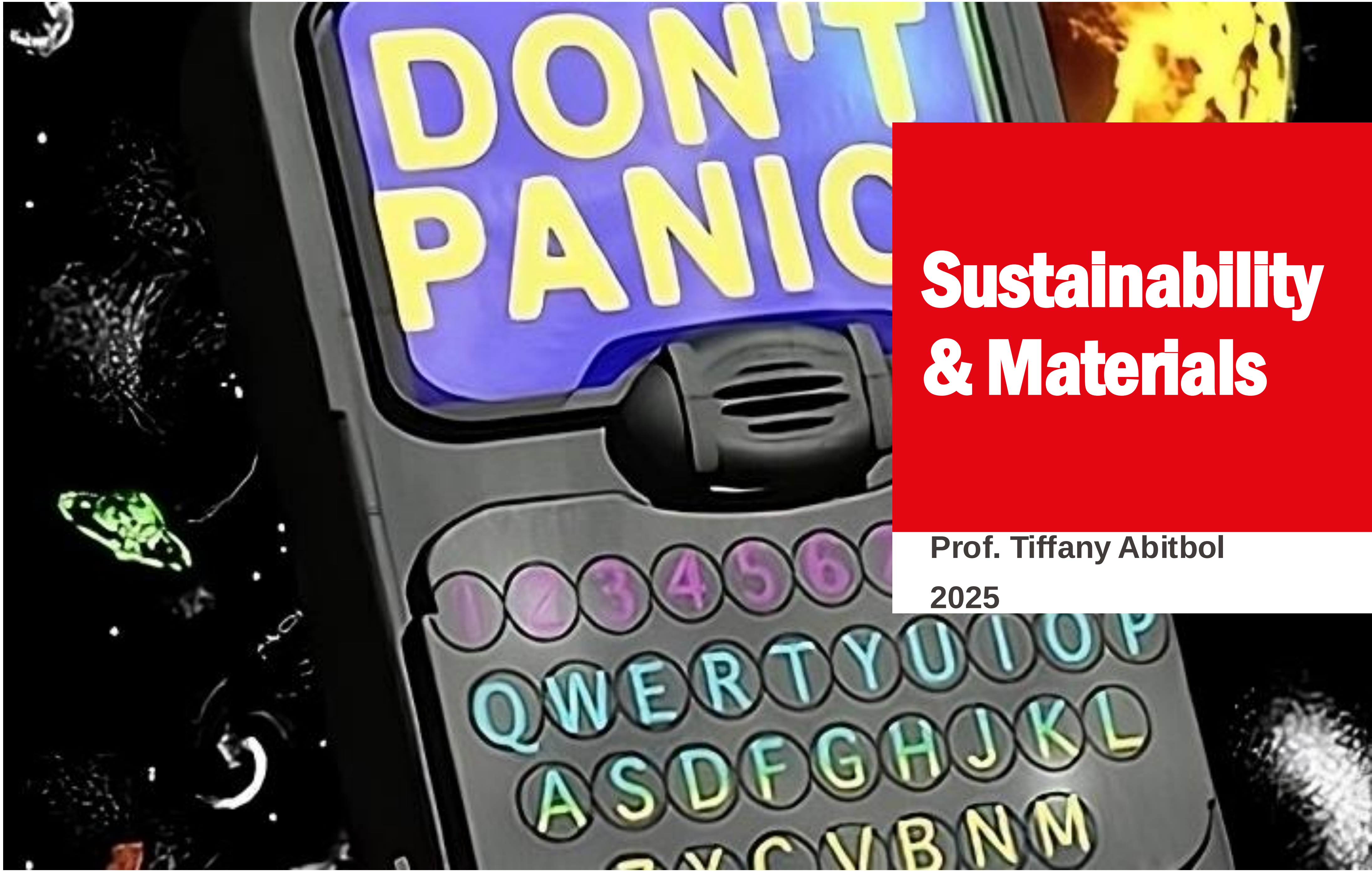
EPFL



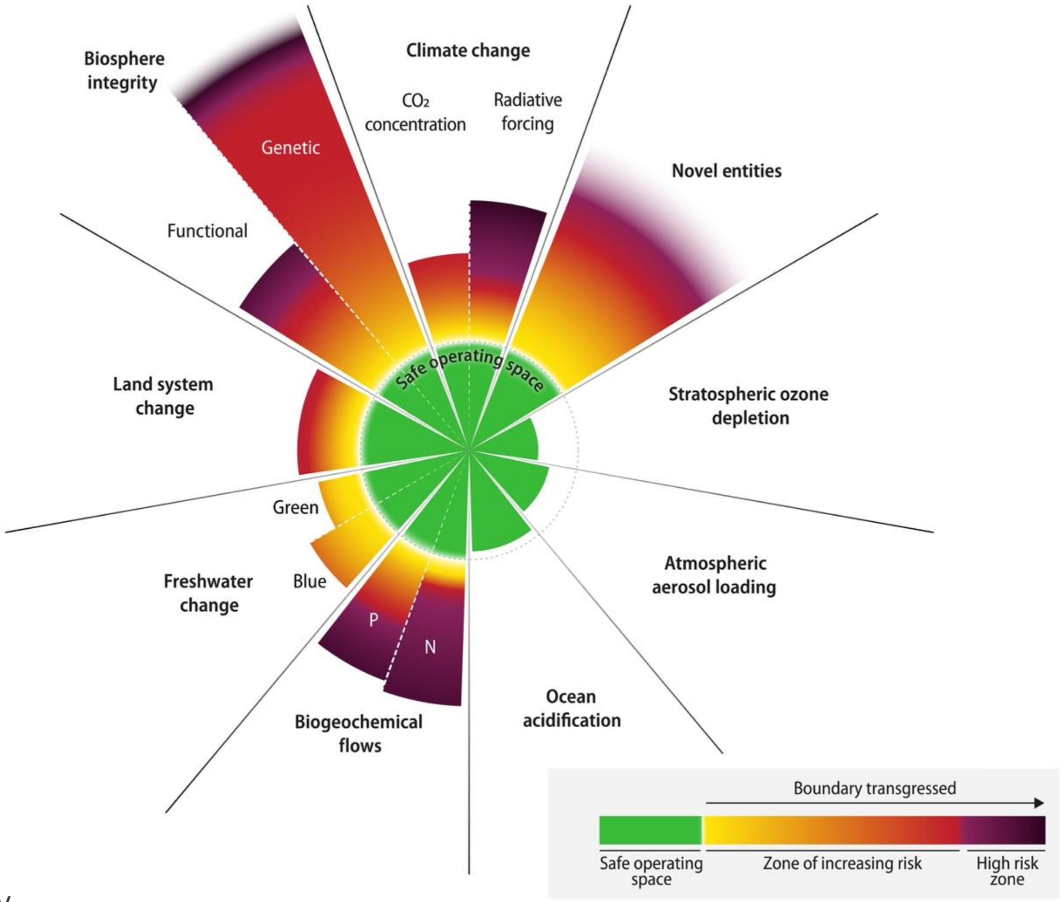
Sustainability & Materials

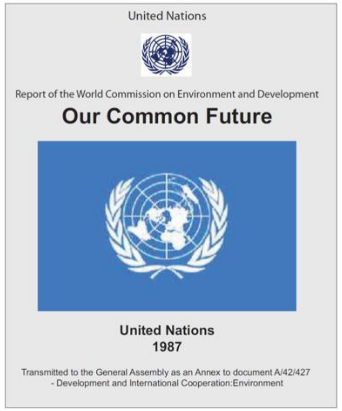
Prof. Tiffany Abitbol

2025

Recap

- Materials & resources
- Sustainability development
- 3 pillars/ 3 capitals
- Planetary boundaries – 6/9 surpassed; closer look at novel entities, the most elusive

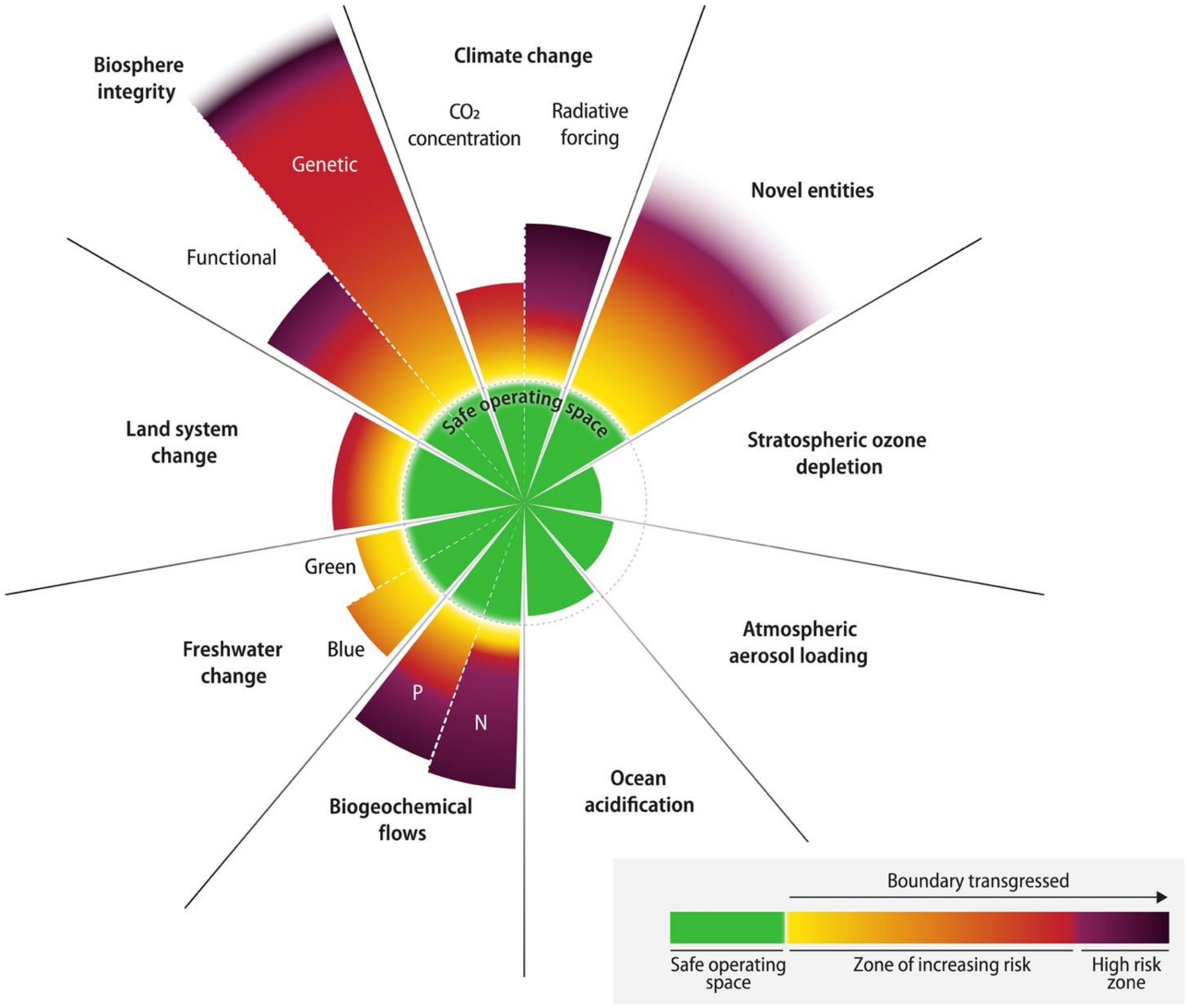




"development that meets the needs of today without compromising the ability of future generations to meet their own needs"

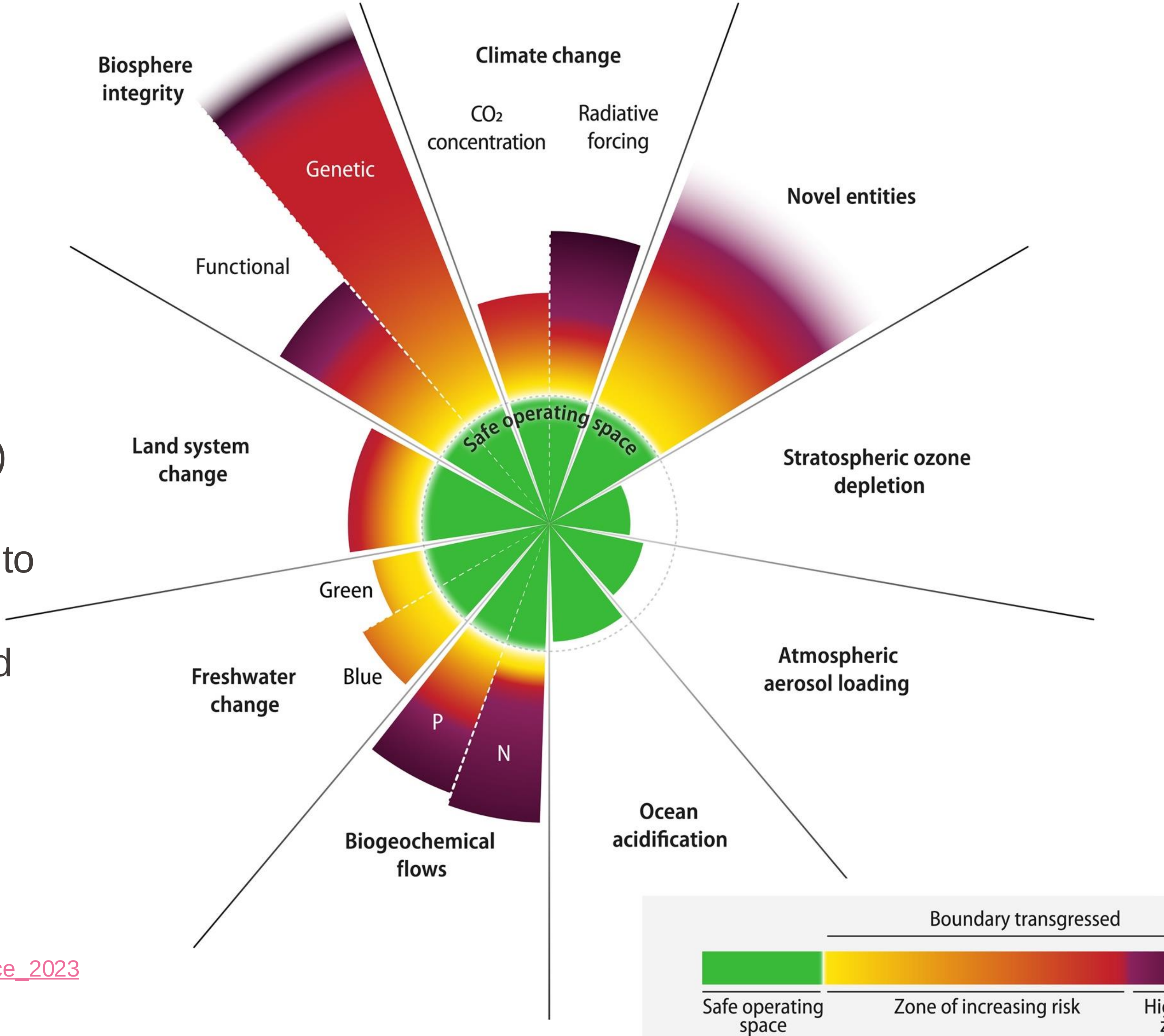
The zones

- Safe operating space (green): low risk, Earth’s systems functioning within natural limits
- Zone of increasing risk/zone of uncertainty: exceeding safe limits but some capacity for adaptation, early signs of system instability, increasing risks of irreversible damage
- High risk zone: a critical threshold may be crossed leading to irreversible damage, collapse, or major shifts



Current View (2023)

- Biodiversity loss
- ~~Novel entities – last week~~
- Ocean acidification (C cycle)
- Climate change (via anthropogenic disturbances to the C cycle)
- Biogeochemical flows (P and N cycles)



Earth beyond six of nine planetary boundaries_Science_2023

Table 1. Proposed planetary boundaries.

