L09

Recap L08

Microbial interactions:

Environment and Ecosystem Services

Limits of microbial Life

Parameter	Limit	Note
Lower temperature	~ −15 °C	Limited by liquid water associated with thin films or saline solutions
Upper temperature	122 °C	Solubility of lipids in water, protein stability
Maximum pressure & Minimum	1,100 atm	Ref. 10
Low light No light	~0.01 μmol $m^{-2} \cdot s^{-1} = 5 \times 10^{-6}$ direct sunlight	Algae under ice and deep sea
pH	0–12.5	
Salinity	Saturated NaCl	Depends on the salt and temperature
Water activity	0.6	Yeasts and molds
	0.8	Bacteria
UV	≥1,000 J m^{-2}	*D. radiodurans*
Radiation	50 Gy/h	*D. radiodurans* growth with continuous dose
	12,000 Gy	Acute dose, higher for dry or frozen state

McKay, 2014

Natural control of microbial growth

TABLE 20.1 Resources and conditions that govern microbial growth in nature

Resources
Carbon (organic, CO_2)
Nitrogen (organic, inorganic)
Other macronutrients (S, P, K, Mg)
Micronutrients (Fe, Mn, Co, Cu, Zn, Mn, Ni)
O_2 and other electron acceptors (NO_3^-, SO_4^{2-}, Fe^{3+})
Inorganic electron donors (H_2, H_2S, Fe^{2+}, NH_4^+, NO_2^-)
Conditions
Temperature: cold → warm → hot
Water potential: dry → moist → wet
pH: 0 → 7 → 14
O_2: oxic → microoxic → anoxic
Light: bright light → dim light → dark
Osmotic conditions: freshwater → marine → hypersaline

Madigan et al. 2018

Key concepts for microbial Life

- **Metabolic diversity**: cellular processes that support growth
  - ★ **Energy is conserved, reducing power is obtain during catabolic reactions and cells growth by decoupling this power to anabolic-biosynthetic reactions (modularity)**
  - ★ **Electron flow via redox provide energy for ATP synthesis via:**
    1. **Substrate level phosphorylation**
    2. **Oxidative phosphorylation**
    3. **Photophosphorilation**

- **Ecological diversity**: interactions between organisms and their environments

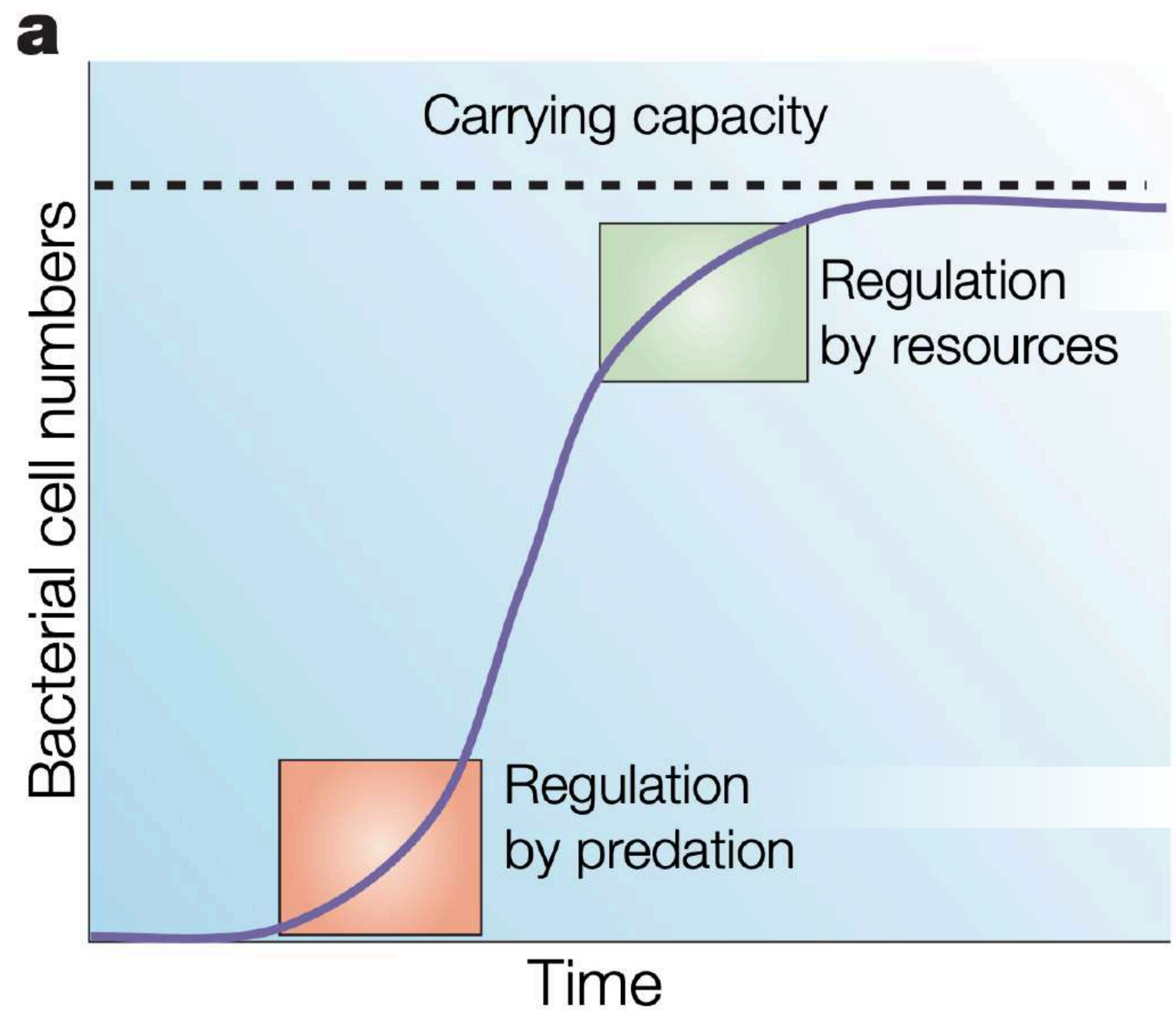
- **Phylogenetic diversity**: evolutionary relationships between organisms

Microbial Ecology

- Study of the **interactions** of microorganisms with their **environment (including organic matter)**, **each other**, and plant and animal species (**other organisms**) —> <u>symbioses,</u> <u>biogeochemical cycles</u> and the <u>interaction</u> of microbes with anthropogenic effects such as pollution and climate change
- Competitions for space
- Competitions for resources (i.e. nutrients, organic matter, energy)
- Predations

Bottom-up & Top-down control, I

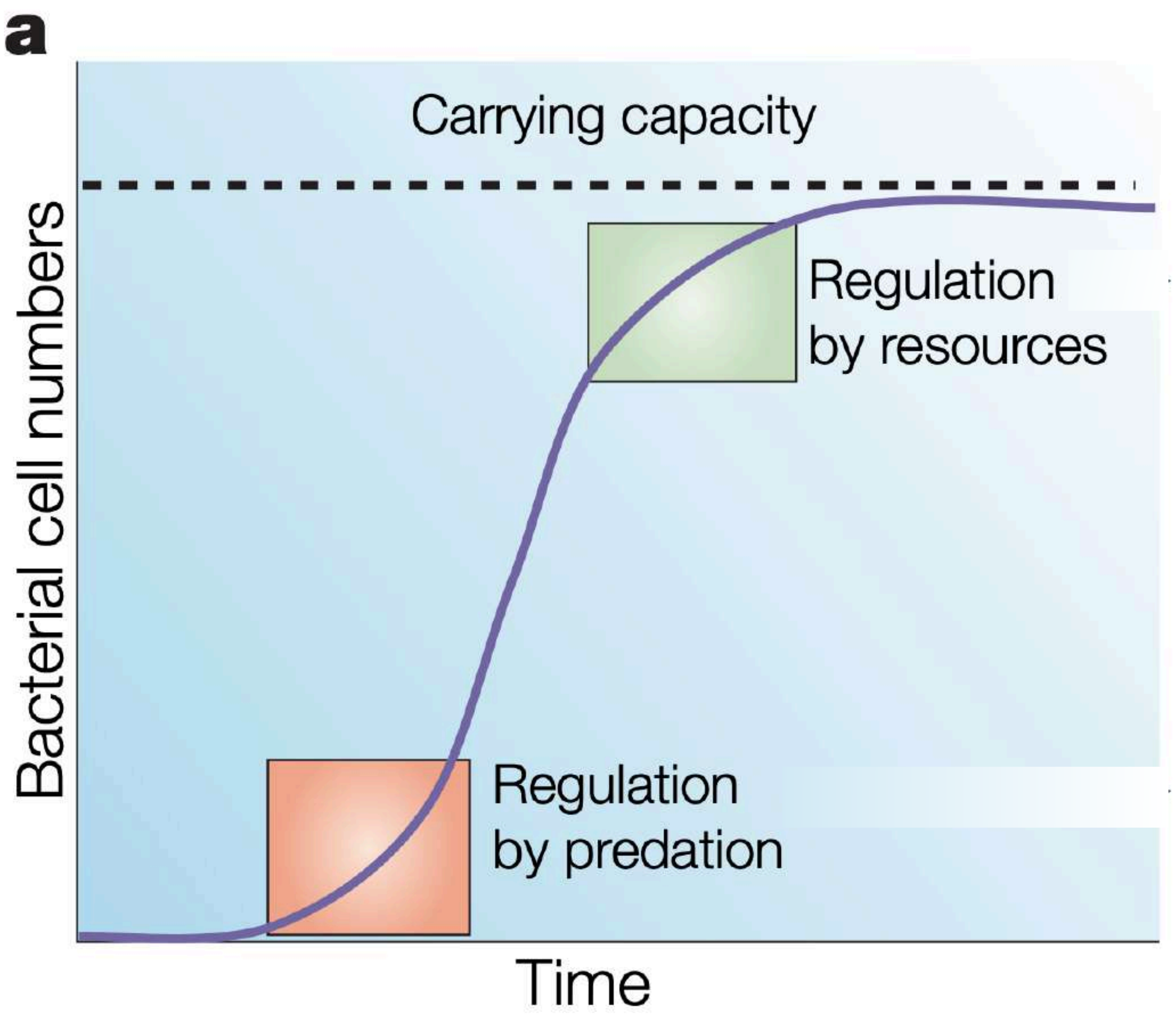
- **Top-down**: Ecological scenario in which the abundance or biomass of organisms is mainly determined **by mortality owing to predation**
- **Bottom-up**: Ecological scenario in which the abundance or biomass of organisms is mainly determined **by a lack of resources and mortality owing to starvation**
- **Carrying capacity** the maximum microbial biomass that can be sustained



Pernthaler, 2005

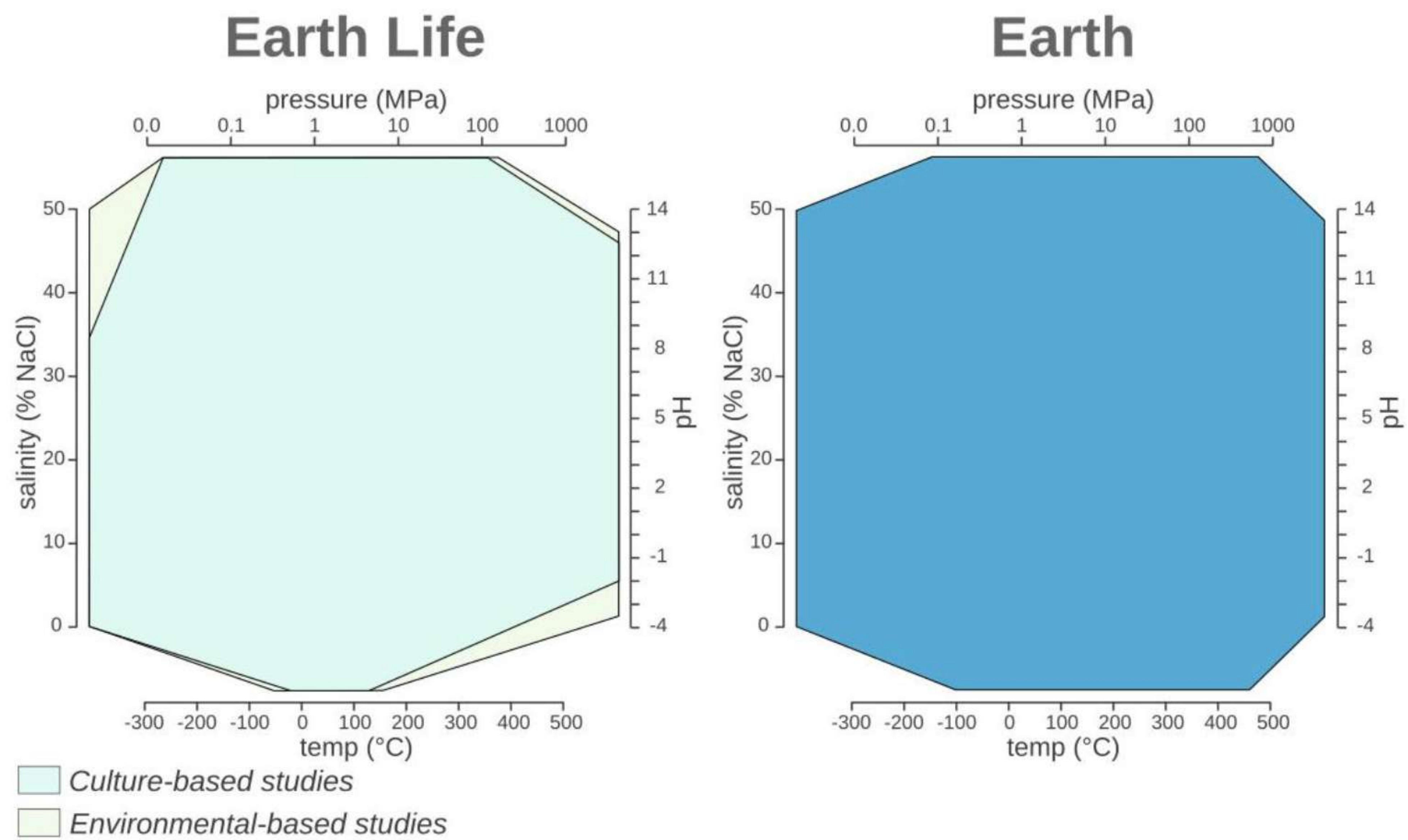
Bottom-up & Top-down control, II

- **Bottom-up (nutrient supply)** and **Top-down (protistan grazing, viral lysis, and antagonistic reaction and bacterial predators)** processes are known to influence and **control microbial community composition and diversity in time and space**
- **Viruses and protists (less studied antagonistic reactions and bacterial predators)** can;
    1. Directly impact bacterial communities: either through their **host specific lysis and size selective grazing respectively**
    2. Indirectly **through the alteration of organic pools by mortality processes**
- Bottom-up (**nutrients, organic matter, energy availability, salinity, pH**) influence the **growth** and the **physiological state** of the microbial community



Pernthaler, 2005

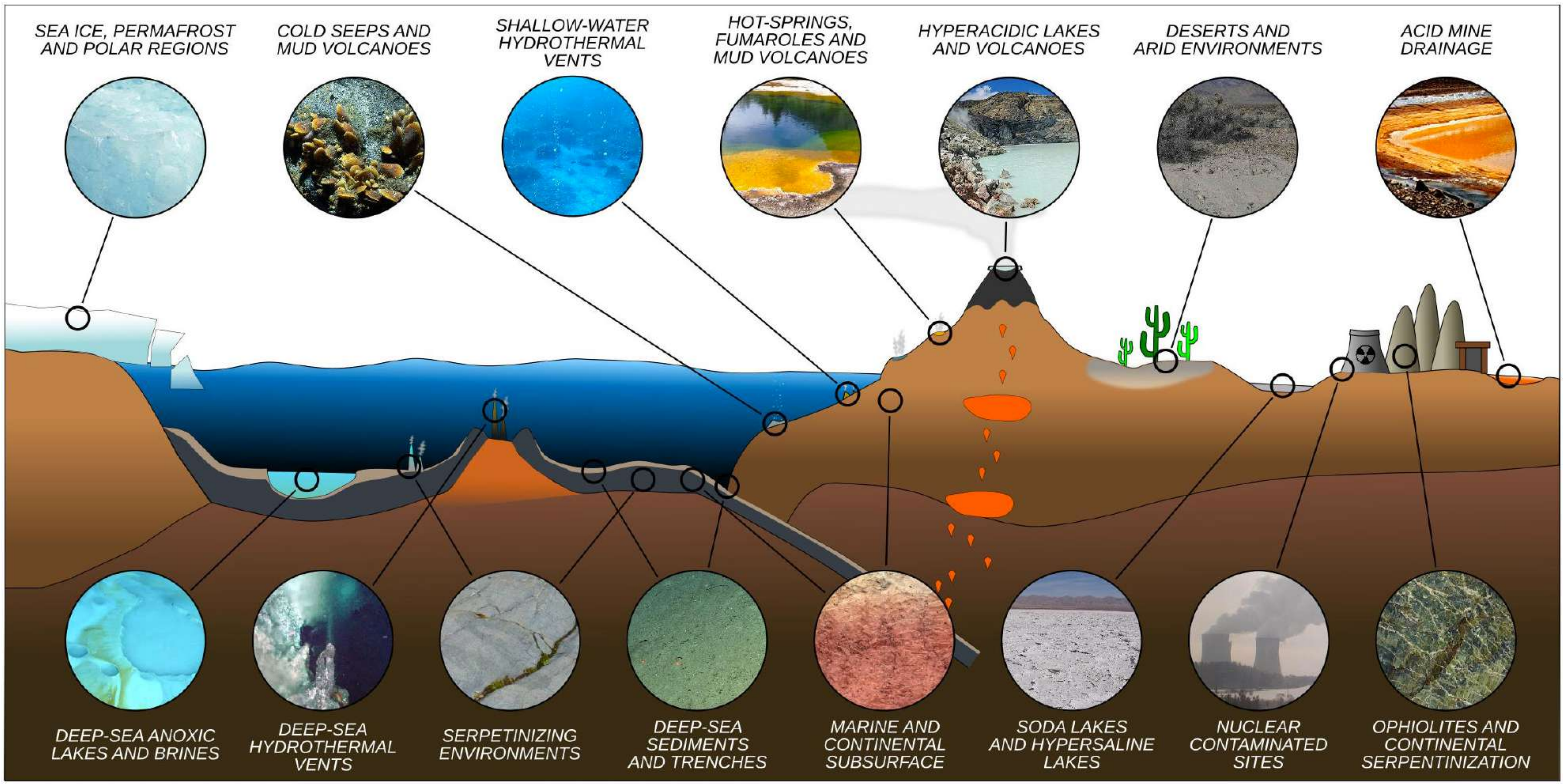
Microbial Life on Earth



Merino et al., 2019

- Earth is bursting with life, and its **biosphere** extends from ~**10 km altitude** to ~**10 km into the oceans and oceanic crust** as well as **~5 km into the continental crust**
- **Biospheric capacity equivalent to ~1% of Earth's geosphere and troposphere —>** a minimum **biospheric volume** of ~1010 km^3

Pressure, temperature, salinity, pH and light define microbial habitat on Earth



Merino et al., 2019

HOW MANY MICROBES ARE ON PLANET EARTH?

