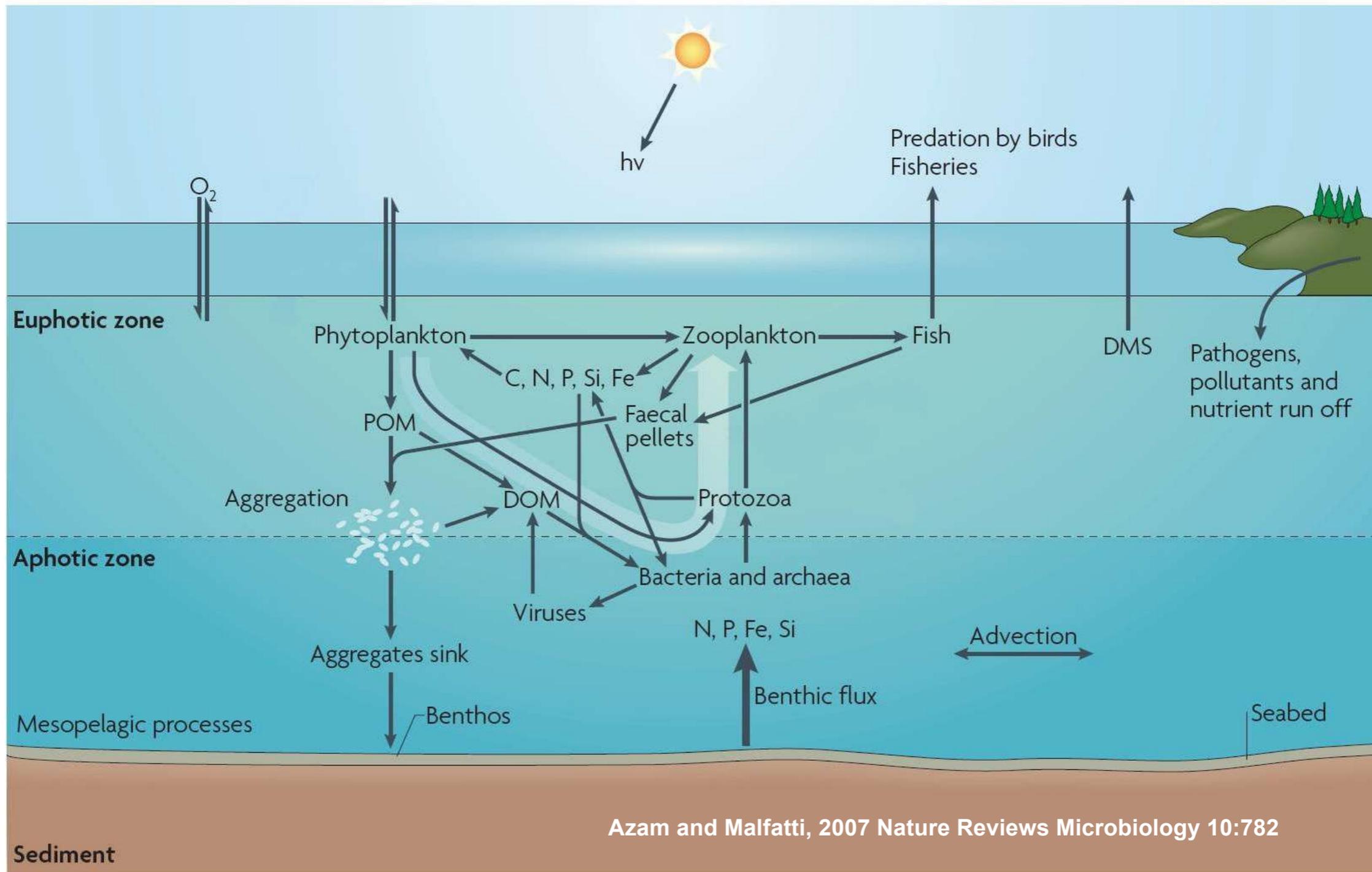


L06c:

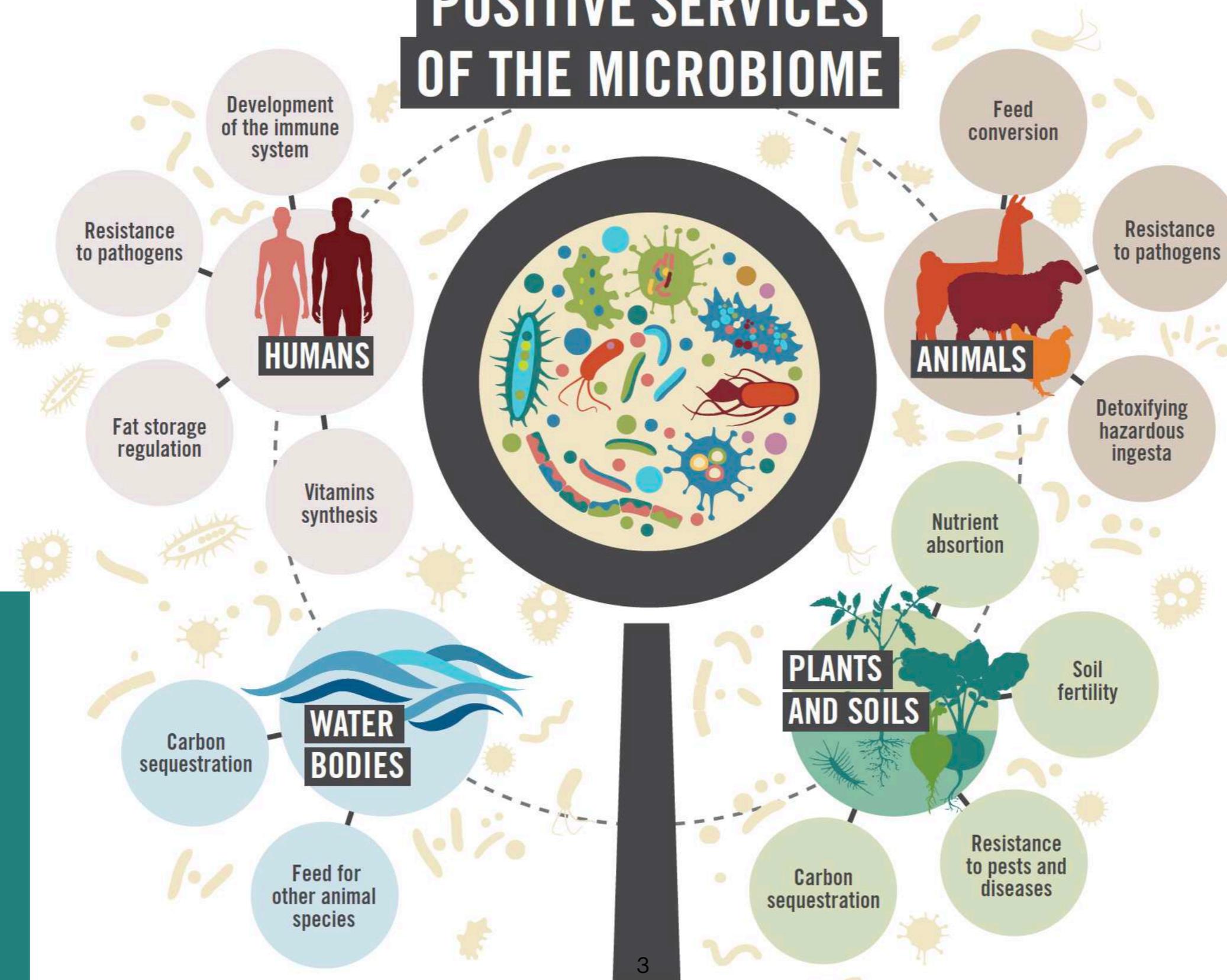
Marine Microbes and Society

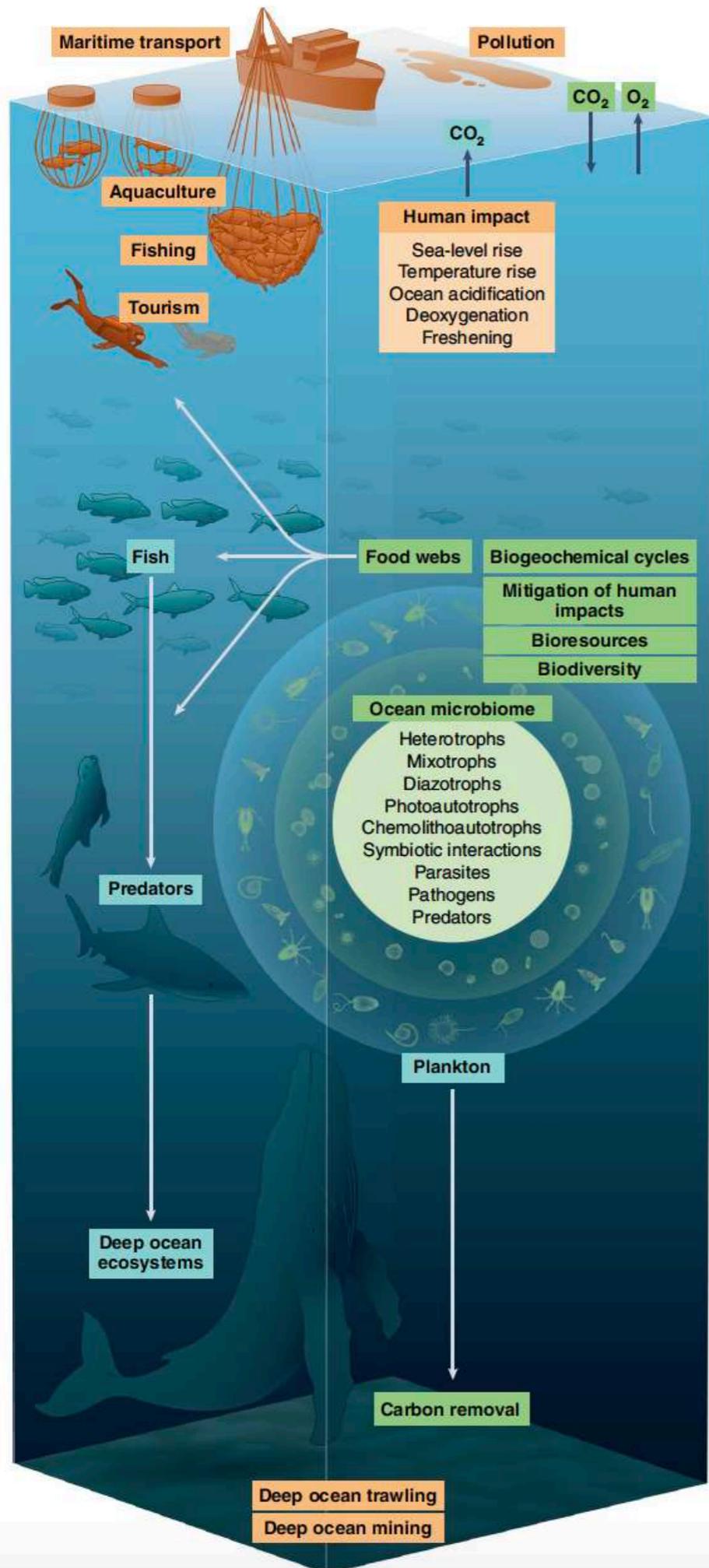
Microbial fingerprint on planet Earth and Human Society



