EPFL

Some background MSE 493

Prof. Tiffany Abitbol

2024

How was it?

Dual carbon sequestration with photosynthetic living materials

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Abstract

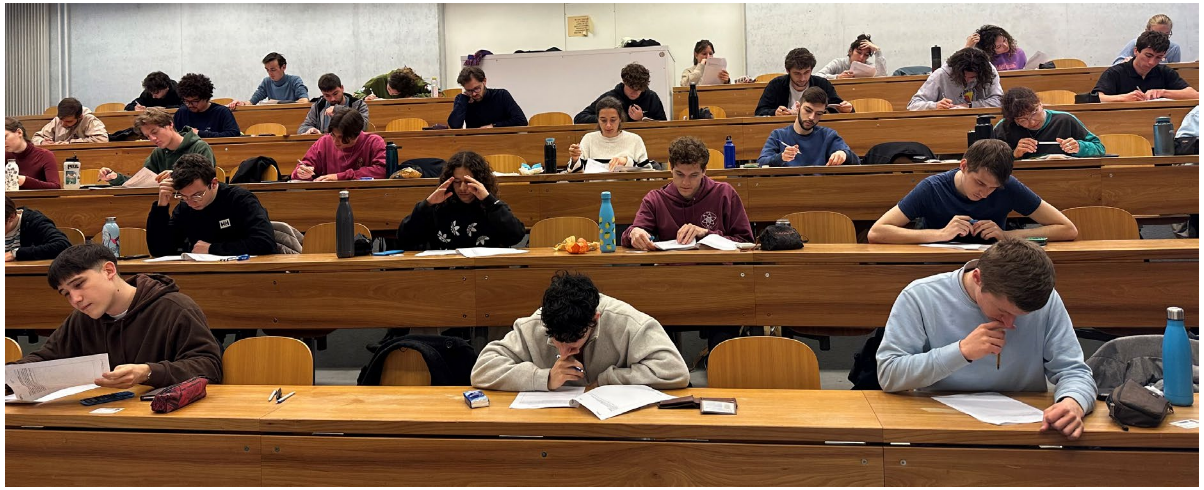
Natural ecosystems offer efficient pathways for carbon sequestration, serving as a resilient approach to remove CO_2 from the atmosphere with minimal environmental impact. However, the control of living systems outside of their native environments is often challenging. Here, we engineered a photosynthetic living material for dual CO_2 sequestration by immobilizing photosynthetic microorganisms within a printable polymeric network. The carbon concentrating mechanism of the cyanobacteria enabled accumulation of CO_2 within the cell, resulting in biomass production. Additionally, the metabolic production of OH^- ions in the surrounding medium created an environment for the formation of insoluble carbonates via microbially-induced calcium carbonate precipitation (MICP). Digital design and fabrication of the living material ensured sufficient access to light and nutrient transport of the encapsulated cyanobacteria, which were essential for long-term viability (more than one year) as well as efficient photosynthesis and carbon sequestration. The photosynthetic living materials sequestered approximately 2.5 mg of CO_2 per gram of hydrogel material over 30 days via dual carbon sequestration, with 2.2 ± 0.9 mg stored as insoluble carbonates. Over an extended incubation period of 400 days, the living materials sequestered 26 ± 7 mg of CO_2 per gram of hydrogel material in the form of stable minerals. These findings highlight the potential of photosynthetic living materials for scalable carbon sequestration, carbon-neutral infrastructure, and green building materials. The simplicity of maintenance, coupled with its scalability nature, suggests broad applications of photosynthetic living materials as a complementary strategy to mitigate CO_2 emissions.

Keywords: living materials, CO_2 sequestration, 3D printing

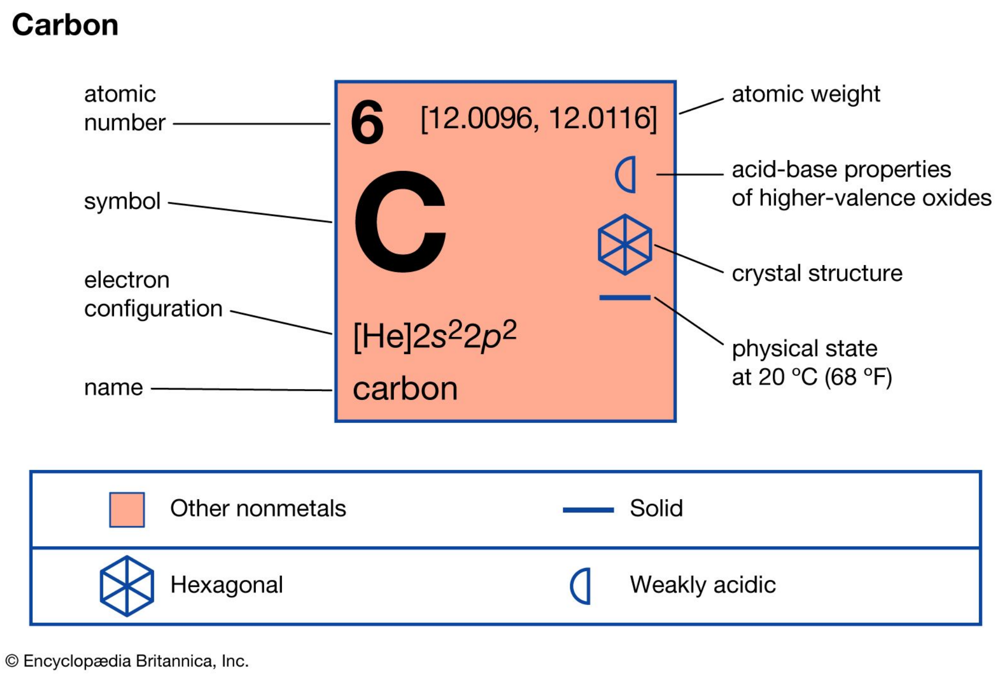
Keywords:

1. Carbon
2. Carbon sequestration
3. Photosynthesis
4. MICP
5. Cyanobacteria
6. Hydrogel – **last few weeks**
7. 3D printing – **last week**
8. Photosynthetic living materials

Flashback to simpler times:
MSE 341 Sustainability and Materials



Carbon



- 18% of human body (second element after oxygen)

Energy currency

- Energy released when bonds are broken to drive cellular processes
- Fuel – food, wood, gas, oil, etc.,

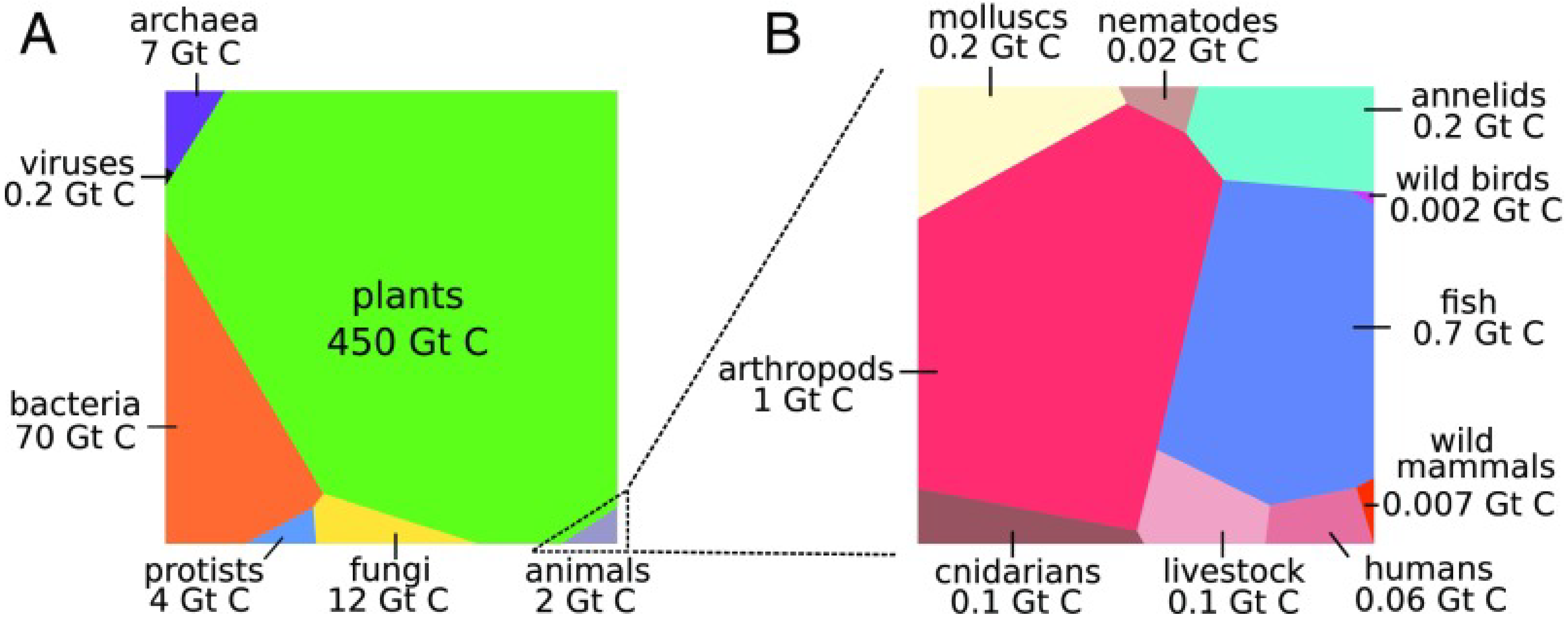
Materials currency

- Carbon is consumed and restructured to produce new biomass
- Plastic, diamond, graphite, steel, etc..

Temperature regulation

- Fast (year-scale) and slow (million-year scale) carbon cycles

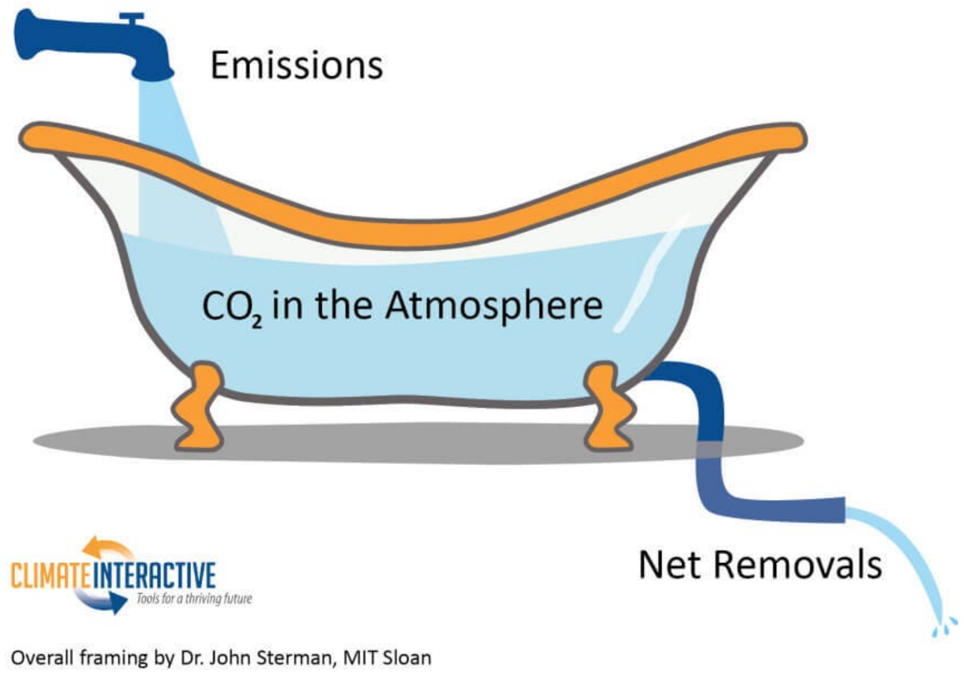
Total global live biomass – 550 billion tonnes carbon



The biomass distribution on Earth_2018

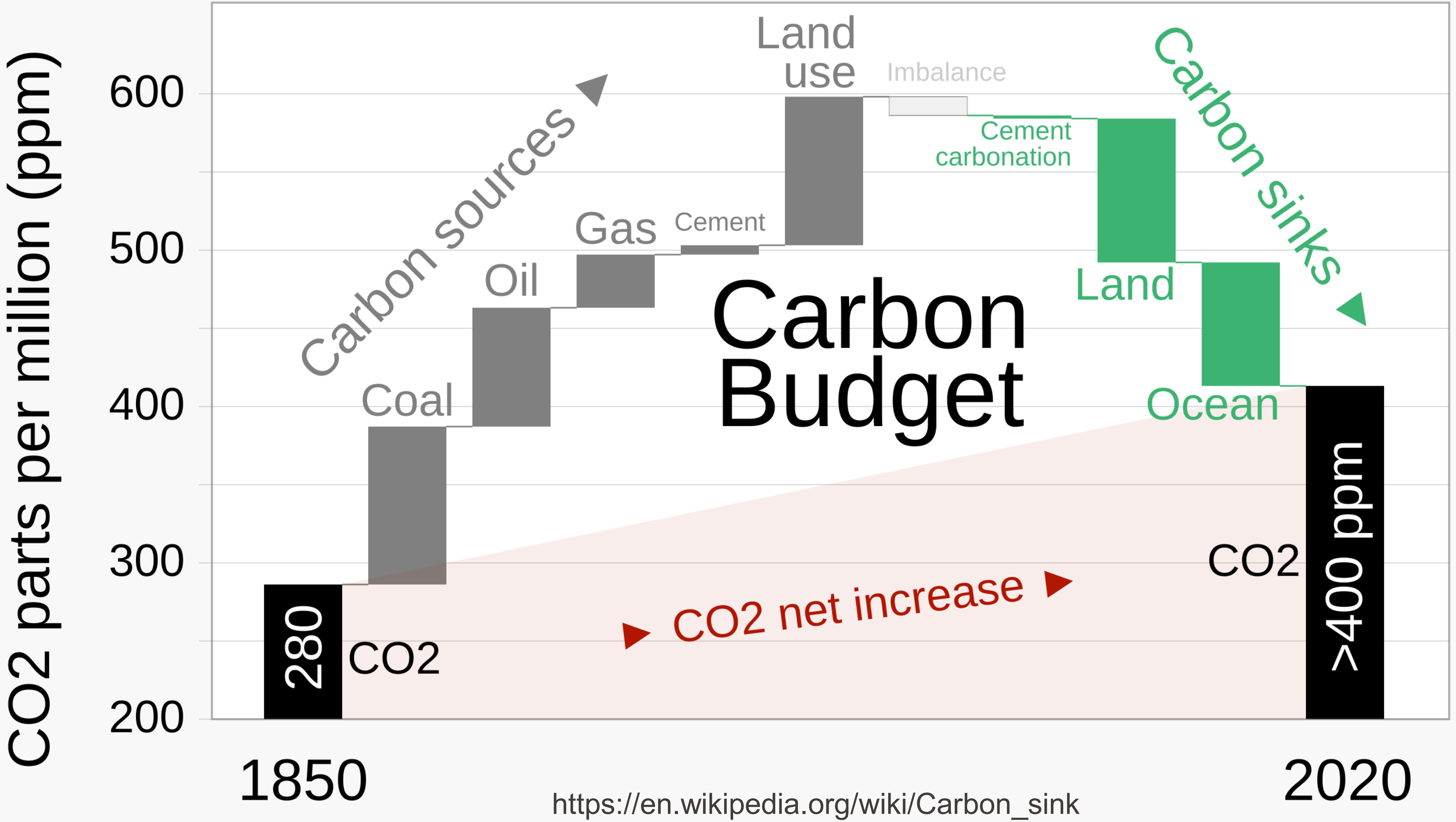
Sinks and Pools

- A pool is the places that carbon can be stored: atmosphere, oceans, soil, etc.,
- A sink is a type of pool that takes in more atmospheric carbon than it releases
- Most important sinks globally: vegetation, ocean