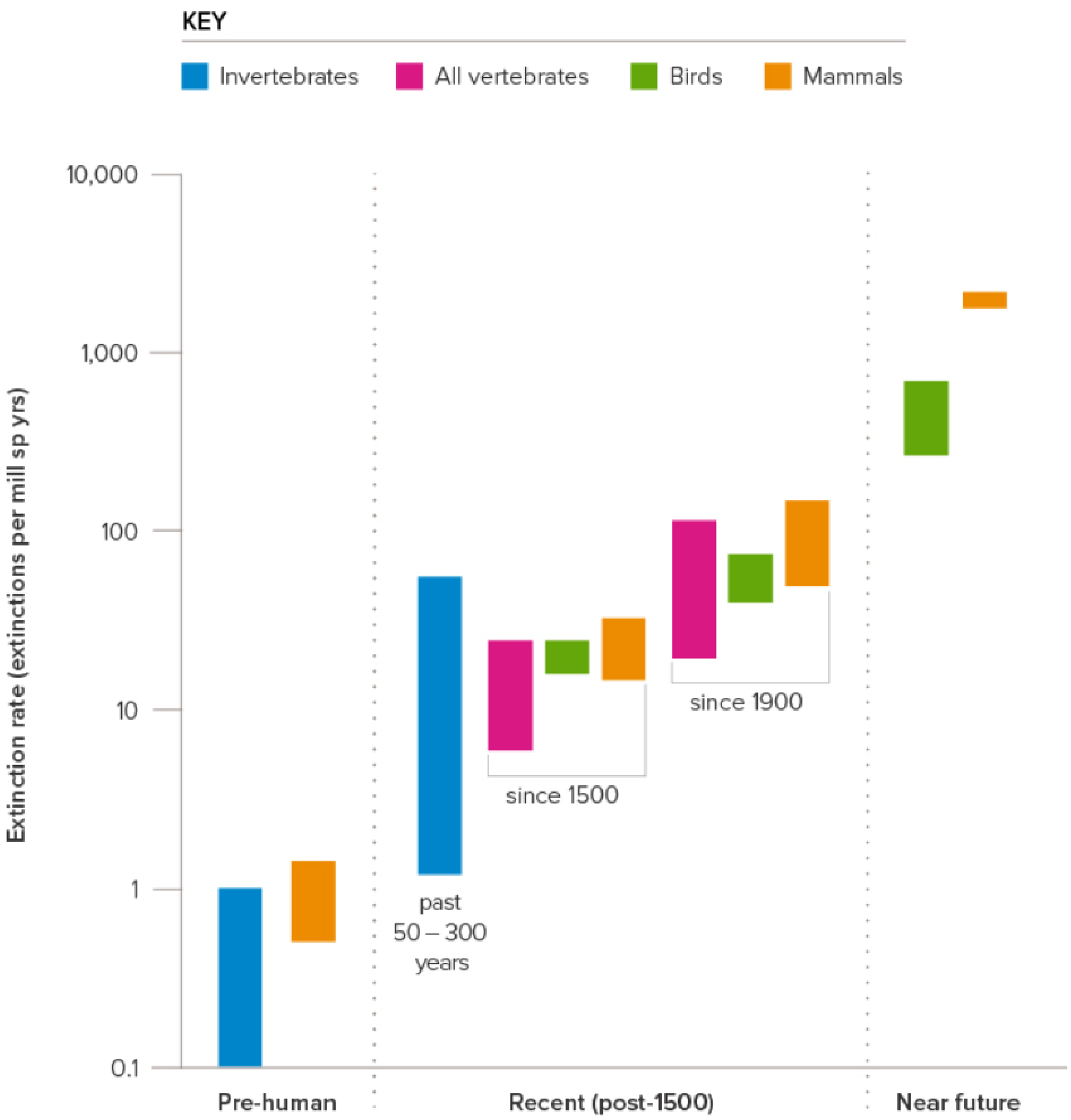
Earth System process	Control variable	Threshold avoided or influenced by slow variable	Planetary Boundary (zone of uncertainty)	State of knowledge*
Rate of biodiversity loss	Extinction rate, extinctions per million species per year (E/MSY)	Slow variable affecting ecosystem functioning at continental and ocean basin scales. Impact on many other boundaries—C storage, freshwater, N and P cycles, land systems. Massive loss of biodiversity unacceptable for ethical reasons.	<10 E/MSY (10–100 E/MSY)	1. Incomplete knowledge on the role of biodiversity for ecosystem functioning across scales. 2. Thresholds likely at local and regional scales. 3. Boundary position highly uncertain.

Ecology and Society 14(2): 32
http://www.ecologyandsociety.org/vol14/iss2/art32/

Biodiversity loss

- Known recent extinctions only a small fraction of total species
- Bird, mammal, amphibian extinctions since 1500 is 1.6%, 1.9%, and 2.1% respectively
- **Extinction rate** for any group of organisms **is the number of extinctions that would occur each year among a million species** (or in 100 years among 10,000 species)
- This rate is estimated to be 100× faster or more than pre-human times
- Impacts difficult to predict but can be catastrophic, e.g., food chain

Graph & text



Human-caused extinctions over time

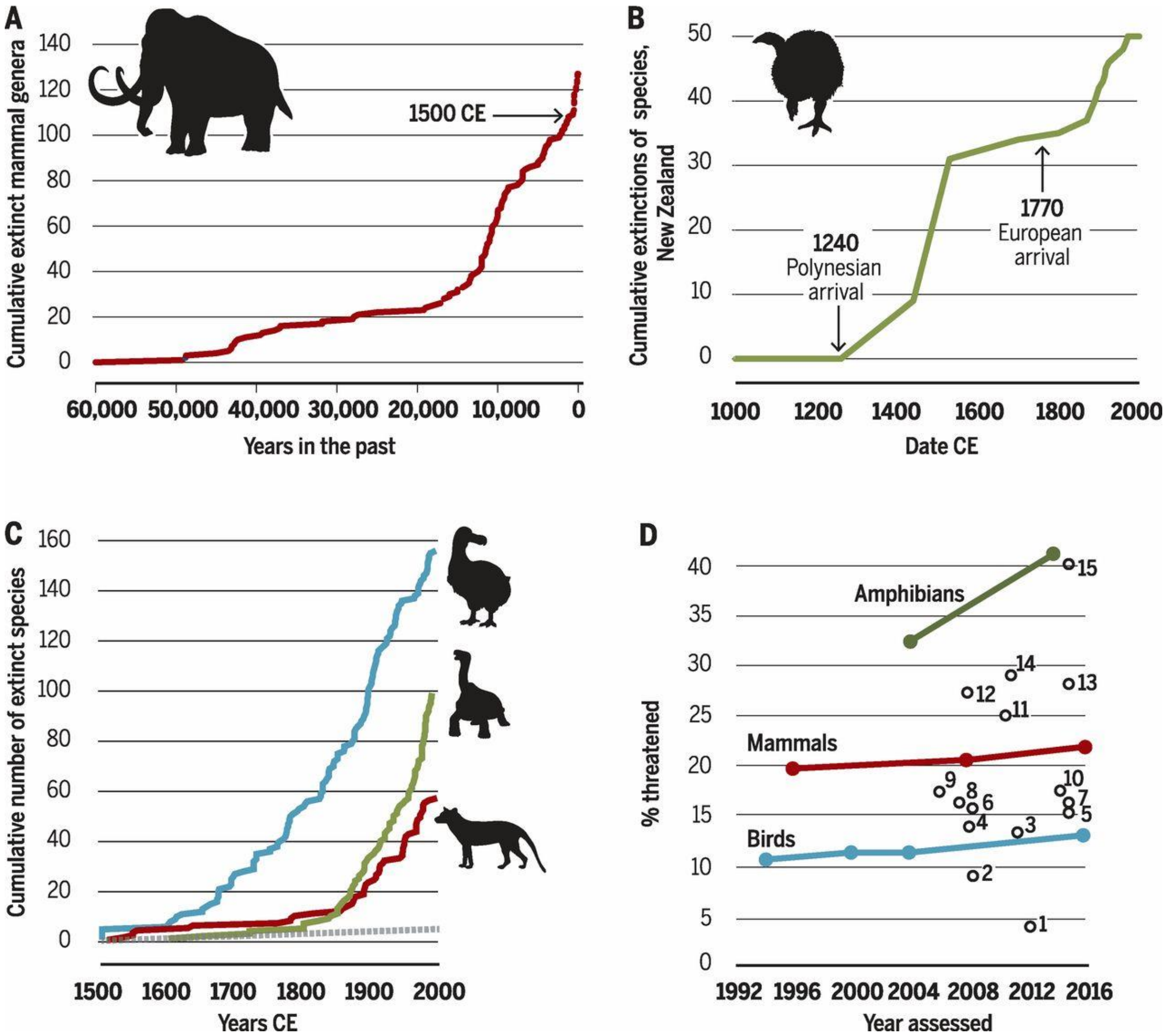


Figure A: mammal genera
Genera ranks above species (species of horses and zebras are in the same genera)

Figure B: vertebrates in New Zealand

Figure C: birds, mammals, other

Figure D: recent trends in % threatened

Christopher N. Johnson *et al.*, Biodiversity losses and conservation responses in the Anthropocene. *Science* **356**,270-275(2017).DOI:10.1126/science.aam9317

Current View (2023)

- ~~Biodiversity loss~~
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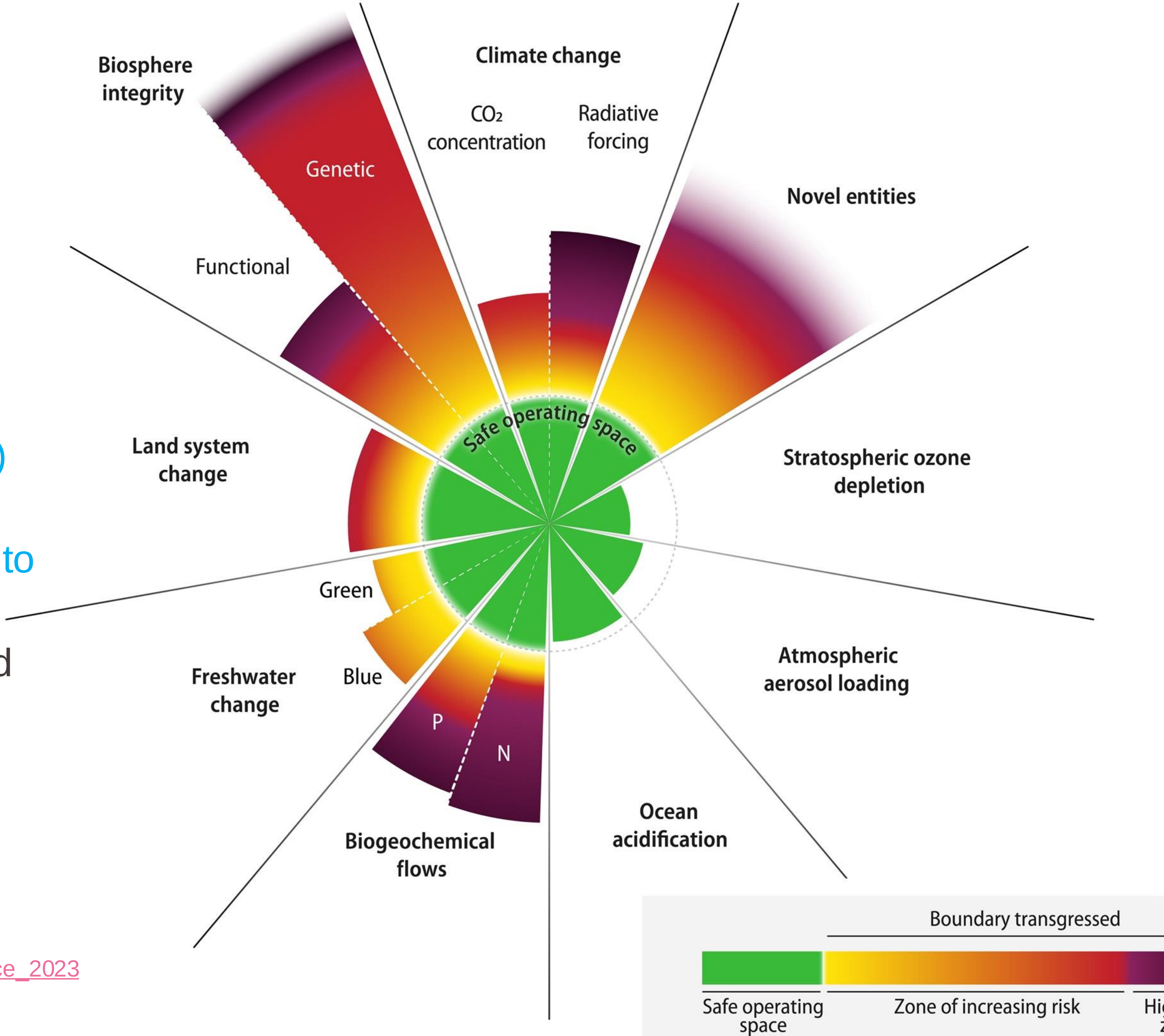
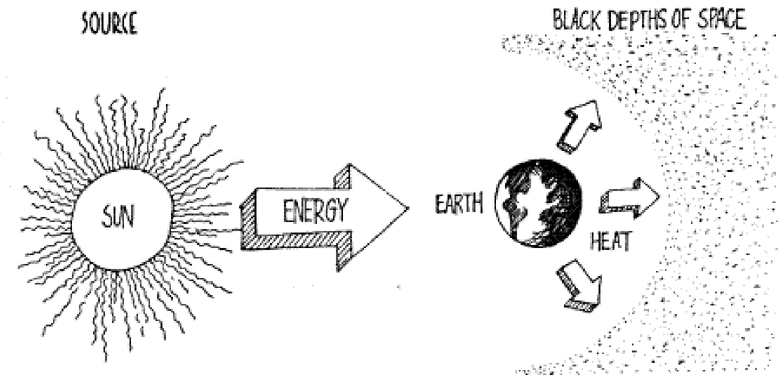


Earth beyond six of nine planetary boundaries_Science_2023

Climate change and ocean acidification : Anthropogenic CO_2

Climate change:



- Atmospheric CO_2 concentration
- *Radiative forcing - heat in versus heat out, complex depending on many factors (clouds, polar ice, gases in the atmosphere);* ***energy balance of the Earth (W/m^2) – tells you how much energy is added or removed from the each m^2 of the earth's surface; positive forcing means more energy trapped – heating (e.g., due to GHGs), vice versa (e.g., due to aerosols reflecting sunlight)***

Ocean acidification:

- *Related to CO_2 dissolved in water*

Table 1. Proposed planetary boundaries.

Earth System process	Control variable	Threshold avoided or influenced by slow variable	Planetary Boundary (zone of uncertainty)	State of knowledge*
Climate change	Atmospheric CO_2 concentration, ppm; Energy imbalance at Earth's surface, W m^{-2}	Loss of polar ice sheets. Regional climate disruptions. Loss of glacial freshwater supplies. Weakening of carbon sinks.	Atmospheric CO_2 concentration: 350 ppm (350–550 ppm) Energy imbalance:+1 W m^{-2} (+1.0–+1.5 W m^{-2})	1. Ample scientific evidence. 2. Multiple sub-system thresholds. 3. Debate on position of boundary.
Ocean acidification	Carbonate ion concentration, average global surface ocean saturation state with respect to aragonite (Ω_{arag})	Conversion of coral reefs to algal-dominated systems. Regional elimination of some aragonite- and high-magnesium calcite-forming marine biota Slow variable affecting marine carbon sink.	Sustain ≥80% of the pre-industrial aragonite saturation state of mean surface ocean, including natural diel and seasonal variability (≥80%–≥70%)	1. Geophysical processes well known. 2. Threshold likely. 3. Boundary position uncertain due to unclear ecosystem response.

