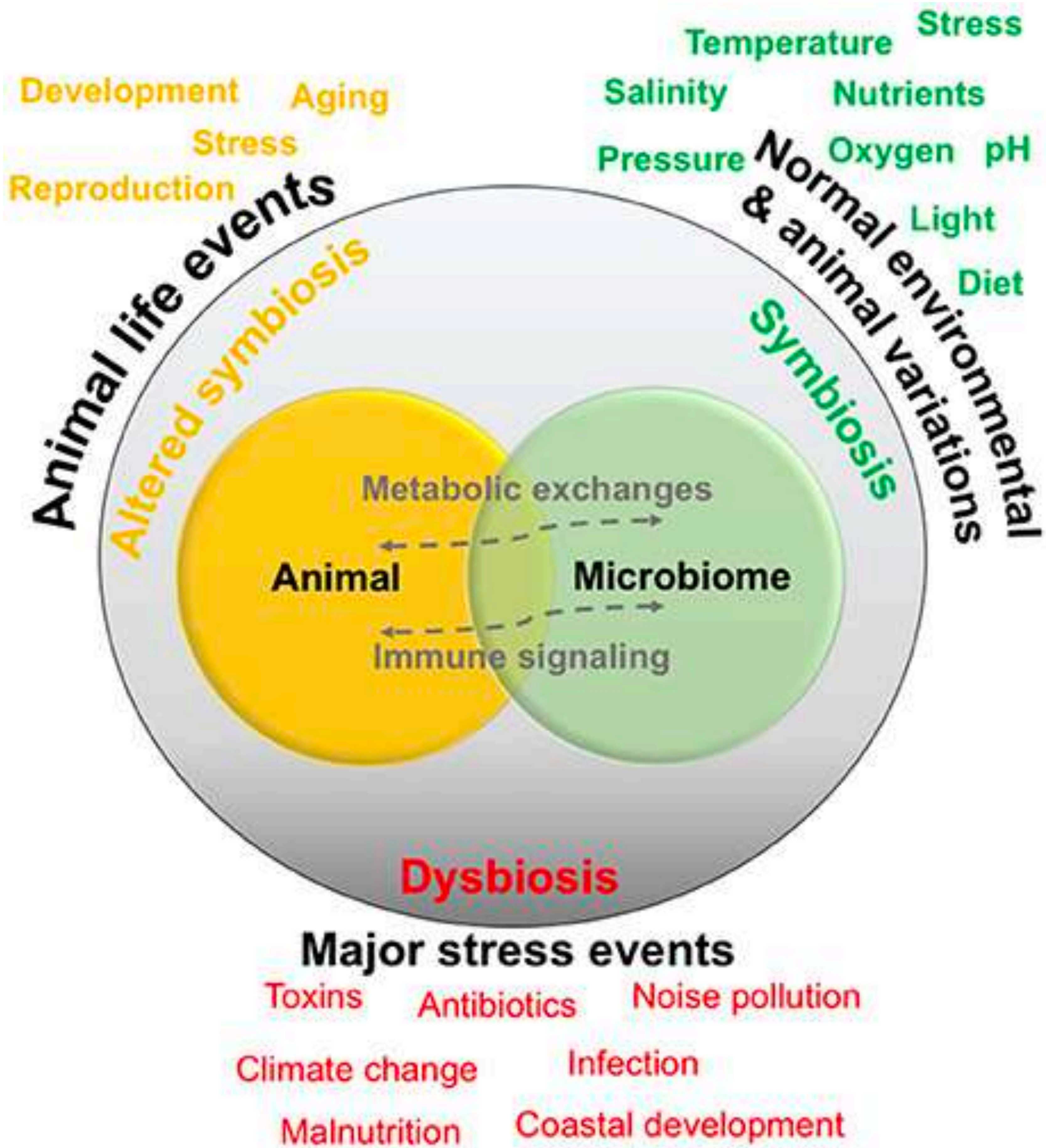
L05:
Marine Microbial Symbioses and Microbial Diseases

Microbial Symbioses and Microbial Diseases a joint *Thesaurus*

Host–microbiome dynamics are generally described as falling into two main categories:

1. Symbiosis, in which the organisms are involved in a normal metabolic and immune signaling interactions

2. Dysbiosis, in which the relationship or interactions are heavily altered, possibly related to a major stress or infection event



- Host-microbiome relationship conceptual model
- Relationships are generally thought to exist in a symbiotic state, and are normally exposed to environmental and animal-specific factors that may cause natural variations
- Some events may change the relationship into a functioning but altered symbiotic state, whereas extreme stress events may cause dysbiosis or a breakdown of the relationship and interactions

Apprill, 2017

Acclimatization: The capacity of a holobiont to adjust to a perturbation through host phenotypic plasticity or restructuring of the microbiome in order to reach a new stable state

Adaptation: A transgenerational process that enhances the fitness of the holobiont through transgenerational acclimatization, heritable microbial community changes, or host/symbiont evolution

Core microbiome: The set of microbial taxa which are consistently and stably prevalent in host individuals of the same species

Dysbiosis: The divergence of a symbiotic microbial community from the community found in healthy individuals

Disease: The impairment of normal function following perturbation or damage. May be, but is not necessarily, induced by a pathogenic microorganism

Functional convergence: In the holobiont context, symbiotic microbial communities with different evolutionary histories that have, via different but analogous pathways, converged upon similar functional solutions

Functional redundancy: The presence of several microbial taxa within an ecosystem or holobiont that perform the same functions, such that the loss of one particular taxon or a shift in the community diversity would not compromise ecosystem function

Holobiont health: A dynamic equilibrium that allows minor fluctuations in terms of diversity or functions to ensure the maintenance of symbiotic homeostasis

Microbiota: The assemblage of microorganisms present in a defined environment or host

Microbiome: The group of microbes, their genetic information, and the surrounding environmental conditions in a defined environment or host

Nested ecosystem: A smaller distinct ecosystem which is contained within and interacts with a larger ecosystem or series of successively larger ecosystems

Opportunistic: An organism that is capable of causing damage to a host under specific conditions, but may also exist as a commensal within the same host under normal conditions

Perturbation: A temporary or persistent change in biotic or abiotic conditions that leads to a response by an ecosystem or holobiont

Resilience: The capacity of a system to recover its initial functional and taxonomical composition and return to an initial stable state following a perturbation

Resistance: The property of a system to remain unchanged and maintain at a stable state upon perturbation

Symbiosis (sensu De Bary): The close association of two or more organisms of a different species. This association may be mutualistic, commensal, or parasitic

Parasitism: An antagonistic symbiotic relationship in which one species is harmed, while the other benefits

Mutualism: A symbiotic relationship in which both interacting species benefit, or are perceived to benefit. Benefit is often only confirmed empirically for the host.

Holobiont means 'whole unit of life', a single ecological unit formed by the host and associated microbes

Marine Microbial Symbioses

Host-microbiome relationship conceptual model, I

Holism is a philosophical notion first proposed by Aristotle in the 4th century BC

Holism states that **systems should be studied in their entirety**, with a focus on the **interconnections between their various components** rather than on the individual parts

Such systems have **emergent properties** that result from the behavior of a system that is "larger than the sum of its parts"

This implies a real paradigm shift of connectivity and coupling at the microscope that influences the macroscale

The term "holobiont" was first introduced in 1991 by Lynn Margulis and initially referred to a **simple biological entity involving a host and a single inherited symbiont**.

It was extended to define a **host and its associated communities of microorganisms (also referred to as the microbiota which corresponds to the collection of microorganisms in interaction with their host and ranging from mutualistic to parasitic interactions**). A host and its microbiota thus constitute a holobiont.

Host-microbiome relationship conceptual model, II

This term is now widely used in different contexts and applies to virtually all metazoans, with current research focusing mainly on human, animal, and plant holobionts.

Rohwer et al. (2002) were the first to use the word “holobiont” to describe a unit of selection sensu Margulis (Rosenberg et al., 2007b) for corals, where the holobiont comprised the cnidarian polyp (host), algae of the family Symbiodiniaceae, various ectosymbionts (endolithic algae, prokaryotes, fungi, other unicellular eukaryotes), and viruses

The term **hologenome** was introduced more recently in 2007 by Ilana Zilber-Rosenberg and Eugene Rosenberg to describe the sum of the host genome and associated microbial genomes, in other words, the collective genomes of a holobiont.

For example, the human genome contains about 20,000 genes, but its hologenome contains >33 million genes brought by its microbiota.

Research in Marine Microbial Symbioses:

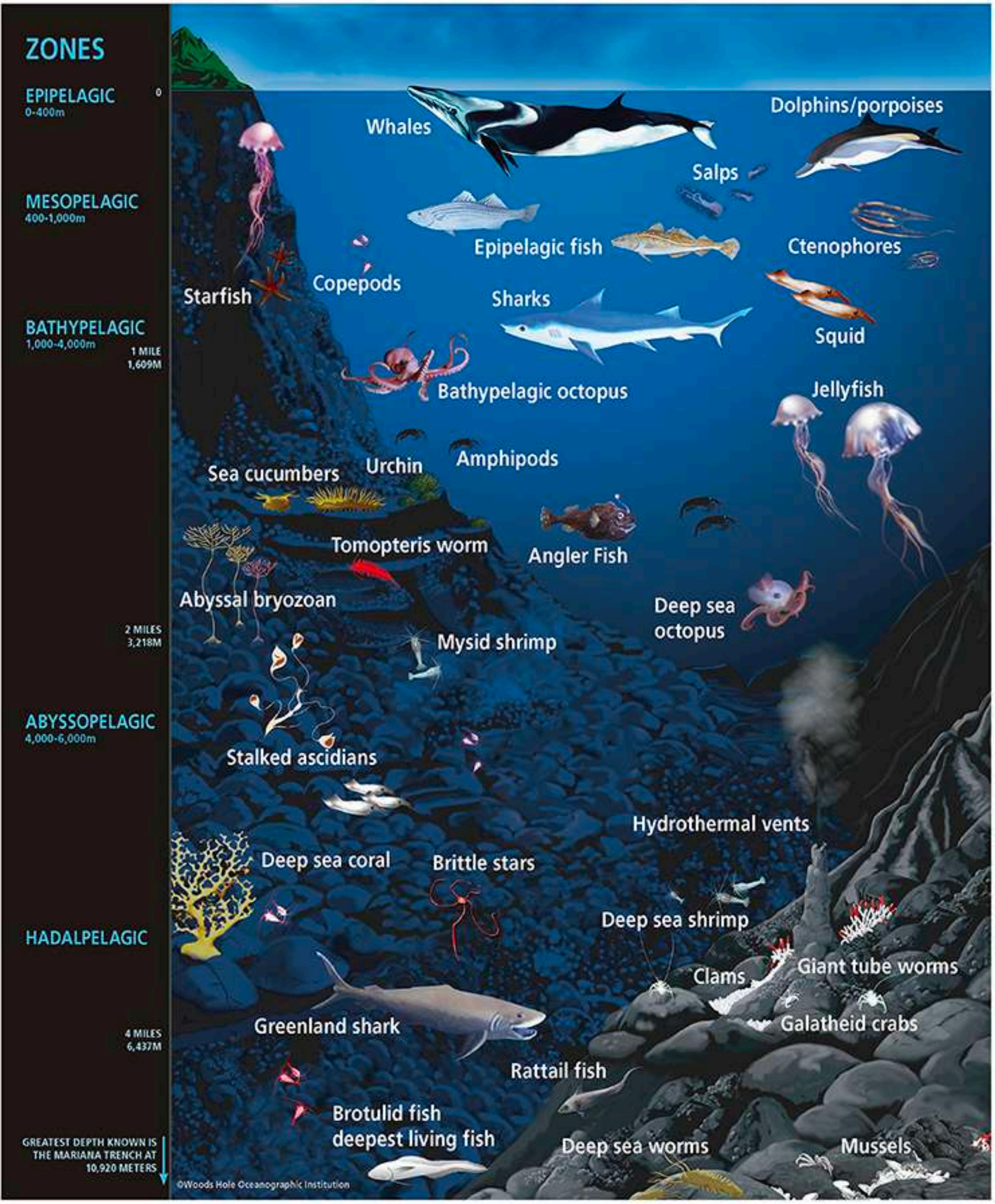
Identifying consistent or "core" microbial members of the microbiome: "who's there" —> to **understand the function** of the cells, the **nature of the associations** to elucidate **role of the microbiome** in animal **health**, **physiology**, **ecology**, and **behaviour**

Understanding **interactions** between the animal, microbiome, and **ocean environment**, including the elements that may define **their exchanges**

Understanding the **chemical signalling** between the **microbes and the animals** and the **secondary metabolite** production and their role in the ecology of the animals

Decipher the factors determining **holobiont composition** and elucidating the impacts and roles of the **different partners** in these complex systems **over time**

..Then microbiota/microbes are everywhere !

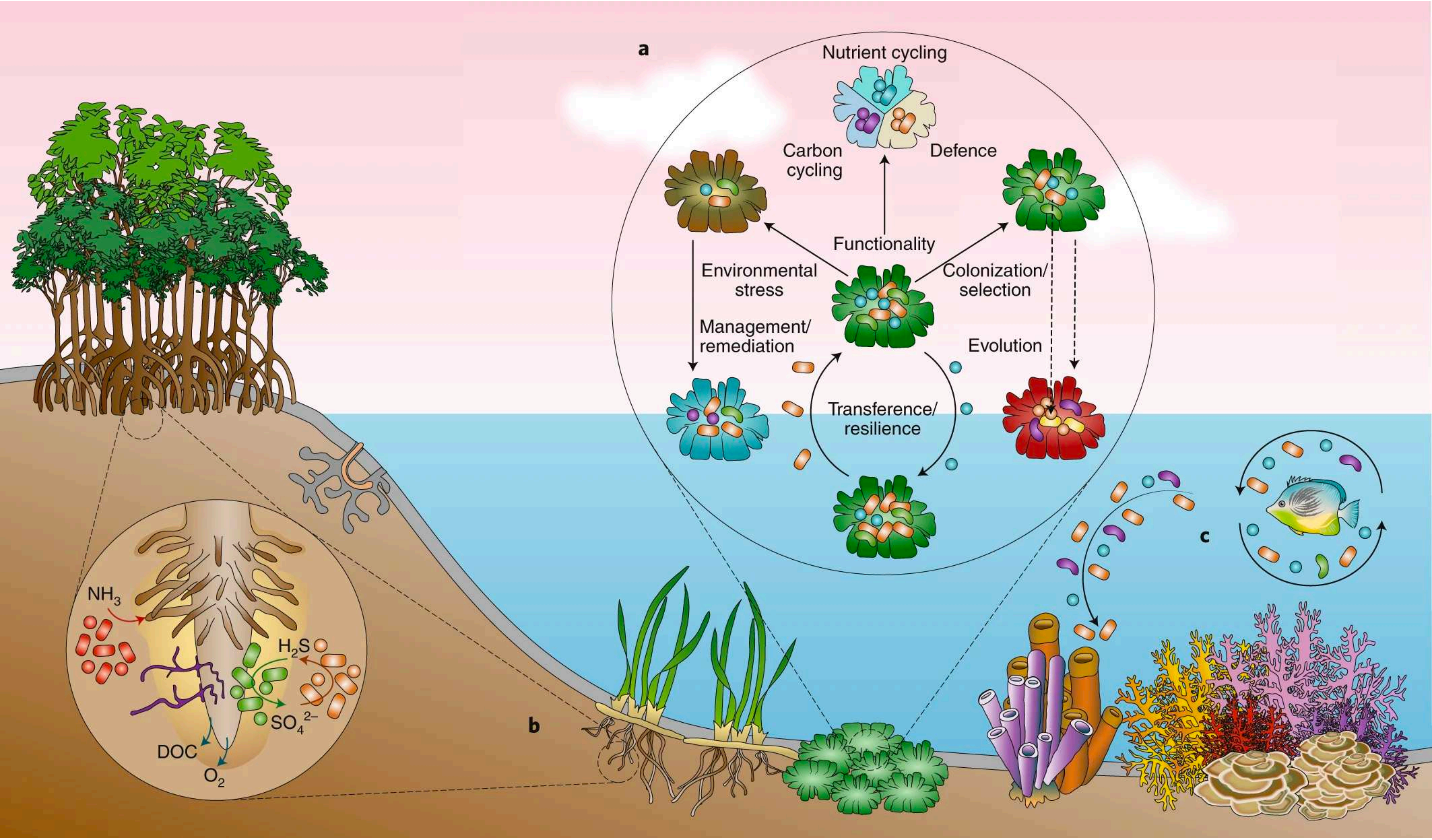


Charismatic oceanic megafauna within their approximate depth-defined ecological habitats

Microorganisms exist on the **surfaces** and **within the tissues** and **organs** of the diverse life inhabiting the ocean, **across all ocean habitats: holobionts**

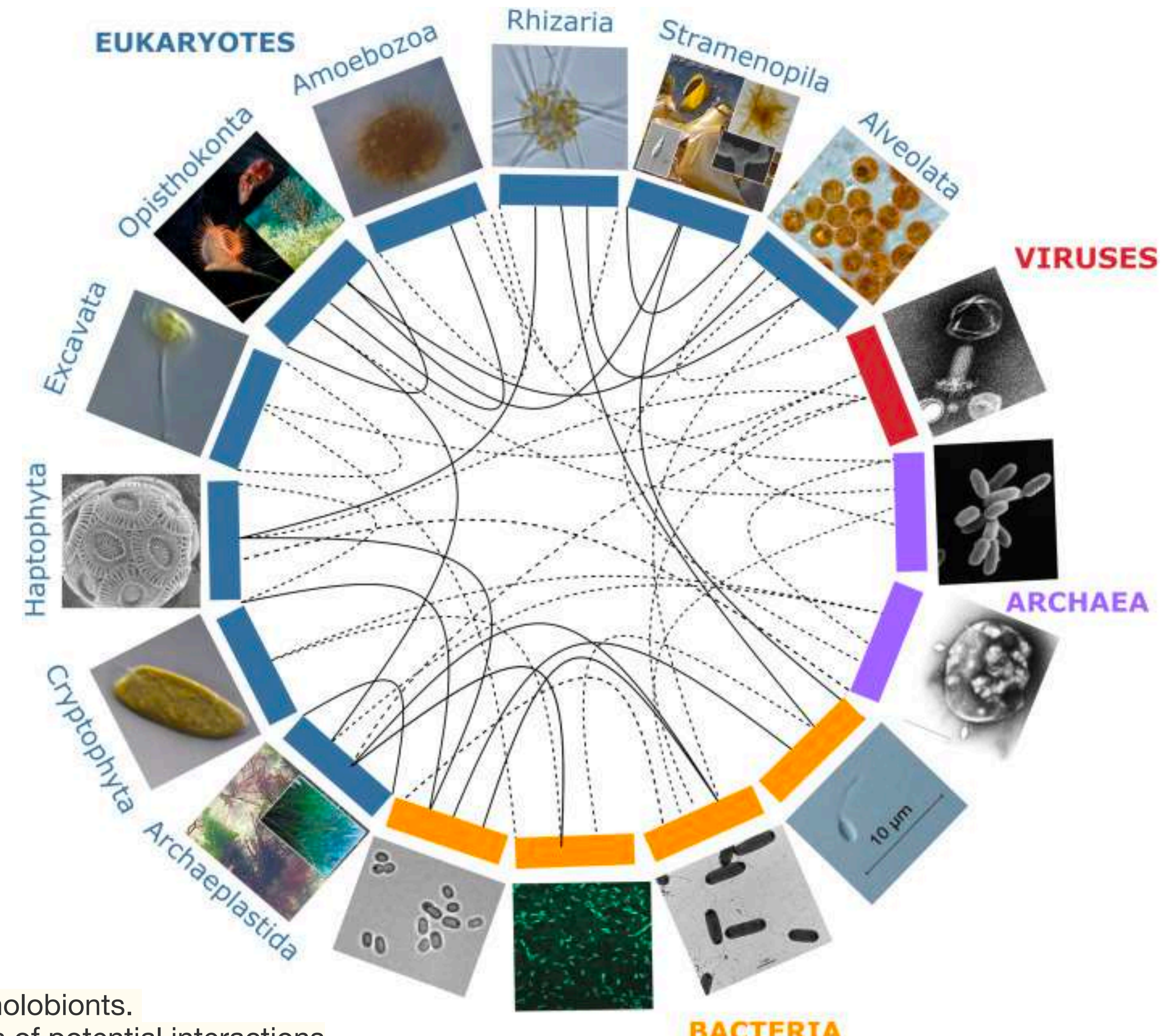
Apprill, 2017

Major research themes in coastal marine microbiome research including primary producers (mangroves, seaweeds, algae) and very productive ecosystems (sponges and corals)