GOOGOL?

Googol (10^{100})

10, 000, 000, 000, 000,
000, 000, 000, 000, 000,
000, 000, 000, 000, 000,
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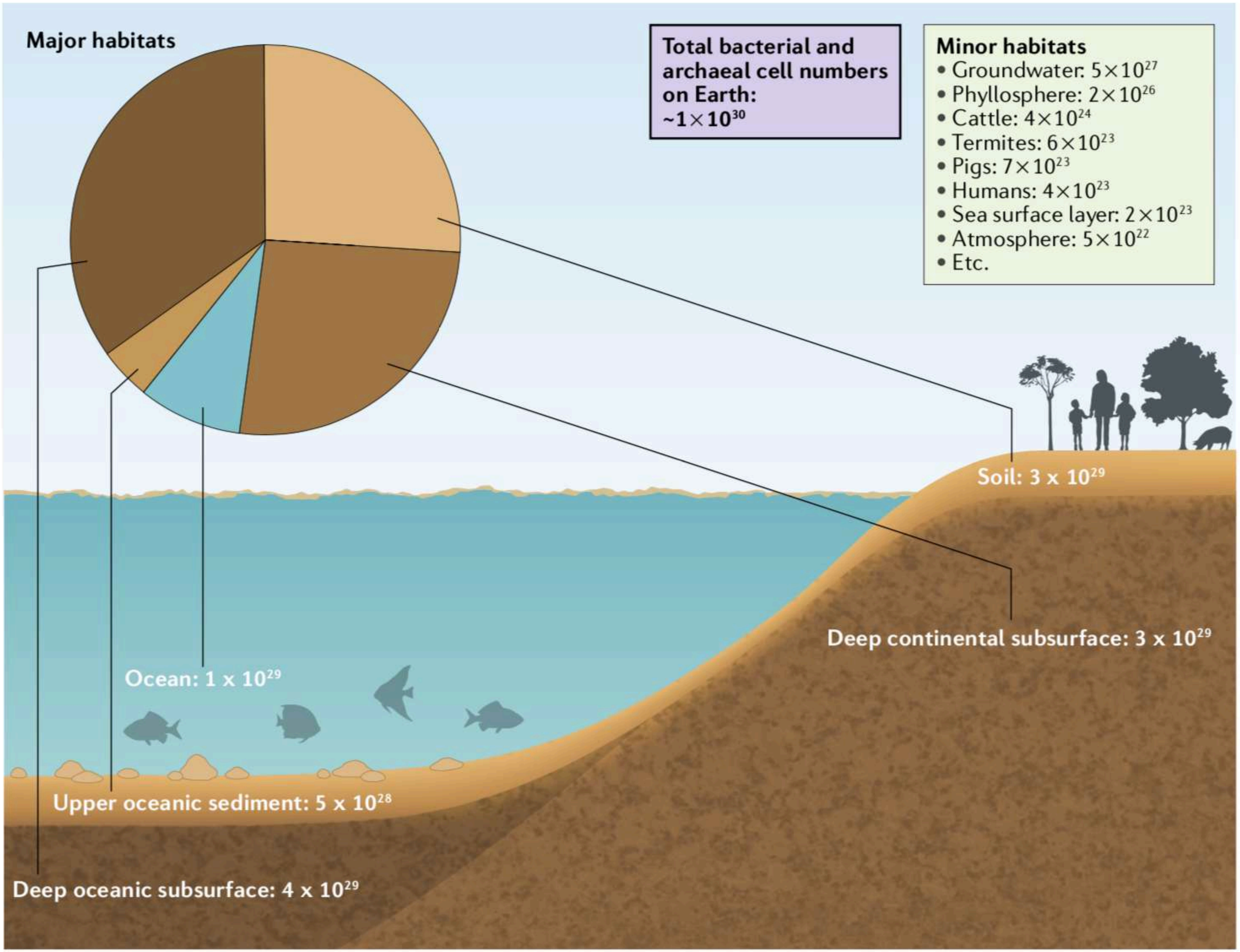
NOT SO MANY!

Microbial abundance in Earth ecosystems



Atmo

Bio

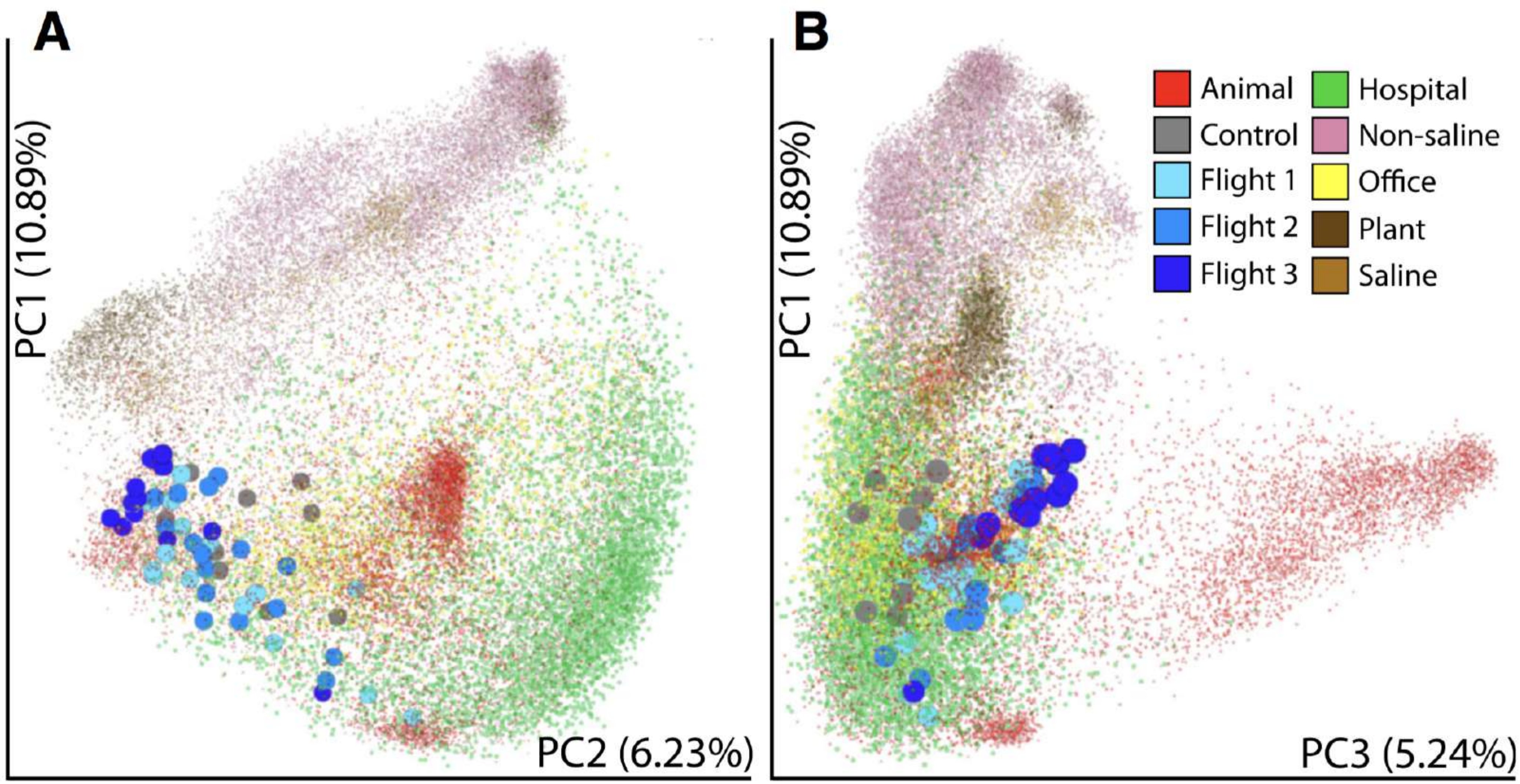
Aqua

Geo

Spheres

Flemming & Wuertz, 2019

Microbes are everywhere

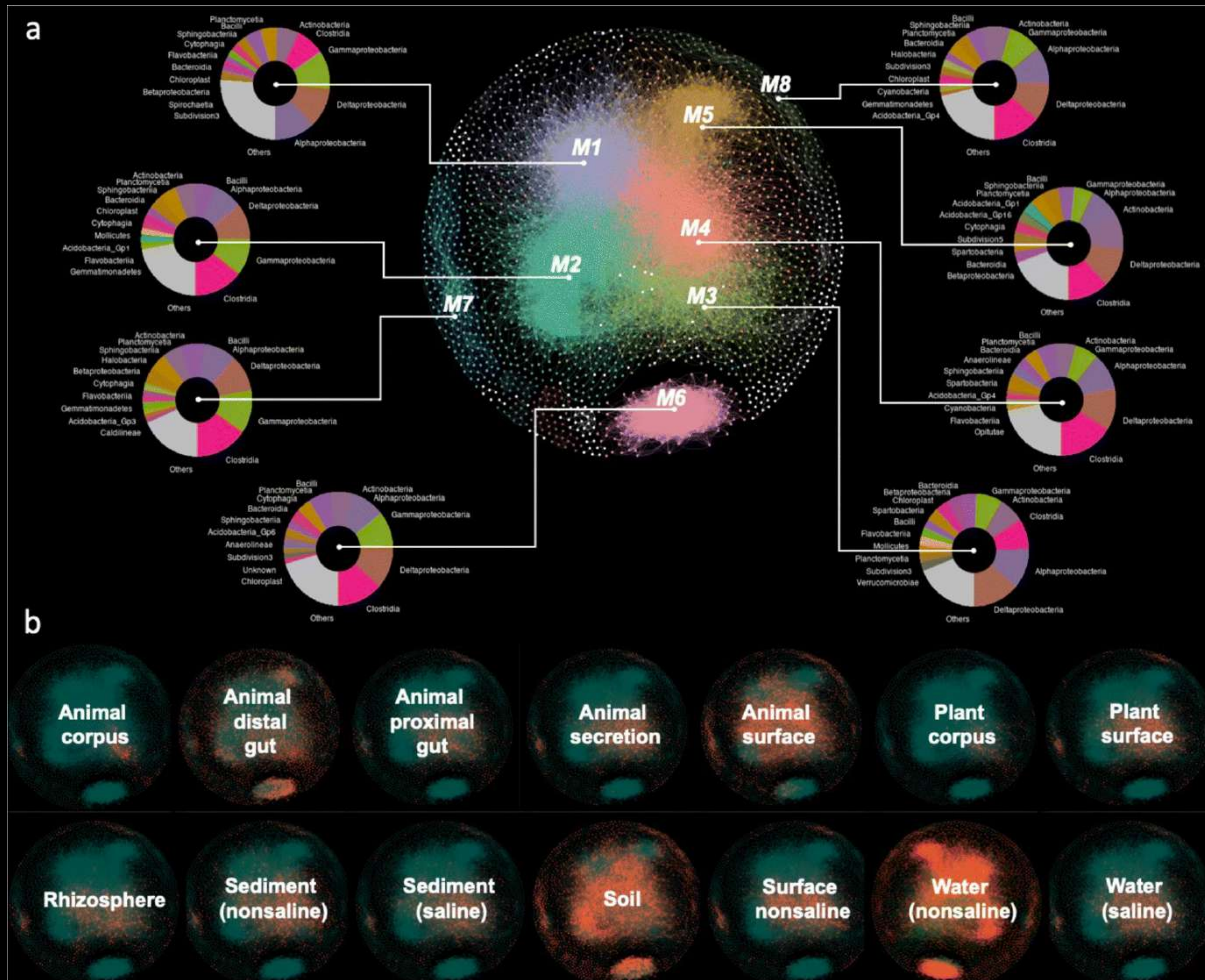


Checinska Sielaff et al., 2019

Comparison of ISS environmental microbiome with microbiomes of Earth

- Principal coordinates analysis of unweighted UniFrac distances from the Earth Microbiome Project [16S rRNA gene, V4], the Hospital Microbiome Project, Qiita study, and the Office Succession Study depicting a PC1 vs. PC2 and b PC1 vs. PC3
- The Hospital Microbiome Project and Office Succession Study are composed predominantly built environment samples (e.g., walls, floors, etc.)
- All three ISS flight sample sets group with the built environment samples: **The primary separation along PC1 is environmental or plant associated samples vs. animal surface, secretion, or built environment. The primary separation along PC3 is whether a sample is associated with the animal gut**

Earth microbial co-occurrence network reveals interconnection pattern across microbiomes

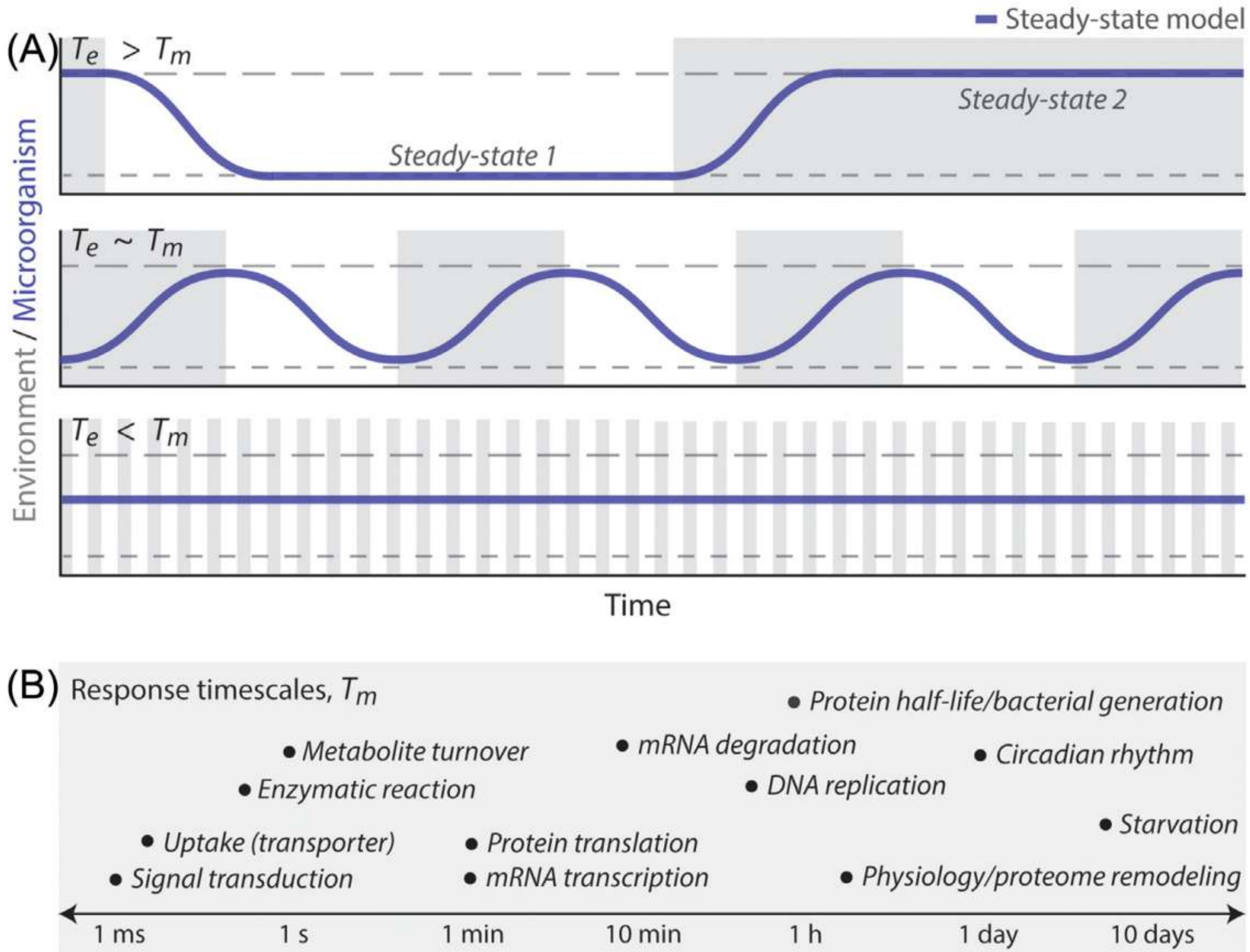


Ma et al., 2020

8 taxonomy distinct modules linked with different environments, which featured environment specific microbial co-occurrence relationships