Ecology and Society 14(2): 32
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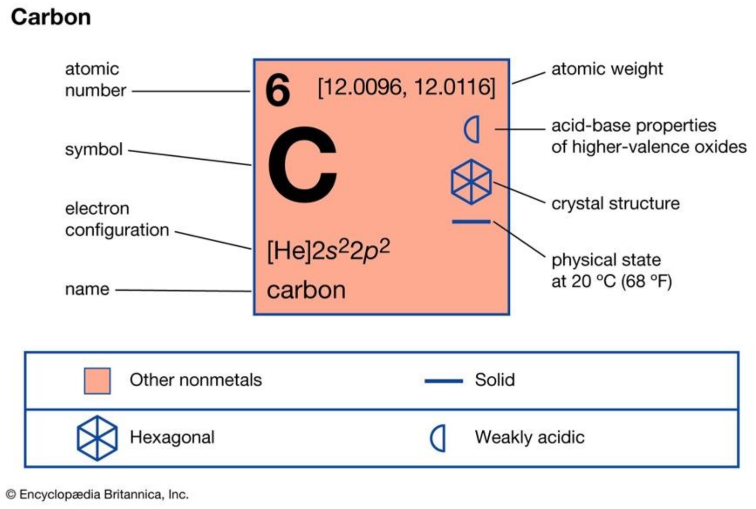
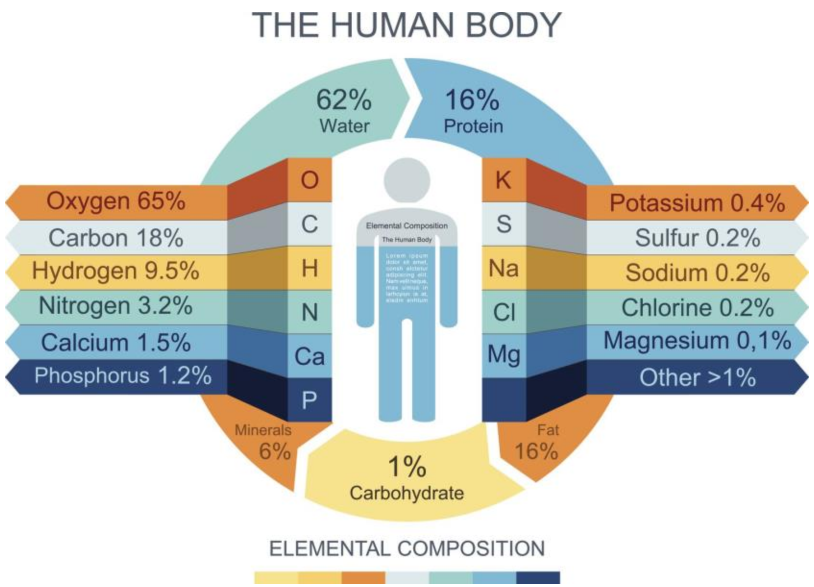
Carbon





Essential to the planet:

- Regulates the Earth's temperature
- Fast cycle (year-scale) vs. slow cycle (million-year scale)

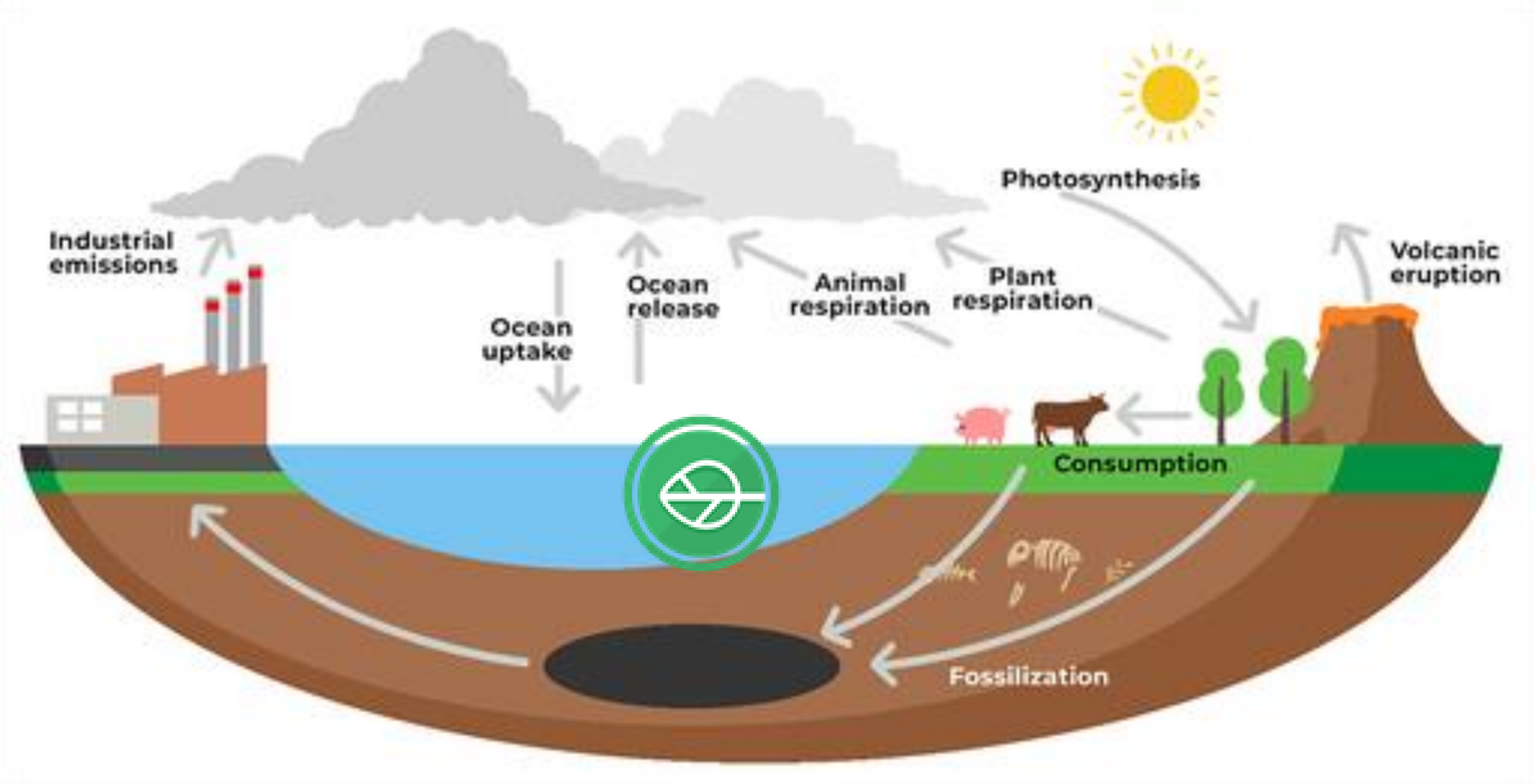
Essential to life:

- 18.5% of the human body (e.g., DNA/RNA, essential to growth and replication)
- Source of energy: energy is released when carbon bonds are broken to drive cellular processes
- Stuff of life: carbon is consumed and restructured into useful biomolecules needed for organisms to grow and thrive

Essential to technology/development:

- Energy/fuel: wood, gas, oil
- Stuff of materials: plastic, steel, ink, diamond, graphite, etc.,

Carbon and climate



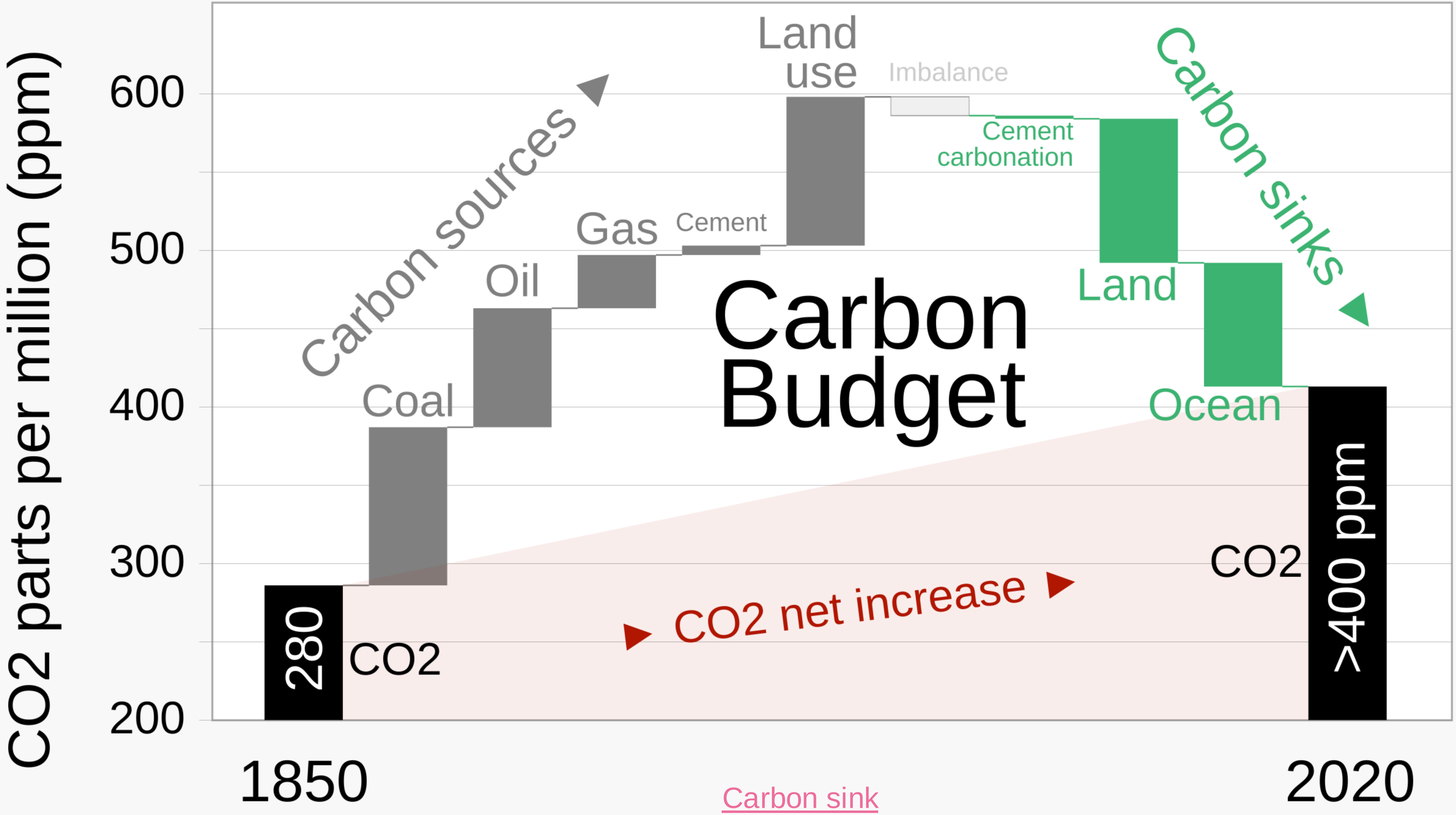
Carbon in the atmosphere is a major regulator of climate: before fossil fuel burning, this concentration was mostly controlled by plants and microorganisms

Carbon - energy currency of the planet

- In a closed system (Spaceship Earth), energy is conserved, and matter is neither created nor destroyed (mostly)
- Carbon as an energy currency
- Present in different **natural carbon pools (**plants, animals, soil, air, water) and cycles between them (How is this currency exchanged between pools?
- Difference between a **pool** and a **sink**? A pool can take in and release carbon, whereas a sink is a type of pool that takes up more carbon than it releases
- Fast and slow cycles

Epcot's Spaceship Earth

Currency of life

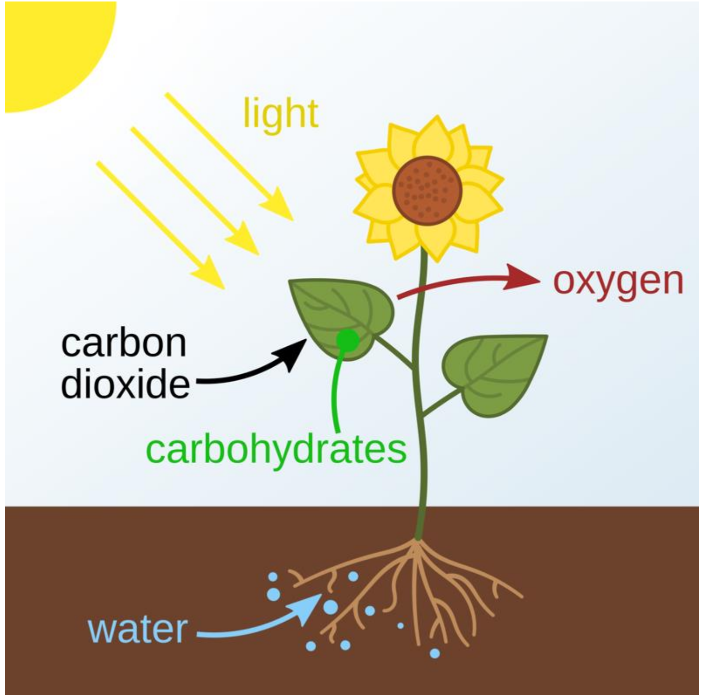


CO2 parts per million (ppm)
600
500
400
300
200
Carbon sources
Coal
Oil
Gas
Cement
Land use
Imbalance
Cement carbonation
Carbon sinks
Land
Ocean
Carbon Budget
280
CO2
CO2 net increase
CO2
>400 ppm
1850
2020

Carbon sink

Energy production

- In most ecosystems, the sun is the source of all energy
- ***Autotrophs*** fix CO_2 from the atmosphere into organic compounds like sugars, lipids, and proteins.
- ***Photoautotrophs,*** plants and microorganisms (algae, cyanobacteria), use photosynthesis to produce biomass
- They absorb specific wavelengths of sunlight using the pigment chlorophyll (or other), converting sunlight to chemical energy (energy stored in bonds)
- ***Heterotrophs*** (like humans) haven't figured out photosynthesis, instead consume these sugars, lipids, and proteins and use the stored energy to power their activities
- Fossil fuels are derived from organic materials, converted by heat and pressure to oil, coal, or natural gas over geologic time "*fossilized sunlight*" – slow cycle



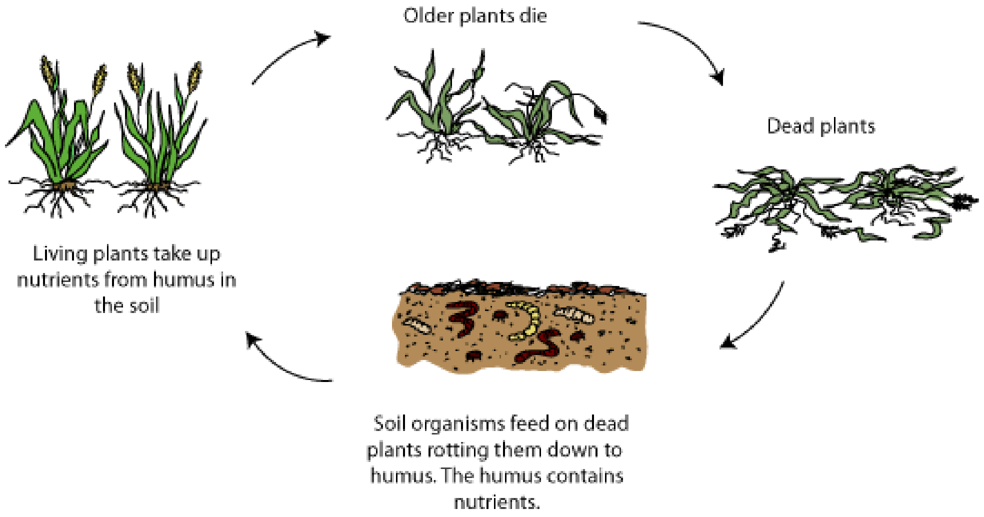
Photosynthesis:
$6CO_2 + 6H_2O$ + light energy $\rightarrow$ $C_6H_{12}O_6$ (glucose) + $6O_2$

Currency of life

Photosynthesis

Energy consumption

- The sugars, lipids, and proteins generated by plants and microbes store energy from the sun in Carbon-Hydrogen (C-H) bonds (chemical energy)
- These are broken down in cells to release energy via *respiration*, and we also break them down from our fuel tanks to release energy via *combustion*
- Although respiration and combustion are very different, they ultimately produce the same result, which is to use oxygen to convert organic compounds containing C-H bonds back into CO_2
- Some organisms use the energy produced by plants directly, some eat organisms that ate plants, some eat organisms that ate organisms that ate plants, and so on; some organisms use a mixture of carbon sources and some use waste products, but ***ultimately food webs lead back to the energy produced by plants and microbes***



Respiration:
$C_6H_{12}O6 + 6O_2 \rightarrow 6CO_2 + 6H_2O$ + chemical energy (ATP)