Trevathan-Tackett et al. 2019

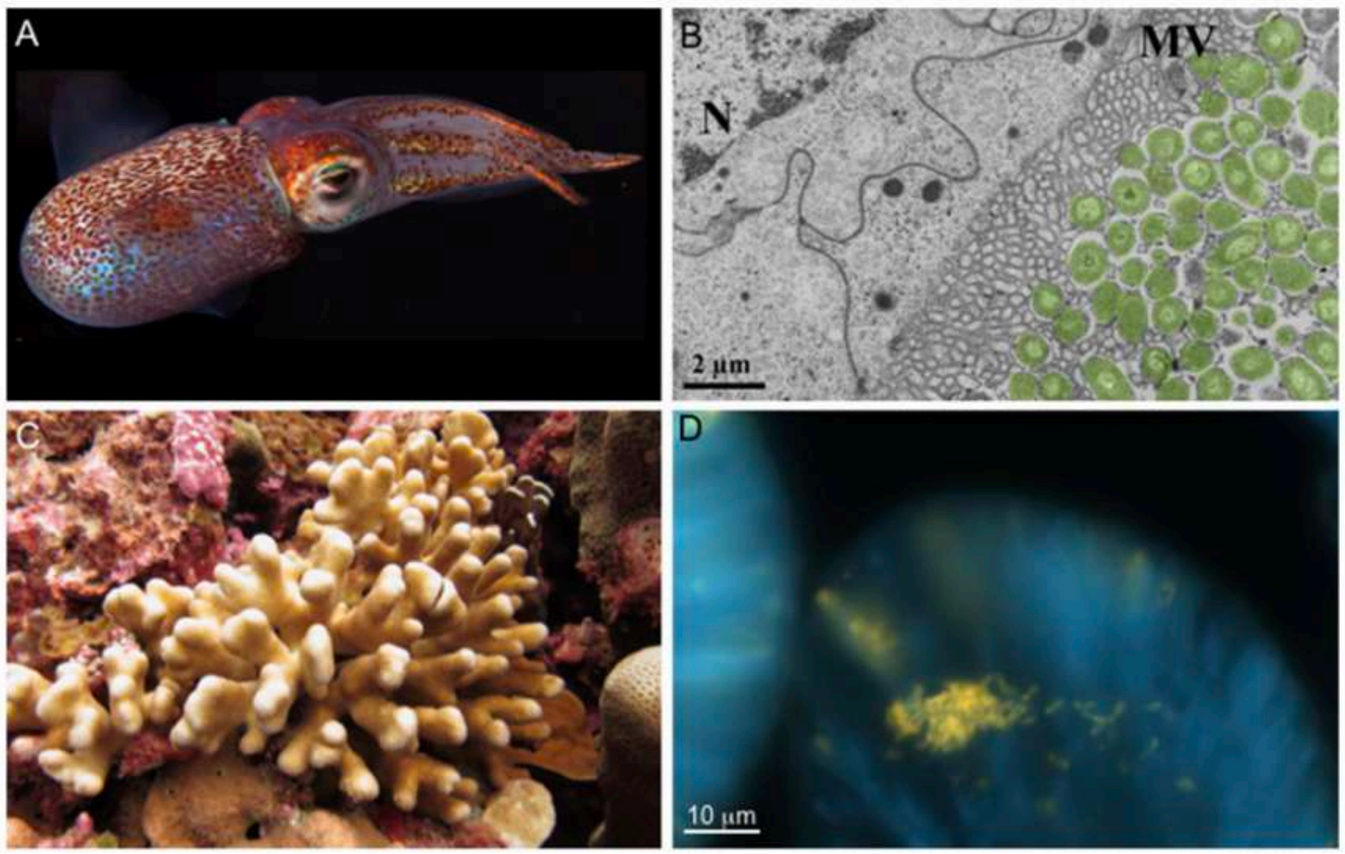
Partners forming marine holobionts



Plain lines correspond to holobionts.
Dashed lines are examples of potential interactions

Dittami et al., 2021

Marine animals and their associated microbiomes, I

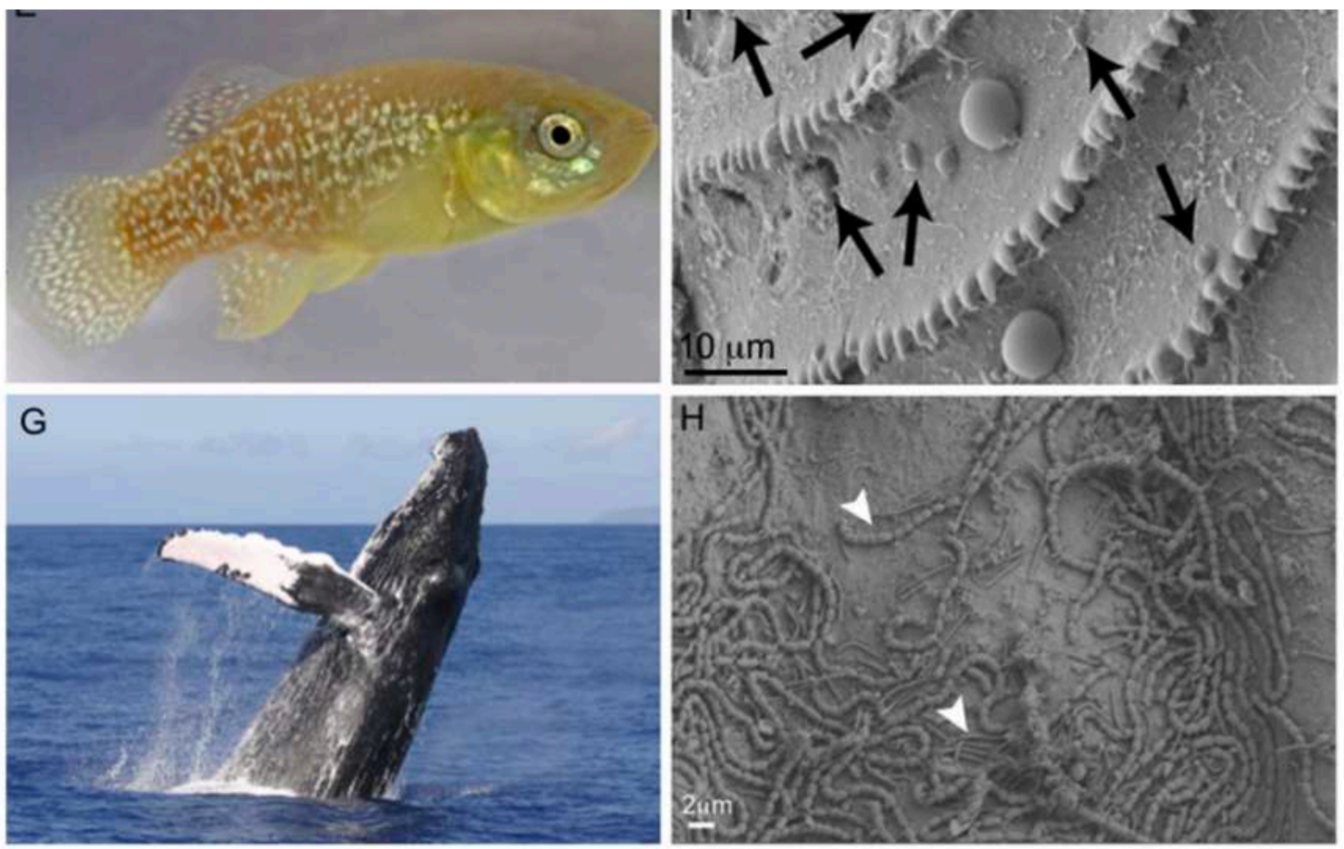


Hawaiian bobtail squid *Euprymna scolopes* (A) and a transmission electron micrograph of *Vibrio fisheri* cells associating with dense microvilli (MV) and in proximity to the epithelial nucleus (N) within the light organ (B)

Reef-building coral *Stylophora pistillata* (C) and a microscopy image of Endozoicomonas cells (probed yellow using in situ hybridization) within the tentacles of a *S. pistillata* host (D)

Apprill, 2017

Marine animals and their associated microbiomes, II

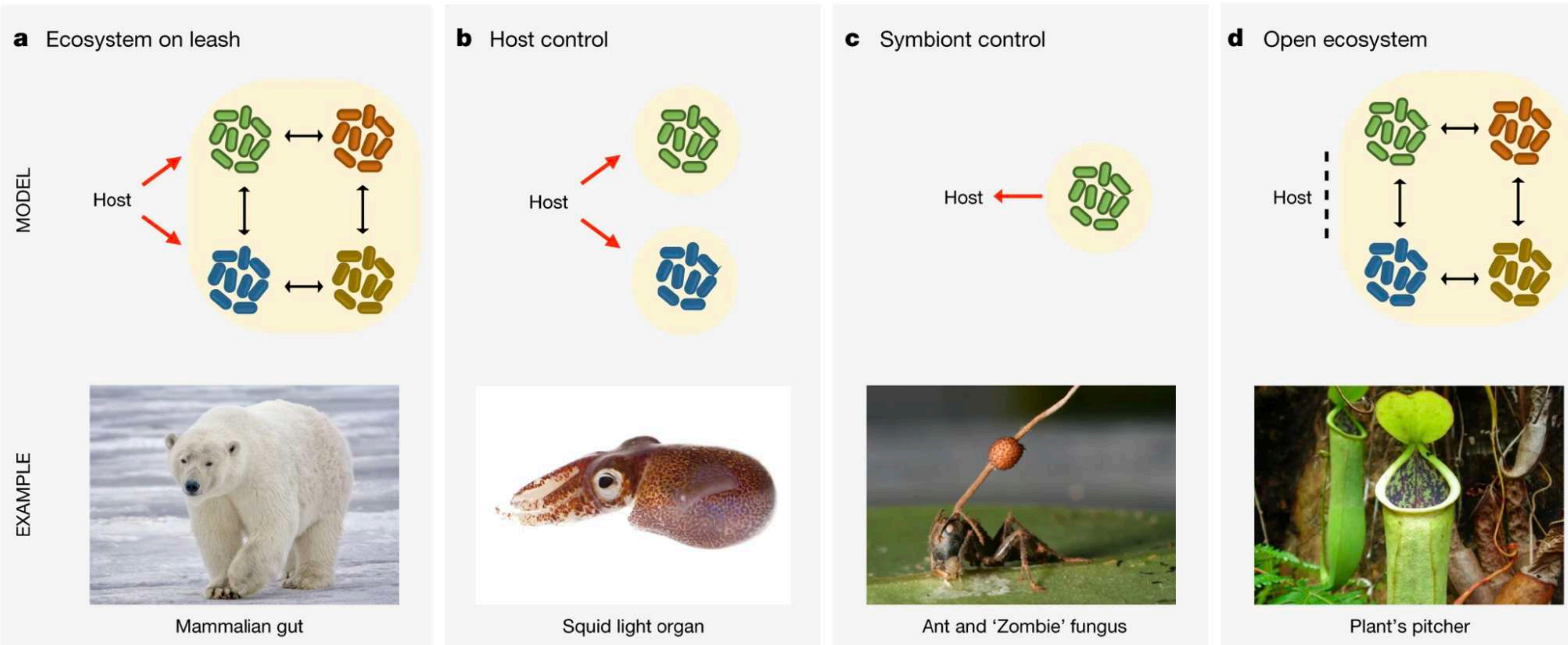


Atlantic killifish *Fundulus heteroclitus* (E) and a scanning electron microscopy (SEM) image of the surface and scales of the fish, with arrows pointing to bacterial-sized cells and larger cells are presumably phytoplankton (F)

Humpback whale *Megaptera novaeangliae* breaching (G) and a scanning electron microscopy image of a humpback's skin surface associated bacteria, with arrows indicating two different cell morphologies

Apprill, 2017

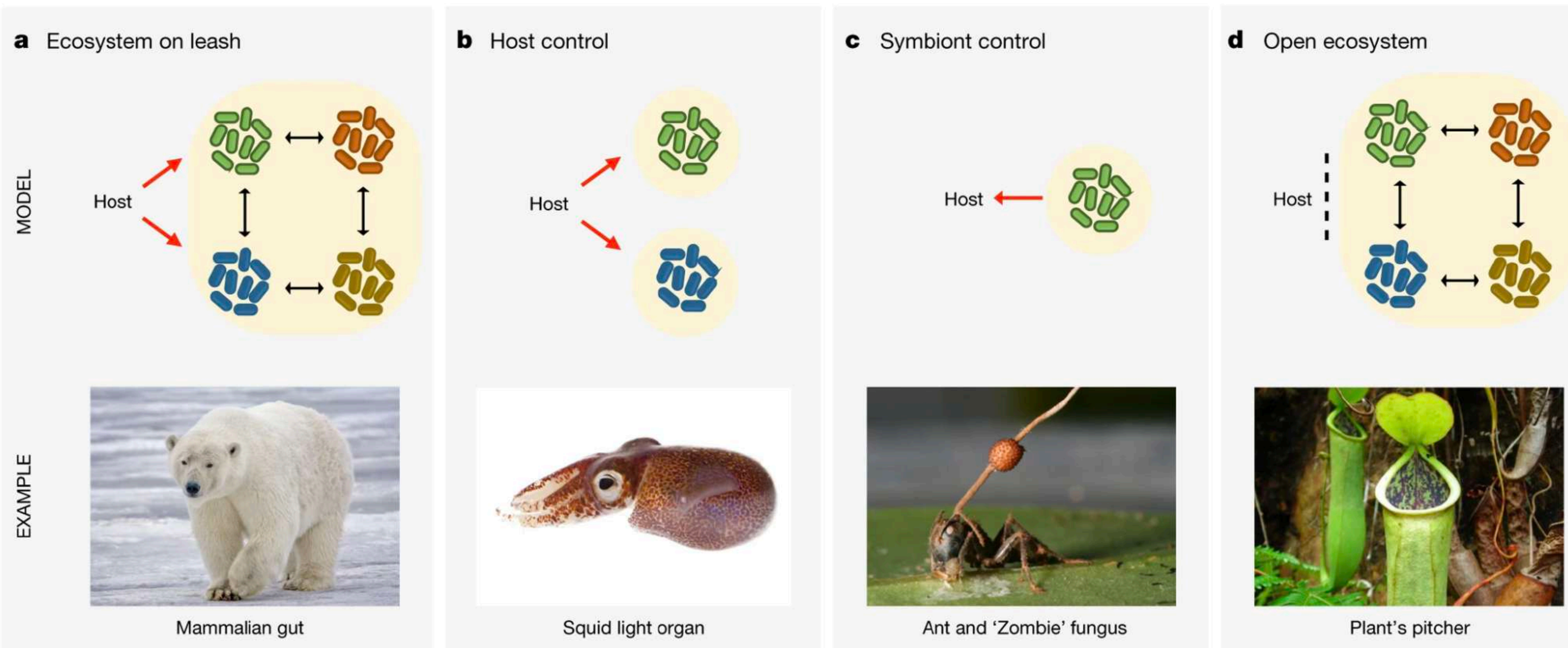
Models of host–microbiome interactions



Black arrows represent ecological interactions within the microbiota, **red arrows indicate mechanisms of control**

Foster et al., 2017

Models of host–microbiome interactions

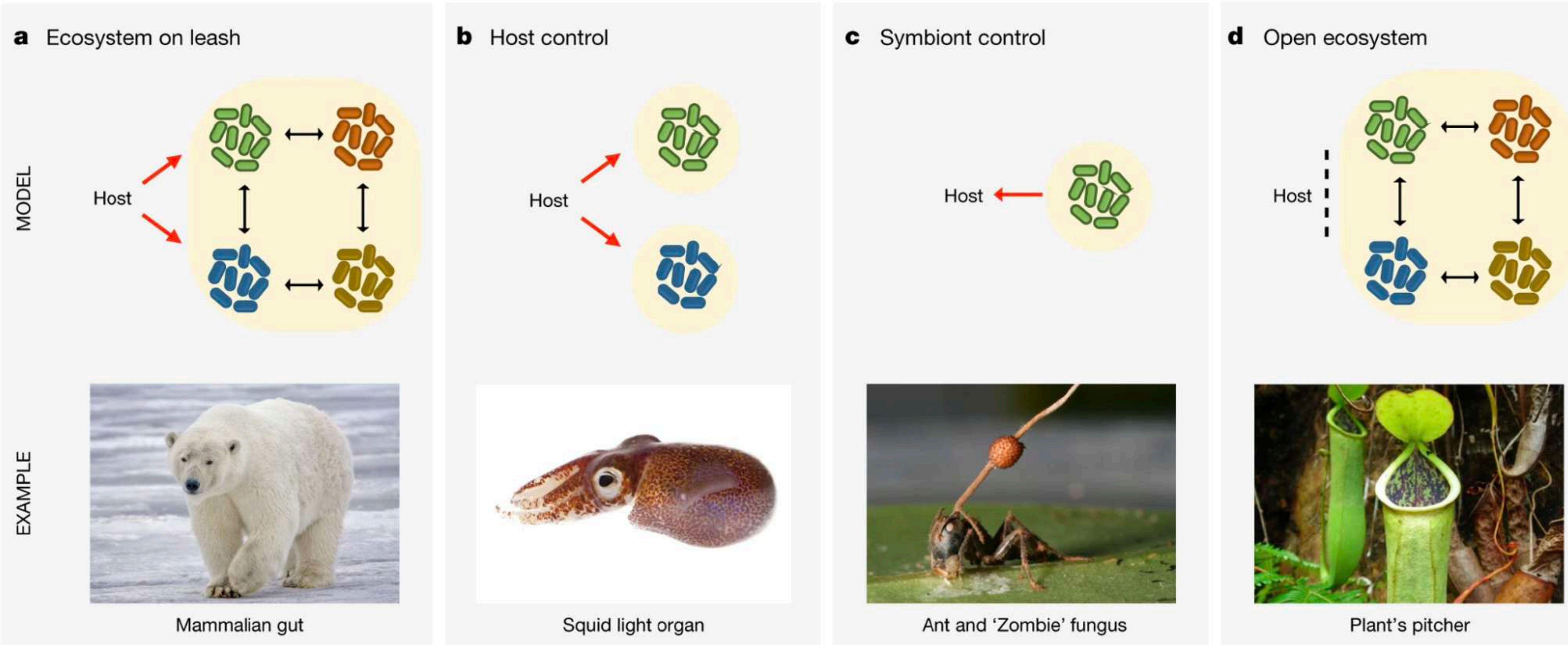


Black arrows represent ecological interactions within the microbiota, **red arrows indicate mechanisms of control**

a, Ecosystem on a leash. When host species interact with a diverse but beneficial microbiota, as occurs in mammals, evolutionary theory predicts that the microbial functions will centre on persistence in the microbiome ecosystem, while the host will attempt to control the microbiota, hence the 'leash' .

Foster et al., 2017

Models of host–microbiome interactions

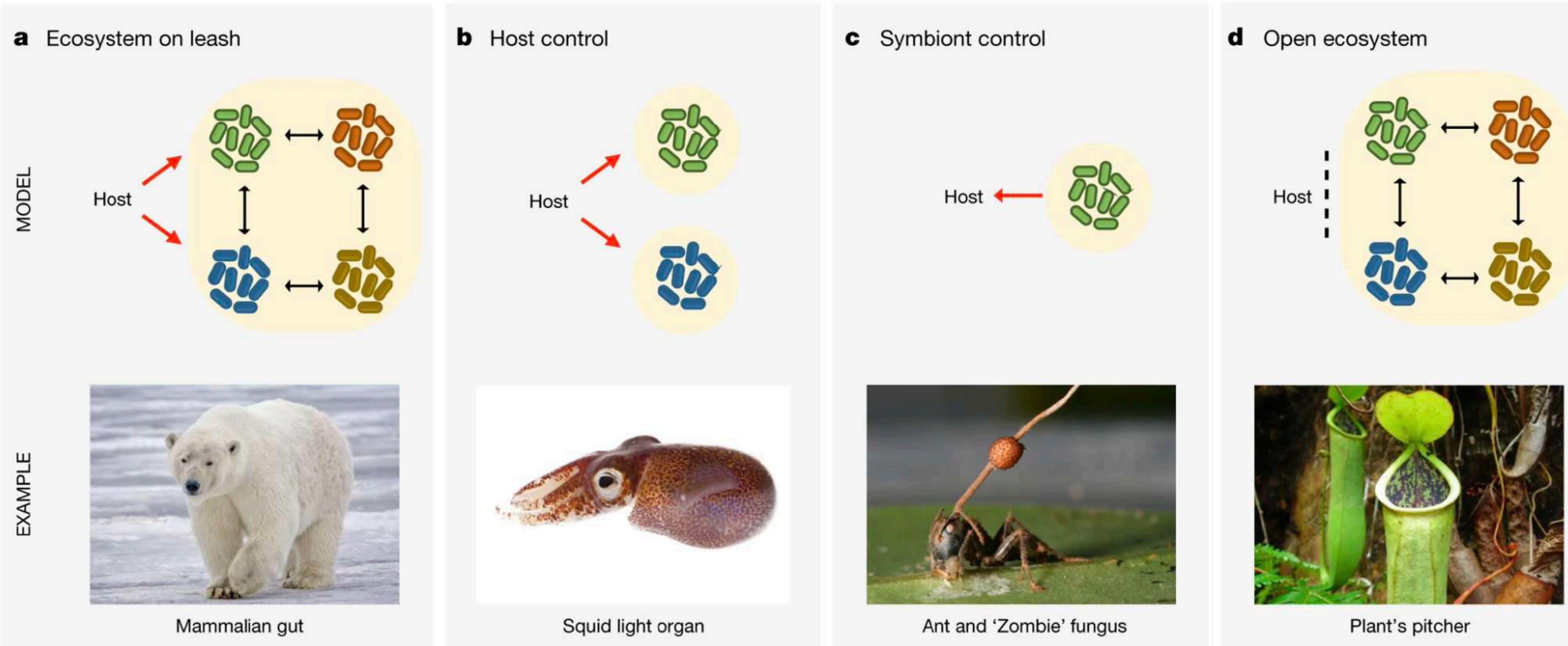


Black arrows represent ecological interactions within the microbiota, **red arrows indicate mechanisms of control**

b, Host control. For interactions involving few microbial strains, ecological complexity is reduced and microbes are primarily shaped by the host environment. Natural selection on the host, therefore, can result in strong shaping and control of the phenotypes of beneficial microbes. The bobtail squid has a specialized light organ, which controls both the access and light production of the symbiotic bacteria that grow inside. One hypothesis is that host enzymes generate bacteriocidal compounds from substrates that become available if the bacteria do not perform the light-producing reaction.

