Uptake by shallow ocean
contributes to
Coral bleaching
gas exchange with water
Production of CO_2
slowly adds to CO_2 in atmosphere
Concentration increase to over 400 ppm
ANTHROPOGENIC CO_2 GENERATION SUBSYSTEM
creating agricultural land
Deforestation by burning
concrete production
Heating calcium carbonate
energy production
Burning fossil fuels



CO_2 SOCME
OCEAN INTERACTION SUBSYSTEM
LAND INTERACTION SUBSYSTEM
ANTHROPOGENIC CO_2 GENERATION SUBSYSTEM
Uptake by plant biome
reacts via consumption & metabolism
Uptake by animal biome
gas exchange with plants
respiration
Uptake by deep ocean
Uptake by ocean biome
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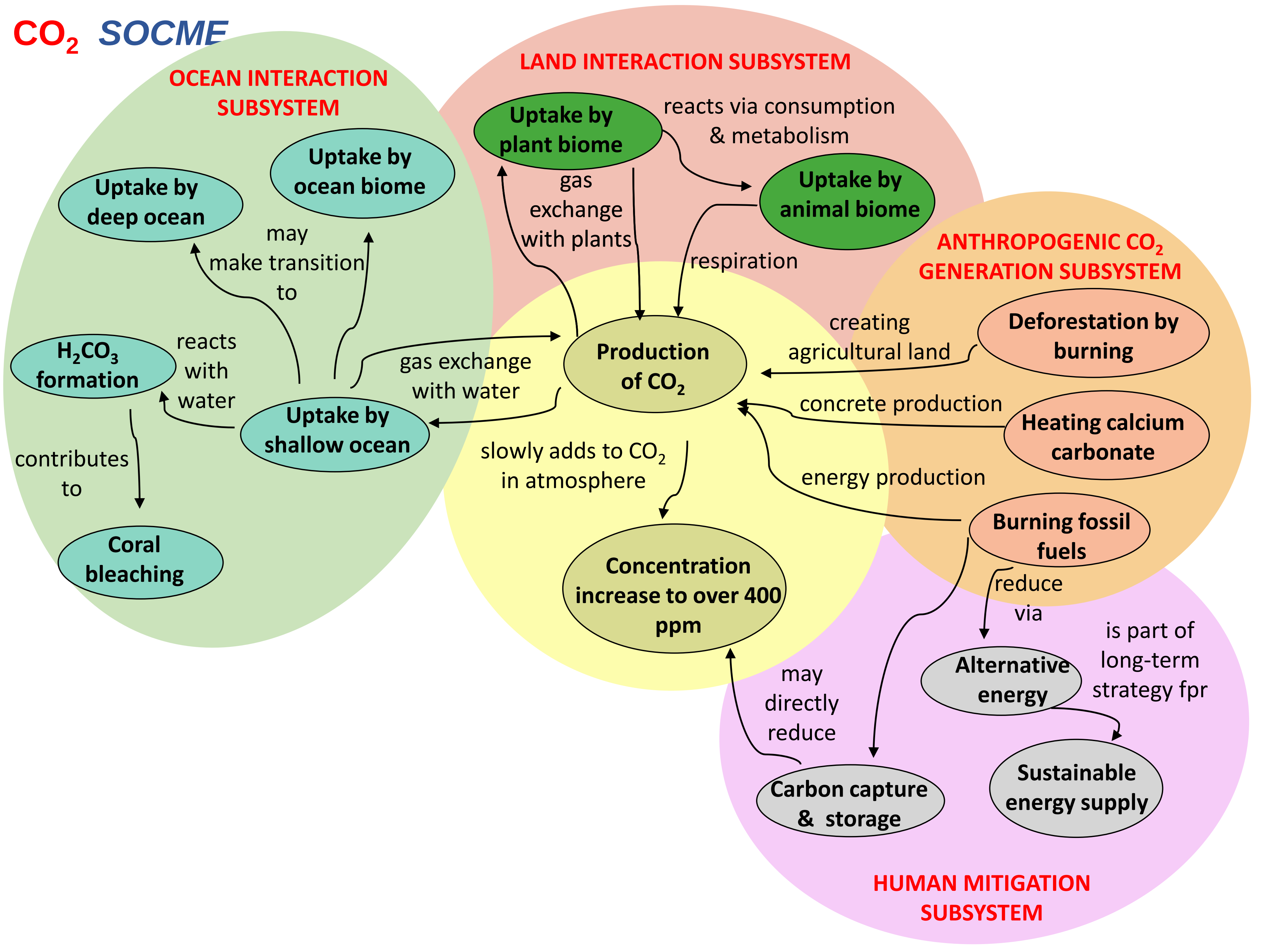