Microbial functions on Earth Ecosystems

POSITIVE SERVICES OF THE MICROBIOME





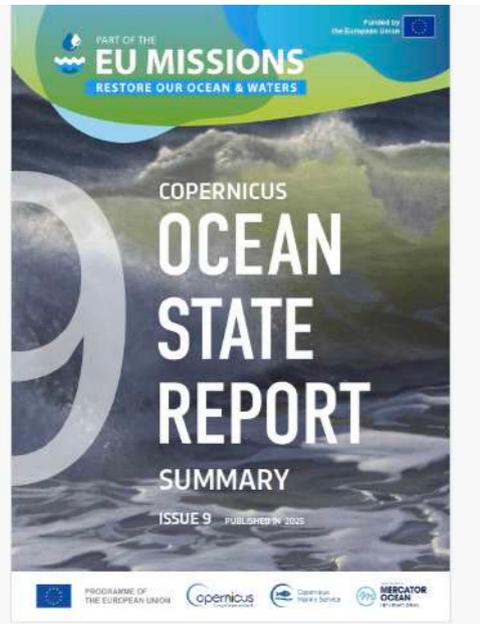
Roles of the ocean microbiome

The ocean microbiome (centre) is composed of a range of prokaryotes, eukaryotic microbes and viruses, which have a **range of different lifestyles driving microbial interactions**

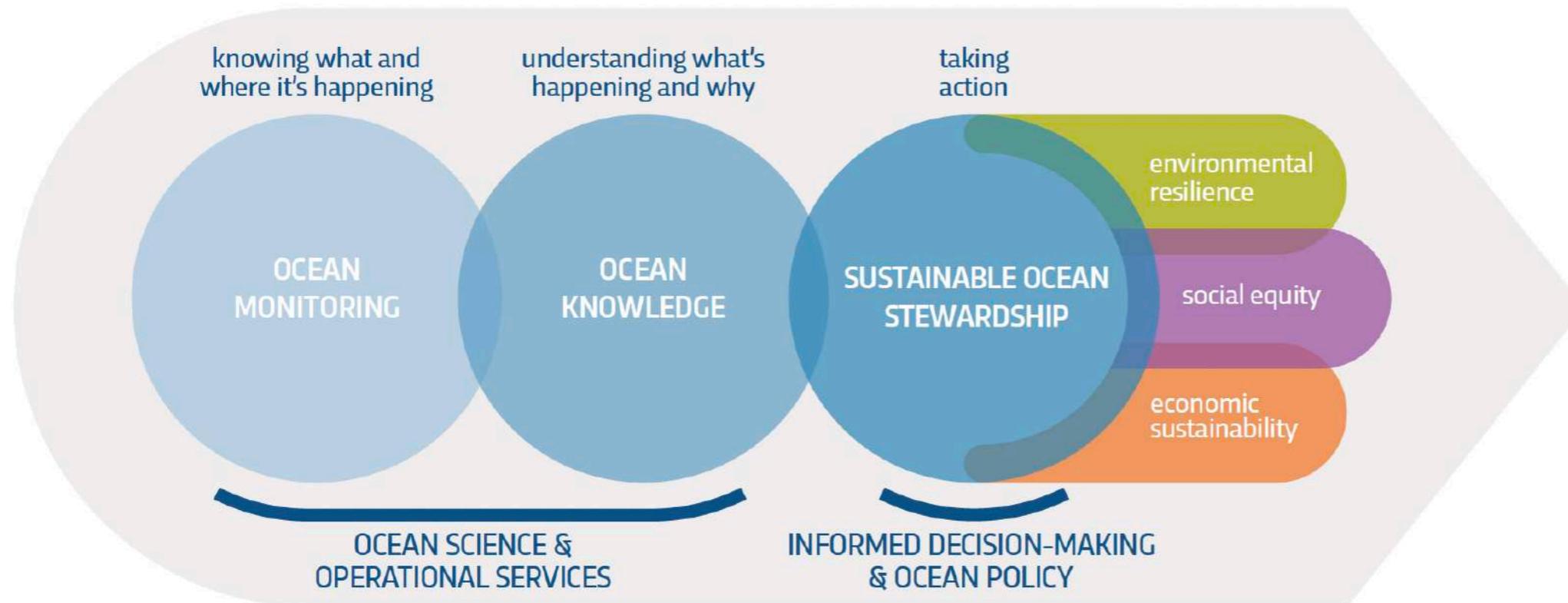
The essential ecosystem services they provide, such as **biogeochemical cycling** (e.g. CO₂ capture, O₂ generation and carbon removal), **mitigation of human activities, bioresources, biodiversity** and **resources for the entire ocean food web**, are shown in green

Humans impact ocean functioning thus microbial functioning in the ocean

Other aspects of the ocean environment are indicated in blue, and interconnections between different components are shown with arrows