Currency of life

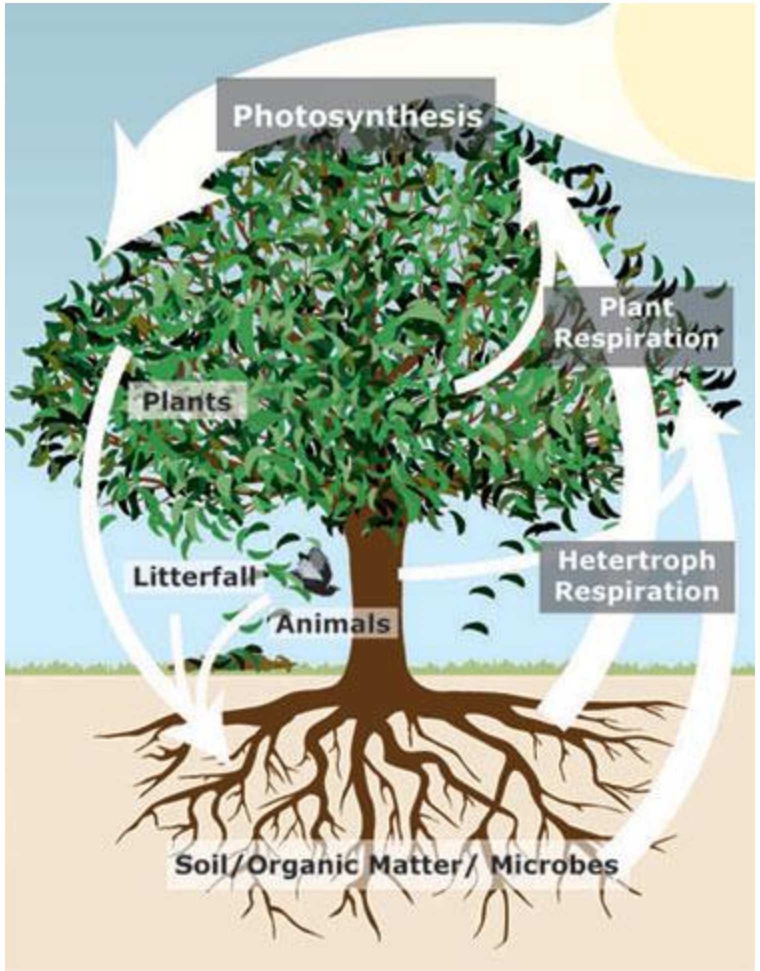
Respiration

Energy balance

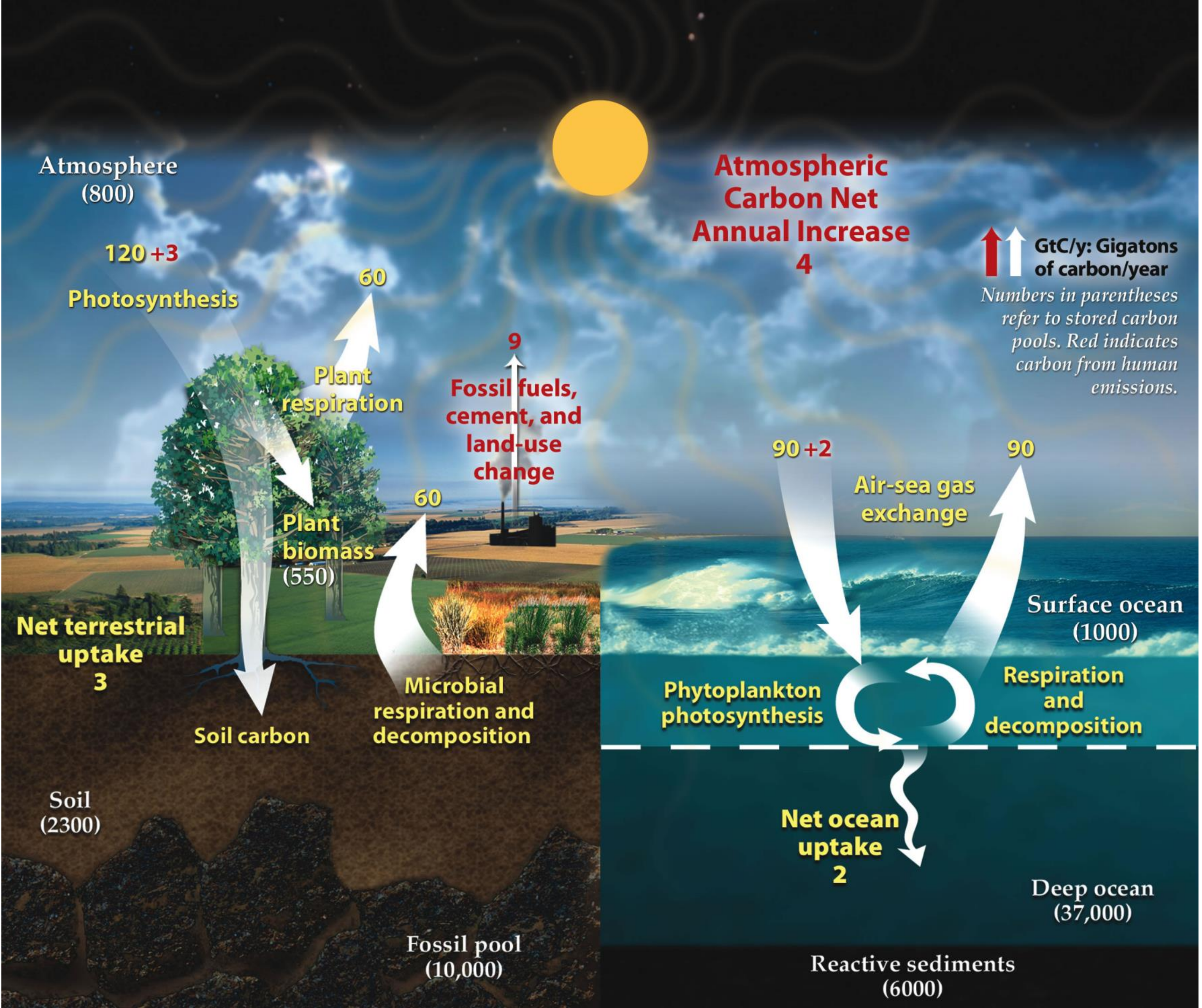
Photosynthesis:
$6CO_2 + 6H_2O$ + light energy → $C_6H_{12}O_6$ (glucose) + $6O_2$

Respiration:
$C_6H_{12}O_6 + 6O_2 \rightarrow 6CO_2 + 6H_2O$ + chemical energy

- Fast cycle – operates in biosphere
- Equations tend to balance over time
- CO_2 fixed by photosynthesis is eventually returned to the atmosphere
- Oxygen and water also tend to balance
- *Net effect of photosynthesis is light energy converted to chemical energy* (sunlight that fuels the entire ecosystem)
- ***Why does burning fossil fuels imbalance the carbon cycle?*** *Hint fast/slow cycles: another question of rate… https://earthobservatory.nasa.gov/features/CarbonCycle*



Currency of life



Global reservoirs/pools of carbon:
oceans (the largest reservoir), **geological reserves of fossil fuels**, the terrestrial surface (**plants and soil**, mainly), and the **atmosphere**.

Fast carbon cycle:
- Yellow (natural fluxes)
- Red (anthropogenic)
- White (stored carbon)

Slow carbon cycle (not shown)
- Volcanic/tectonic activities

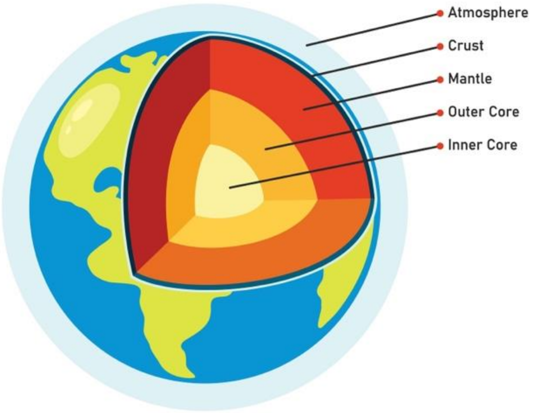
Global warming accelerates soil respiration_Nature_2023

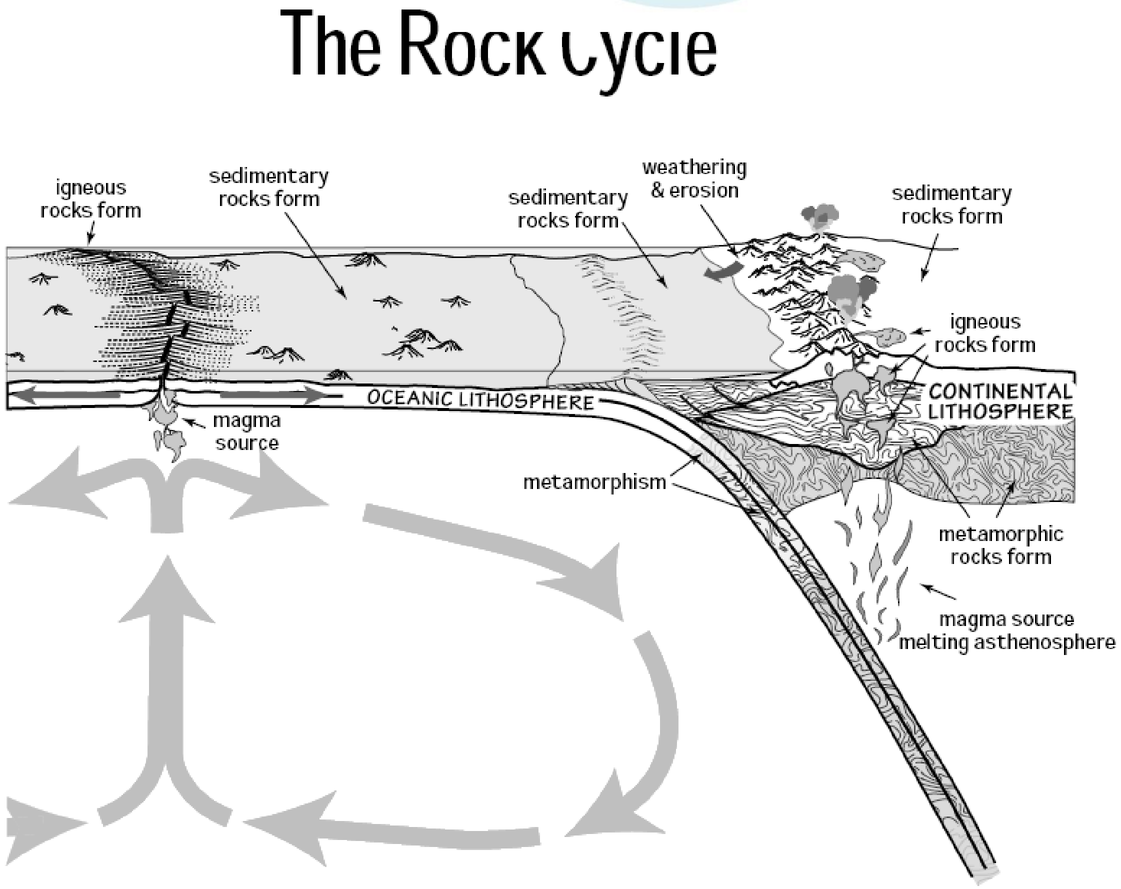
Carbon cycle

EPFL

The slow carbon cycle

- Moves carbon through crust, between rocks, soil, ocean, and atmosphere (10-100 million tonnes of carbon per year)
- Carbon in the ocean precipitates to the ocean floor where it can form sedimentary rock and be subducted into the Earth’s mantle
- Mountain building processes result in the return of this geologic carbon to the Earth's surface
- Weathering of rocks returns carbon to the atmosphere and ocean
- Exchange between the ocean and atmosphere can take centuries
- Weathering of rocks can take millions of years





Slow carbon cycle

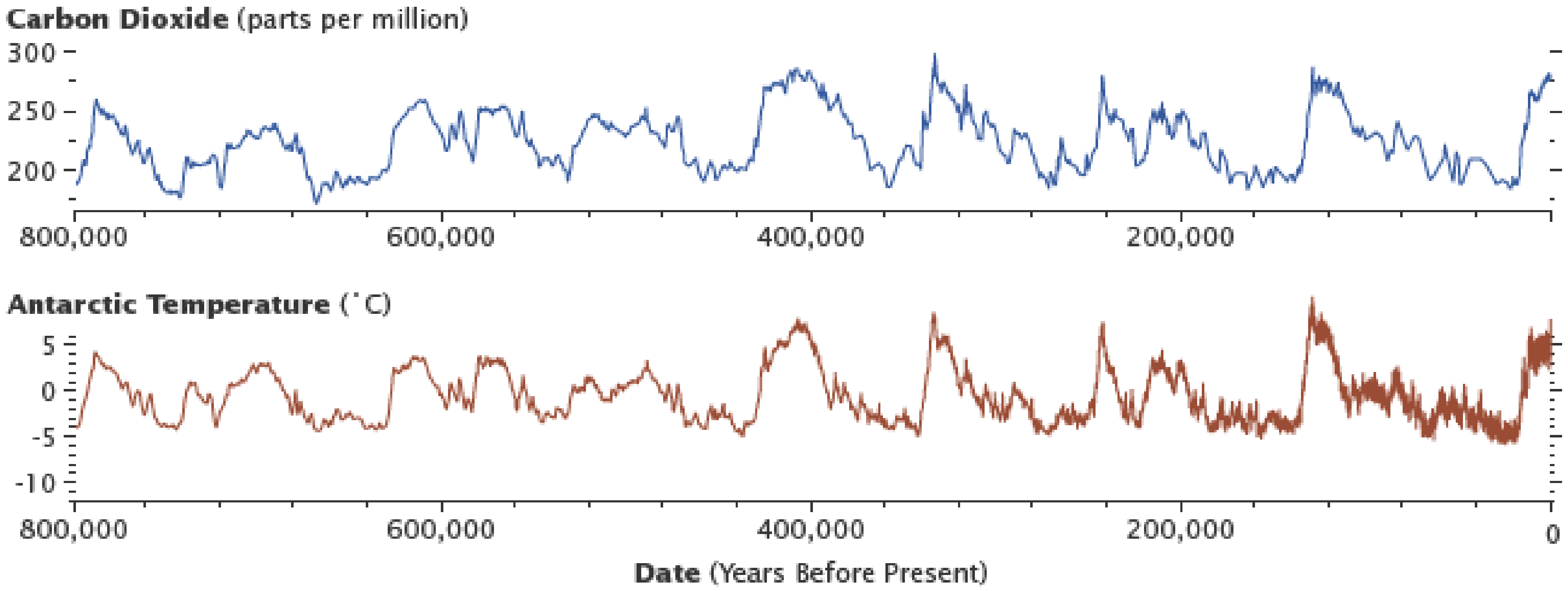
Biogenic vs. Fossil Fuel Carbon

- Biogenic carbon
  - Fast cycle (years)
  - Released from the decay or are burning of recently living organisms
  - Generally, balanced reactions, but can still lead to a net increase in CO_2 emissions if, for example, burning and deforestation outpace regrowth

- Fossil carbon
  - Slow cycle
  - Released from carbon stored for millions and millions of years
  - Cannot be replaced at the rate it is depleted
  - Net increase in CO_2 emissions

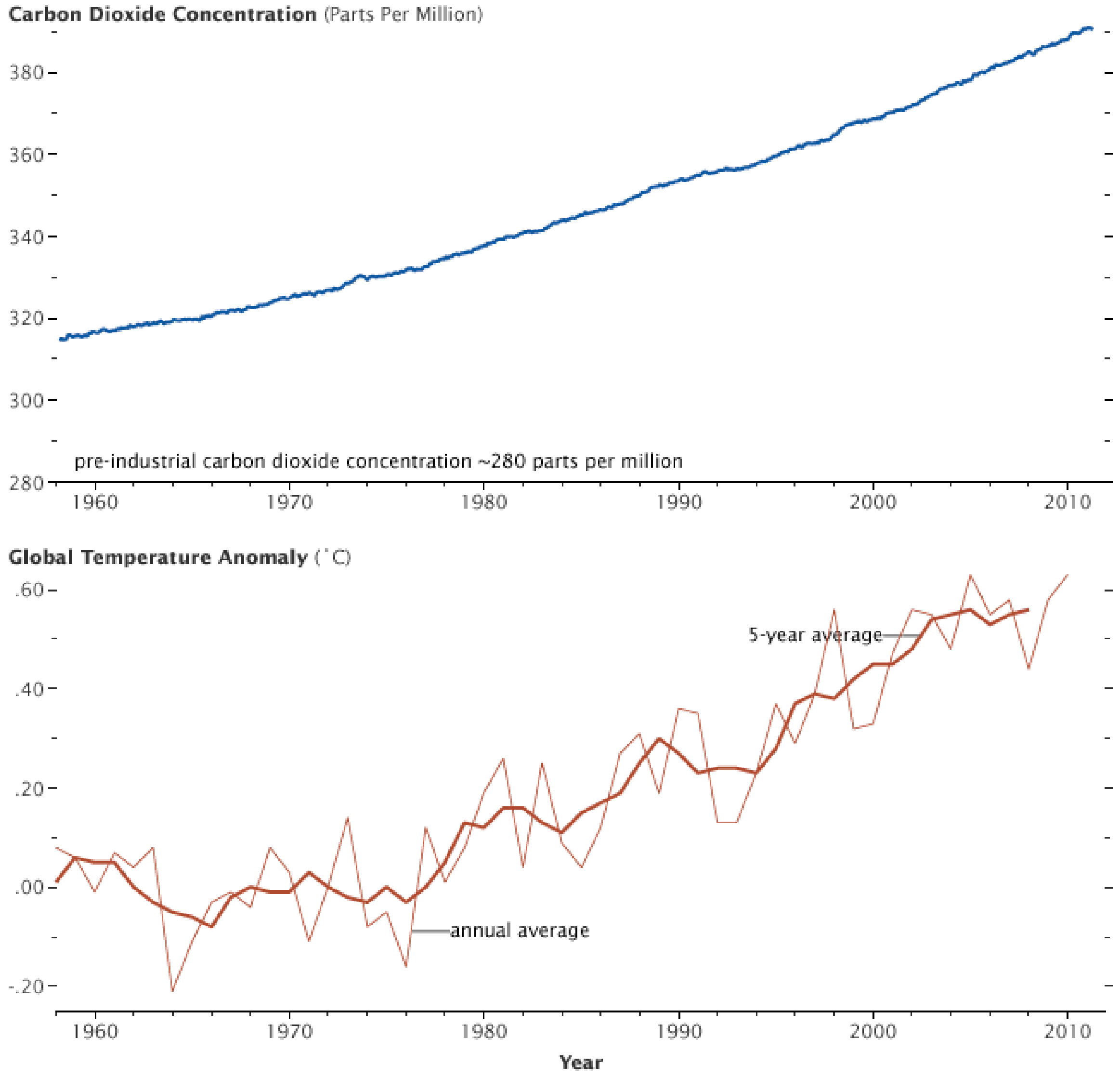
Natural variations in the carbon cycle

- Left-unperturbed, the planet maintains a relatively stable concentration of CO_2 in the atmosphere, with a close correspondence to temperature