Foster et al., 2017

Models of host–microbiome interactions

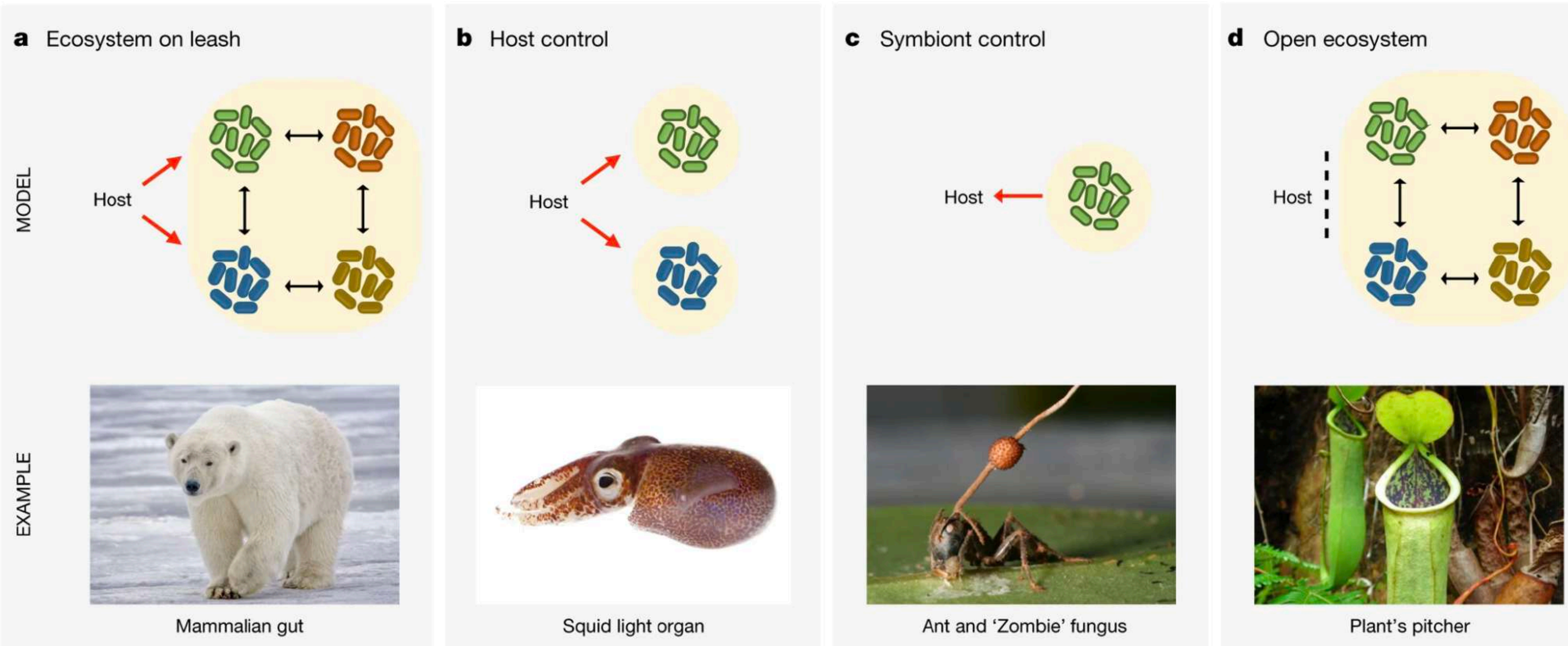


Black arrows represent ecological interactions within the microbiota, **red arrows indicate mechanisms of control**

c. Symbiont control. Low microbial diversity also increases the potential for microbes to affect global host traits—including survival, reproduction and behaviour—and receive a fitness benefit from doing so.This may select for adaptations that function to increase host fitness, such as enzymes that feed the host, but slow microbial growth. However, this can also enable symbiont manipulation of the host, such as for 'zombie' fungi, infection with which causes ants to move to a position ideal for fungal development.

Foster et al., 2017

Models of host–microbiome interactions



Black arrows represent ecological interactions within the microbiota, **red arrows indicate mechanisms of control**

d, Open ecosystem. A host carries a complex ecosystem without evolved control mechanisms beyond compartmentalization. This is most likely to occur if the microbiota are rarely either a threat or a benefit. Pitcher plants use pools of water to kill and digest prey. Although these plants regulate the pool by releasing enzymes and acids to promote digestion, there is currently little evidence that the plants have dedicated mechanisms to regulate the pool microbiota.

Foster et al., 2017

What is spatial microscale context of the associated microbial communities in the holobiont?

Biofilm, I

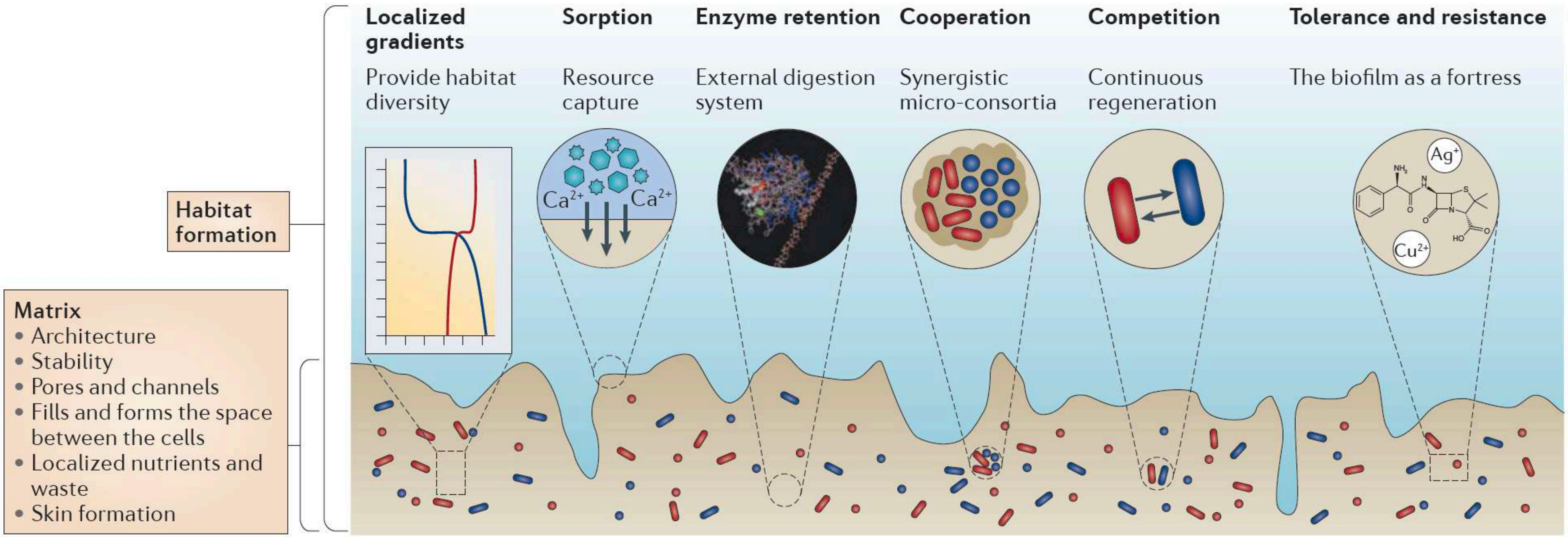
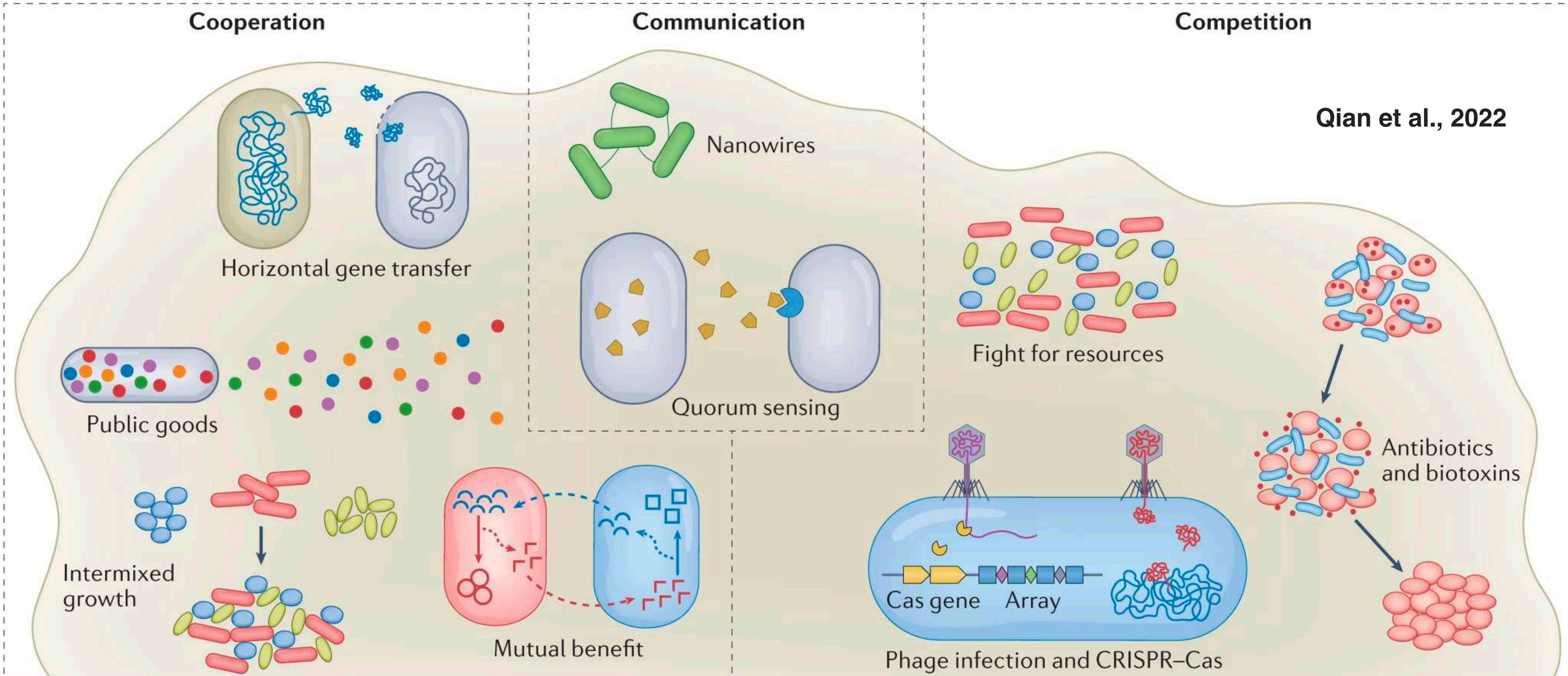


Figure 1 | **Emergent properties of biofilms and habitat formation.** Bacterial cells in biofilms can be considered to be habitat formers, owing to their generation of a matrix that forms the physical foundation of the biofilm. The matrix is composed of extracellular polymeric substances (EPS) that provide architecture and stability to the biofilm. Nutrients and other molecules can be trapped both by sorption to EPS molecules and to the pores and channels of the matrix, whereas skin formation by hydrophobic EPS molecules enhances the ability of the biofilm to survive desiccation. Biofilms derive several emergent properties — that is, properties that are not predictable from the study of free-living bacterial cells — from the EPS matrix. These properties include localized gradients that provide habitat diversity, resource capture by sorption, enzyme retention that provides digestive capabilities, social interactions and the ability, through tolerance and/or resistance, to survive exposure to antibiotics.

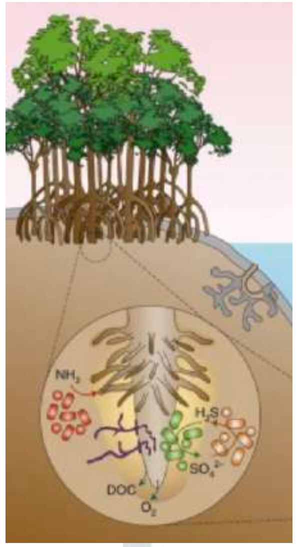
Flemming et al., 2016

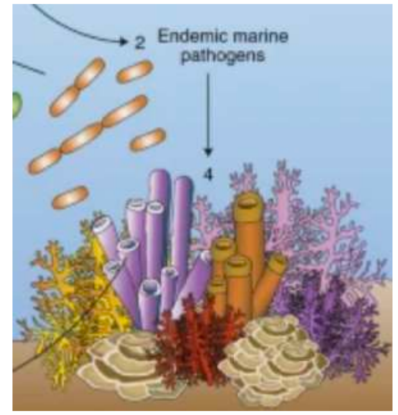
Microbial interactions in marine biofilms

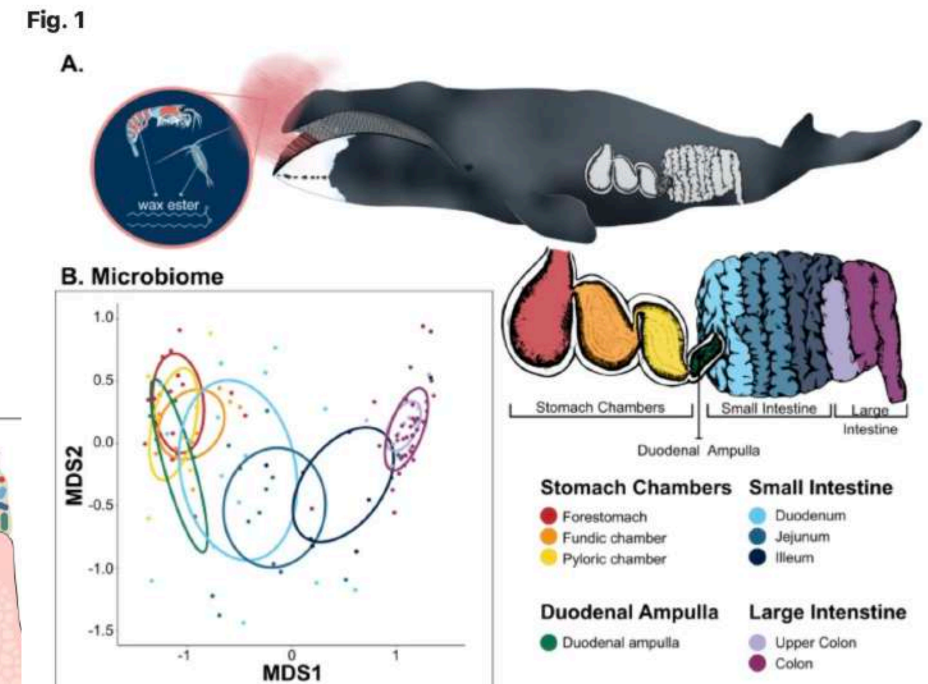


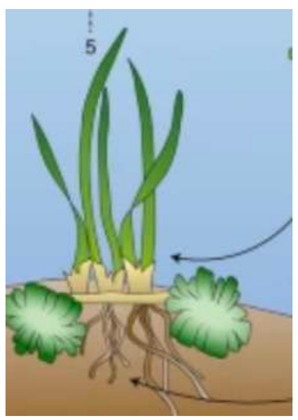
- Cooperation can help microorganisms gain advantages, for example, through compounds that promote collaboration, the uptake of nutrients and horizontal gene transfer.
- Competition is pervasive in multispecies biofilms owing to limited space and resources; it drives evolution and has an essential role in shaping the biofilm structure and physiological activities.
- Chemical communication (such as quorum sensing) and electrical communication (such as nanowires) regulate social behaviours in microbial communities

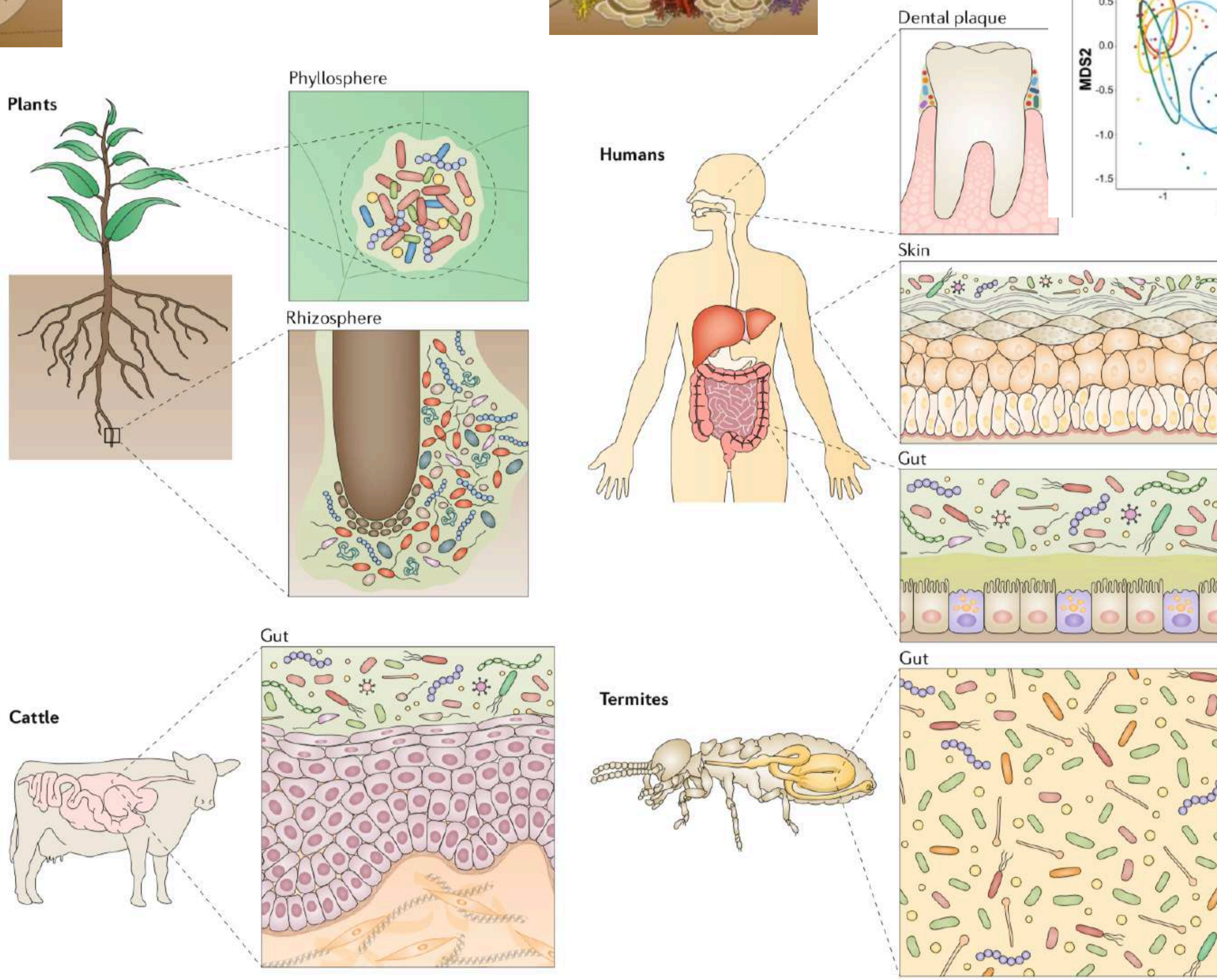
Microbial biofilms in Eukarya

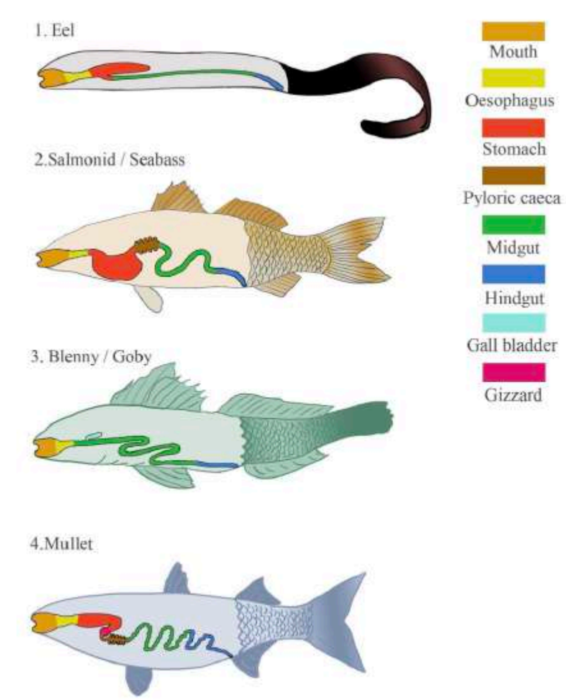












Trevathan-Tackett et al., 2019
Flemming & Wuertz, 2019
Miller et al., 2019
Egerton et al., 2018

What is the benefit for the host to have microbes?