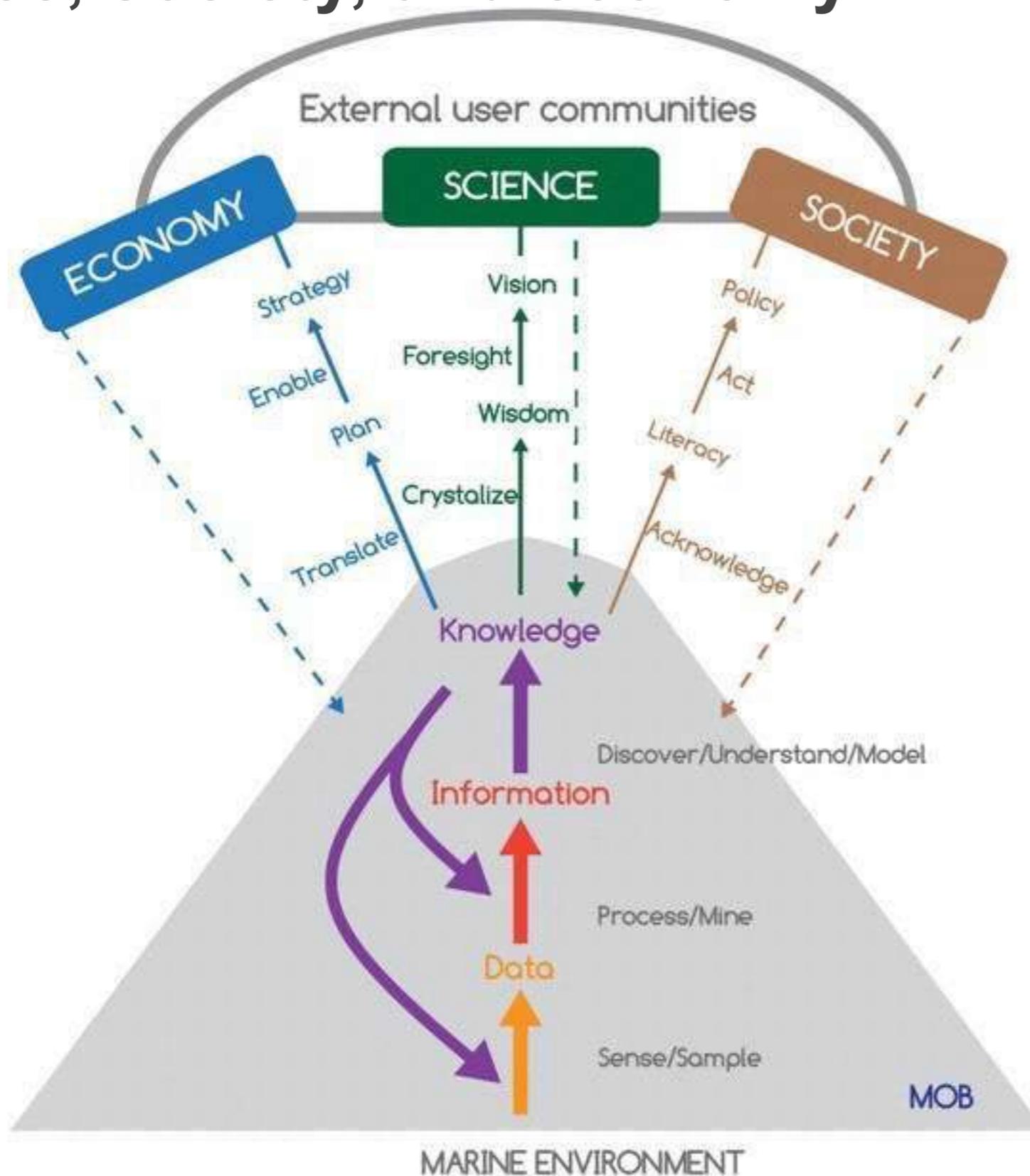


A PATHWAY TO ACTION



MOB-based hierarchy of understanding for science, society, and economy

Marine OBservatory structure (MOB)



WHY?

Science-based governance of the ocean

Our goal: a vibrant ocean ecosystem

This knowledge will help us design the most effective ways to **restore marine and coastal habitats, support a sustainable blue economy and adapt to a changing climate.**