Nasa_ Carbon cycle

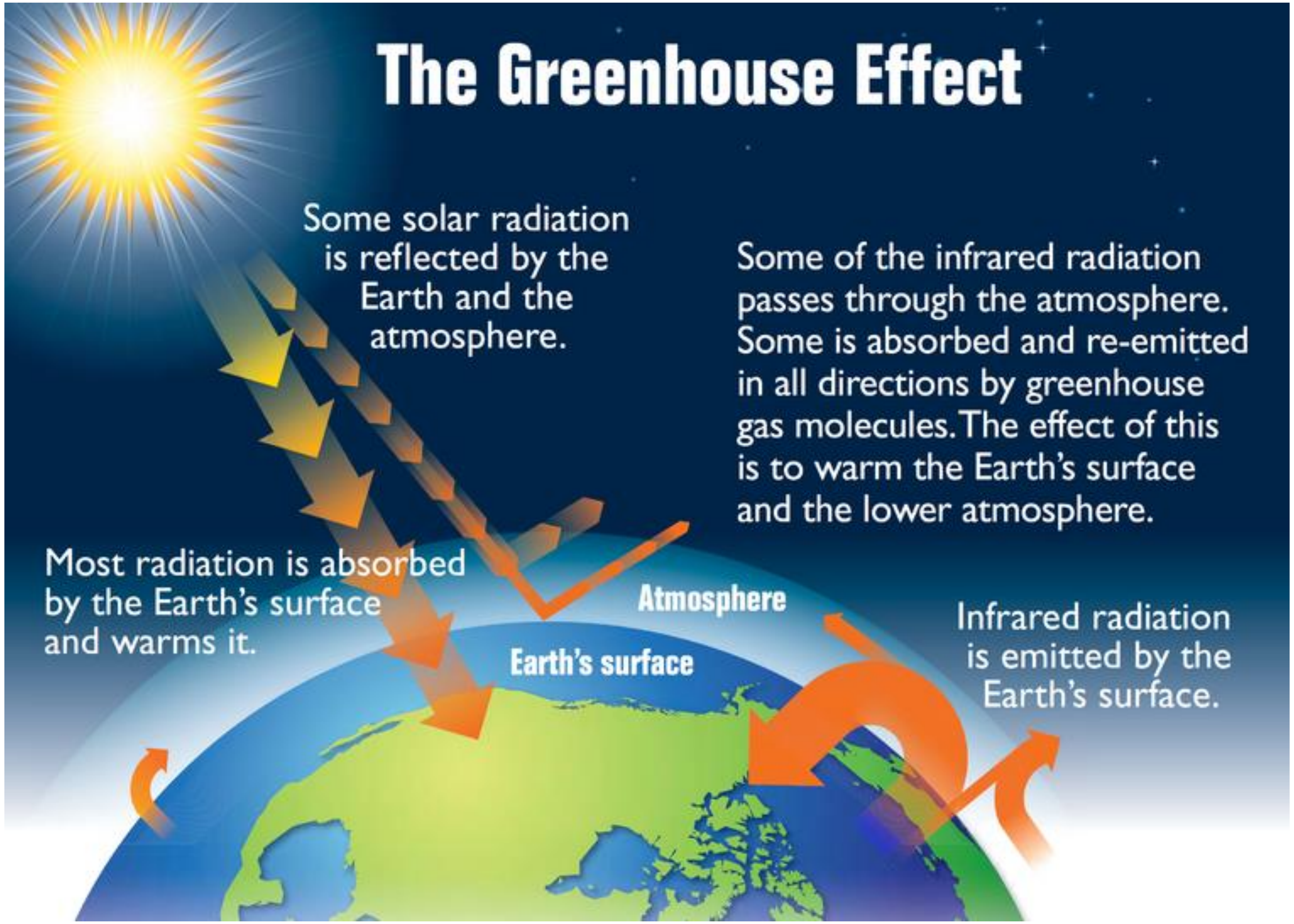
What if we perturb the cycle?



- Slow cycle takes ca. 100 million years, whereas the fast cycle takes ca. 10-100 years (living thing lifespan)
- By burning fossil fuels, we shift carbon from the slow cycle into the fast cycle (carbon from the Earth's crust is extracted and burned for energy)
- Corresponding increase in *global temperature anomaly = departure from along term average*

[Nasa _ Carbon cycle]

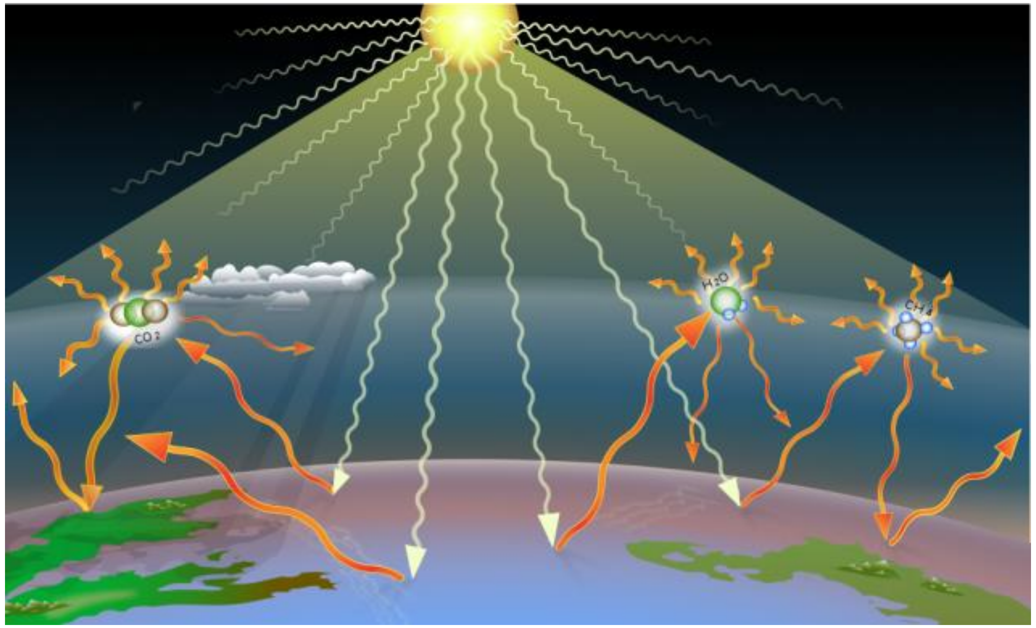
Greenhouse effect – it's not global warming!

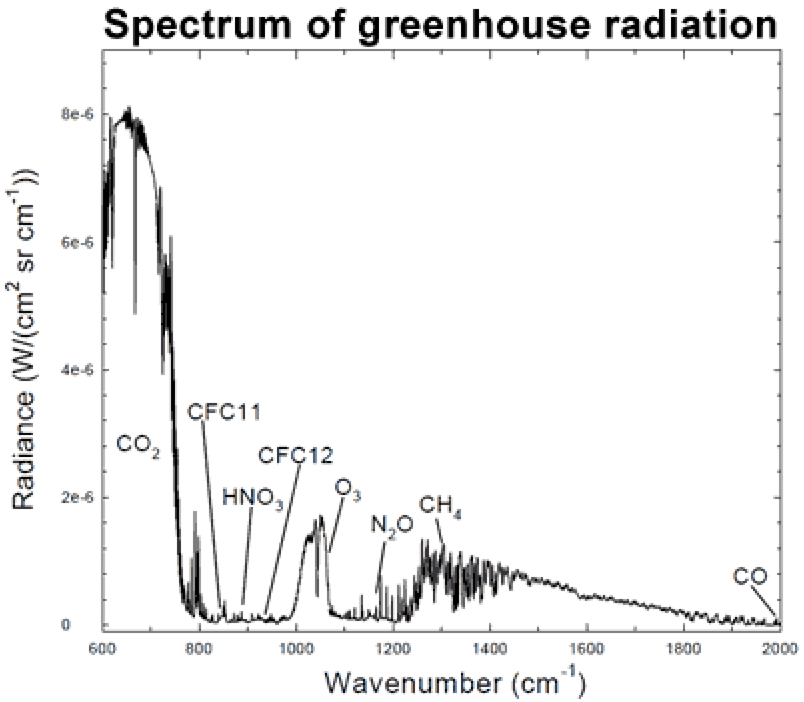


- Not particularly related to green light
- "Blanket" of gases around the planet
- Naturally part of makeup of the atmosphere
- Sunlight absorbed by earth and re-emitted as infrared (heat)
- Some infrared passes through the atmosphere, some is absorbed & re-emitted by greenhouse gases (GHGs) in all directions to heat the Earth's surface and lower atmosphere
- "Goldilocks planet" – not too hot or too cold
- Helps maintain temperature at 15 °C (avg)

https://climate.nasa.gov/faq/19/what-is-the-greenhouse-effect/
https://energyeducation.ca/encyclopedia/Greenhouse_effect

Global warming





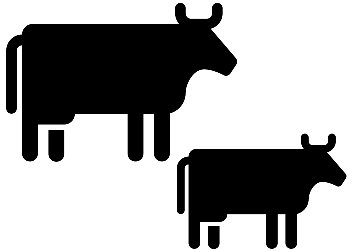
- Earth absorbs sunlight and reradiates it as infrared (heat)
- GHGs absorb specific infrared wavelengths
- If unimpeded, infrared travels through the atmosphere and back into space
- Excess GHGs (like CO_2) absorb infrared light, re-emits it in all directions, leading to warming beyond the greenhouse effect – global warming

Global warming

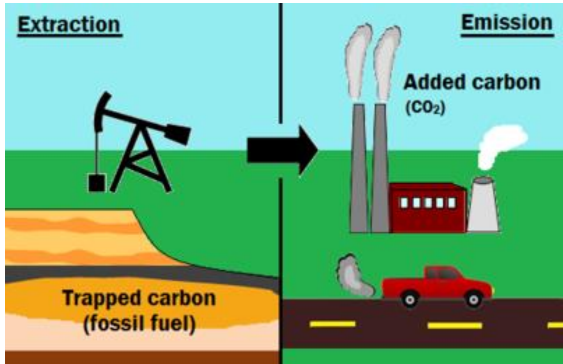
Greenhouse gases (GHGs)

Gases that trap heat in the atmosphere:

- **Carbon dioxide (CO_2)** – *burning fossil fuels, solid waste, trees, biological materials, chemical reactions (cement manufacture)*
- **Methane (CH_4)** – *production/transport of coal, natural gas, oil, agriculture/livestock emissions, decay of organic waste in municipal solid waste landfills*



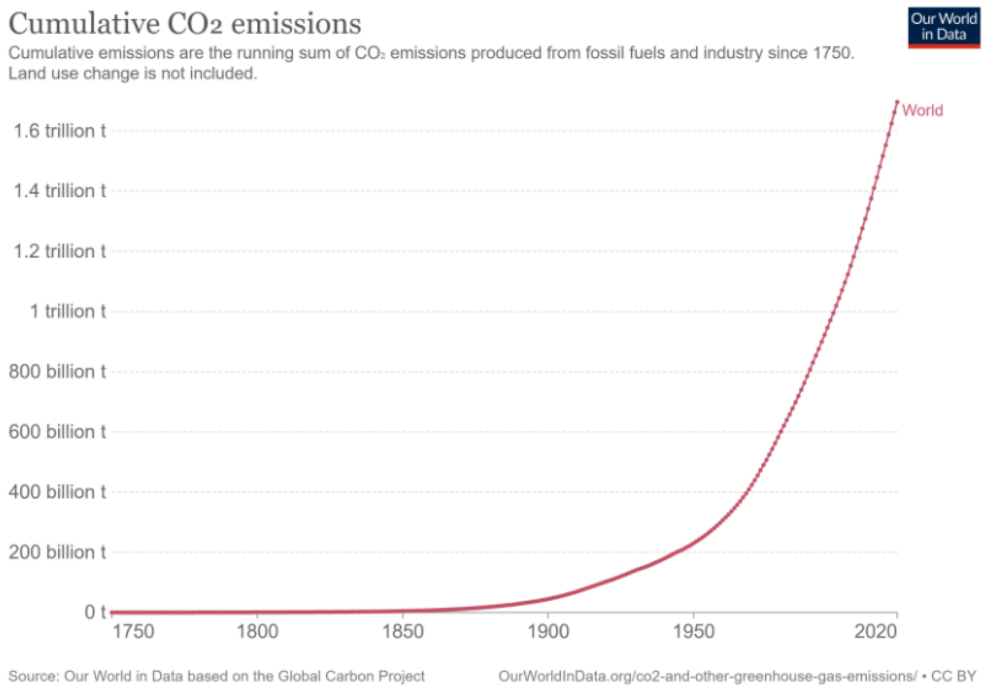
- **Nitrous oxide (N_2O)** – *agriculture, fuel combustion, wastewater management, and industrial processes*
- **Fluorinated gases** – *various household, commercial, industrial uses, emitted at lower amounts but have a high **global warming potential** (GWP), for a given amount of mass trap way more heat than CO_2*

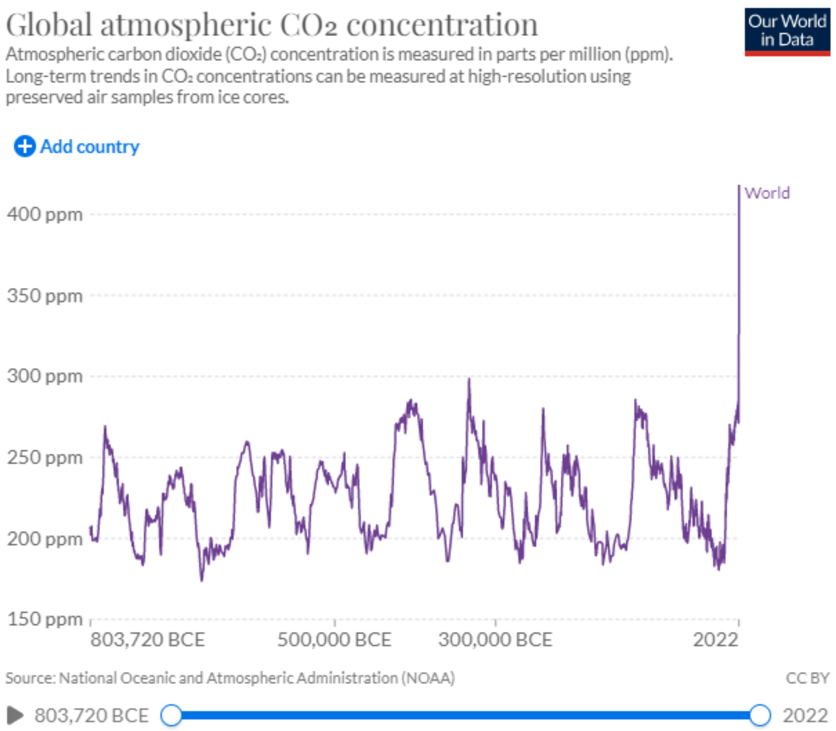


https://www.epa.gov/ghgemissions/overview-greenhouse-gases
https://energyeducation.ca/encyclopedia/Anthropogenic_carbon_emissions

