L07d

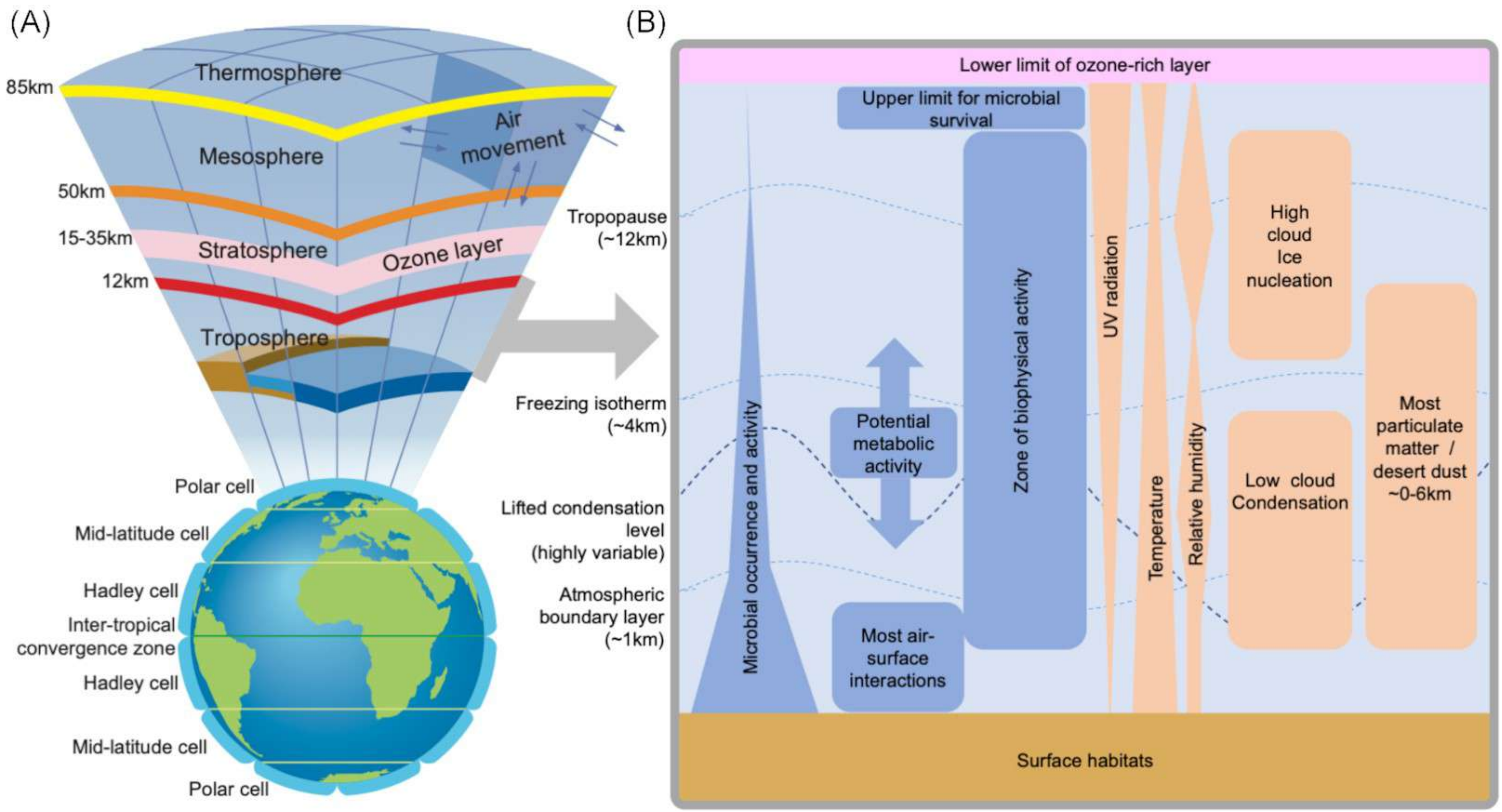
Microbial Ecology

- Study of the **interactions** of microorganisms with their **environment (including organic matter)**, **each other**, and plant and animal species (**other organisms**) —> symbioses, biogeochemical cycles, climate change

  - **Atmosphere as a microbial environment**
  - **Biogeochemical cycles in the environment (including pollution)**
  - **Anthropocene and Climate Change**

ATMOSPHERE

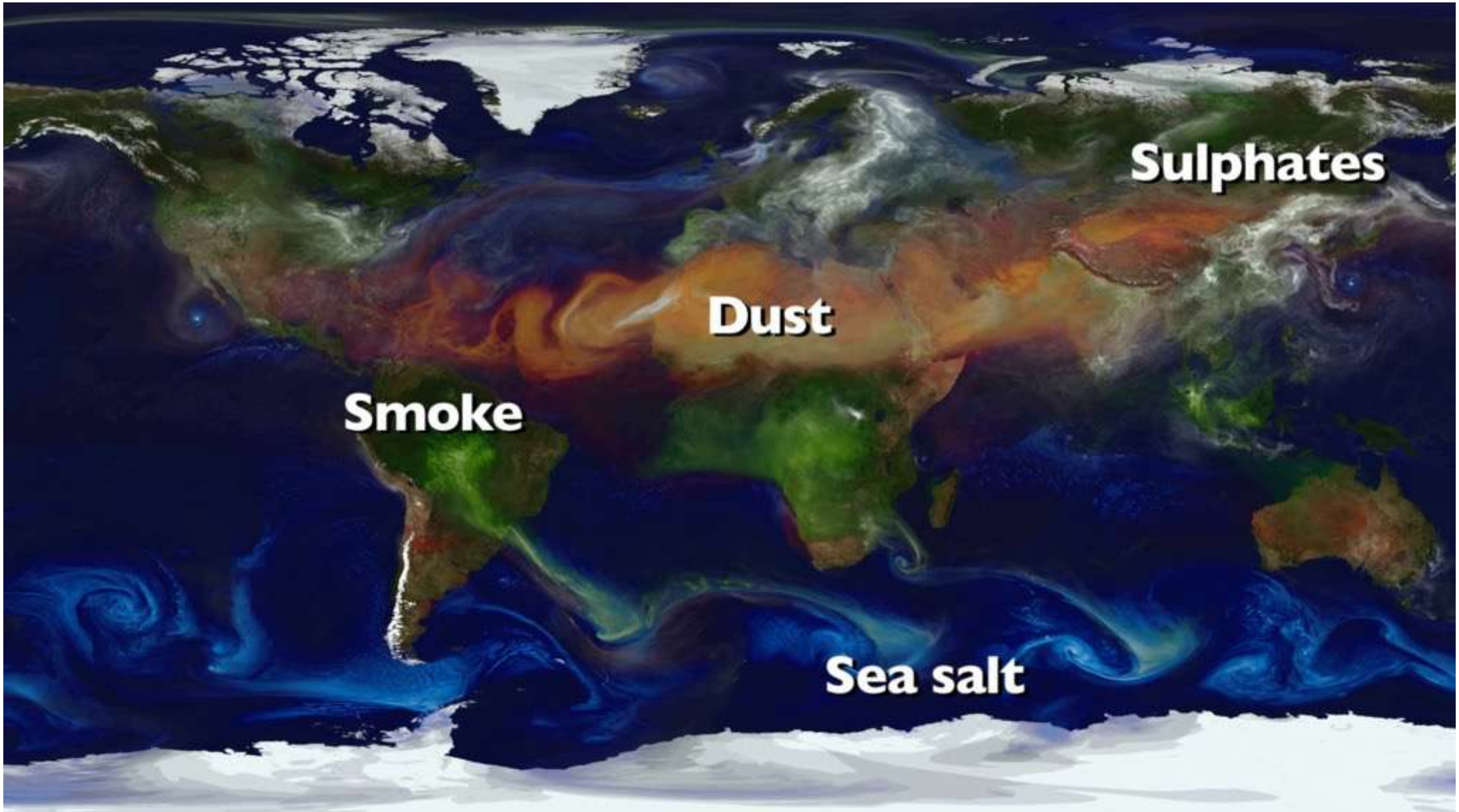
The atmospheric ecological niche



Šantl-Temkiv et. al., 2022

The atmospheric boundary layer delineates the region of air closest to the surface where the bulk of surface–atmosphere interactions occur, and this includes exchange of microorganisms with terrestrial and marine ecosystems

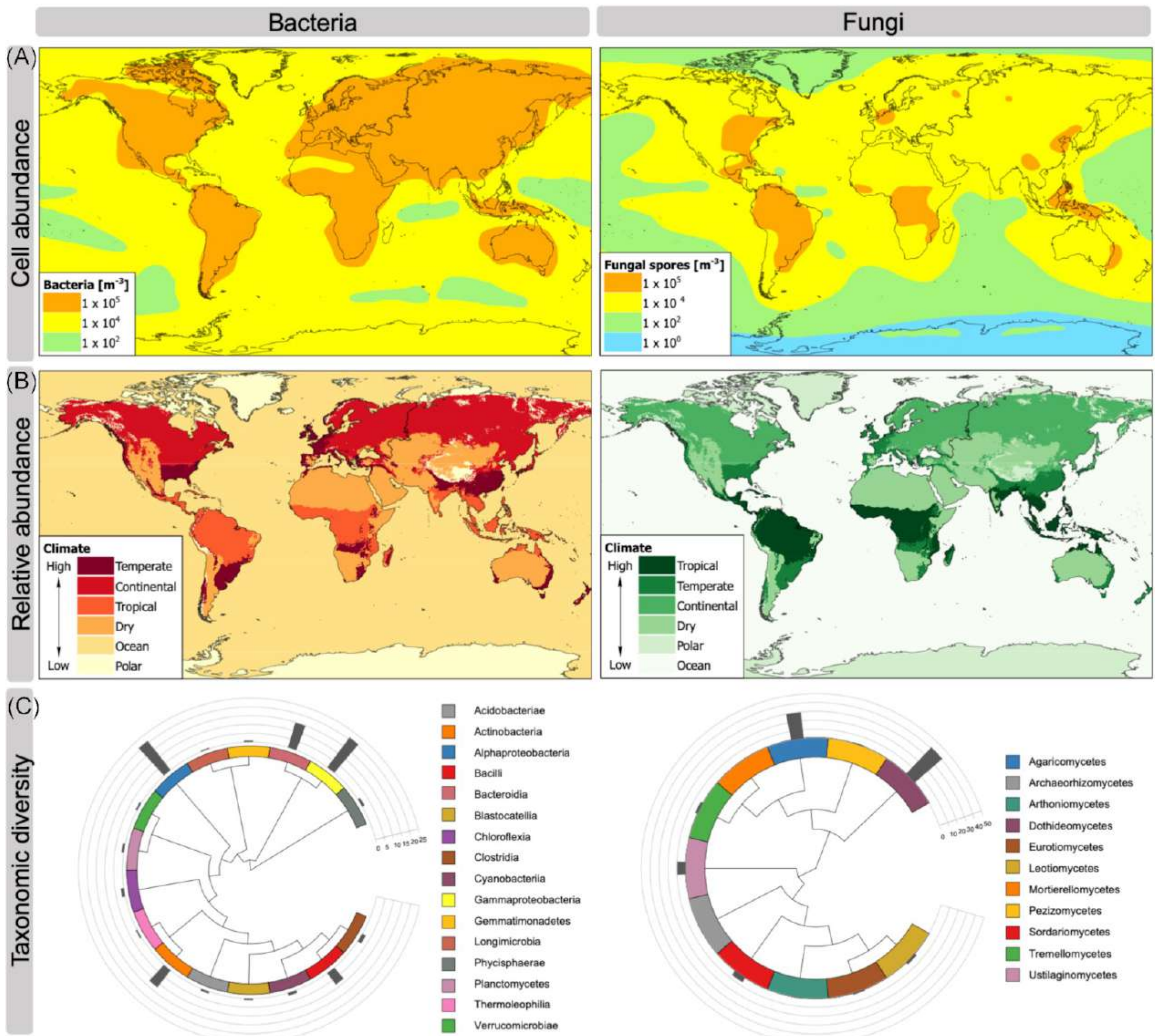
One Atmosphere that we all breath



Diverse aerosol particles
Atmospheric aerosols are a collection of small liquid droplets and/or solid particles suspended in air
Microbes exchange: 6 × 10^4 and 1.6 × 10^7 microbes per m^2 of ocean per day

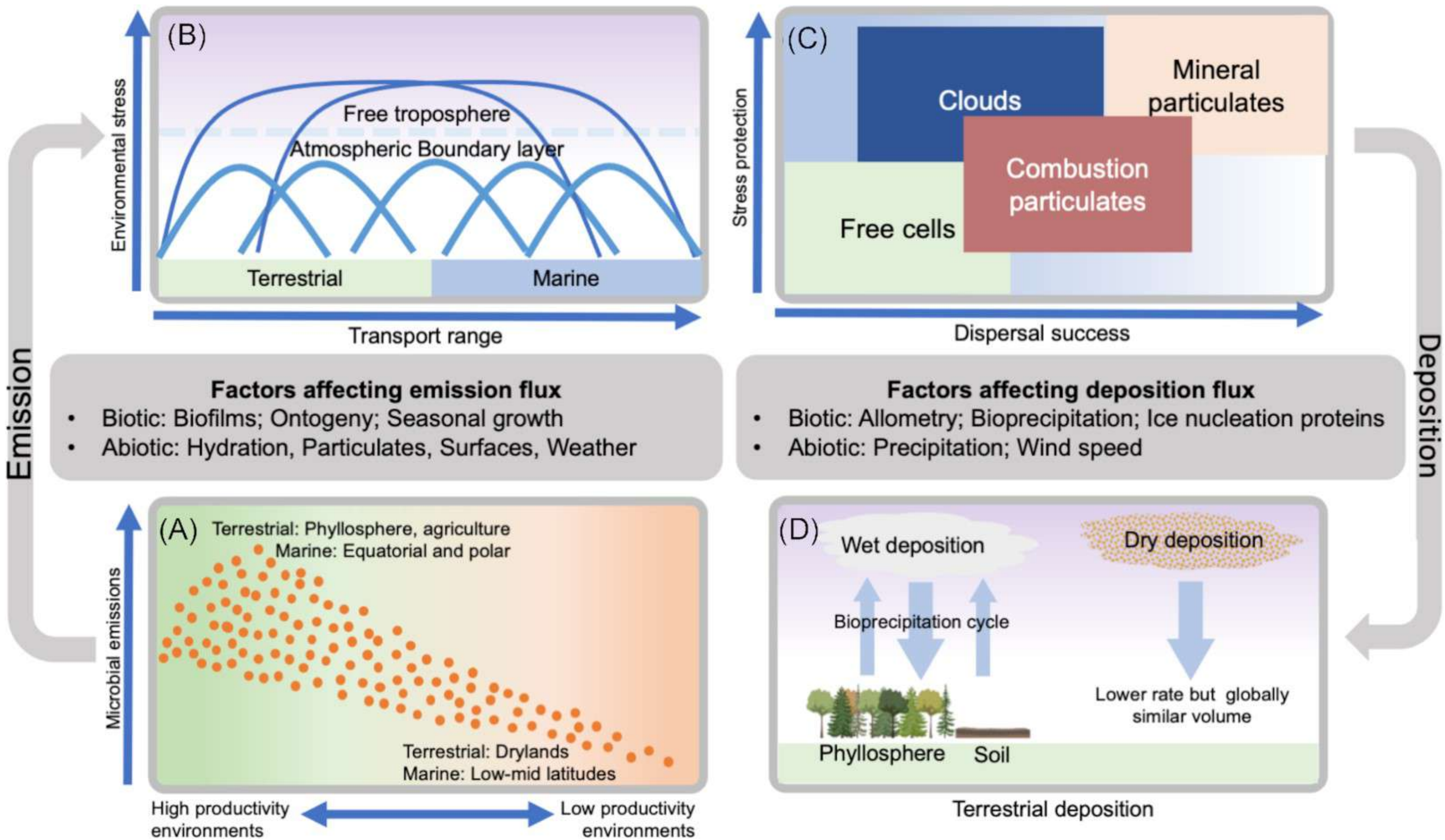
https://caice.ucsd.edu/

Patterns of microbial diversity and abundance in the atmosphere



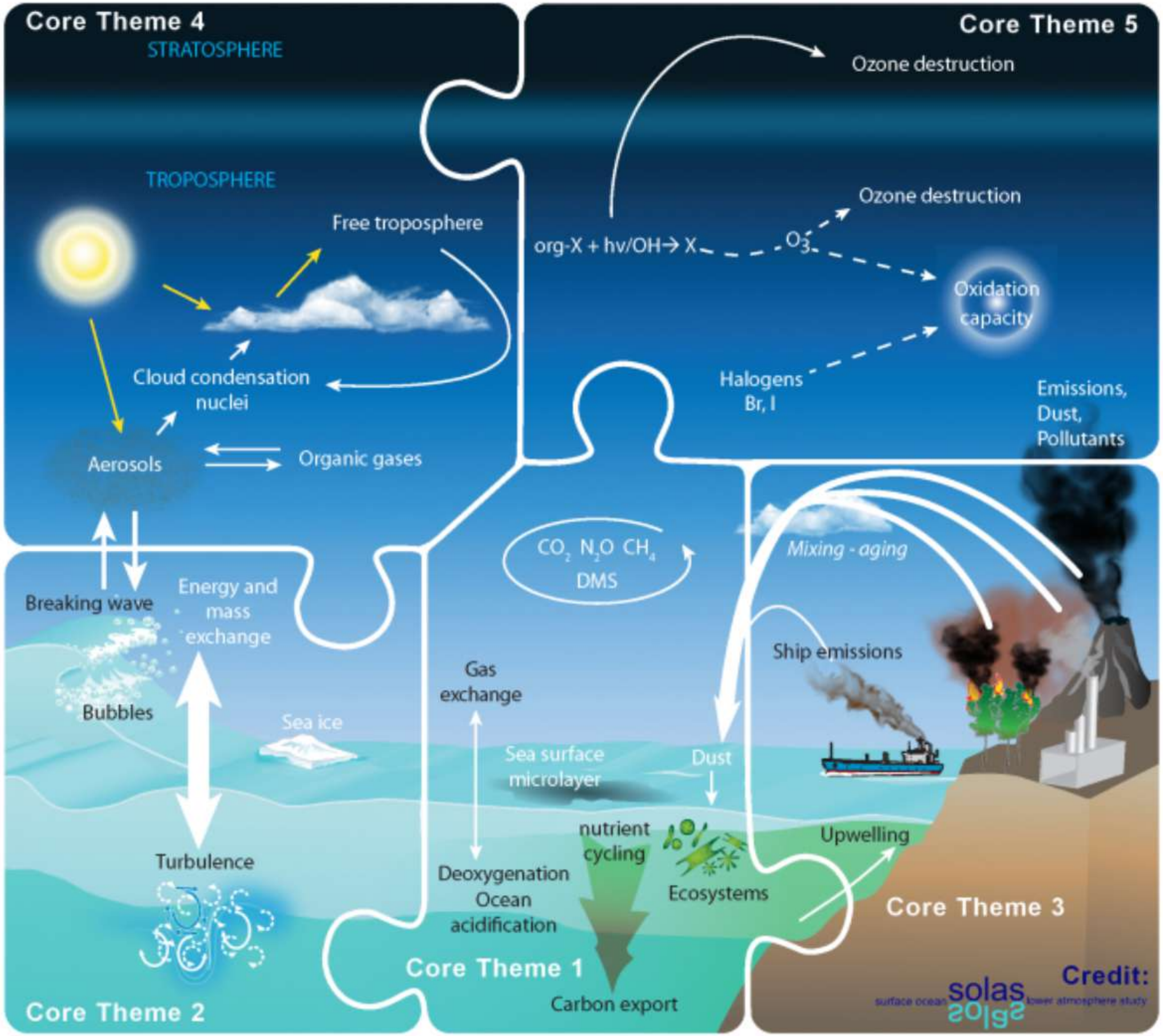
Šantl-Temkiv et. al., 2022

Factors affecting atmospheric microbial transport and macroecological outcomes



Šantl-Temkiv et. al., 2022

Bacteria and bacterial metabolisms influence atmosphere and climate
Ocean and atmosphere are ONE ecosystem

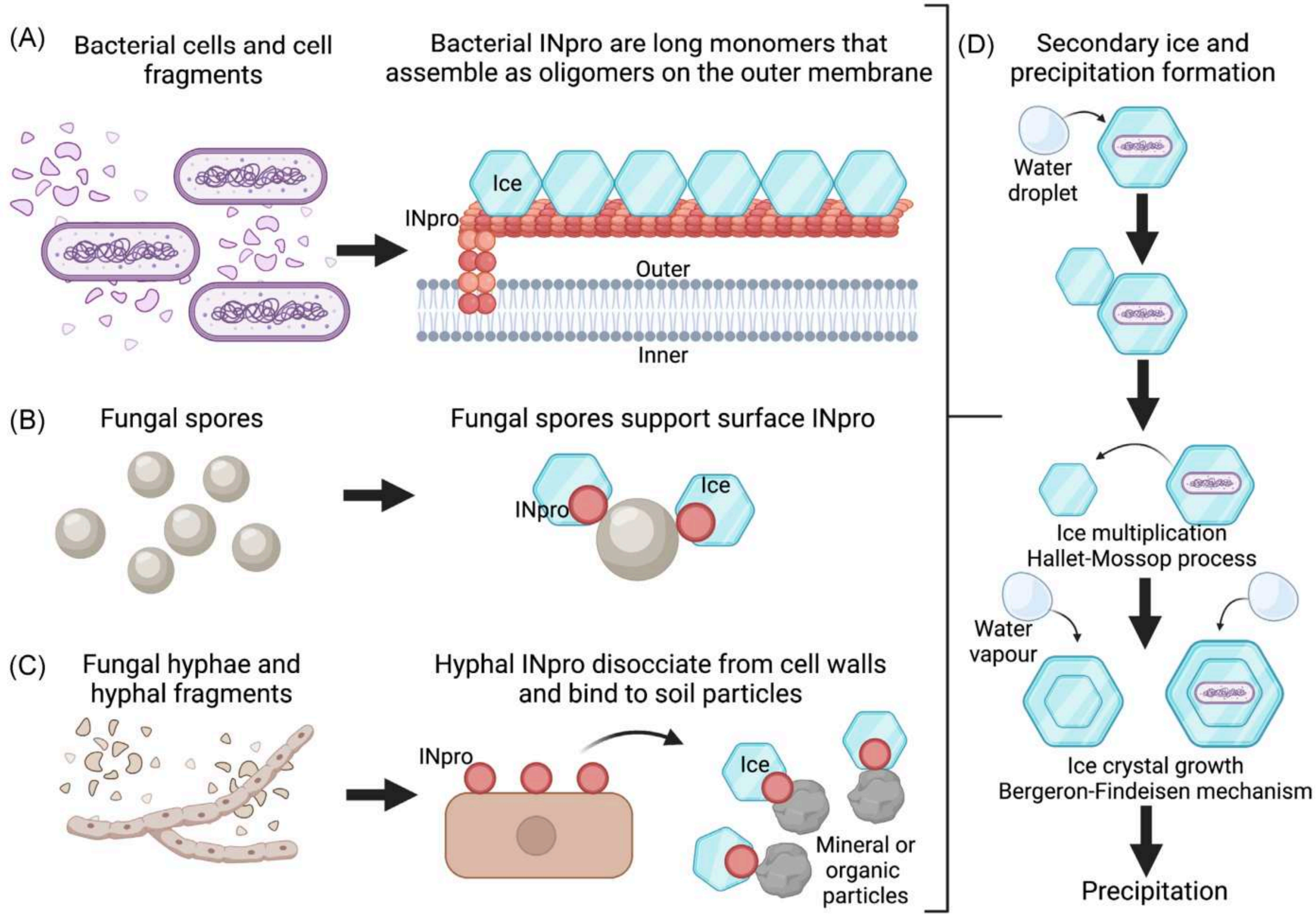


http://www.solas-int.org/about/solas.html

https://caice.ucsd.edu/

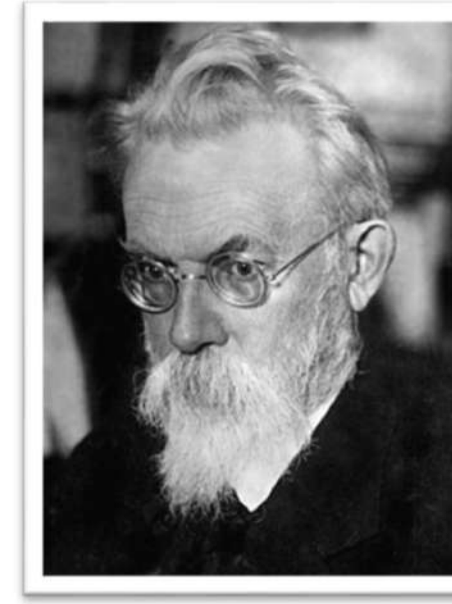
Law et al. 2013

Biophysical role of atmospheric microorganisms in ice nucleation



Šantl-Temkiv et. al., 2022

- And what about pathogens?



BIOGEOCHEMICAL CYCLES

The term “biogeochemistry” was first coined by Vladimir Ivanovič Vernadsky in 1926

Madsen, 2011

https://ingvambiente.com/2022/04/15/la-straordinaria-visione-del-mondo-di-vladimir-vernadsky/

Biogeochemical processes

Table 1 | **Examples of physiological processes catalysed by microorganisms in biosphere habitats**

Process	Nature of process	Typical habitat
Carbon cycle		
Photosynthesis	Light-driven CO_2 fixation into biomass	Ow, Fw, FwS, Os
C respiration	Oxidation of organic C to CO_2	All
Cellulose decomposition	Depolymerization, respiration	Sl
Methanogenesis	CH_4 production	Sw, FwS, Os
Aerobic CH_4 oxidation	CH_4 becomes CO_2	All
Anaerobic CH_4 oxidation	CH_4 becomes CO_2	Os
Biodegradation		
Synthetic organic compounds	Decomposition, CO_2 formation	All
Petroleum hydrocarbons	Decomposition, CO_2 formation	All
Fuel additives (MTBE)	Decomposition, CO_2 formation	Sl, Sw, Gw
Nitroaromatics	Decomposition, CO_2 formation	Sl, Sw, Gw
Pharmaceuticals, personal care products	Decomposition	Sl, Sw, Gw
Chlorinated solvents	Compounds are dechlorinated through respiration in anaerobic habitats	Sl, Sw, Gw

Madsen, 2005

As, arsenic; C, carbon; CH_4, methane; CO_2, carbon dioxide; Fe, iron; FeS, iron sulphide; Fw, freshwater; FwS, freshwater sediment; Gw, groundwater; H_2, hydrogen; Hg, mercury; Hg^{2+}, mercuric ion; MTBE, methyl tertiary butyl ether; N_2, nitrogen; NH_3, ammonia; NH_4^+, ammonium; NO_2^-, nitrite; NO_3^-, nitrate; Os, ocean sediments; Ow, ocean waters; S^0, elemental sulphur; S^{2-}, sulphide; Sl, soil; SO_4^{2-}, sulphate; Sw, sewage; U, uranium.

Nitrogen cycle		
N_2 fixation	N_2 gas becomes NH_3	Sl, Ow
NH_4^+ oxidation	NH_3 becomes NO_2^-, NO_3^-	Sl, Sw
Anaerobic NH_4^+ oxidation	NO_2^- and NH_3 become N_2 gas	Sw, Os
Denitrification	NO_3^- is used as an electron acceptor and converted to N_2 gas	Sl, Sw
Sulphur cycle		
S_2 oxidation	S^{2-} and S^0 become SO_4^{2-}	Os, FwS
SO_4^{2-} reduction	SO_4^{2-} is used as an electron acceptor and converted to S^0 and S^{2-}	Os, Sw, Gw
Other elements		
H_2 oxidation	H_2 is oxidized to H^+, electrons reduce other substances	Sw, Sl, Os, FwS
Hg methylation and reduction	Organic Hg is formed and Hg^{2+} is converted to Hg	FwS, Os
(per)chlorate reduction	Oxidants in rocket fuel and other sources are converted to chloride	Gw
U reduction	U oxyanion is used as an electron acceptor; therefore immobilized	Gw
As reduction	As oxyanion is used as an electron acceptor; therefore toxicity is diminished	FwS, Gw
Fe oxidation, acid mine drainage	FeS ores are oxidized, strong acidity is generated	FwS, Gw

Madsen, 2005

As, arsenic; C, carbon; CH_4, methane; CO_2, carbon dioxide; Fe, iron; FeS, iron sulphide; Fw, freshwater; FwS, freshwater sediment; Gw, groundwater; H_2, hydrogen; Hg, mercury; Hg^{2+}, mercuric ion; MTBE, methyl tertiary butyl ether; N_2, nitrogen; NH_3, ammonia; NH_4^+, ammonium; NO_2^-, nitrite; NO_3^- , nitrate; Os, ocean sediments; Ow, ocean waters; S^0, elemental sulphur; S^{2-}, sulphide; Sl, soil; SO_4^{2-}, sulphate; Sw, sewage; U, uranium.