Climate Bathtub Simulation

https://en.wikipedia.org/wiki/Carbon_sink



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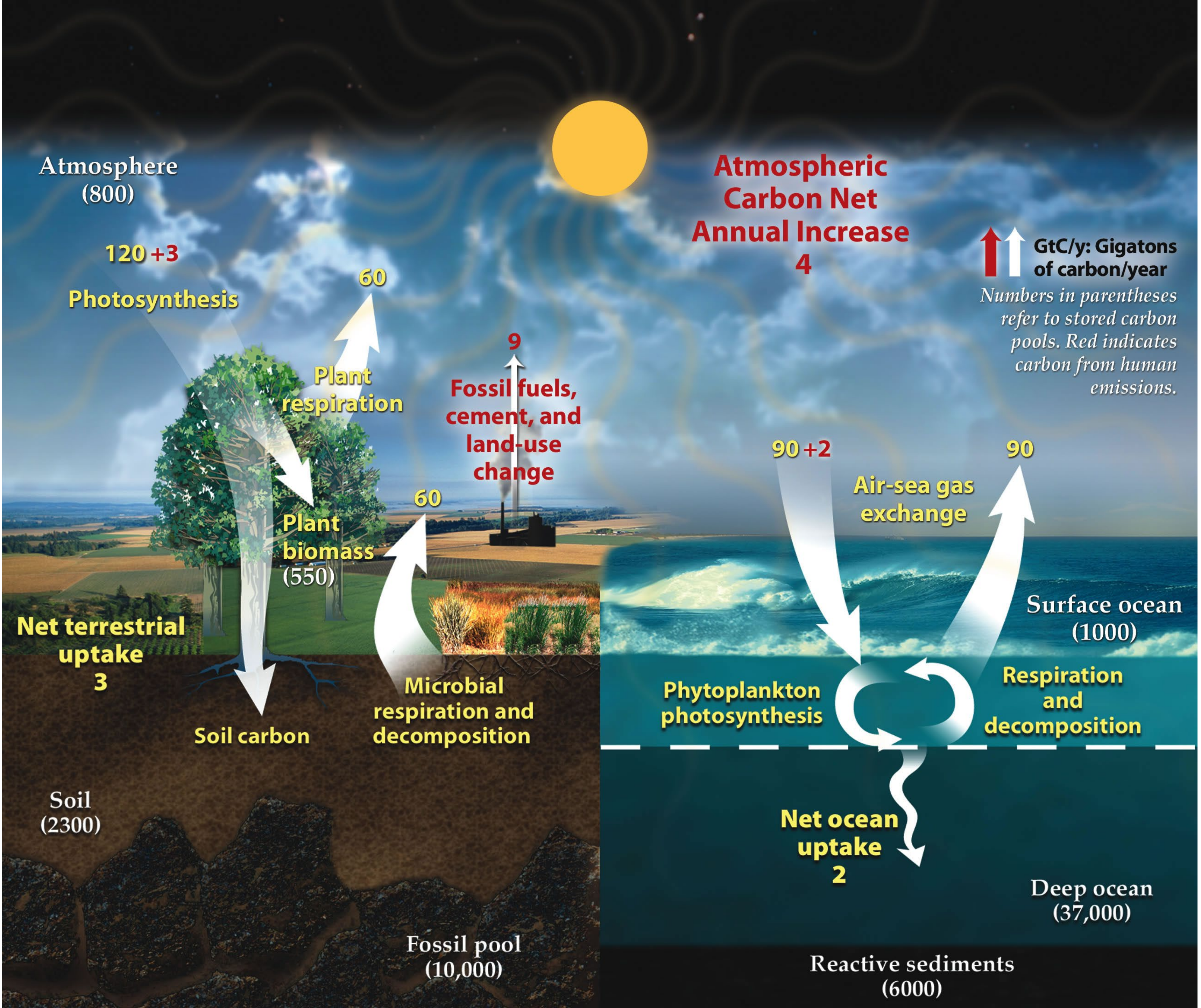


Global pools of carbon (white): oceans (the largest reservoir), geological reserves of fossil fuels, the terrestrial surface (plants and soil, mainly), and the atmosphere.

Fast carbon cycle:

- Yellow (natural fluxes)
- Red (anthropogenic)
- White (stored carbon)

Slow carbon cycle (not shown)

- Volcanic/tectonic activities

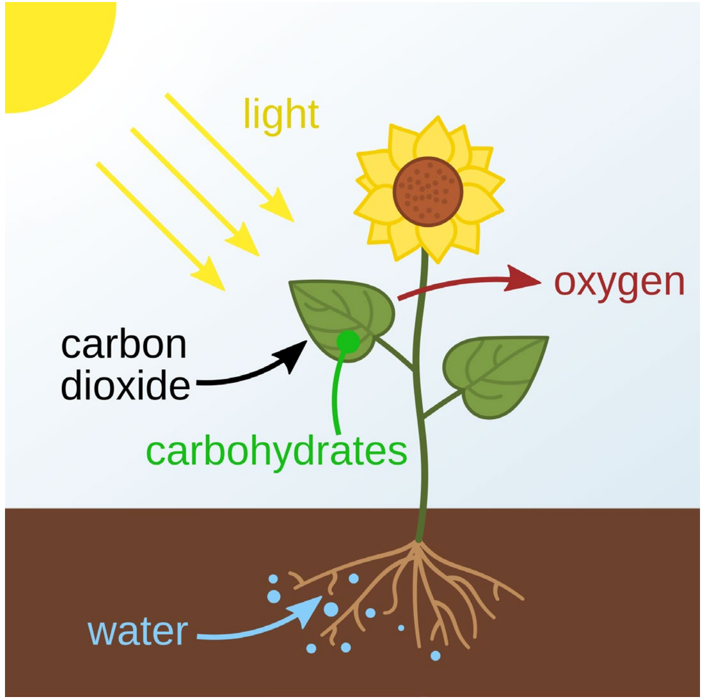
Global warming accelerates soil respiration_Nature_2023

Carbon cycle

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) don't do 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

Carbon sequestration?

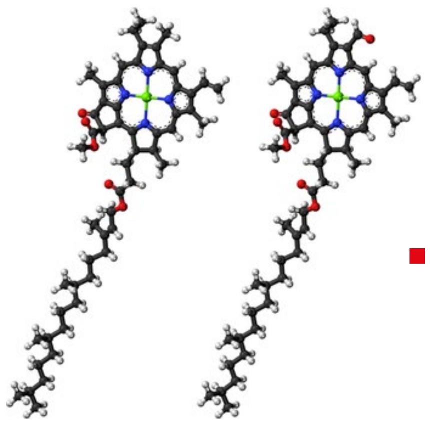


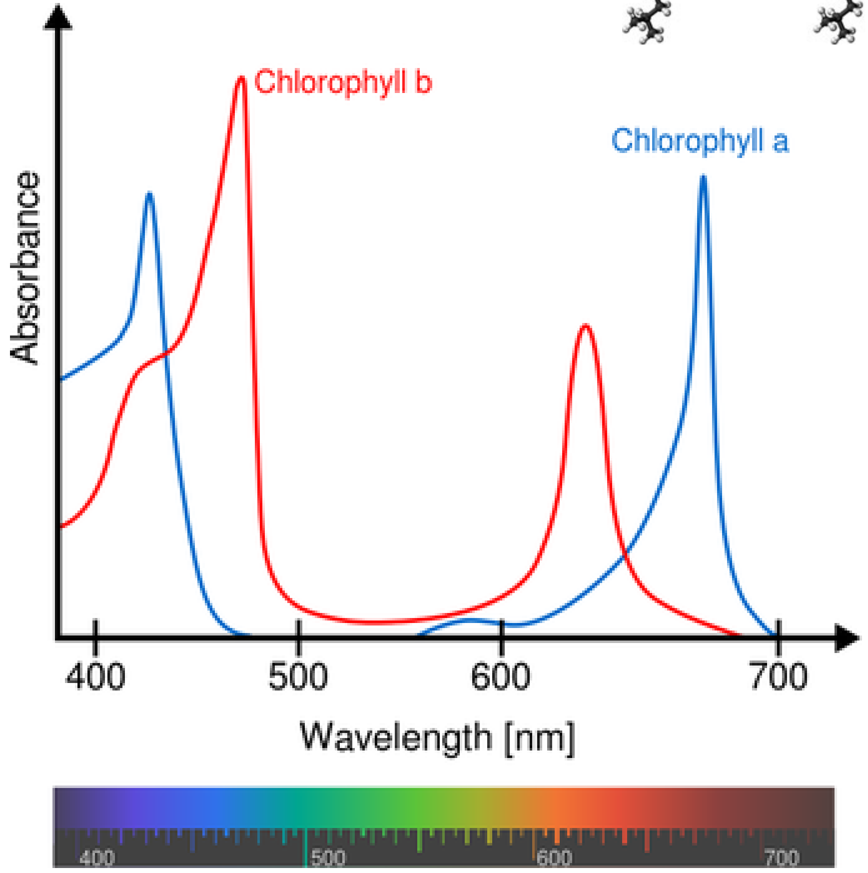
Photosynthesis:
$6CO_2 + 6H_2O$ + light energy → $C_6H_{12}O_6$ (glucose) + $6O_2$

Currency of life

Photosynthesis

Chlorophyll



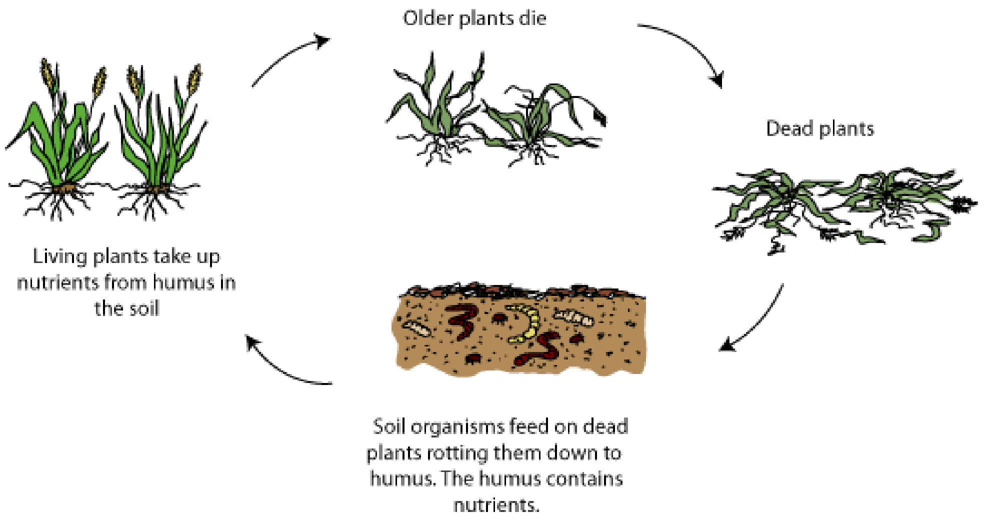


- 6 types, chlorophyll a and b are the most abundant in plants
- Comes from Greek for green (*chloros*) leaf (*phyllon*)
- Chlorophyll a absorbs violet and orange
- Chlorophyll b absorb blue and yellow
- (cyanobacteria also have phycobiliproteins; phycocyanin and allophycocyanin)

Chlorophyll

Energy consumption

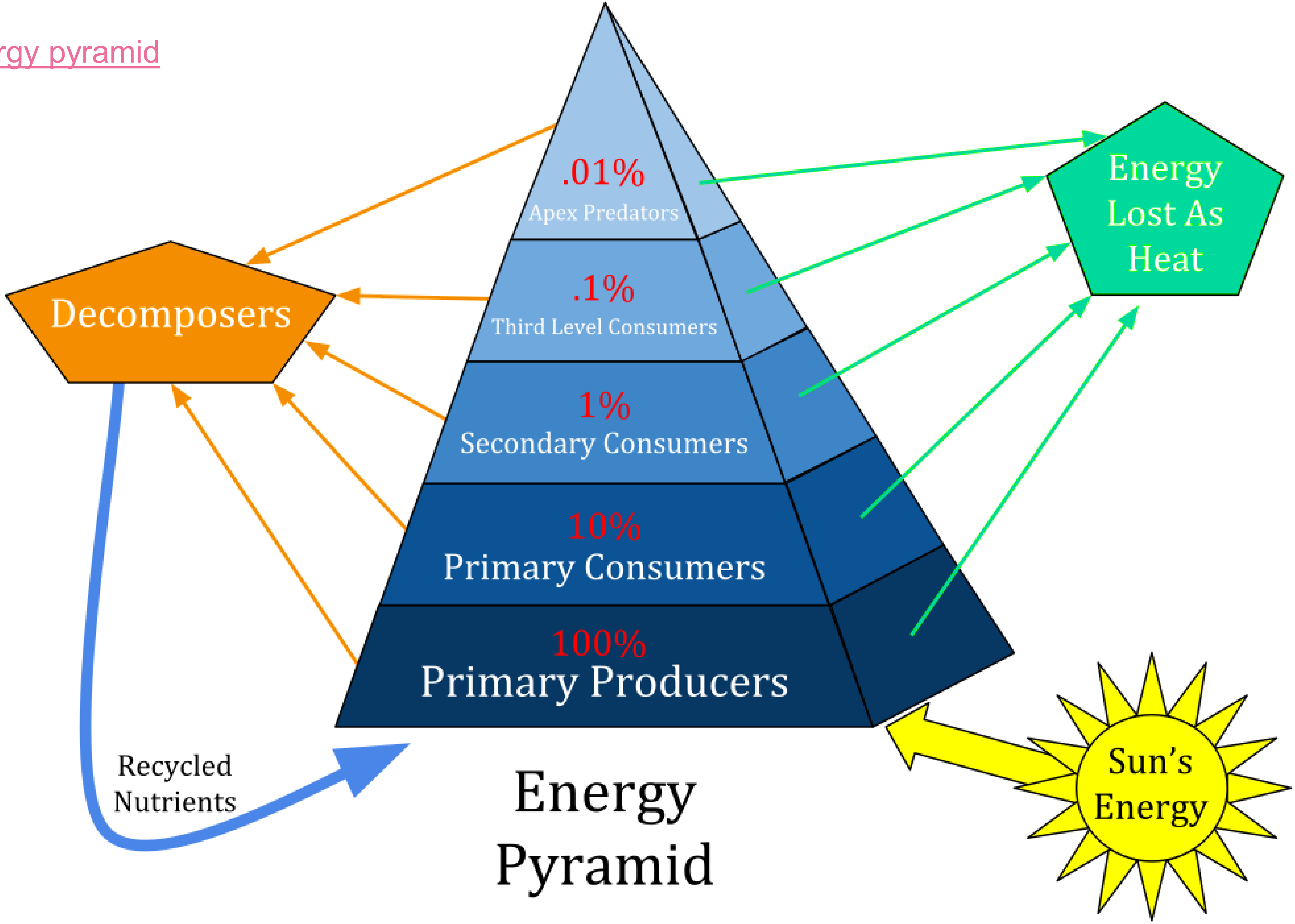
- The sugars, lipids, and proteins generated by plants and microbes store energy from the sun in carbon-hydrogen (C-H) bonds (chemical energy)
- These are broken down in cells to release energy via *respiration*, and we also break them down from our fuel tanks to release energy via *combustion*
- Although 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 (primary producers)***