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Concentration increase to over 400 ppm
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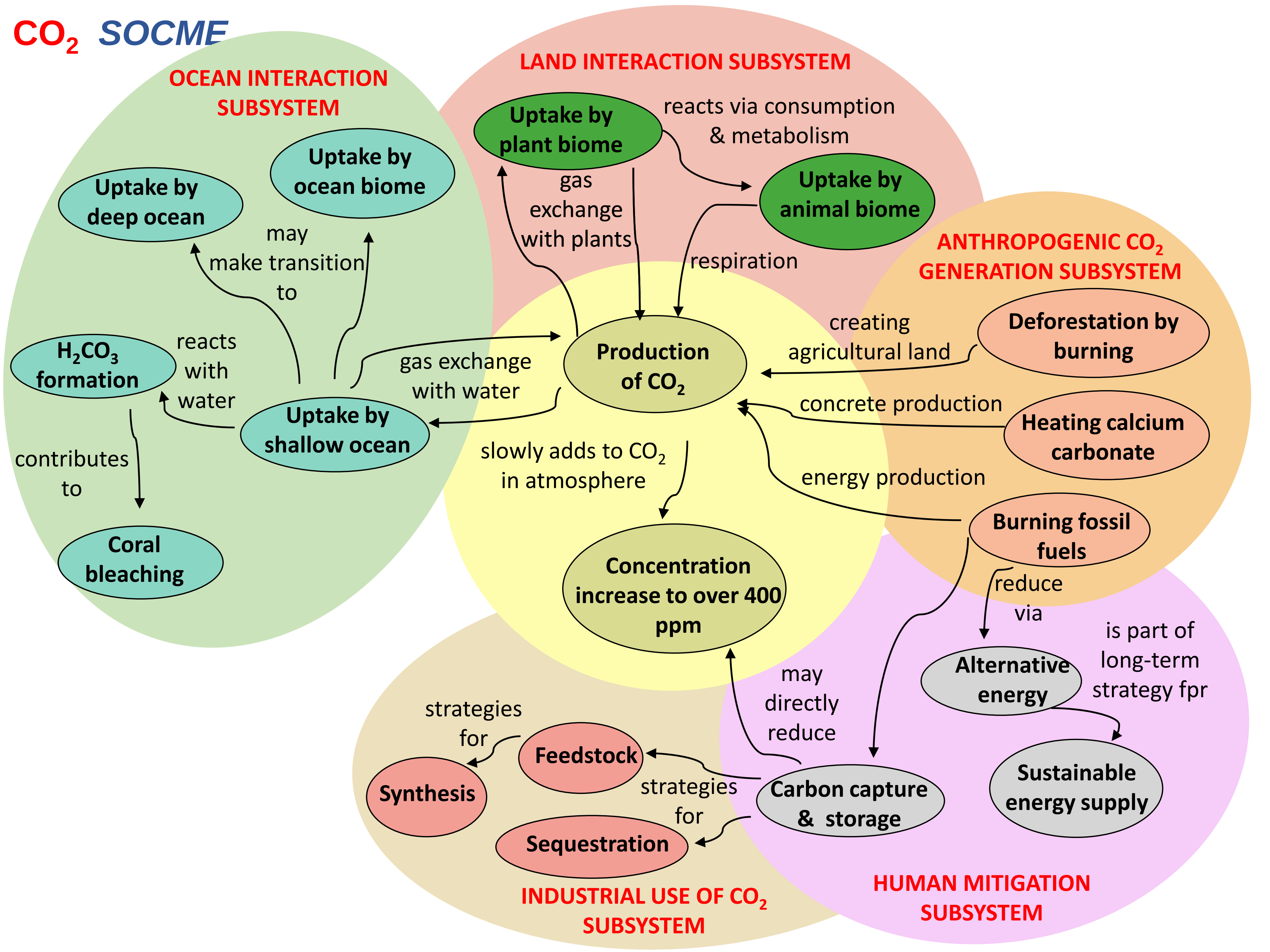
Alternative energy
is part of long-term strategy fpr
Sustainable energy supply
may directly reduce
Carbon capture & storage