From Microscale to Macroscale (*e.g.* Global scale, Human Scale, Ecosystem scale)

Microbial dynamics depend on the relative timescales between environmental fluctuations and microbial responses



Timescale of environmental fluctuation (Te) and the timescale of a microbial response (Tm)

Nguyen et al., 2020

Elemental abundances by mass

1	Cosmic, %		Earth's crust, %		Humans, %		Bacteria (*E. coli*), %	
1	H	70.7	O	46.6	O	64	O	68
2	He	27.4	Si	27.7	C	19	C	15
3	O	0.958	Al	8.13	H	9	H	10.2
4	C	0.304	Fe	5.00	N	5	N	4.2
5	Ne	0.174	Ca	3.63	Ca	1.5	P	0.83
6	Fe	0.126	Na	2.83	P	0.8	K	0.45
7	N	0.110	K	2.59	S	0.6	Na	0.40
8	Si	0.0706	Mg	2.09	K	0.3	S	0.30
9	Mg	0.0656	Ti	0.44	Na	0.15	Ca	0.25
10	S	0.0414	H	0.14	Cl	0.15	Cl	0.12

McKay, 2014

Microbes transform elements
Microbes move cycle elements
Microbes change the redox state of the elements

Implication for ecosystem functioning

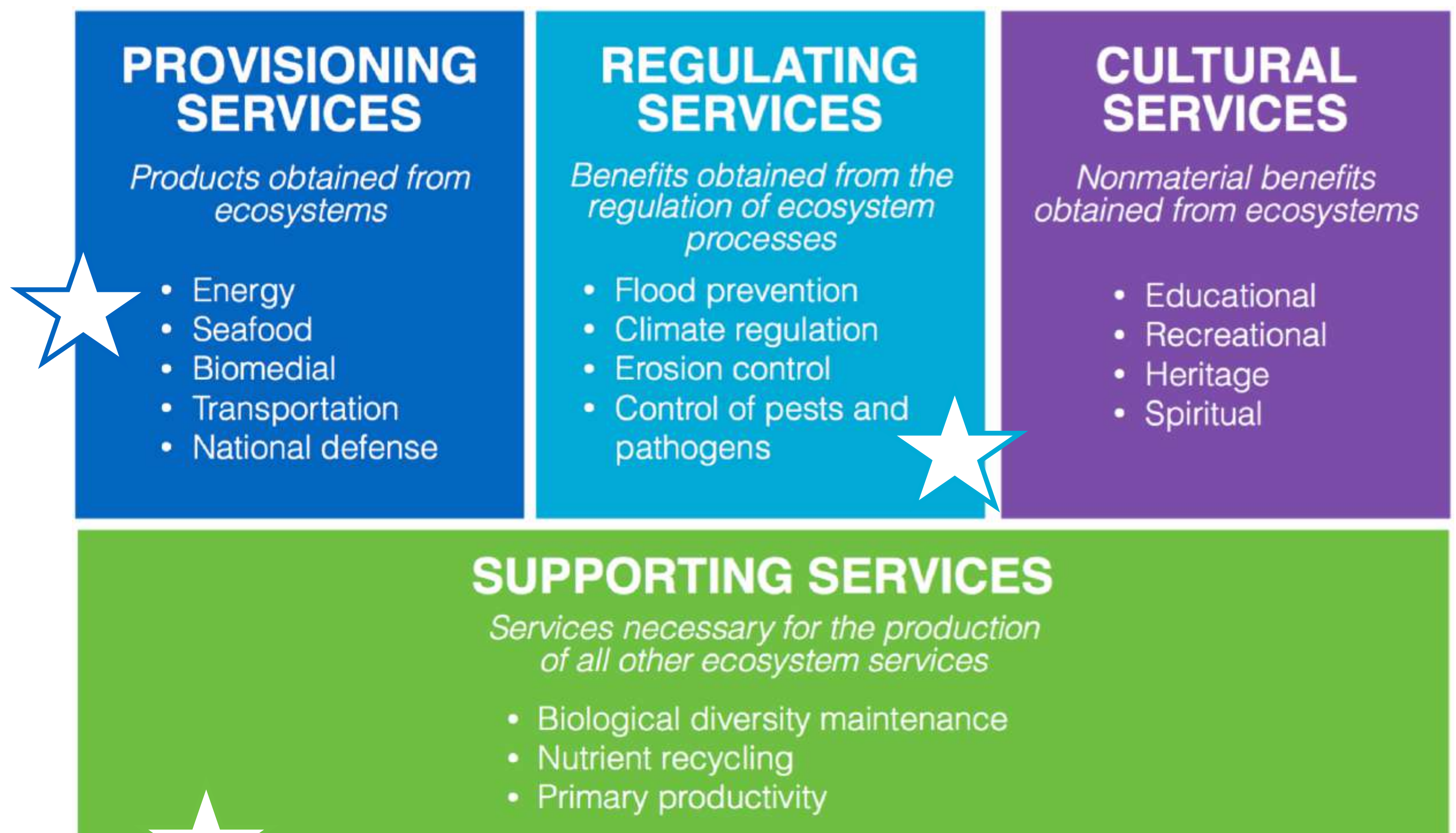
Ecosystem & Ecosystem services

Ecosystems consist of organisms, their environments, and all of the **interactions among the organisms and environments**

The organisms are members of populations and communities and are adapted to habitats —> species richness and abundance

Ecosystem services: outputs, conditions, or processes of natural systems that directly or indirectly benefit humans or enhance social welfare

https://www.millenniumassessment.org/en/index.html



source: *Final Recommendations of the Interagency Ocean Policy Taskforce, 2010*

Microbes drive ecosystem services

Table 1 | Major groups of microbes and ecosystem services they provide.

Microbial group	Process	Ecosystem service	Ecosystem service category
Heterotrophic bacteria/ archaea	Organic matter breakdown, mineralization	Decomposition, nutrient recycling, climate regulation, water purification	Supporting and regulating
Photoautotrophic bacteria	Photosynthesis	Primary production, carbon sequestration	Supporting and regulating
Chemo(litho)autotrophic	Specific elemental transformations (e.g., NH_4^+, S_2^-, Fe_2^+, CH_4 oxidation)	Nutrient recycling, climate regulation, water purification	Supporting and regulating
Unicellular phytoplankton	Photosynthesis	Primary production, carbon sequestration	Supporting and regulating
Archaea	Specific elemental transformation (e.g., metals, CH_4 formation, NH_4^+ oxidation), often in extreme habitats.	Nutrient recycling, climate regulation, carbon sequestration	Supporting and regulating
Protozoa	Mineralization of other microbes	Decomposition, nutrient recycling, soil formation	Supporting
Fungi	Organic matter breakdown and mineralization	Decomposition, nutrient recycling, soil formation, primary production (i.e., mycorrhizal fungi)	Supporting
Viruses	Lysis of hosts	Nutrient recycling	Supporting
All	Production of metabolites (e.g., antibiotics, polymers), degradation of xenobiotics, genetic transformation, and rearrangement	Production of precursors to industrial and pharmaceutical products	Provisional
All	Huge diversity, versatility, environmental and biotechnological applications	Educational purposes, getting students interested in science	Cultural

The last column depicts the ecosystem service category as was defined in the Millennium Ecosystem Assessment (2005). Modified from Ducklow, 2008.

Bodelier, 2011

Microbial ecosystem services

Tiny microbes keep the ecosystem functioning

BEST ENVIRONMENTAL ENGINEERS

HOW, WHEN, WHERE?

Microbial ecosystem services

Tiny microbes keep the ecosystem functioning

BEST ENVIRONMENTAL ENGINEERS

HOW, WHEN, WHERE?

HOW: small scale interaction with molecules and microbes (producing O_2 & degrading/respiring organic matter)

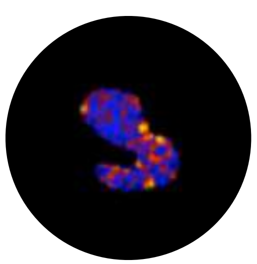
Microbial ecosystem services

Tiny microbes keep the ecosystem functioning

BEST ENVIRONMENTAL ENGINEERS

HOW, WHEN, WHERE?

HOW: small scale interaction with molecules and microbes (producing O_2 & degrading/respiring organic matter)



WHEN: Always, since the beginning of life and still changing

Microbial ecosystem services

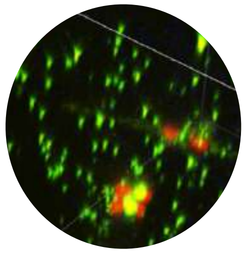
Tiny microbes keep the ecosystem functioning

BEST ENVIRONMENTAL ENGINEERS

HOW, WHEN, WHERE?

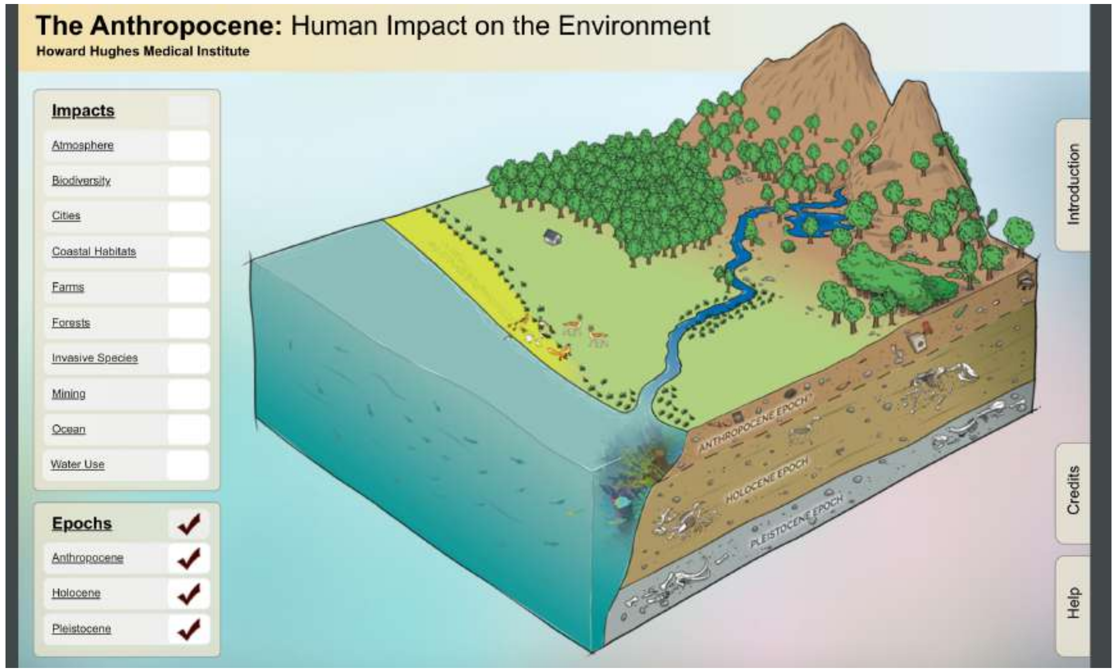
HOW: small scale interaction with molecules and microbes (producing O_2 & degrading/respiring organic matter)

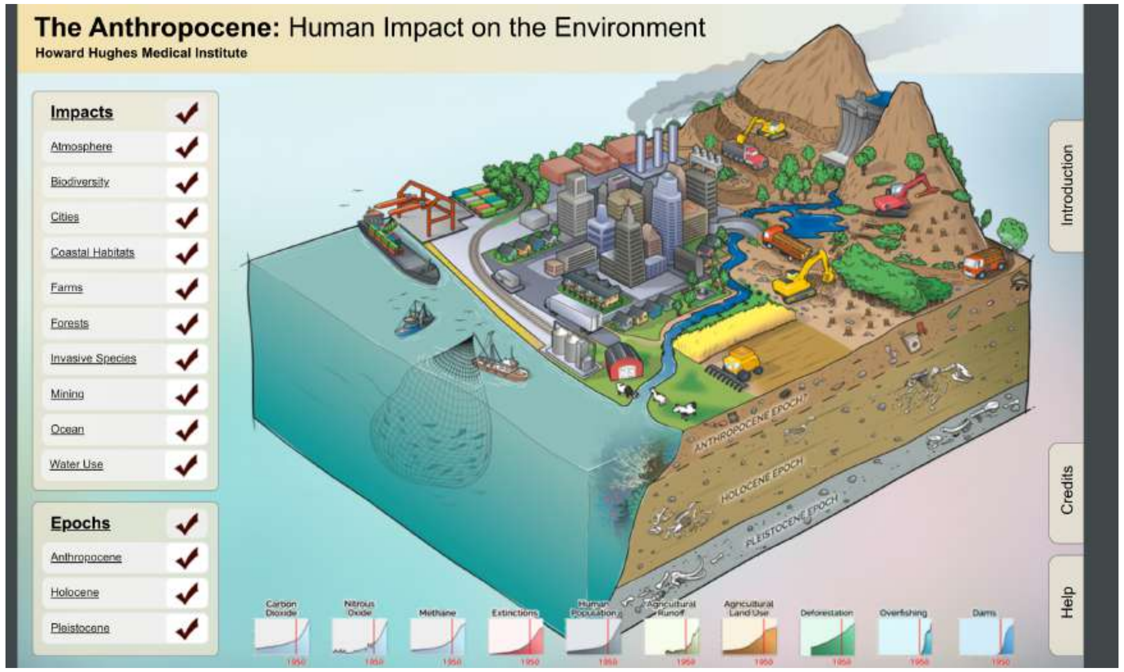
WHEN: Always, since the beginning of life and still changing