Mitigating and adapting to climate change

Supporting a sustainable blue economy

Restoring marine and coastal habitats

Boosting biodiversity

**#MissionOcean
#EUMissions**

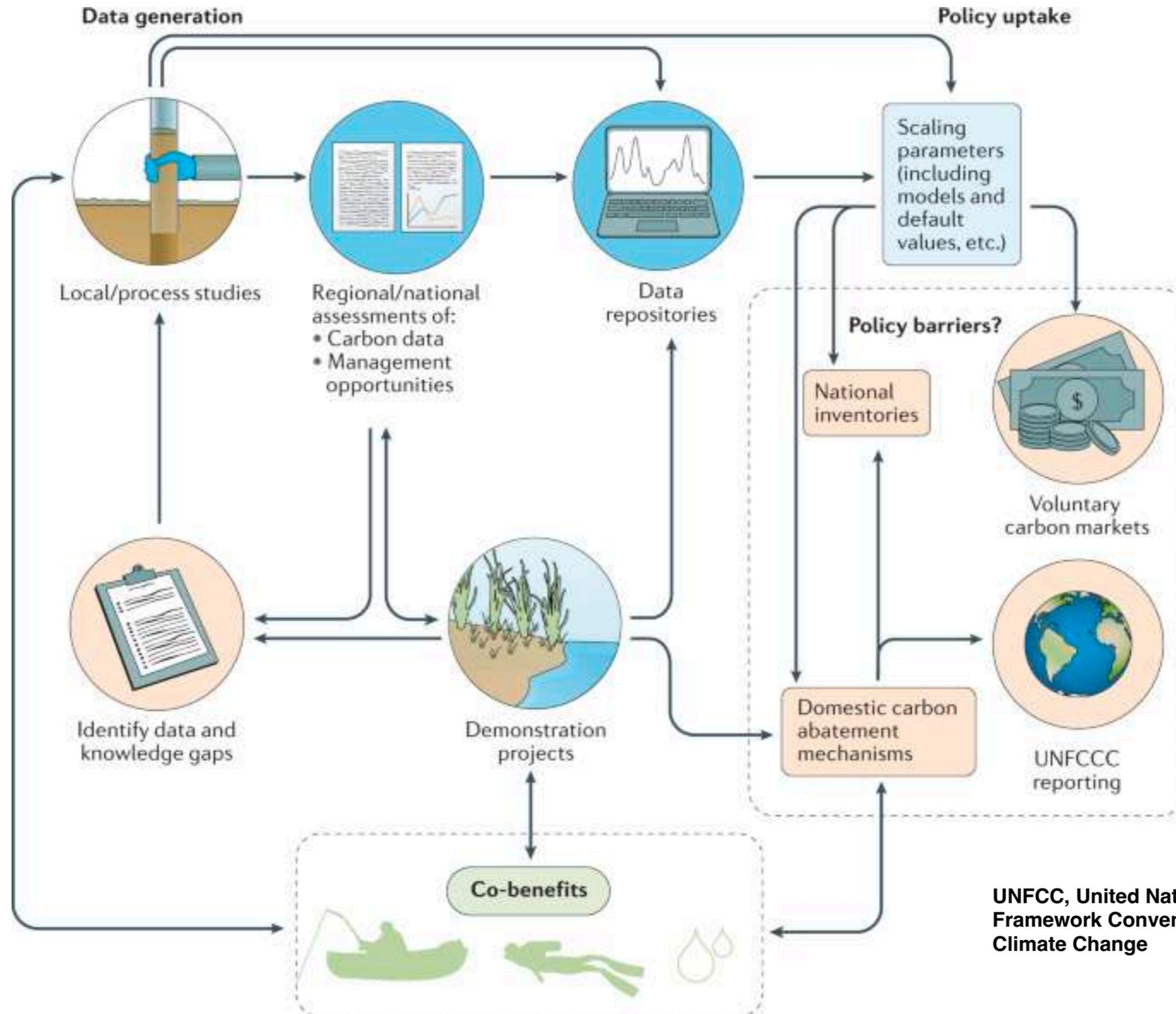
**EU
MISSIONS**

RESTORE OUR OCEAN & WATERS BY 2030

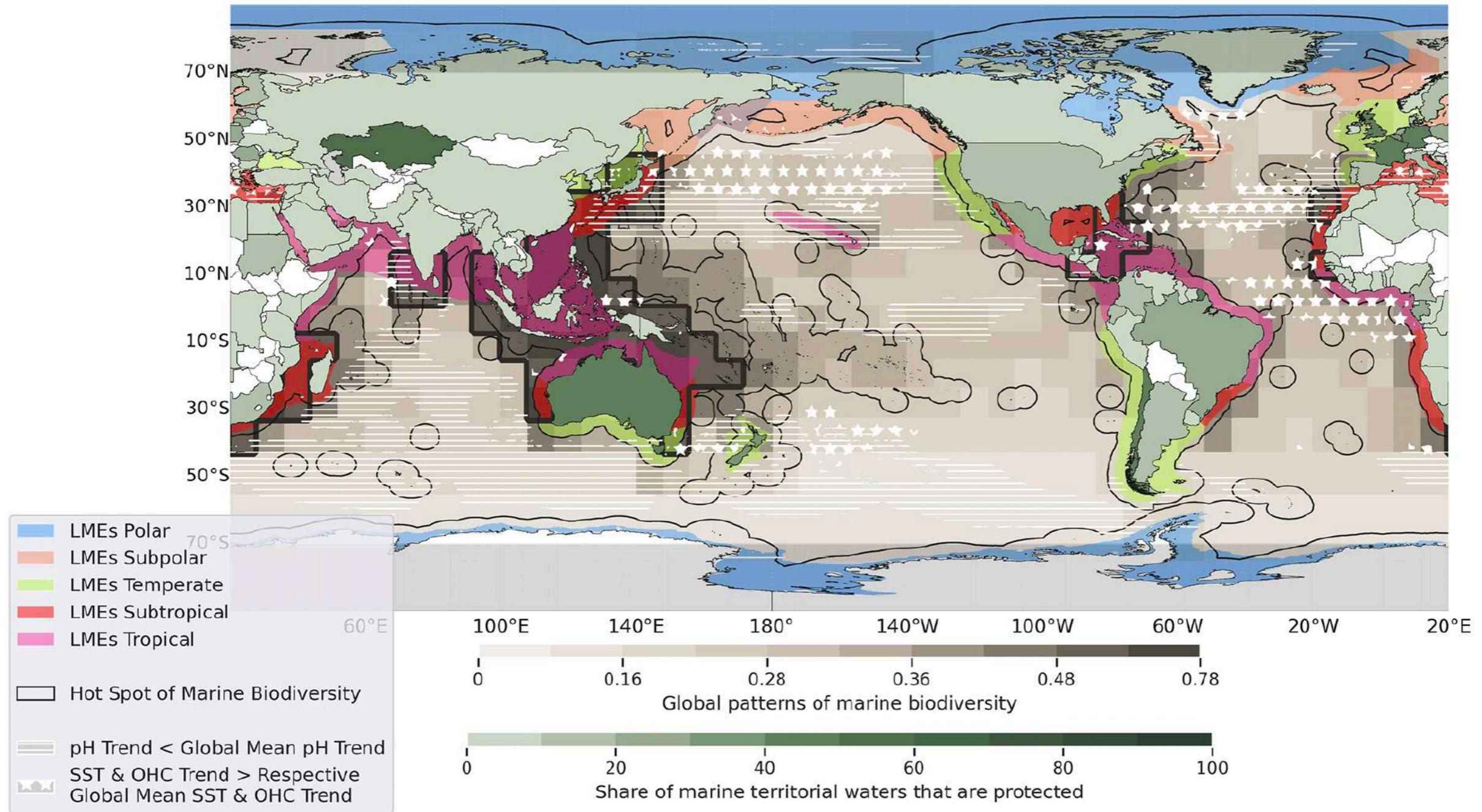
Research and
Innovation

© European Union, 2022
ISBN 978-92-76-49483-6 |
DOI 10.2777/343496 | KI-06-22-164-EN-N
Illustrations by Zinzi Moons

Science for decision making and policy a virtuous roadmap



UNFCC, United Nations Framework Convention on Climate Change



Global patterns of marine biodiversity shown in the ocean (brown gradient), with hotspots surrounded by bold dark-brown polygons
Share of marine territorial waters that are protected in 2022 shown on land (green gradient, EEZ)
 Large marine ecosystems (LMEs) are shown in colours along the coasts
The boundaries of Areas Beyond National Jurisdiction (ABNJ)/High Seas are materialized by black lines off the coasts

Stars represent where 95% of the local sea surface temperature (SST) and ocean heat content (OHC) trend ranges surpass the 1982-2024 global average

Horizontal hatching is the same but for the pH trend for the period 1985–2022

The Caspian Sea is shaded in grey, as data were not available, except for the share of marine territorial waters of the surrounding countries

Who does **own** the ocean?



Exclusive Economic Zones are shown in white

High seas, or areas beyond national jurisdiction, are shown in light green

Image courtesy of Sumaila et al. In prep./ Global Ocean Commission/ The High Seas and Us: Understanding the Value of High-Sea Ecosystems



The High Seas Treaty, also known as the agreement on **Biodiversity Beyond National Jurisdiction** or '**BBNJ**'

The High Seas Treaty, also known as the agreement on **Biodiversity Beyond National Jurisdiction** or 'BBNJ', was signed in New York on 20 September 2023, in the margins of the United Nations High Level Week.

In addition to the EU as organisation, **many countries signed the treaty**.