Life on Earth depends on the evolution of non-equilibrium redox chemistry of the intertwined C, H, O, N, P, S

All organisms derive energy for growth and maintenance by moving electrons from a substrate to a product

All substrates and products must ultimately be cycled

Biological processes are paired

Photoautotrophic microorganisms are responsible for about half of CO_2 fixation and O_2 production on Earth

Heterotrophic microorganisms are responsible for much of the return reaction: the oxidation of organic matter back into CO_2

The temporal and spatial separation of photoautotrophy and heterotrophy in the global environment drives the biological sequestration of carbon, the reduction of atmospheric CO_2, and the maintenance of elevated atmospheric and oceanic O_2

Chemoautotrophic microorganisms also fix CO_2 and, together with anaerobic heterotrophic metabolisms, carry out diverse chemical transformations including the fluxes of nitrogen and sulphur to and from biologically available states

Across scale integration of biogeochemistry aka microbial metabolism

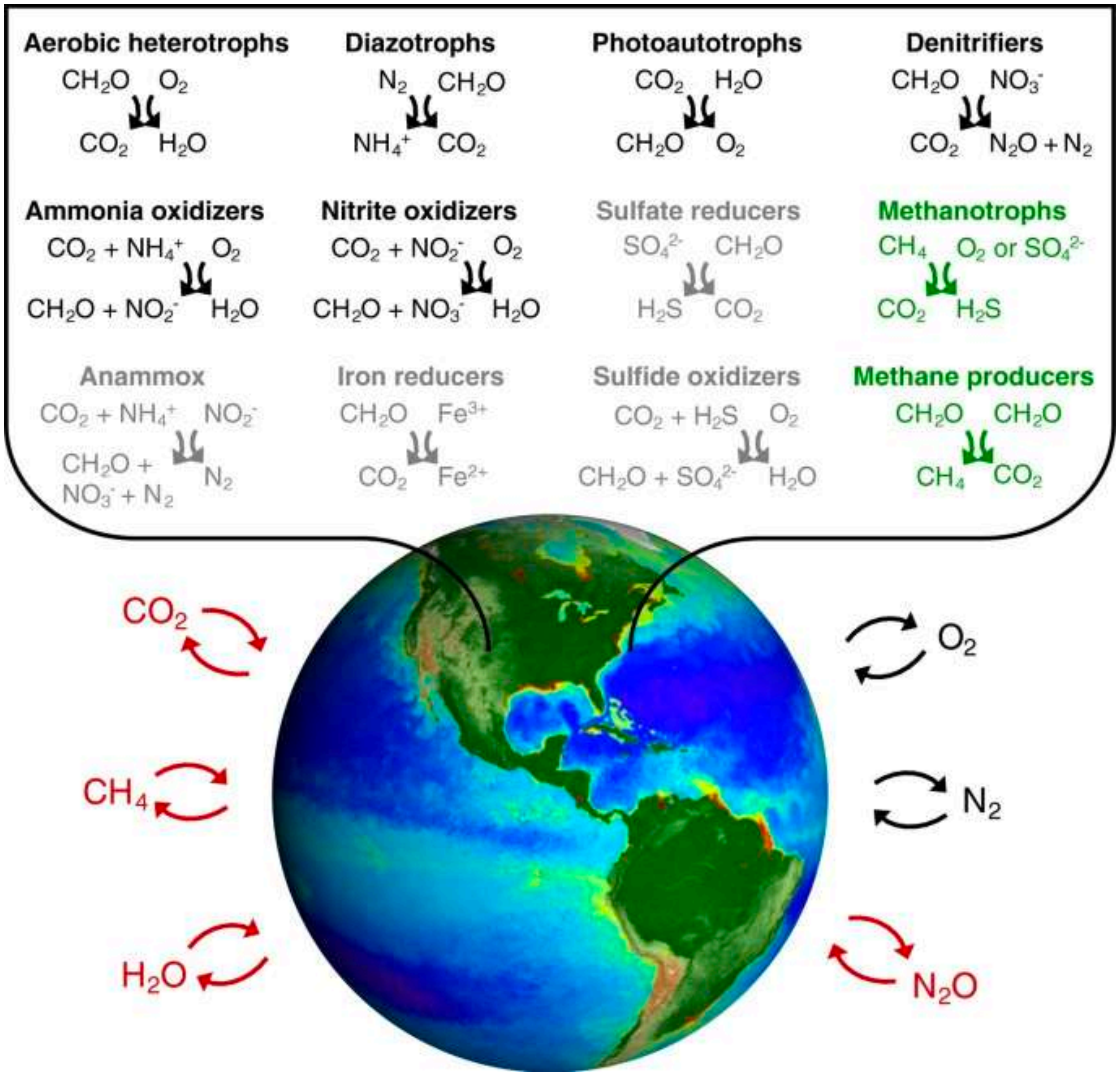
From a scale of cubic centimeters to one of the entire planet, Earth habitats can be viewed as complex mixtures of reduced and oxidized materials in chemical disequilibrium

Ultimately, this disequilibrium is maintained by constant influx of radiant energy from the sun, and constant efflux of heat and reduced materials (e.g. CH_4, H_2S, H_2) from the Earth's core

Nutrient cycle	Process	Operational definition
Carbon	Photosynthesis	Light-driven CO_2 fixation into biomass
	Carbon Respiration	Oxidation of organic C to CO_2
	Methanogenesis	Methane production
	Aerobic methane oxidation	Methane becomes CO_2
	Anaerobic methane oxidation	Methane becomes CO_2
Nitrogen	Nitrogen fixation	N_2 gas becomes ammonia
	Ammonium oxidation	Ammonia becomes nitrite, nitrate
	Anaerobic ammonium oxidation	Nitrite and ammonia become N_2 gas
	Denitrification	Nitrate is used as an electron acceptor and converted to N_2 gas
Sulfur	Sulfur oxidation	Sulfide and sulfur become sulfate
	Sulfate reduction	Sulfate is used as an electron acceptor and converted to sulfur and sulfide
Other elements	Hydrogen oxidation	Hydrogen is oxidized to H^+, electrons reduce other substances
	Uranium reduction	Uranium oxycation is used as an electron acceptor; hence immobilized
	Iron reduction	Ferric ion is used as electron acceptor and converted to Fe^{2+}

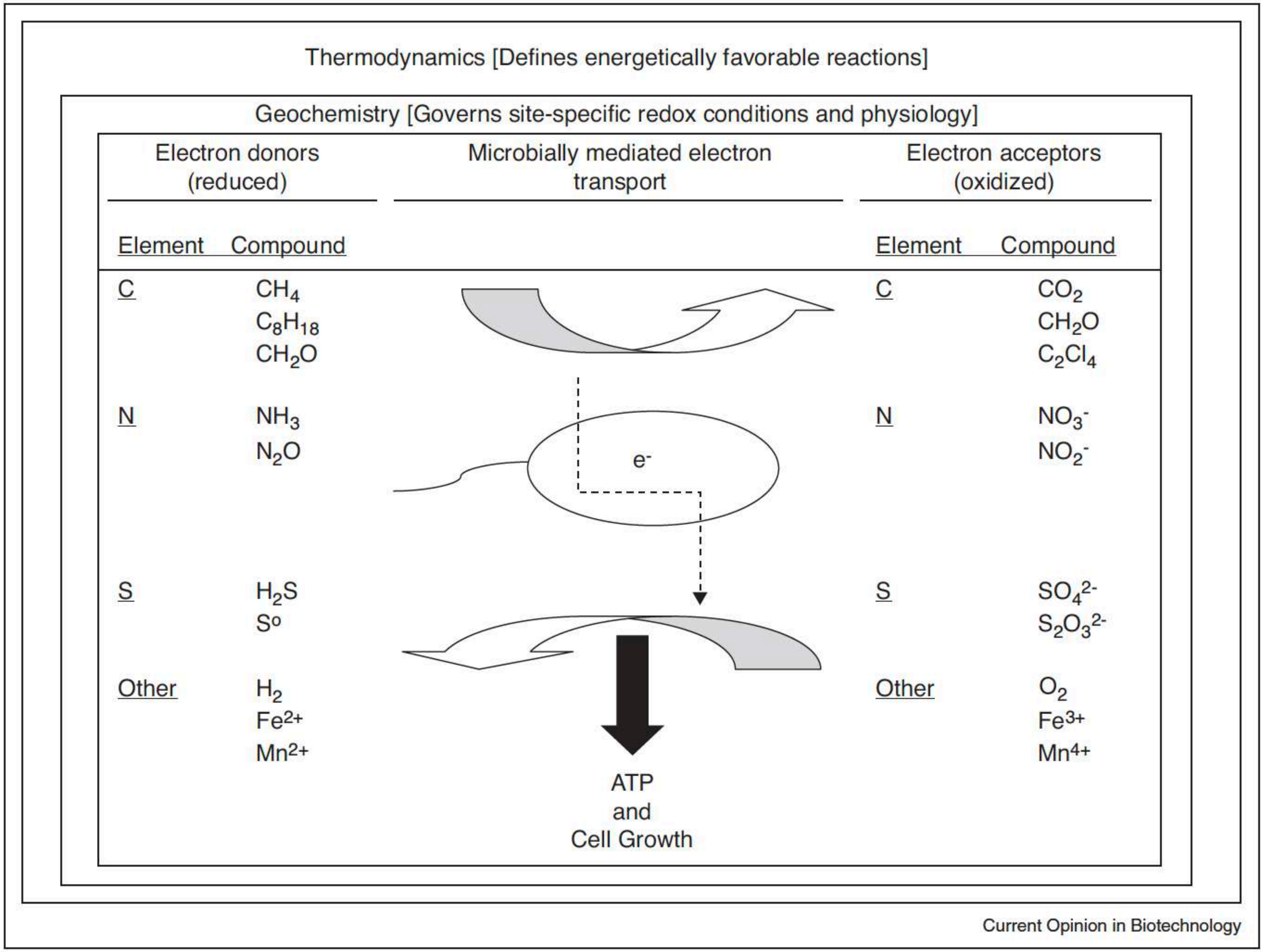
Madsen, 2011

Key microbially driven redox transformations



Zakem et al., 2020

Figure 1



Conceptual view of how microorganisms catalyze biogeochemical reactions between electron donors and electron acceptors that occur in habitats such as soil, sediments, and waters. The specific reactions that occur in a given habitat are governed by both local geochemistry and the laws of thermodynamics. Each electron donor ''half reaction'' (upper curved arrow, center) must be coupled to an electron acceptor ''half reaction'' (lower curved arrow, center).

Madsen, 2011

Microbial metabolic pathways shaping Earth ecosystem

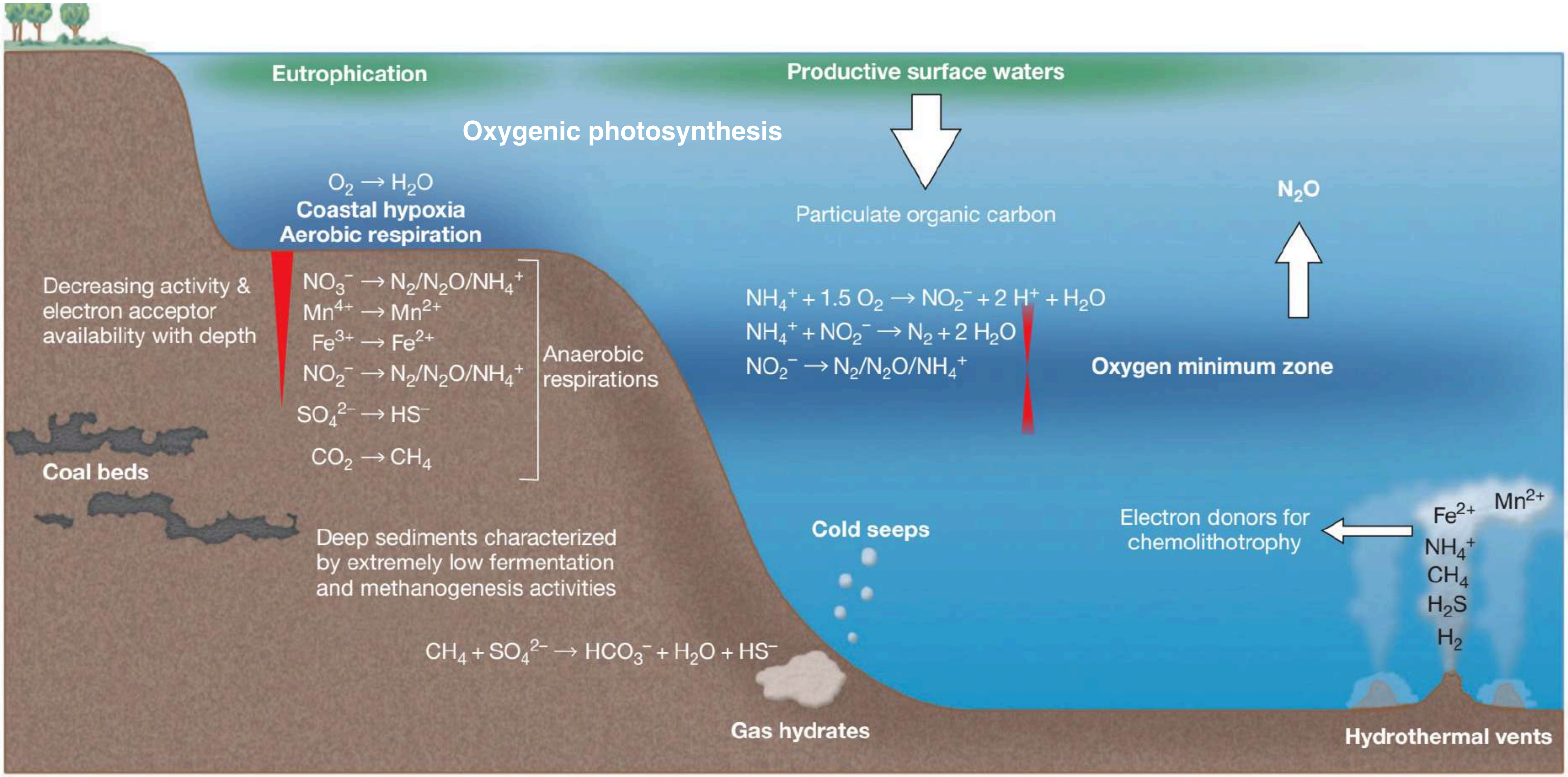
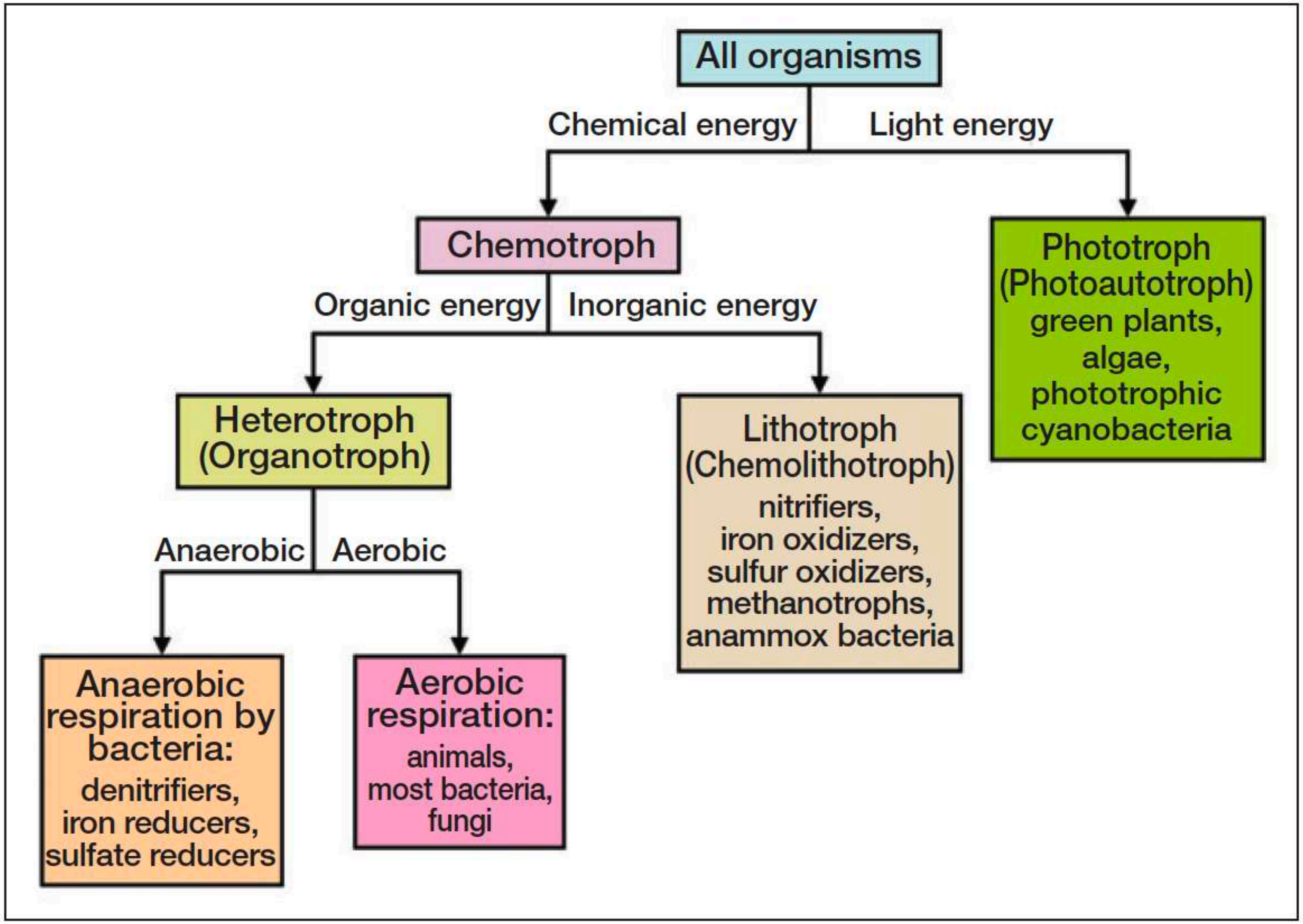


Figure 20.20 Diversity of marine systems and associated microbial metabolic processes. Decreasing electron acceptor availability with depth into the sediment or with increasing distance into an oxygen minimum zone is indicated by red wedges. Sulfate becomes limiting only at greater depths in marine sediments. The indicated metabolic diversity is covered in Chapter 14.

Madigan et al. 2018

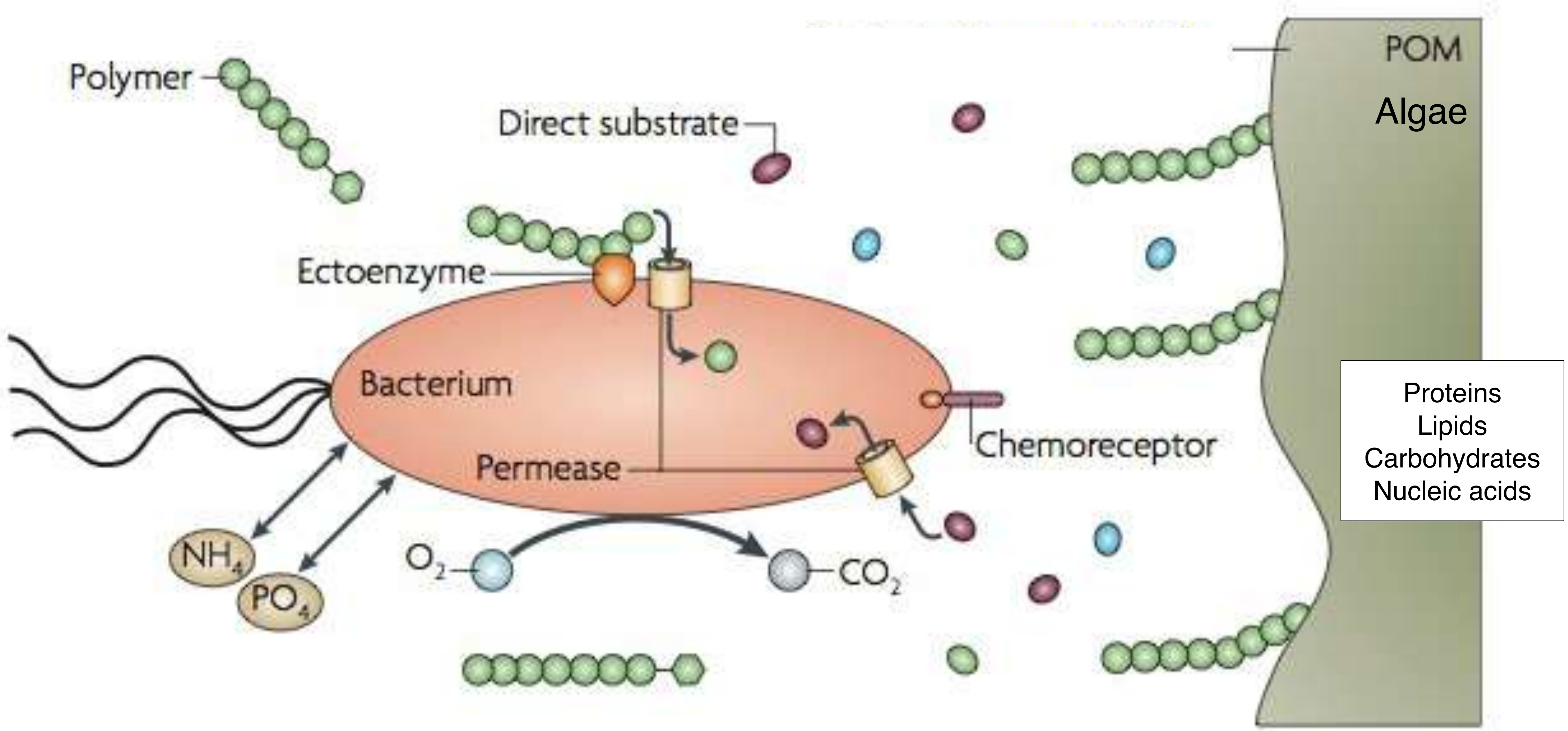
Classification of organisms based on their primary source of energy



Burgin et al., 2011

Microbial interaction with organic matter

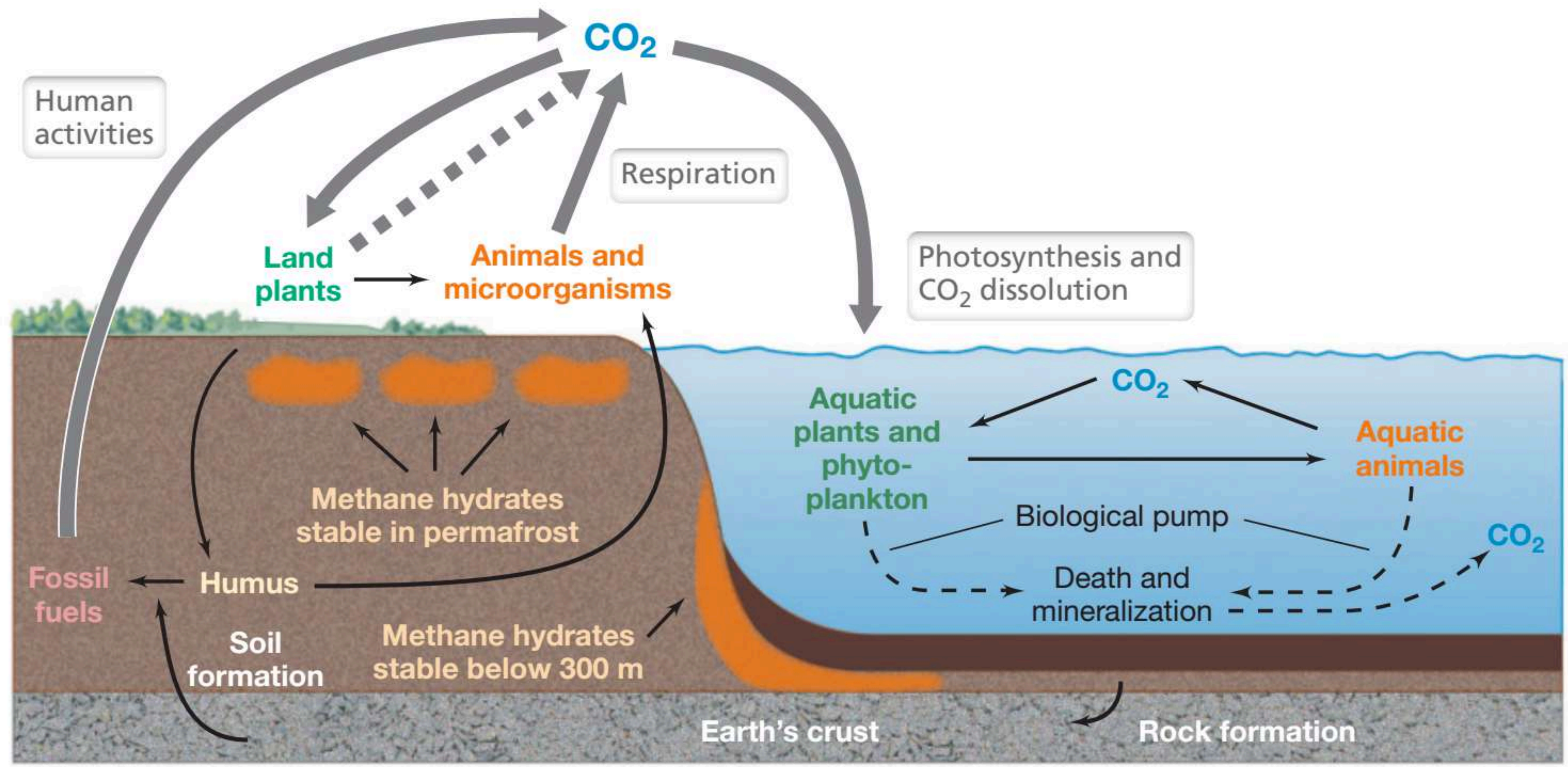
By Farooq Azam



Azam and Malfatti, 2007 Nature Reviews Microbiology 10:782

- **Expression at the surface of enzymes to cleave nutrients**
- **Significance of spatial coupling hydrolysis-uptake (permease) on the cell**
- **In Autotrophic and heterotrophic microbes**
- **Coordinated behavior and biochemistry in space and time**

Carbon cycle



Madigan et al. 2018

Major Carbon Reservoirs on Earth

Reservoir	Percent of Total[a]
Rocks and sediments	99.5[b]
Oceans	0.05
Methane hydrates	0.014
Fossil fuels	0.006
Terrestrial biosphere	0.003
Aquatic biosphere	0.000002

[a] Total carbon, 76×10^{15} tons
[b] 80% inorganic

- Carbon and Oxygen cycles are connected
- Biota is important not as reservoir but as way to move the elements
- Photosynthesis-Respiration
- Majority as carbonates
- Methane and methane clathrate

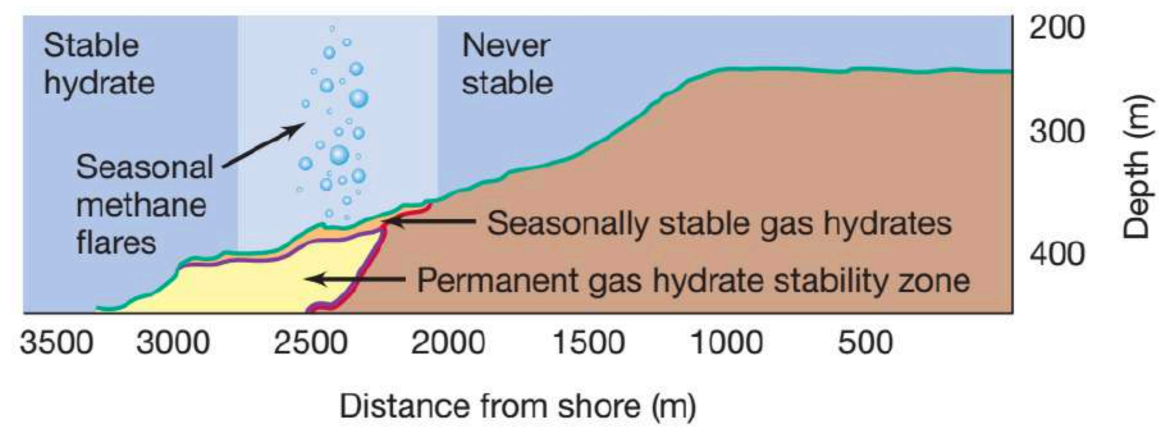
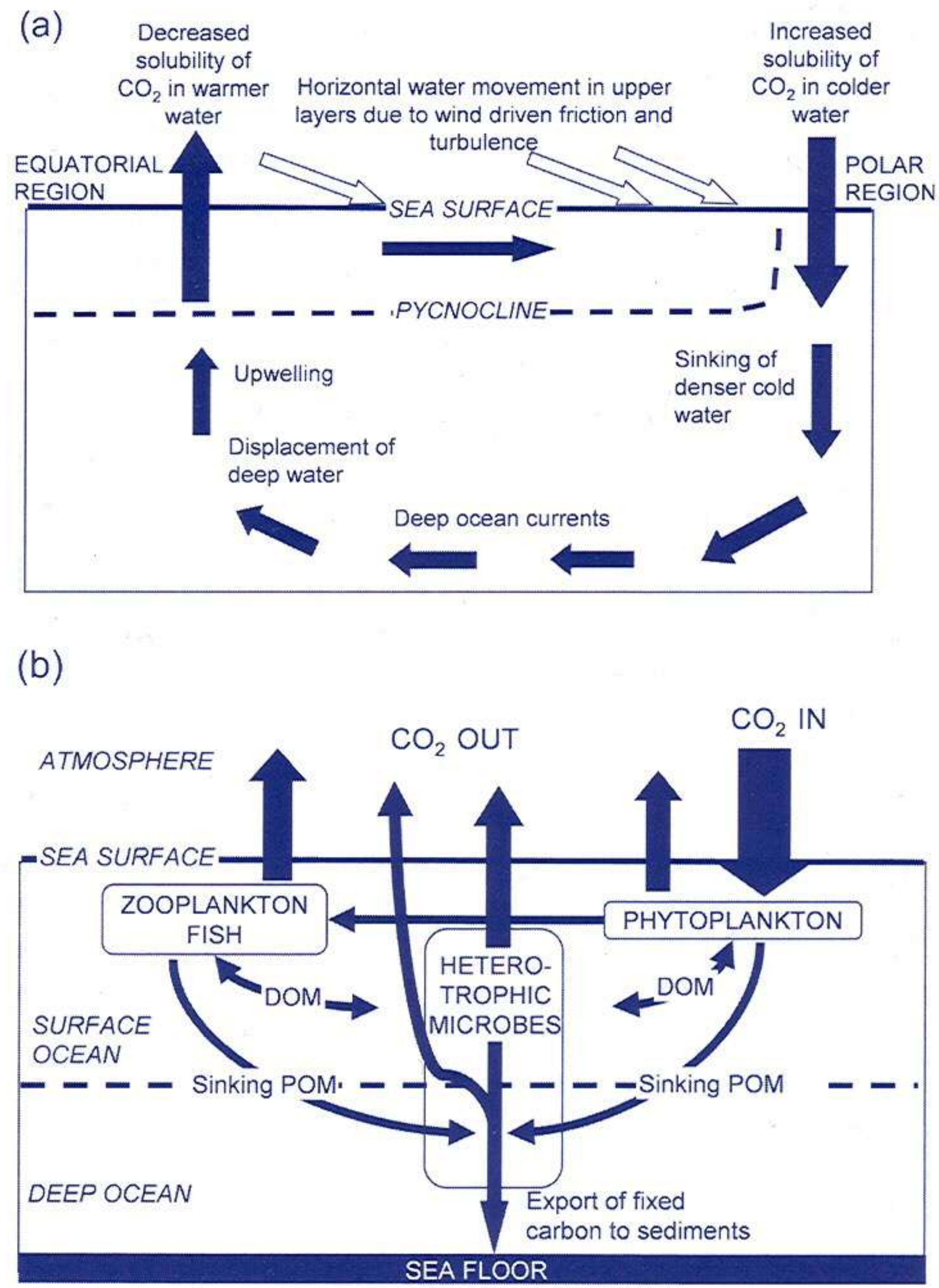


Figure 21.4 Seasonal flares of methane bubbling from methane hydrates. Methane hydrates in shallow coastal sediments are sensitive to seasonal changes in bottom water temperature. Flares of methane bubbles are observed when water temperatures warm by as little as 1–2°C.