WHERE: in every environment

Humans as structuring force on Earth



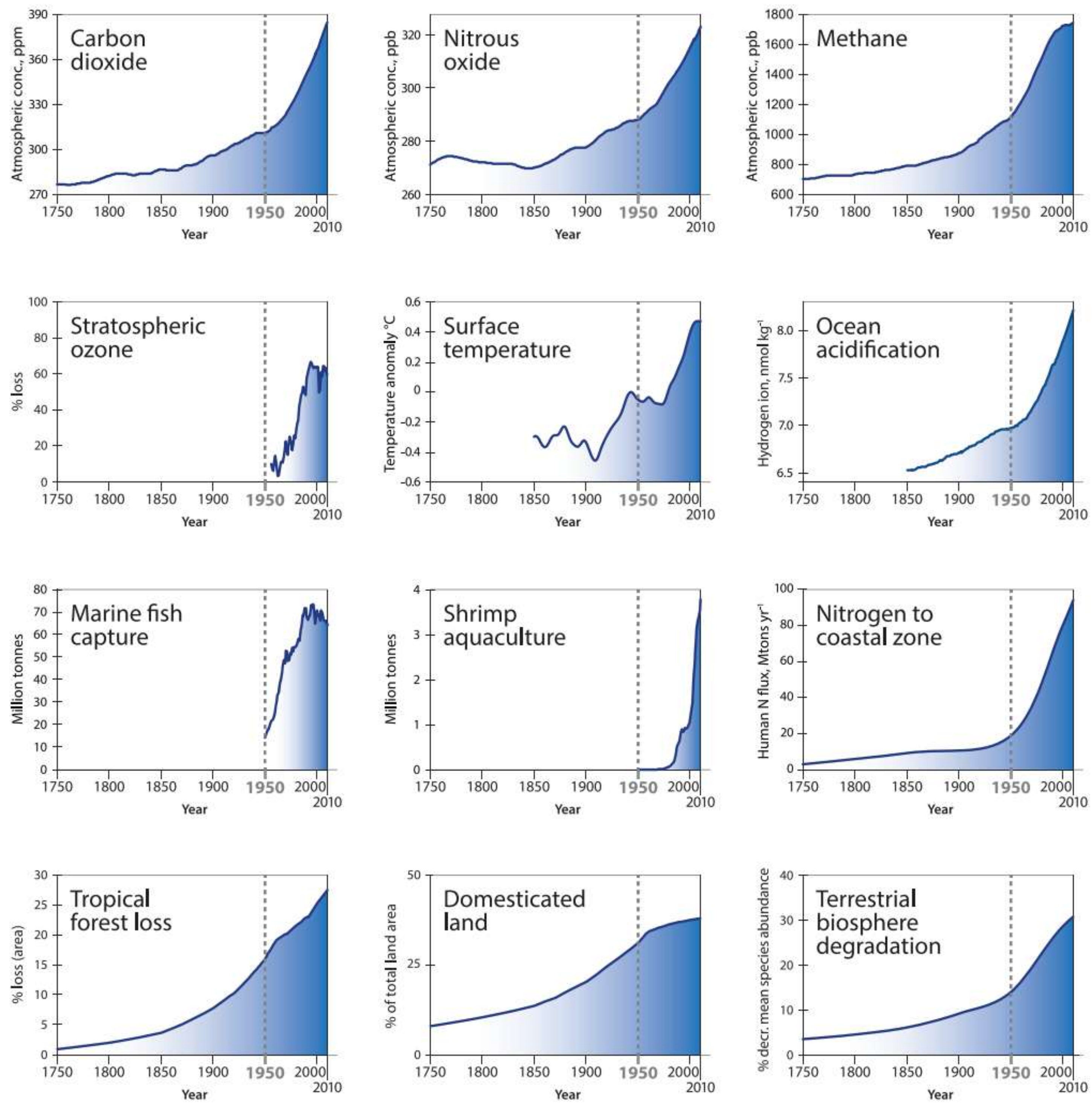


- **Humans as pervasive shaping forces**
- **Massive environmental anthropization of Earth**
- **Great acceleration:**
  1. **Socio-economic trends**
  2. **Earth System natural process**
  3. **Earth System not-natural processes**

https://media.hhmi.org/biointeractive/click/anthropocene/

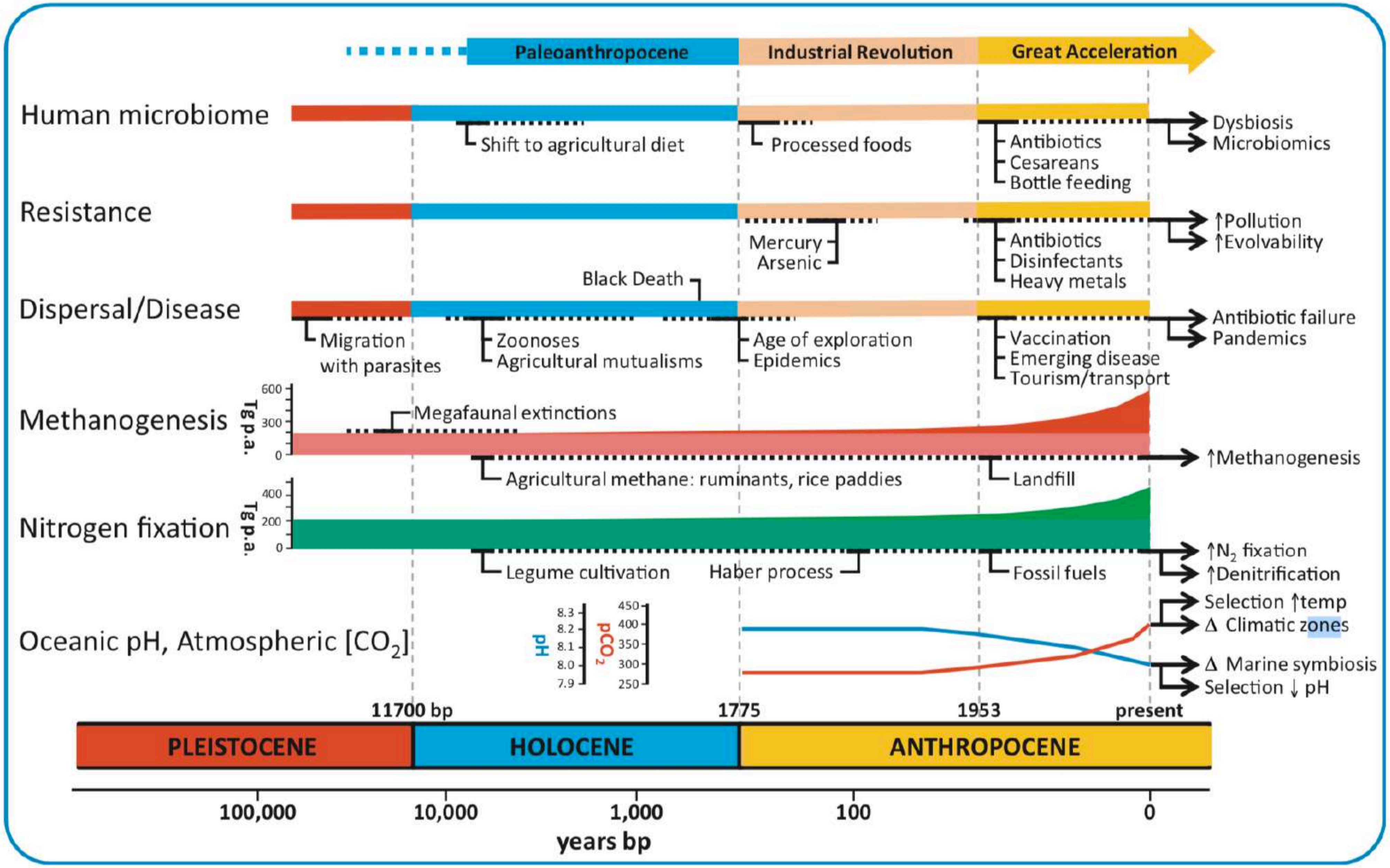
Anthropocene

Steffen et al., 2011



…unfortunately the limit is not even more the sky

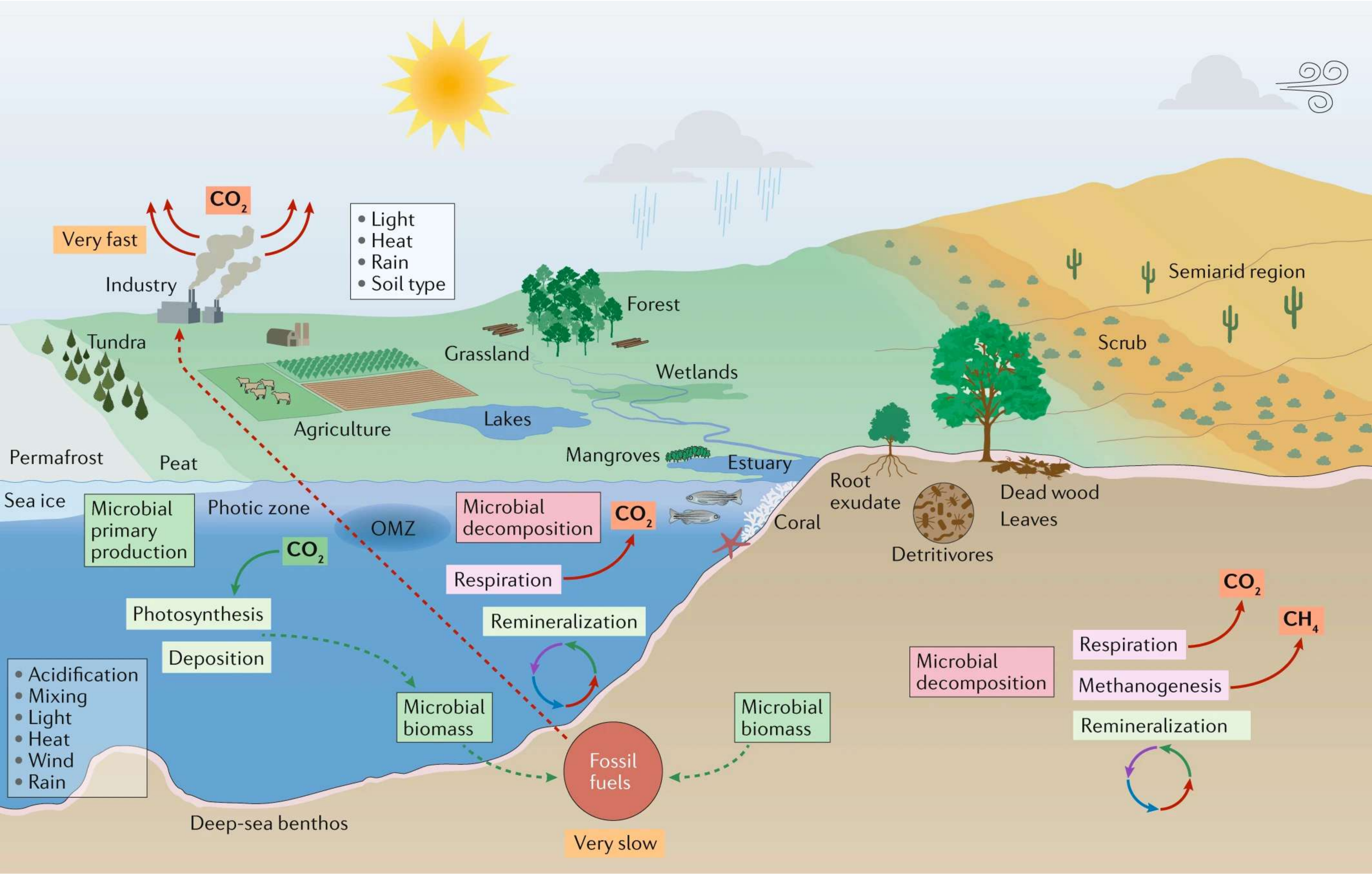
Microbiology in the Anthropocene



Gillings & Paulsen, 2014

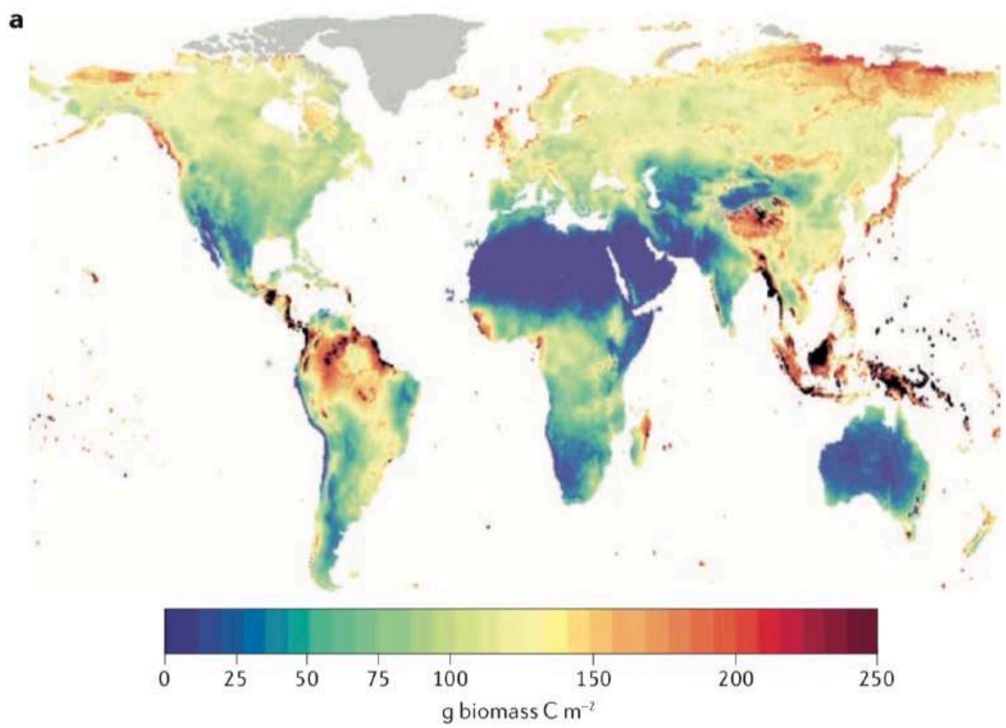
- Human influences on microbial ecology and evolution
- Suggested date of 1953 for the start of the Great Acceleration is based on the publication of DNA structure (Watson and Crick, 1953) and the increased frequency of nuclear tests during that year (see Crutzen and Stoermer, 2000)

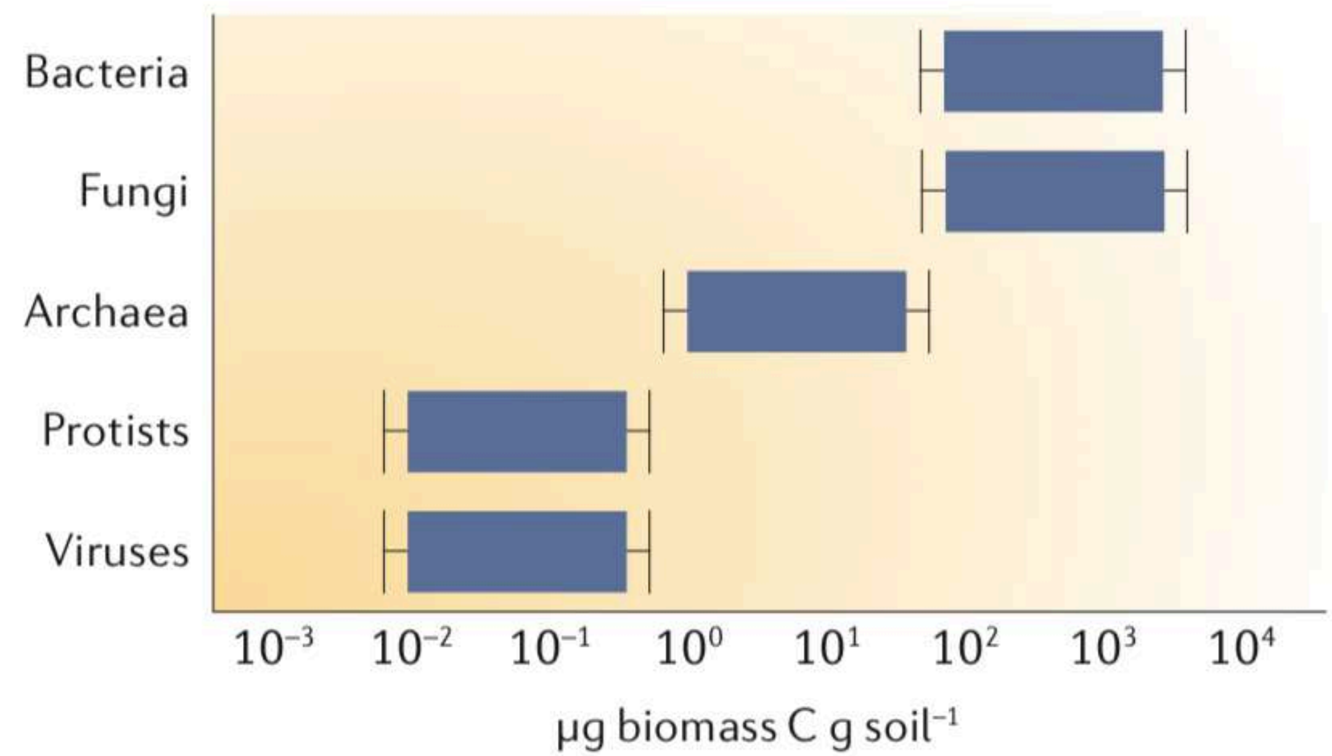
Microbes are everywhere and are shaping our Earth