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

Currency of life

Respiration



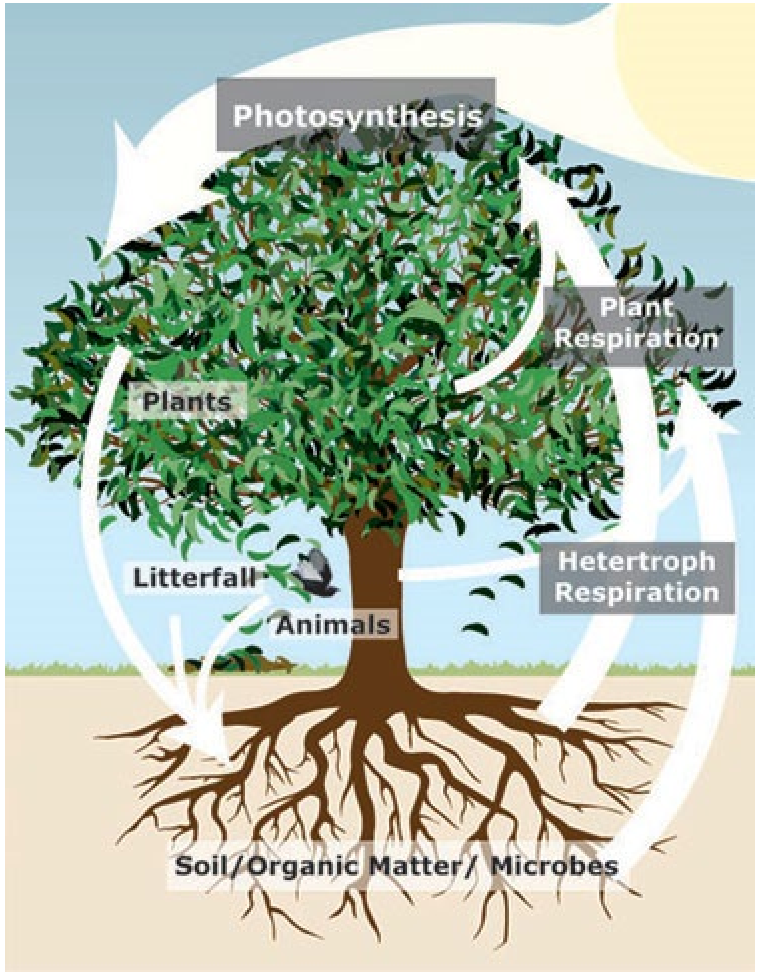
.01%
Apex Predators
.1%
Third Level Consumers
1%
Secondary Consumers
10%
Primary Consumers
100%
Primary Producers
Decomposers
Energy Lost As Heat
Recycled Nutrients
Energy Pyramid
Sun's Energy

Energy balance

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

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

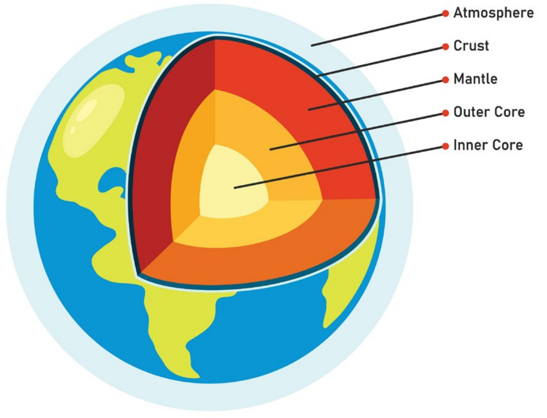
- Fast cycle – operates in biosphere
- Equations tend to balance over time
- CO_2 fixed by photosynthesis is eventually returned to the atmosphere
- Oxygen and water also tend to balance
- Net effect of photosynthesis is light energy converted to chemical energy (sunlight that fuels the entire ecosystem)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