CO_2 SOCME
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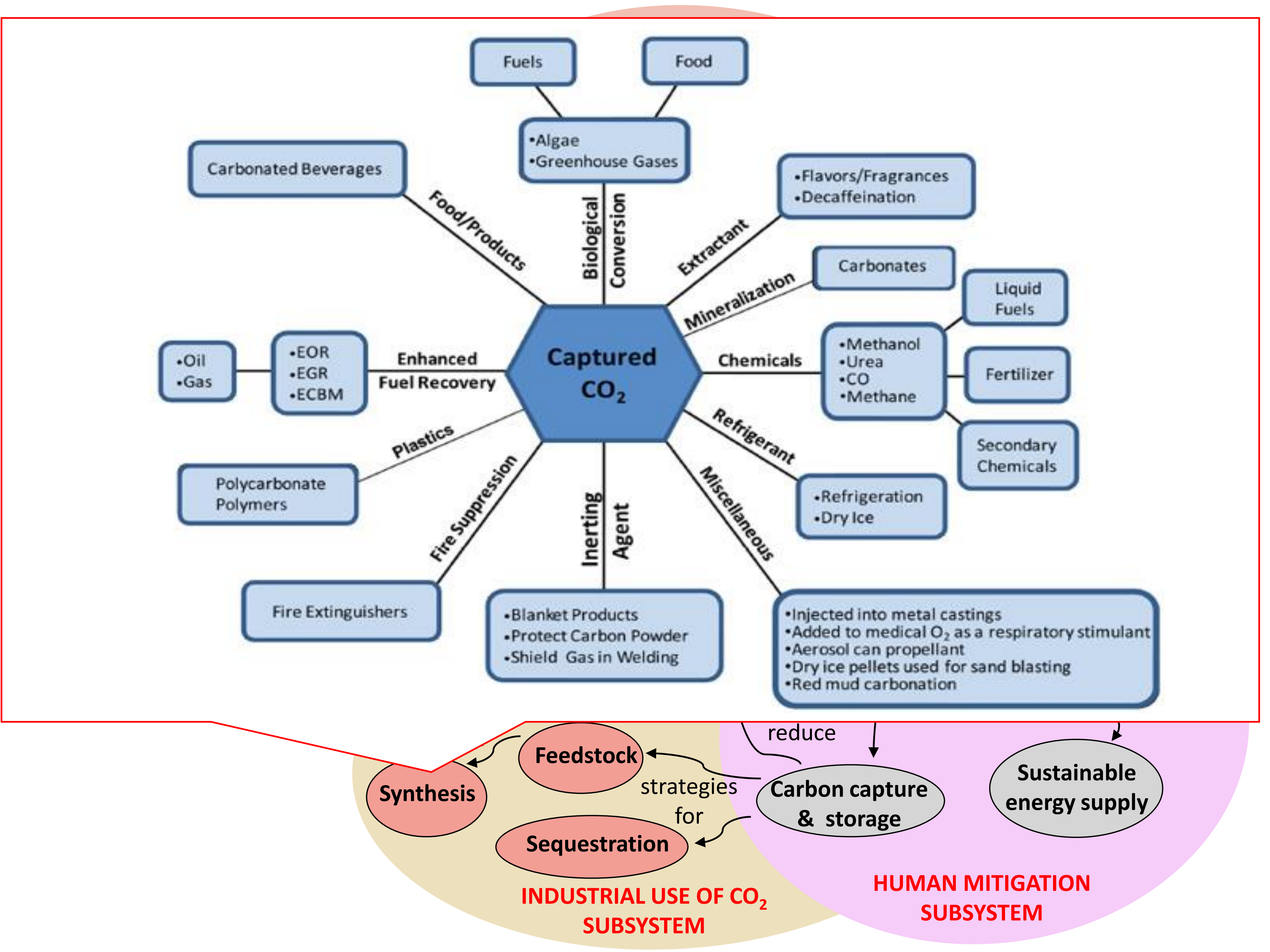
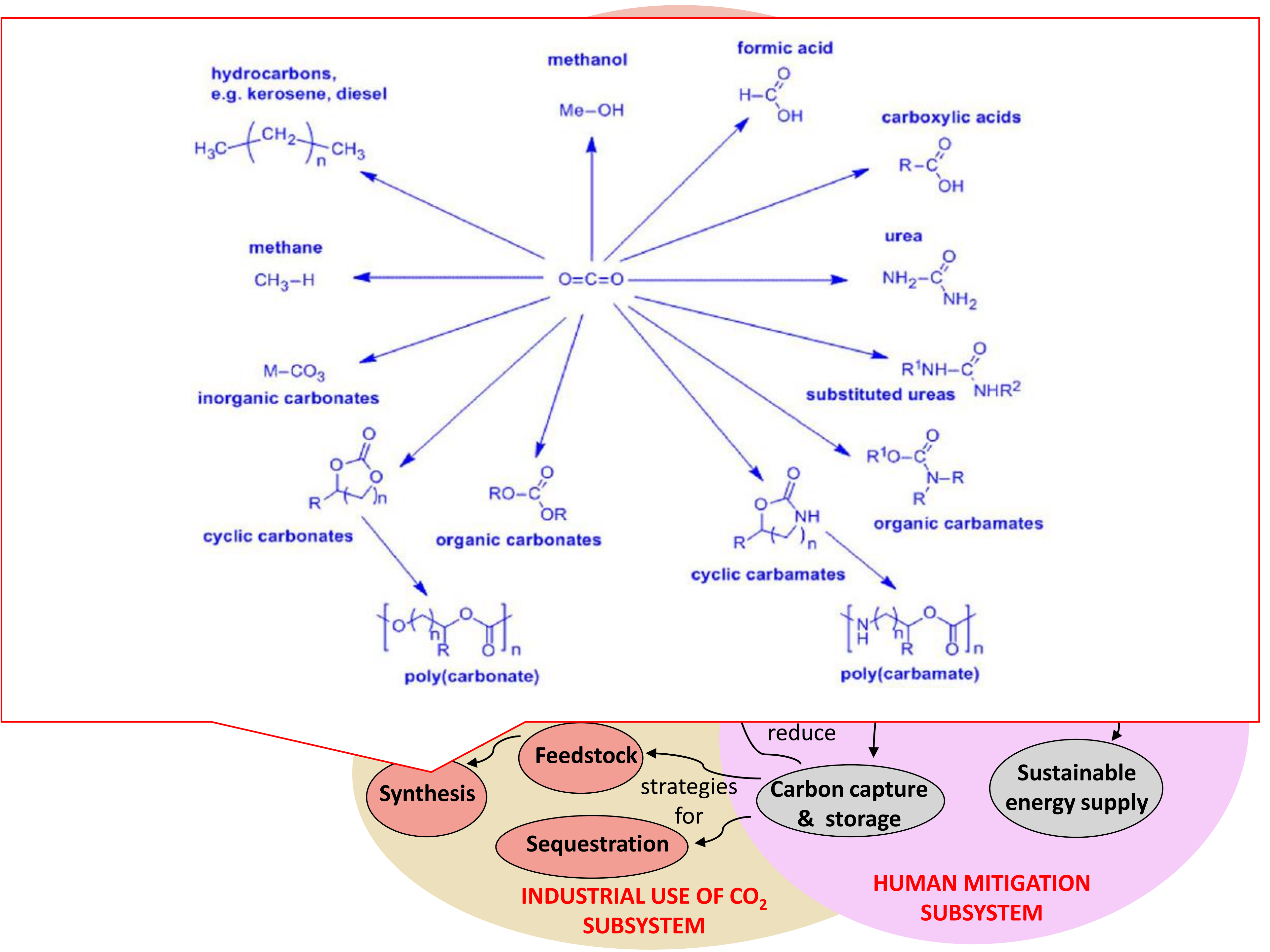