Cavicchioli et al. 2019

Soil as a microbial environment

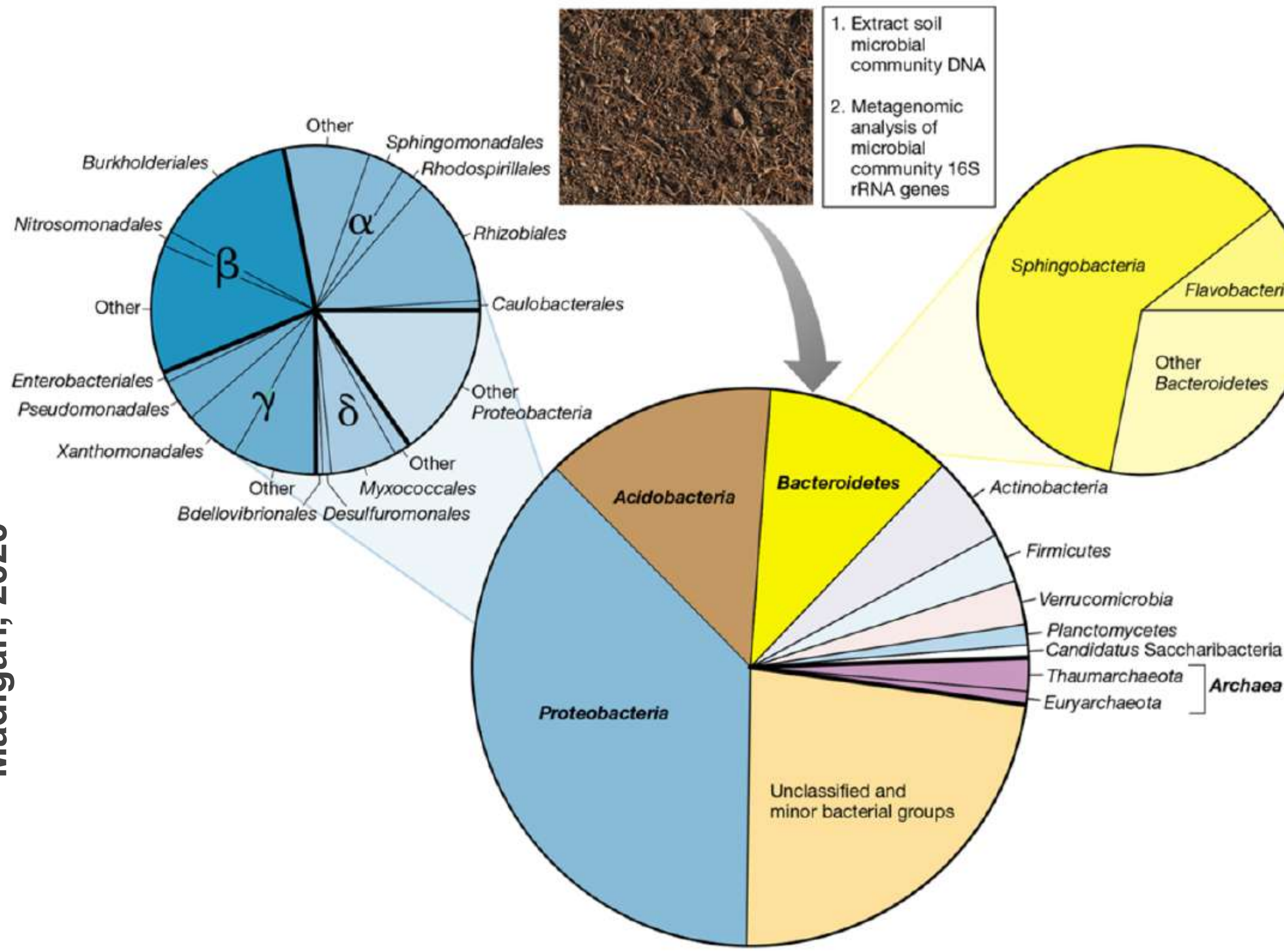




Fierer, 2017

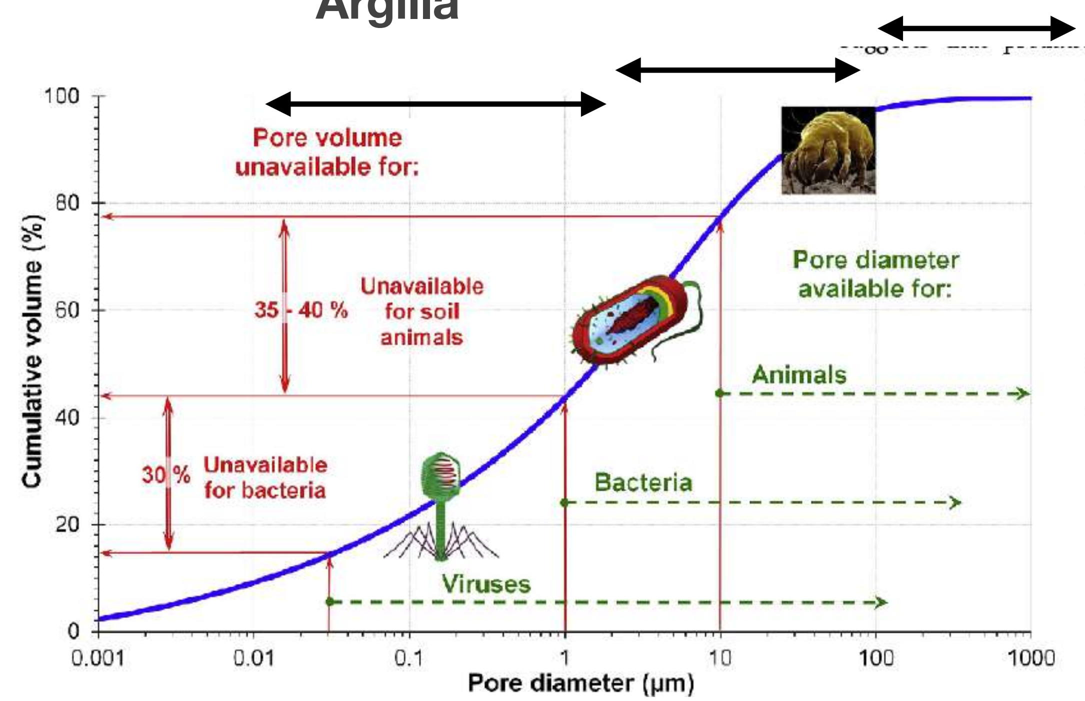
- Microbial biomass (approximation), the sum of all microbial groups: bacteria, fungi, archaea, protists and viruses varies across the globe
- **Biomass can vary** substantially across soils, and the biomass of protists and viruses is highly uncertain
- **>90% of soil viruses seem to be strongly adsorbed** to clays and other soil surfaces
- Unclear what viruses % that are found in soil are even capable of infecting their microbial prey

Microbial diversity in soil



Madigan, 2020

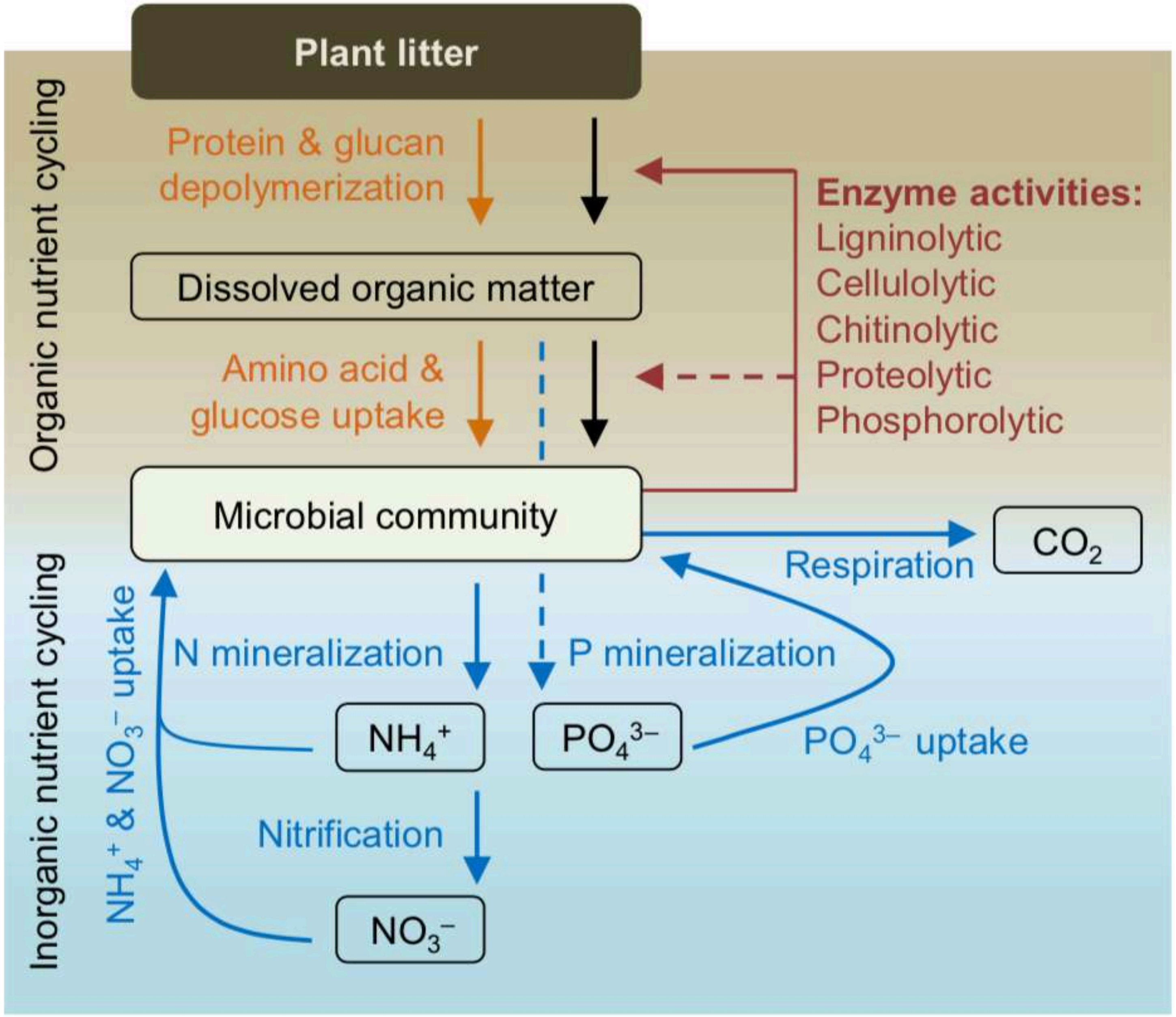
- **Highly structured environment**
- **Micro and macro aggregate**
- **Water flow**



- **< 1% of the available soil surface area is typically occupied by microorganisms**
- **Biotic or abiotic constraints on the microbial colonization** of soil surfaces
- **>95% of total microbial biomass pool are dormant/ inactive** at a given point in time

Interconnected inorganic and organic nutrient cycling

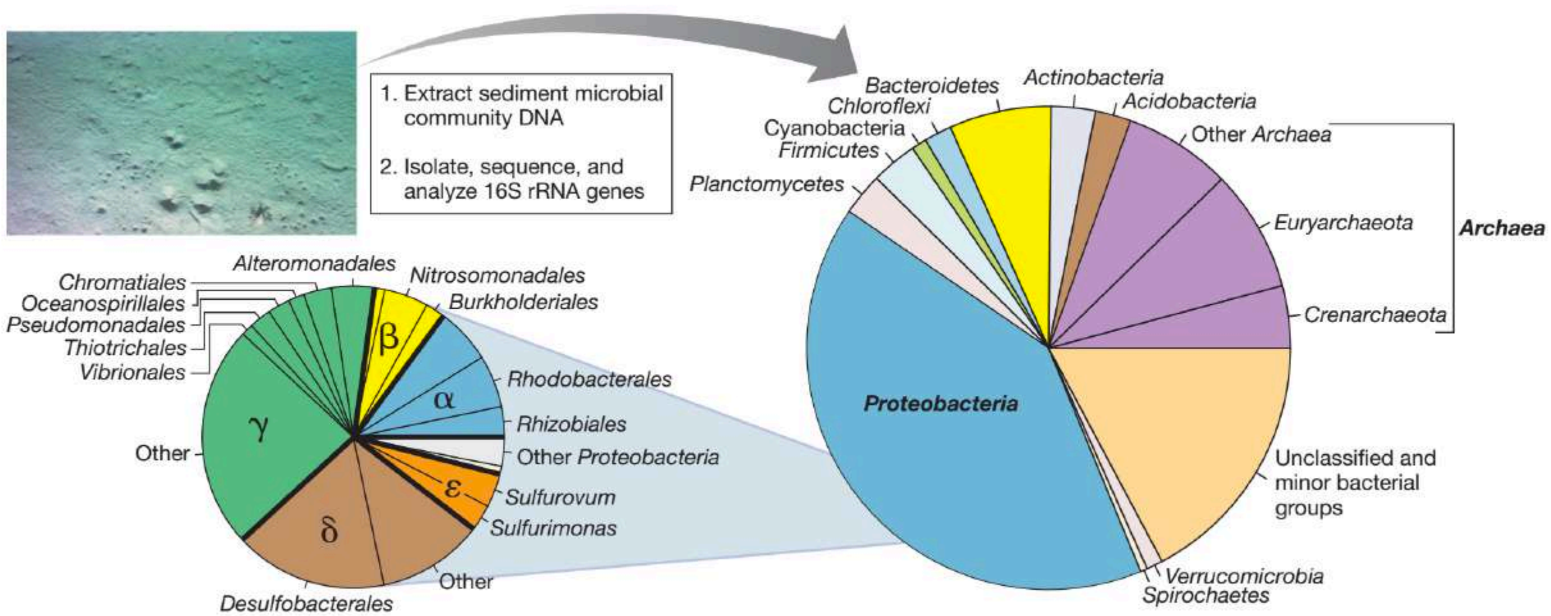
- Biogeochemical complexity within the soil community
- Coupling between primary production and organic matter decomposition
- Coupling organic matter decomposition and nutrient cycling



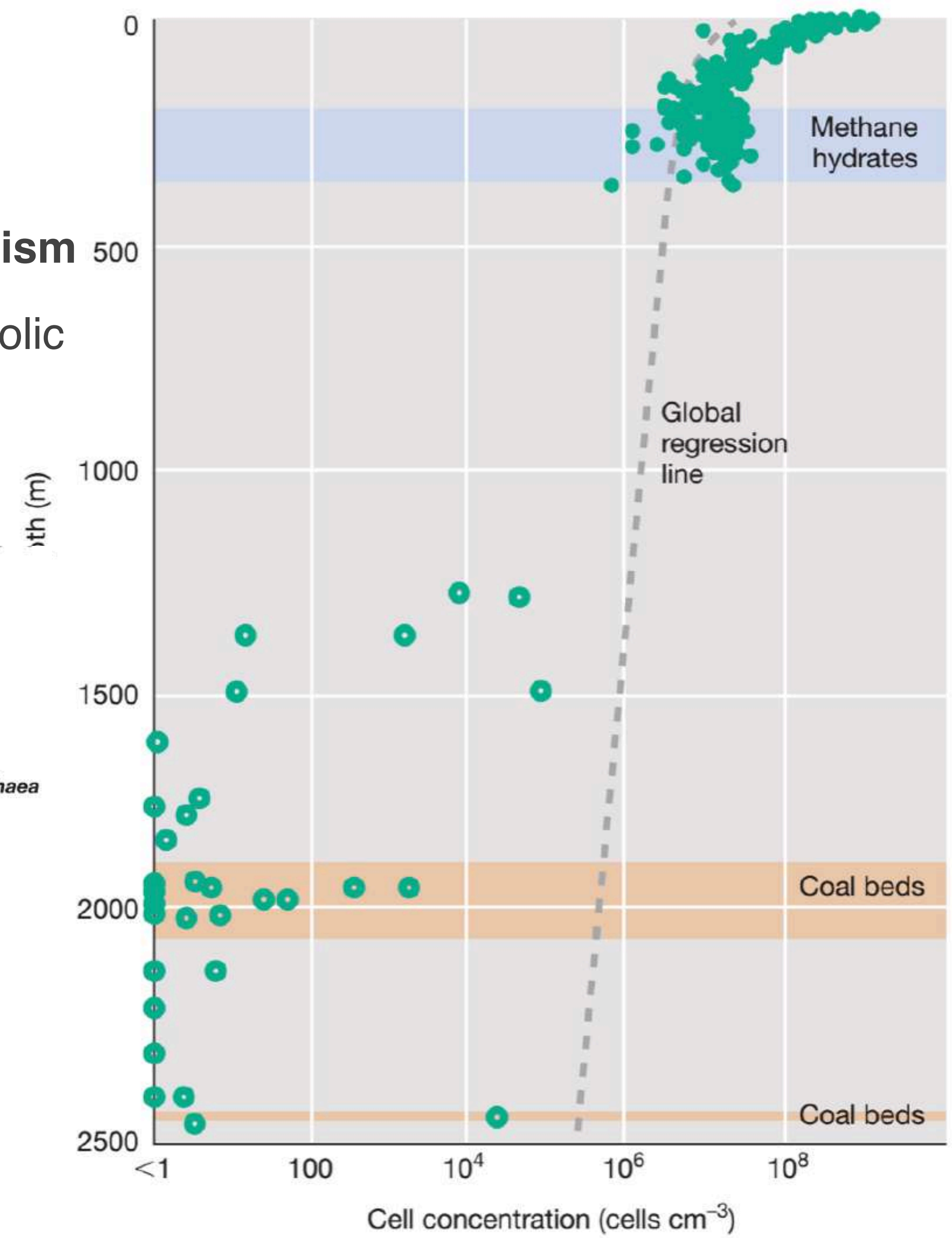
Mooshammer et al., 2020

Sediment as a microbial environment

- Structured 3D environment at **high pressure at low temperature**
- **Constant flow of organic matter**
- **Steep chemical gradient —> redox species available —>metabolism**
- Hydrothermal vents, cold seeps, brines, carcasses as oasis of metabolic diversity (e.g. symbiosis, temperature, relatively fresh organic matter)