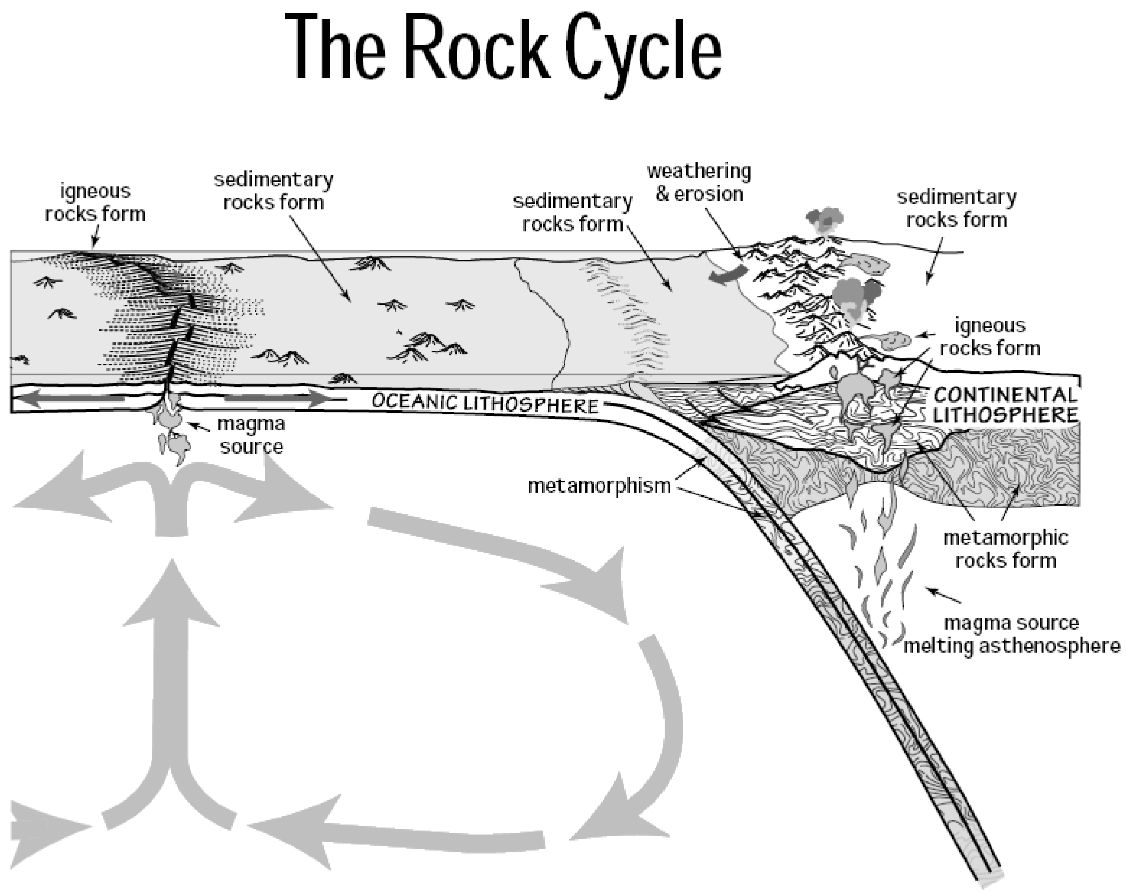


Currency of life

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

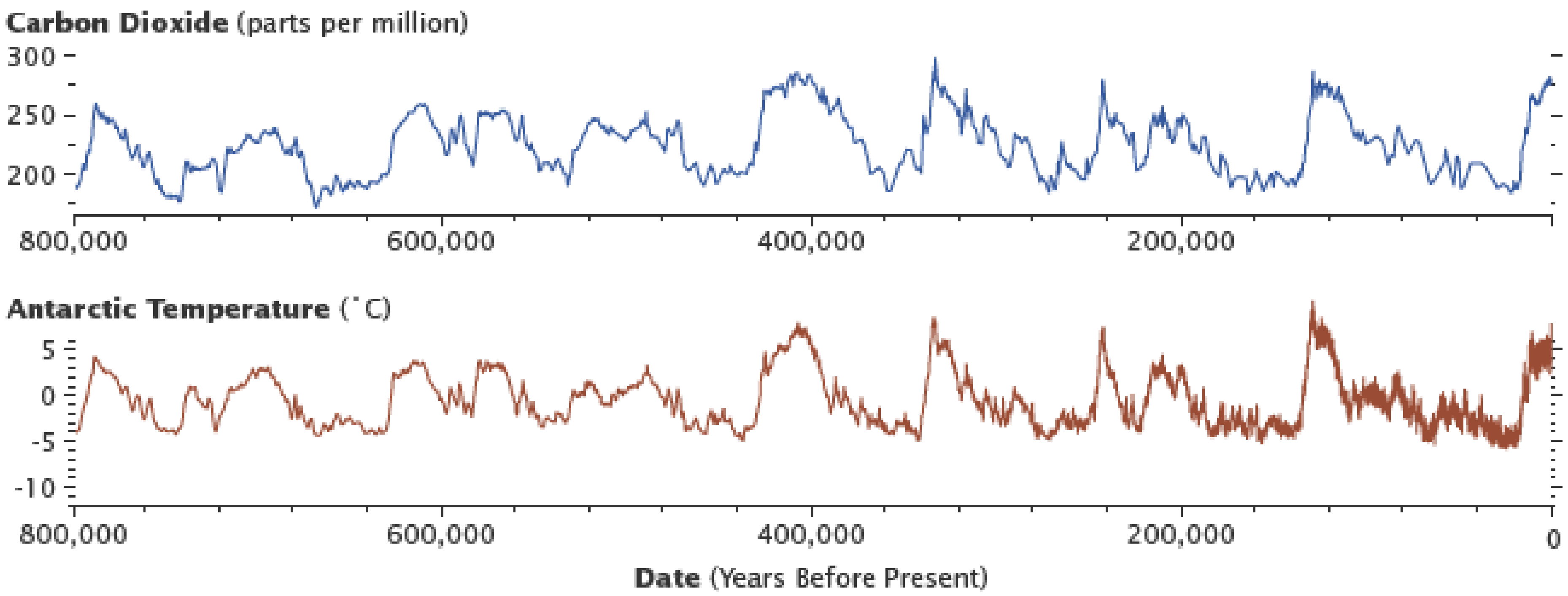




Slow carbon cycle

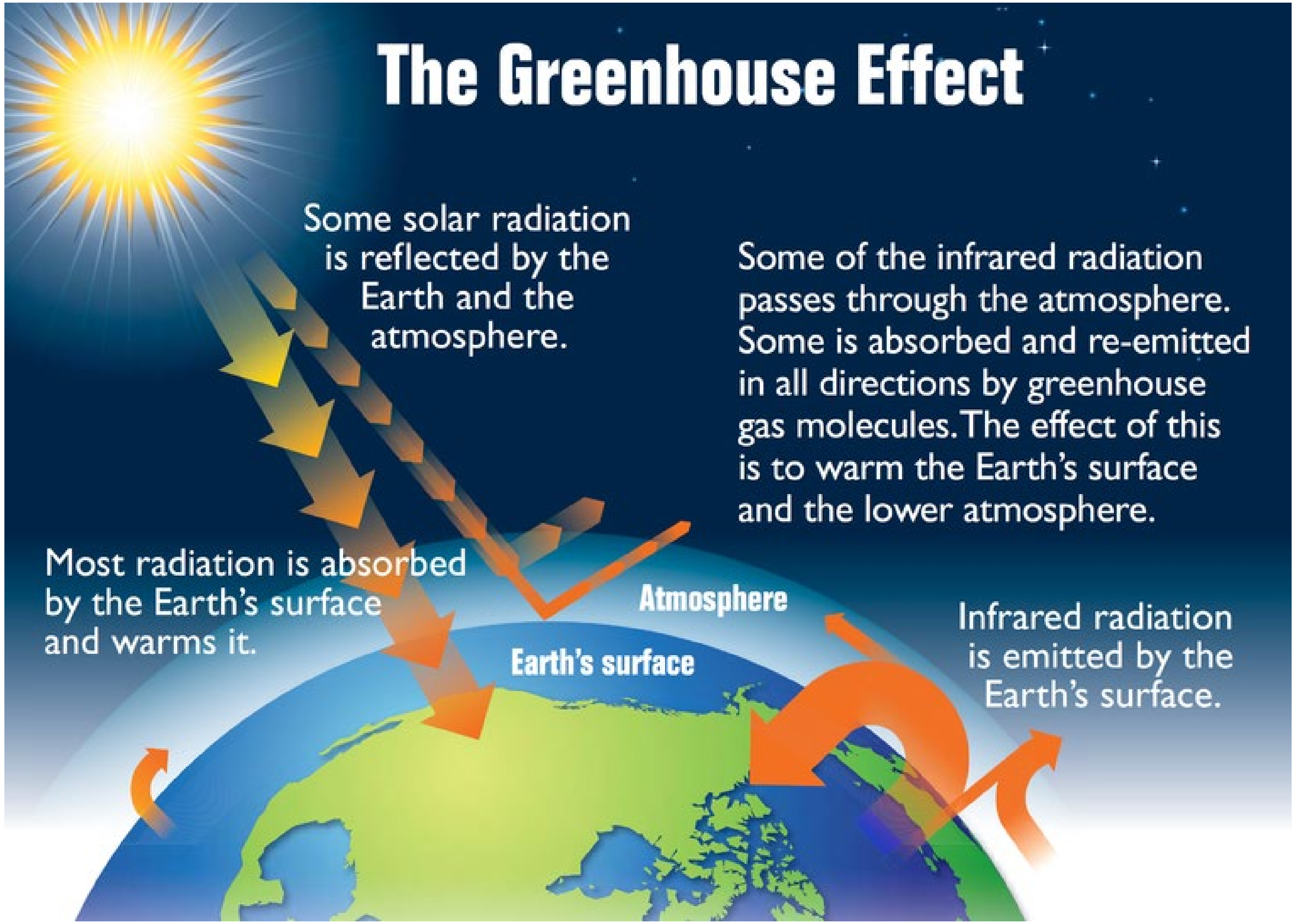
Natural variations in the carbon cycle

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



Nasa _ Carbon cycle

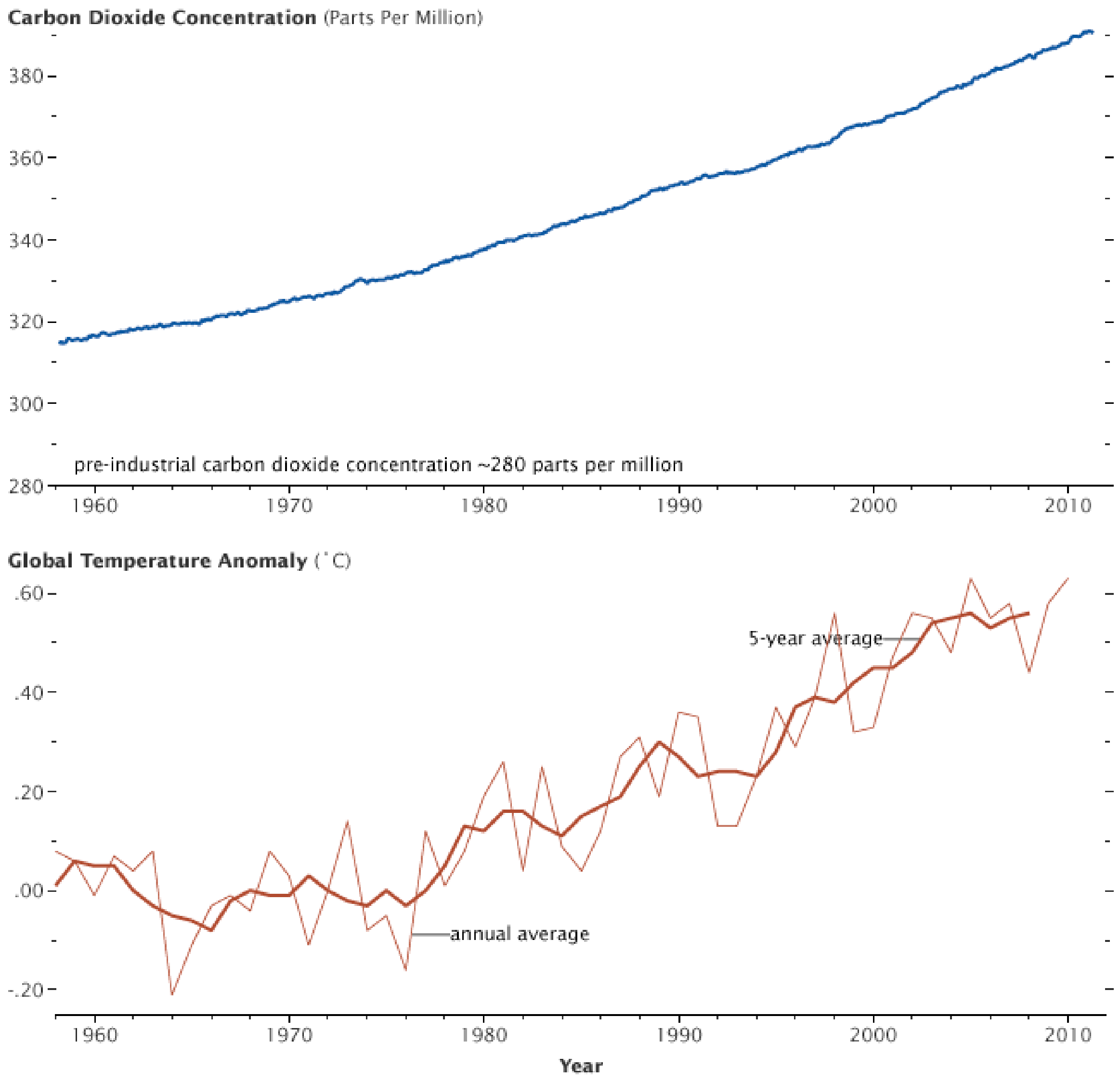
Greenhouse effect – it's not global warming!



- "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 absorbed and 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

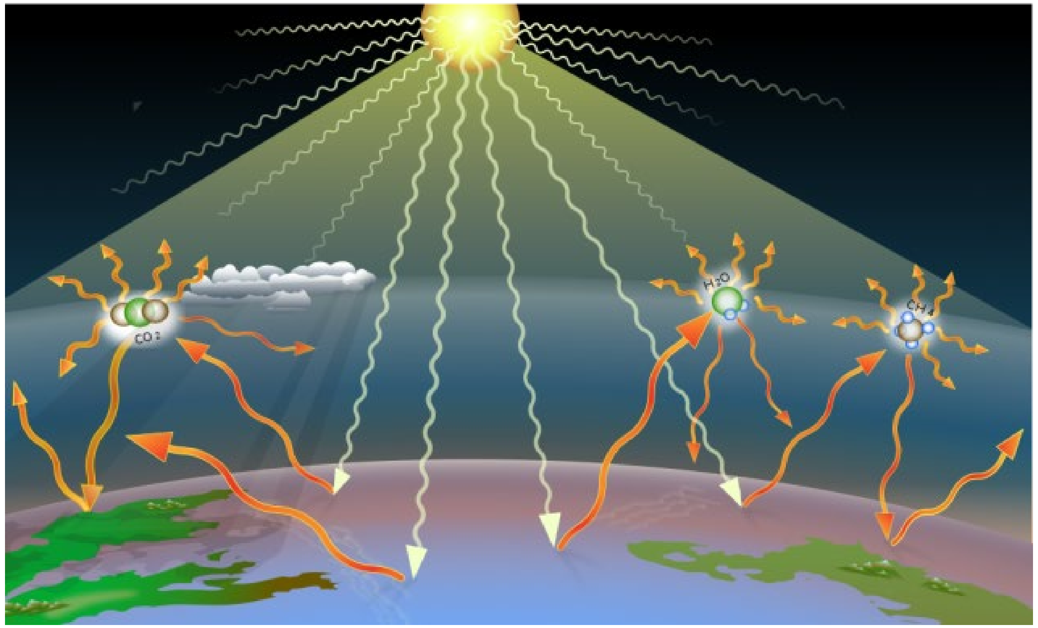
What if we perturb the cycle?

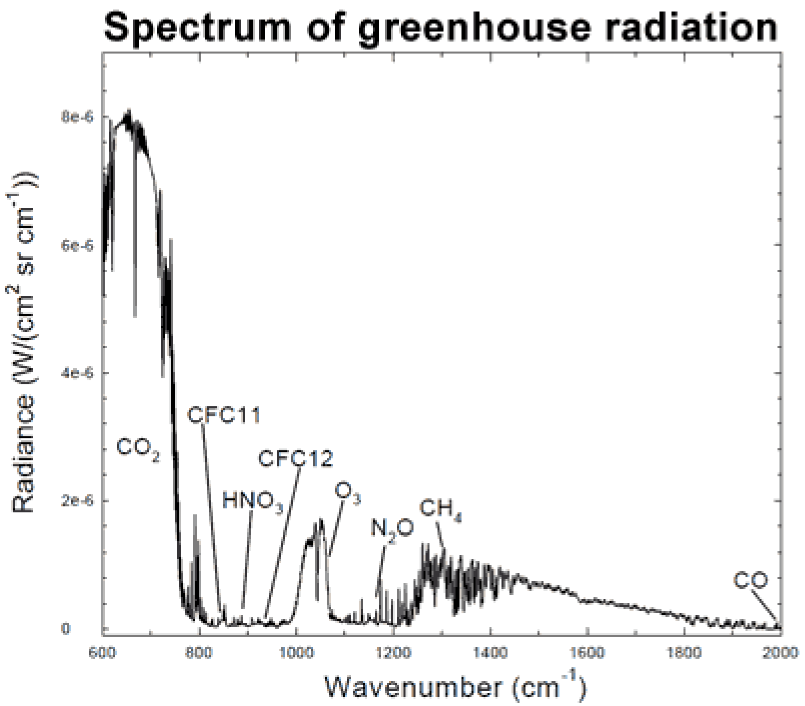


- Slow cycle takes ca. 100 million years, whereas the fast cycle takes ca. 10-100 years (living thing lifespan)
- By burning fossil fuels, we shift carbon from the slow cycle into the fast cycle (carbon from the Earth's crust is extracted and burned for energy)
- Corresponding increase in *global temperature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

Nasa _ Carbon cycle

Global warming





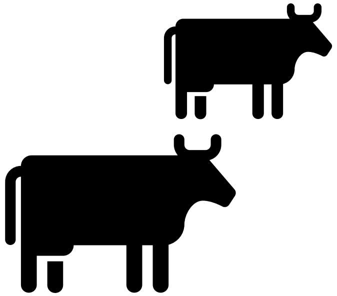
- Earth absorbs sunlight and reradiates it as infrared (heat)
- GHGs absorb specific infrared wavelengths
- If unimpeded, infrared travels through the atmosphere and back into space
- Too high a concentration of GHGs (like CO_2) is a problem, as these gases absorb infrared light, re-emit it in all directions, leading to warming beyond the greenhouse effect – global warming

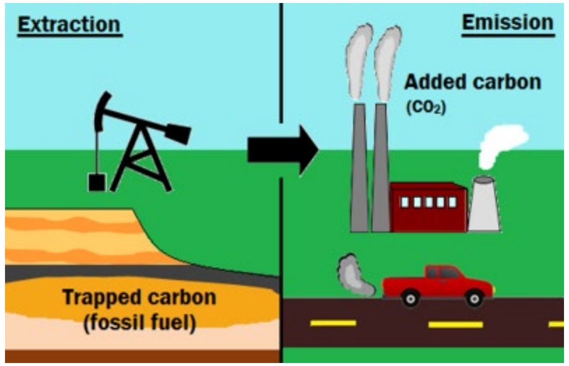
Global warming

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

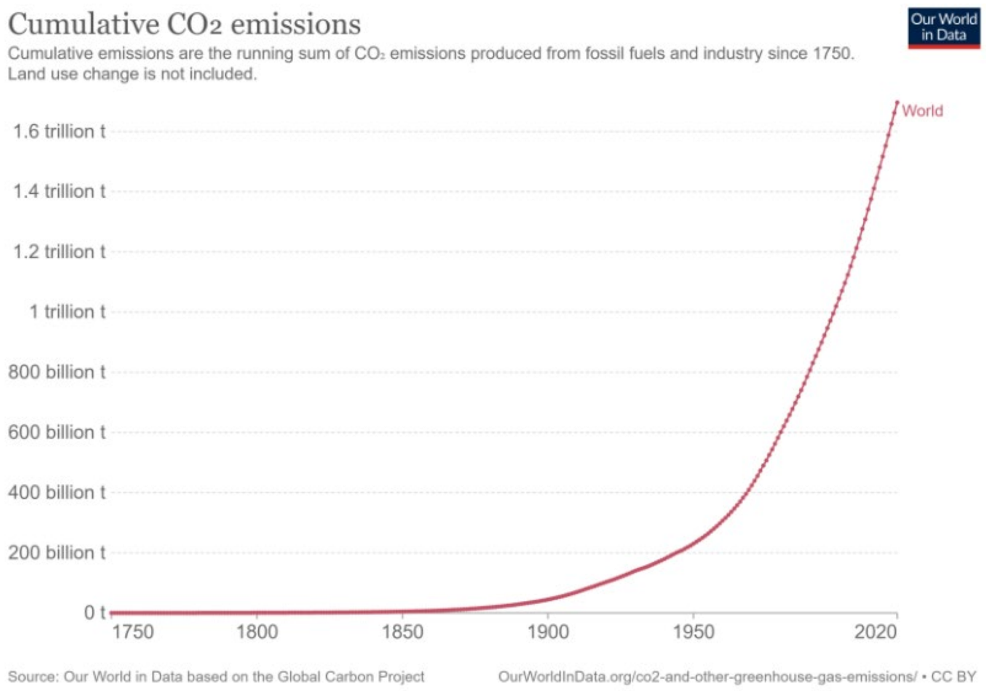


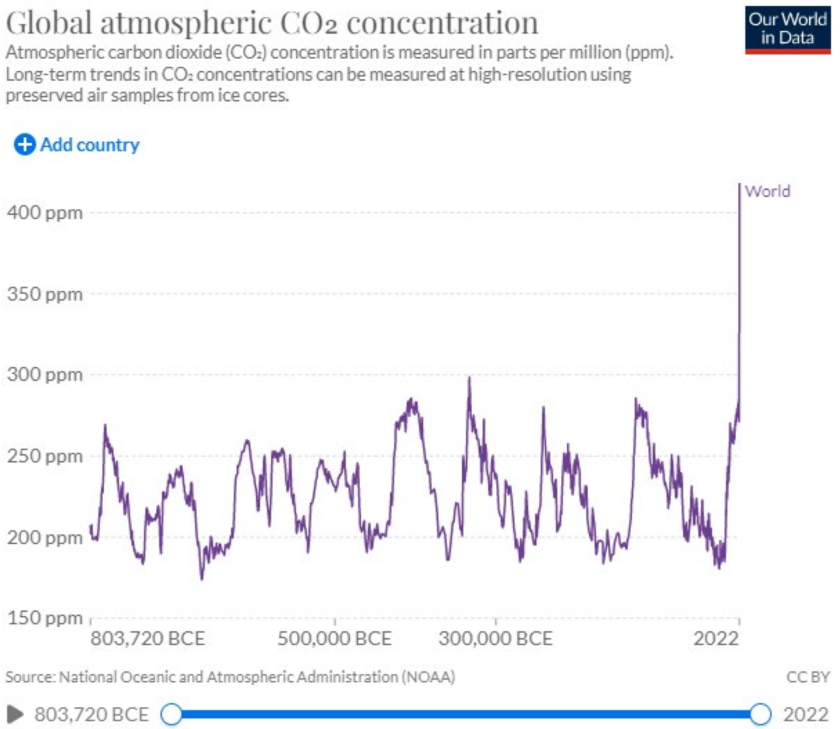


https://www.epa.gov/ghgemissions/overview-greenhouse-gases
https://energyeducation.ca/encyclopedia/Anthropogenic_carbon_emissions

Anthropogenic activities related to carbon emissions

- CO_2 emissions associated with human activity
- Most of the increase occurring after 1950