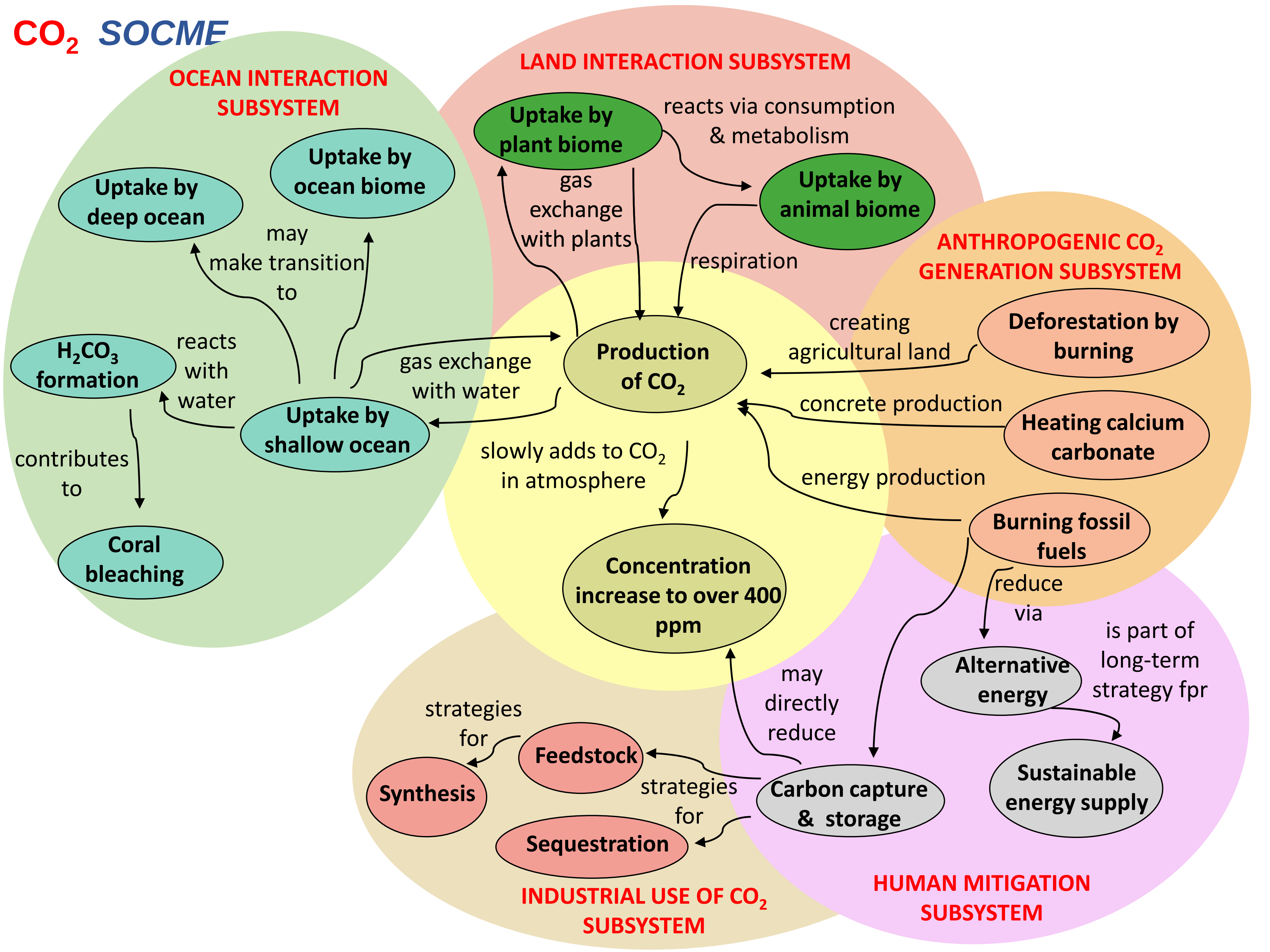
strategies for
Feedstock
strategies for
Synthesis
Sequestration