….a closer look at the microbial metabolisms and associated genes

Chemosymbiotic microbes provide energy and nutrients to host

Recap: Key terms for chemosynthetic symbionts

Key term	Definition
Chemosynthetic symbiont	Umbrella term for all symbionts that obtain energy from the oxidation of reduced inorganic compounds or C_1 compounds. Electron donors: reduced inorganic compounds (e.g., hydrogen sulfide, hydrogen, carbon monoxide) or organic C_1 compounds (e.g., methane). Carbon sources: inorganic (carbon dioxide) or organic (e.g., methane, short-chain fatty acids) compounds.
Chemolithoautotroph	Chemosynthetic bacteria that obtain energy from the oxidation of inorganic compounds and use inorganic carbon to generate biomass. Electron donors: reduced inorganic sulfur compounds, hydrogen, carbon monoxide. Carbon source: inorganic (carbon dioxide).
Chemoorganoheterotroph	Chemosynthetic bacteria that obtain energy from the oxidation of organic compounds and use organic carbon to assimilate biomass. Electron donors: C_1 organic compounds (e.g., methane). Carbon sources: organic compounds (e.g., methane).
Chemolithoheterotroph	Chemosynthetic bacteria that obtain energy from the oxidation of inorganic compounds and use organic carbon to generate biomass. Electron donors: reduced inorganic compounds (e.g., H_2S). Carbon sources: organic compounds (e.g., short-chain fatty acids).
Mixotroph	Chemosynthetic bacteria that use both inorganic and organic carbon sources to build biomass.

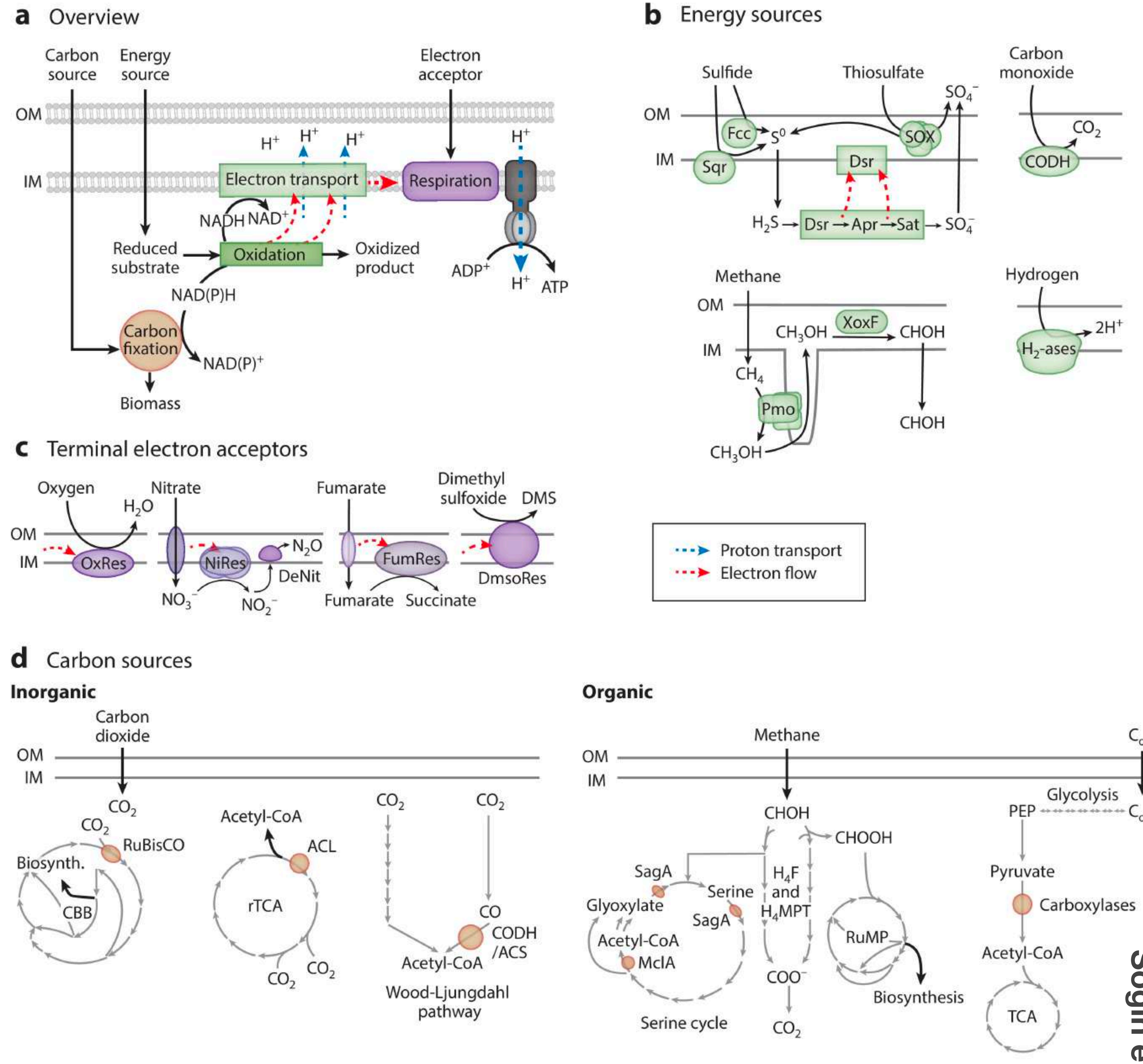
Sogin et al., 2021

Chemosynthesis metabolic structure

1.**Oxidation of reduced inorganic substrates** or **methane** to generate energy and reducing power (equivalents)

2. This energy powers **carbon fixation or assimilation**.

While there are **many ways** chemosynthetic symbionts can perform chemosynthesis, *the core central pathways for gaining energy from sulfide and methane, and for fixing carbon dioxide, are **conserved** across most symbionts*

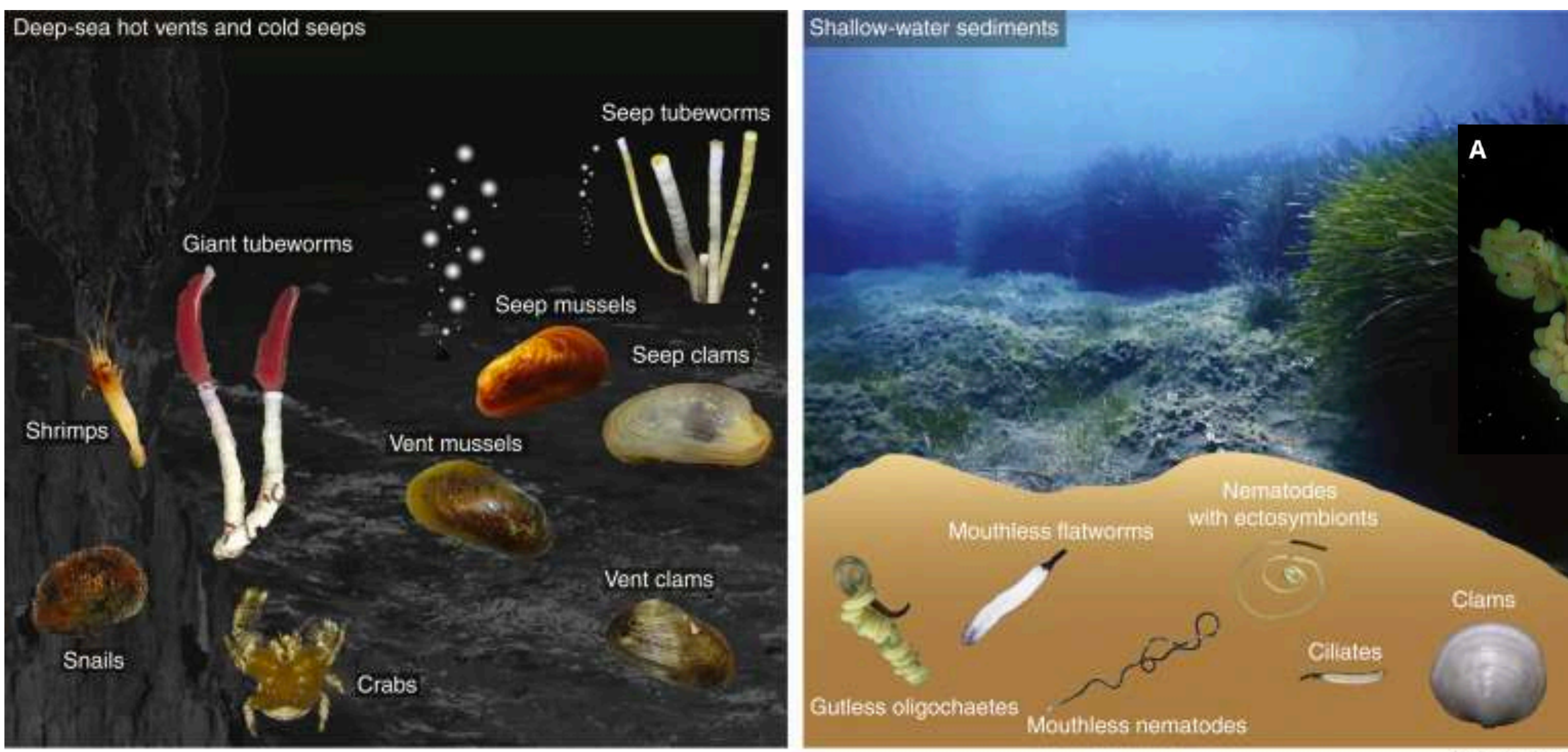


Sogin EM, et al. 2021
Annu. Rev. Microbiol. 75:695–718

Sogin et al., 2021

Marine Microbial Chemosynthetic Symbiosis, I

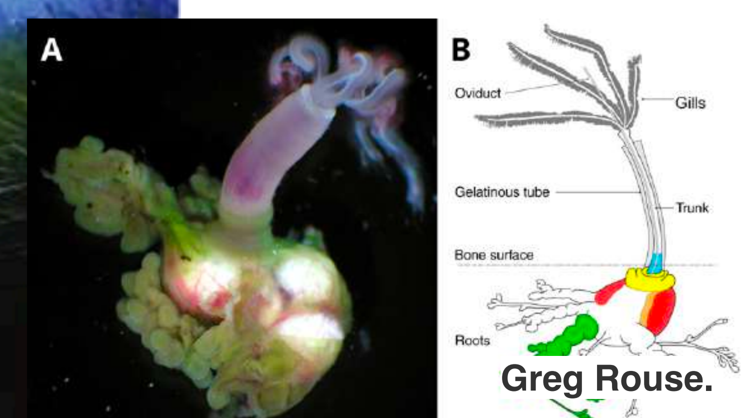
- The Russian microbiologist **Sergei Winogradsky** realized that some bacteria fix CO_2 in the absence of light through a process later coined **chemosynthesis**
- Instead of using light as an energy source, chemosynthetic microorganisms **use chemical energy released during the oxidation of reduced compounds** such as sulfide **to produce biomass**
- **Photosynthesis** and **chemosynthesis** are the only known forms of primary production on our planet



Current Biology

Login et al., 2020

Whale fall

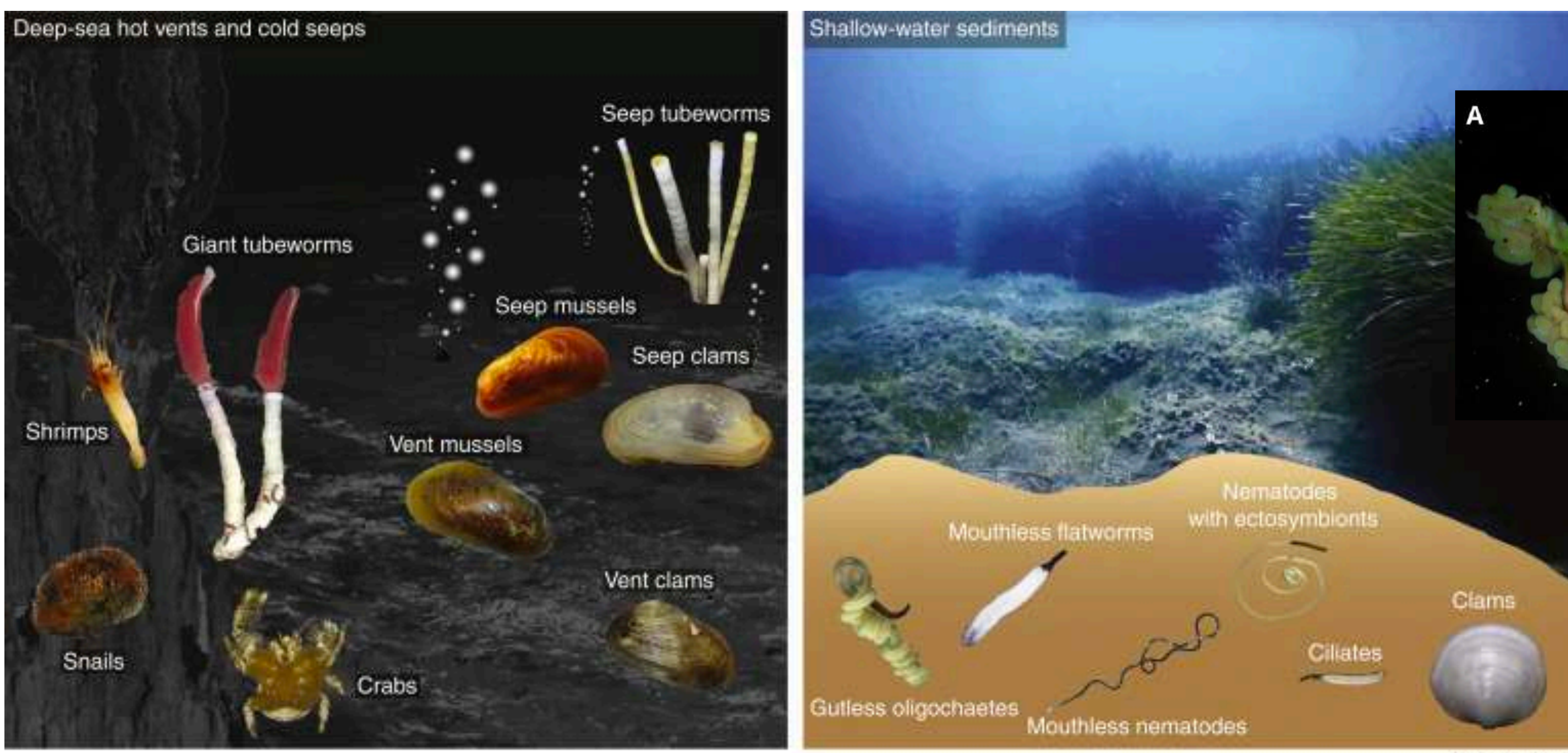


Greg Rouse.

Marine Microbial Chemosynthetic Symbiosis, II

- Chemosymbioses **evolved independently and multiple times** in many different types of eukaryotes through convergent evolution
- **The symbionts gain energy by oxidizing reduced chemical compounds,** such as sulfide or methane**, to fix CO_2 and other small carbon compounds into biomass, to provide themselves and their hosts with nutrition**
- The hosts, marine protists and invertebrates, typically occur in *habitats that lack enough organic matter to support a heterotrophic lifestyle*

Login et al., 2020



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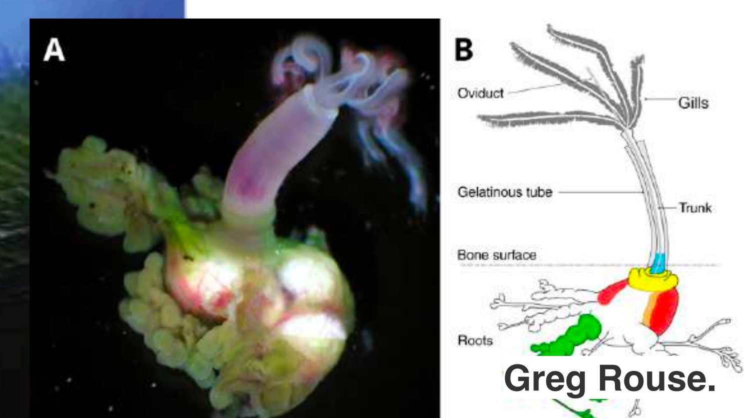
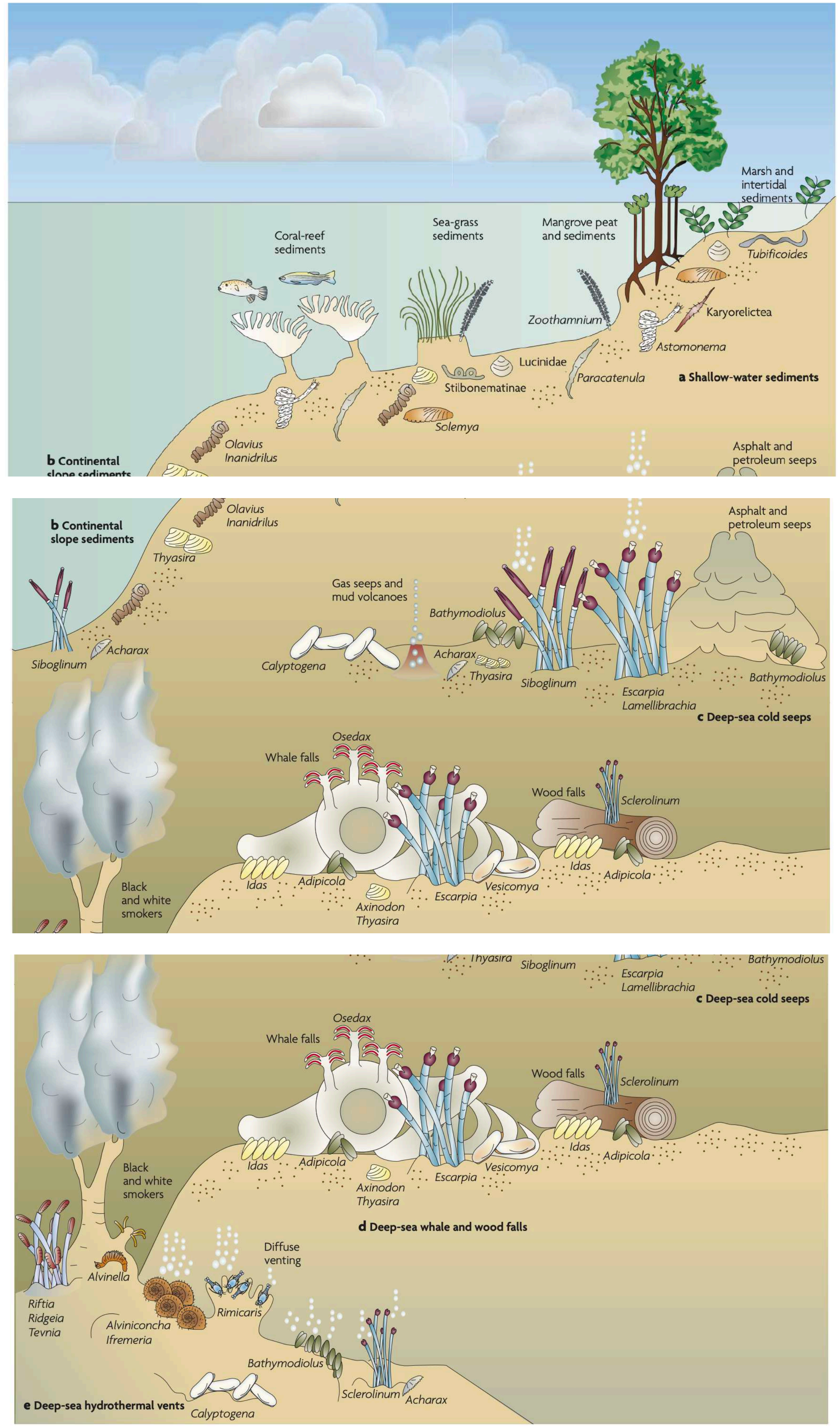


Greg Rouse.