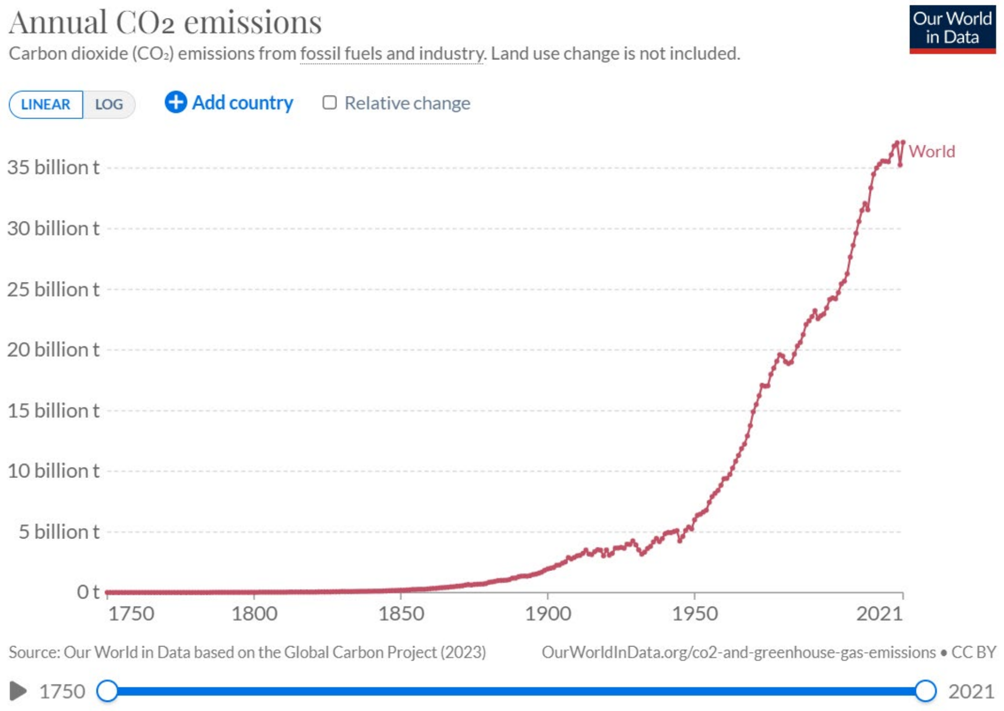


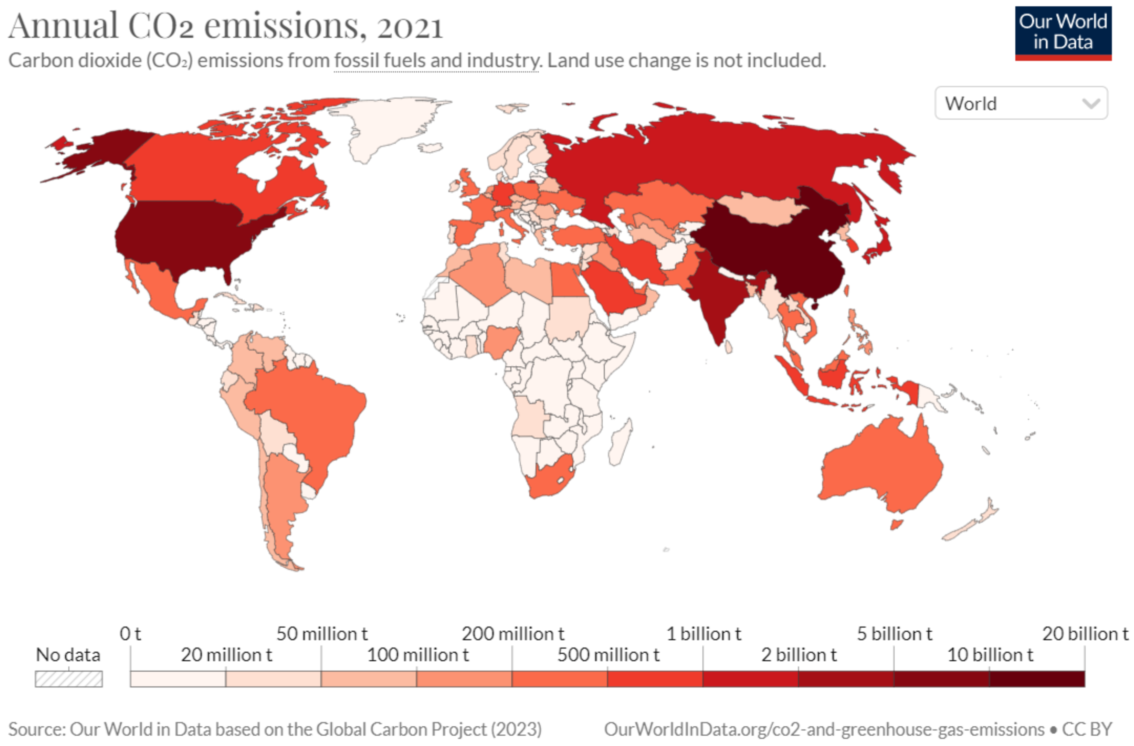


https://ourworldindata.org/co2-and-greenhouse-gas-emissions

Carbon emissions (fossil fuels + industry)

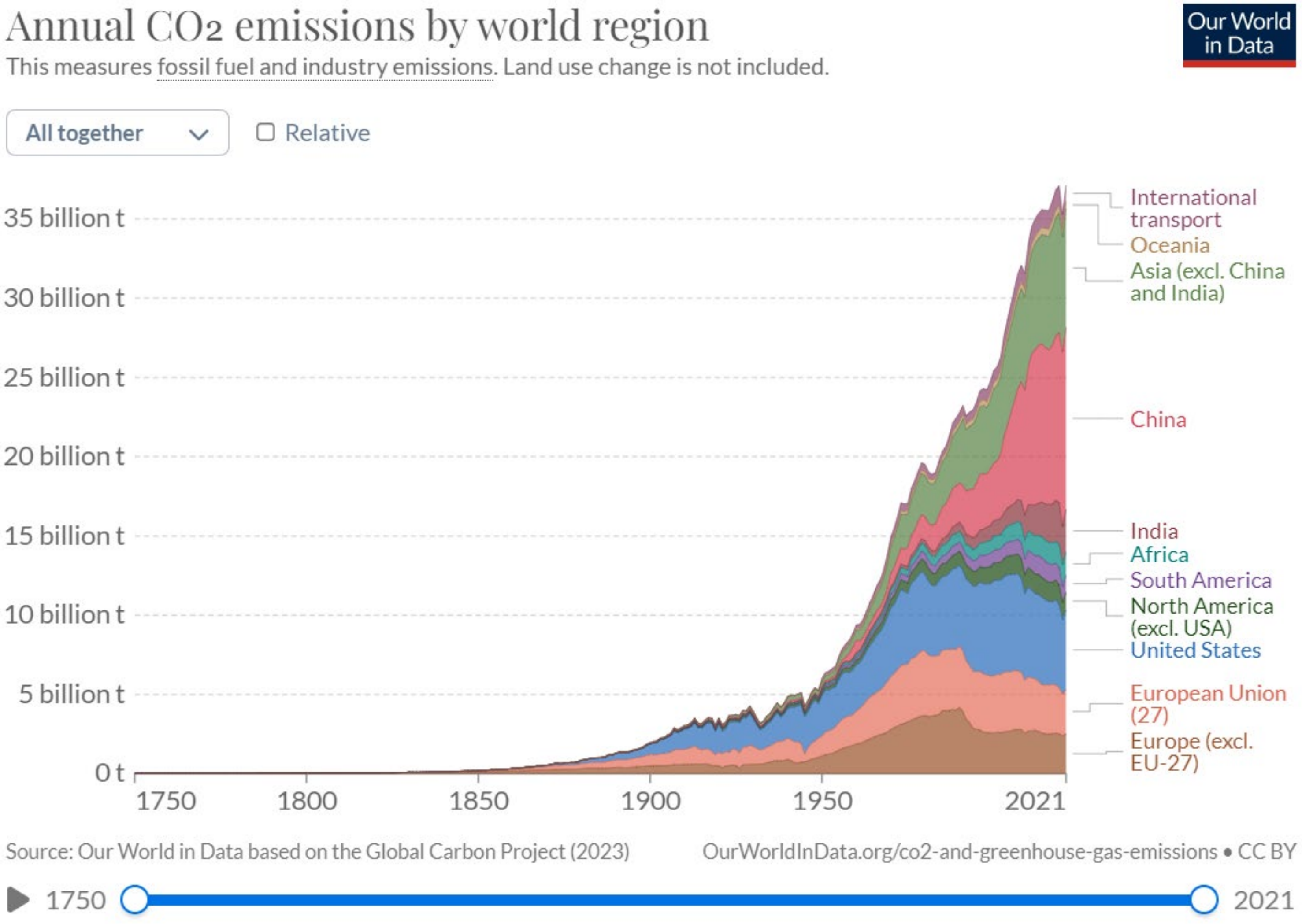
Global CO2 emissions





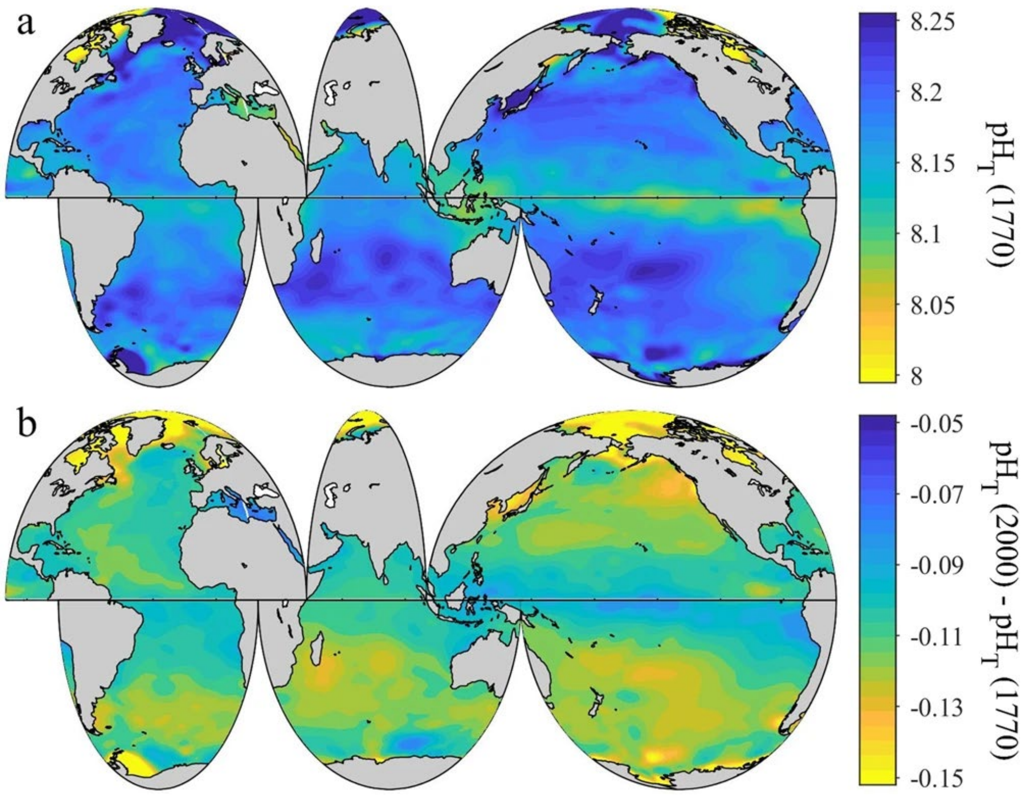
- In 1950 – 6 billion tonnes global CO_2 emissions
- In 1990 – almost 4-fold increase to 22 billion tonnes
- Current – more than 34 billion tonnes/year

Carbon emissions



- Well into 20th century, emissions dominated by Europe and US – e.g., 90% of emissions in 1900, and >85% of annual emissions even by 1950
- Scenario changed after 1950 with significant rise in emissions in the rest of the world, most notably in China
- Europe and US now account for less than 1/3 of global emissions

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

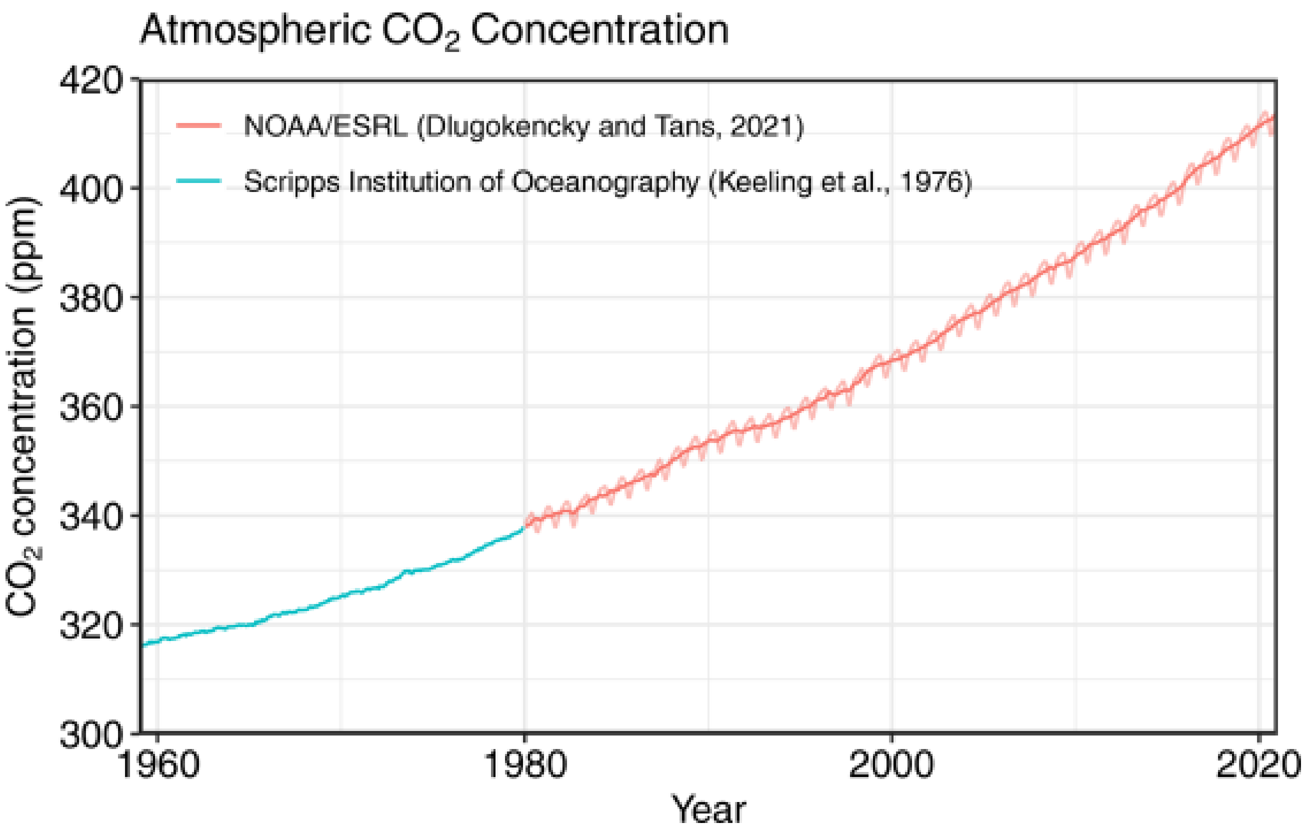
Dynamic equilibrium:

- CO_2 (dissolved) + $H_2O \rightleftharpoons H_2CO_3$
- $H_2CO_3 \rightleftharpoons H^+ + HCO_3^-$
- $HCO_3^- \rightleftharpoons 2H^+ + CO_3^{2-}$

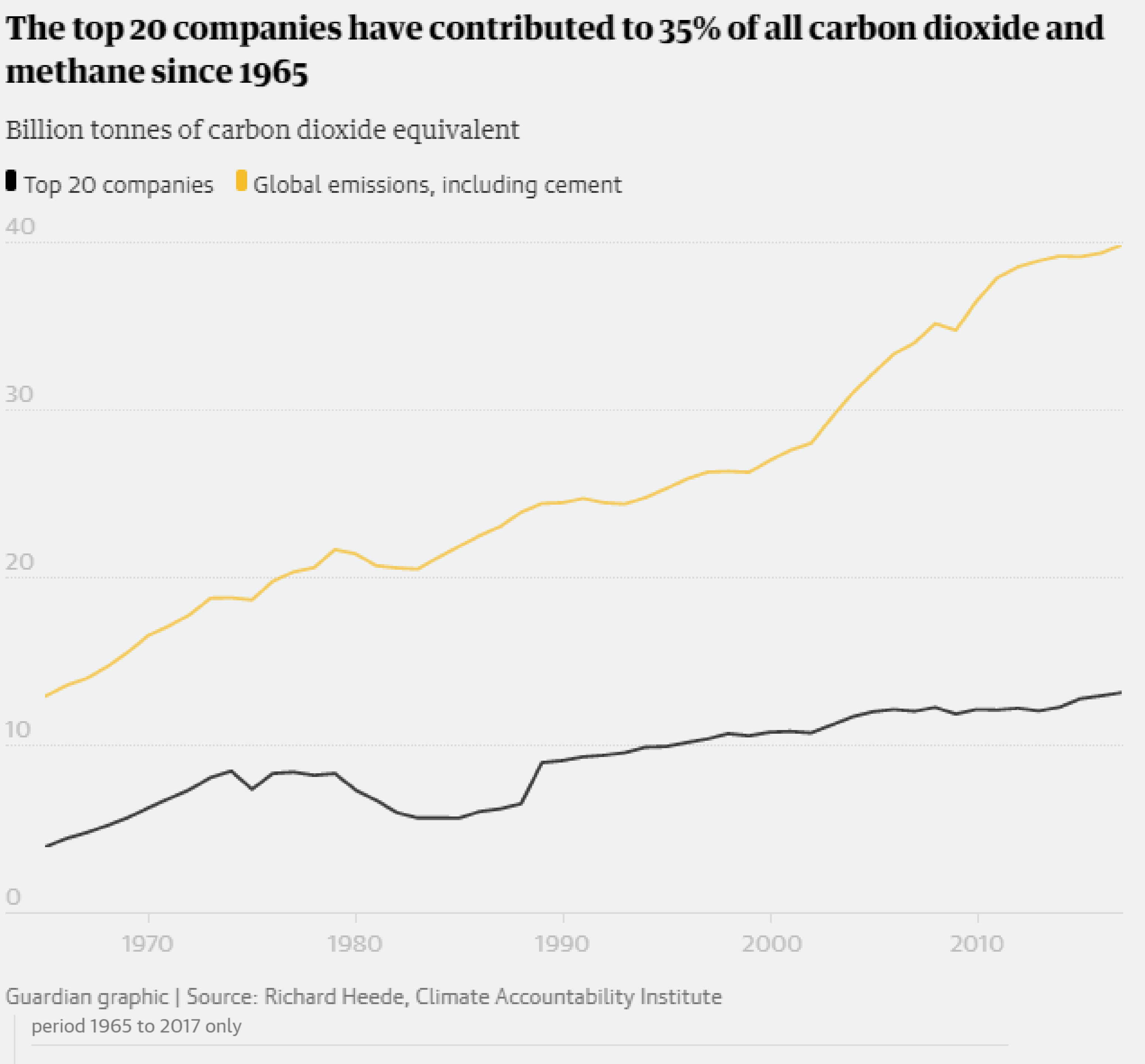
- Typically this buffering system keeps ocean pH relatively stable at around 8
- Too much CO_2, buffer capacity is reduced, and net effect is acidification
- Interferes with shell formation
- Colder waters are more vulnerable to acidification due to their ability to hold more dissolved gases

Global carbon breakdown

- Emissions up 49% from pre-industrial levels to 421 ppm in 2022 from 277 ppm in 1750



Global carbon budget

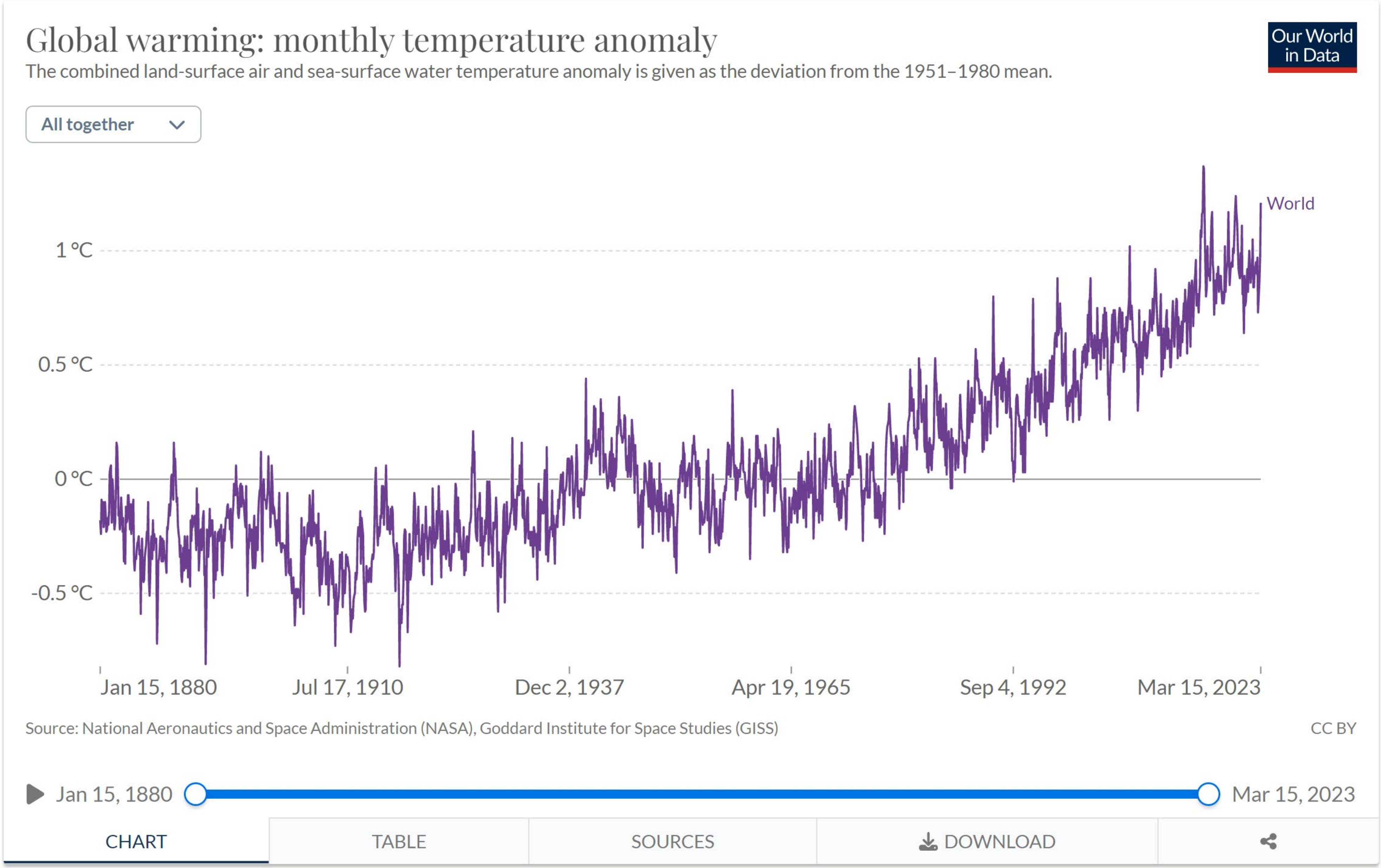


Top 20 CO_2 emitting companies

"The great tragedy of the climate crisis is that seven and a half billion people must pay the price – in the form of a degraded planet – so that a couple of dozen polluting interests can continue to make record profits. It is a great moral failing of our political system that we have allowed this to happen."

The Guardian article_2019

Global temperature anomaly



Anthropogenic carbon

Where does it come from?

89%

34.8 $GtCO_2/yr$

Fossil fuel emissions

11%

4.1 $GtCO_2/yr$

Emissions from land use change

(mostly deforestation)

- Mainly from burning fossil fuels
- Small part from new cement

[Global carbon budget](#)

[Global Carbon Project](#)

Anthropogenic carbon

Where does it go?

48%
18.6 $GtCO_2$/yr
Atmosphere

29%
11.2 $GtCO_2$/yr
Vegetegation & Soils
(terrestrial biosphere)

26%
10.2 $GtCO_2$/yr
Oceans
(terrestrial biosphere)

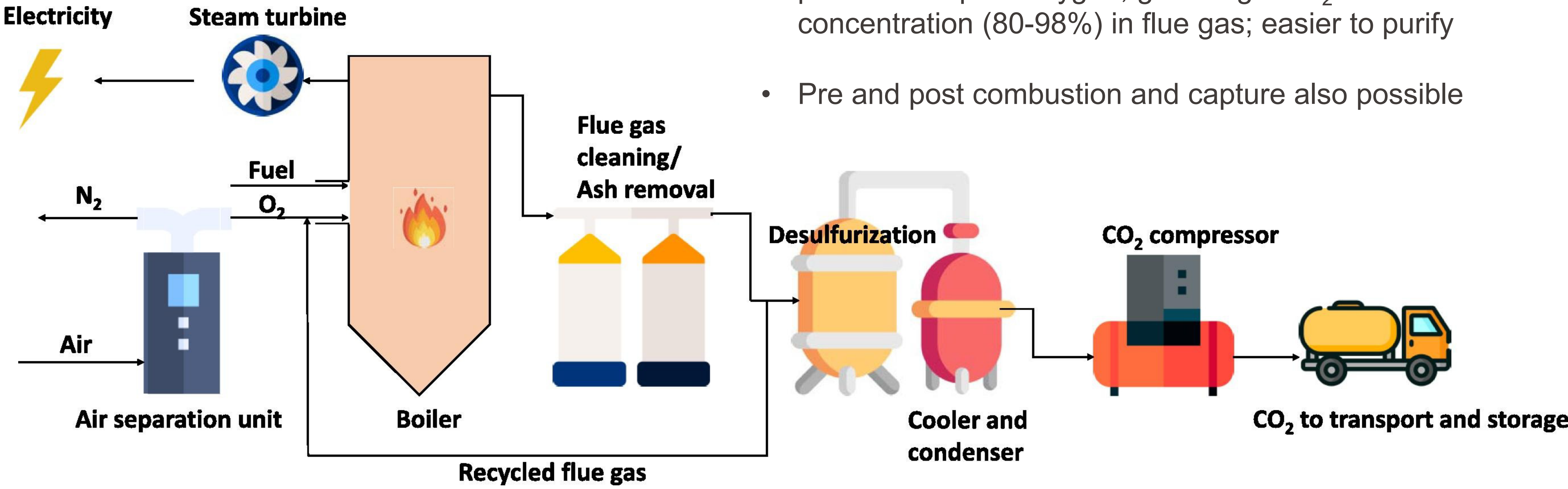
- From 2011-2020: about 55% of global emissions absorbed by terrestrial biosphere and oceans
- The remainder goes to the atmosphere!

Global carbon budget

Global Carbon Project

Limiting CO_2 emissions

- Flue gas from burning fossil fuels: 70% N_2, 15% CO_2, lesser amounts H_2O, NO_X, CO, SO_X
- Oxy-fuel combustion capture – combustion in the presence of pure oxygen; gives high CO_2 concentration (80-98%) in flue gas; easier to purify
- Pre and post combustion and capture also possible



https://doi.org/10.1016/j.cej.2021.130884

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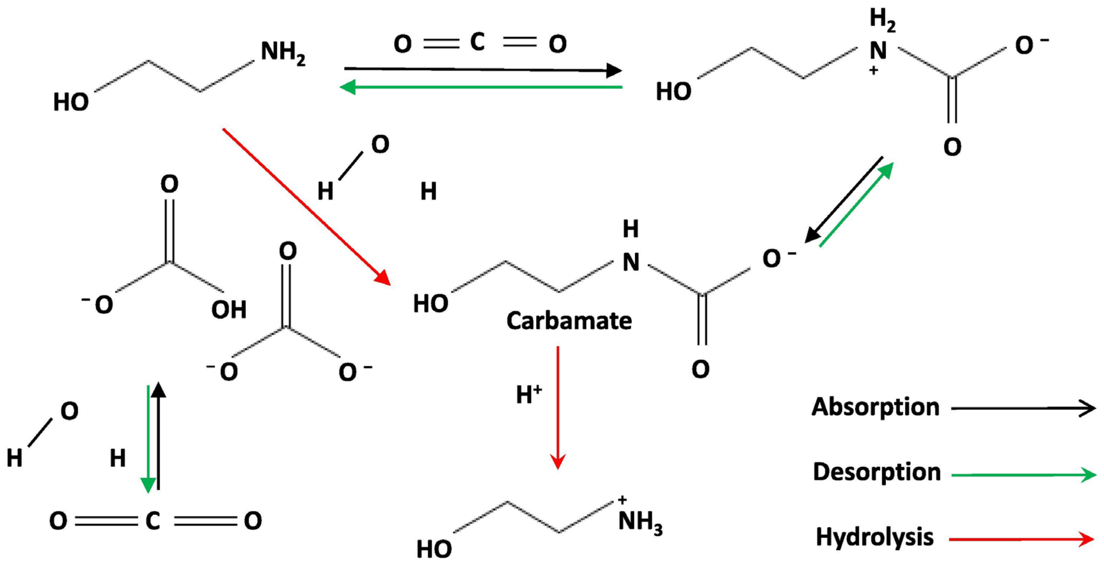
Conventional CO_2 capture - absorption

- Gas mixture containing CO_2 is reacted with a solvent that can dissolve gaseous CO_2 into a liquid phase
- Depending on solvent, absorption can be physical or chemical
- In chemical absorption, solvents, like MEA (monoethanolamine) or other amine-based alkali solvents, form strong bonds with CO_2 under atmospheric conditions
- First method that has been implemented on an industrial-scale for post-combustion carbon capture



Other methods:
Adsorption
Membranes

https://doi.org/10.1016/j.cej.2021.130884

What can we do with CO_2 after it is captured? Storage & utilization

Storage:

1. Geological storage (underground, depleted oil/gas reservoirs)
2. Ocean storage (deep water/sea floor)
3. Mineral carbonation (convert CO_2 to insoluble carbonates)

Utilization:

1. Enhanced oil recovery (EOR) – inject CO_2 into oil fields to enhance oil recovery, CO_2 remains underground after oil extraction
2. Industrial uses – manufacture of fuels, chemicals, materials
3. Agriculture – enhancing plant growth in greenhouses
4. Food and beverage – carbonation, preservation
5. Biofuel – feeding to bacteria or algae to produce biofuel

https://doi.org/10.1016/j.cej.2021.130884

Carbon capture and storage (CCS)

- CCS dates back to the 1970s – idea of collecting, pipeline transporting, and storing CO_2 into deep ocean reservoirs or cavities of natural gas and oil – preventing its emission to the atmosphere (2018 Nobel Prize in Economics)

- Worry – risk of ocean acidification caused by leaks

- From article: only 19 active CCS facilities, with an annual storage capacity pf **40 million tons**, equivalent to about 0.1% total annual CO_2 emissions

https://doi.org/10.1016/j.cej.2021.130884

How many Gt of CO_2 do we need to remove from the atmosphere?