The agreement provides for the common governance of **about half of the Earth's surface** and **95% of the ocean's volume**, the largest habitat on our blue planet, to:

- promote equity and fairness
- tackle environmental degradation
- fight climate change, and
- prevent biodiversity loss in the high seas

High Seas: deep sea mining

Article

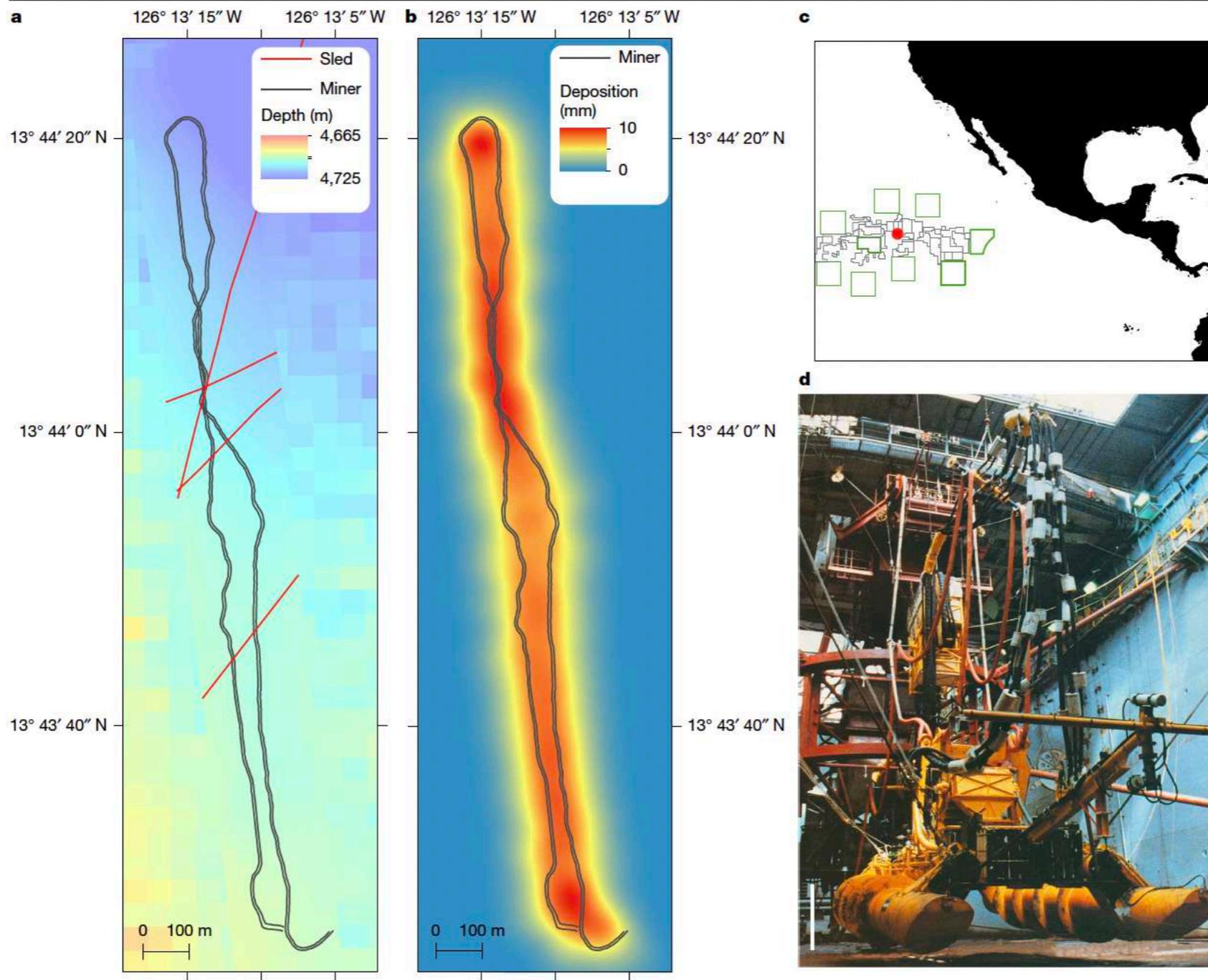
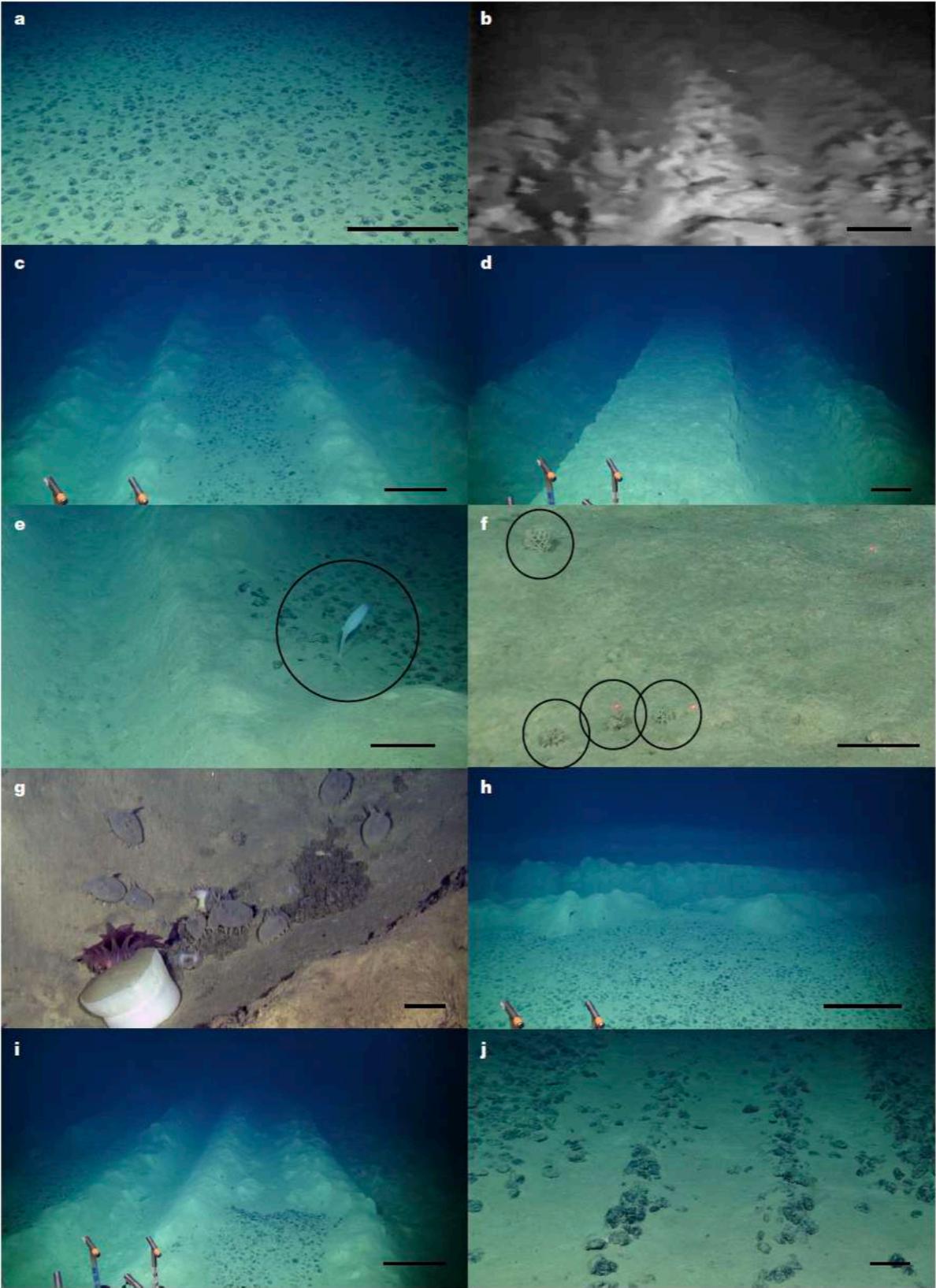