Solubility Pump, SP

- The biggest oceanic carbon reservoir is the dissolved inorganic carbon (DIC) pool, which is formed by biological pump (BP)-mediated transportation of organic carbon (in the form of particulate organic matter; POM) into the ocean interior and its subsequent remineralization, as well as by the solubility pump (SP) (which is driven by differences in CO_2 partial pressure)

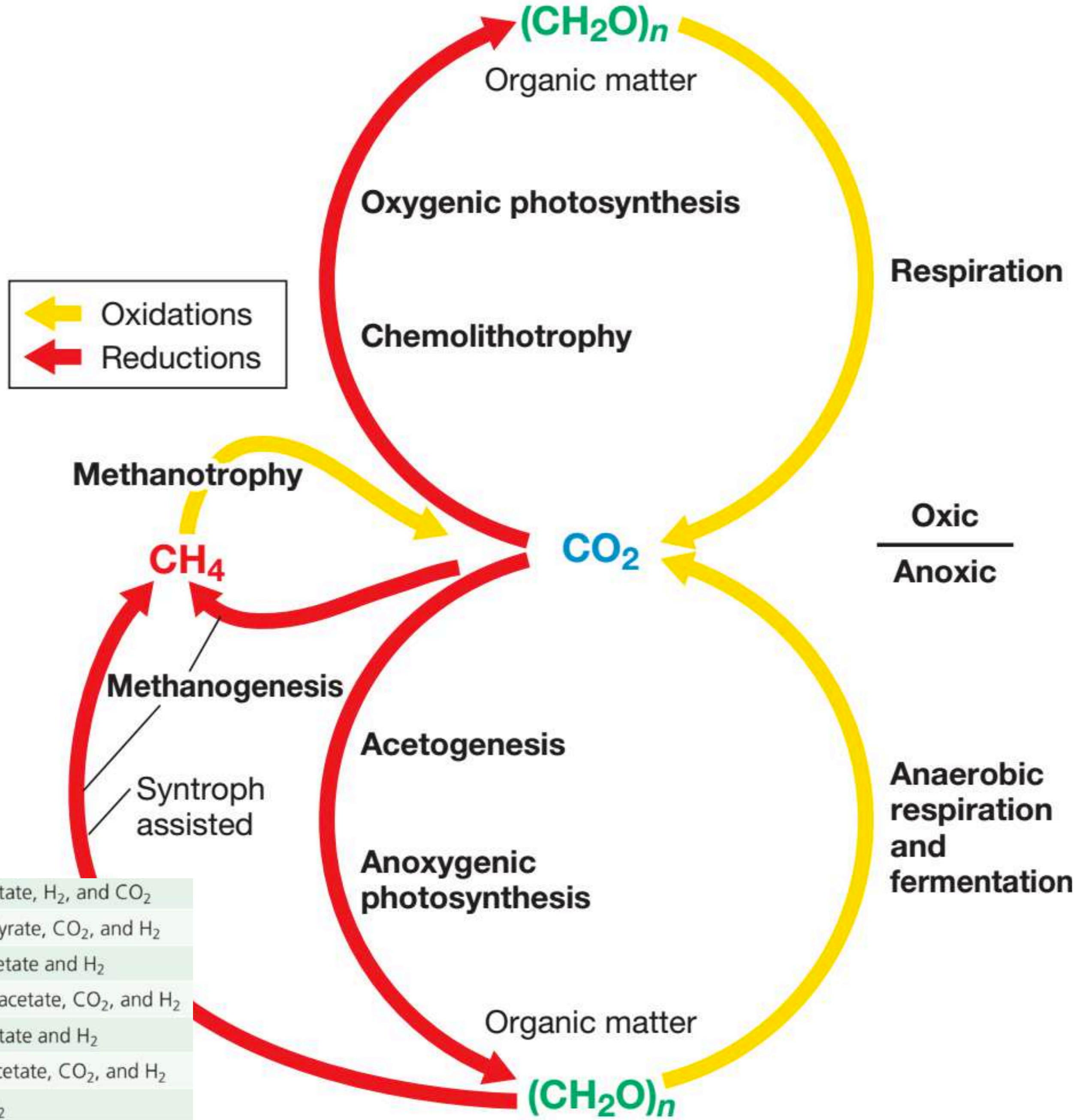
Biological Pump, BP



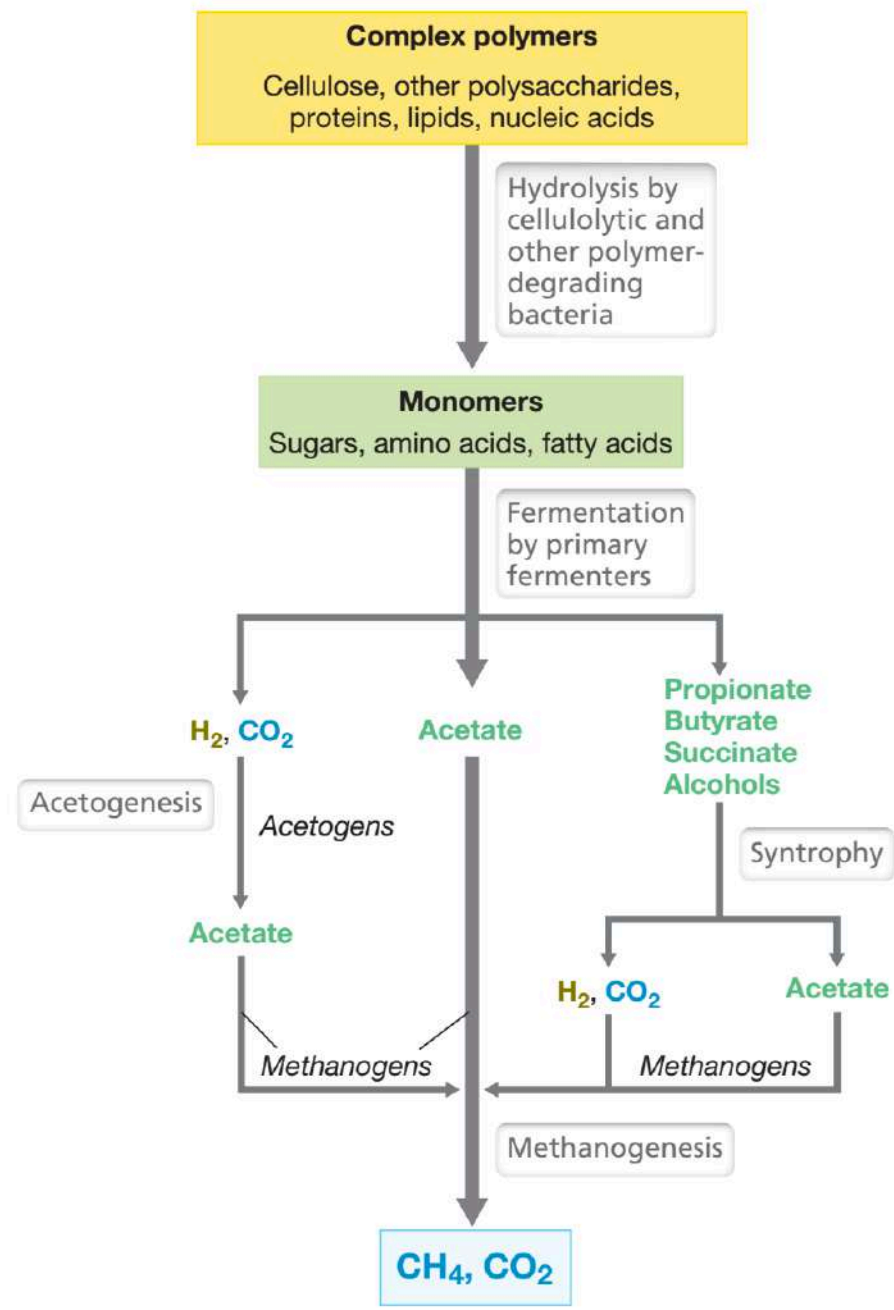
Munn, 2004

Redox cycle for Carbon

- Autotrophic processes CO_2 —> organic matter
- Heterotrophic processes: organic matter —> CO_2



Fermentation of glucose to acetate, H_2, and CO_2
Fermentation of glucose to butyrate, CO_2, and H_2
Fermentation of butyrate to acetate and H_2
Fermentation of propionate to acetate, CO_2, and H_2
Fermentation of ethanol to acetate and H_2
Fermentation of benzoate to acetate, CO_2, and H_2
Methanogenesis from $H_2 + CO_2$
Methanogenesis from acetate
Acetogenesis from $H_2 + CO_2$

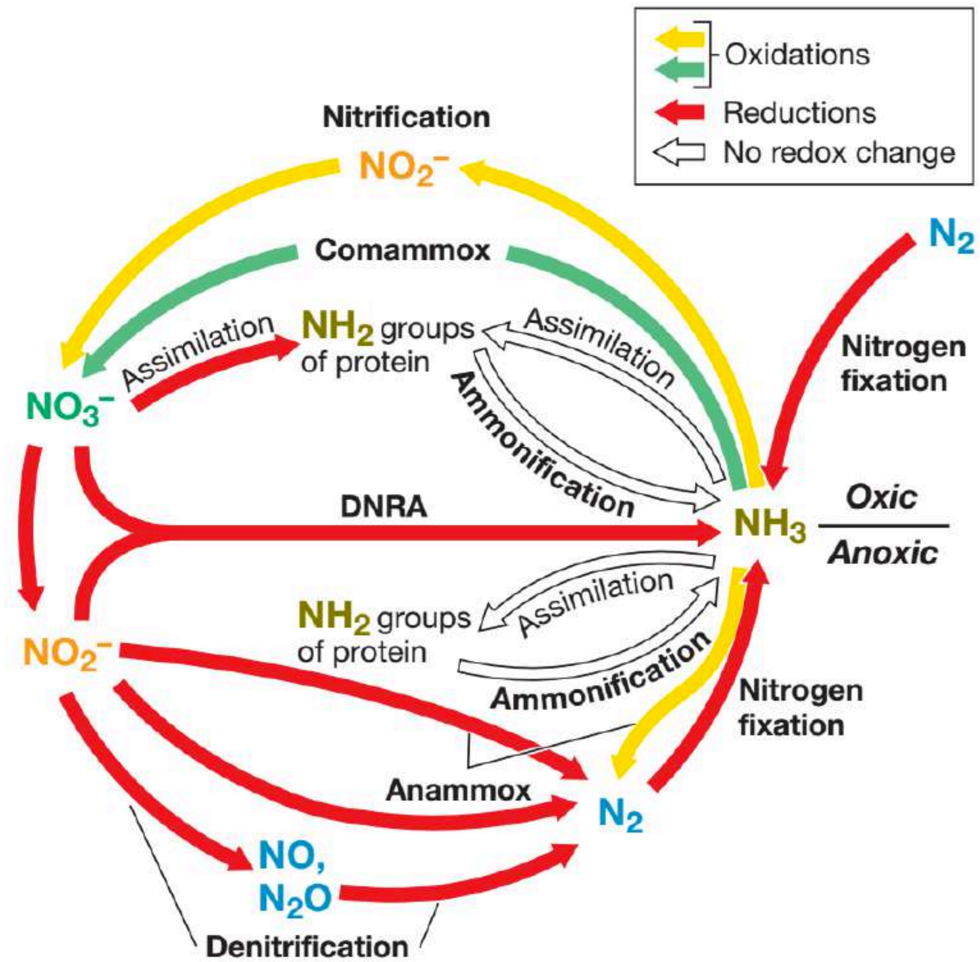


Madigan et al. 2018

Nitrogen cycle

Key Processes and Microbes in the Nitrogen Cycle

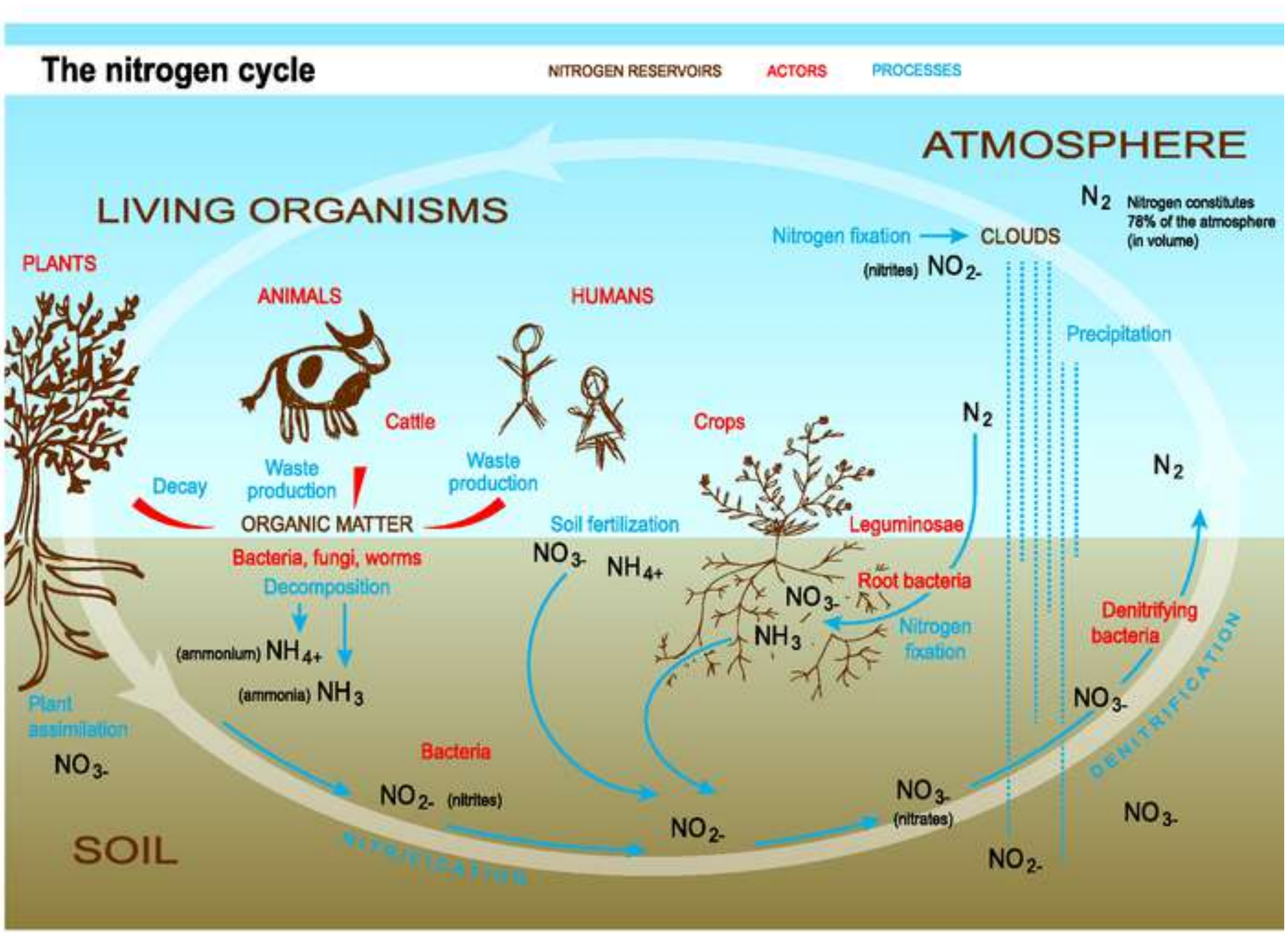
Processes	Example organisms
Nitrification ($NH_4^+ \rightarrow NO_3^-$)	
$NH_4^+ \rightarrow NO_3^-$	Comammox (*Nitrospira* species)
$NH_4^+ \rightarrow NO_2^-$	*Nitrosomonas*, *Nitrosopumilus* (*Archaea*)
$NO_2^- \rightarrow NO_3^-$	*Nitrobacter*
Denitrification ($NO_3^- \rightarrow N_2$)	*Bacillus*, *Paracoccus*, *Pseudomonas*
N_2 Fixation ($N_2 + 8\ H \rightarrow NH_3 + H_2$)	
Free-living	
Aerobic	*Azotobacter* Cyanobacteria
Anaerobic	*Clostridium*, purple and green phototrophic bacteria *Methanobacterium* (*Archaea*)
Symbiotic	*Rhizobium* *Bradyrhizobium* *Frankia*
Ammonification (organic-N $\rightarrow NH_4^+$)	Many organisms can do this
Anammox ($NO_2^- + NH_3 \rightarrow 2\ N_2$)	*Brocadia*



Madigan et al. 2018

- N_2 is stable and major reservoir of N on Earth
- Only few microbes can use N_2
- N_2O and NO species are important in the atmosphere —> depletion O_3, acid rain and warming (300x more than CO_2)
- DNRA: dissimulative nitrate reduction to ammonia (human gut)
- Anammox: Ammonia oxidation in anoxic sediments

Nitrogen cycle on land

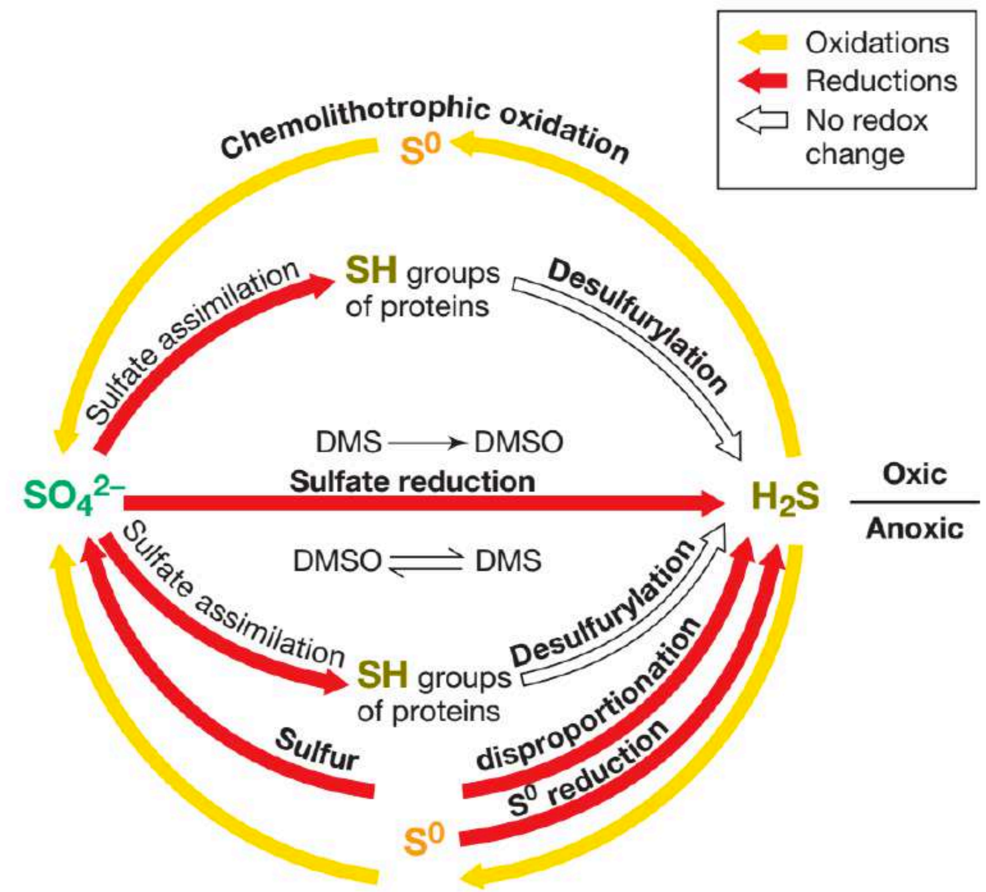


https://www.eea.europa.eu/data-and-maps/figures/the-nitrogen-cycle

Sulfur cycle

Key Processes and Microbes in the Sulfur Cycle

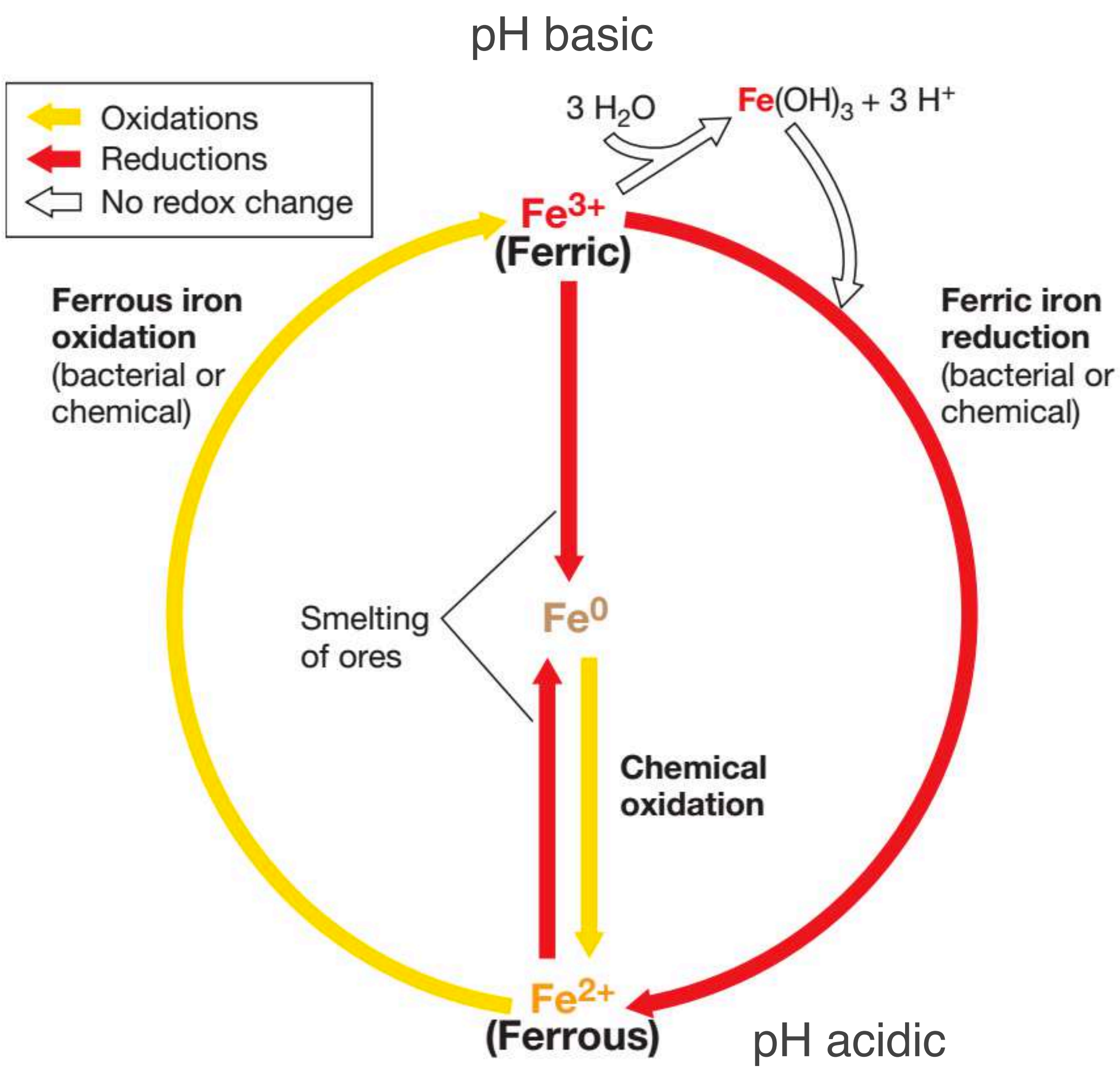
Process	Example organisms
Sulfide/sulfur oxidation ($H_2S \rightarrow S^0 \rightarrow SO_4^{2-}$)	
Aerobic	Sulfur chemolithotrophs (*Thiobacillus*, *Beggiatoa*, many others)
Anaerobic	Purple and green phototrophic bacteria, some chemolithotrophs
Sulfate reduction (anaerobic) ($SO_4^{2-} \rightarrow H_2S$)	*Desulfovibrio*, *Desulfobacter* *Archaeoglobus* (*Archaea*)
Sulfur reduction (anaerobic) ($S^0 \rightarrow H_2S$)	*Desulfuromonas*, many hyperthermophilic *Archaea*
Sulfur disproportionation ($S_2O_3^{2-} \rightarrow H_2S + SO_4^{2-}$)	*Desulfovibrio*, and others
Organic sulfur compound oxidation or reduction ($CH_3SH \rightarrow CO_2 + H_2S$) ($DMSO \rightarrow DMS$)	Many organisms can do this
Desulfurylation (organic–S $\rightarrow H_2S$)	Many organisms can do this