Chemosynthetic symbioses in different marine habitats

Dubilier et al., 2008



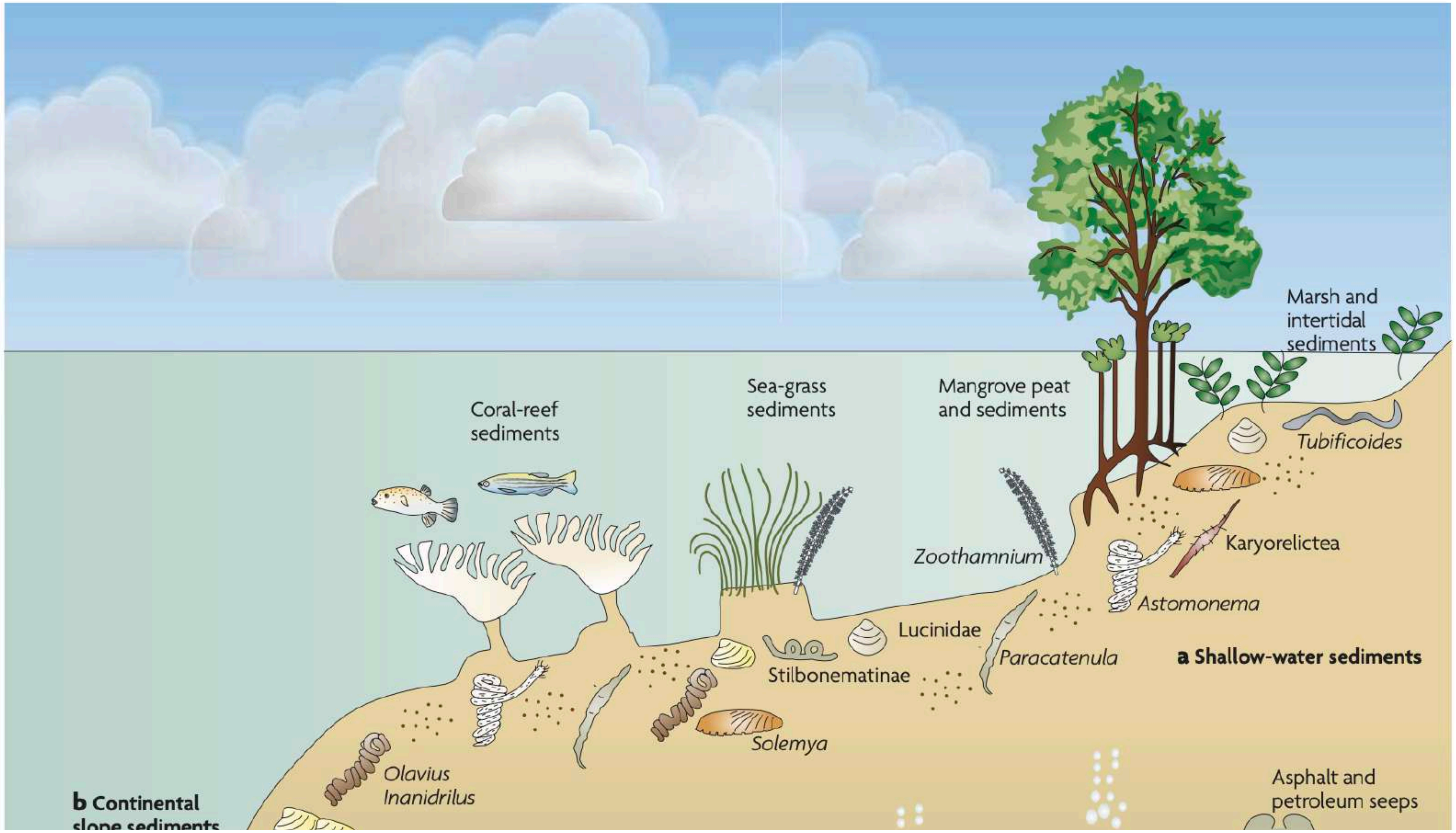
Chemosynthetic symbioses occur in a wide range of marine habitats, including shallow-water sediments (a), continental slope sediments (b), cold seeps (c), whale and wood falls (d), and hydrothermal vents (e).

Some host groups are found in **only one habitat** (such as Osedax on whale bones), whereas others occur in **several different environments** (such as thyasirid clams, which are found in shallow-water sea-grass sediments and in the deep sea at cold seeps, whale falls and hydrothermal vents).

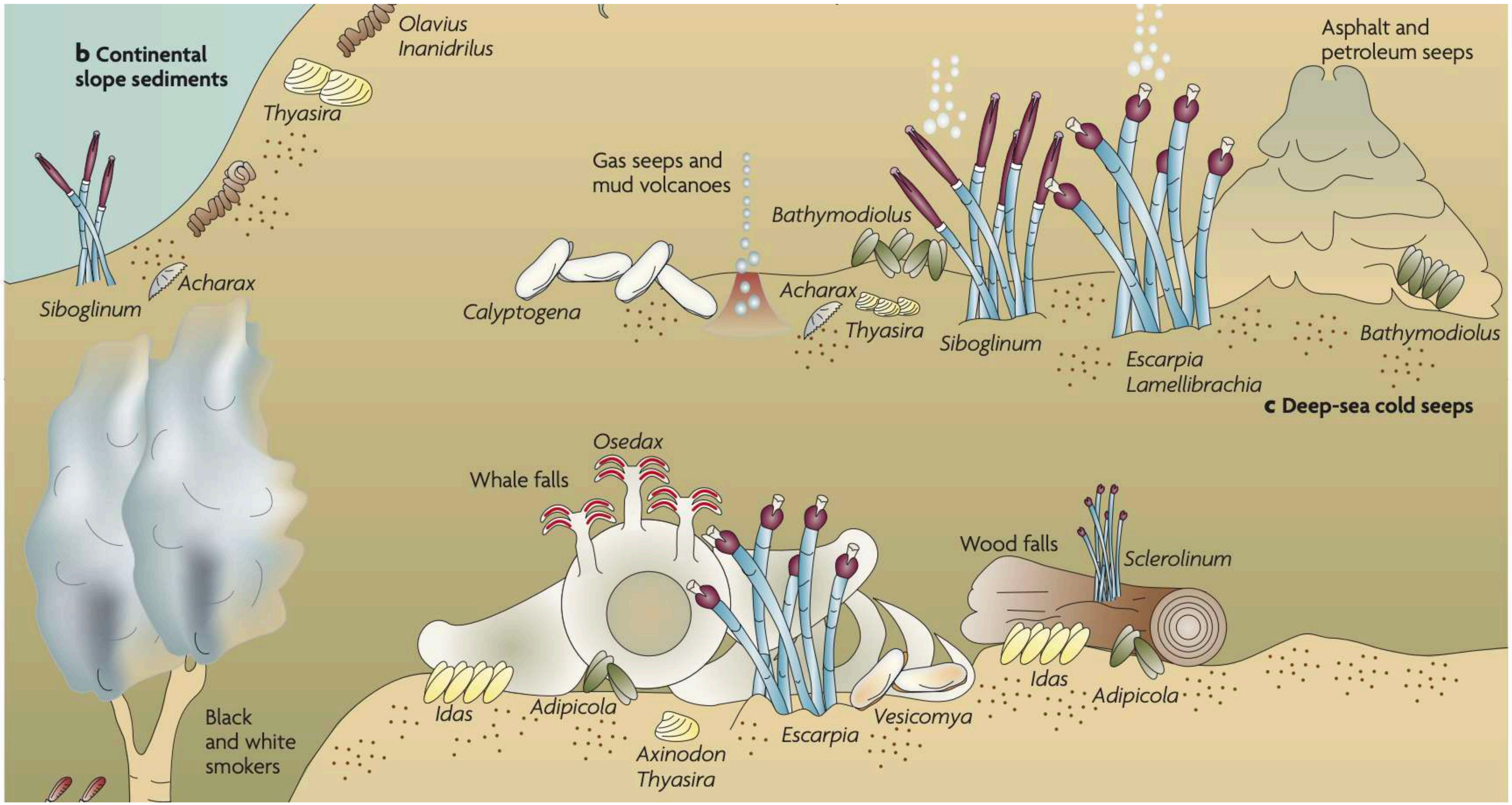
The animals are not drawn to scale; for example, Idas and Adipicola mussels are much smaller than Bathymodiolus mussels

Chemosynthetic symbioses in different marine habitats

Dubilier et al., 2008



Chemosynthetic symbioses



Dubilier et al., 2008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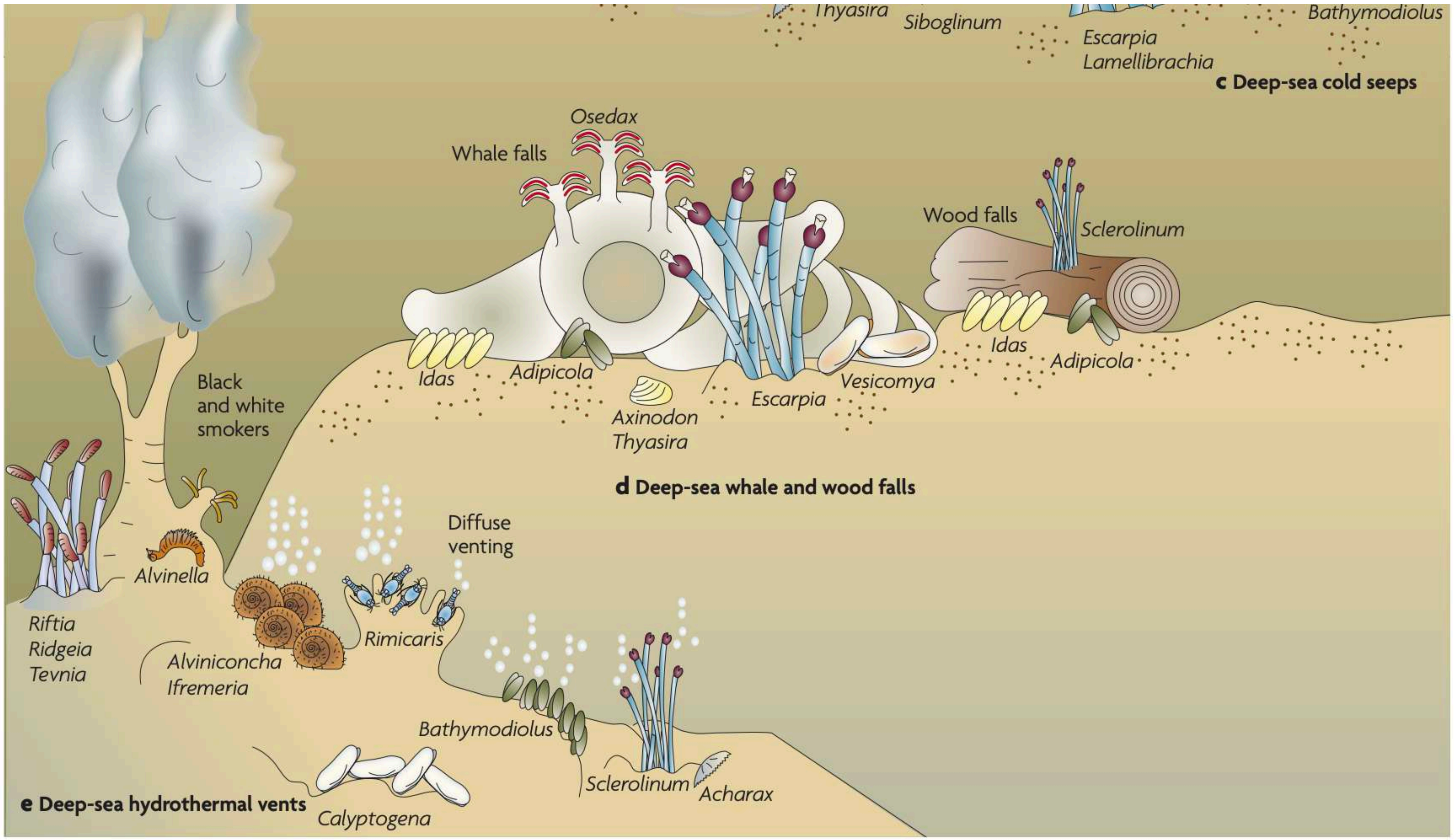
Chemosynthetic symbioses

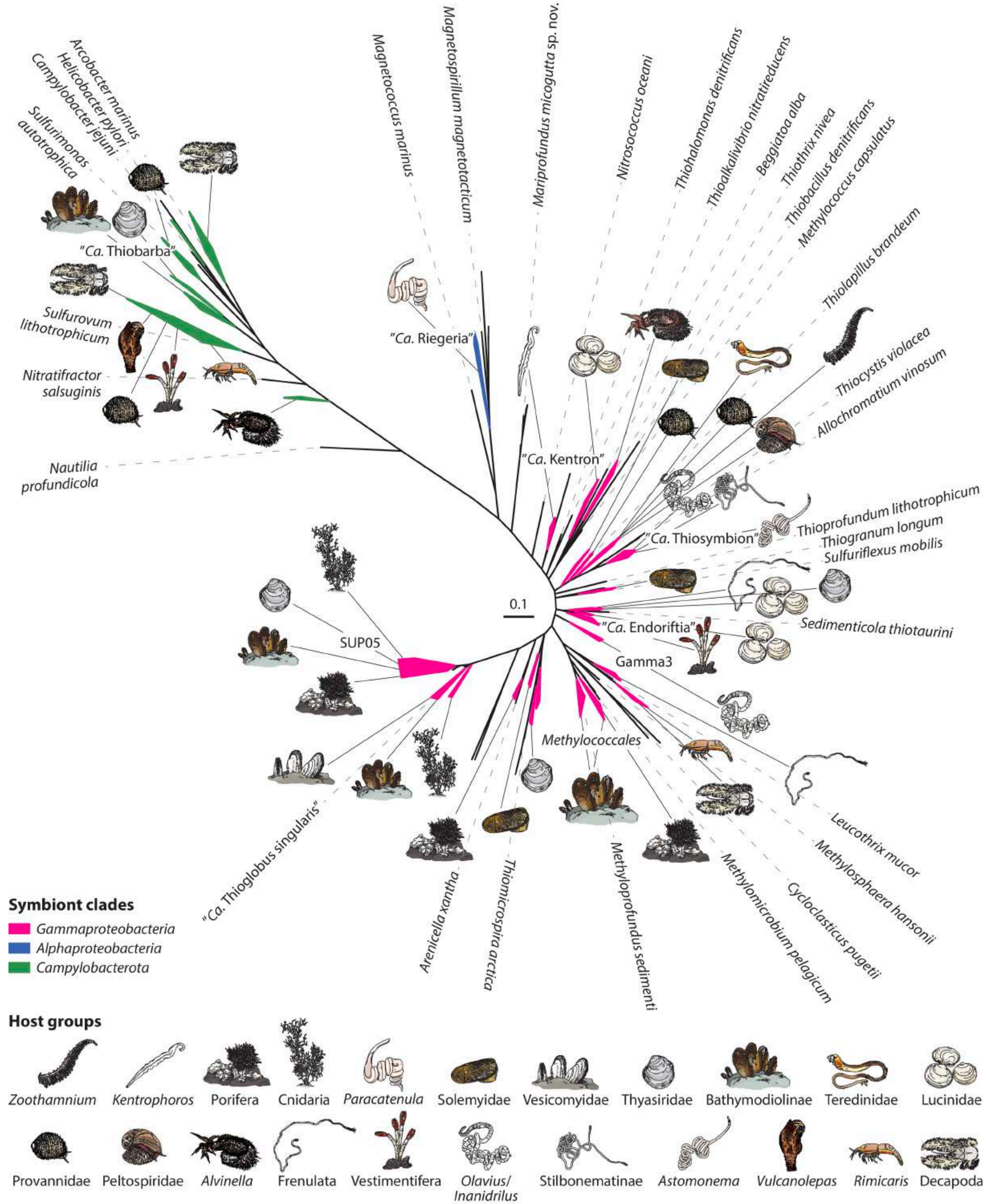


Dubilier et al., 2008

https://www.pbs.org/video/how-giant-tube-worms-survive-at-hydrothermal-vents-cpms1j/

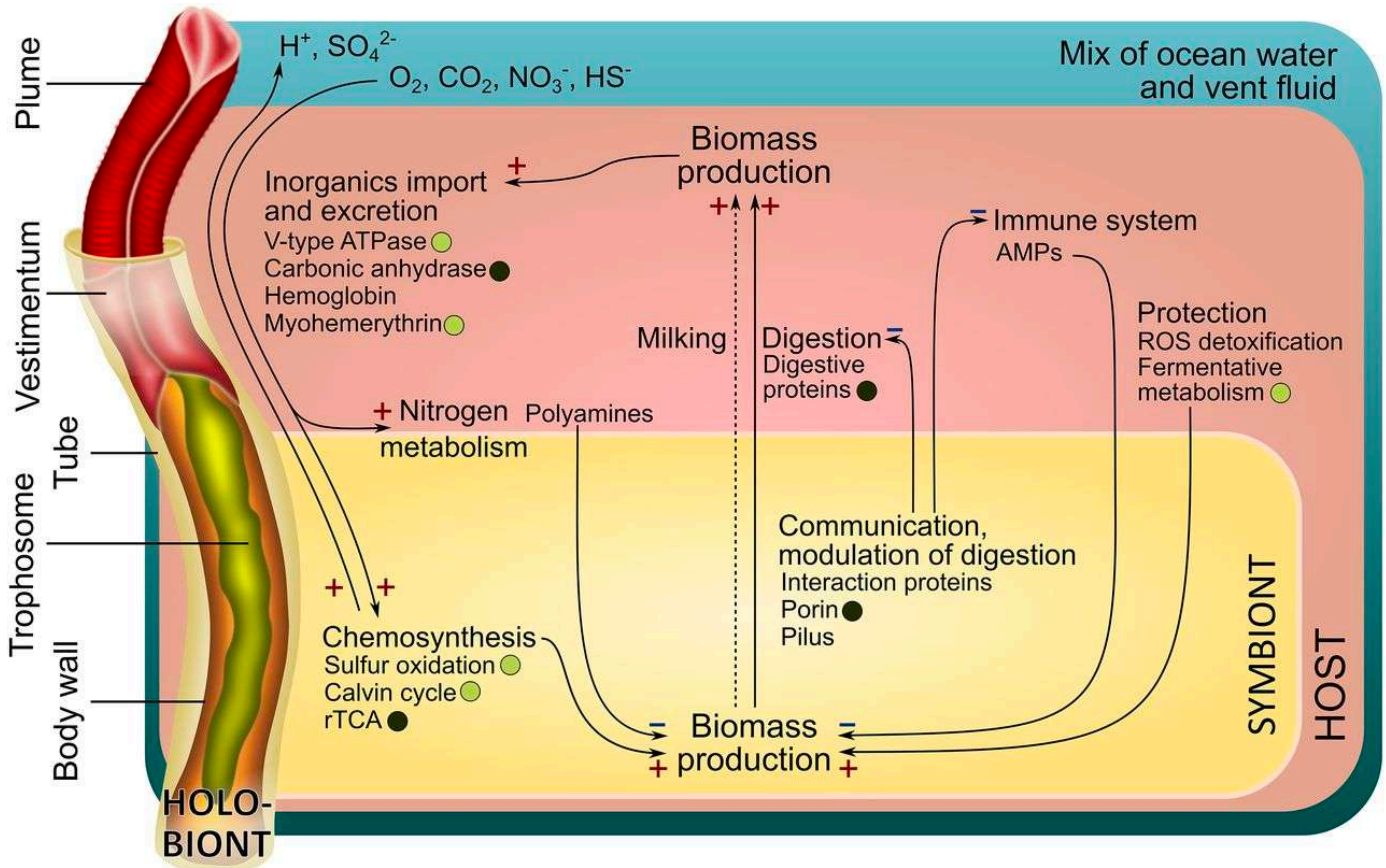
Phylogenetic diversity of chemosymbionts