Anthropogenic activities related to carbon emissions

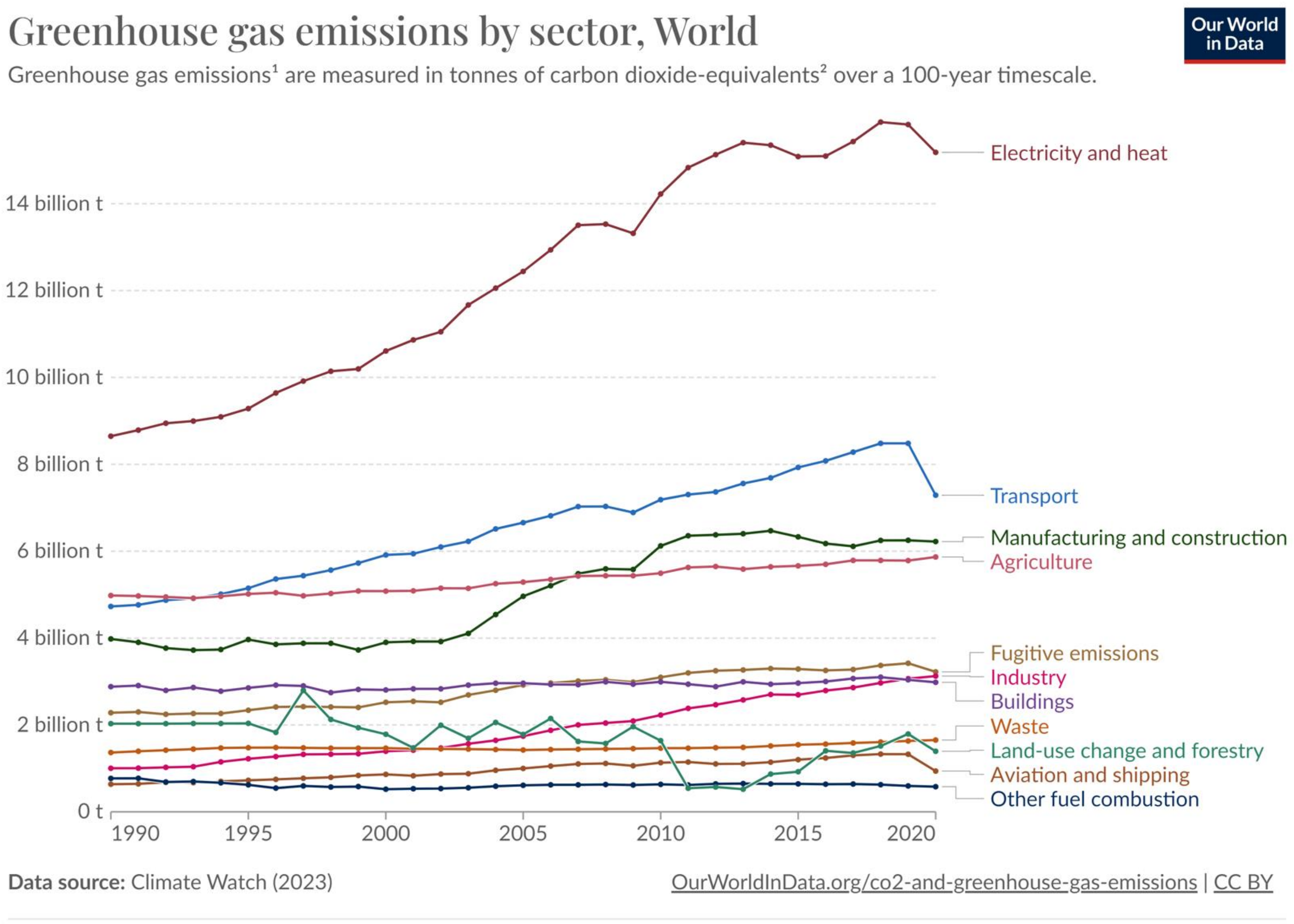
- CO_2 emissions associated with human activity (GHG! Climate change!) Global warming!
- Most of the increase occurring after 1950





https://ourworldindata.org/co2-and-greenhouse-gas-emissions

Examples GHG emissions by sector



Currently, construction sector associated with ≈ 40% of global carbon emissions (Industry and Buildings)

Embodied carbon in building sector materials

- Approx. 30 billion tonnes of concrete used annually
- Why? Cheap, easy to make, good properties
- Concrete is a composite made by adding sand and gravel to cement, whisking the mixture with water and pouring it into molds before it dries (simplified!)
- Making the cement is the most carbon-intensive part: fossil fuels are used to heat a mixture of limestone and clay to more than 1,400 °C in a kiln → approx. 600 kg CO_2/tonne cement

Numbers from: Concrete needs to lose its colossal carbon footprint; 2021

Table 1. Proposed planetary boundaries.

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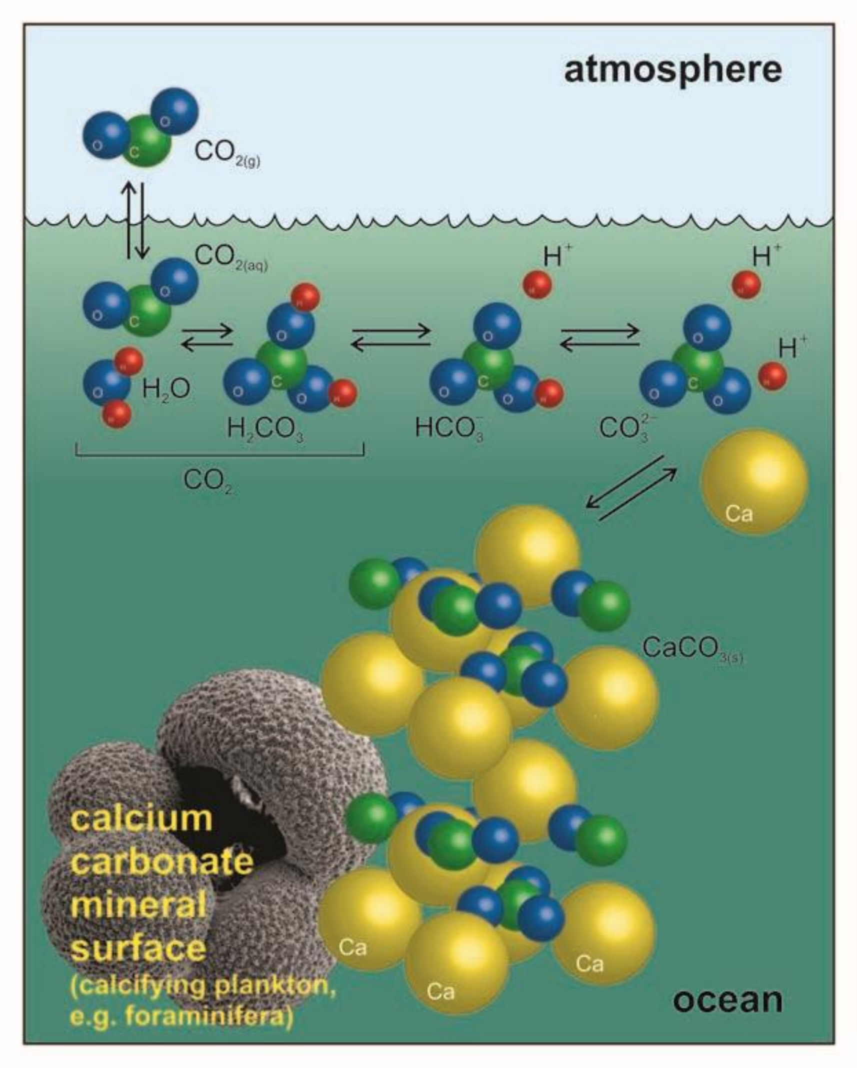
Ocean acidification	Carbonate ion concentration, average global surface ocean saturation state with respect to aragonite (Ω_{arag})	Conversion of coral reefs to algal-dominated systems. Regional elimination of some aragonite- and high-magnesium calcite-forming marine biota Slow variable affecting marine carbon sink.	Sustain ≥80% of the pre-industrial aragonite saturation state of mean surface ocean, including natural diel and seasonal variability (≥80%–≥70%)	1. Geophysical processes well known. 2. Threshold likely. 3. Boundary position uncertain due to unclear ecosystem response.

Aragonite is a crystal form of $CaCO_3$

Ecology and Society 14(2): 32
http://www.ecologyandsociety.org/vol14/iss2/art32/

Ocean acidification



ocean-acidification

(1) $CO_2 + H_2O \leftrightarrow H_2CO_3$ *Carbonic acid*

(2) $H_2CO_3 \leftrightarrow HCO_3^- + H^+$ *Bicarbonate*

(3) $HCO_3^- \leftrightarrow CO_3^{2-} + H^+$ *Carbonate*

BUFFERING EFFECT:

(4) $CO_{2(aq)} + CO_3^{2-} + H_2O \leftrightarrow 2HCO_3^-$

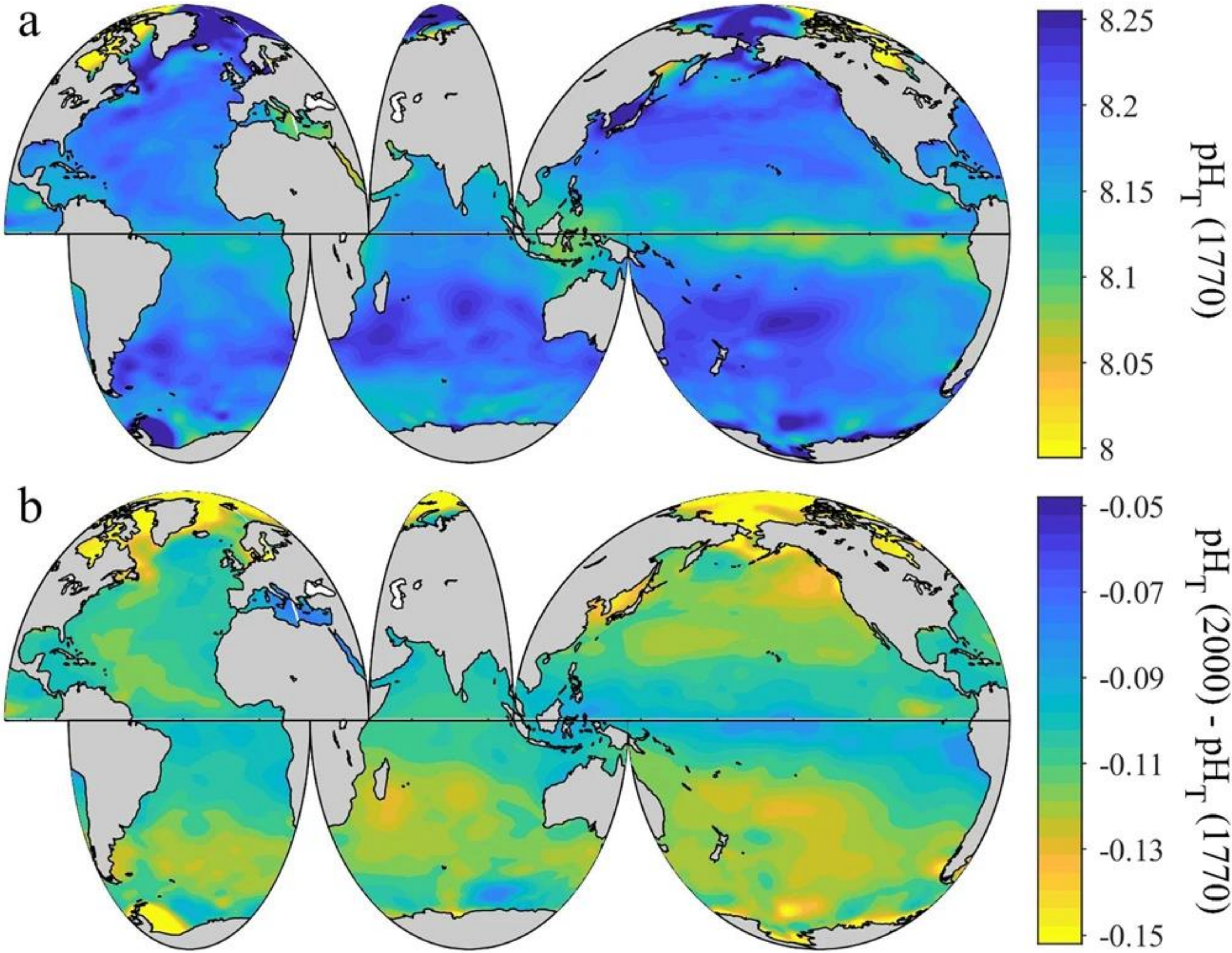
Not all CO_2 dissociates into carbonic acid, some is **neutralized** by carbonate ions, so the drop in pH is not as large as you might expect

ACIDIFICATION (with excess carbon dioxide):

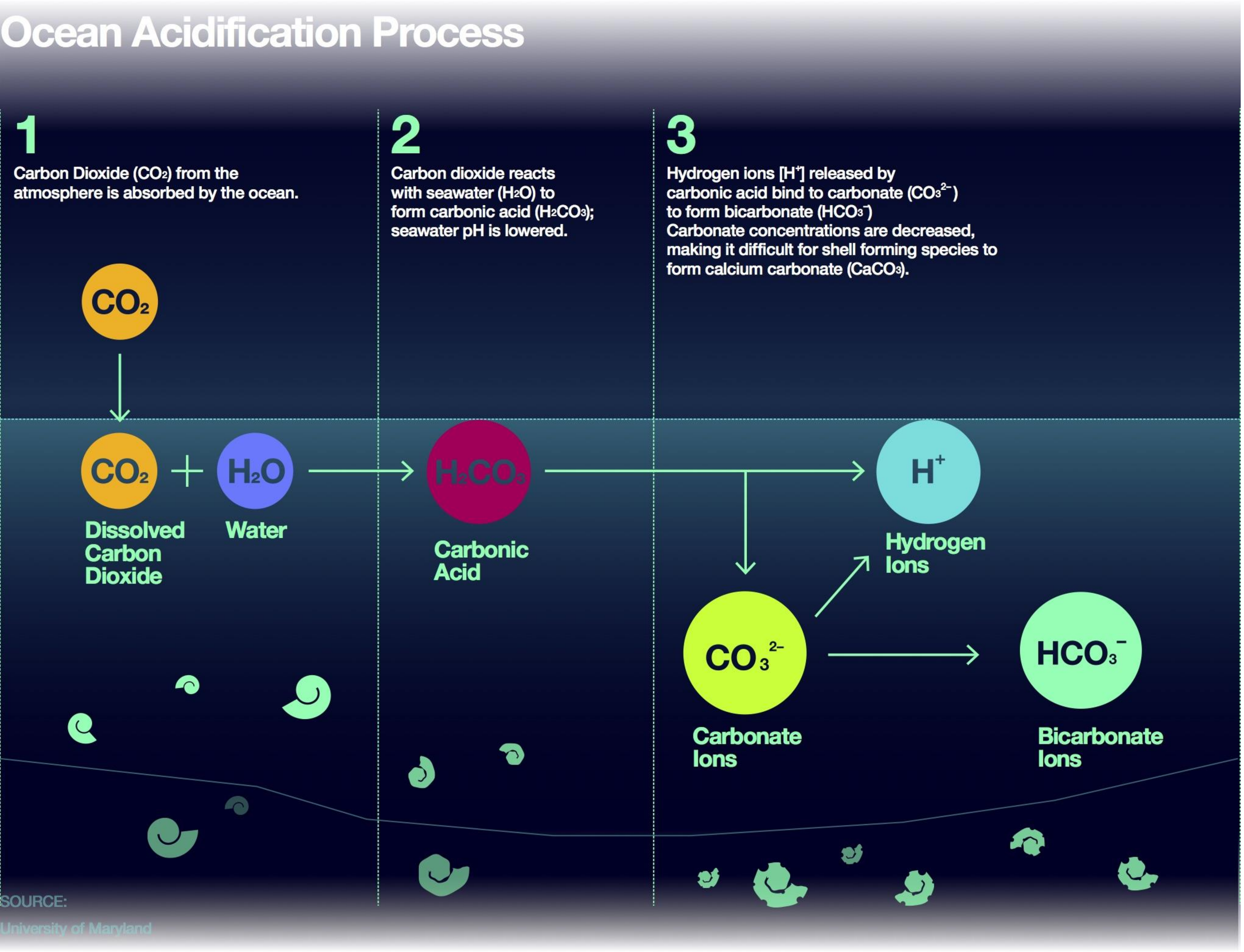
Under acidic conditions/excess CO_2, bicarbonate is dominant because the acid shifts (reaction 3) toward more bicarbonate and less carbonate.