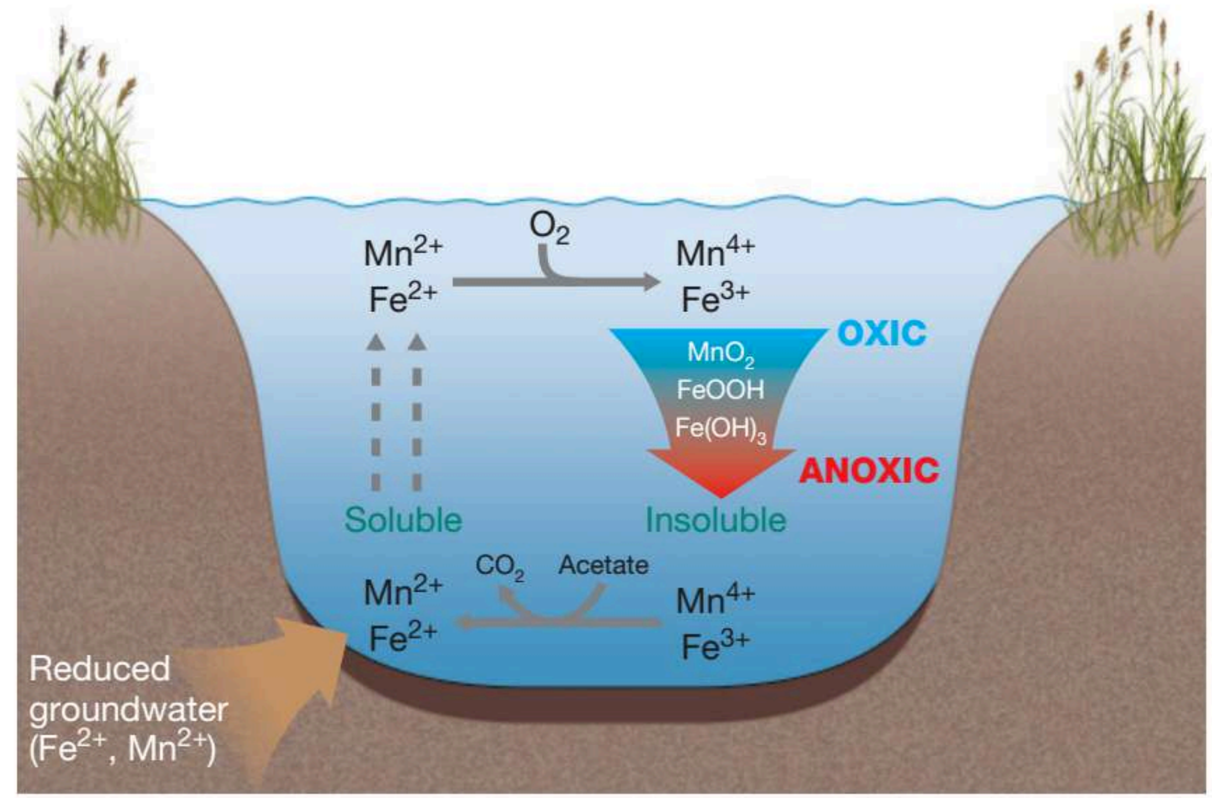


Madigan et al. 2018

- Sulfate is synthesized into organic sulfur compounds by phytoplankton
- Sulfur metabolites are subsequently released by phytoplankton into the labile dissolved organic sulfur (DOS) pool, with secondary contributions by grazers and heterotrophic bacteria
- Bacteria take up sulfur metabolites such as sulfonium compounds (DMSP, dimethylsulfoniopropionate), sulfonates, sulfate esters and thiols from the labile component of the DOS pool
- DMSP—> DMS (dimethyl sulfide-broccoli smell)—> after UV oxidation—> cloud condensation nuclei

Ferric-Ferrous wheel





Madigan et al. 2018

- Iron and Manganese in oxide sediment are e⁻ acceptors —> reduced former are soluble —> utilized or oxidized —> precipitation
- Siderophores, special ligands for Iron uptake, QS regulated

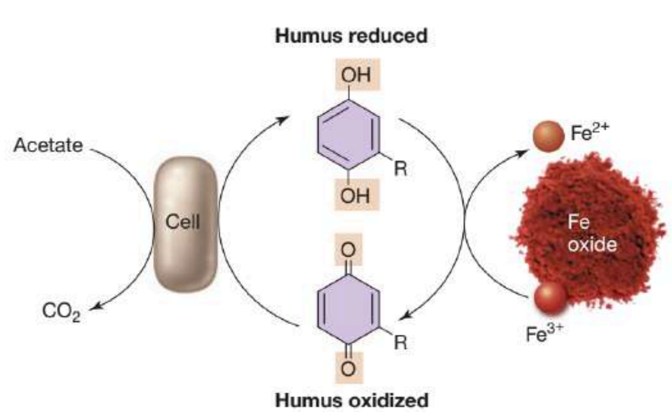
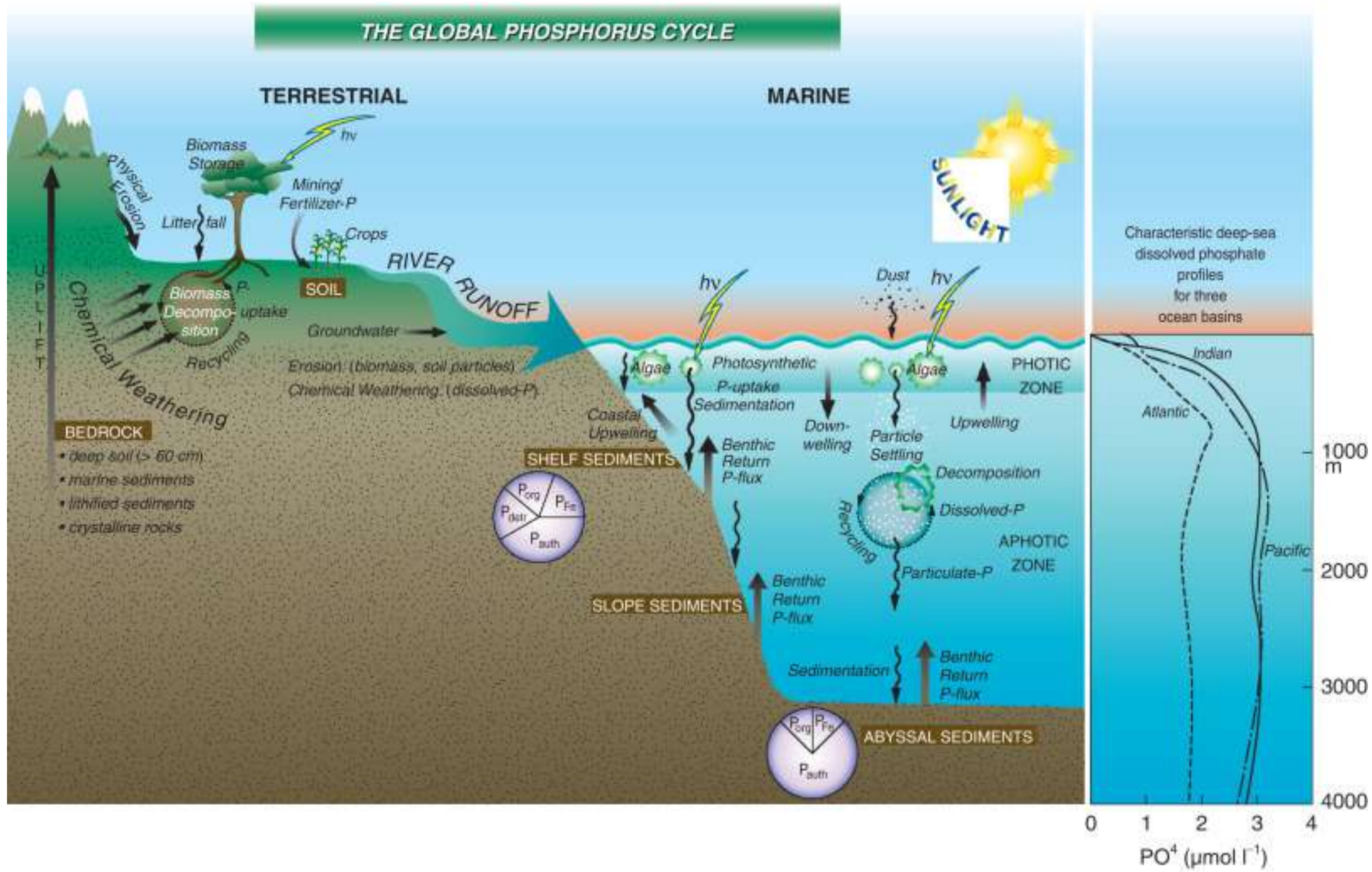


Figure 21.12 Role of humic substances in humus as an electron shuttle in microbial metal reduction. Quinone-like functional groups in humus are reduced by acetate-oxidizing bacteria. The reduced humus then donates electrons to metal oxides, releasing reduced soluble iron (Fe^{2+}) and oxidized humus. The cycle continues as oxidized humus is again reduced by the bacteria.

Phosphorus cycle

Ruttenberg (2000) and Sverdrup HV, Johnson MW and Fleming RH (1942)



- Different chemical/mineral forms in marine sediments: P_{org}, organic phosphorus; P_{Fe}, iron-bound phosphorus; P_{detr}, detrital apatite; P_{auth}, authigenic/biogenic apatite
- P_{org}, P_{Fe}, and P_{auth} reservoirs represent potentially reactive phosphorus pools
- P_{detr} pool is detrital apatite weathered off the continents and passively deposited in marine sediments, not important in abyssal sediments, far from continents

Marine Calcium cycle

- Calcareous microalgae, Coccolitophores and Foraminifera
- Authochtonous material—> sedimentation
- Pressure is important in carbonate dissolution
- pH is important in carbonate dissolution

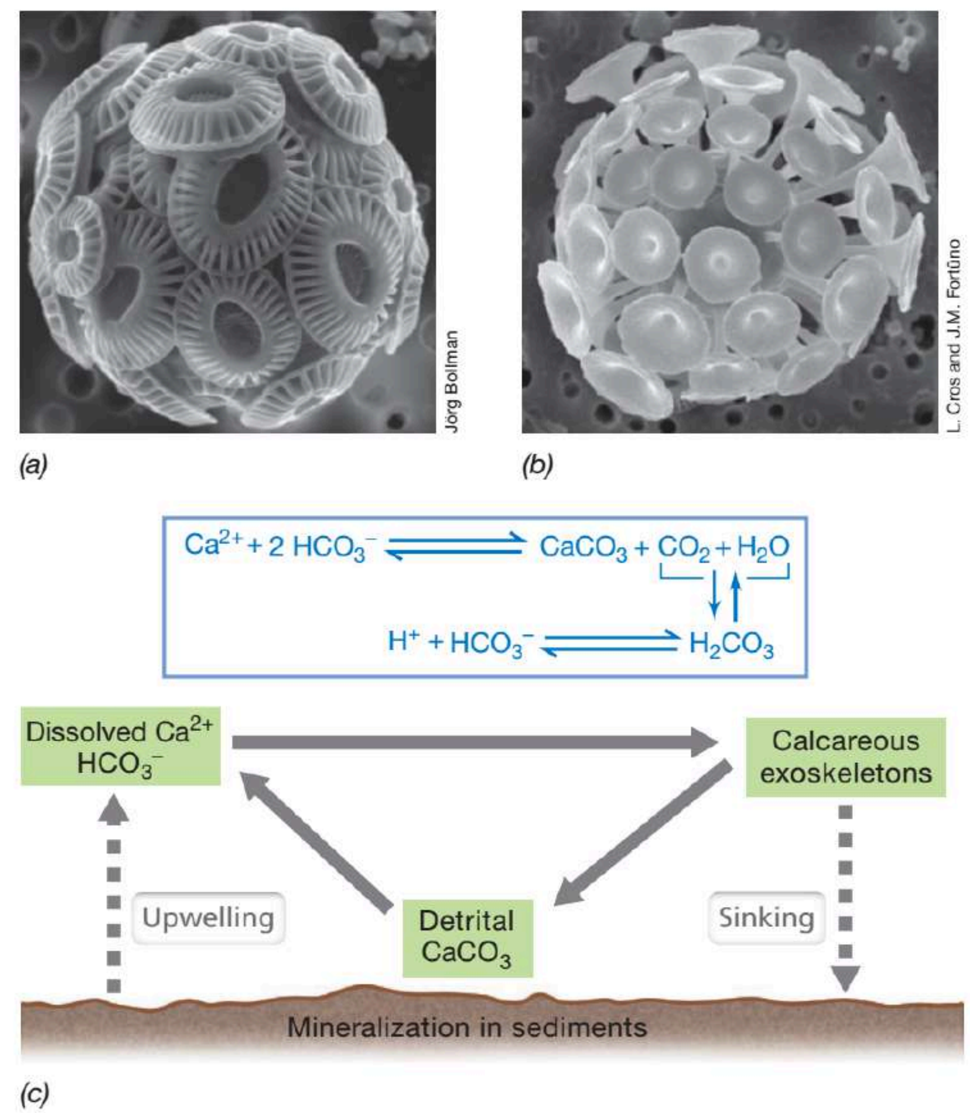


Figure 21.15 The marine calcium cycle. Scanning electron micrographs of cells of the calcareous phytoplankton *(a) Emiliania huxleyi* and *(b) Discosphaera tubifera*. The exoskeletons of these coccolithophores are made of calcium carbonate ($CaCO_3$). A cell of *Emiliana* is about 8 µm wide and a cell of *Discosphaera* is about 12 µm wide. *(c)* The marine calcium cycle; dynamic pools of Ca^{2+} are shaded in green. Detrital $CaCO_3$ is that in fecal pellets and other organic matter from dead organisms. Note how H_2CO_3 formation lowers ocean pH when it dissolves to form H^+ and HCO_3^-.

Madigan et al. 2018

Marine Silica Cycle

- Diatom and Flagelates
- Authochtonous material—> sedimentation
- Protein, silaffin, stabilized the nanostructure at sea ~pH 8
- Bacteria degrading protein on diatom frustule induce silica dissolution at pH8

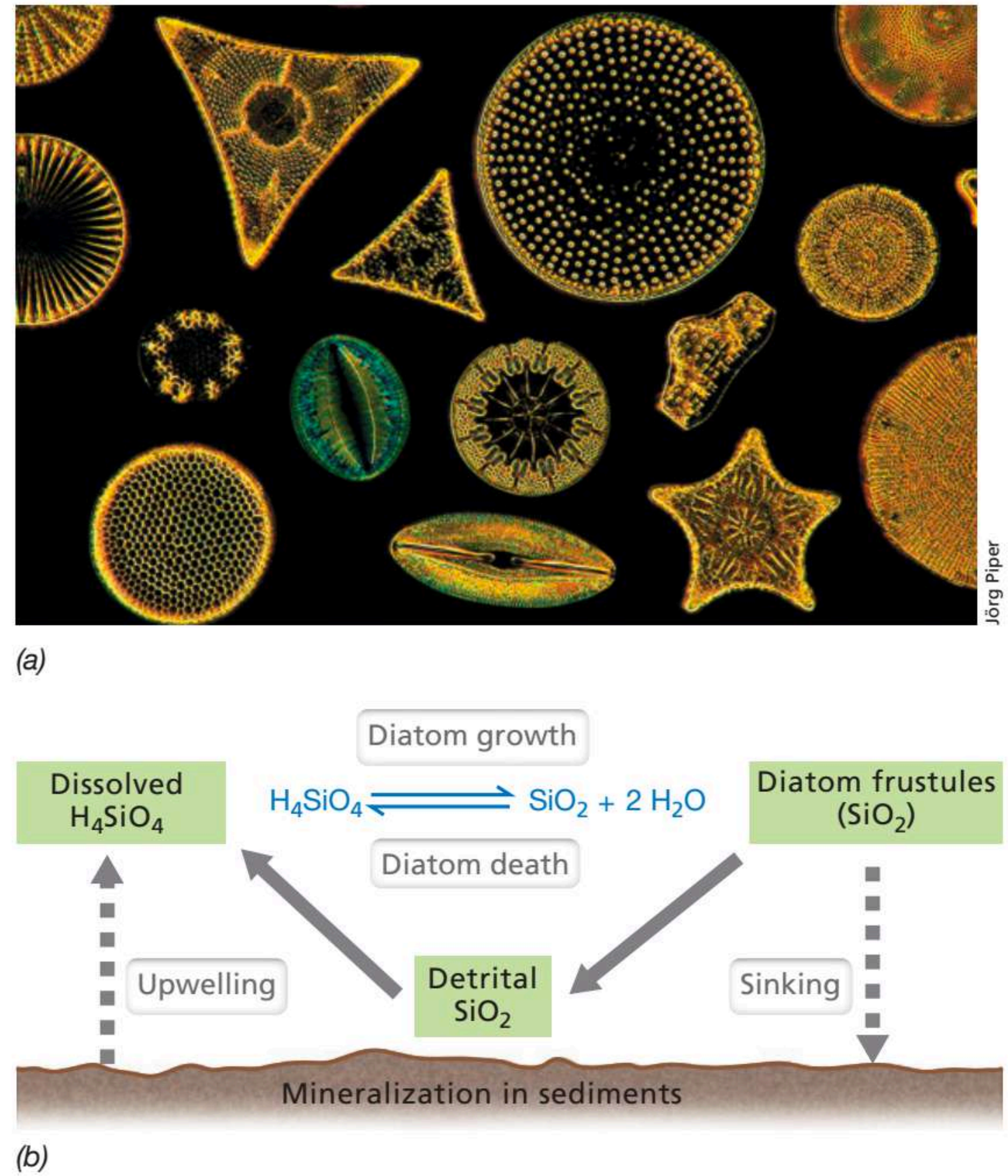
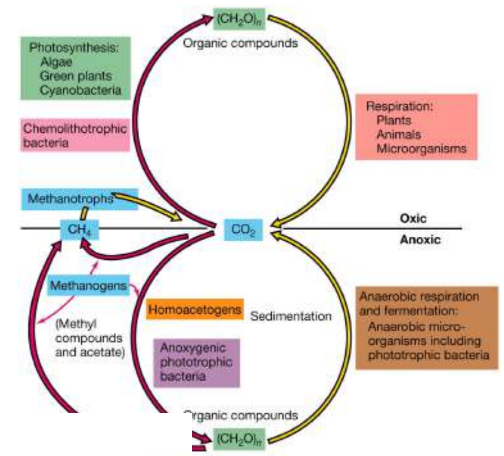


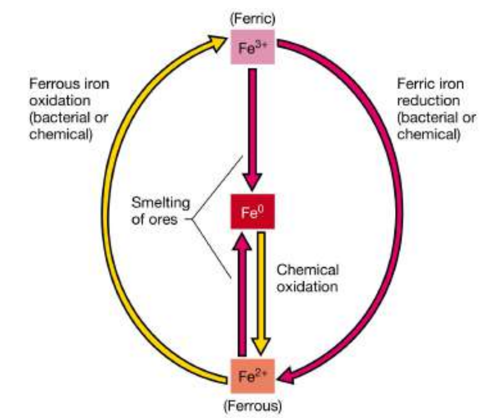
Figure 21.16 The marine silica cycle. *(a)* Dark-field photomicrograph of a collection of diatom shells (frustules). The frustules are made of SiO_2. *(b)* The marine silica cycle; dynamic pools of Si are shaded in green.

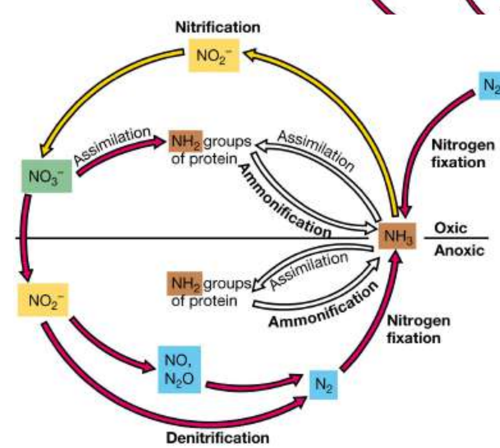
Madigan et al. 2018

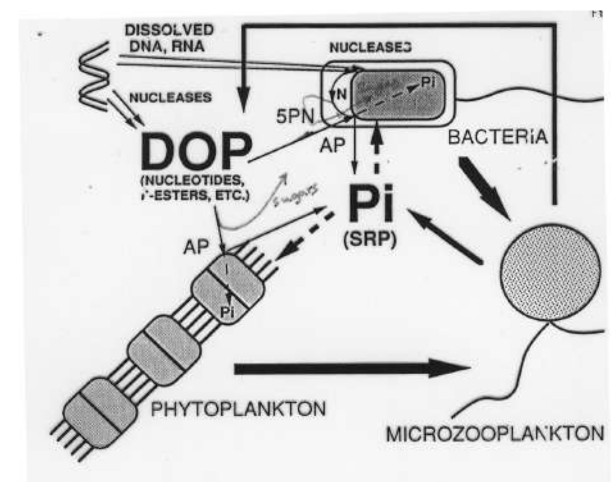
Interconnected cycles on Earth

- All nutrient cycles are interconnected
- Nutrient cycles are coupled via biology

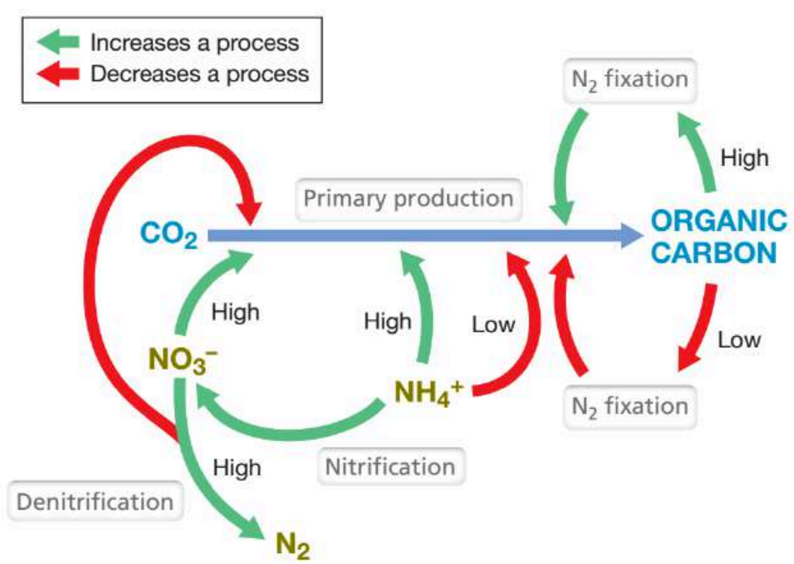


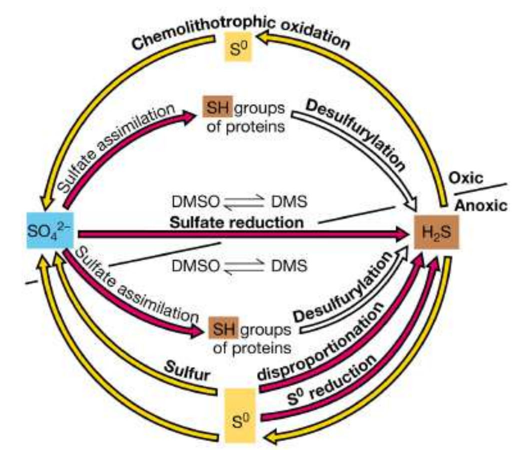






Madigan et al. 2018





Redfield ratio or Redfield stoichiometry is the atomic ratio of carbon, nitrogen and phosphorus found in phytoplankton and throughout the deep oceans C:N:P = 106:16:1 (Redfield A.C., 1934)

Microbes are master recyclers
Microbes respire/utilize organic matter and give off nutrients to other organisms
Microbes are the main forces in the biogeochemical cycles of the elements

There are other compounds in the bacteria as well as in humans etc. metals, radioactivity, drugs, pollutants, etc…

Mercury cycle

- Hg^0 (volatile) elemental mercury major form in the atmosphere, photochemically oxidized to Hg^{2+}
- Toxicity: Hg^0~Hg^{2+} < CH_3Hg^+ & CH_3-Hg-CH_3 (volatile)
- CH_3Hg^+ bioaccumulated and biomagnificated in trophic levels
- In anaerobic sediment Hg^{2+} —> CH_3Hg^+ by sulphate-reducing and iron-reducing bacteria

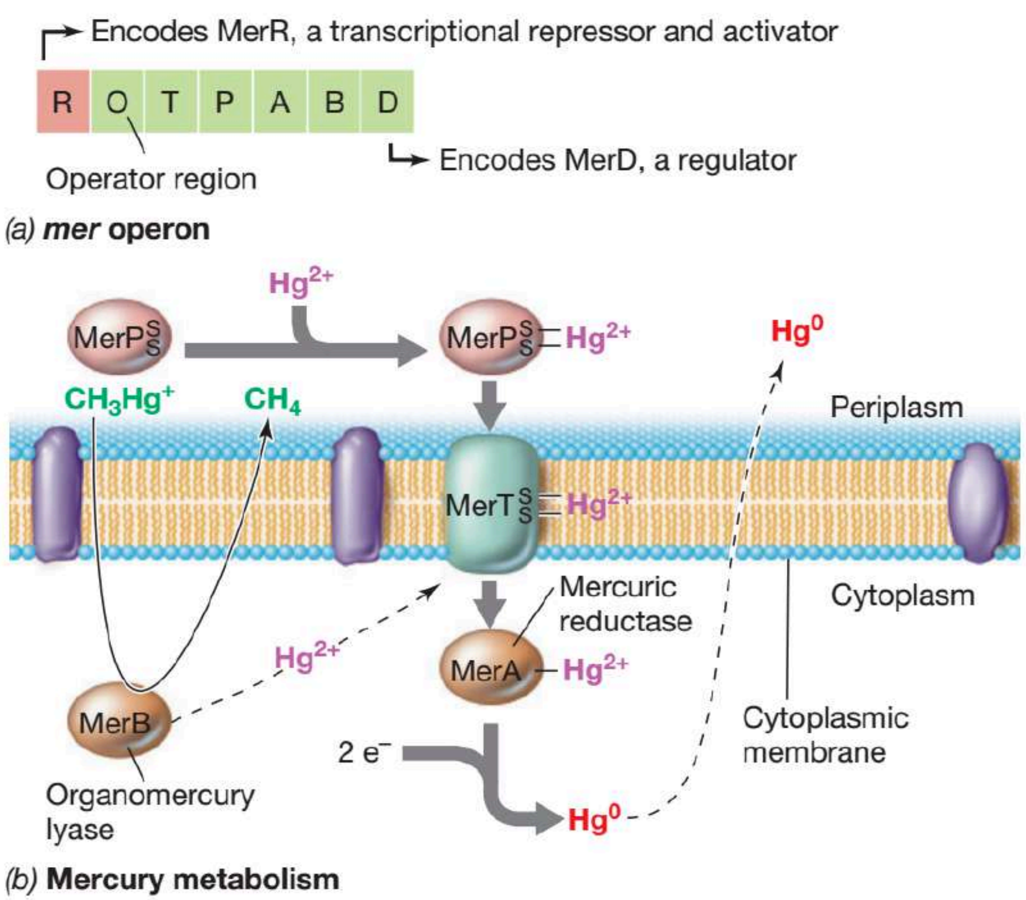
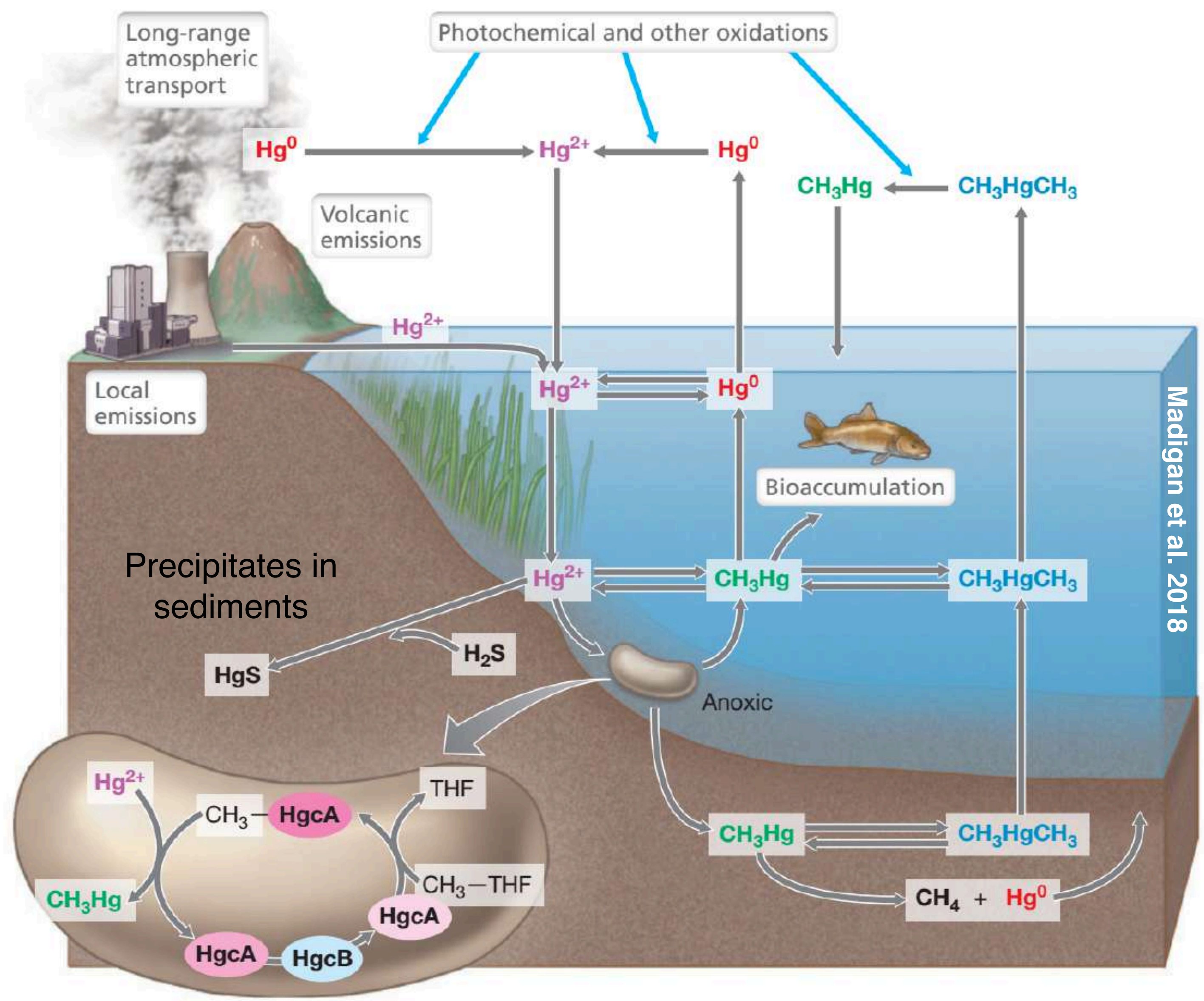
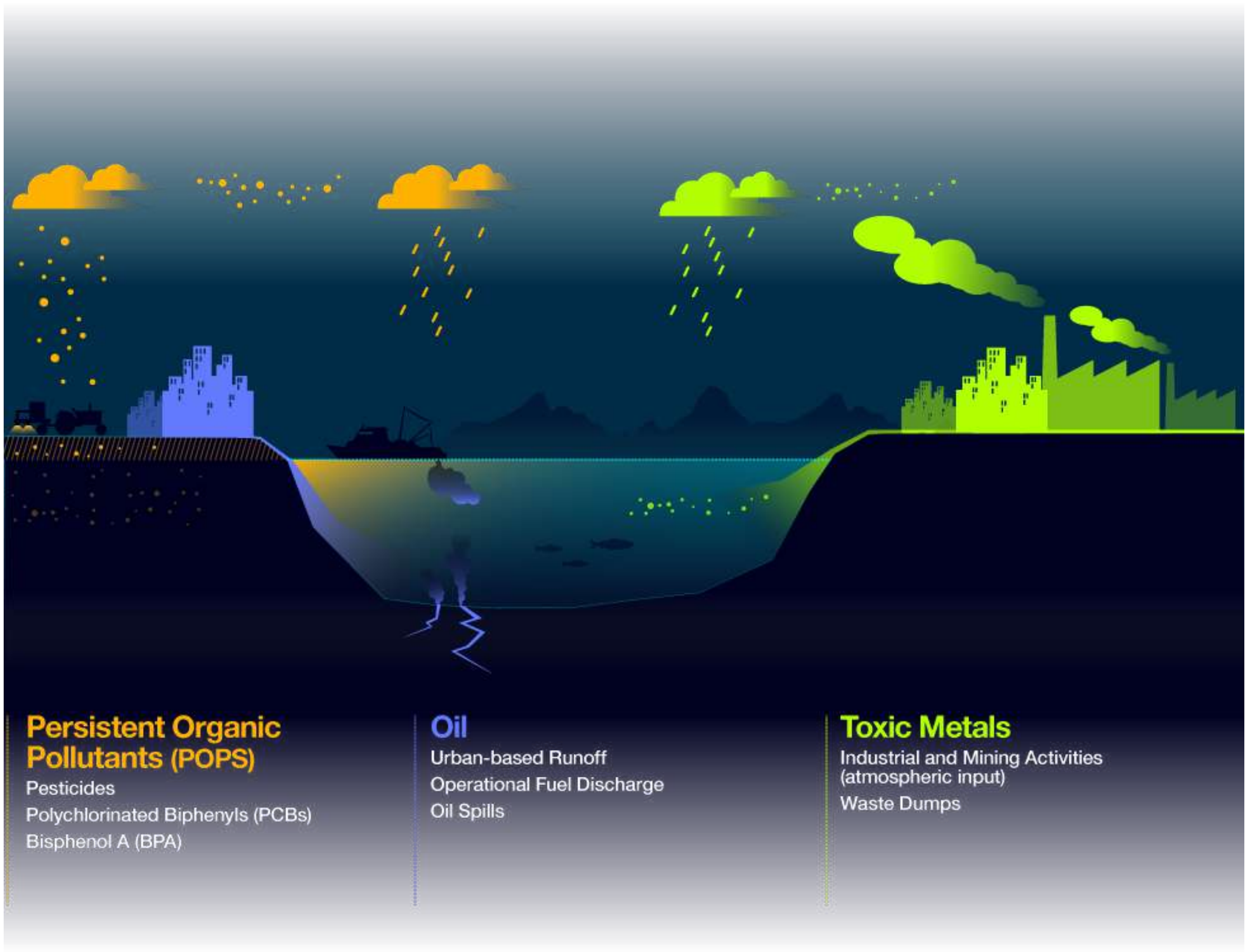