Sogin et al., 2021



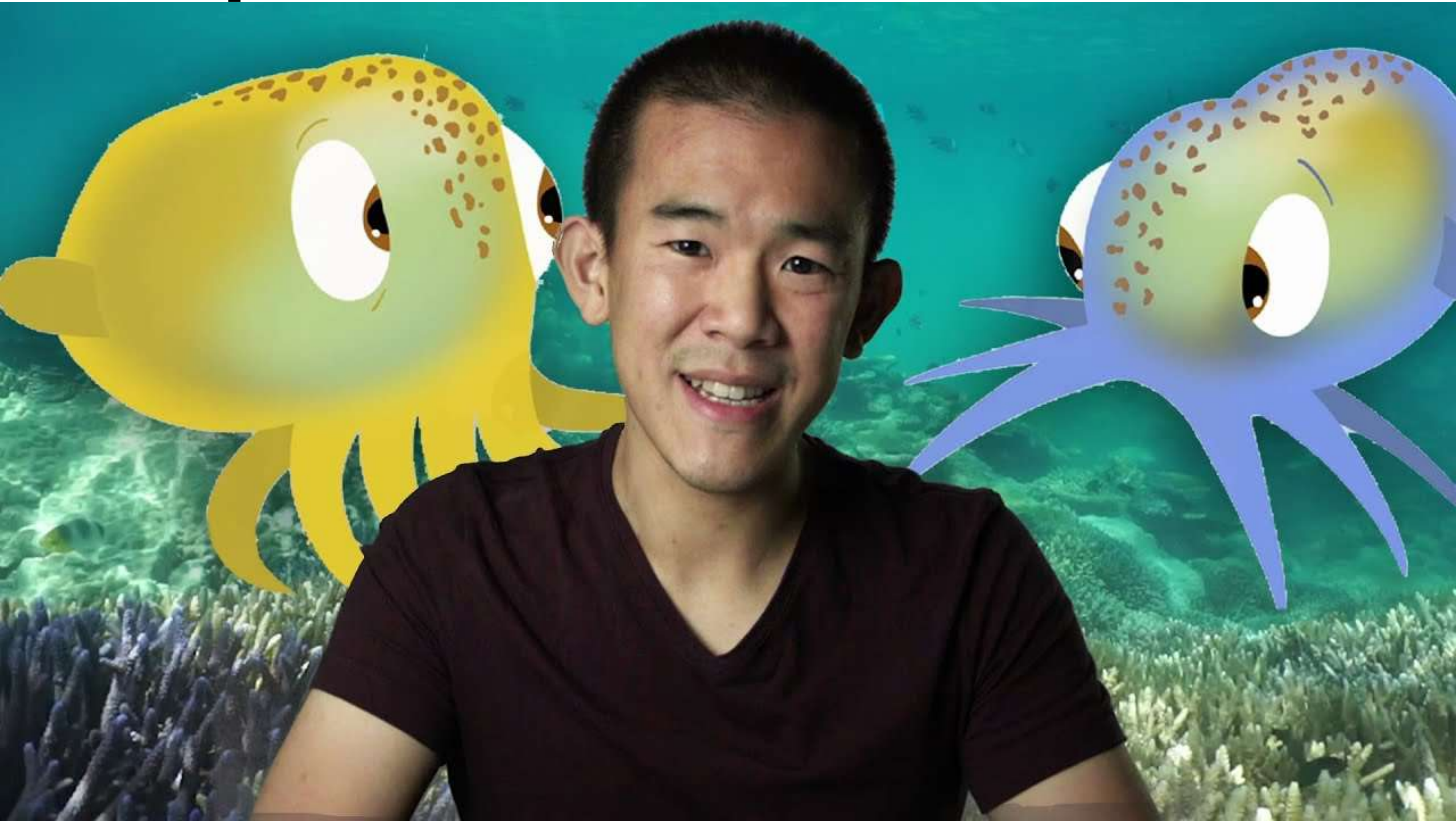
Sogin EM, et al. 2021
Annu. Rev. Microbiol. 75:695–718

Host-Microbe Interactions in the Chemosynthetic *Riftia pachyptila* Symbiosis



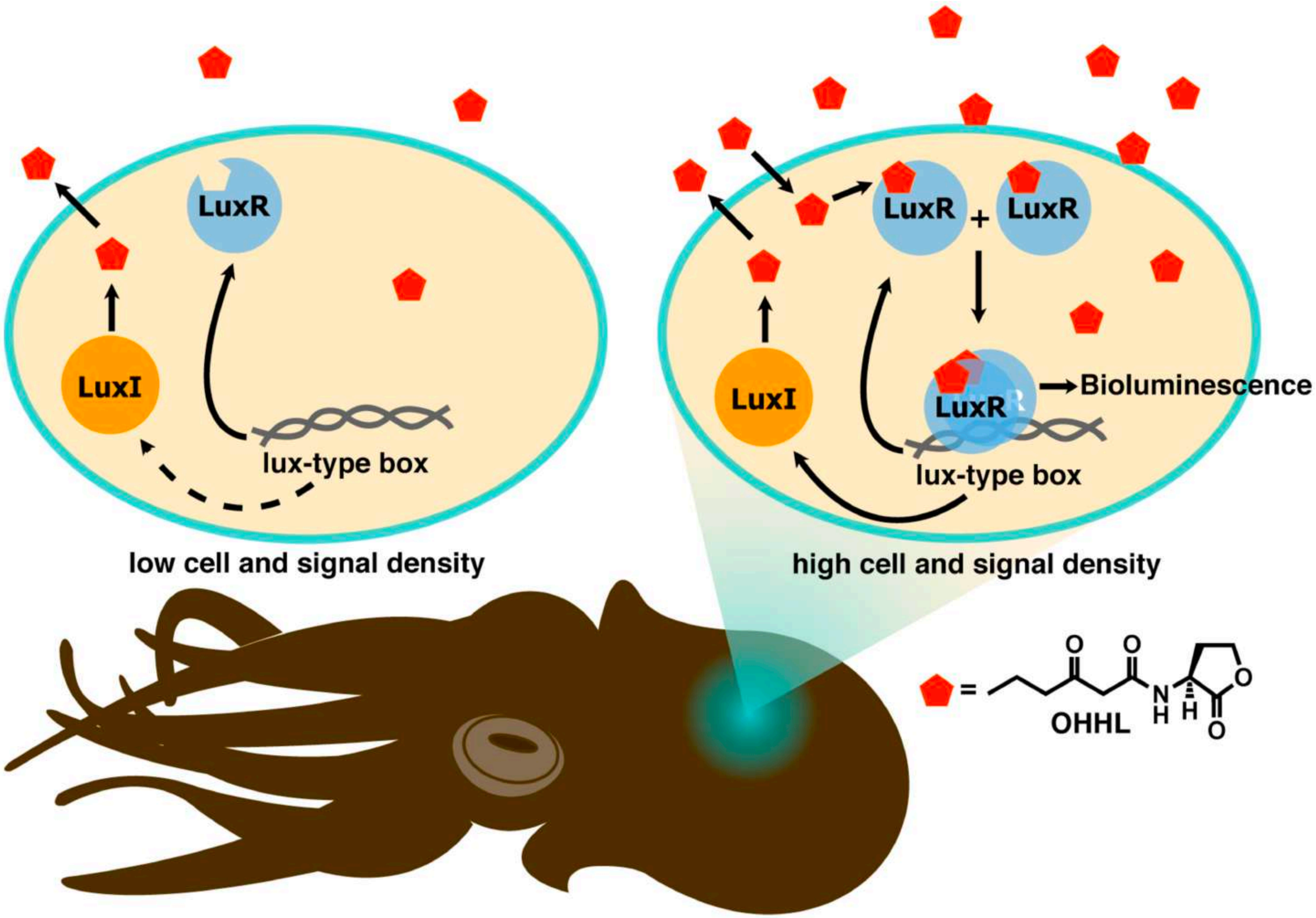
Hinzie et al., 2019

Microbial communication shapes behaviour in host



Relationship between *Vibrio fischeri* and the Hawaiian bobtail squid (*Euprymna scolopes*) and light production (=microbial communication)

Mattman & Blackwell, 2010



Bacteria mediated (Quorum sensing based communication) light production in deep sea fish for mating and hunting

Photosynthetic microbes in marine symbioses

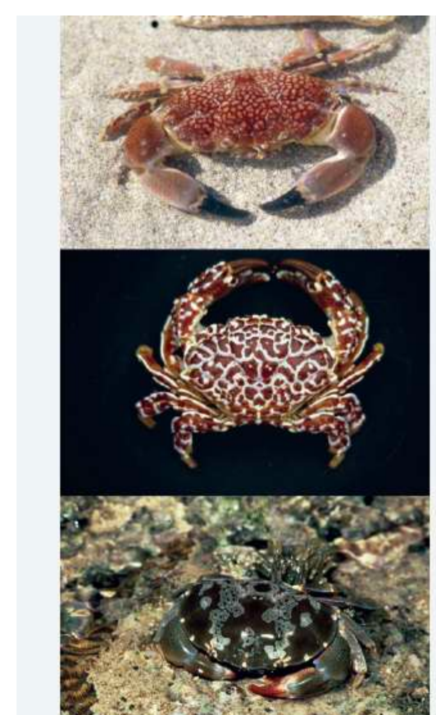
- Tunicata, Ascidians: oxygenic and anoxygenic photosynthetic bacteria
- Tridacna gigas hosts Zooxanthellaes
- Cnidaria, corals: Zooxanthellaes

Google engine

Microbial protection in marine symbioses

- Bryozoans, moss looking colonial animals
  - Bacterial endosymbiont, Candidatus Endobugula sertula produces polykeyides, bryostatins for protection of larvae due to lack of palatability
- Puffer fish and xhantid crabs have endocellular symbiotic bacteria have been proposed as a possible source of eukaryotic TTX, tetrodotoxin (Na+ channel blocker)

Lovell and Libby Langstroth © California Academy of Sciences



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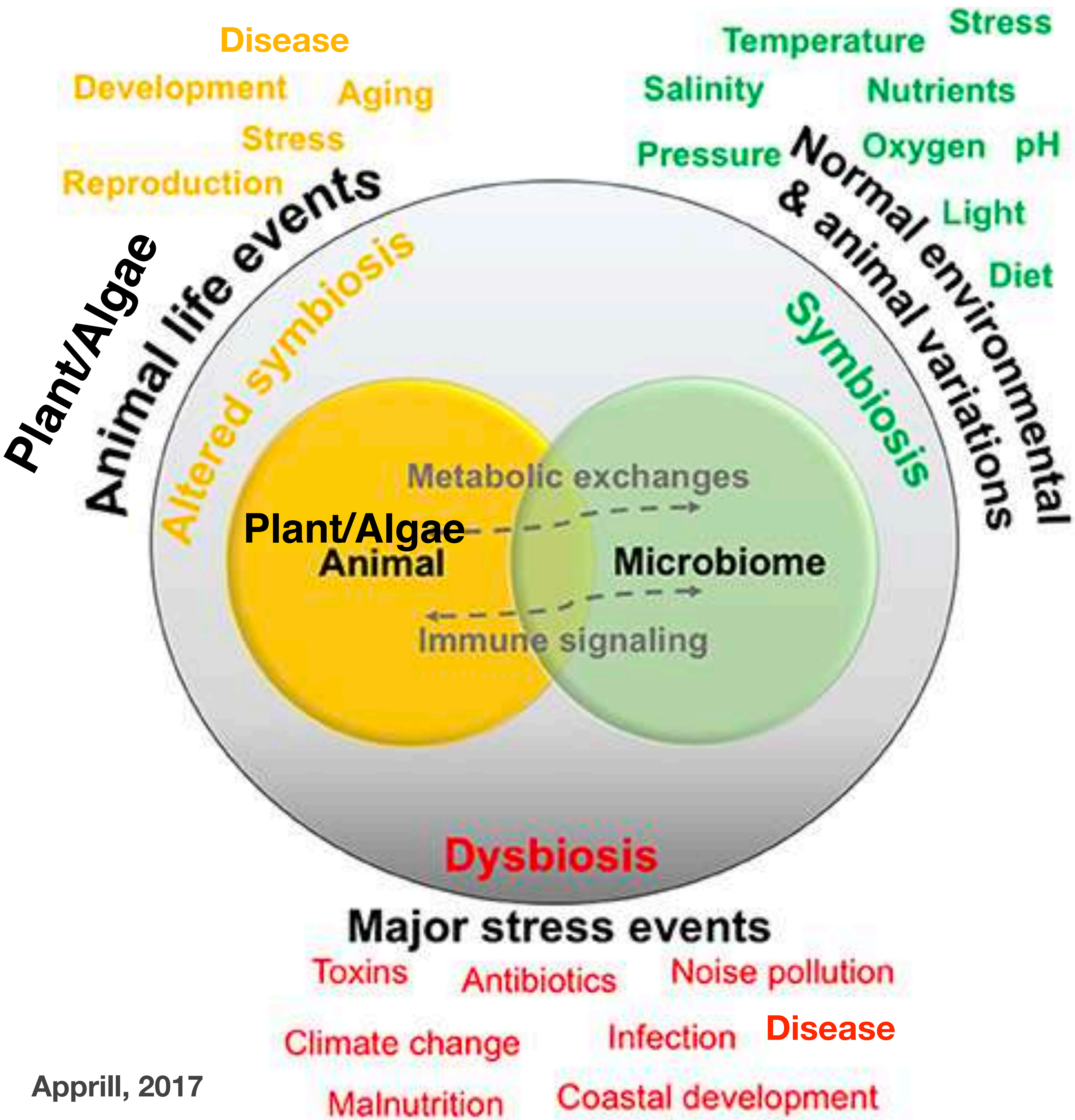
Marine Microbial Diseases

Health and Disease



Apprill, 2017

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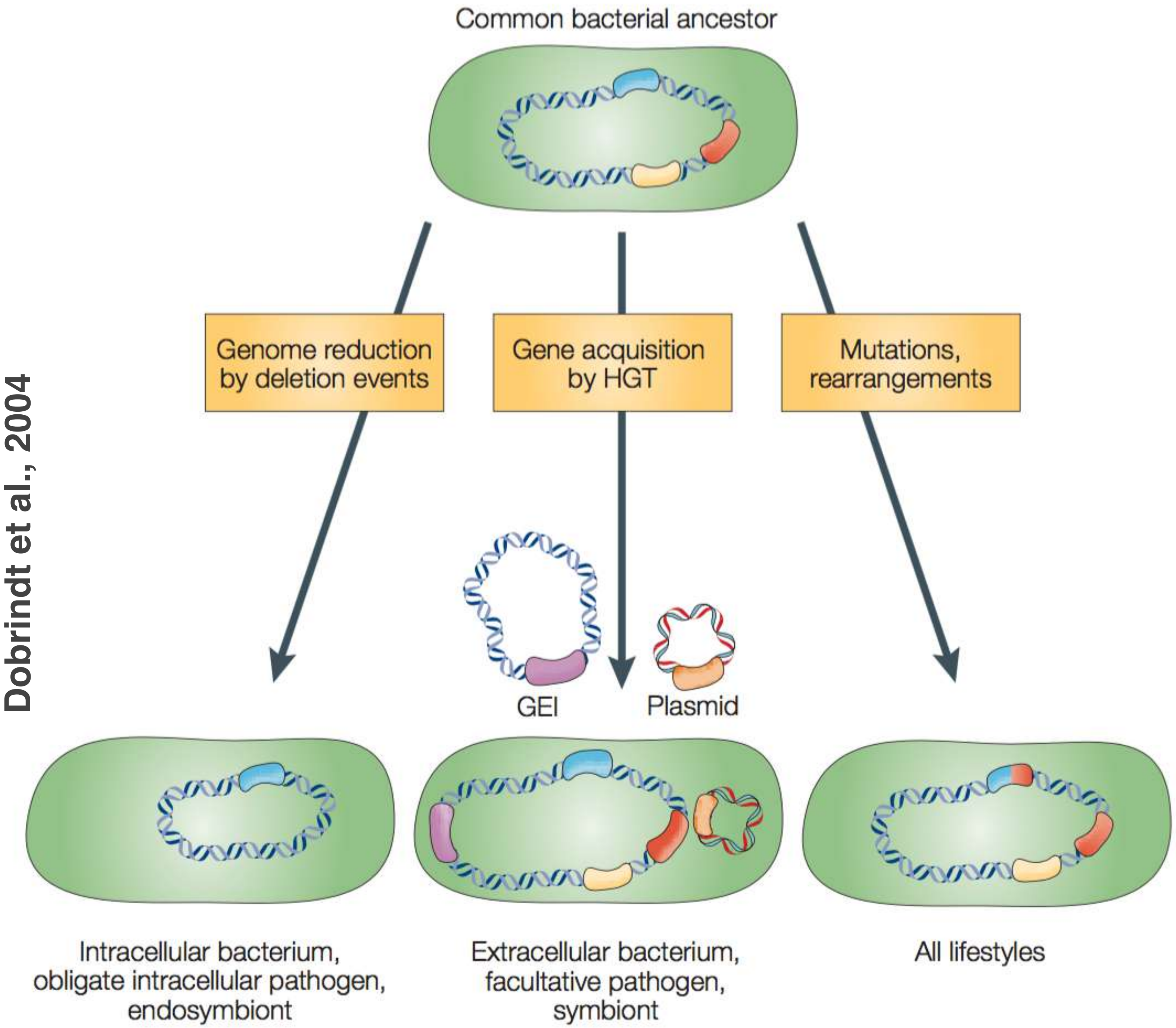
Microbial evolution by acquisition and loss of genetic information



Dobrindt et al., 2004

Genome structure reflects bacterial lifestyle

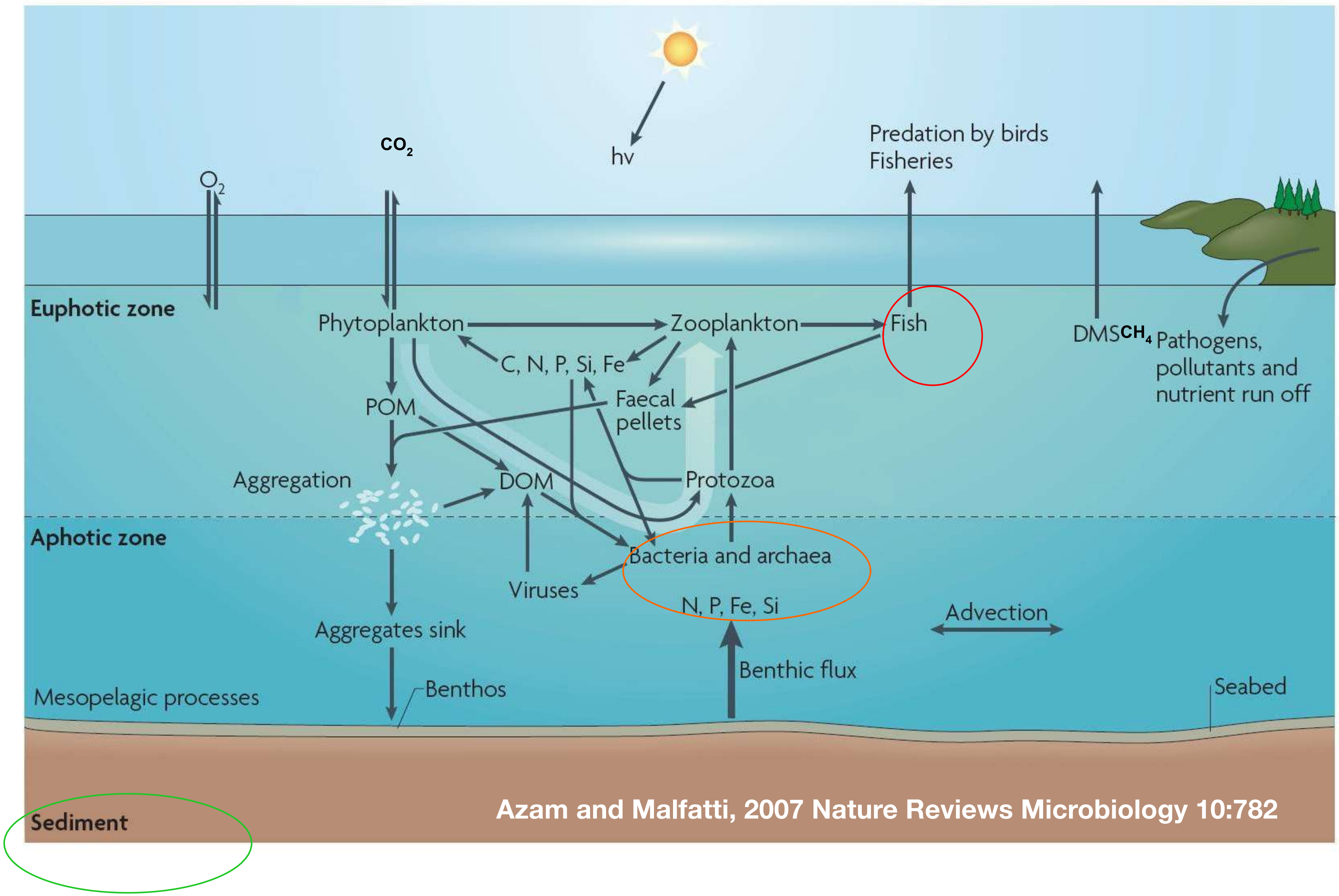
Genome reduction: common in **intracellular bacteria** (obligate intracellular pathogens, endosymbionts) **strictly host-dependent bacterial variants** — relying on the host cell to compensate for the gene functions that are lost

Gene acquisition by horizontal transfer between different species is common in **extracellular bacteria** (facultative pathogens, symbionts), which involves mobile genetic elements, such as **plasmids**, **genomic islands (GEIs)** and bacteriophages (not shown), increases the versatility and adaptability of the recipient —allows bacteria to adapt to a new or changing environment