Fuels
Food
•Algae
•Greenhouse Gases
Carbonated Beverages
Food/Products
Biological Conversion
Extractant
•Flavors/Fragrances
•Decaffeination
Carbonates
Mineralization
Liquid Fuels
Captured CO_2
Enhanced Fuel Recovery
•Oil
•Gas
•EOR
•EGR
•ECBM
Chemicals
•Methanol
•Urea
•CO
•Methane
Fertilizer
Secondary Chemicals
Plastics
Polycarbonate Polymers
Refrigerant
•Refrigeration
•Dry Ice
Fire Suppression
Inerting Agent
Miscellaneous
Fire Extinguishers
•Blanket Products
•Protect Carbon Powder
•Shield Gas in Welding
•Injected into metal castings
•Added to medical O_2 as a respiratory stimulant
•Aerosol can propellant
•Dry ice pellets used for sand blasting
•Red mud carbonation
reduce
Feedstock
Synthesis
strategies for
Sequestration
Carbon capture & storage
Sustainable energy supply
INDUSTRIAL USE OF CO_2 SUBSYSTEM
HUMAN MITIGATION SUBSYSTEM


hydrocarbons,
e.g. kerosene, diesel
methanol
Me–OH
formic acid
carboxylic acids
urea
methane
CH_3–H
O=C=O
M–CO_3
inorganic carbonates
substituted ureas
organic carbamates
cyclic carbonates
organic carbonates
cyclic carbamates
poly(carbonate)
poly(carbamate)
reduce
Feedstock
Synthesis
strategies
for
Carbon capture
& storage
Sustainable
energy supply
Sequestration
INDUSTRIAL USE OF CO_2
SUBSYSTEM
HUMAN MITIGATION
SUBSYSTEM



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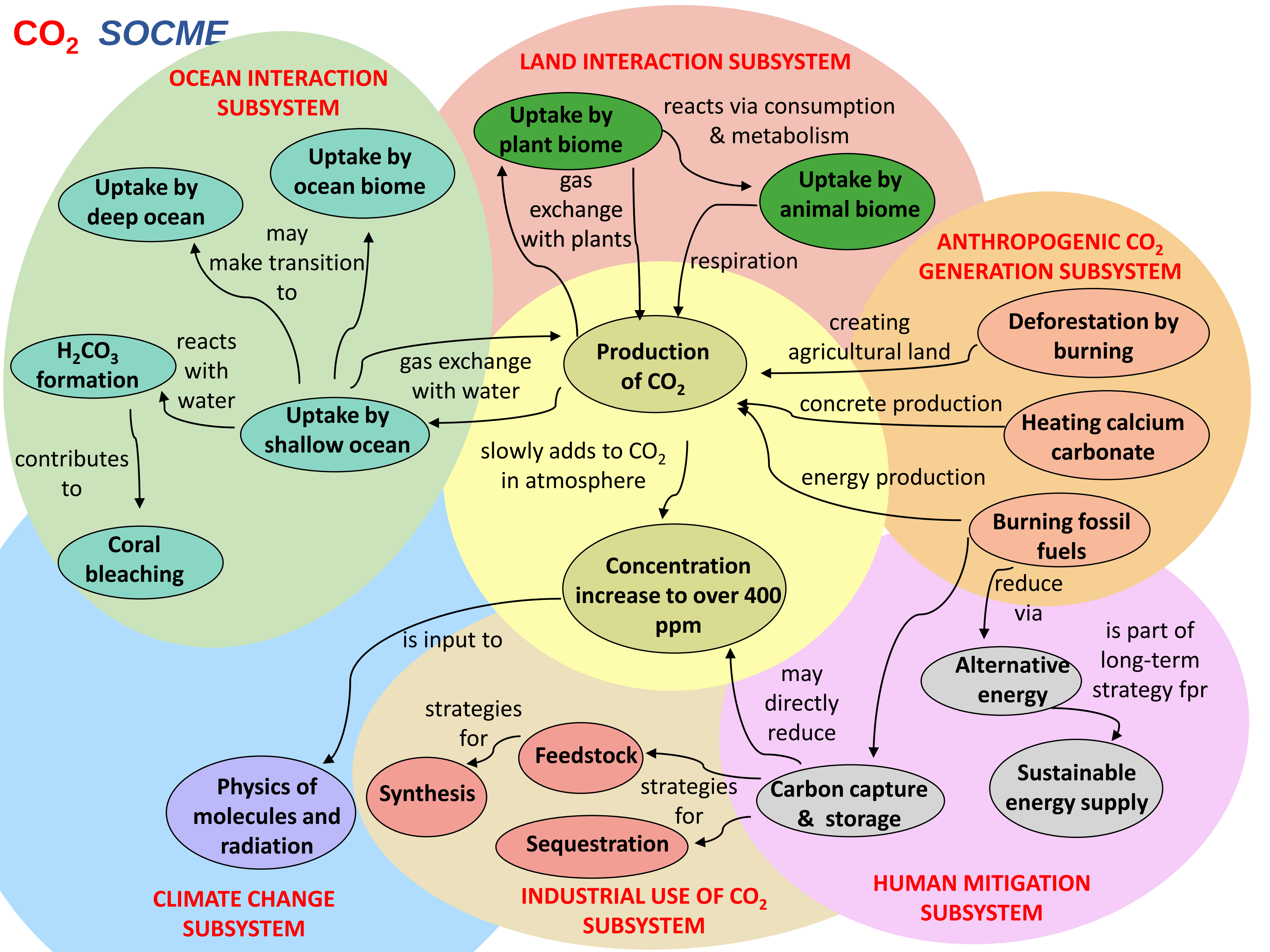
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Synthesis
strategies for
Carbon capture & storage
Sustainable energy supply
Physics of molecules and radiation
Sequestration
CLIMATE CHANGE SUBSYSTEM
INDUSTRIAL USE OF CO_2 SUBSYSTEM
HUMAN MITIGATION SUBSYSTEM