EPFL

Ocean acidification



Jiang, LQ., Carter, B.R., Feely, R.A. *et al.* Surface ocean pH and buffer capacity: past, present and future. *Sci Rep* **9**, 18624 (2019). https://doi.org/10.1038/s41598-019-55039-4

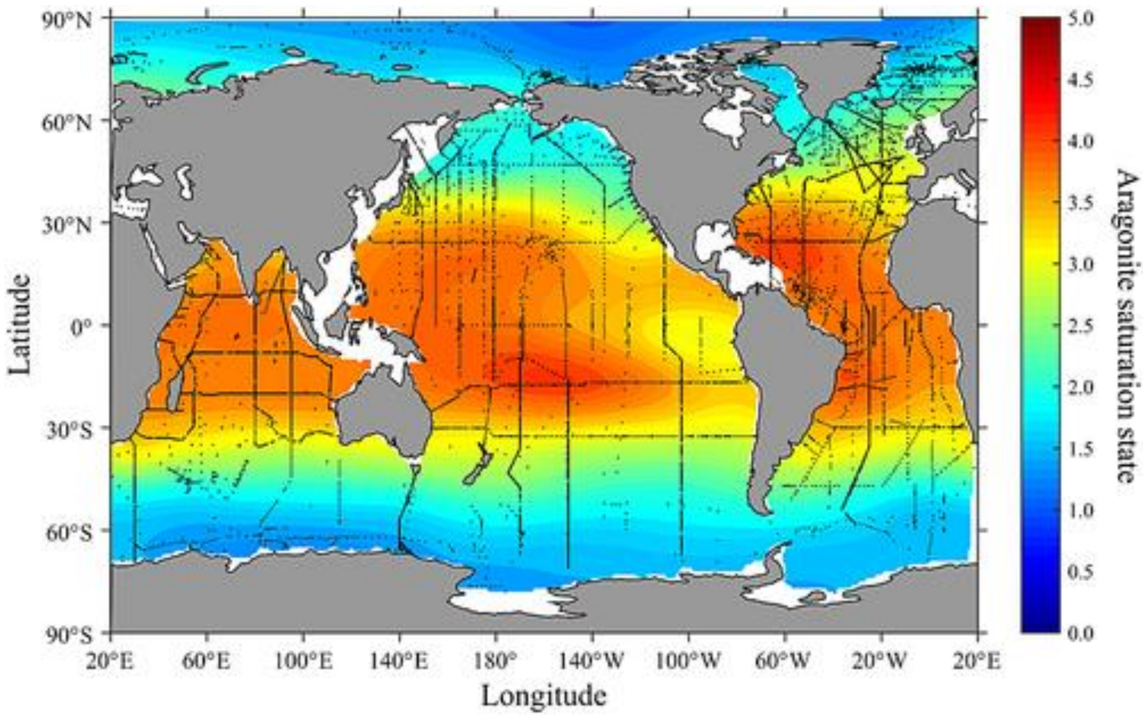


- Interferes with shell formation
- Rate of CO_2 absorption decreases with increasing water temperature
- Polar surface waters more impacted

Aragonite saturation state (Ωaragonite)

- Aragonite is needed for marine life with shells or skeletons made of calcium carbonate ($CaCO_3$), e.g., coral, plankton, mollusks
- Ωaragonite is the ratio of the concentration of calcium carbonate to the concentration of dissolved CO_2 in the ocean
- < 1 is undersaturated = favors dissolution; difficult for organisms to build shells and skeletons

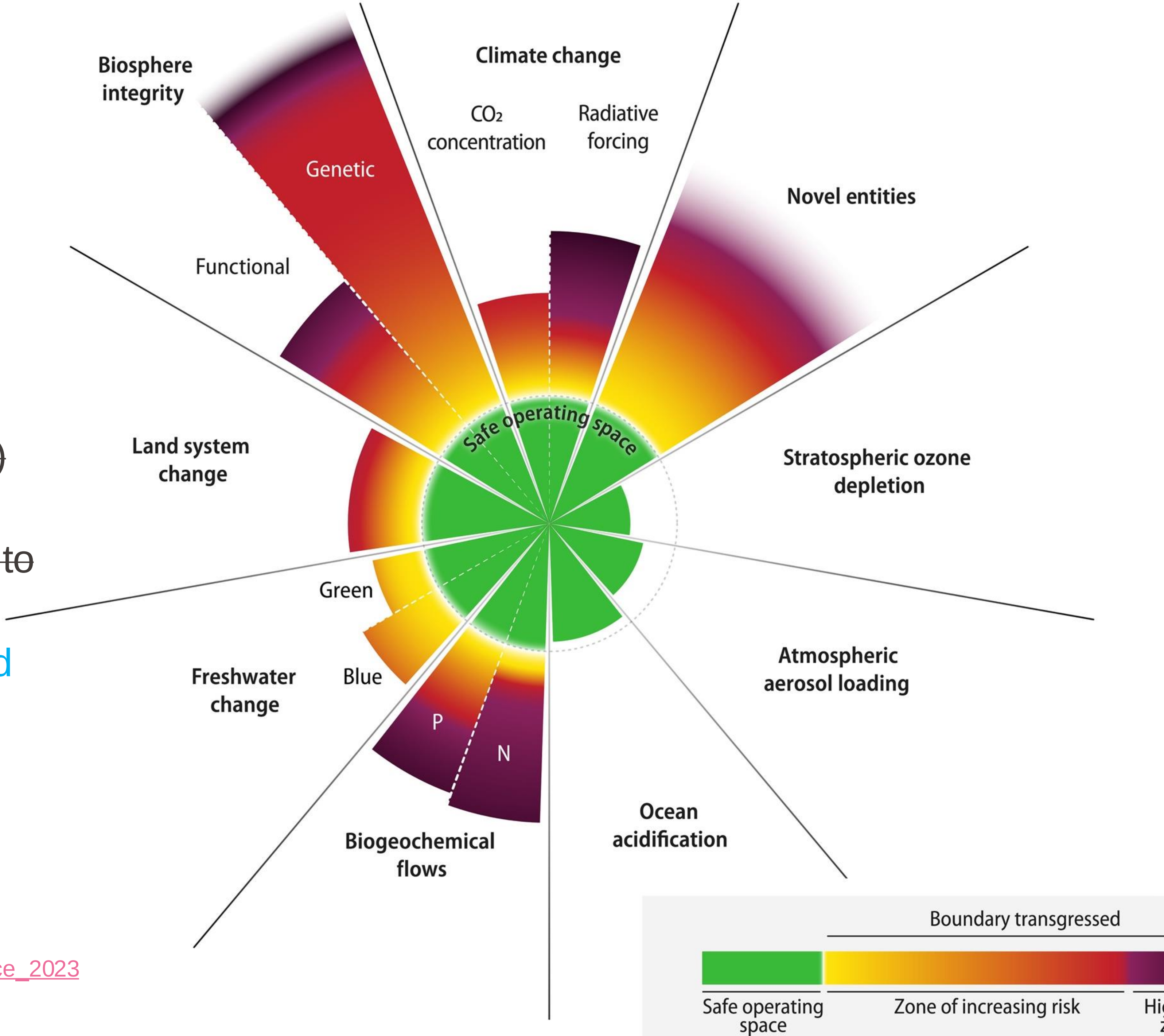
Aragonite saturation state (Ω_{arag}) in surface waters of the global oceans:



https://agupubs.onlinelibrary.wiley.com/doi/full/10.1002/2015GB005198

Current View (2023)

- ~~Biodiversity loss~~
- ~~Novel entities – last week~~
- ~~Ocean acidification (C cycle)~~
- ~~Climate change (via anthropogenic disturbances to the C cycle)~~
- Biogeochemical flows (P and N cycles)



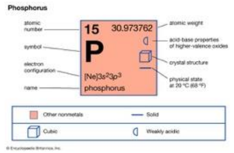
Earth beyond six of nine planetary boundaries_Science_2023

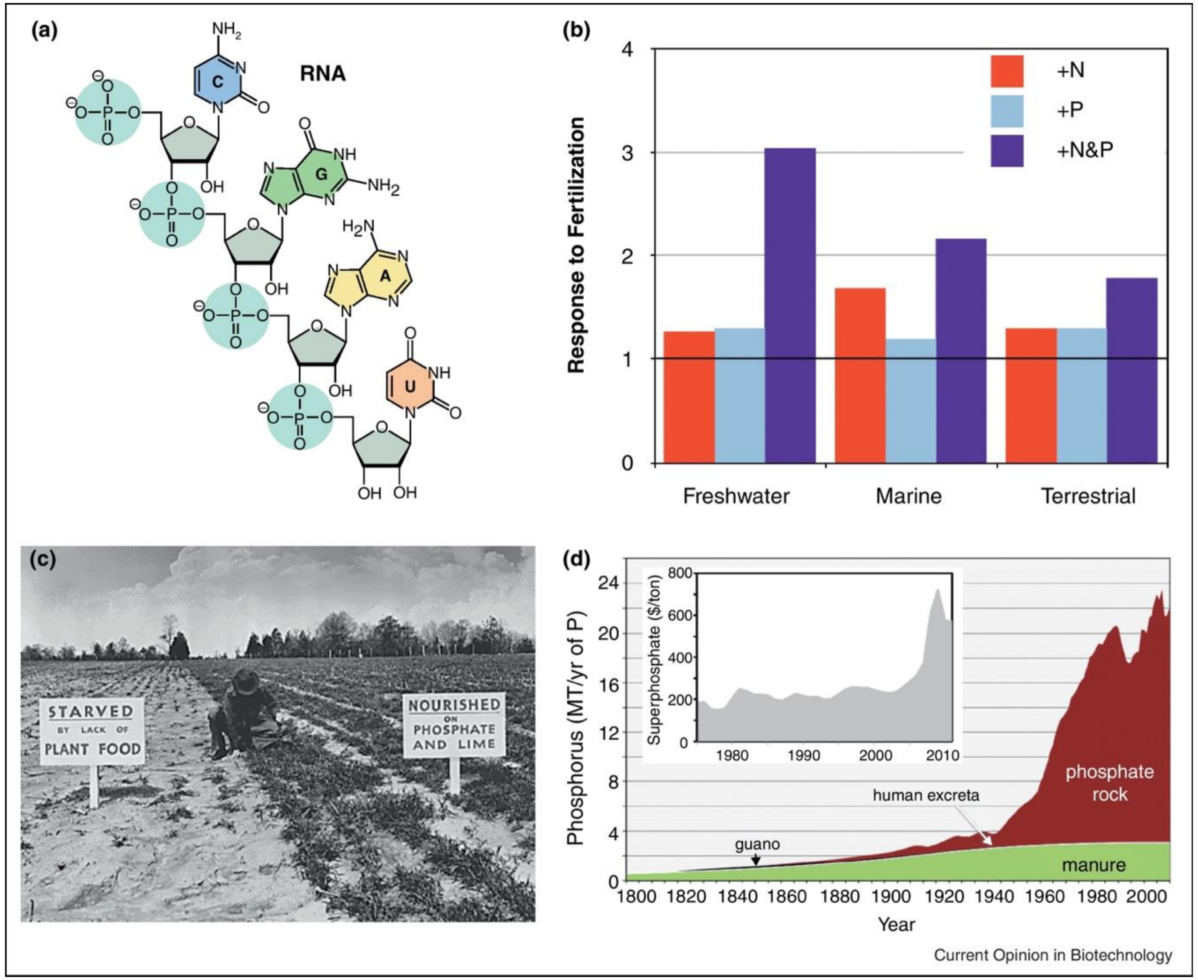
Table 1. Proposed planetary boundaries.

Earth System process	Control variable	Threshold avoided or influenced by slow variable	Planetary Boundary (zone of uncertainty)	State of knowledge*
Biogeo-chemical flows: interference with P and N cycles	P: inflow of phosphorus to ocean, increase compared with natural background weathering N: amount of N_2 removed from atmosphere for human use, Mt N yr^{-1}	P: avoid a major oceanic anoxic event (including regional), with impacts on marine ecosystems. N: slow variable affecting overall resilience of ecosystems via acidification of terrestrial ecosystems and eutrophication of coastal and freshwater systems.	P: < 10× (10× - 100×) N: Limit industrial and agricultural fixation of N_2 to 35 Mt N yr^{-1}, which is ~ 25% of the total amount of N_2 fixed per annum naturally by terrestrial ecosystems (25%–35%)	P: (1) Limited knowledge on ecosystem responses; (2) High probability of threshold but timing is very uncertain; (3) Boundary position highly uncertain. N: (1) Some ecosystem responses known; (2) Acts as a slow variable, existence of global thresholds unknown; (3) Boundary position highly uncertain.

Ecology and Society 14(2): 32
http://www.ecologyandsociety.org/vol14/iss2/art32/

Phosphorous

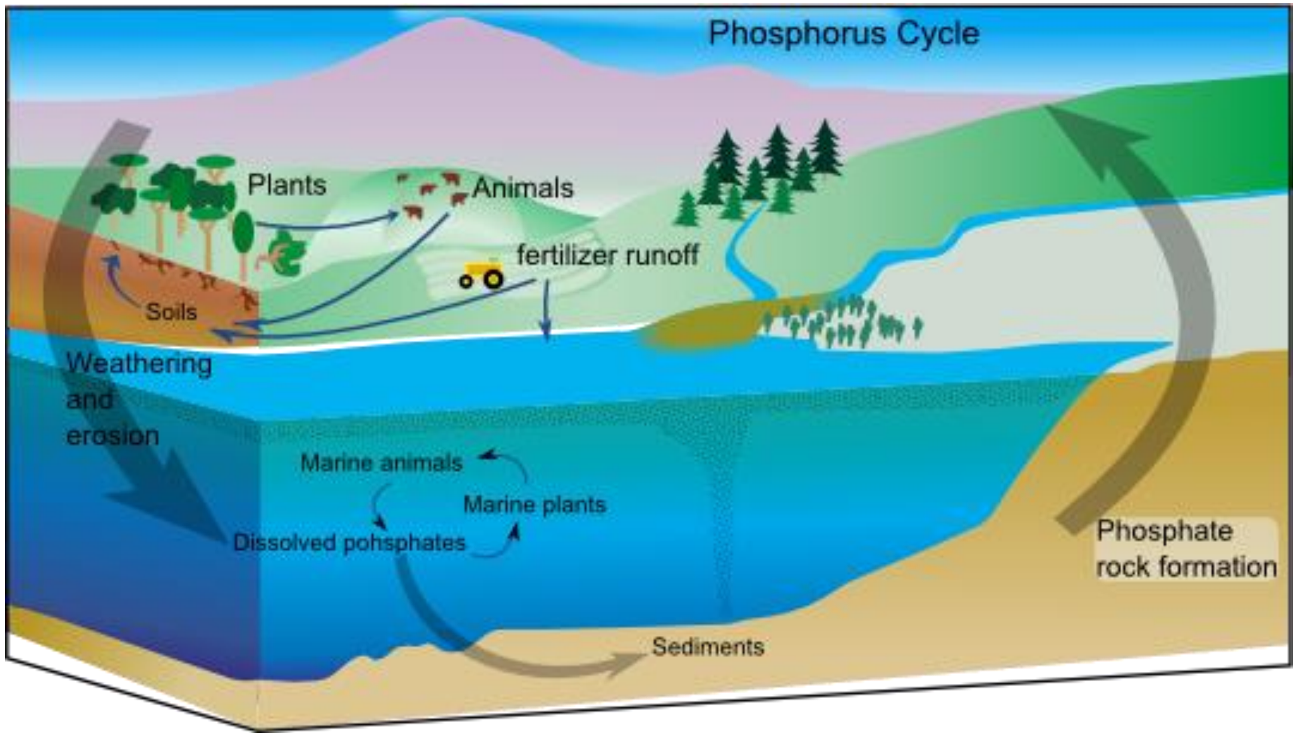




- Essential to life (DNA, RNA, ATP)
- Often limiting nutrient for growth
- Sedimentary rocks that contain phosphate (PO_4^{3-}) minerals
- Rock erosion and weathering leads to dissolved phosphates in the soil and waterways (ocean sediments)
- Main use: fertilizer – phosphate ores are converted to phosphoric acid and then ammonium phosphate, also detergents

Elser JJ, Phosphorus: a limiting nutrient for humanity?, Current Opinion in Biotechnology, 23, Issue 6,2012, Pages 833-838, https://doi.org/10.1016/j.copbio.2012.03.001.

Phosphorous cycle



(1) Weathering and erosion of rocks containing PO_4^{3-} minerals; occurs over thousands to millions of years; movement to soil and waterways as dissolved phosphates

(2) Absorption of phosphates by plants through their roots

(3) Consumption of plants by animals to obtain phosphates

(4) Decomposition of plants and animals by decomposers to return phosphates to the soil; also excrement

(5) Sedimentation of phosphates in ocean; can form phosphate containing rocks over the geologic timescale (millions of years)

Phosphorous imbalance

- Anthropogenic influence on cycle due to phosphate mining, run-off from fertilizers and sewage
- Eutrophication
- Factors that increase erosion implicated (storms)
- Limited resource mined from phosphate rock
- Phosphorous from waste treatment plants can be recovered instead of flushed away

Eutrophication

Eutrophication is a widespread problem in aquatic ecosystems around the world (Vollenweider 1968, NRC 1993, Nixon 1995). Eutrophic lakes exhibit many undesirable traits, including excessive growth of algae and other aquatic plants (Figure 1; Smith 1998). In response to overenrichment with nutrients, the phytoplankton community may shift to bloom-forming nuisance algae, which are harmful to other organisms (Smith 1990). Decomposition of algal blooms can lead to foul odors and oxygen depletion, which can in turn lead to fish kills (Carpenter et al. 1998, Smith 1998). Other problems associated with eutrophication include the presence of toxins, unpalatability of drinking water (Lawton and Codd 1991), extirpation of native plants (Gleick 1998, Smith 1998), and loss of biodiversity (NRC 1993, Smith 1998).