Figure 21.18 Mechanism of mercury transformations and resistance. *(a)* The *mer* operon. MerR can function as either a repressor (in the absence of Hg^{2+}) or a transcriptional activator (in the presence of Hg^{2+}). *(b)* Transport and reduction of Hg^{2+} and CH_3Hg^+; the Hg^{2+} is bound by cysteine residues in the MerP and MerT proteins. MerA is the enzyme mercuric reductase and MerB is organomercury lyase.



Chemical pollution

http://www.oceanhealthindex.org/methodology/components/chemical-pollution



- 'Chemical' refers to a compound or substance that has been purified or manufactured by humans
- More than 100,000 chemicals are used commercially (Daly 2006), and many enter the marine environment via atmospheric transport, runoff into waterways, or direct disposal into the ocean

CLIMATE: Anthropocene and climate change

Climate, Climate Change and Microbes

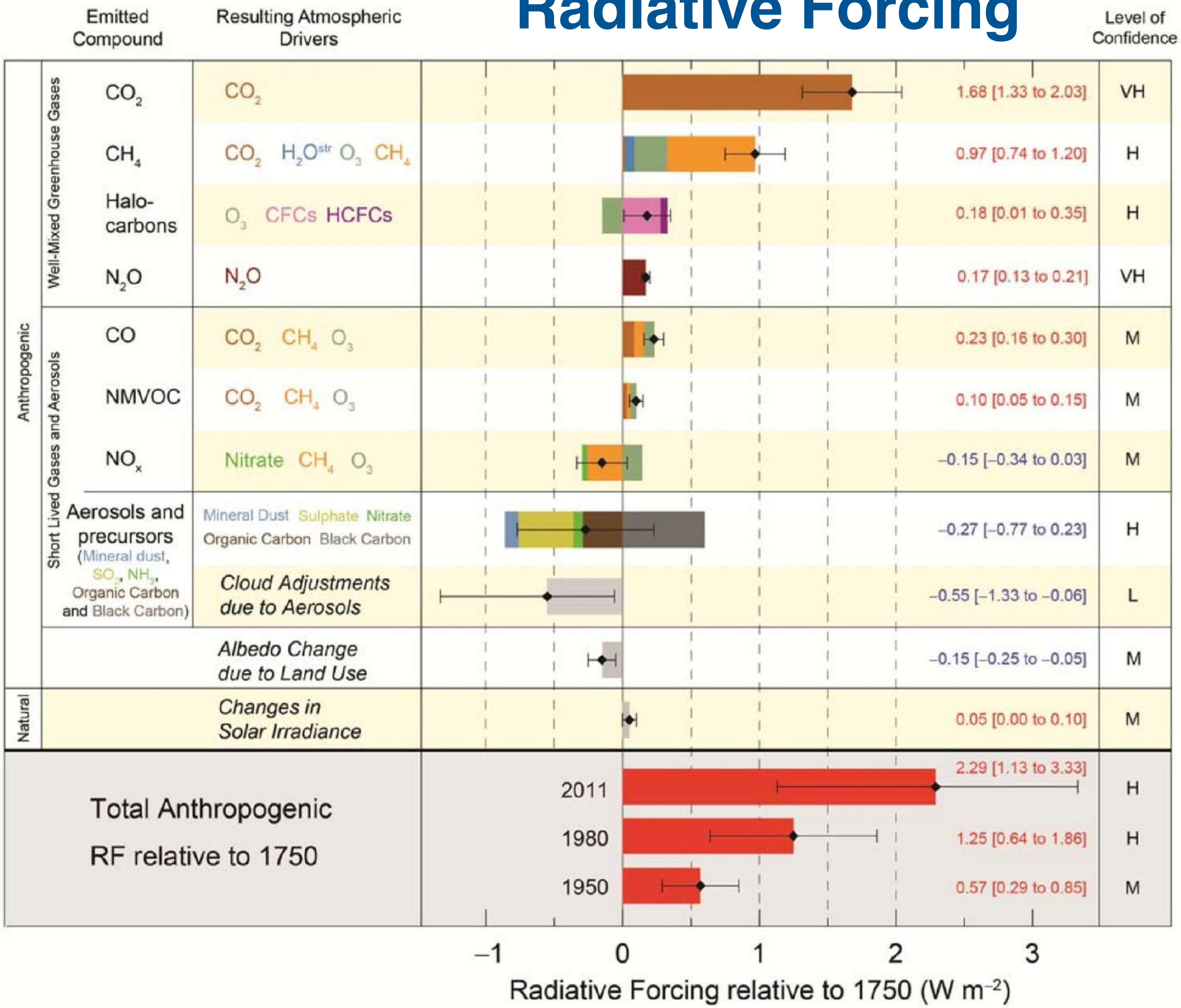
- **Climate is the general weather over a long period (>30 years)**
- Climate can include rainfall, temperature, snow or any other weather condition

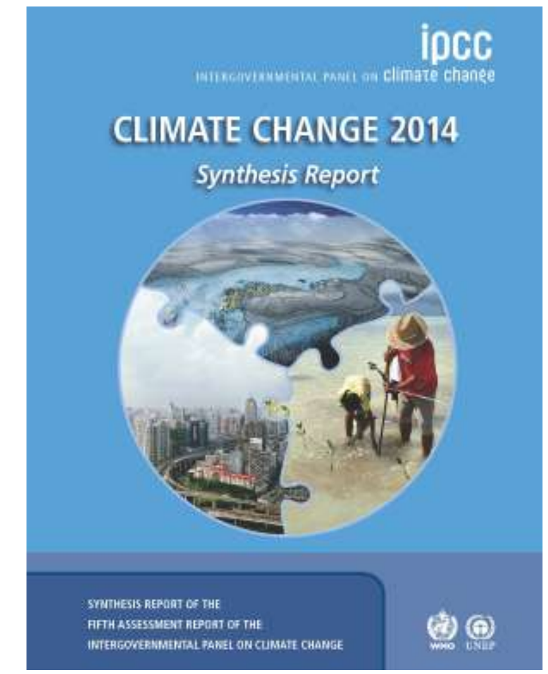
- Earth climate system comprises five **components**:
    - The atmosphere
    - The biosphere (living things)
    - The cryosphere (ice, such as sea ice, glaciers, ice sheets and permafrost)
    - The hydrosphere (water on, under or above the Earth’s surface, such as oceans, lakes, rivers and clouds)
    - The lithosphere (the Earth’s crust)

- Climate system can change because of either 1. internal variability (e.g., natural variation of climate components) or external forcings (e.g., variations in the Earth’s orbit or the output from the Sun, volcanoes and **human activities**)

- **Climate change**: intense droughts, water scarcity, severe fires, rising sea levels, flooding, melting polar ice, catastrophic storms and declining biodiversity

Radiative Forcing

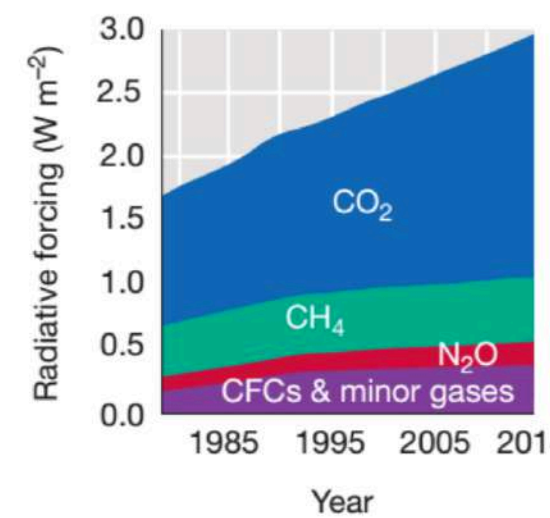




Rate of energy change per unit area at the top of the atmosphere

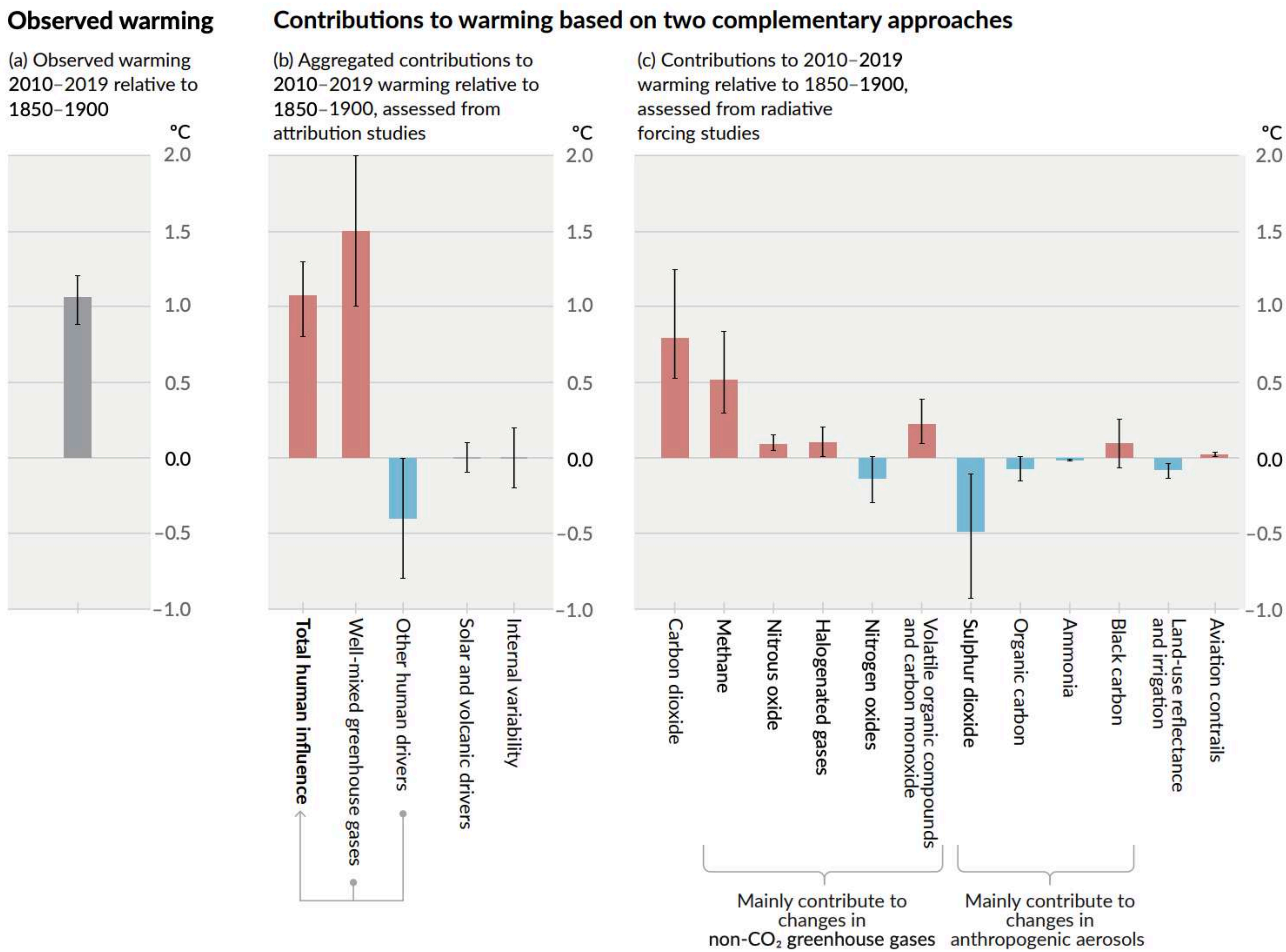
<u>RF is capacity of a gas or other forcing agents to affect energy gas balance </u>(incoming solar radiation and outgoing IR)

Cooling ← → **Warming**



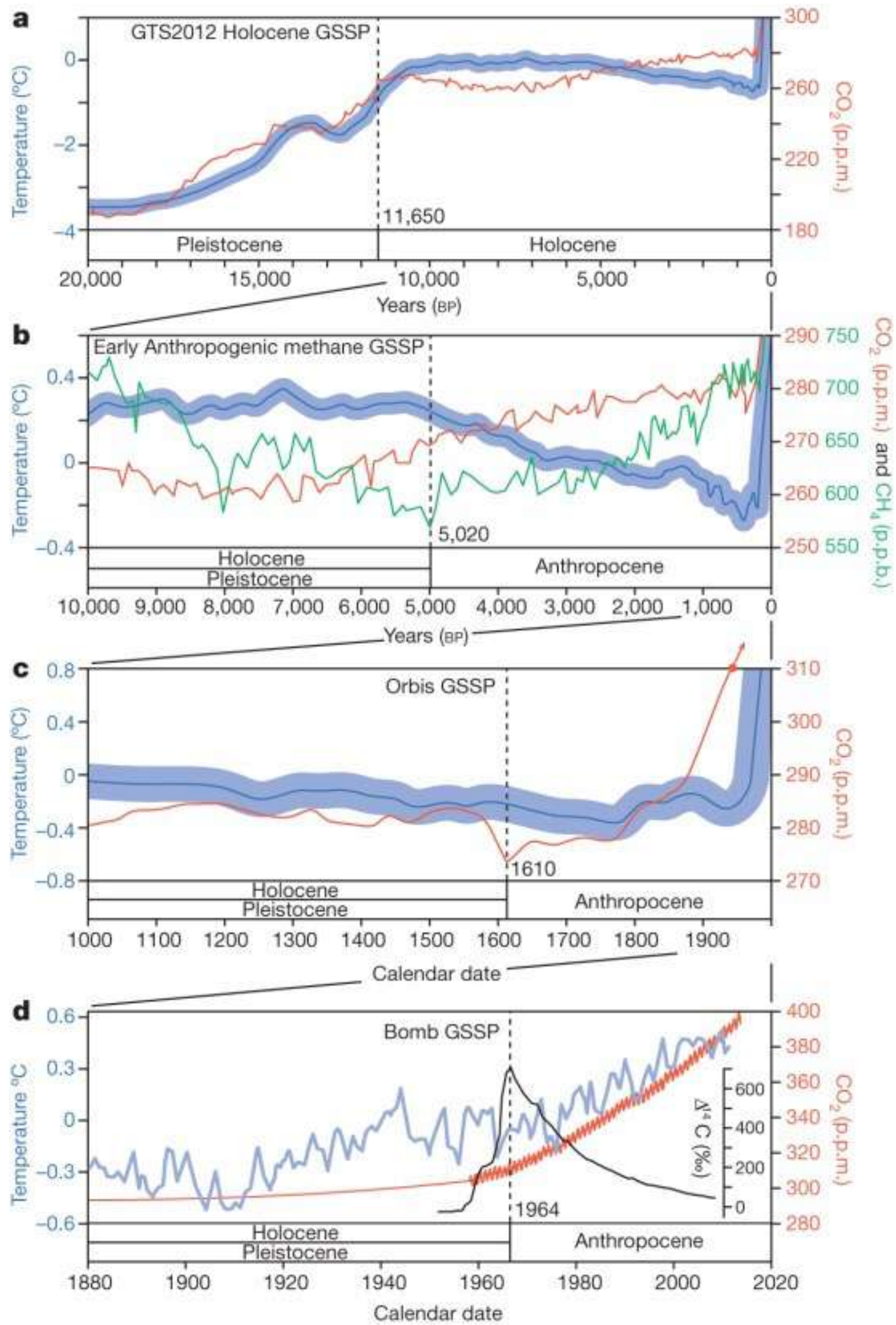
Madigan et al. 2018

IPCC AR6 report



Defining the beginning of the Anthropocene

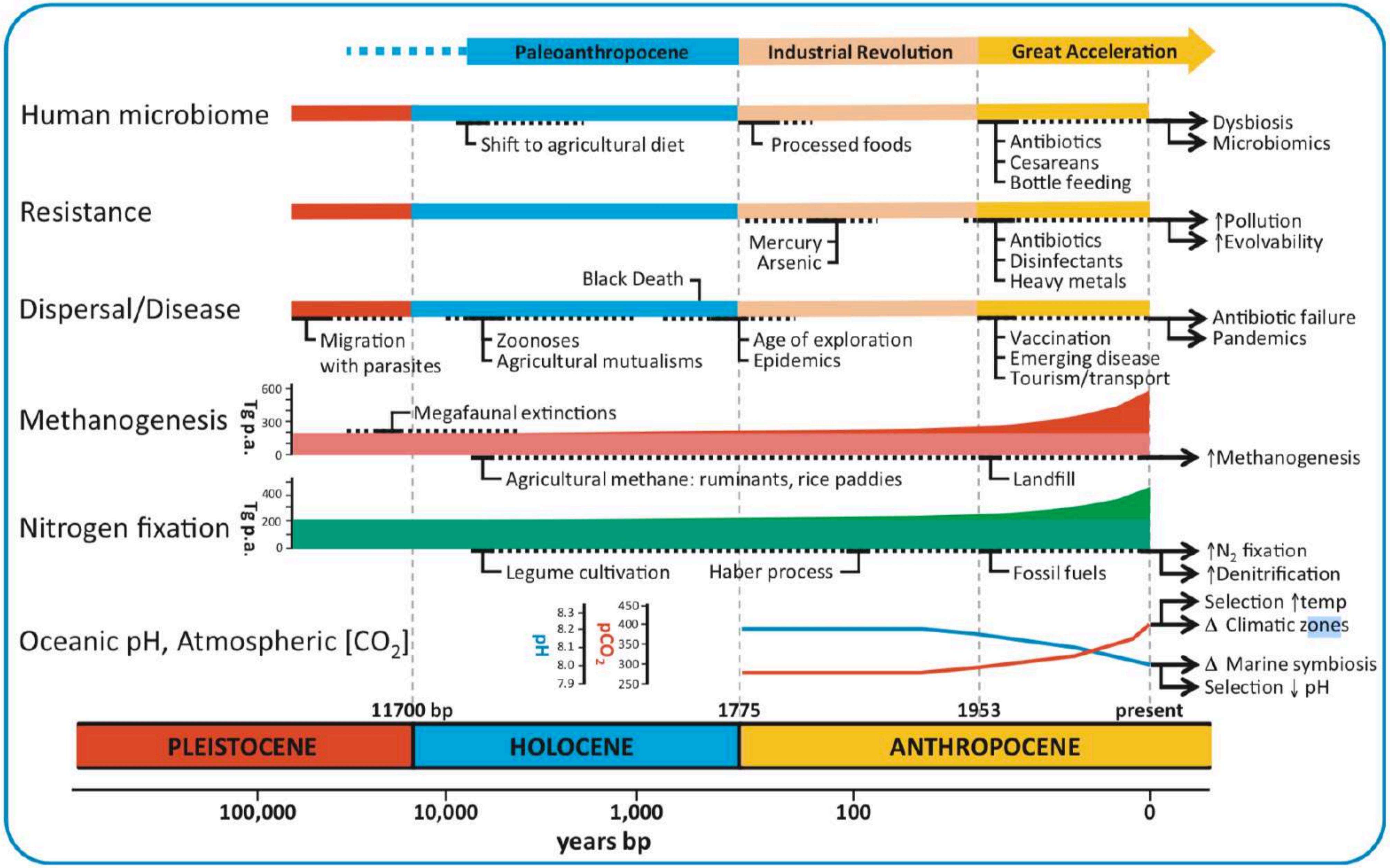
SL Lewis & MA Maslin *Nature* 519, 171-180 (2015) doi:10.1038/nature14258



- Human dominated geological epoch
- Proposed beginning: 1610 and 1964
- Great acceleration in socio-economic trends:
  - Population
  - Energy use
  - Water use
  - Fertilizer consumption
  - Transportation
- Great acceleration in earth system trends:
  - Nitrous oxide
  - Methane
  - Marine fish capture
  - Aquaculture
  - Tropical forest loss

www.anthropocene.info

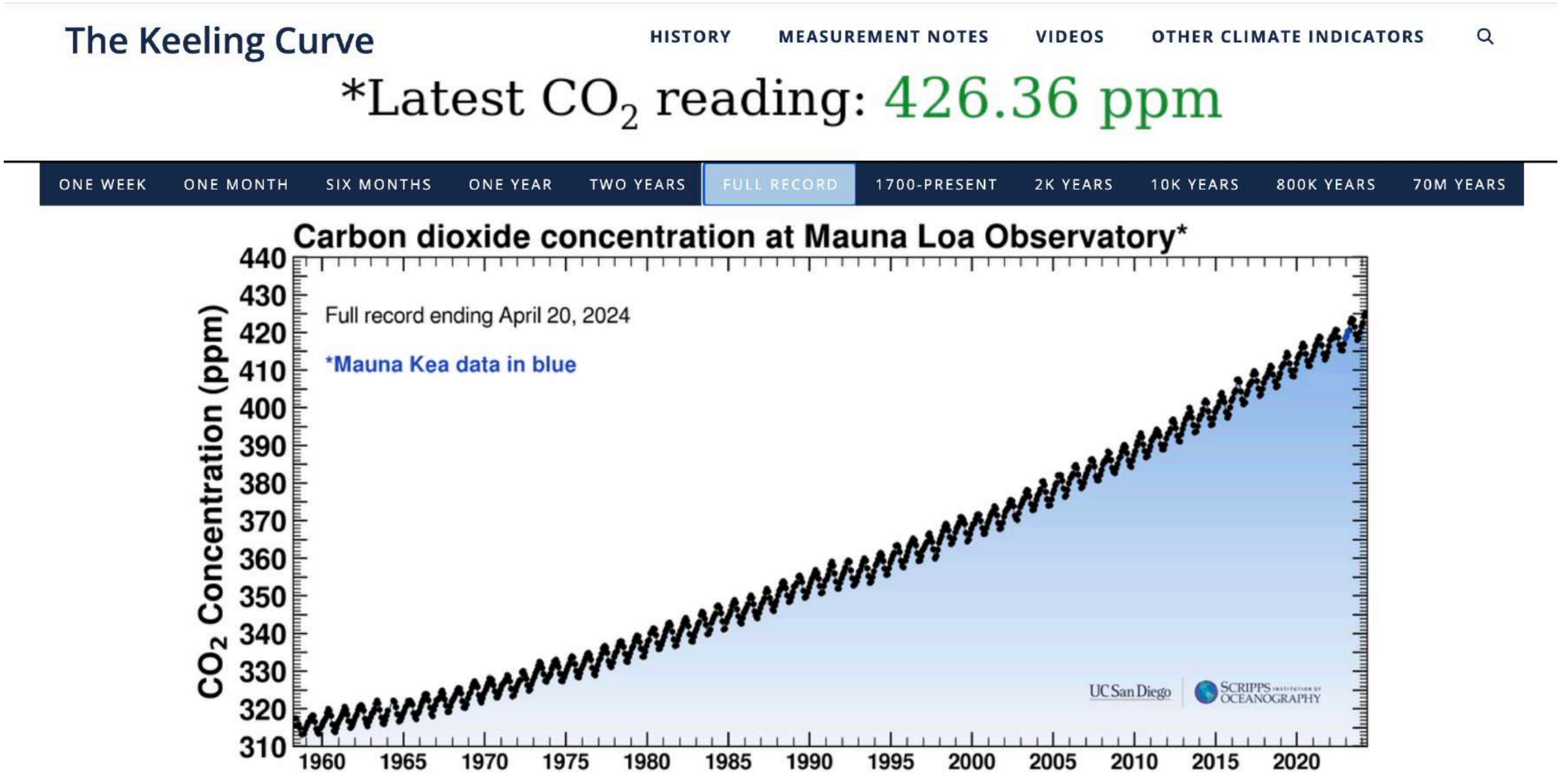
Microbiology in the Anthropocene



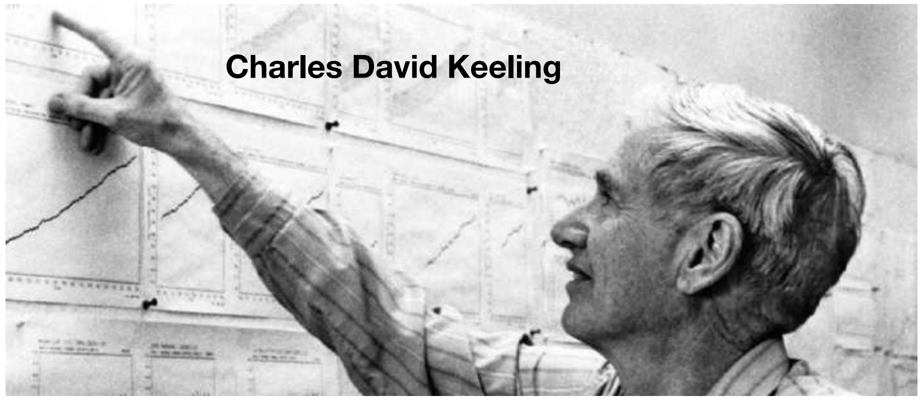
Gillings & Paulsen, 2014

- Human influences on microbial ecology and evolution
- Suggested date of 1953 for the start of the Great Acceleration is based on the publication of DNA structure (Watson and Crick, 1953) and the increased frequency of nuclear tests during that year (see Crutzen and Stoermer, 2000)