Beer's Law (Beer-Lambert-Bouguer Law)

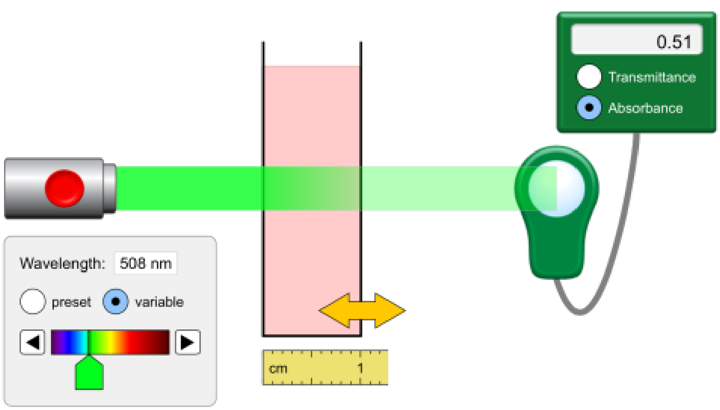
Absorbance is proportional to concentration

$$A = \varepsilon L C$$

- A: absorbance
- ε: Molar absorptivity constant (depends on solute, solvent, wavelength)
- L: length of path travelled by light
- C: Solution concn (mol/L)

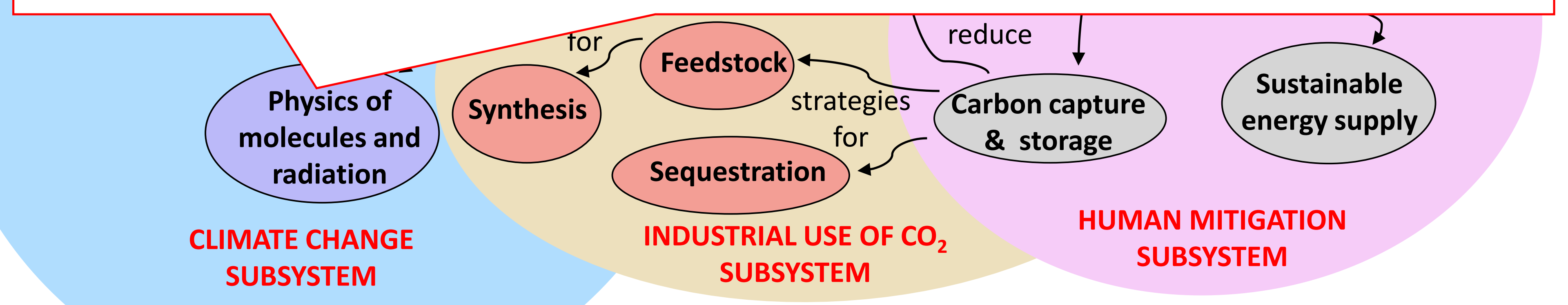
Pierre Bouguer (1729)