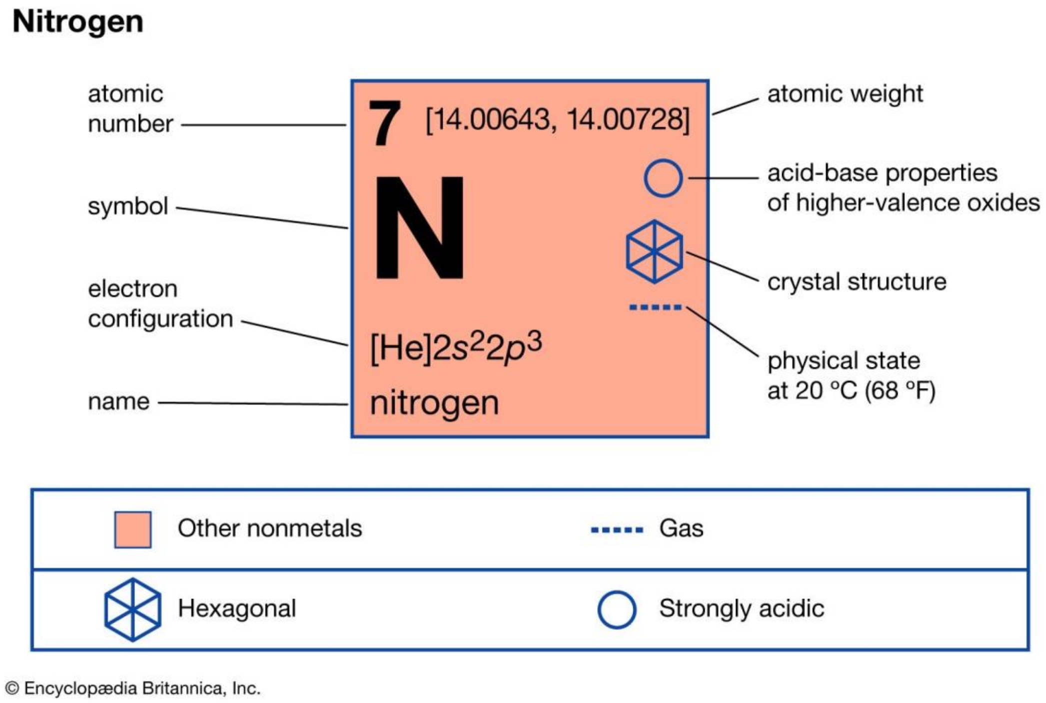
Eutrophication is also a problem in many nearshore marine areas. Eutrophication has been linked to the hypoxic "dead zone" in the Gulf of Mexico (Turner and Rabalais 1991, 1994). Nearshore eutrophication can lead to coral reef death (Smith 1998) or shellfish poisoning of humans (Anderson 1994, Anderson and Garrison 1997). Moreover, the symptoms of eutrophication in both fresh and salt waters can lead to loss of aesthetic, ecological, and economic value of aquatic ecosystems.

Figure 1. Algal bloom on a eutrophic lake, Lake Mendota, in Madison, Wisconsin.

Excess P input from point sources such as sewage treatment plants has been curtailed in freshwaters of the developed world since passage of the Clean Water Act and similar laws. However, nonpoint source pollution, which originates from diffuse, intermittent sources that are difficult to identify, is still an important water-quality problem (NRC 1992, Duda 1993). In fact, the major source of P in freshwater in the United States is nonpoint source flux from land to water (NRC 1993, Sharpley et al. 1994, Daniel et al. 1994).

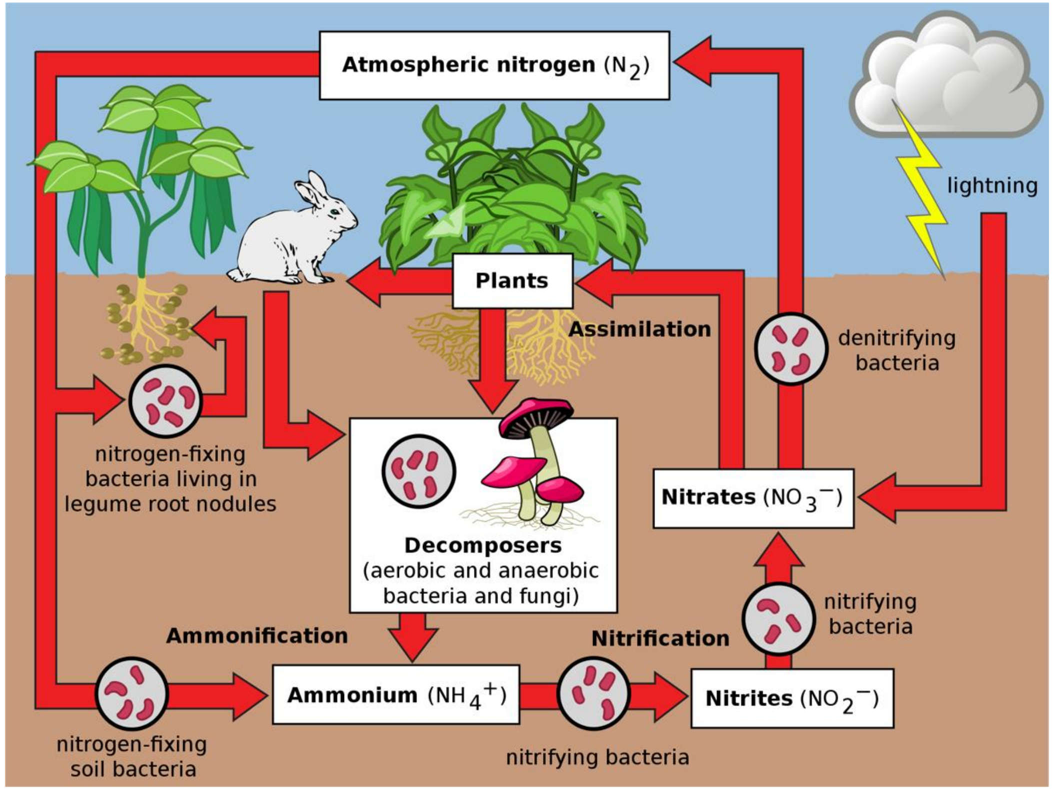
Bennett EM, et al. Human Impact on Erodable Phosphorus and Eutrophication: A Global Perspective: Increasing accumulation of phosphorus in soil threatens rivers, lakes, and coastal oceans with eutrophication, *BioScience*, 51, 227–234, https://doi.org/10.1641/0006-3568(2001)051[0227:HIOEPA]2.0.CO;2

Nitrogen



- Essential to life (DNA, RNA)
- Limiting nutrient for the growth of living organisms
- Found in soil, plants, water, air, animals, bacteria
- **Approximately 78% of atmosphere**
- Uses: fertilizer, nitric acid, explosives, nylon, dyes

Nitrogen cycle in 5 steps



(1) Fixation

- *Most living things can't use nitrogen gas (N_2), so the first step is for bacteria to "fix" the nitrogen in the atmosphere, converting it to usable forms like ammonium*

(2) Nitrification

- *bacterial conversion of ammonium into nitrites and then into nitrates*

(3) Assimilation

- *plants absorb nitrates through their roots; nitrates are used to make proteins, nucleic acids, and other essential compounds*

(4) Ammonification

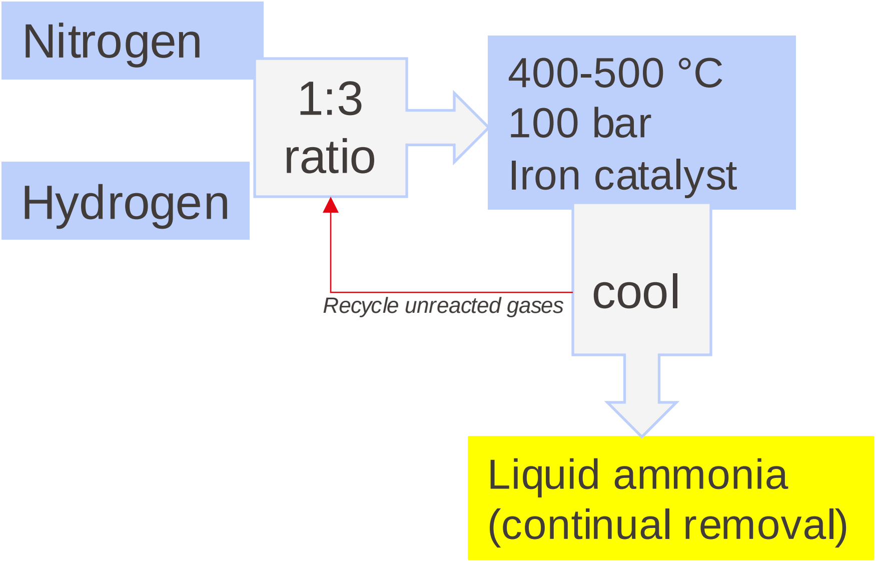
- *After plants and animals die, decomposers (like bacteria and fungi) break them down, releasing nitrogen back to the soil as ammonium; also excrement*

(5) Denitrification

- Certain types of bacteria in the soil, convert nitrates into nitrogen gas, which is released back into the atmosphere

Nitrogen cycle

Anthropogenic nitrogen – the Haber process



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

$CH_4(g) + H_2O \rightarrow H_2(g) + CO(g)$

Key elements:

- Hydrogen from steam reforming of natural gas, nickel catalyst; reacts with nitrogen gas to give ammonia
- Fritz Haber won the Nobel prize in Chemistry in 1918 for nitrogen fixation, but was also shunned post WWII for his contribution to chemical warfare

- In the 19th and 20th centuries, increasing demand for N_2 (fertilizer, weapons)
- N_2 in atmosphere is stable and unreactive
- Haber process had a major impact on population growth

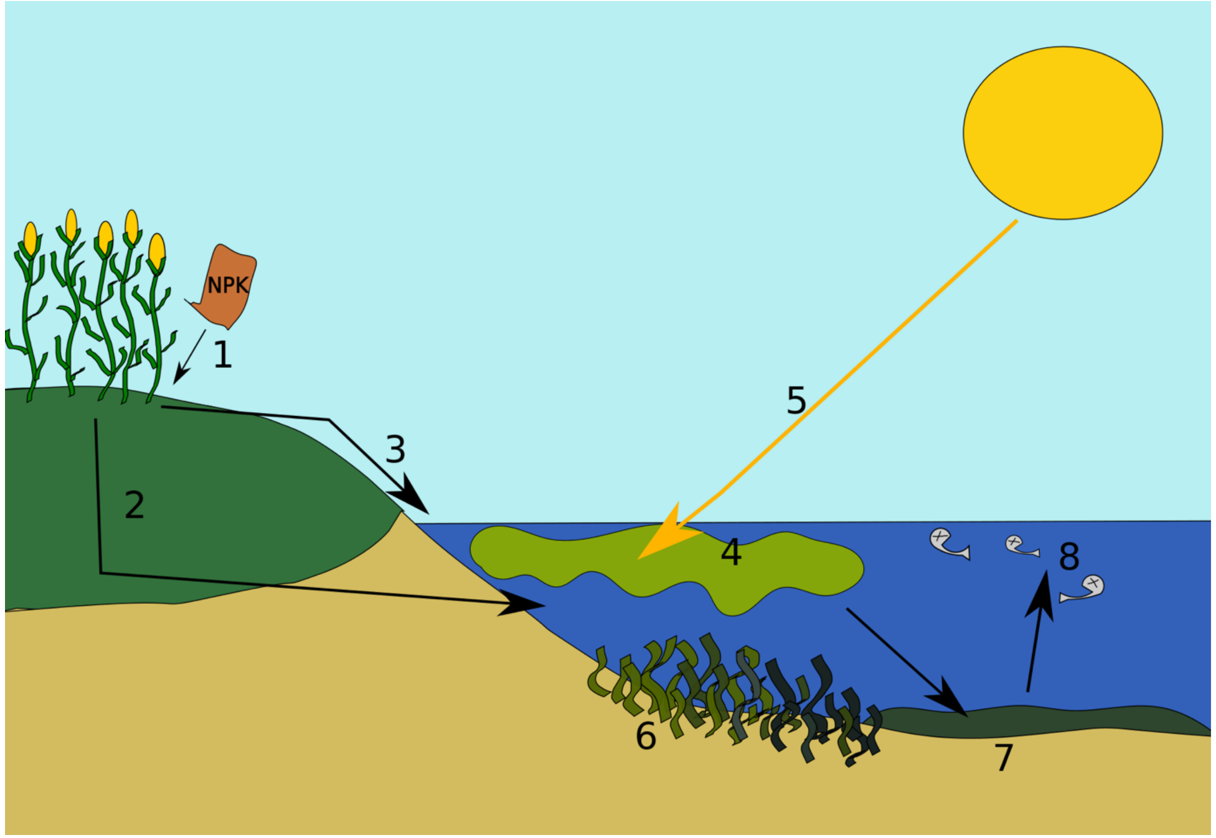
"Without ammonia, there would be no inorganic fertilizers, and *nearly half the world would go hungry*. Of all the century's technological marvels, the Haber-Bosch process has made the most difference to our survival."

From: Smil, V. Detonator of the population explosion. *Nature* **400**, 415 (1999). https://doi.org/10.1038/22672

Nitrogen imbalance

- In balance, essential to plant growth

- Eutrophication of water sources due to excess nitrogen
  - Overgrowth of plants and algae
  - Block light, preventing photosynthesis
  - Dead plants/algae decomposed by bacteria
  - Deplete waterways of dissolved oxygen needed for life
  - Leads to “dead zones”



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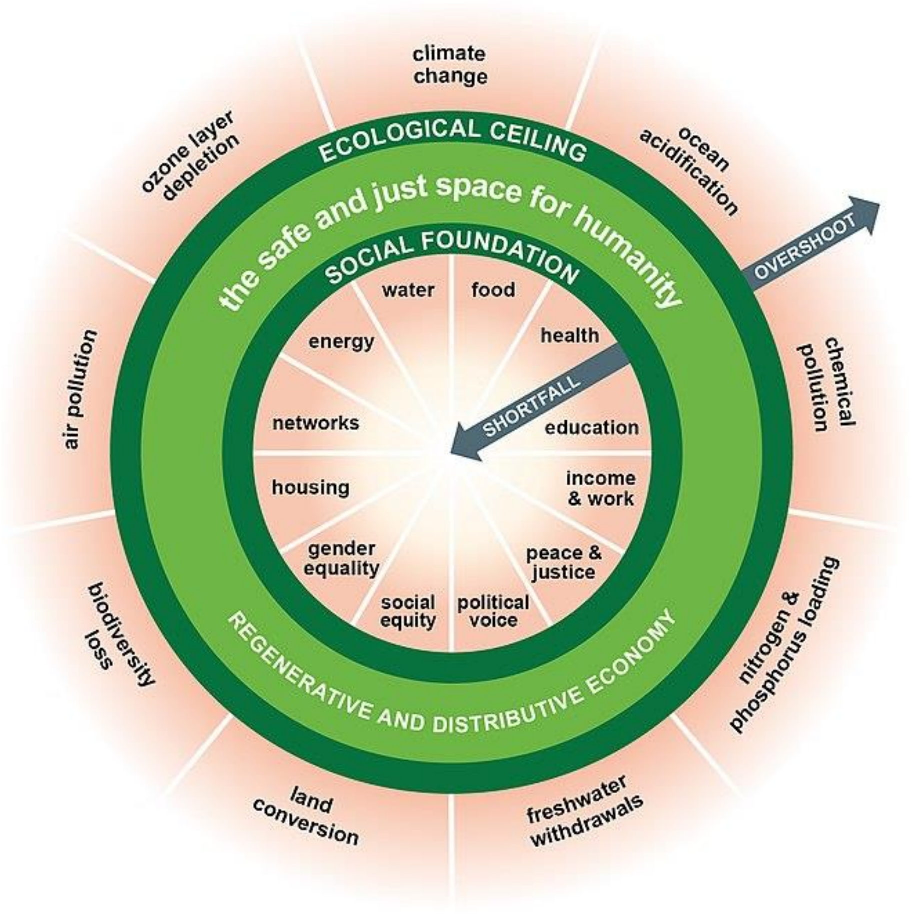
Beyond planetary boundaries: The Doughnut



- Framework for sustainable development
- Extension of planetary boundaries concept to consider *social* and *economic* aspects (human well-being)
- Combines planetary boundaries with *social boundaries*
- Doughnut “hole” proportion of people lacking life’s essentials (12 social foundations)
- Doughnut “crust” ecological boundaries that life depends on and must not be transgressed
- Economy is prosperous when social foundations are met *without* overshooting ecological boundaries

Doughnut Wiki

Take aways

- A deep dive on a few more planetary boundaries
- The threshold value that must not be surpassed is defined in terms of a pre-industrial value
- Safe space vs. zone of increasing risk, where the boundary is surpassed but correction is thought possible due to the Earth's resilience, vs. zone of high risk, with presumed catastrophic effects
- A starting understanding of the interrelation between different boundaries – can you think of others than what we discussed today? Recall: interconnectedness of Earth systems and subsystems
- Another formulation that considers a social framework – the doughnut