Fig. 1 | Maps of the OMCO track area. a, Multibeam bathymetry map overlaid with interpreted tracks of mining vehicle (in the photograph, **d**) and epibenthic sleds used for nodule collection in 1978. **b**, Modelled sediment deposition from plume generated by mining vehicle with central point of mining vehicle track overlaid (black). **c**, General location of test area (red dot) in the CCZ showing

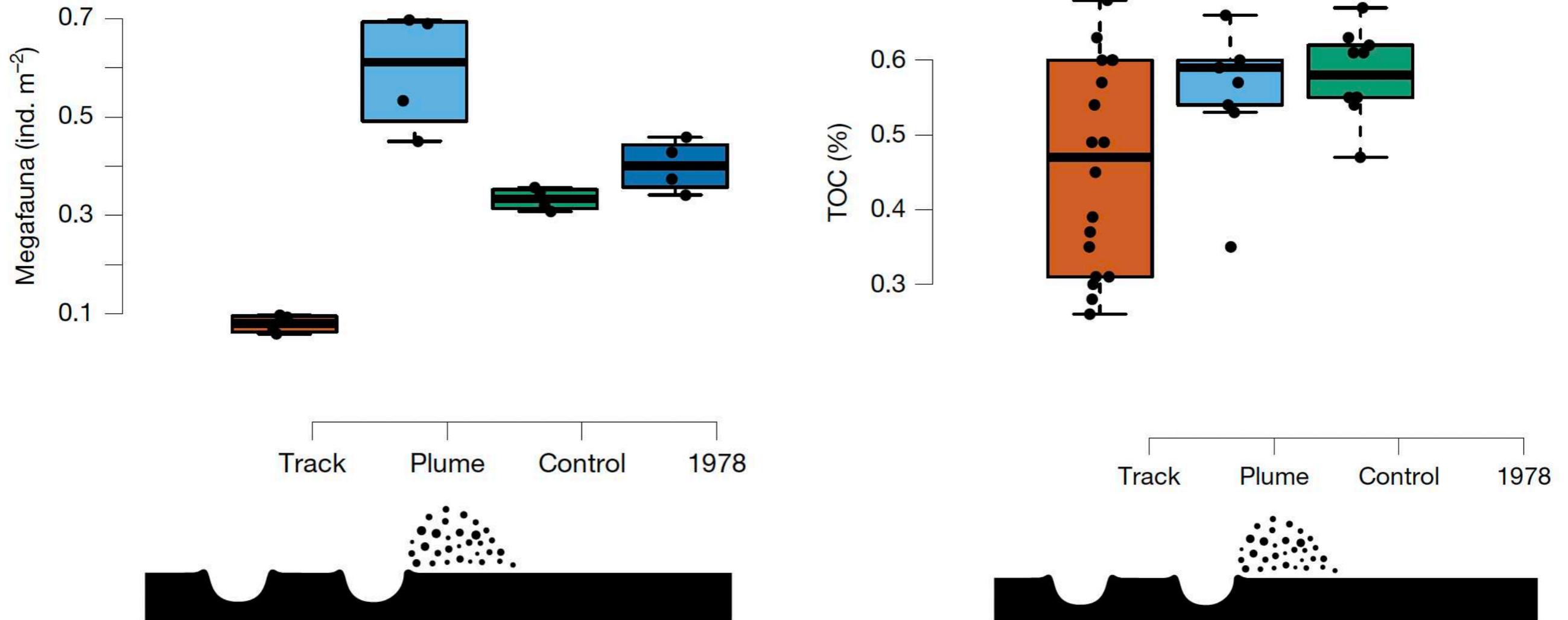
International Seabed Authority designated Areas of Particular Environmental Interest (green) and exploration contract areas (grey). Datum WGS 1984 for all maps. **d**, Photograph of a mining vehicle in the moon pool of the *Hughes Glomar Explorer* vessel in 1979. Scale bar, 2 m. Credit: Photo in **d** from ref. 39, reproduced under a Creative Commons licence CC BY 4.0.