1 Gt = 1 billion metric tonnes
Ppm = parts per million
Mass of the atmosphere = 5.1 $\times 10^{18}$ kg
MW of air is 29 g/mol (mix of gases, 78% nitrogen)
MW of CO_2 = 44 g/mol

- Let's say we would like to remove 100 ppm of CO_2 from the atmosphere to bring us down to 300 ppm
- Mass of 100 ppm CO_2 in atmosphere = 100/1000000* 5.1 $\times 10^{18}$ kg* 44/29 = 7.7 $\times 10^{14}$ kg = **770 Gt**
- Geological storage capacity is estimated at 675-900 Gt for depleted oil/gas fields & 1000-10000 Gt for deep saline formations
- Easy peasy? (Capturing CO_2 from air is not straightforward and highly energy intensive!)

Carbon capture, utilization, and storage (CCUS)

- Enhanced oil recovery (EOR)
- Enhanced gas recovery (EGR)
- Enhanced coalbed recovery (ECBR)
- Enhanced water recovery

- Is continuing fuel extraction a good long term solution?

https://doi.org/10.1016/j.cej.2021.130884

CCU and CCUS

- CCU and CCUS are viewed as “short-term partial solutions to reduce atmospheric CO_2 concentrations?”

Why?

- Address symptoms (high CO_2 levels) but not root cause (emissions)
- Buy time until better solutions can be developed and implemented
- 85-95% capture rates
- Target point sources
- Enormous infrastructure would need to be put in place
- High cost and energy requirements
- Limits to the amount of CO_2 that can be safely stored underground

https://doi.org/10.1016/j.cej.2021.130884

Mineral carbonation as a mimic for natural weathering

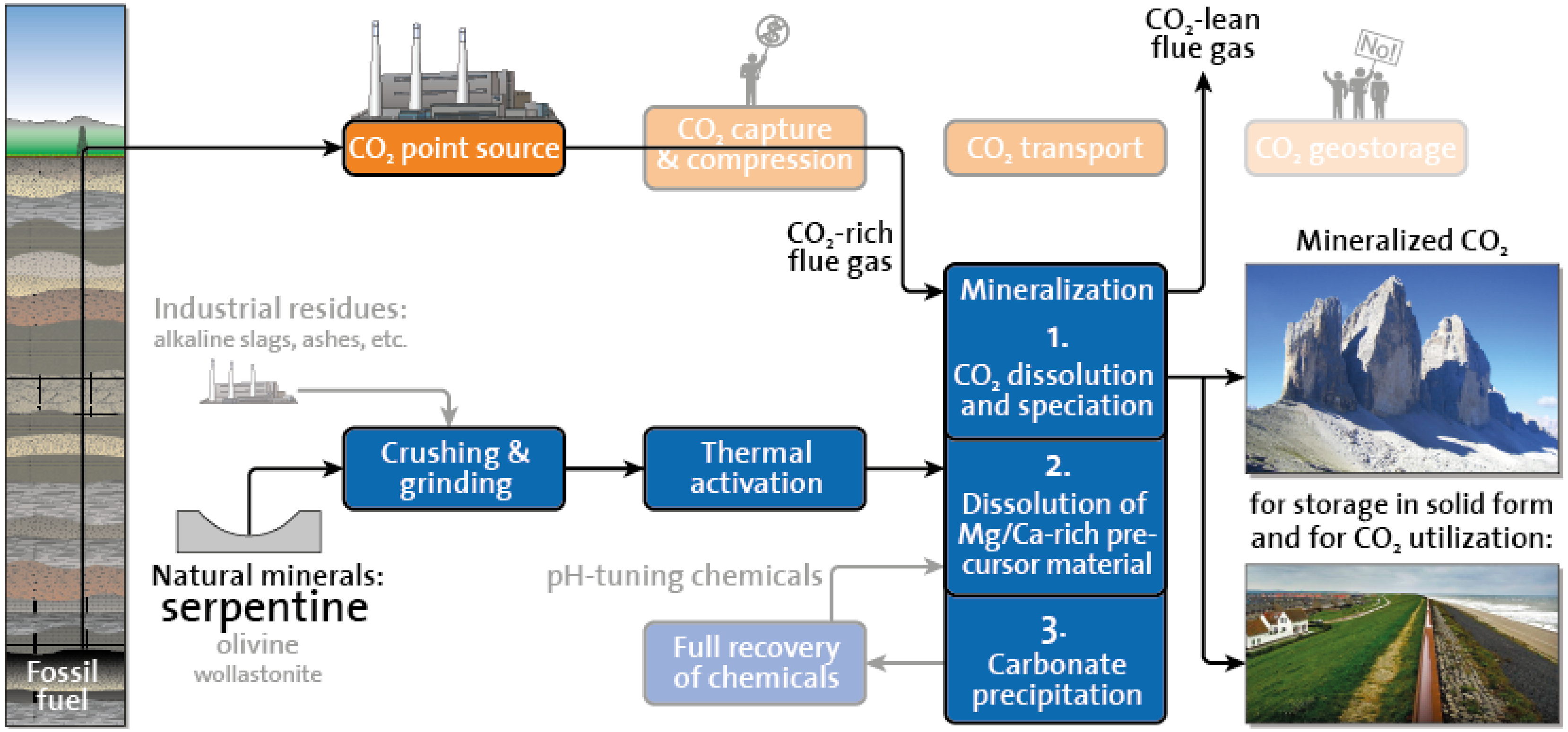
Natural weathering:

- Rocks rich in calcium and magnesium silicates react with CO_2 over long period in a process called chemical weathering
- CO_2 dissolves in rain water, forming carbonic acid (H_2CO_3), which reacts with the silicate minerals, producing bicarbonate (HCO_3^-) and metal ions. These ions can precipitate as carbonate minerals (e.g., limestone).

Engineered weathering:

- CO_2 is captured from industrial sources or air, mixed with water to form carbonic acid solution & exposed to finely ground silicates, producing bicarbonate and metal ions, which can be precipitated into carbonate minerals