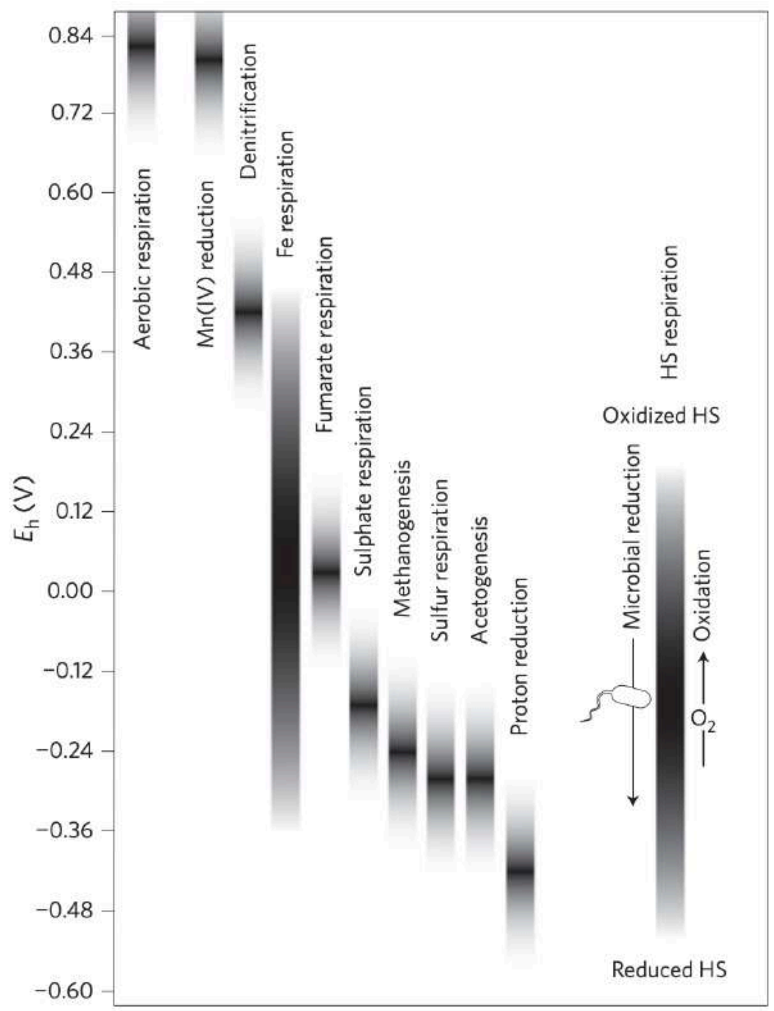
Madigan et al. 2018



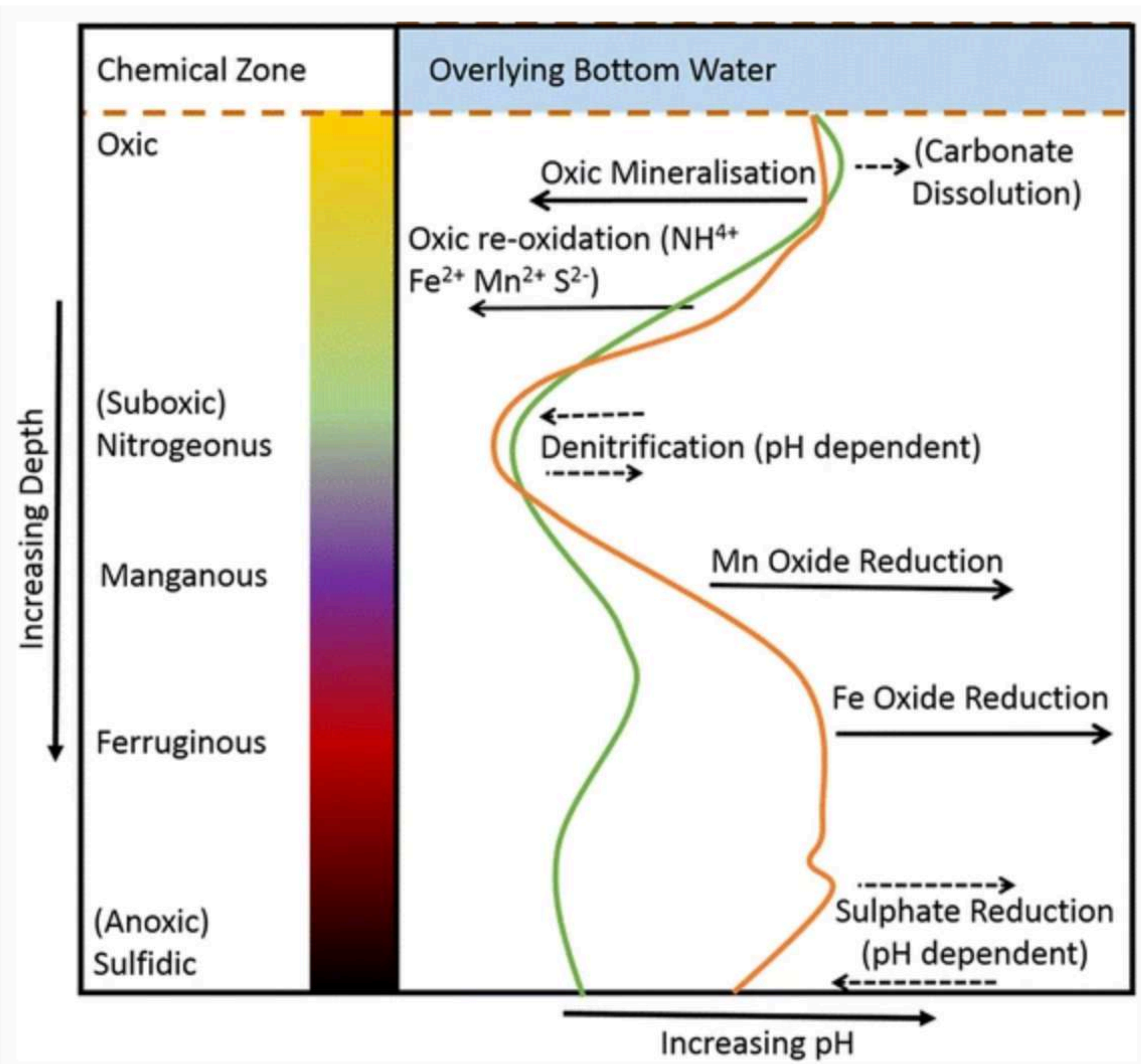
Madigan et al. 2018

Microbial metabolisms in the sediment

- Microbes able to respire in multiple ways will always choose available acceptors with the biggest potential difference to the donor
- Organic matter degradation
- Nutrient cycling



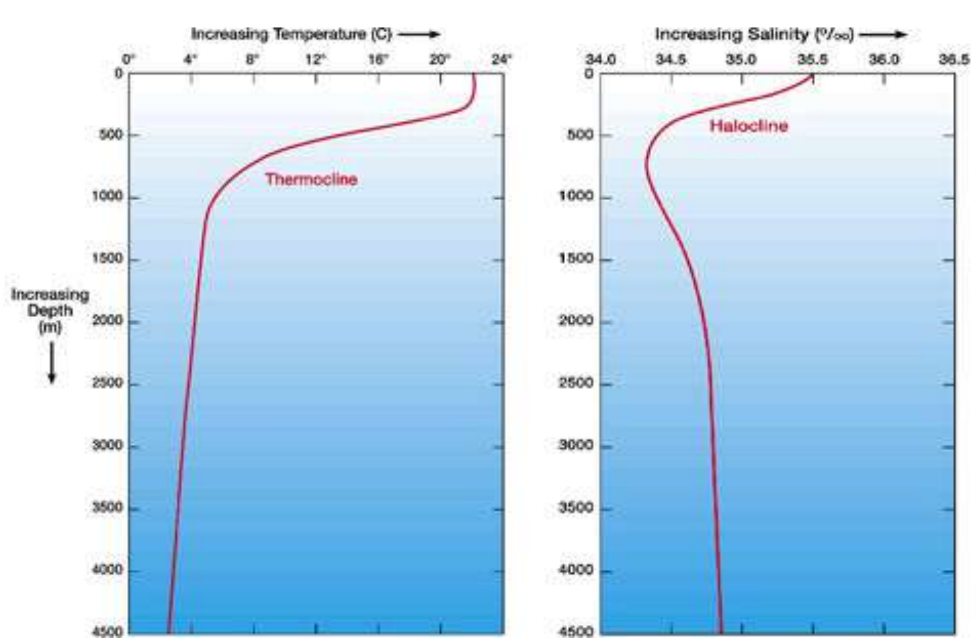
Klüpfel et al., 2014

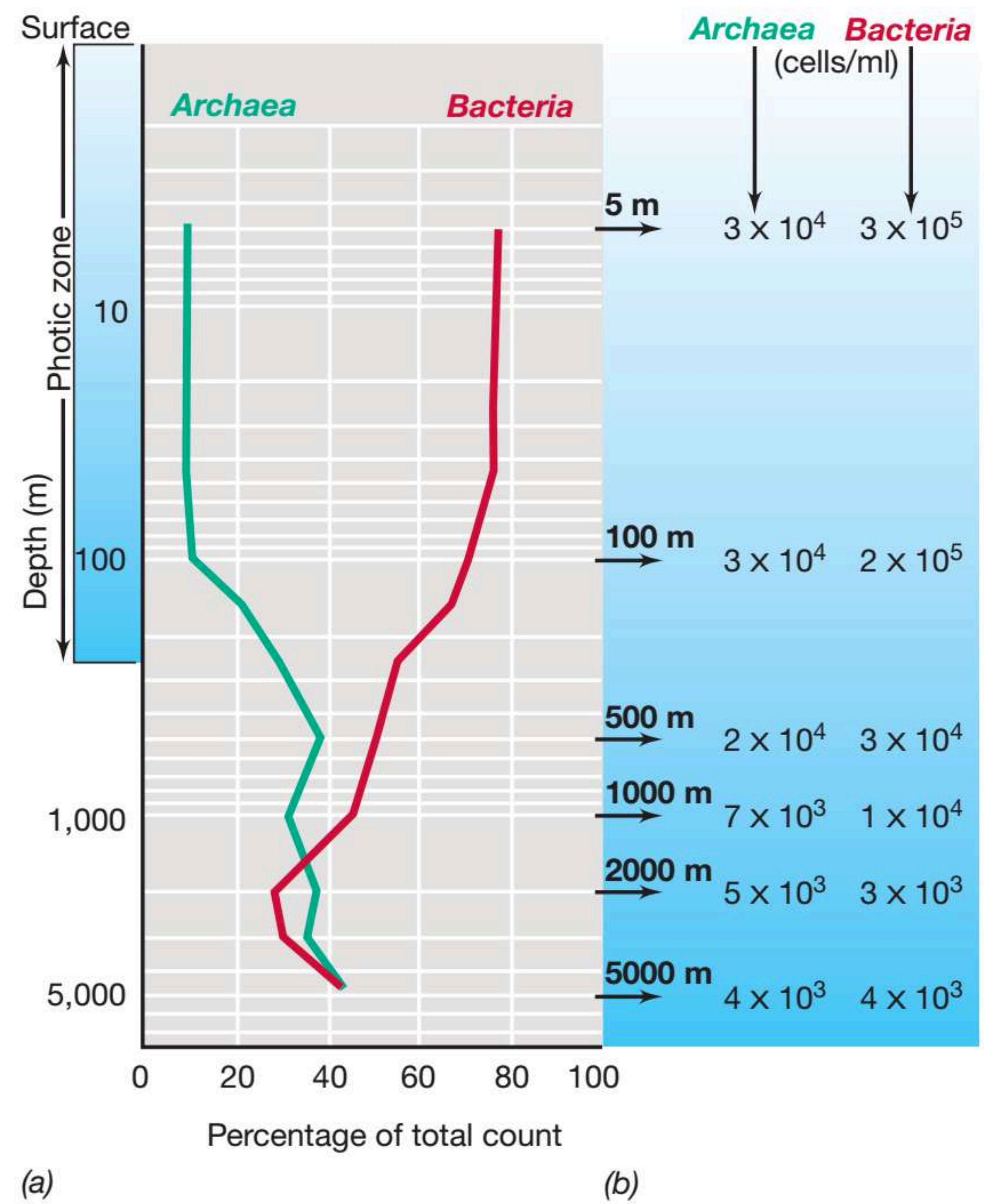


Silburn et al., 2017

Ocean as a microbial ecosystem

- Photic zone 0-200 m
- More than 96% of ocean is dark and with a constant temperature (~ 4^{0}C)
- Microbes in coastal ocean $1X10^{6}$ cells/mL
- Archaea dominate at depth
- Primary production sustain ocean interior—> organic matter degradation and sediment too!