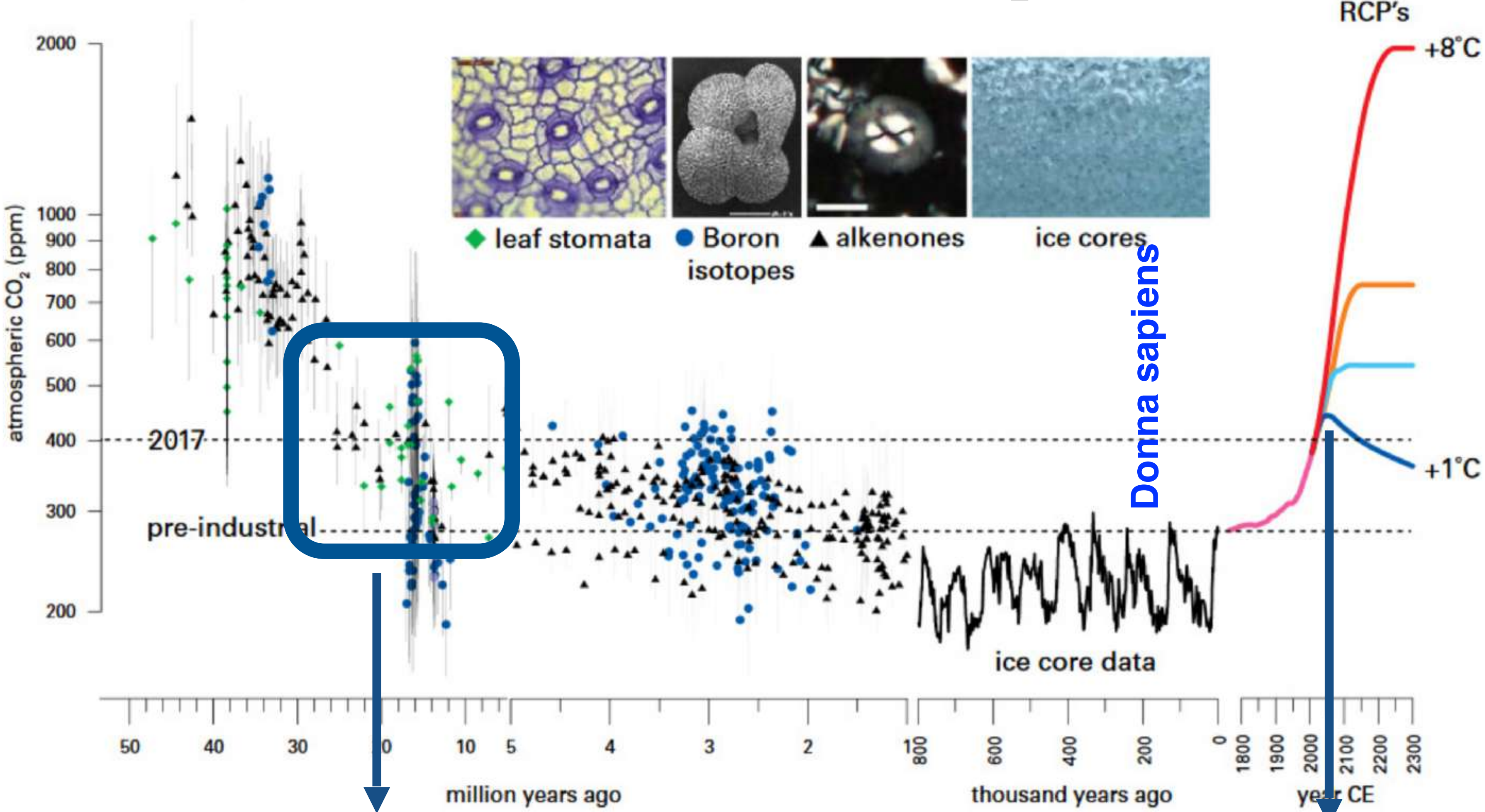
CO_2 trends on our planet



https://keelingcurve.ucsd.edu/

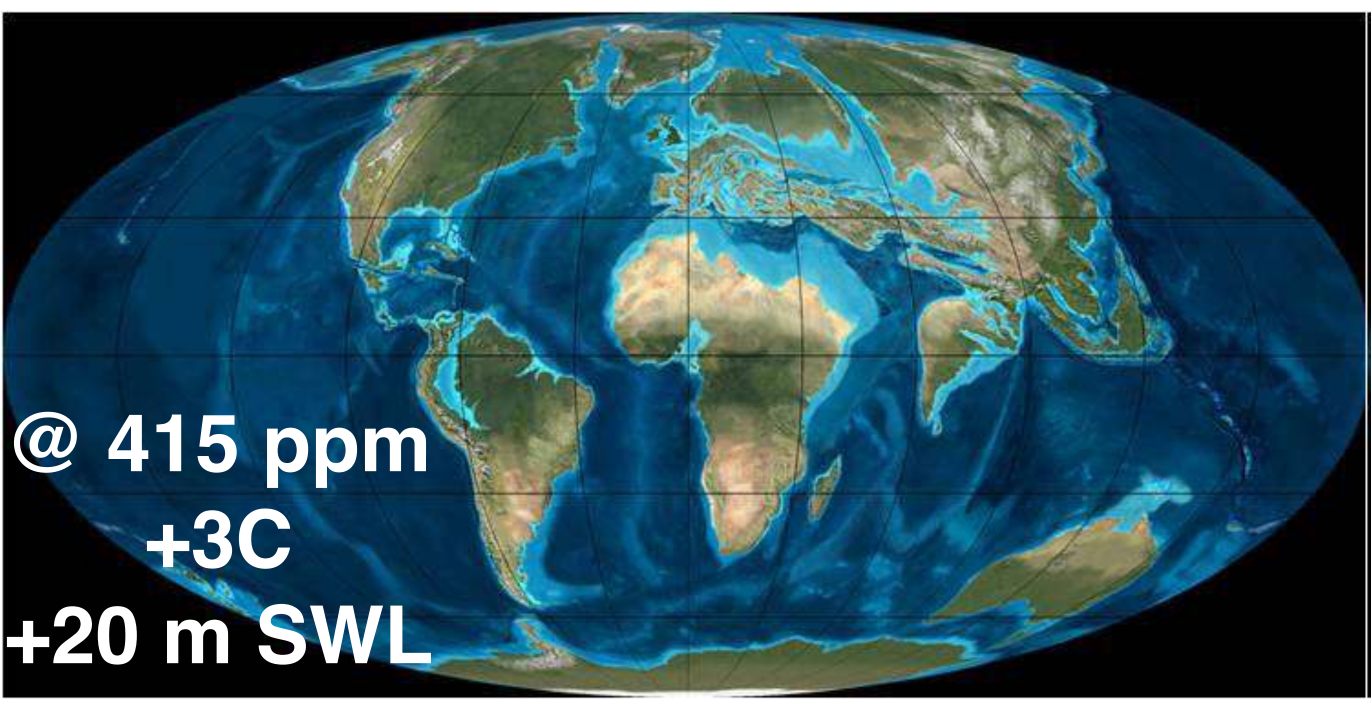


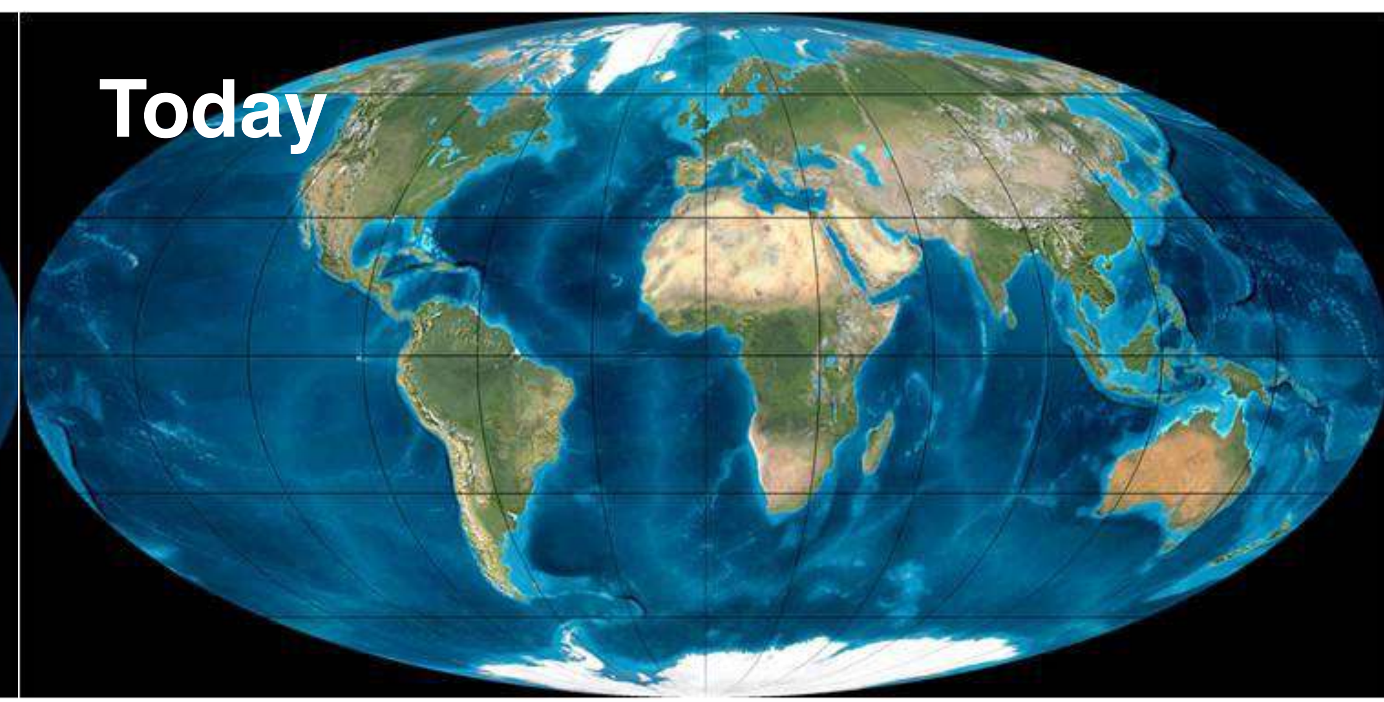
A look into the past



Representative Concentration Pathways, emission scenarios

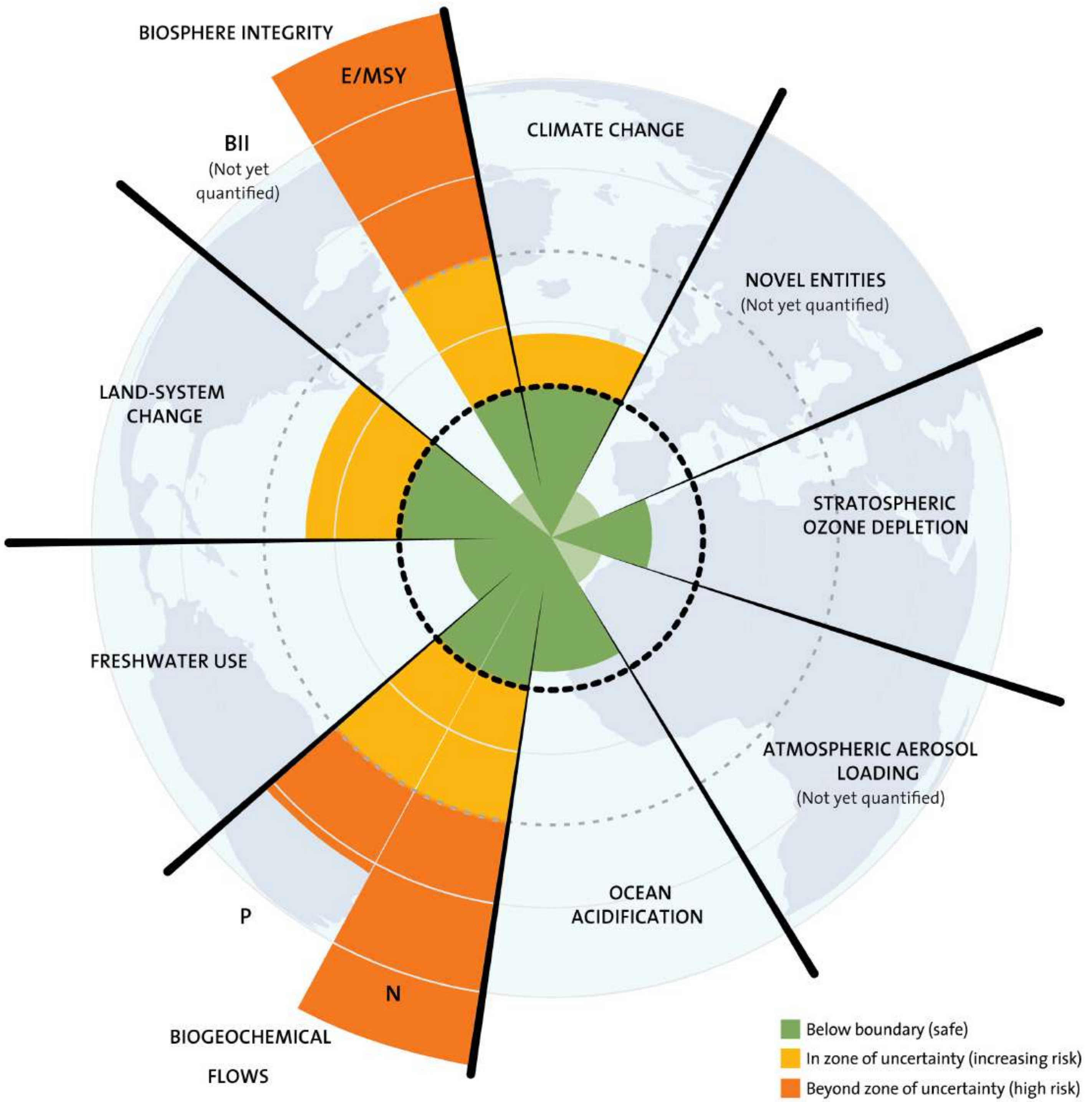
Inglis et al., 2015 Mills et al., 2018





http://www.thefosterlab.org/blog

Planetary Boundaries



Nine processes that regulate the stability and resilience of the Earth system

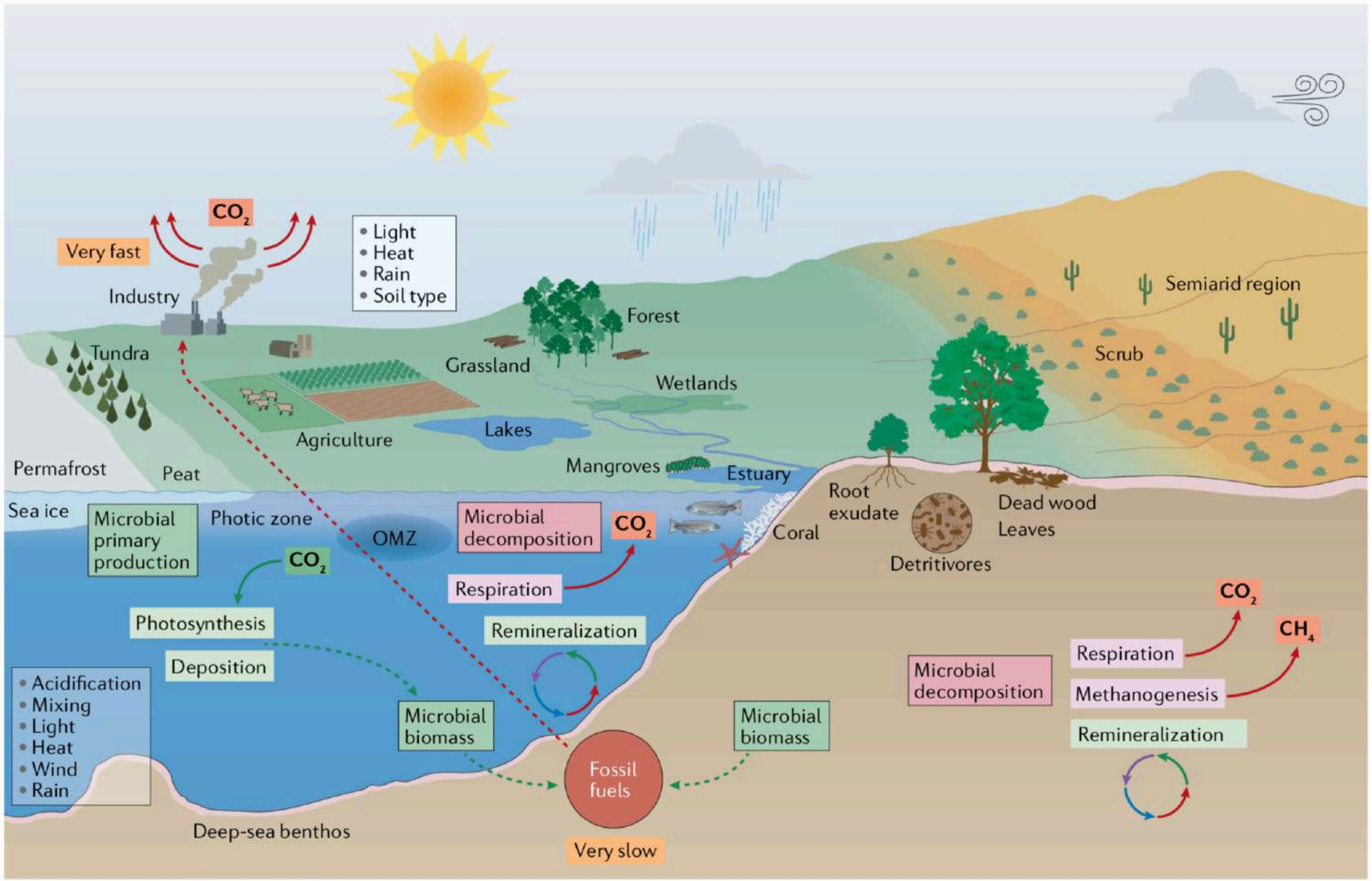
PB define a safe operating space with biophysical boundaries within which humanity can continue to develop and thrive for generations to come

Human pressure must be included in understanding Earth System

Foci of human induced changes on Earth

Rockström, J., Steffen, W., Noone, K., Persson, Å., et.al. 2009. A safe operating space for humanity. Nature 461: 472-475

Microbes and Climate Change



Cavicchioli et al. 2019

- In marine environments, microbial primary production contributes substantially to CO_2 sequestration
- Marine microorganisms also recycle nutrients for use in the marine food web and in the process release CO_2 to the atmosphere
- In a broad range of terrestrial environments, microorganisms are the key decomposers of organic matter and release nutrients in the soil for plant growth as well as CO_2 and CH_4 into the atmosphere

Biogeochemical processes

Table 1 | **Examples of physiological processes catalysed by microorganisms in biosphere habitats**

Process	Nature of process	Typical habitat
Carbon cycle		
Photosynthesis	Light-driven CO_2 fixation into biomass	Ow, Fw, FwS, Os
C respiration	Oxidation of organic C to CO_2	All
Cellulose decomposition	Depolymerization, respiration	Sl
Methanogenesis	CH_4 production	Sw, FwS, Os
Aerobic CH_4 oxidation	CH_4 becomes CO_2	All
Anaerobic CH_4 oxidation	CH_4 becomes CO_2	Os
Biodegradation		
Synthetic organic compounds	Decomposition, CO_2 formation	All
Petroleum hydrocarbons	Decomposition, CO_2 formation	All
Fuel additives (MTBE)	Decomposition, CO_2 formation	Sl, Sw, Gw
Nitroaromatics	Decomposition, CO_2 formation	Sl, Sw, Gw
Pharmaceuticals, personal care products	Decomposition	Sl, Sw, Gw
Chlorinated solvents	Compounds are dechlorinated through respiration in anaerobic habitats	Sl, Sw, Gw

Madsen, 2005

As, arsenic; C, carbon; CH_4, methane; CO_2, carbon dioxide; Fe, iron; FeS, iron sulphide; Fw, freshwater; FwS, freshwater sediment; Gw, groundwater; H_2, hydrogen; Hg, mercury; Hg^{2+}, mercuric ion; MTBE, methyl tertiary butyl ether; N_2, nitrogen; NH_3, ammonia; NH_4^+, ammonium; NO_2^-, nitrite; NO_3^- , nitrate; Os, ocean sediments; Ow, ocean waters; S^0, elemental sulphur; S^{2-}, sulphide; Sl, soil; SO_4^{2-}, sulphate; Sw, sewage; U, uranium.

Nitrogen cycle		
N_2 fixation	N_2 gas becomes NH_3	Sl, Ow
NH_4^+ oxidation	NH_3 becomes NO_2^-, NO_3^-	Sl, Sw
Anaerobic NH_4^+ oxidation	NO_2^- and NH_3 become N_2 gas	Sw, Os
Denitrification	NO_3^- is used as an electron acceptor and converted to N_2 gas	Sl, Sw
Sulphur cycle		
S_2 oxidation	S^{2-} and S^0 become SO_4^{2-}	Os, FwS
SO_4^{2-} reduction	SO_4^{2-} is used as an electron acceptor and converted to S^0 and S^{2-}	Os, Sw, Gw
Other elements		
H_2 oxidation	H_2 is oxidized to H^+, electrons reduce other substances	Sw, Sl, Os, FwS
Hg methylation and reduction	Organic Hg is formed and Hg^{2+} is converted to Hg	FwS, Os
(per)chlorate reduction	Oxidants in rocket fuel and other sources are converted to chloride	Gw
U reduction	U oxyanion is used as an electron acceptor; therefore immobilized	Gw
As reduction	As oxyanion is used as an electron acceptor; therefore toxicity is diminished	FwS, Gw
Fe oxidation, acid mine drainage	FeS ores are oxidized, strong acidity is generated	FwS, Gw

Madsen, 2005

As, arsenic; C, carbon; CH_4, methane; CO_2, carbon dioxide; Fe, iron; FeS, iron sulphide; Fw, freshwater; FwS, freshwater sediment; Gw, groundwater; H_2, hydrogen; Hg, mercury; Hg^{2+}, mercuric ion; MTBE, methyl tertiary butyl ether; N_2, nitrogen; NH_3, ammonia; NH_4^+, ammonium; NO_2^-, nitrite; NO_3^- , nitrate; Os, ocean sediments; Ow, ocean waters; S^0, elemental sulphur; S^{2-}, sulphide; Sl, soil; SO_4^{2-}, sulphate; Sw, sewage; U, uranium.

Microbial aquatic ecosystems and climate, I

- Rising temperature —> biological processes, reduce water density and thereby stratification and circulation—> organismal dispersal and nutrient transport
- Precipitation, salinity and winds also affect stratification, mixing and circulation
- Nutrient inputs from air, river and estuarine flows also affect microbial community composition and function, and climate change affects all these physical factors
- By fixing carbon and nitrogen, and remineralizing organic matter, marine microorganisms form the basis of ocean food webs and thus global carbon and nutrient cycles
- The sinking, deposition and burial of fixed carbon in particulate organic matter to marine sediments is a key, long-term mechanism for sequestering CO_2 from the atmosphere
- **The balance between regeneration of CO_2 and nutrients via remineralization versus burial in the seabed determines the effect on climate change**
- Oceans have acidified by ~0.1 pH units since preindustrial times, with further reductions of 0.3–0.4 units predicted by the end of the century

Microbial aquatic ecosystems and climate, II

- **Marine phytoplankton perform half of the global photosynthetic CO_2 fixation** (net global primary production of ~50 Pg C per year, petagram= 10^{15}g) and **half of the oxygen production** despite amounting to only ~1% of global plant biomass
- In comparison with terrestrial plants, marine phytoplankton are distributed over a larger surface area, are exposed to less seasonal variation and have markedly faster turnover rates than trees (days versus decades)
- Phytoplankton respond rapidly on a global scale to climate variations.
- **Chemolithoautotrophic archaea and bacteria fix CO_2 under dark conditions in deep ocean waters and at the surface during polar winter**
- **Oxygen minimum zones (OMZs) have expanded** in the past 50 years as a result of ocean warming, which **reduces oxygen solubility**
- **OMZs are global sinks for reactive nitrogen**, and microbial production of N_2 and N_2O accounts for ~25–50% of nitrogen loss from the ocean to the atmosphere
- OMZs are the l**argest pelagic methane reservoirs** in the ocean and contribute substantially to open ocean methane cycling
- Ocean warming, acidification, eutrophication and overuse (for example, fishing, tourism) together cause the decline of coral reefs and mangroves

Carbon export deep ocean and climate change

Henson et al., 2022

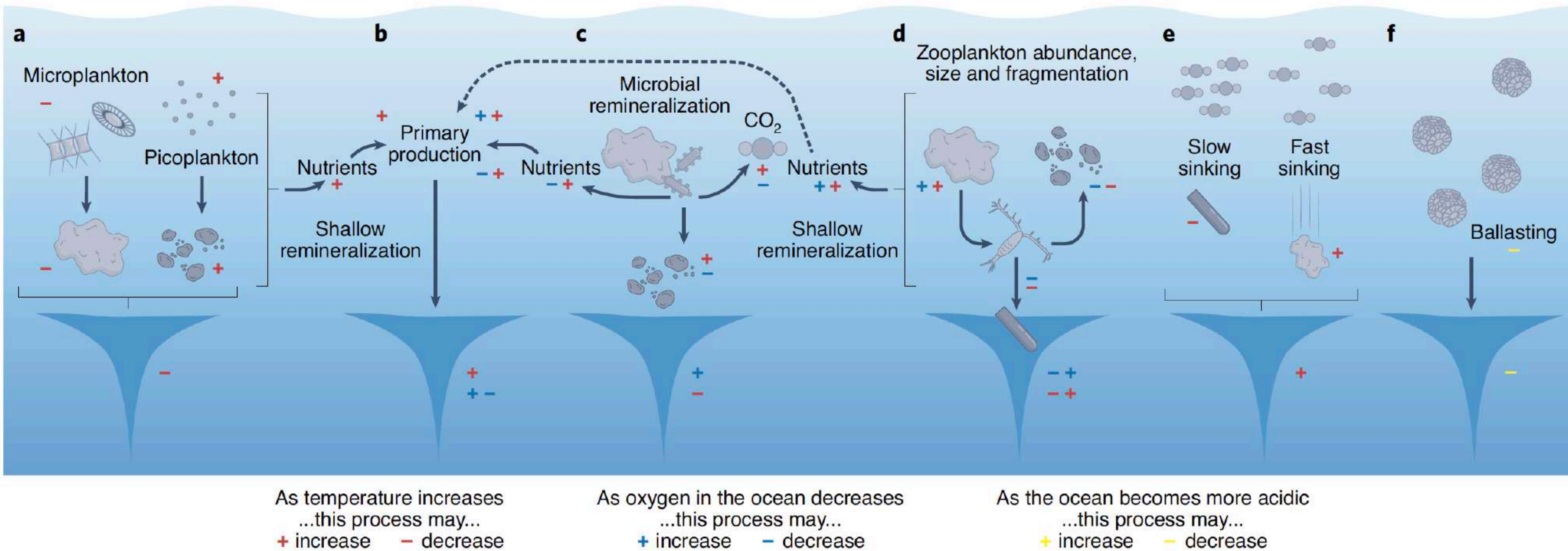


Fig. 2 | Potential response of export processes to climate change. Export will change in response to increasing temperature, decreasing oxygen concentration and ocean acidification. **a**–**f**, Potential responses in phytoplankton size (**a**), primary production (**b**), rate of microbial remineralization (**c**), zooplankton abundance and size (**d**), water viscosity (**e**) and mineral ballast (**f**). However, there are high uncertainties in both the direction of many of these responses and the effect on export flux due to complex feedbacks.