Mineralization



Prof. Dr. Marco Mazzotti
Mechanical and Process Engineering

https://spl.ethz.ch/research/development/carbonation.html

Photosynthesis: nature-made CCU (carbon capture and utilization) technology

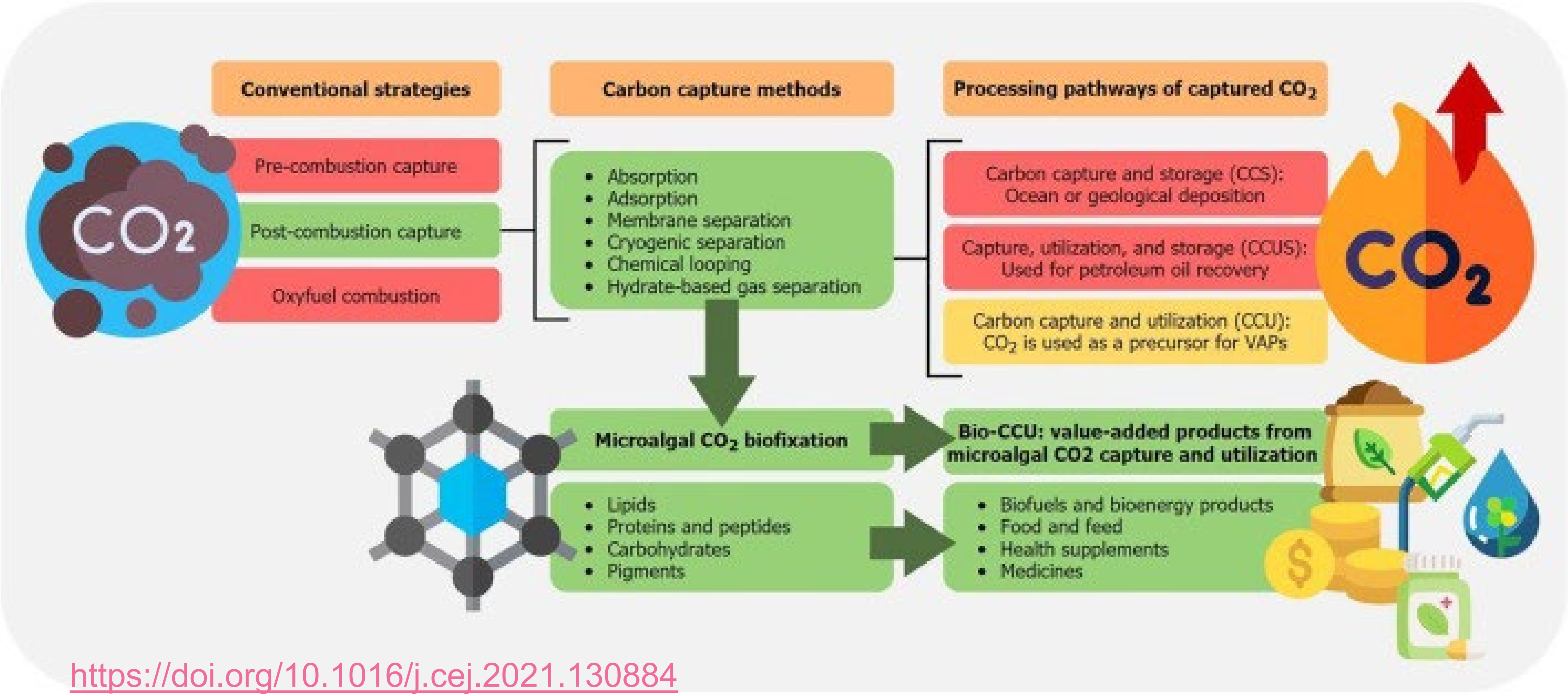


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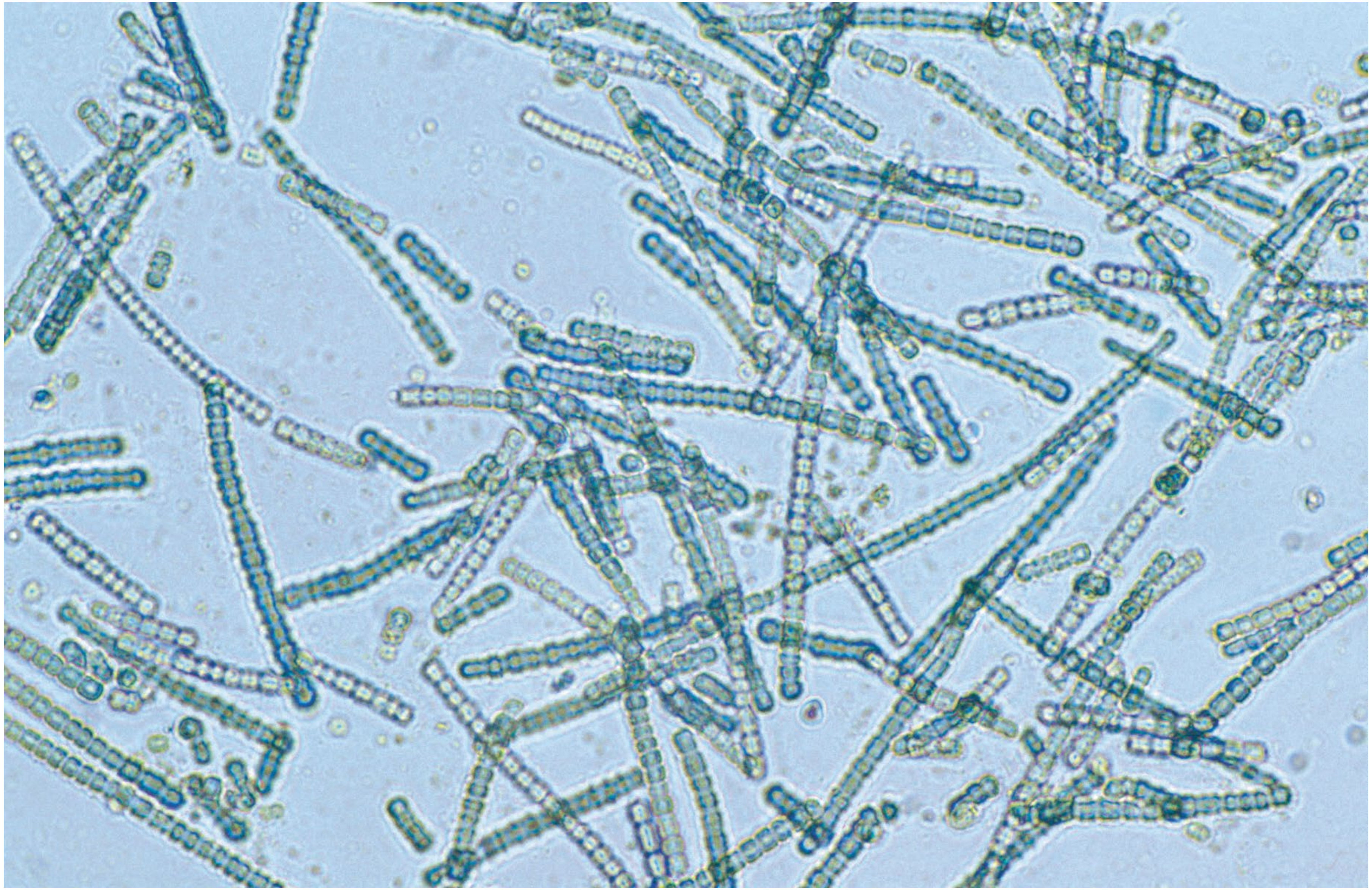
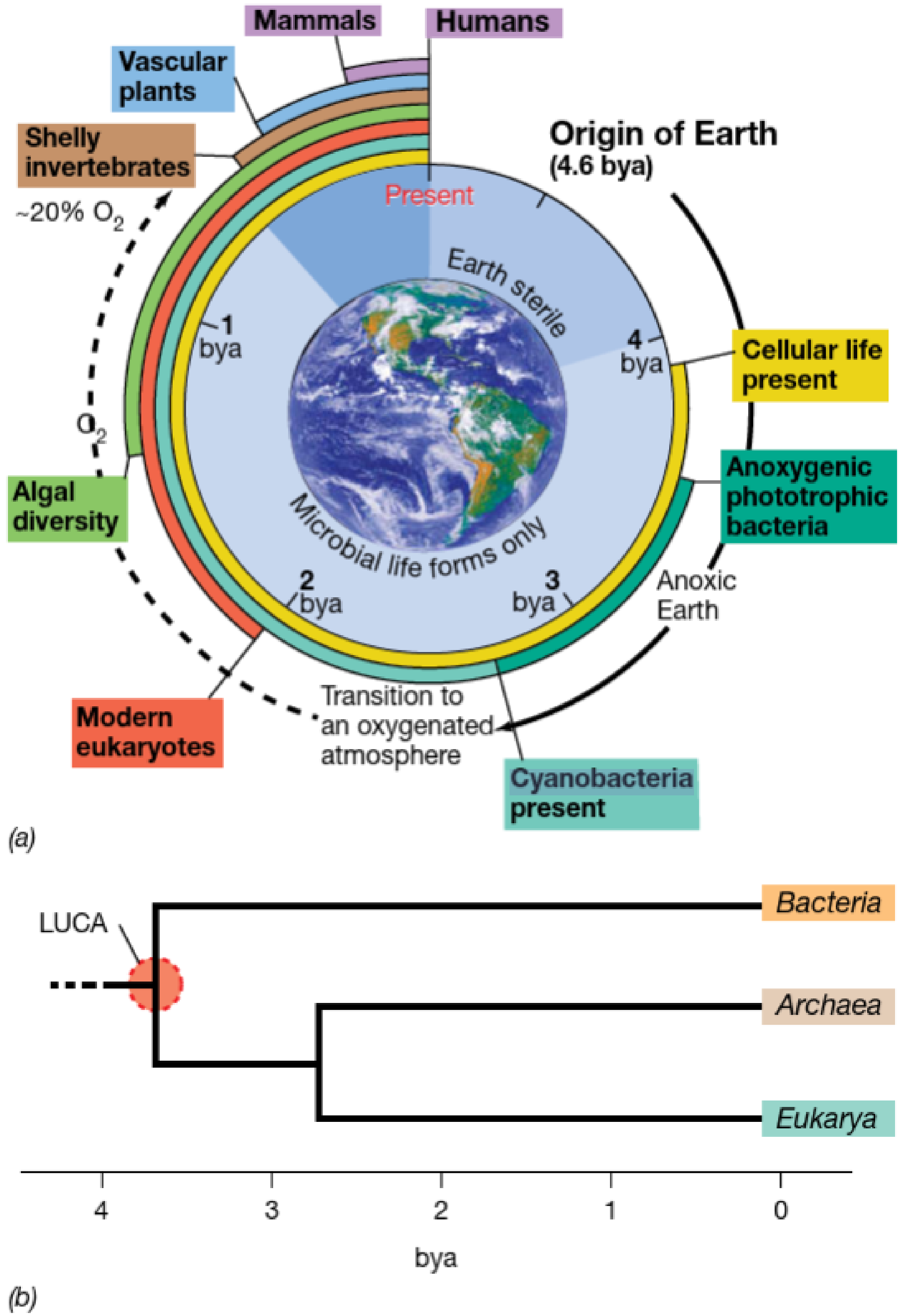
Table 1
CO_2 bio-fixation efficiency by various microalgae species under different experimental conditions.

Species	CO_2 %	Aeration rate	CO_2 biofixation rate	Temperature (°C)	Initial pH	Culture medium	Biomass production	References
Botryococcus braunii	10% mixed with N_2	0.1 vvm	356 mg/L/day	20	–	BG11	0.41 g/L	[117]
	20% mixed with N_2	0.1 vvm	532 mg/L/day	20	–	BG11	0.26 g/L	
Scenedesmus sp.	10% mixed with N_2	0.1 vvm	347 mg/L/day	20	–	BG11	0.90 g/L	
	20% mixed with N_2	0.1 vvm	2177 mg/L/day	20	–	BG11	1.95 g/L	
Heynigia riparia SX01	0.03% (Ambient air)	0.13 vvm	0.27 g/L/day	28	8	BG-11	1.28 g/L	[118]
	5% mixed with air	0.13 vvm	0.37 g/L/day	28	8	BG-11	2.37 g/L	
	10% mixed with air	0.13 vvm	0.46 g/L/day	28	8	BG-11	2.76 g/L	
	15% mixed with air	0.13 vvm	0.71 g/L/day	28	8	BG-11	3.28 g/L	
Chlorella vulgaris ESP-31 (wild type)	Simulated flue gas containing 25% CO_2	0.1 vvm	53.35 mg/L/day	40	7.4	BG-11	0.15 g/L	[119]
Chlorella vulgaris ESP-31 (mutant 283)	Simulated flue gas containing 25% CO_2	0.1 vvm	272.06 mg/L/day	40	7.4	BG-11	0.78 g/L	
Chlorella vulgaris ESP-31 (mutant 359)	Simulated flue gas containing 25% CO_2	0.1 vvm	194.03 mg/L/day	40	7.4	BG-11	0.64 g/L	
Dunaliella salina	Ambient air	0.5 vvm	0.055 g/L/day	24	8	f/2 medium	~ 0.22 g/L	[68]
	6% mixed with air	0.5 vvm	0.067 g/L/day	24	8	f/2 medium	~ 0.26 g/L	
	20% mixed with air	0.5 vvm	0.016 g/L/day	24	8	f/2 medium	~ 0.09 g/L	
	20% mixed with N_2 (constant flow rate)	0.5 vvm	0.043 g/L/day	24	8	f/2 medium	~ 0.30 g/L	
	20% mixed with N_2 (gradual increasing CO_2 level)	0.5 vvm	0.106 g/L/day	24	8	f/2 medium	~ 0.16 g/L	
Chlorella vulgaris P12	2% mixed with air	0.4 vvm	1.5 g/L/day	30	7	Synthetic medium	6.90 g/L	[120]
	6% mixed with air	0.4 vvm	2.29 g/L/day	30	7		10 g/L	
	10% mixed with air	0.4 vvm	1.93 g/L/day	30	7		8.60 g/L	
Chlorella sp.	Flue gas containing 10% CO_2	0.5 vvm	261 mg/L/day	28	8.1	Domestic wastewater + poultry waste	1.20 g/L	[121]
Scenedesmus obtusiusculus	Flue gas containing 4–5% CO_2	–	111.4 mg/L/day	28	8	BG-11	1.09 g/L	[122]
Chlorella vulgaris (ISC-23)	6% mixed with air	0.5 vvm	3.222 g/L/day	27	7.4	BG11	14.30 g/L	[123]
Chlorella sp. LAMB 31 (high-CO2 tolerant strain)	40% mixed with air	–	0.144 g/L/day	26	6	BG11	~ 1 g/L	[124]
Chlorella sp. LAMB 122 (high-CO2 non-tolerant strain)	40% mixed with air	–	0.017 g/L/day	26	6	BG11	~ 0.32 g/L	
Chlorella sp. C-1 (control set)	Ambient air	0.5 vvm	0.357 g/L/day	30	7–8	3N-BBM	1.22 g/L	[125]
Chlorella sp. E–1 (experimental set)	Flue gas containing 10% CO_2	0.5 vvm	0.469 g/L/day	30	7–8	3N-BBM	1.69 g/L	

Cyanobacteria



[Cyanobacteria]



A MICROBIAL PLANET

- Estimated Earth age = 4.6 billion years
- Microbial cells appeared 3.8-4.3 bya
- In first 2 billion y, earth was anoxic
- Only microorganisms with anerobic metabolisms
- Phototropic organisms (harvest energy from sun) appeared within the first billion years
- The 1st of these were anoxygenic (non-oxygen producing)
- Nearly 1 billion years later, cyanobacteria evolved
- Cyanobacteria are oxygenic photoautotrophs and started the process of oxygenating the atmosphere
- After oxygenation, multicellular organisms began to evolve, eventually plants and animals in the last half billion years
- 80% of life's history was exclusively microbial

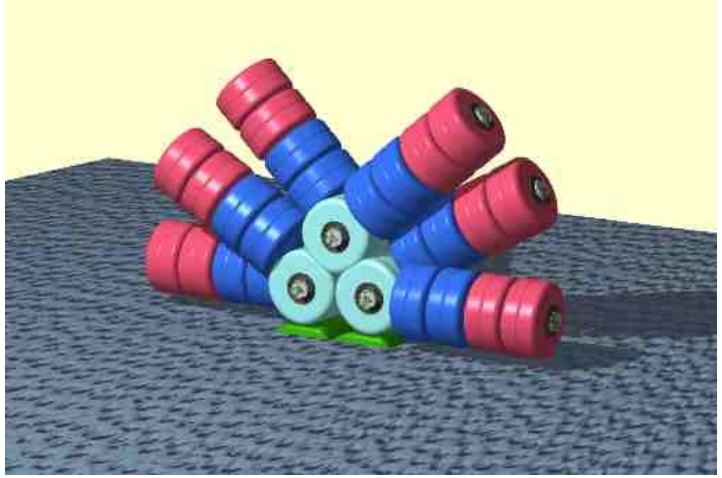
Brock Biology of Microorganisms, Global Edition

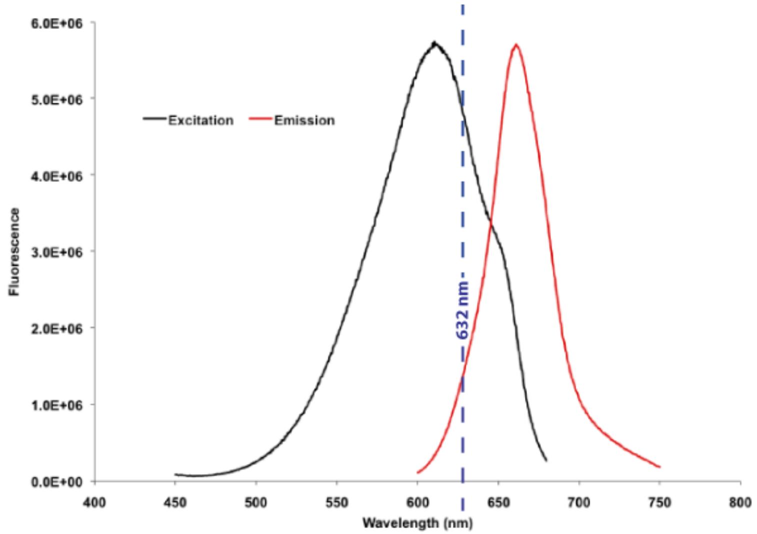
Cyanobacteria (formerly called blue-green algae)

- Gram negative
- Chromophores: Chlorophyll a, phycobilins (phycocyanin and allophycocyanin), carotenoids
- Light absorption: Chlorophyll a absorbs blue and red, phycobilins absorb green and orange – combination targets broad visible spectral range
- Light harvesting complex called phycobilisomes
- Fixate carbon, produce oxygen (oxygenic photosynthesis)

Phycobilisome

The layout of protein subunits in a phycobilisome





Fluorescence and emission spectra for SureLight® P3 in 100 mM sodium phosphate (pH 7.2), 1mM EDTA, and 1mM sodium azide. Scans were normalized to equalize peak heights.

Microbially induced calcite precipitation (MICP)

- Different mechanisms, of which photosynthesis is one
- CO_2 and HCO_3- uptake by photosynthesis increases local pH
- Shifts equilibrium to favor CO_3^{2-}
- Cyanobacteria EPS can bind Ca^{+2}
- EPS acts a nucleation site for $CaCO_3$ crystal formation

Other mechanisms:

- *Urea hydrolysis*
- *Ammonification*
- *Denitrification*
- *Sulfate reduction*
- *Methane oxidation*

https://doi.org/10.3389/fmats.2019.00126

Features of cyanobacteria relevant to CCS

- Thrive at high CO_2 levels (e.g., flue gas)
- Halophilic - can be cultured in marine waters or other high salinity waters (e.g., brine from petroleum refining)
- Thermophilic – tolerate high temperatures (e.g., flue gas)
- Can enrich the amount of CO_2 up to 1000-fold the surrounding media
- Article describes calcification by cyanobacteria as “as a niche technology, preferably linked to small coal-fired power plants, natural gas systems, municipal solid waste combustion, and CO_2-emitting industries such as cement manufacture, and iron and steel production. If nation-wide distributions of such units were to be deployed in countries such as the U.S.A., China and India, the impact in mitigation of global greenhouse gas emissions could be enormous”

https://doi.org/10.1016/j.copbio.2010.03.017

Abstract

Natural ecosystems offer efficient pathways for carbon sequestration, serving as a resilient approach to remove CO_2 from the atmosphere with minimal environmental impact. However, the control of living systems outside of their native environments is often challenging. Here, we engineered a photosynthetic living material for dual CO_2 sequestration by immobilizing photosynthetic microorganisms within a printable polymeric network. The carbon concentrating mechanism of the cyanobacteria enabled accumulation of CO_2 within the cell, resulting in biomass production. Additionally, the metabolic production of OH^- ions in the surrounding medium created an environment for the formation of insoluble carbonates via microbially-induced calcium carbonate precipitation (MICP). Digital design and fabrication of the living material ensured sufficient access to light and nutrient transport of the encapsulated cyanobacteria, which were essential for long-term viability (more than one year) as well as efficient photosynthesis and carbon sequestration. The photosynthetic living materials sequestered approximately 2.5 mg of CO_2 per gram of hydrogel material over 30 days via dual carbon sequestration, with 2.2 ± 0.9 mg stored as insoluble carbonates. Over an extended incubation period of 400 days, the living materials sequestered 26 ± 7 mg of CO_2 per gram of hydrogel material in the form of stable minerals. These findings highlight the potential of photosynthetic living materials for scalable carbon sequestration, carbon-neutral infrastructure, and green building materials. The simplicity of maintenance, coupled with its scalability nature, suggests broad applications of photosynthetic living materials as a complementary strategy to mitigate CO_2 emissions.

Keywords: living materials, CO_2 sequestration, 3D printing

Keywords:

1. Carbon
2. Carbon sequestration
3. Photosynthesis
4. MICP
5. Cyanobacteria
6. Hydrogel – **last few weeks**
7. 3D printing – **last week**
8. Photosynthetic living materials