Point mutations and genetic rearrangements constantly contribute to evolution of new gene variants in **all types** of bacteria

HGT, horizontal gene transfer

Marine biogeochemical C cycle is coupled with N, S, Fe, P, Si, Metal cycles



Azam and Malfatti, 2007 Nature Reviews Microbiology 10:782

MICROBES AND DISEASE I

A few harmful microbes, for example **less than 1% of bacteria, can invade humans** and other (the host) organisms and cause illness

In **humans**, there is also strong evidence that **microbes** may **contribute** to many **non–infectious chronic diseases** such as some forms of cancer and coronary heart disease

Different **diseases** are caused by different types of micro-organisms and by **non-trasmittible chemicals (such as toxin)**

Microbes that cause disease are called pathogens

In marine systems, there are polymicrobial diseases and it is difficult to define a single causative agent but probably alteration of the microbiota living within the host play a major role in the development of disease

In marine systems, it is difficult to validate the Koch's Postulates

MICROBES AND DISEASE II

It is important to remember that:

- A pathogen is a micro-organism that has the potential to cause disease
- An infection is the invasion and multiplication of pathogenic microbes in an individual or population
- Disease is when the infection causes damage to the individual's vital functions or systems
- An infection does not always result in disease!
- According to the relationship: microbes-host, host-environment, and microbes-environment some microbe can become occasional pathogen

MICROBES AND DISEASE III

To cause an infection, microbes must enter in the host body

The site at which they enter is known as the portal of entry

According to the structure of the organisms, microbes can enter the body through the four sites listed below (if a superior animal):

- Respiratory tract, gills or nose/mouth
- Gastrointestinal tract, mouth oral cavity and Food Vacuoles
- Urogenital tract
- Breaks in the skin surface/ Exoskeleton

MICROBES AND DISEASE IV

To make humans/organisms ill microbes have to:

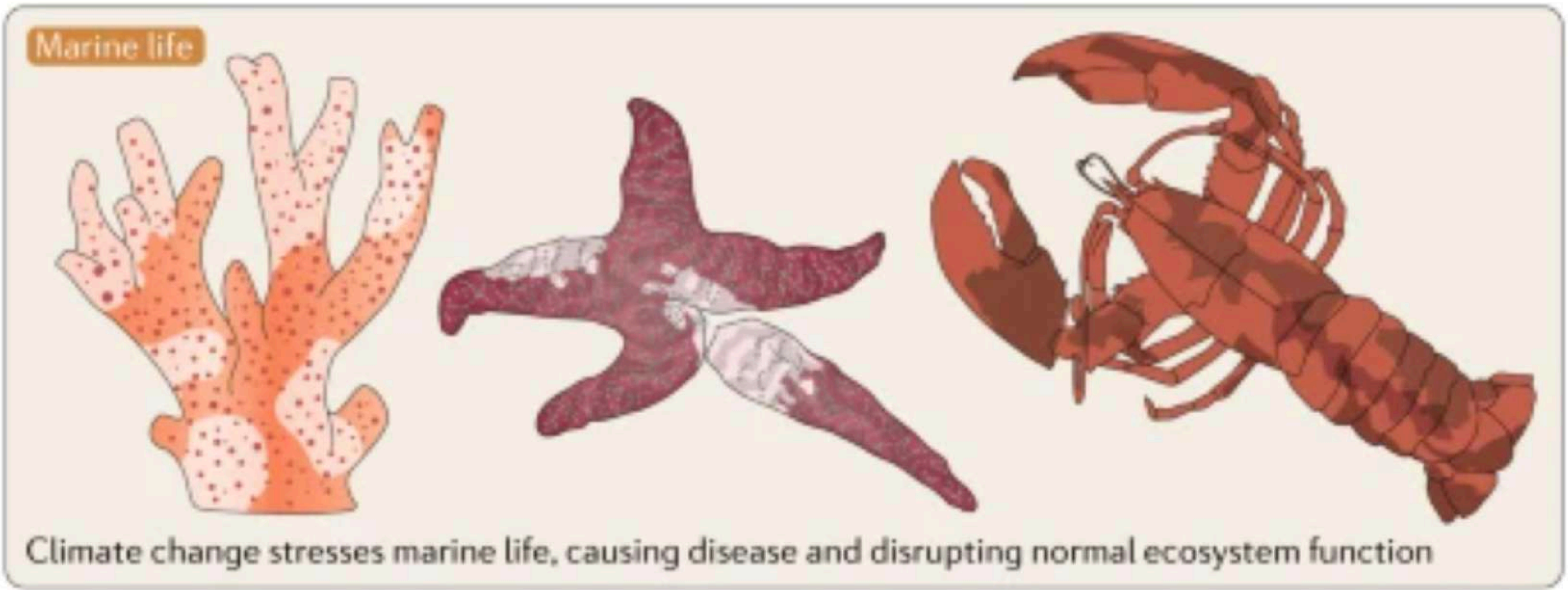
- Reach their target site in the body
- Attach to the target site they are trying to infect so that they are not dislodged
- Multiply rapidly, out competing the microbial symbiotic communities
- Obtain their nutrients from the host
- Avoid, escape and survive attack by the host’s immune system

Human Activities & DISEASE

Environmental Threats:

- Overfishing, breaking no-take zone
- Noise pollution
- Pollution (inorganic chemical, sewage and organic chemical)
- Physical damage from boats, diving activities
- Ocean acidification
- Ocean temperature increase
- Invasive species
- Marine urbanisation and habitat destruction
- Poor water quality (transparency, nutrient and organic matter loads)
- Aquaculture and Mariculture

Anthropogenic climate change stresses native life, thereby enabling pathogens to increasingly cause disease



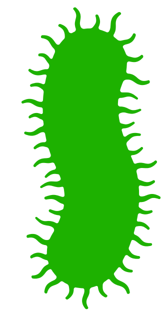
Cavicchioli et al., 2019

Health ⟷ Disease

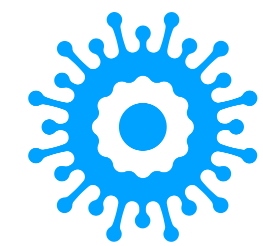
Disease

- Corals
- Sponges
- Echinoderms - Molluscs - Crustaceans
- Fishes
- Birds & Reptiles
- Seagrasses & Seaweeds
- Marine Mammals
- Humans

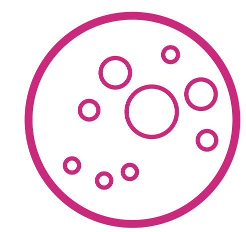
- Bacteria



- Viruses

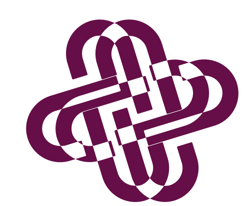


- Protists



- Fungi

- Toxins, produced by marine organisms



MARINE TOXINS

Ciminiello et al., 2013

TOXINS I

Table 1. Marine toxin groups and their responsible algae.

	Toxin group	Syndrome	Genus	Species	Reference
Hydrophilic toxins	Domoic acid	ASP	Pseudo-nitzschia	australis, calliantha, cuspidata, delicatissima, fraudulenta, galaxiae, multiseries, multistriata, pseudodelicatissima, pungens, seriata, turgidula	[25]
	Saxitoxins	PSP	Alexandrium	angustitabulatum, catenella, fundyense, lusitanicum, minutum, tamarense, tamiyavanichii	[26–28]
			Gymnodinium	catenatum	[26]
			Pyrodinium	bahamense	[26]
Lipophilic toxins	Brevetoxins	NSP	Karenia	brevis, brevisulcata, mikimotoi, selliformis, papilionacea	[8,29] [30]
			Chatonella	cf. verruculosa	[30]
	Okadaic acid and dinophysistoxins and pectenotoxins [1]	DSP	Phalacroma	rotundatum	[31]
			Prorocentrum	arenarium, belizeanum, concavem, lima	[32]
			Dinophysis	acuminata, acuta, arenarium, caudate, fortii, mitra, norvegica, ovum, rotundata, sacculus, tripos	[33–38]
	Yessotoxins		Protoceratium	reticulatum	[29,39]
			Lingulodinium	polyedrum	[29]
			Gonyaulax	polyhedra	[29]
	Azaspiracids	AZP	Azadinium	spinosum	[40]
	Spirolides	–	Alexandrium	ostenfeldii, peruvianum	[41,42]
	Gymnodimines	–	Karenia	selliforme	[43]
			Gymnodium	mikimotoi	[44]

- Dinoflagellates and Diatoms are main producers of toxins
- Phycotoxins are non-proteinaceous substance, heat-tolerant
- Microbes influence toxin production
- Microbes can kill micro algae thus causing the release of the toxin in the surrounding water
- Microbes can degrade toxins
- Cyanobacteria produce toxins
- Fat-soluble toxins become concentrated by biomagnification = passing up food web

Ciminiello et al., 2013

Action mechanism of marine toxins

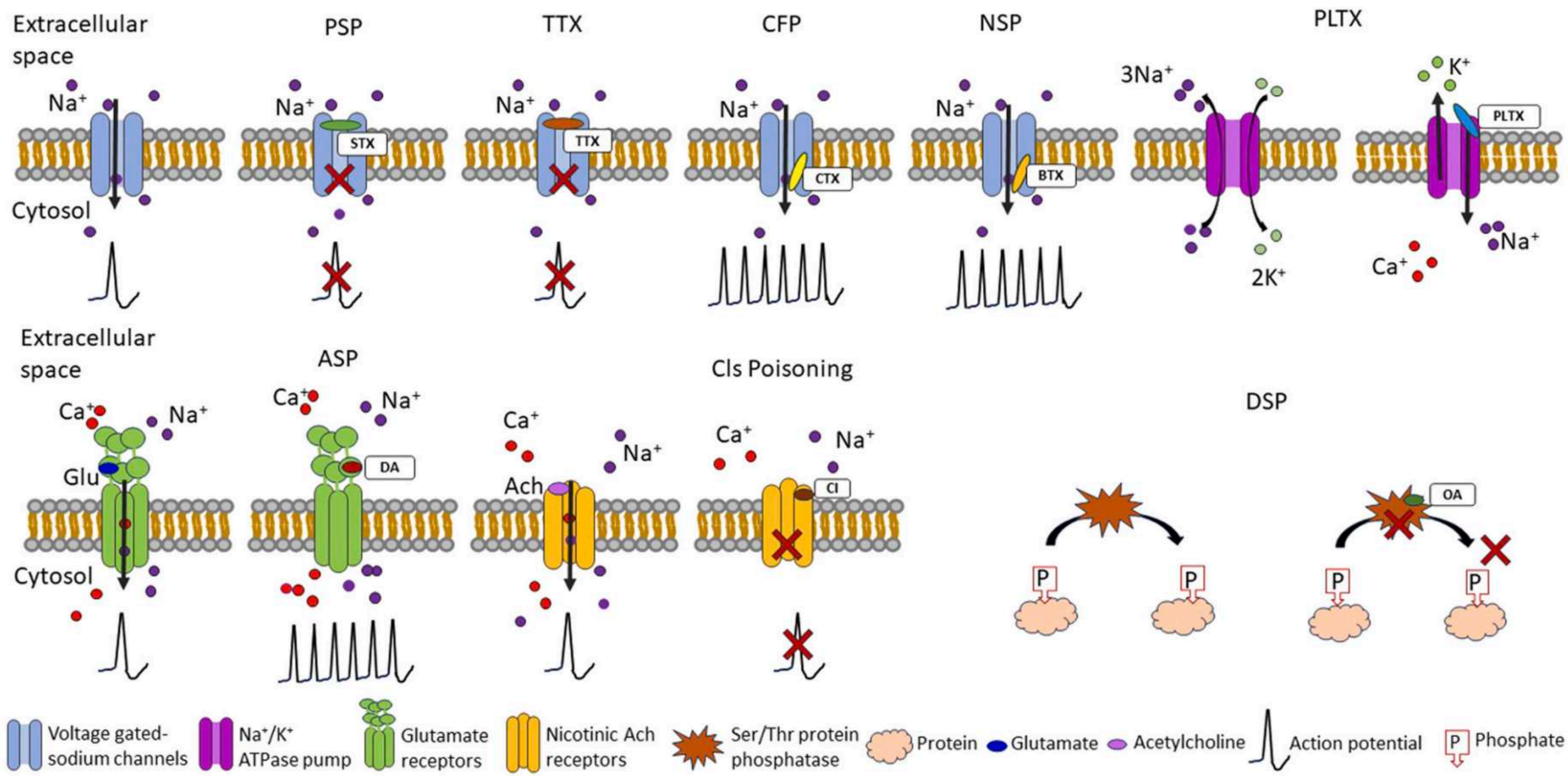
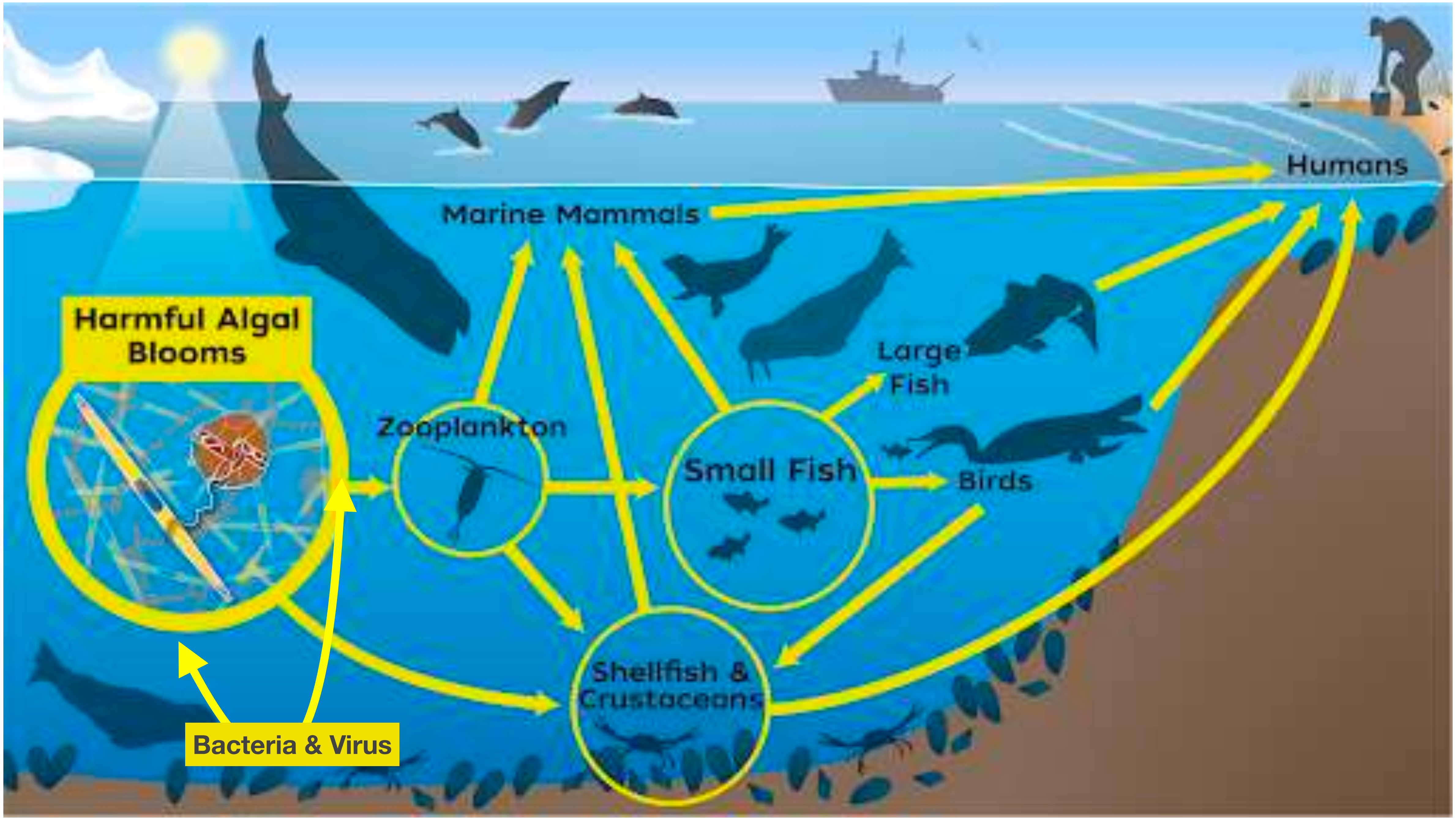


Fig. 1. Action mechanism of marine toxins. Modified from Louzao et al. (2022).

Bian et al., 2024

Toxic food web



https://coastalscience.noaa.gov/news/harmful-algal-blooms-may-soon-wreak-havoc-in-arctic-alaska/

TOXINS II

- Most toxins block Na^+ voltage-gated channel of nerve cells
- Low concentration
- Almost immediate symptoms

	Disease or Condition					
	Ciguatera fish poisoning (CFP)	**Neurotoxic shellfish poisoning (NSP)**	**Paralytic shellfish poisoning (PSP)**	**Domoic acid poisoning and amnesiac shellfish poisoning (ASP)**	**Diarrheic shellfish poisoning (DSP)**	**Azaspiracid shellfish poisoning (AZP)**
Toxin-producing organism	Dinoflagellates: *Gambierdiscus toxicus*, possibly others	Dinoflagellates: *Karenia brevis* and other *Karenia* species	Dinoflagellates: *Gymonodinium catenatum*, *Pyrodinium bahamense*, *Alexandrium* species	Diatoms: *Pseudo-nitzchia* species	Dinoflagellates: *Dinophysis* species, *Prorocentrum lima*	Dinoflagellates: *Proroperidiunium* species
Toxin(s)	Ciguatoxins, Maitotoxin, Scaritoxin	Brevetoxins	Saxitoxins	Domoic acid	Okadaic acid	Azaspiracid
Foods likely to be contaminated	Reef fish such as barracuda, grouper, red snapper, and amberjack	Shellfish, primarily mussels, oysters, scallops	Shellfish, primarily scallops, mussels, clams, oysters, and cockles, Some fish and crabs	Shellfish, primarily scallops, mussels, clams, oysters, Possibly some fish species	Shellfish, primarily scallops, mussels, clams, oysters	Shellfish
Short-term symptoms	Nausea, Vomiting, Diarrhea, Stomach pain	Nausea, Vomiting, Diarrhea, Stomach pain, Numbness of lips, tongue, and throat, Dizziness	Nausea, Vomiting, Diarrhea, Shortness of breath, Irregular heartbeat, Numbness of mouth and lips, Weakness	Nausea, Vomiting, Diarrhea, Stomach pain, Shortness of breath, Irregular heartbeat, Abnormal hot and cold sensations, Memory loss, Disorientation, Seizures, Possibly coma	Nausea, Vomiting, Diarrhea, Stomach pain, Possibly chills, Headache, Fever	Nausea, Vomiting, Diarrhea, Stomach pain
Long-term symptoms	Abnormal hot and cold sensations, Pain, Weakness, Low blood pressure	Unknown	Unknown	Possibly amnesia	Unknown	Unknown
Treatment	Supportive care (treatment of symptoms), Possibly IV mannitol	Supportive care	Supportive care, Possibly respiratory support	Supportive care, especially for older people and those with kidney disease	Supportive care	Supportive care

U.S. Department of Health and Human Services
Centers for Disease Control and Prevention

www.cdc.gov/habs

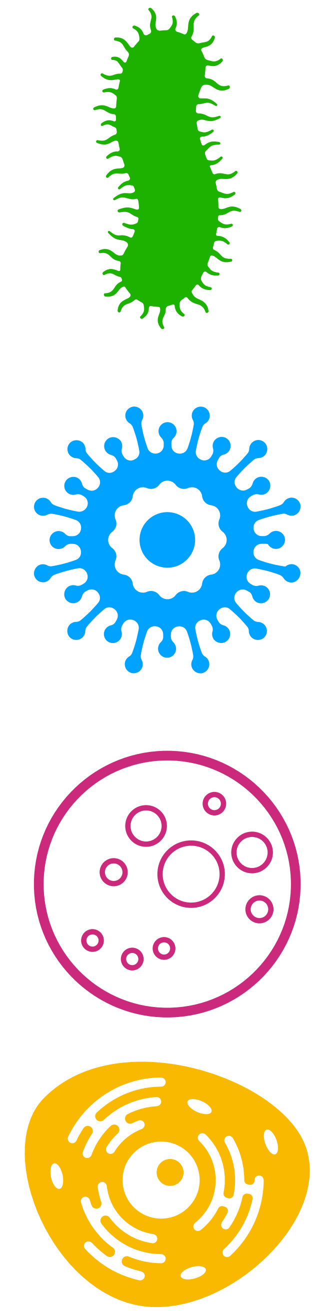
Effects of some biotoxins in marine/estuarine fish

https://www.bionte.com/en/navigating-biotoxins-in-aquaculture-challenges-impacts-and-detection-strategies/