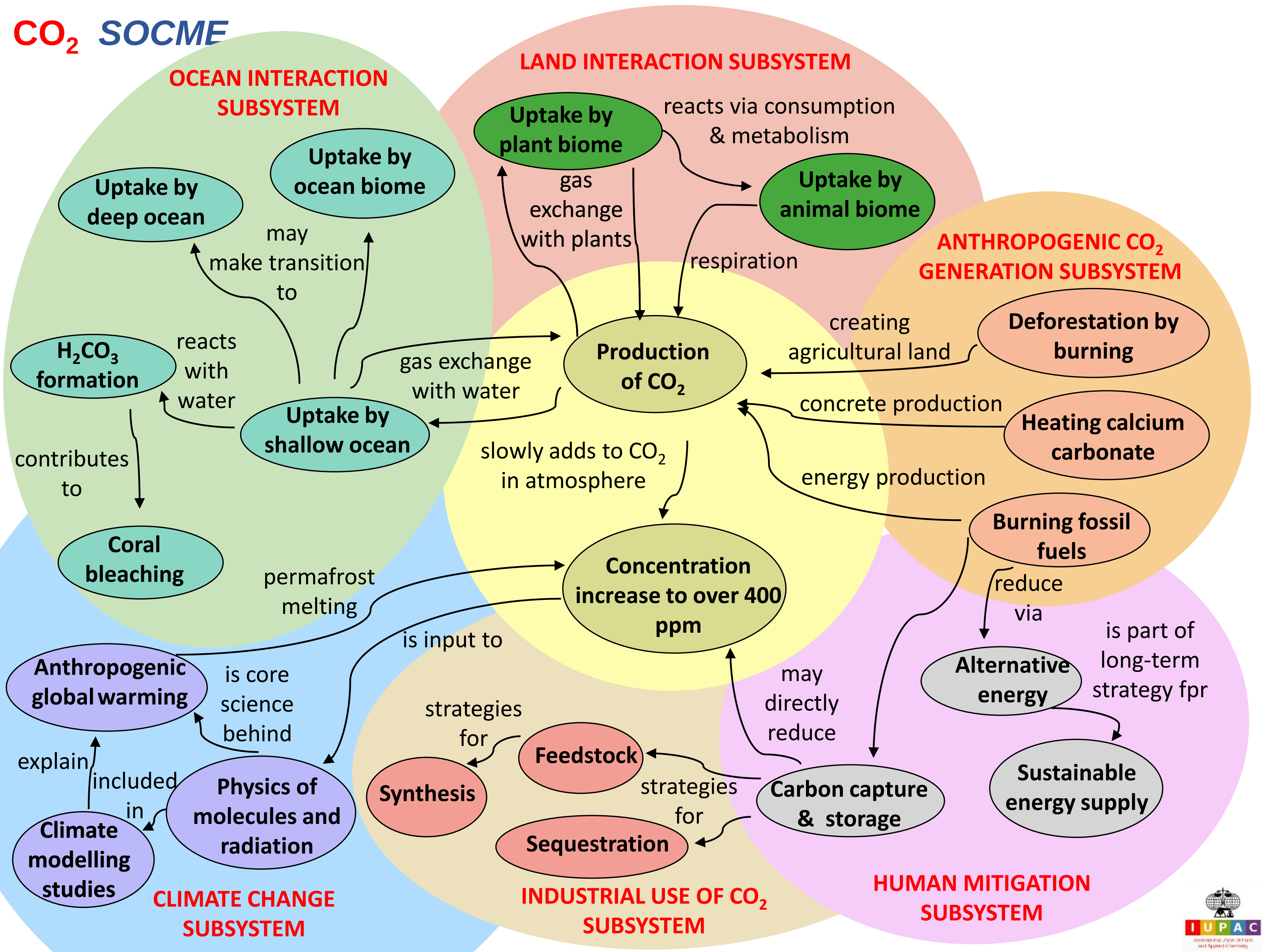
Light intensity diminishes exponentially with distance as it passes through the atmosphere



Extend to consider:

- Absorption of light at different wavelengths by N_2, O_2, CO_2, CH_4, etc
- Energy absorbed by atmospheric gases
  - How much?
  - What happens to it?
  - Nature of the greenhouse effect?

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is input to
Anthropogenic global warming
is core science behind
Physics of molecules and radiation
explain
included in
Climate modelling studies
strategies for
Feedstock
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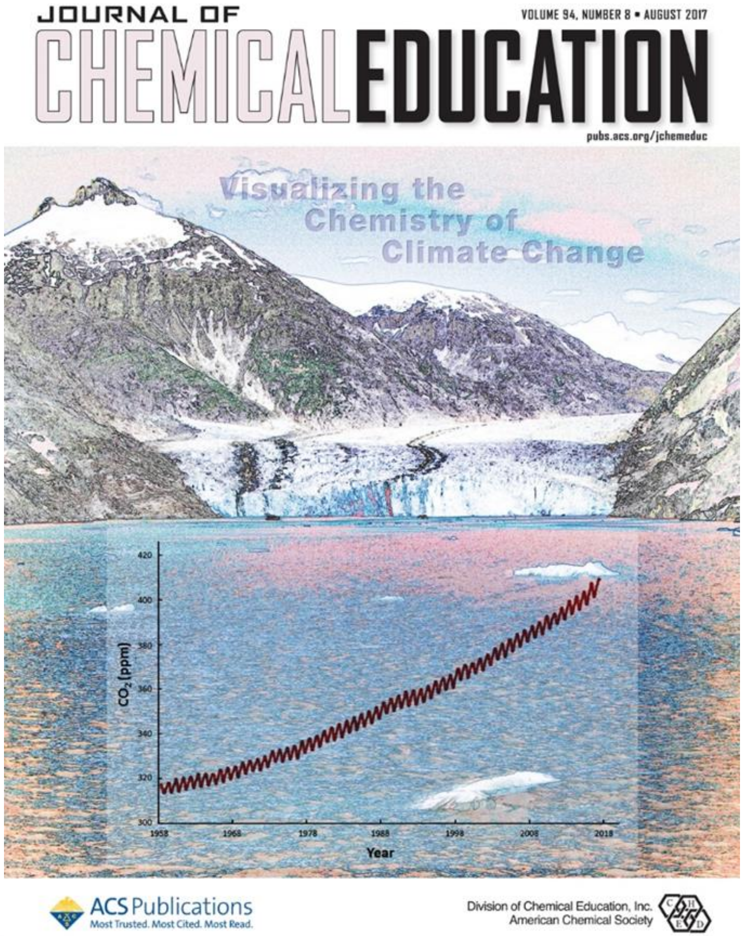
Visualizing the Chemistry of Climate Change