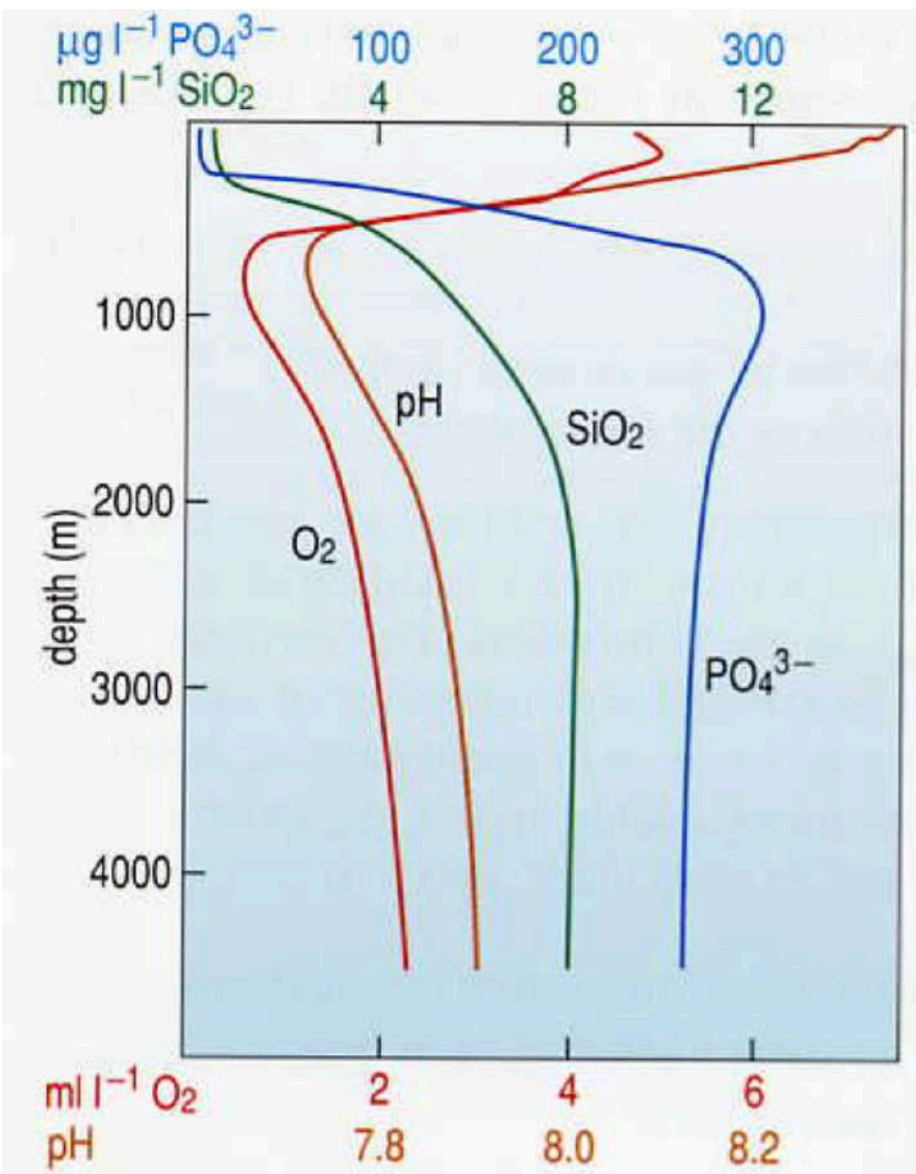


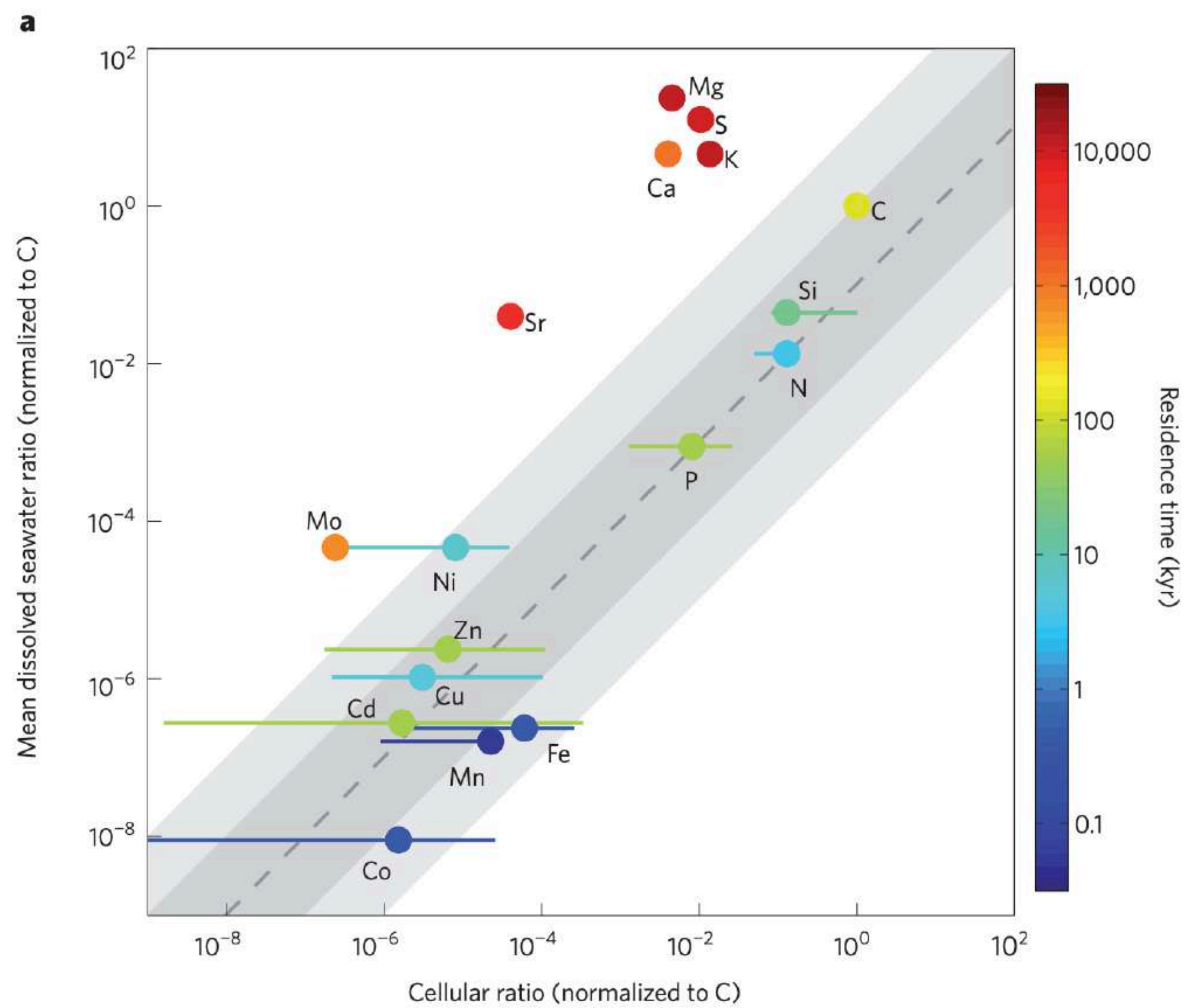


Madigan et al. 2018

Ocean: Organic matter decomposition/respiration —> nutrient recycling

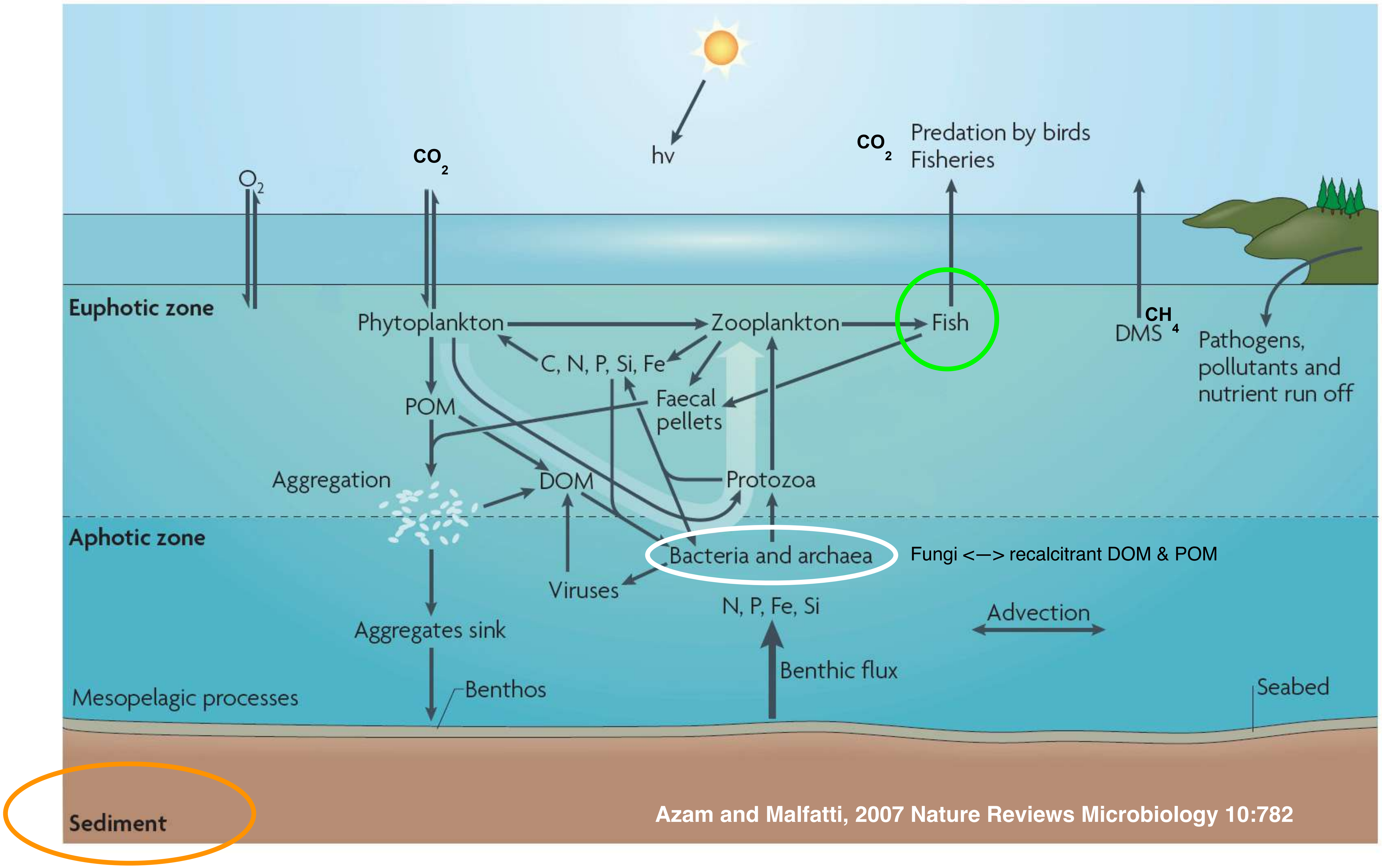
- Microbial degradation of organic matter in the water column generate nutrient fluxes available for primary producers (limiting nutrients based on cell demands)
- Microbial action with organic matter at the microscope structure ocean-basin scale





Moore et al., 2013

Fate of fixed carbon in ocean ecosystem



Seasonality —> high and low production

Microbial metabolic pathways shaping Earth ecosystem

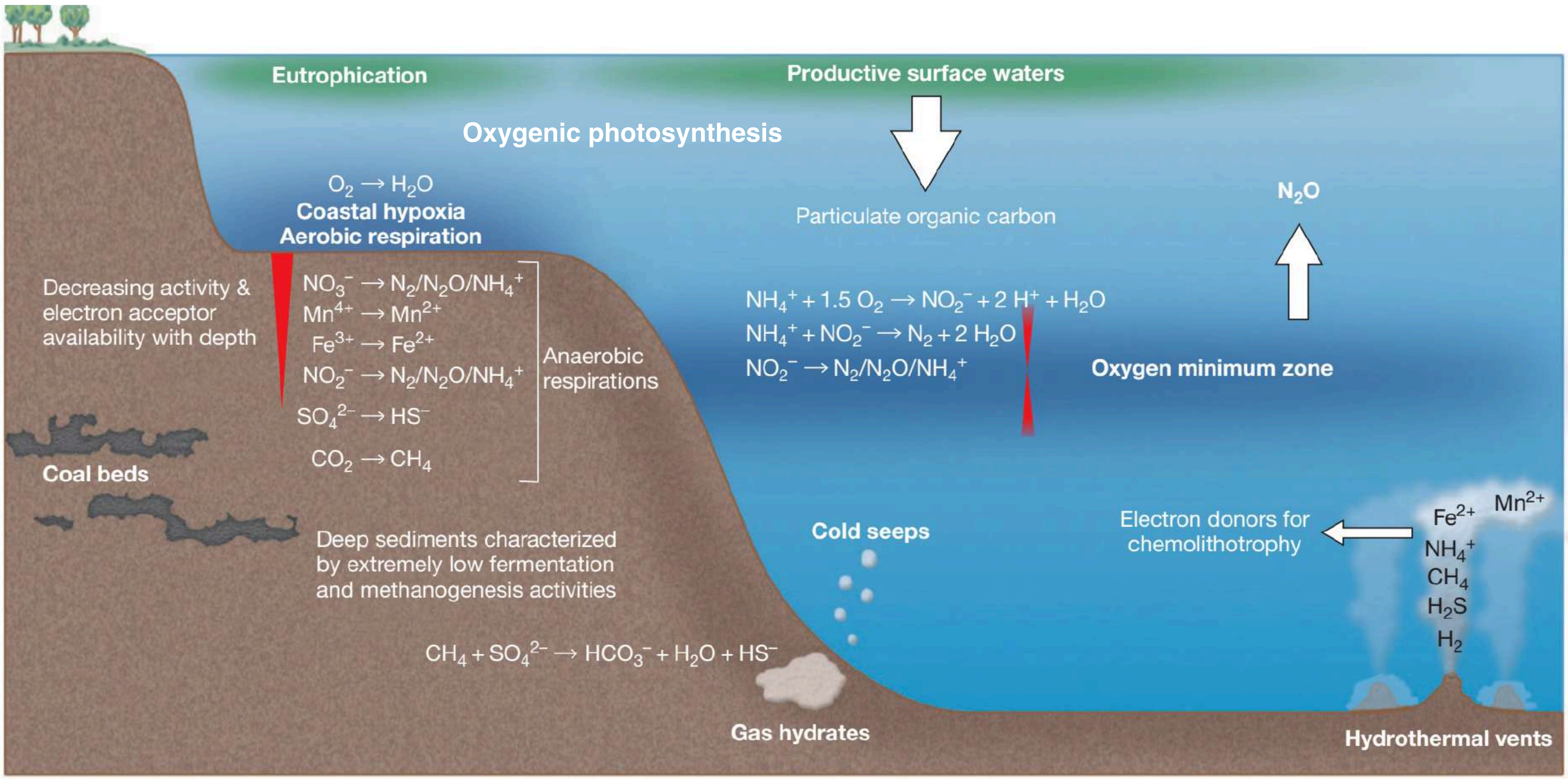


Figure 20.20 Diversity of marine systems and associated microbial metabolic processes. Decreasing electron acceptor availability with depth into the sediment or with increasing distance into an oxygen minimum zone is indicated by red wedges. Sulfate becomes limiting only at greater depths in marine sediments.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

Madigan et al. 2018

Microbial Diversity-Metabolic Diversity

- **Coupling of microbial diversity and metabolic diversity keep the ecosystem functioning**
- Microbes influence habitability
- Habitability influence microbes
- Habitability is a binary continuum

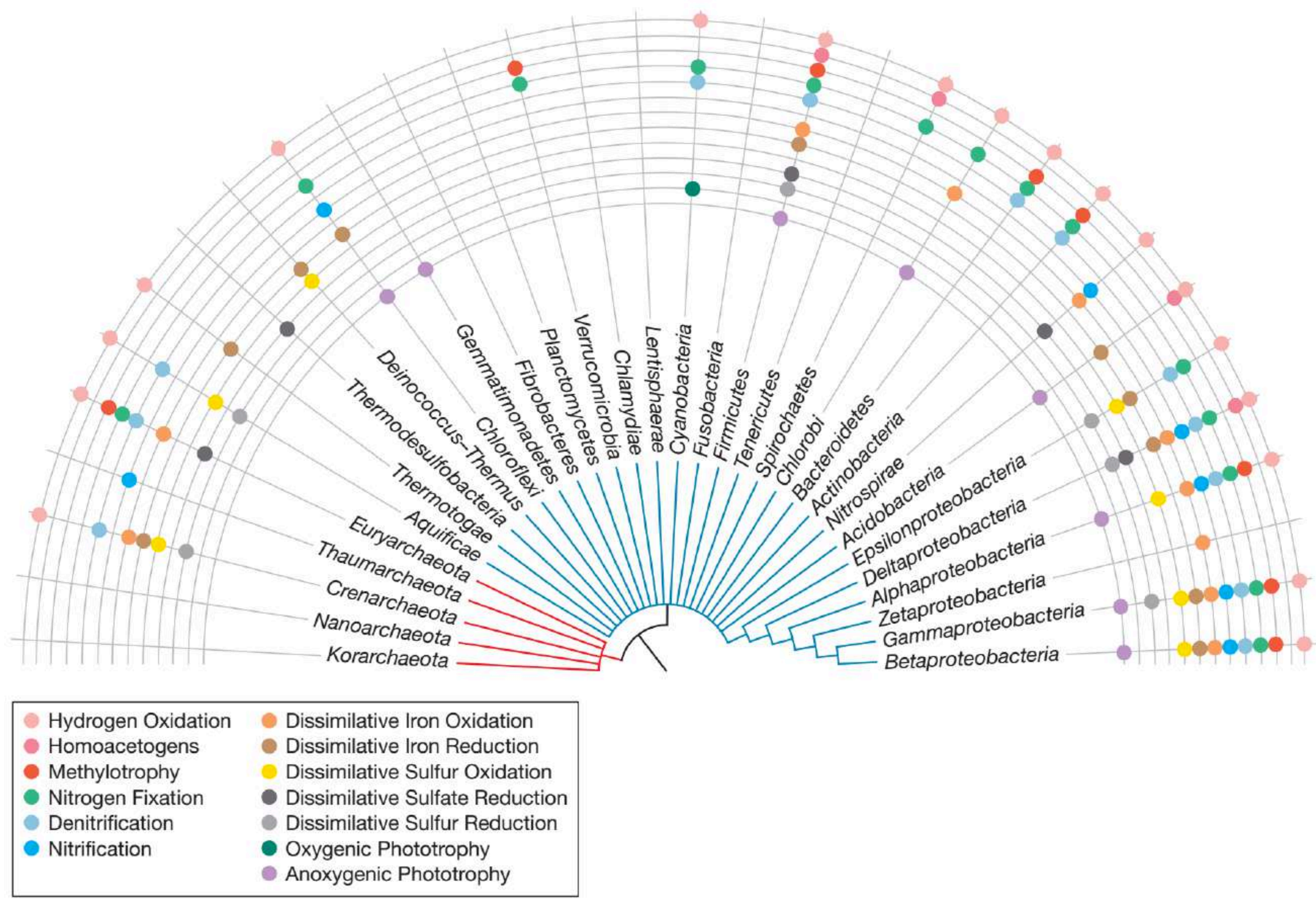
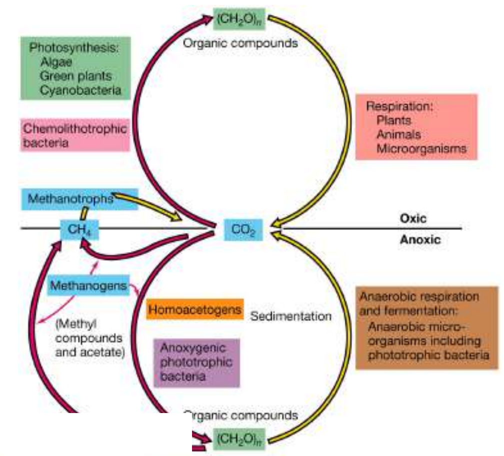


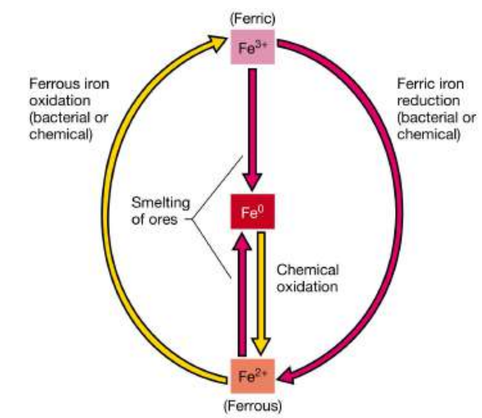
Figure 15.1 Major functional traits mapped across major phyla of *Bacteria* and *Archaea*. The dendrogram shows relationships between microbial phyla as inferred by analysis of 16S ribosomal RNA gene sequences. Blue branches are used to denote phyla of *Bacteria* and red branches phyla of *Archaea*. Colored circles indicate phyla that contain at least one species with a functional trait indicated in the color key.