Species	Exposure Route/Challenge	Toxin Effects in Fish	Reference
Early life stages			
Yellowtail	Dissolved okadaic acid 120–175 μg L^{-1}	Mortality of fish eggs; Unclear effect on gene expression.	Le Du et al., 2017
Sheepshead minnow and Silversides	A mixture of toxic dinoflagellates: *Dinophysis acuminata* and *Alexandrium catenella*	Mortality of fish larvae; Impact on growth rates; Impact on swimming activity	Rountos et al., 2019
Juveniles			
Seabass	Toxic dinoflagellates (*P. lima*)	Altered swimming behavior Abstinence from feeding; Death.	Ajuzie et al., 2007
Seabass	Artemia that fed on *P. lima* and/or artificial feed containing *P. lima*	Histological alterations in gills (swollen and lifted epithelium, ruptured lamellae) and liver (necrosis, loss of tissue architecture, hydropic degeneration, hypertrophy, and dissociation of hepatocytes).	Ajuzie et al., 2007
Gilthead seabream	Dissolved okadaic acid 7500 μg L−1	Inducer oxidative stress; Histological alterations in gills and liver tissues.	Souid et al., 2018
Ringneck blenny	Artemia that fed on *P. lima*	Increase of opercular beat frequency.	Neves et al., 2020
Zebra seabream	Artificial feed containing 1300 μg OA eq. kg−1 followed by the increased stimulus of swim current velocity	Reduction in swimming performance.	Corriere et al., 2020

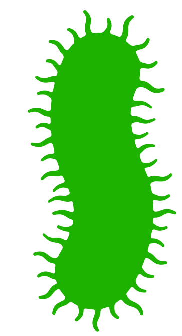
Study case: Coral holobiont

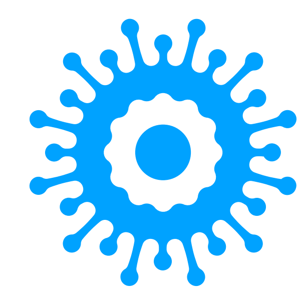
- **High temperature** and solar irradiation induces **coral bleaching**, algal symbiont is ejected, more prone to infections and algae overgrowth
- Disease: loss of tissue, change in color and exposure of skeleton
- *Vibrio shiloi* (now *V. shilonii*) and *Vibrio coralliitycus:* bleaching
- Black band and white band disease: polymicrobial, vectors: snails, fishes and worms
- Fungus *Aspergillus sydowii:* purple lesion
- Brown band disease: protist
- Viruses targeting the holobiont



Study case: Sponge holobiont

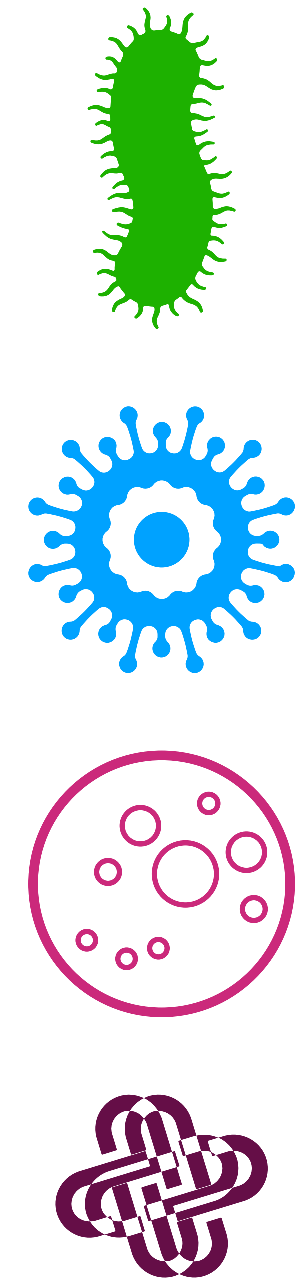
- Disease: loss of tissue, change in color and necrosis and damage of internal structure due to bacteria digestion and then sponges crumble due to water pressure
- Less studied than Corals
- Bacteria: Pseudoalteromonas agarivorans
- Viruses targeting the holobiont



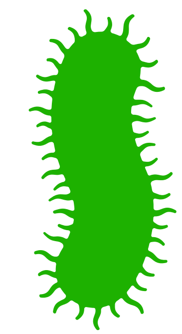


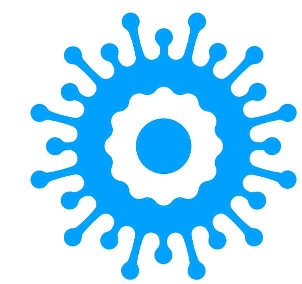
Study cases: Echinoderms - Molluscs - Crustaceans

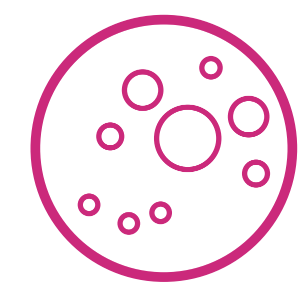
- Echinoderms: ecosystem value, Atlantic and Pacific disease distribution, many genera have been affected, possibly some virus/unknown —> importance as top predator
- Molluscs: economic value (e.g. food and jewels), filter-feeders, Vibrio and other bacteria, viruses, protists and toxins
    - Oyster, Mussel, Clam, Abalone, Scallop
- Crustaceans: economic value, Vibrio (luminescence vibriosis) and other bacteria, viruses, protists and toxins
    - Lobster, Crab, Shrimp, Prawn

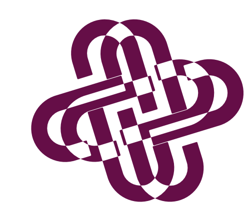


Study case: Fishes



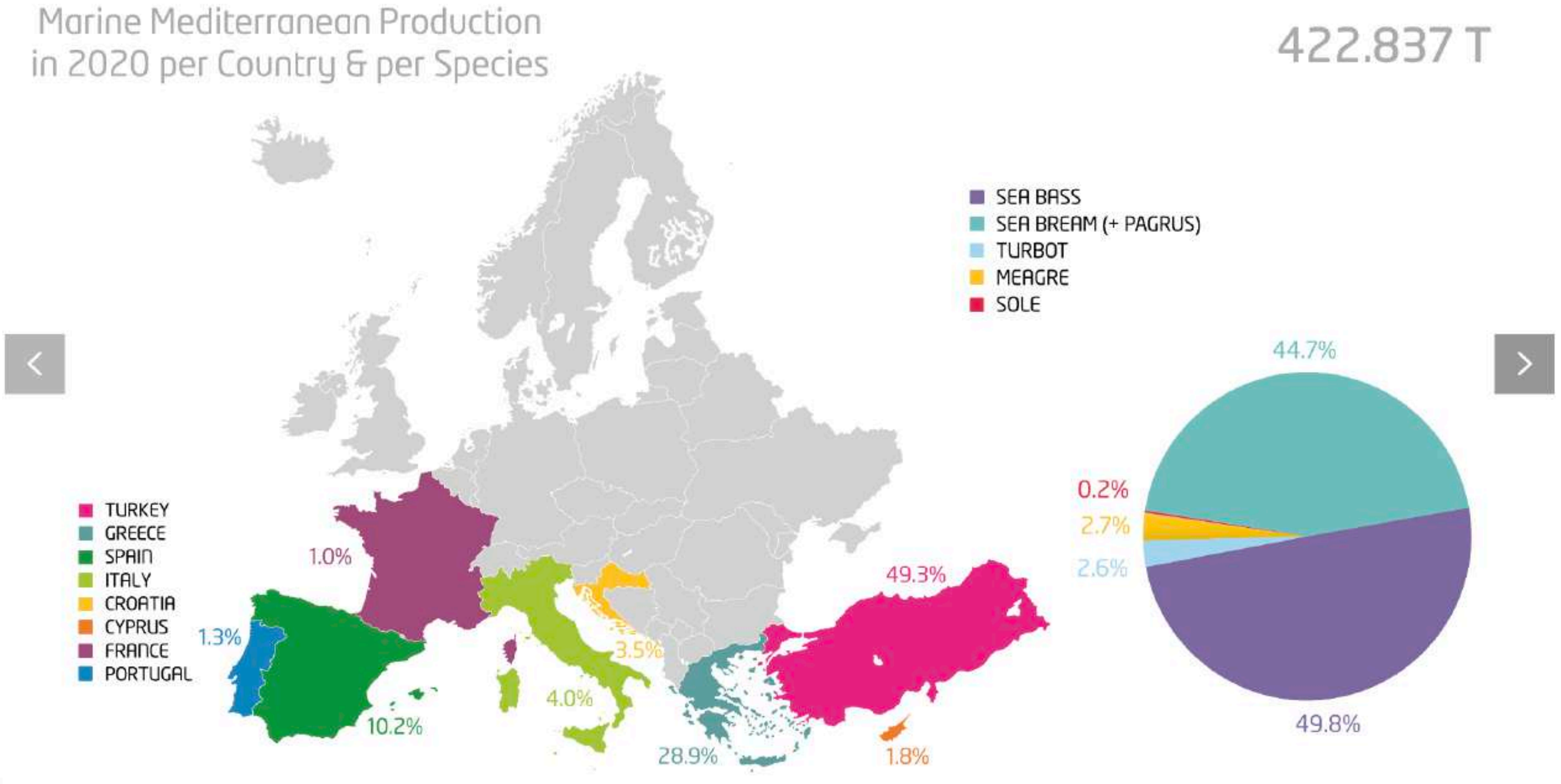


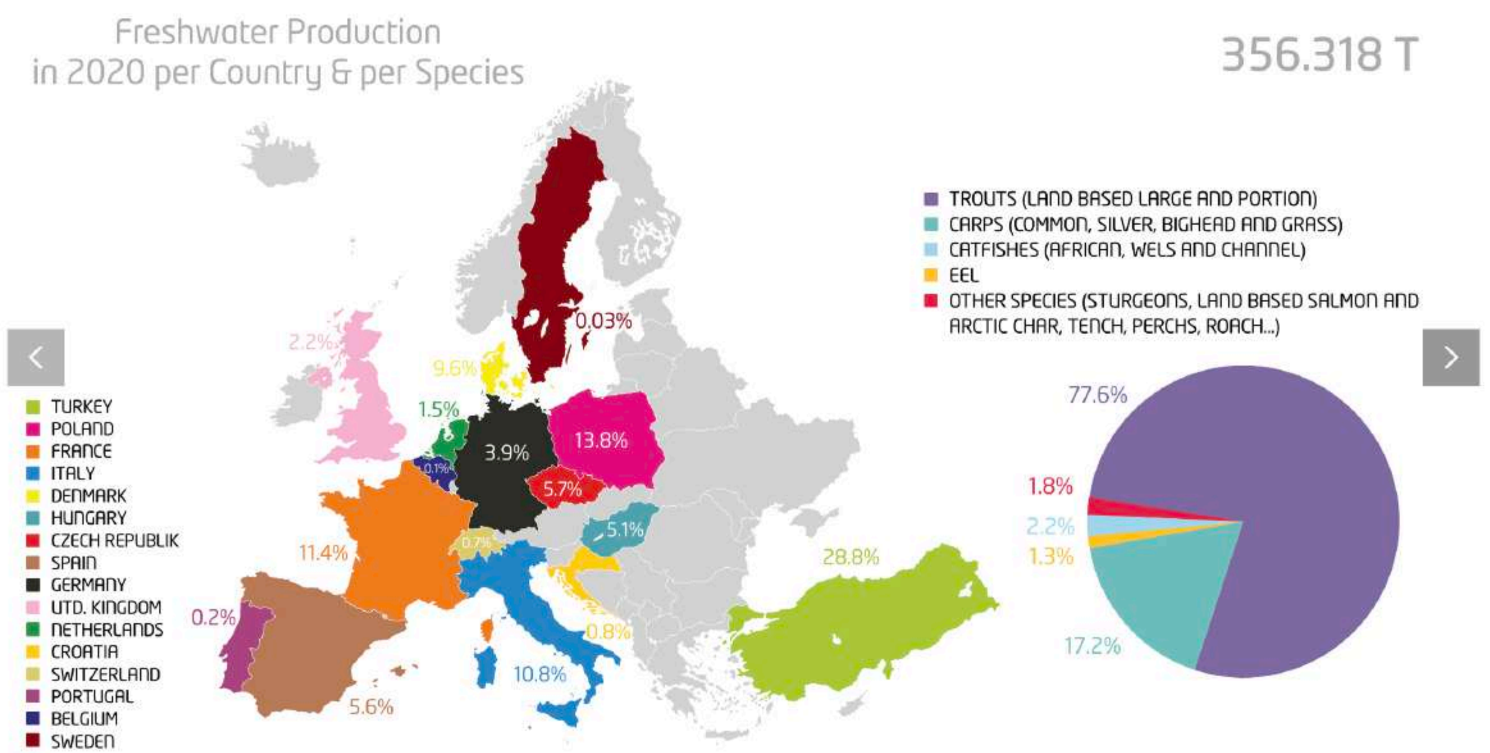




- Economic value and ecosystem value
- Aquaculture <—> Wild stocks
- *Vibrio anguillarum,* 1893, mass mortality in eel and other bacteria
- *Vibrio ordalii, Vibrio salmonicida* (now *Aliivibrio salmonicida*), *Vibrio vulnificus, Moritella viscosa, Photobacterium damsela piscicida, Aeromoas salmonicida, Tenacibacter maritimus, Piscirikettia, Francisella, Renibacterium salmoninarum, Mycobacterium, Nocardia, Lactococcus, Streptococcus*
- Viruses
- Protists: gill occlusion
- Toxins: HABs
    - Salmon, Cod, Gilthead Sea Bream, Sea Bass, Yellowtail, Ayu, Flounder, Turbot, Tuna, Halibut
- Disease: 1. Systemic bacteremia or viremia and hemorragies; 2. Skin, muscle, gill lesions; 3. Chronic proliferative lesions
- Use of antibiotic and vaccine

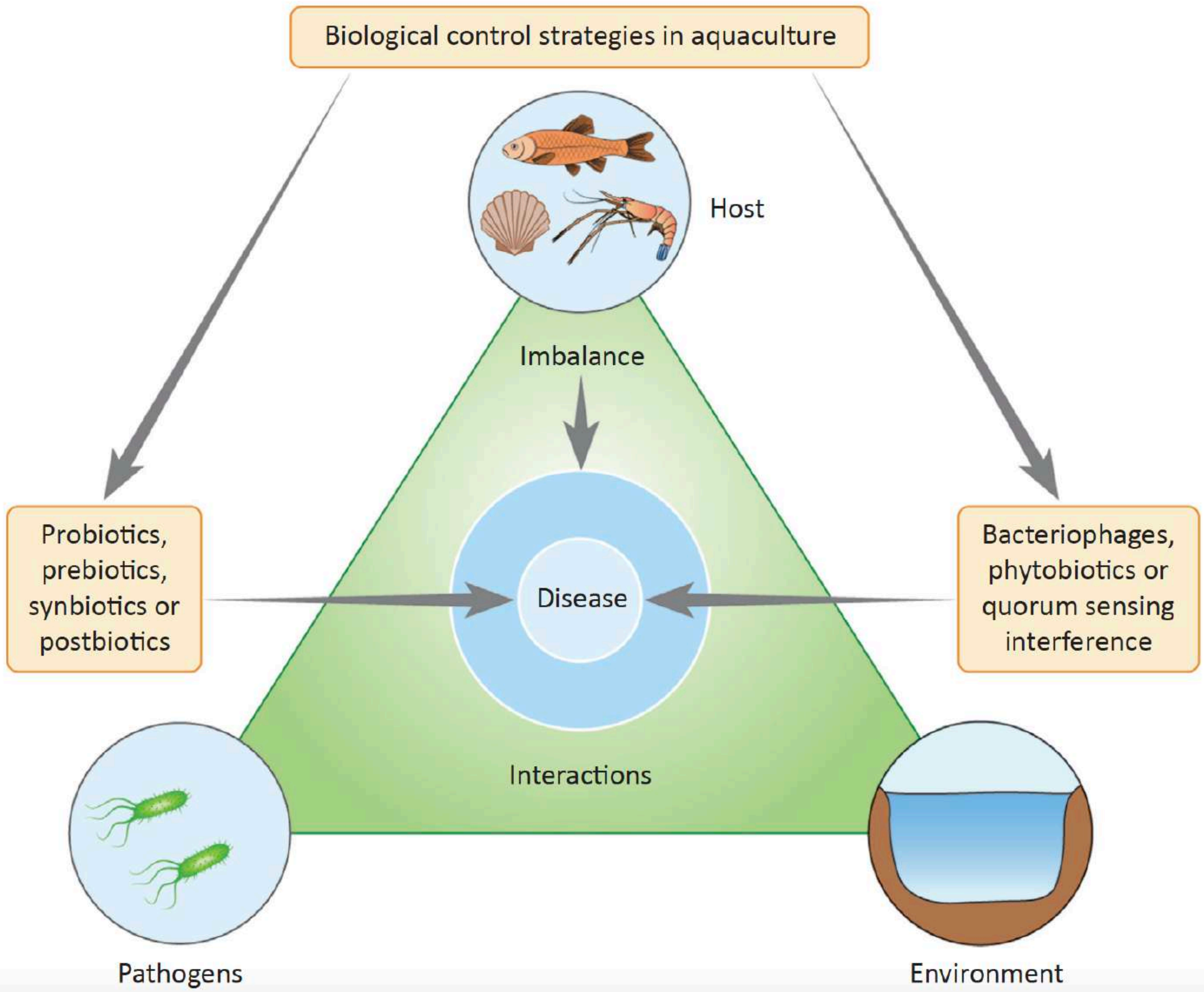
Aquaculture in EU





https://feap.info/index.php/data/

Biological Approaches for Disease Control in Aquaculture



Pérez-Sánchez et al., 2019

Glossary

Bacteriophages: viruses that infect bacterial cells.

Microbiota: all commensal, symbiotic, and pathogenic microorganisms sharing a defined niche (e.g., intestinal ecosystem).

Phytobiotics: plant-derived natural bioactive compounds which are added to the diet to improve nutrition and health in farm animals and humans [59].

Postbiotics: nonviable bacterial products or metabolic byproducts from probiotic microorganisms that have biological activity in the host [60].

Prebiotics: fermented ingredients that selectively stimulate the growth and/or activity in the gastrointestinal microbiota that confers benefits upon host well being and health [21].

Probiotics: formulations of live microorganisms which, when administered in adequate amounts, confer a health benefit on the host [61].

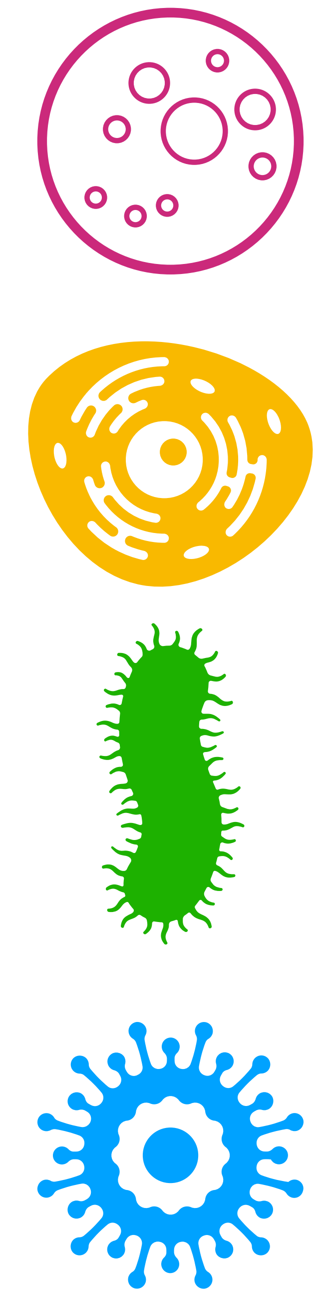
Synbiotics: combination of probiotics and prebiotics, which can result in additive or synergistic effects [23].

Study case: Birds & Reptiles

- Ecosystem value
- Seabirds are a taxonomically varied group of nearly 350 bird species (around 3.5% of all birds) that depend on the marine environment for at least part of their life cycle
- Birds:Toxins bioaccumulated in fish
- ~1% of Reptiles are marine, 7 species are turtles
- Reptiles: Viruses promoting tumors in turtles

Study case: Seagrasses and Seaweeds

- Ecosystem value, economic value
- Eelgrass and turtlegrass: protists and fungus-like
- Macroalgae: bacteria, fungi and viruses



Study case: Marine Mammals

- Ecosystem values
- Very similar to humans
- Marine mammals:
  - **Cetaceans** (whales, dolphins, and porpoises),
  - **Pinnipeds** (seals, sea lions, and walruses),
  - **Sirenians** (manatees and dugongs),
  - **Marine fissipeds** (polar bears and sea otters)
- Bacteria (Brucella, Leptospira and Mycobacterium), Viruses, Protists, Fungi and Toxins