www.VC3chem.com



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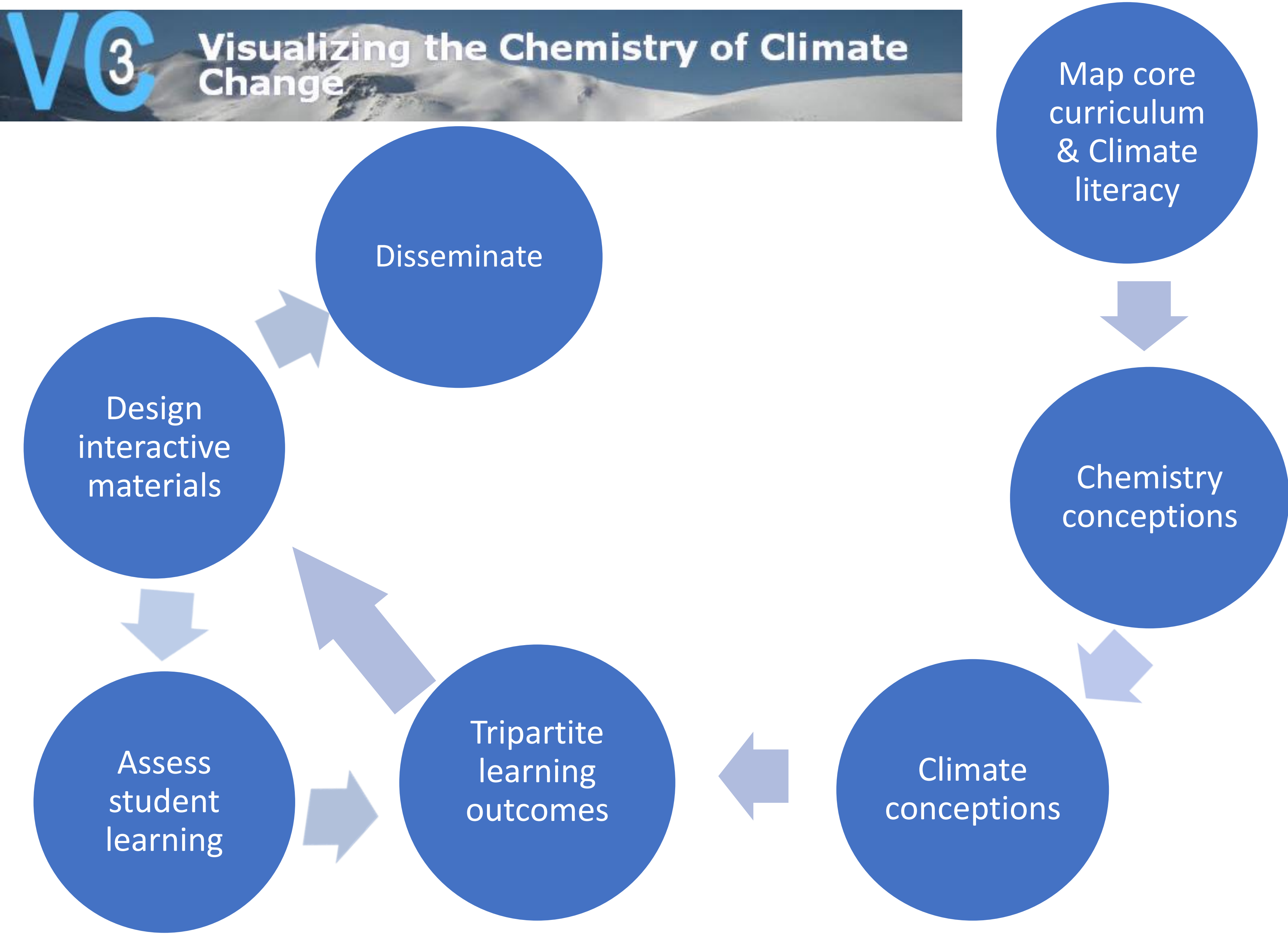
- Mary Kirchhoff (ACS)
- Lallie McKenzie (Oregon)
- Cathy Middlecamp (Wisconsin)
- Tom Holme, Evaluator (Iowa State)

Mahaffy, et al., J Chem Ed, 2017, DOI: 10.1021/acs.jchemed.6b01009

The King's Centre for Visualization in Science

CRYSTAL - ALBERTA

CRSNG NSERC


VC3
Visualizing the Chemistry of Climate Change
Map core curriculum & Climate literacy
Chemistry conceptions
Climate conceptions
Tripartite learning outcomes
Design interactive materials
Disseminate
Assess student learning

Examples of Rich Context Concept Questions

- **Isotopes**: How is 800,000 years of temperature data determined from ice core samples?
- **Gases:** Which atmospheric gases support life directly? Which gases support life by regulating the energy balance of our planet?
- **Acids/Bases:** How does atmospheric carbon dioxide influence the pH of the ocean? What are the implications for marine ecosystems?
- **Thermochemistry:** How is the way we power our planet altering Earth's energy balance?

Acknowledgments

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- the entire STICE Steering Group for contributing to the STICE programme

Look out for:

- Special Issue of the Journal of Chemical Education on Reimagining chemistry education: Systems thinking, and green and sustainable chemistry

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