Madigan et al. 2018

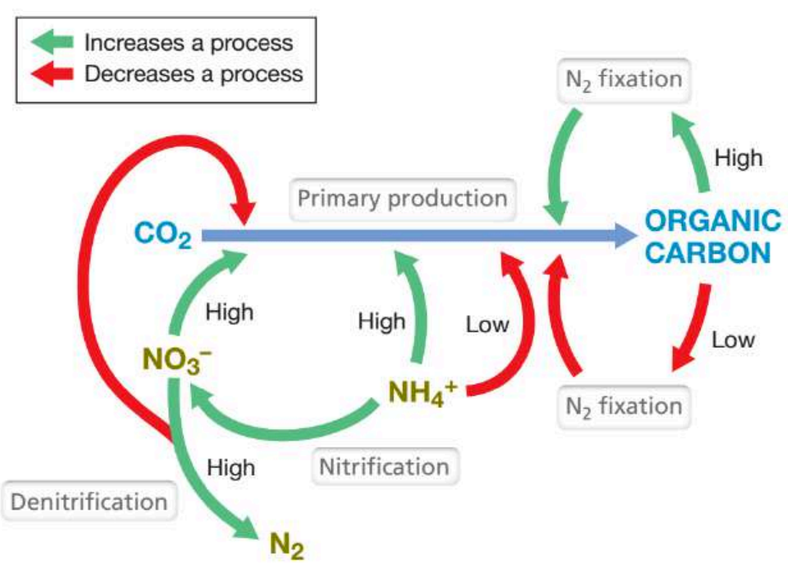
Interconnected cycles on Earth

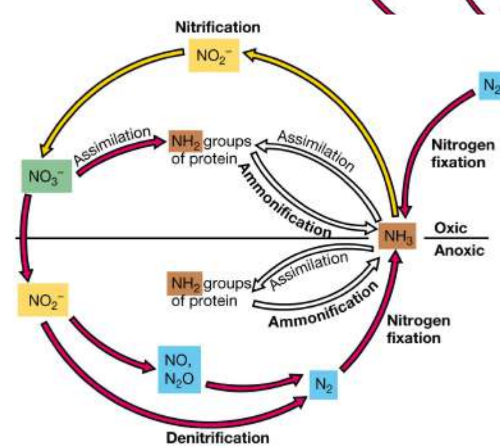
- All nutrient cycles are interconnected
- Nutrient cycles are coupled via biology

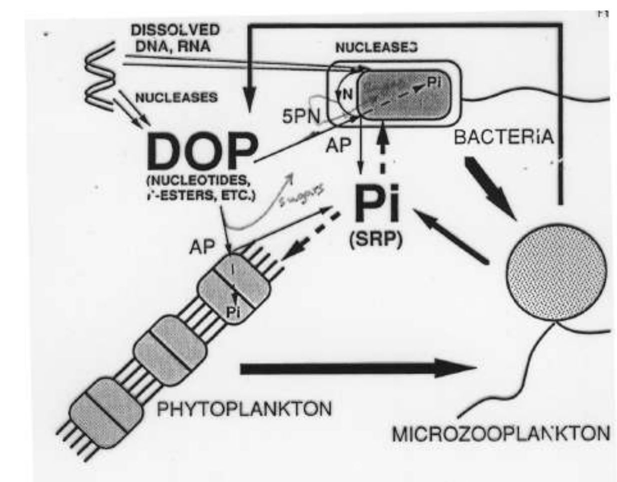


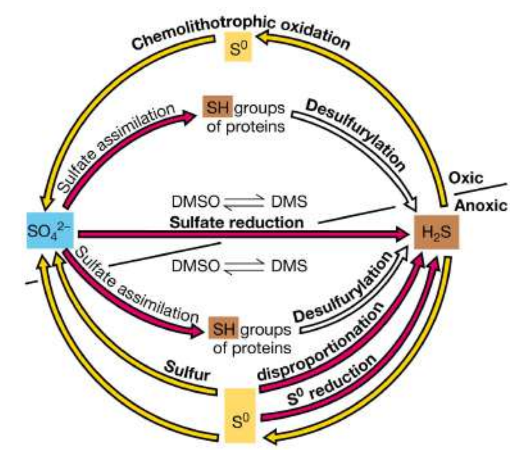


Madigan et al. 2018









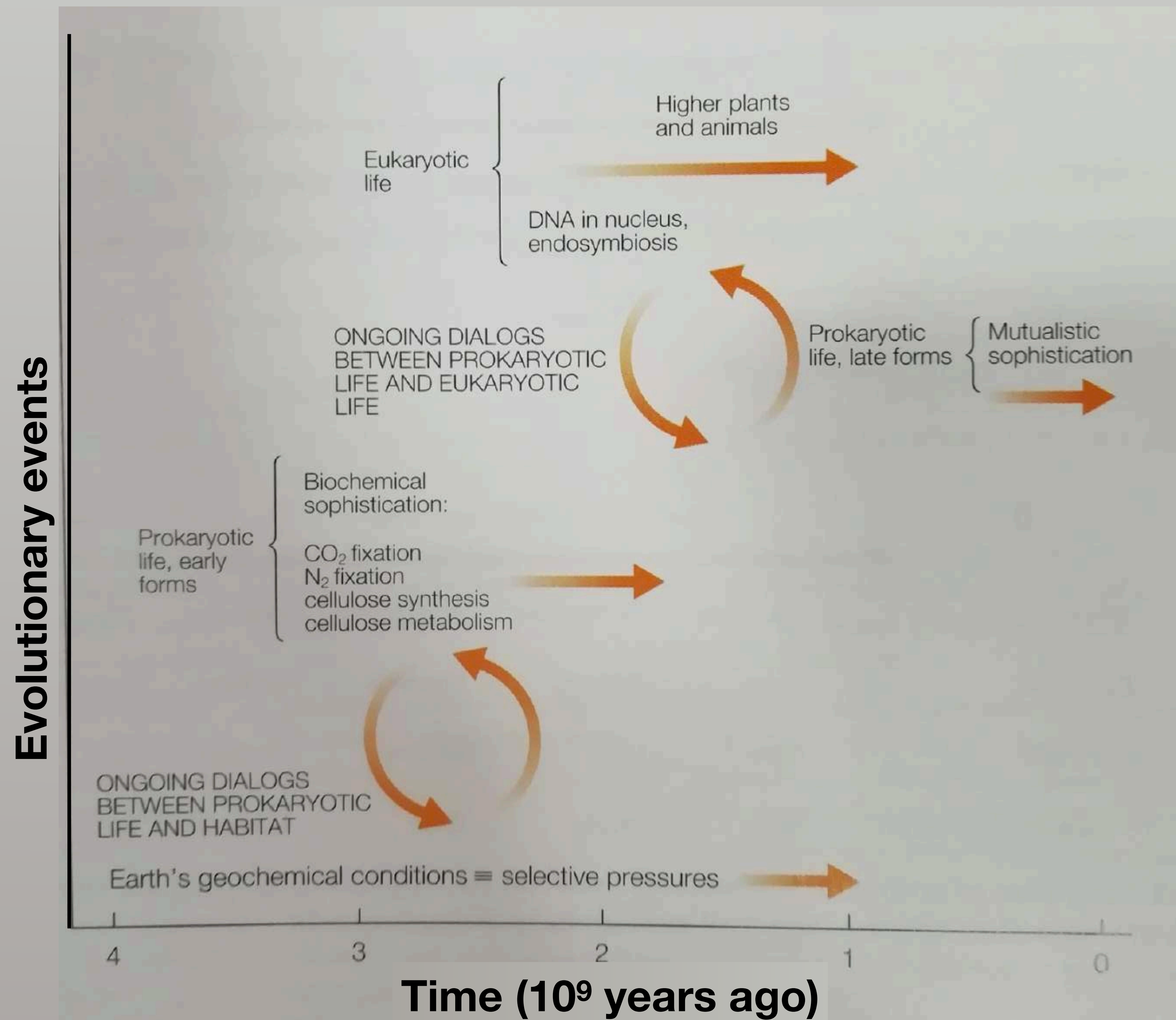
Redfield ratio or Redfield stoichiometry is the atomic ratio of carbon, nitrogen and phosphorus found in phytoplankton and throughout the deep oceans C:N:P = 106:16:1 (Redfield A.C., 1934)

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…

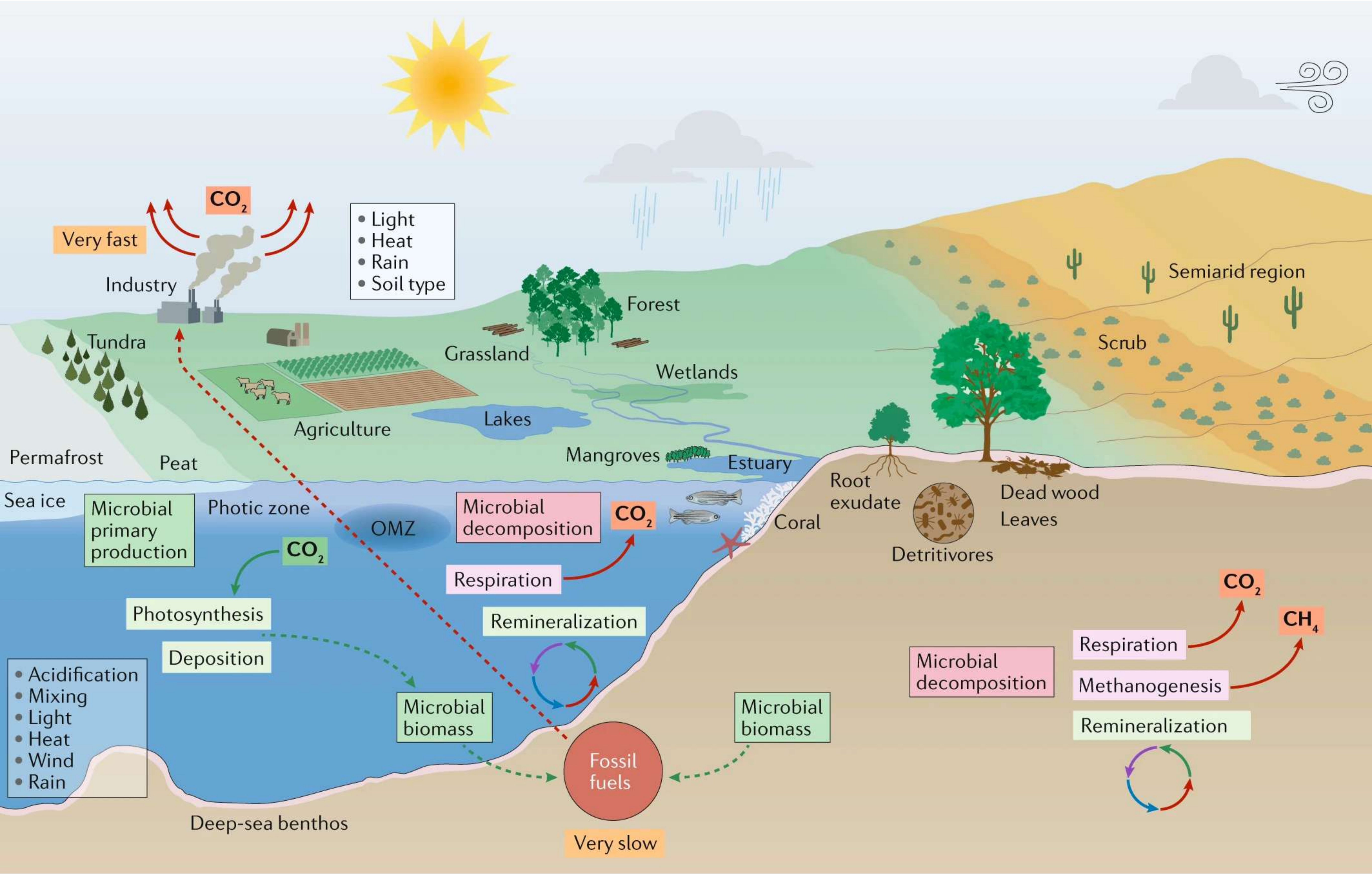
Continuum of microbial interactions

- **Evolution at the species level**
- Evolution of **interactions and behaviors**
- *Microbial interactions link microbial diversity with metabolic diversity*
- *Microbial interactions has structured the environment*
- *Microbes-Human interactions are important foci to understand health & disease*



Madsen, 2016

Microbes regulating EARTH climate



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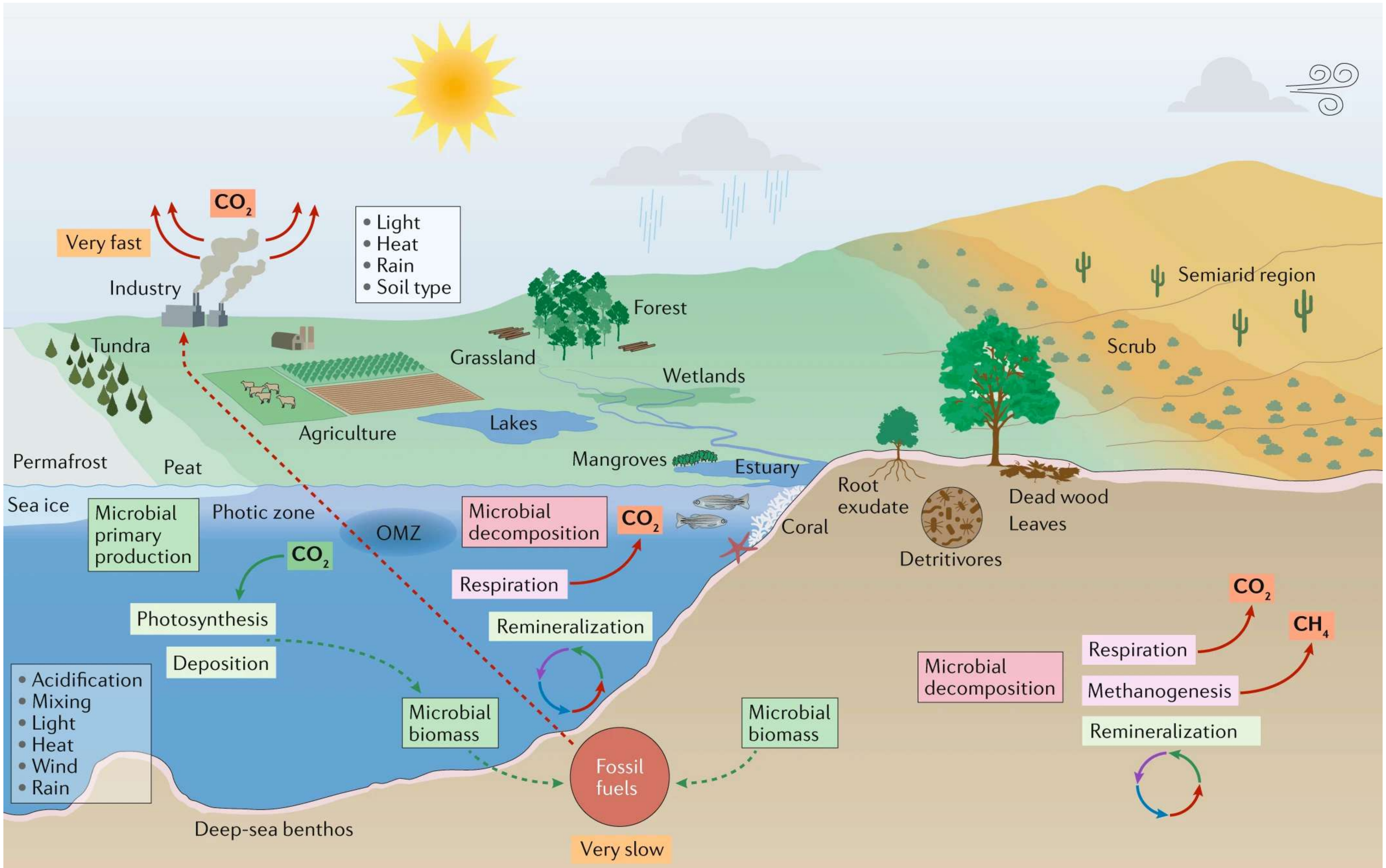
Microbes have prominent roles related to climate change via their metabolisms.

They produce and consume the three dominant gases that are responsible for 98% of the increased warming: carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O).

Photo- or chemoautotrophic growth (cyanobacteria, algae, nitrifiers), methanotrophy (methane oxidizers), and nitrous oxide reduction (denitrifiers) use these gases.

Carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O)



+ URBAN ENVIRONMENT

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Mitigation of carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O)

- Geoengineering solutions to stock CO_2
- Managing landfill CH_4 emission —> coupling with bioreactors for new product production or heat and designing new landfill with methanotrophs
- Reducing CH_4 emission from cattle (rumen microbes)—> changing societal culture for raising livestock
- Sequestering C via CH_4 from wastewater treatment facilities —> pyrolytic conversion
- NOx mitigation, N_2O is a product of ammonia oxidation in oxic conditions, in anoxic condition is produced by coupling NO reduction to oxidation od e- donors (Fe, S, organics by the denitrifies) —> estuaries, soils, <u>landfills, wastewater bioreactors —>to force efficient denitrification</u>