Microbial terrestrial ecosystems and climate, I

- There is ~**100-fold more terrestrial biomass** than marine biomass, and terrestrial plants account for a large proportion of Earth's total biomass
- Terrestrial plants perform roughly **half of net global primary production**
- **Soils store ~2,000 billion tonnes of organic carbon**, which is more than the combined pool of carbon in the atmosphere and vegetation
- Plants remove CO_2 from the atmosphere through photosynthesis and create organic matter that fuels terrestrial ecosystems
- Conversely, autotrophic respiration by plants (60 Pg C per year) and heterotrophic respiration by microorganisms (60 Pg C per year) release CO_2 back into the atmosphere (balance)

Microbial terrestrial ecosystems and climate, II

- Forests cover ~30% of the land surface, contain ~45% of terrestrial carbon, make up ~50% of terrestrial primary production and sequester up to 25% of anthropogenic CO_2
- Grasslands cover ~29% of the terrestrial surface
- Non-forested, arid and semiarid regions (47%) are important for the carbon budget and respond differently to anthropogenic climate change than forested regions
- Lakes make up ~4% of the non-glaciated land ares and shallow lakes emit substantial amounts of CH_4
- **Peat** (torba decomposed plant litter) covers ~3% of the land surface and, due to plant productivity exceeding decomposition, intact peatlands function as a **global carbon sink and contain ~30% of global soil carbon**
- In **permafrost**, the accumulation of carbon in organic matter (remnants of plants, animals and microorganisms) far exceeds the respiratory losses, creating the largest terrestrial **carbon sink** —> Climate warming of 1.5–2 °C (relative to the global mean surface temperature in 1850–1900) is predicted to reduce permafrost by 28–53% (compared with levels in 1960–1990) thereby making large carbon reservoirs available for microbial respiration and greenhouse gas emissions

Microbial terrestrial ecosystems and climate

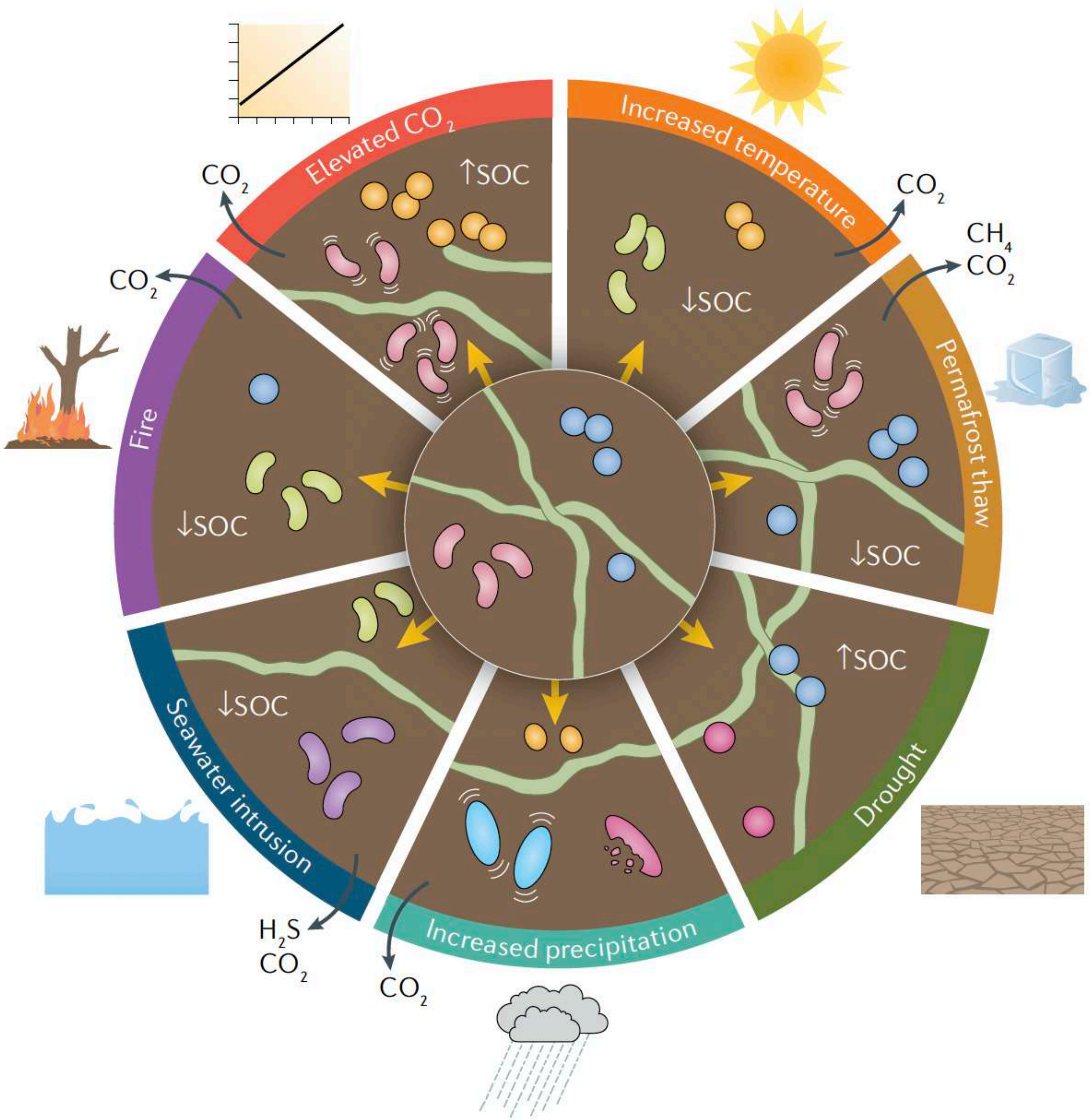
- In peatlands, decay-resistant litter (for example, antimicrobial phenolics and polysaccharides of *Sphagnum* mosses) inhibits microbial decomposition, and water saturation restricts oxygen exchange and promotes the growth of anaerobes and release of CO_2 and CH_4

  ➡ Increased temperature and reduced soil water content caused by climate change promote the growth of vascular plants (ericaceous shrubs) but reduce the productivity of peat moss

  ➡ Changes in plant litter composition and associated microbial processes (for example, reduced immobilization of nitrogen and enhanced heterotrophic respiration) are switching peatlands from carbon sinks to carbon source

- According to the World Bank (World Bank data on agricultural land), nearly **40% of the terrestrial environment is devoted to agriculture** —> this proportion is predicted to increase, leading to substantial changes in soil cycling of carbon, nitrogen and phosphorus, among other nutrients

Soil microbiomes and climate change



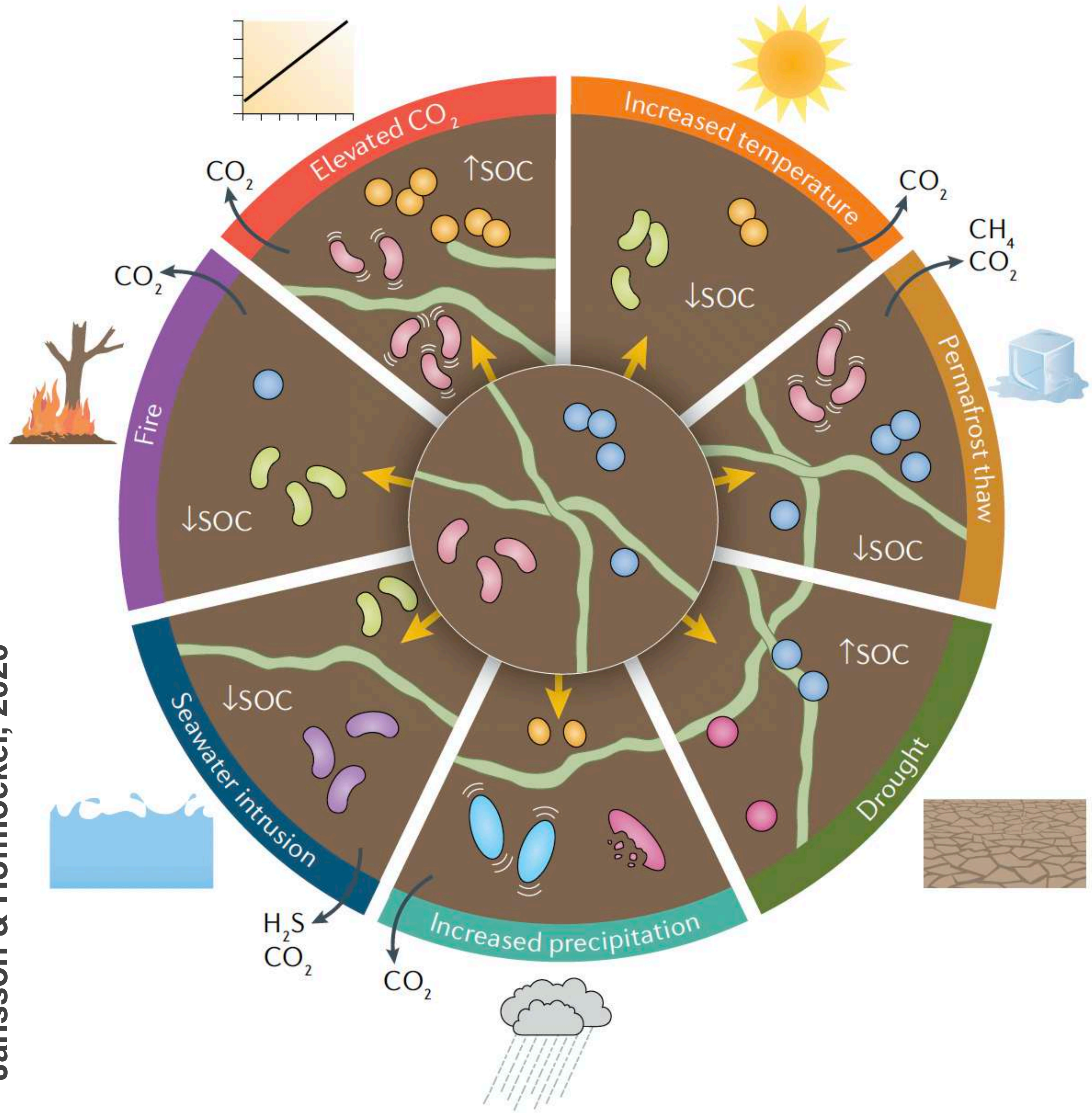
Jansson & Hofmockel, 2020

A soil microbial community of bacteria, archaea (red and blue) and fungal hyphae (green) in the absence of climate change pressures is depicted in the centre.

Examples of climate responses are shown at the periphery (note that changes in cell colour to orange, green or purple indicate a community shift).

Increases or decreases in soil organic carbon (SOC) are indicated by up and down white arrows, respectively.

Soil microbiomes and climate change



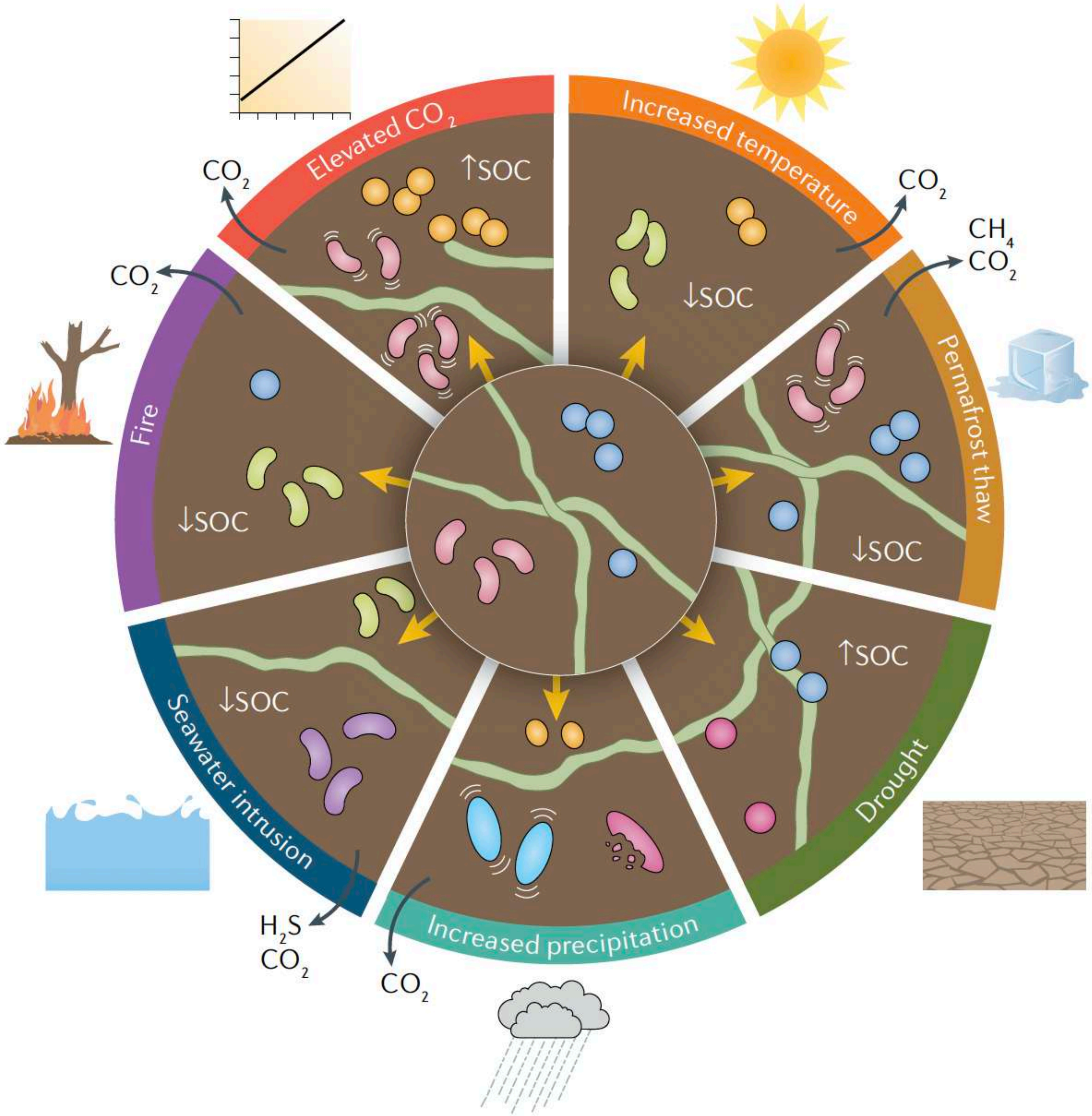
Jansson & Hofmockel, 2020

Elevated CO_2 —> an increase in carbon below ground due to increases in plant growth, with corresponding increases in soil microbial biomass and shifts in community composition. In the long term,SOC may decompose at a faster rate than it is formed.

White lines indicate increased microbial activity

Increased temperature —> in loss of SOC, shifts in bacterial and/or archaeal compositions and decreases in fungal abundance. **Permafrost thaw** results in a deepening of the seasonally thawed active layer and an increase in microbial degradation of SOC. Viruses have been detected in thawed permafrost and have been implicated in carbon cycling. Depending on landscape hydrology, methanogens in wetter and more anaerobic areas can generate CH_4.

Soil microbiomes and climate change

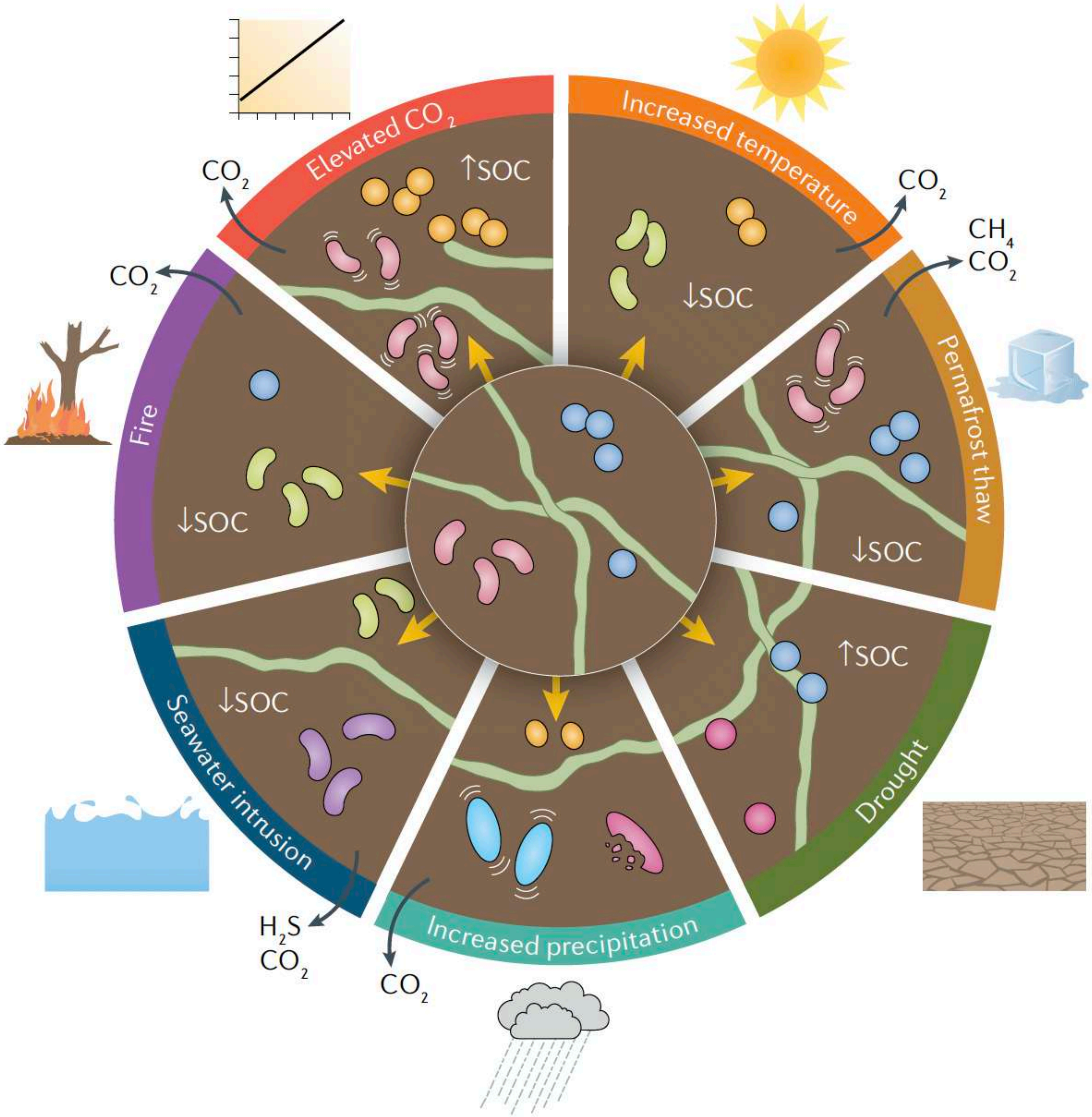


Jansson & Hofmockel, 2020

Drought —> in less decomposition of SOC, lower microbial biomass and less CO_2 production. Surviving bacteria may produce molecules to retain cell turgor (osmolytes) and/or enter a dormant physiological state (as represented by a change in shape of the red cell). Under drought, fungal hyphae can be better suited to bridge disconnected soil pores and serve as a fungal highway for other microbial cells.

Increased precipitation can increase water saturation and anaerobic soil zones. Here, a case for wetting dry soil when there is a sudden increase in water and nutrient availability , which may cause some cells to burst (as shown by the burst red cell) and serve as a substrate for other cells to become more active (white lines by blue cells indicate increased activity), respire and produce CO_2 (Birch effect); there can also be some community shifts.

Soil microbiomes and climate change

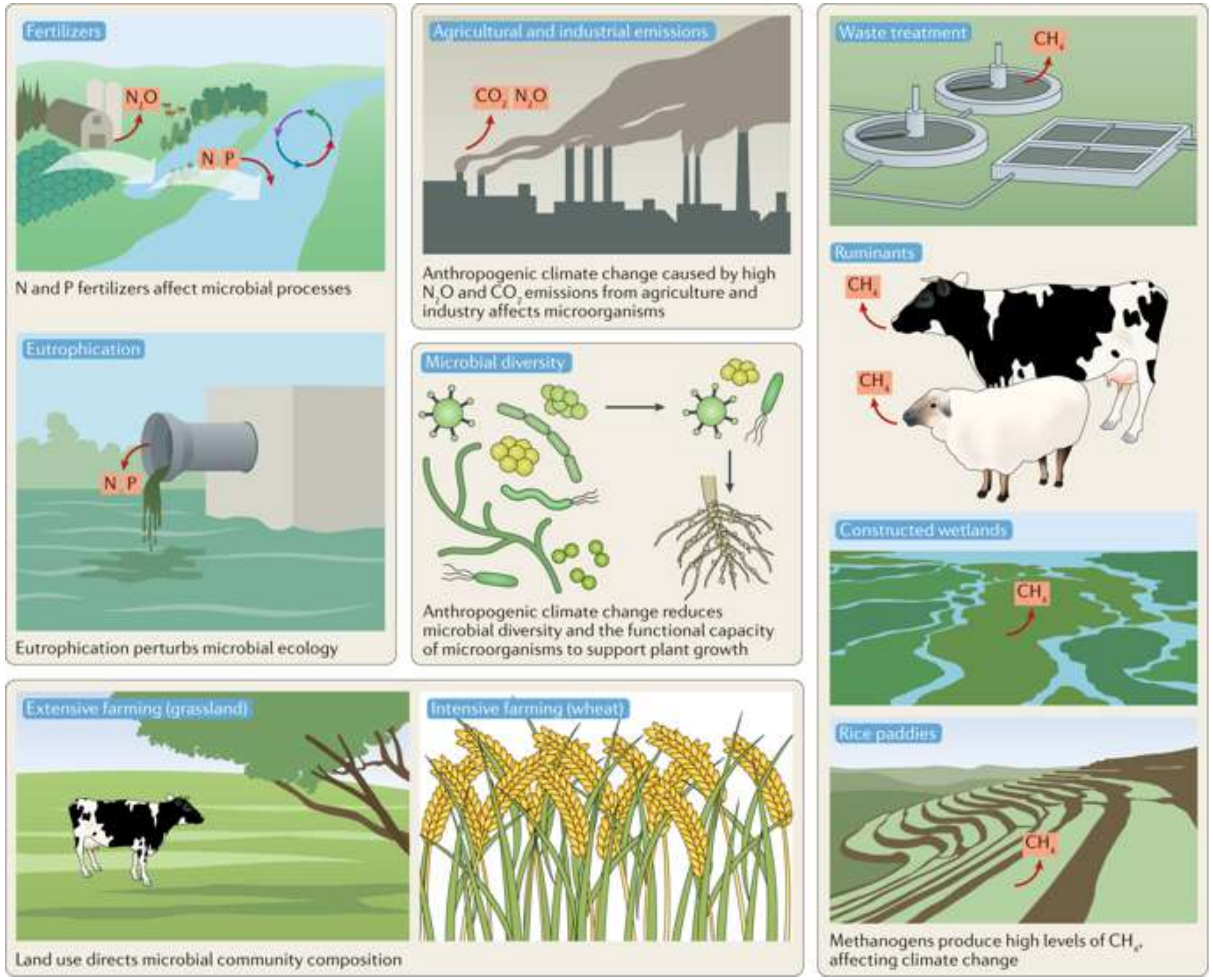


Jansson & Hofmockel, 2020

Seawater intrusion —> increase soil saturation and anaerobic zones. Furthermore, saltwater can introduce alternate electron acceptors (for example, sulfate) that can result in community shifts (purple cells represent sulfate-reducing bacteria).

Fire —> in a turnover of soil carbon and nitrogen stocks, reduction in microbial biomass, depletion of fungi and some community shifts.

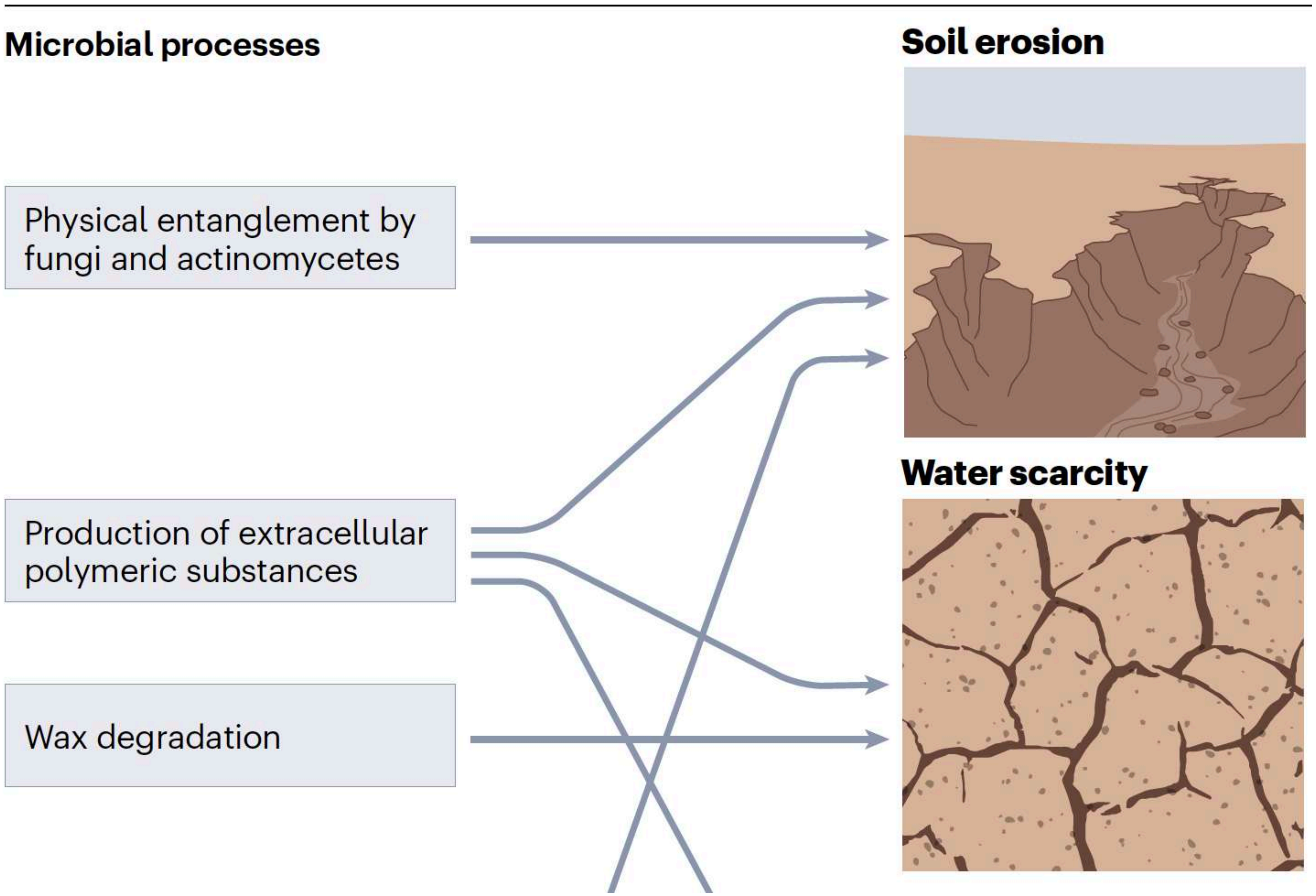
Human footprint on microbes

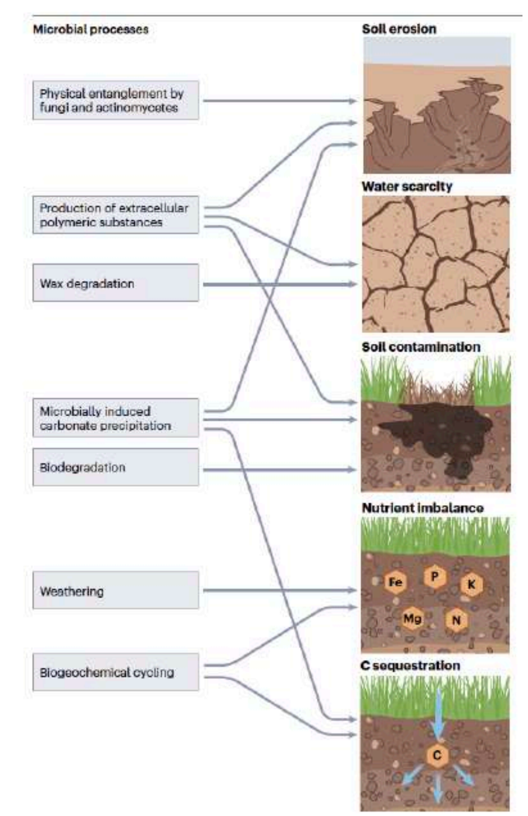


Cavicchioli et al. 2019

- Agricultural practices influence microbial communities in specific ways
- **Land usage** (*plant type*) and **sources of pollution** (*fertilizers*) **perturb microbial community** composition and function, thereby **altering natural cycles of carbon, nitrogen and phosphorus** transformations
- Methanogens produce substantial quantities of methane directly from ruminant animals (*cattle, sheep and goats*) and saturated soils with anaerobic conditions (*rice paddies and constructed wetlands*)
- Human activities that cause a reduction in microbial diversity also reduce the capacity for microorganisms to support plant growth

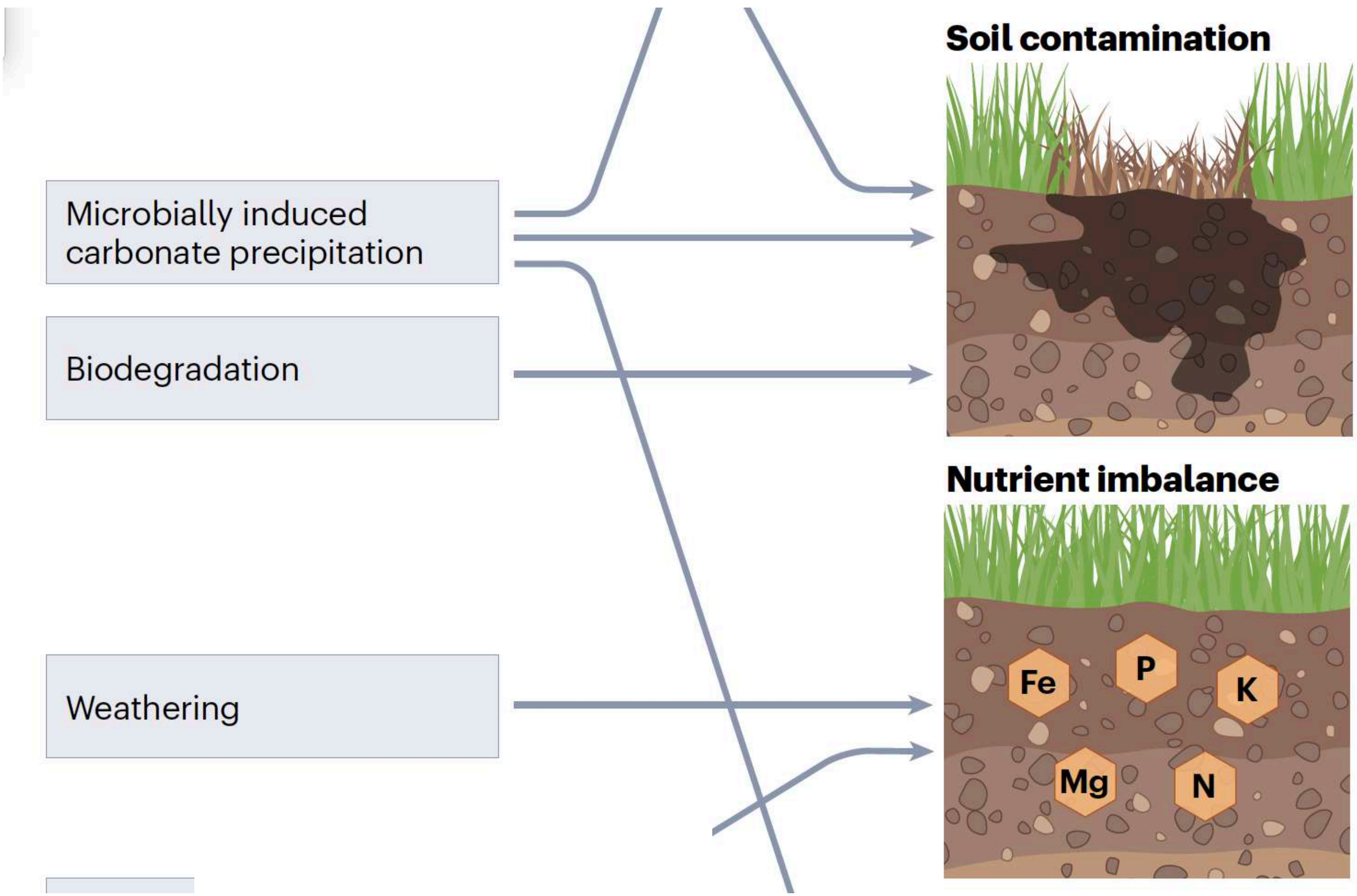
Harnessing microbial communities to combat soil threats and global change, I

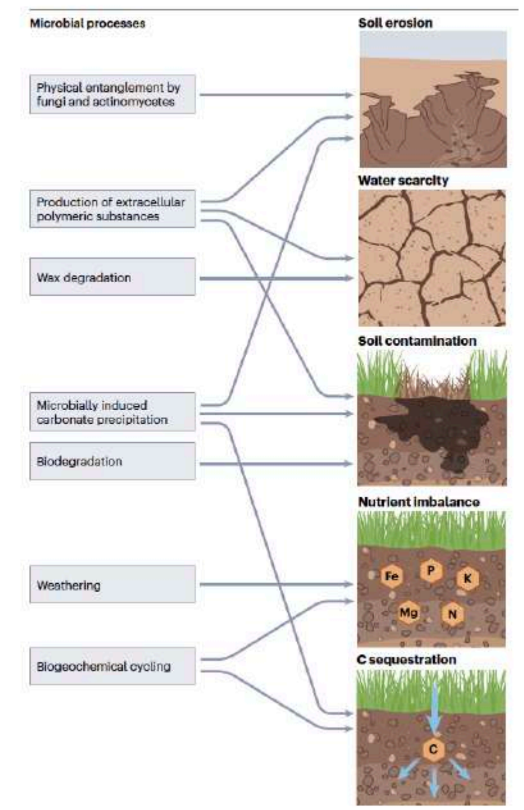




Philippot et al., 2023

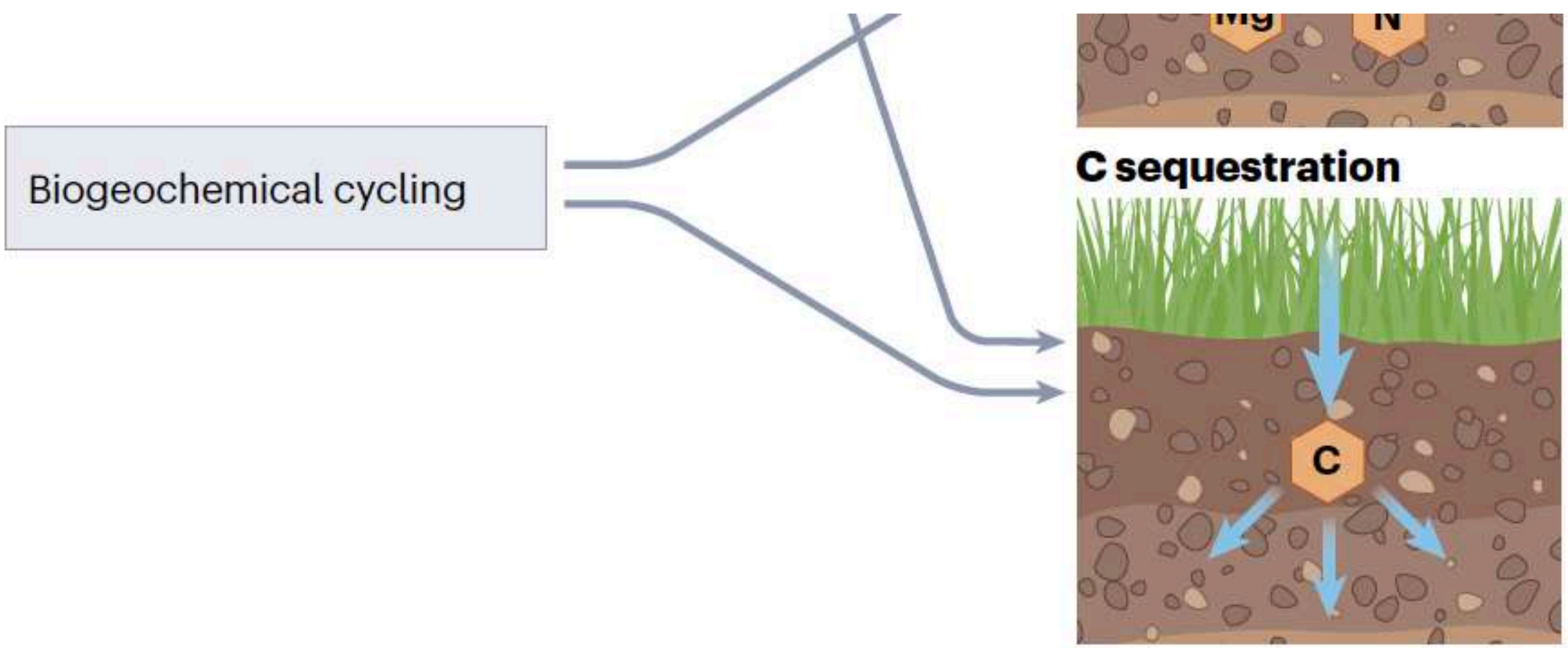
Harnessing microbial communities to combat soil threats and global change, II

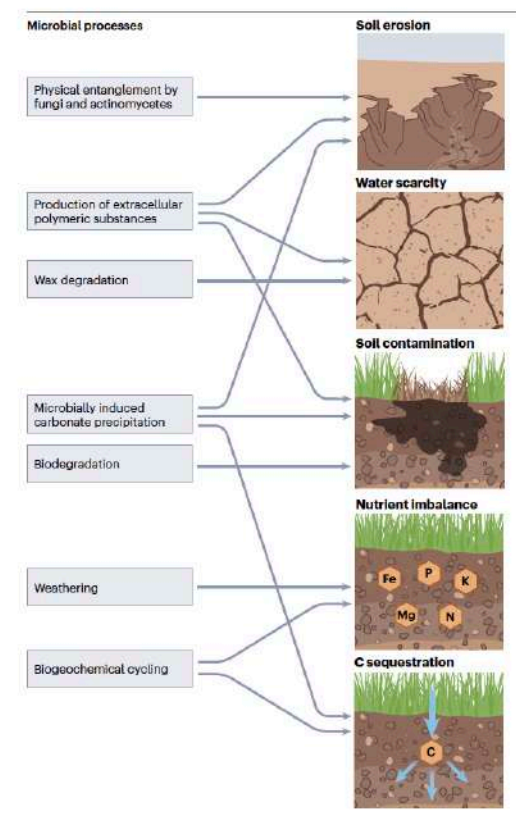




Philippot et al., 2023

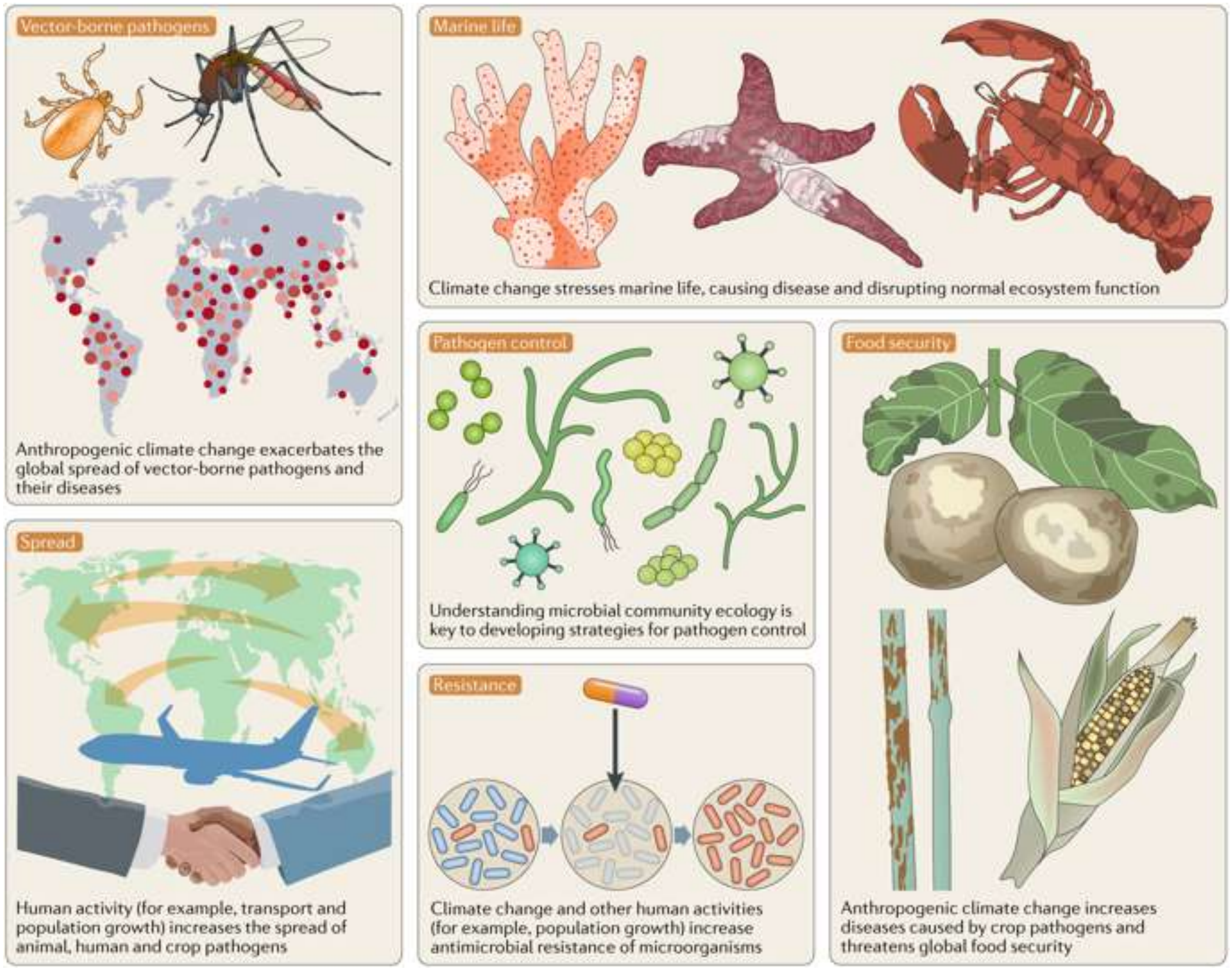
Harnessing microbial communities to combat soil threats and global change, III





Philippot et al., 2023

Microbial pathogens and climate change



Cavicchioli et al. 2019

- Anthropogenic climate change **stresses** native life, thereby **enabling pathogens to increasingly cause disease**
- The impact on **aquaculture, food-producing animals and crops threatens** global food **supply**
- Human activities, such as population growth and transport, combined with climate change increase antibiotic resistance of pathogens and the **spread of waterborne and vector-borne pathogens**, thereby increasing diseases of humans, other animals and plants

17 **blueprints** for **peace and prosperity** for **people** and the **planet**, now and into the future

2021 2030 United Nations Decade of Ocean Science for Sustainable Development

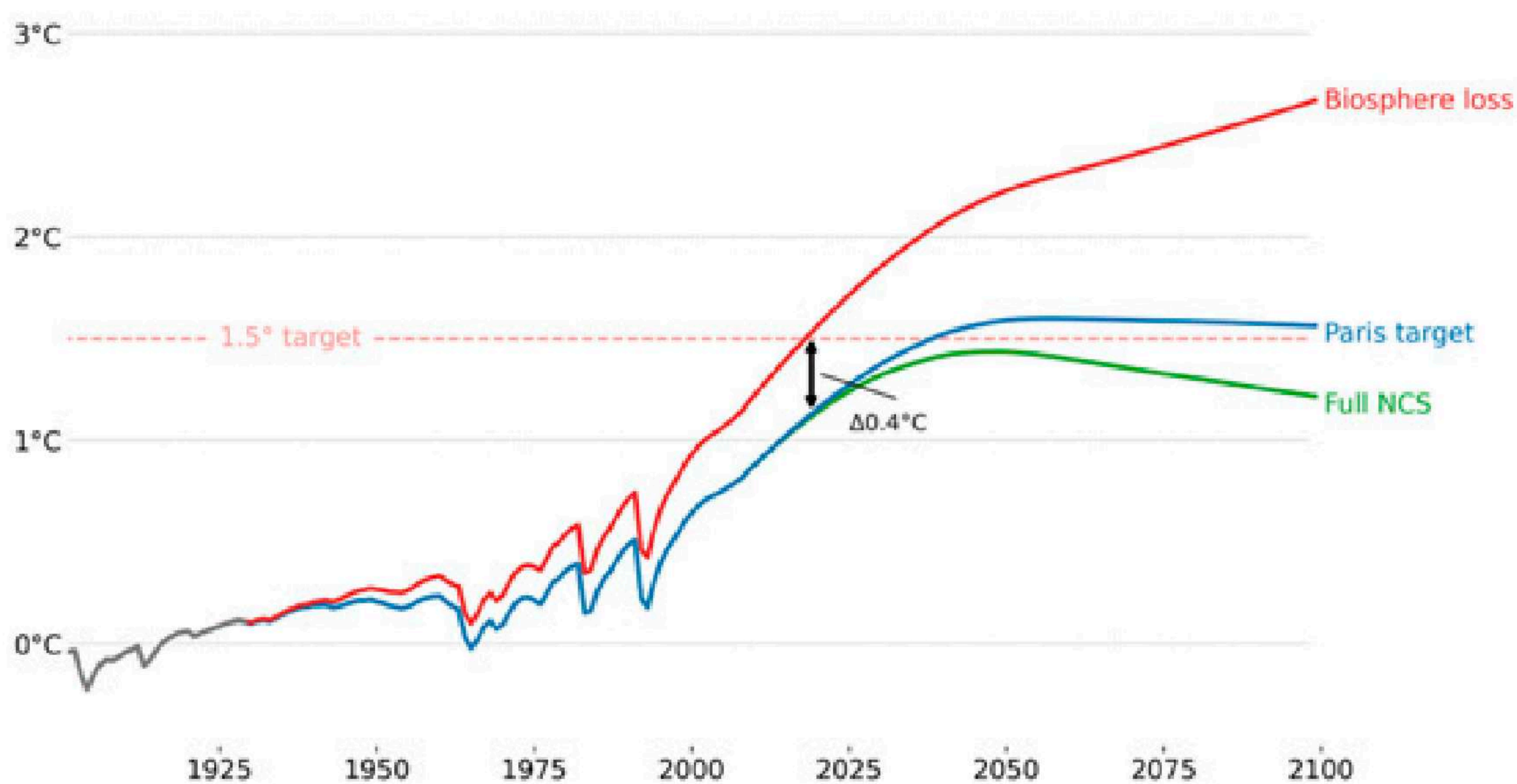
Decade Motivation: reverse the cycle of decline in ocean health

2021 2030 United Nations Decade of Ocean Science for Sustainable Development

…the science needed for the ocean and the future that we want

Carbon sinks in major biomes (SI Appendix, Table 1). Grey areas indicate regions dominated by agriculture

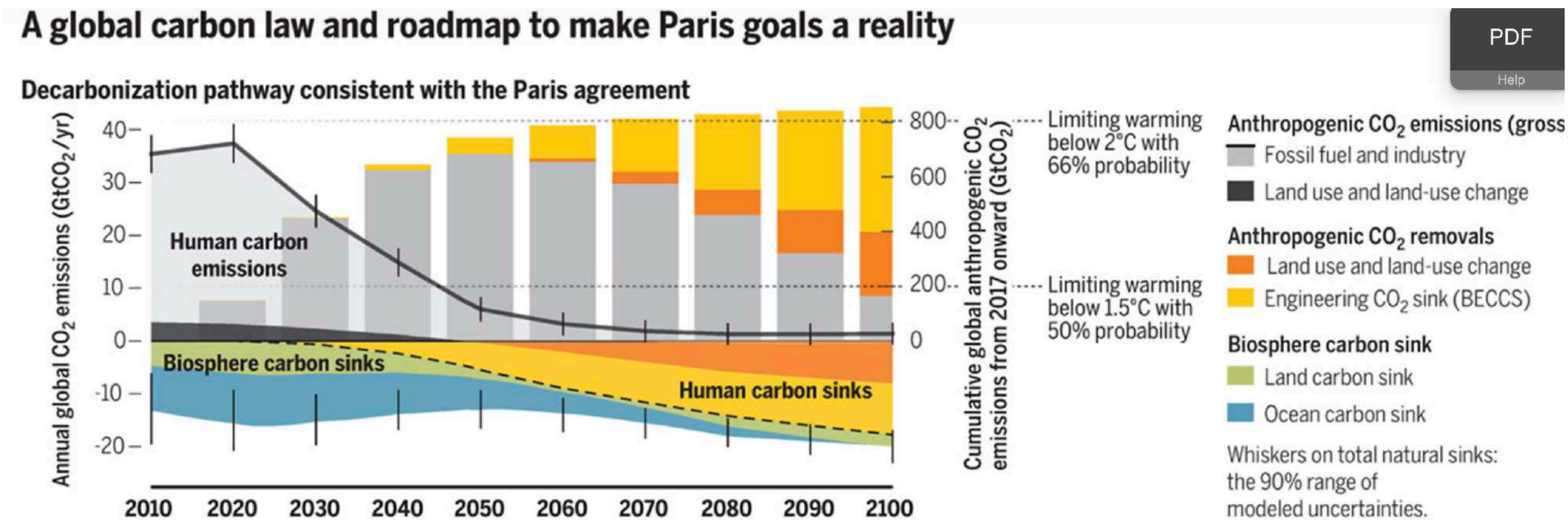
GLOBAL EARTH AGENDA:



Rockström et al., 2021

GLOBAL EARTH AGENDA:

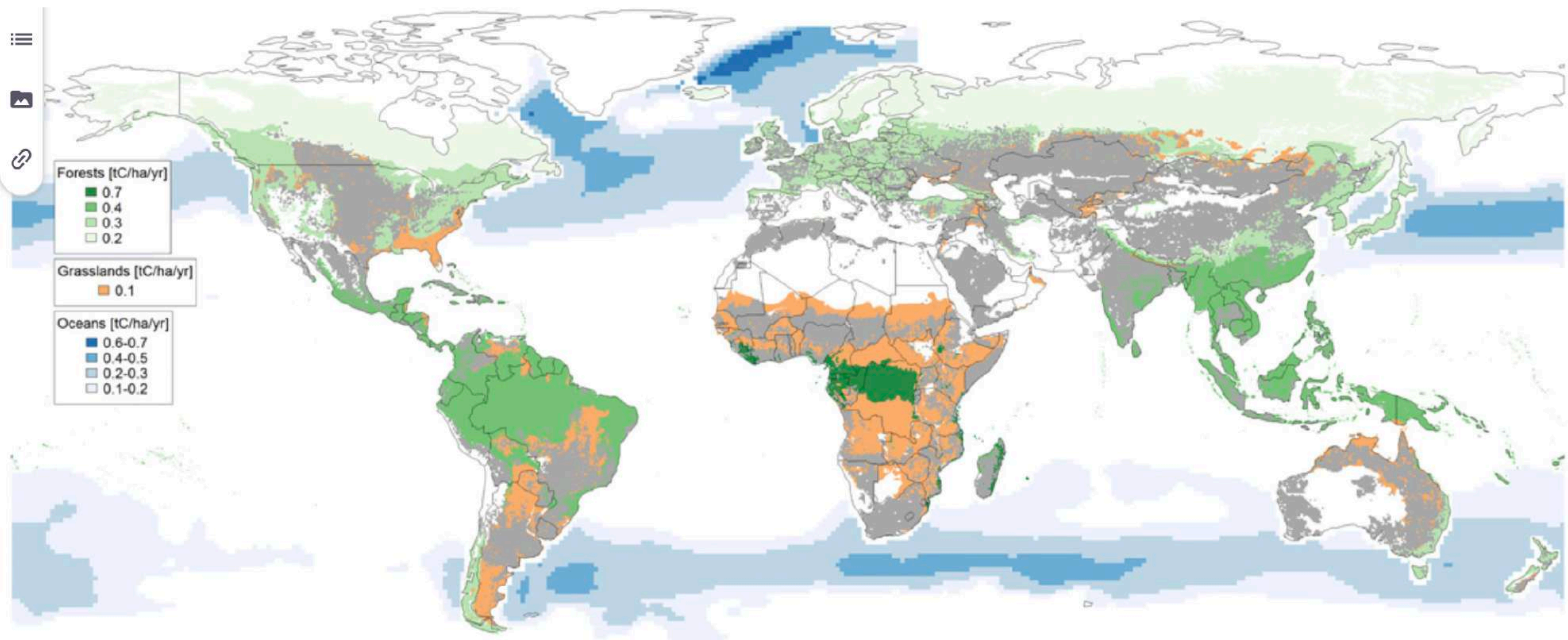
1. A roadmap for rapid decarbonization



Rockström et al., 2017

GLOBAL EARTH AGENDA:

2. A biosphere stewardship that protects carbon sinks and builds resilience, I

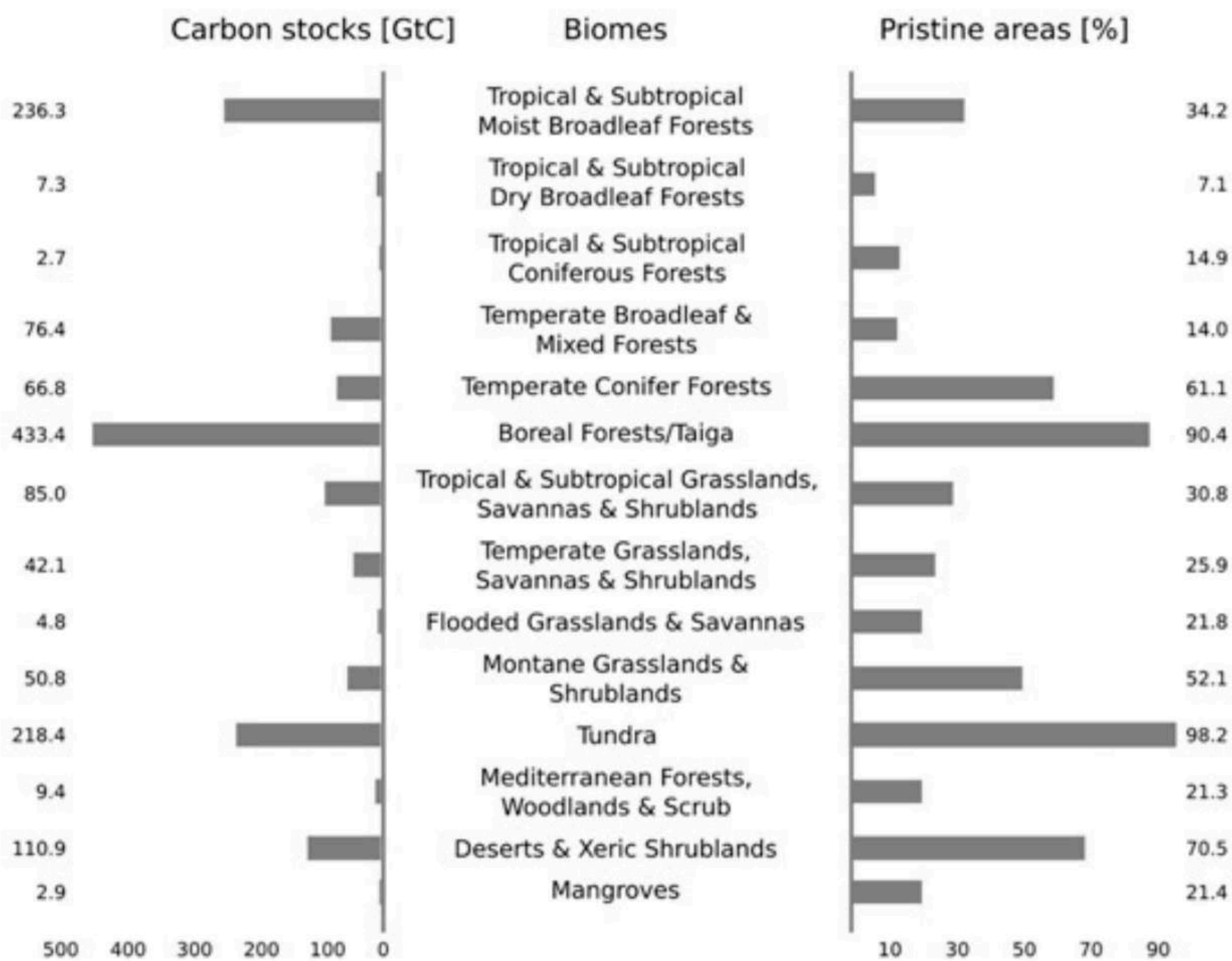


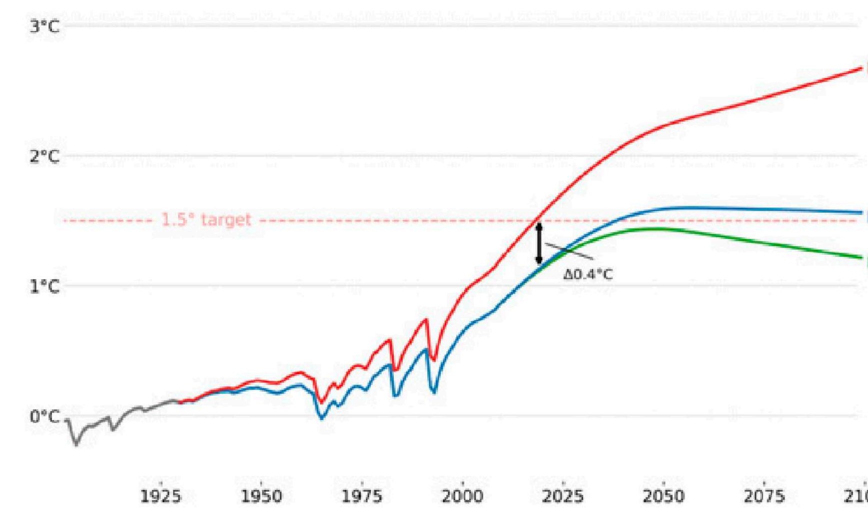
Carbon sinks in major biomes
Grey areas indicate regions dominated by agriculture

Rockström et al., 2021

GLOBAL EARTH AGENDA:

2. A biosphere stewardship that protects carbon sinks and builds resilience, II





Rockström et al., 2021