1978

2023

Long-term impact and biological recovery in a deep-sea mining track



Our results show that **mining impacts** in the **abyssal ocean** will be **persistent** over at **least decadal timeframes** and **communities** will remain **altered** in directly disturbed areas, despite some recolonization

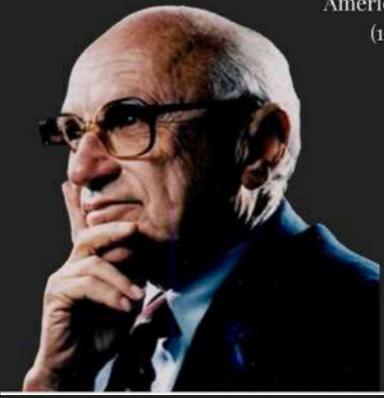


Ray Troll

There is no such thing as
a Free Lunch.

—
MILTON FRIEDMAN

American Economist
(1912-2006)

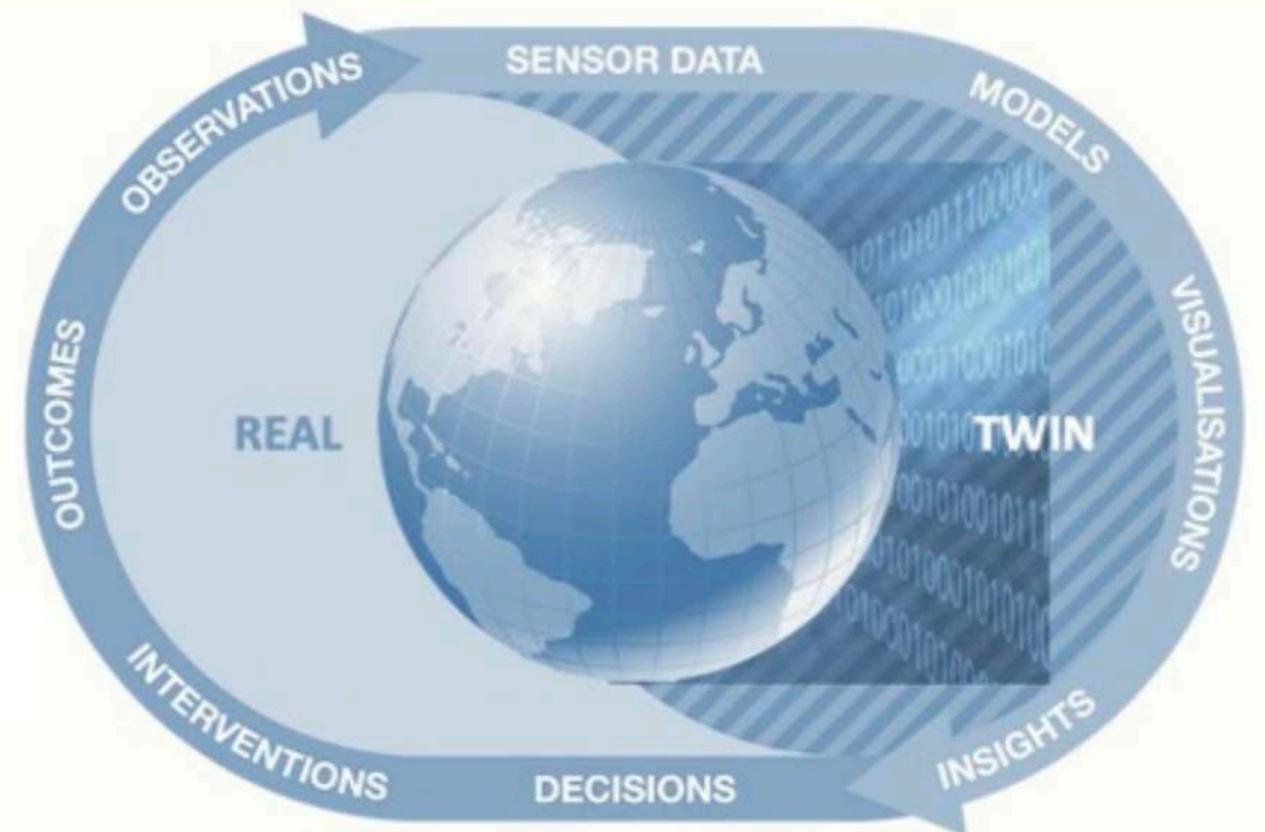
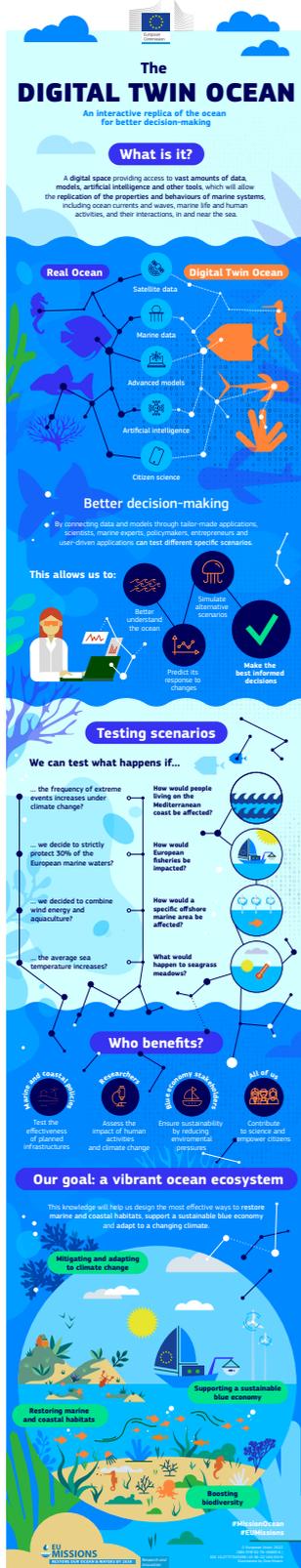


Digital Twins of the Ocean I

Digital twins are virtual representations of physical objects and systems - the physical or real twin (in this case the ocean or a part of it) - which have been widely applied in the engineering realm for tasks such as engine optimization and port management

Digital twins include predictive and data-driven models that users can interact with to support their needs

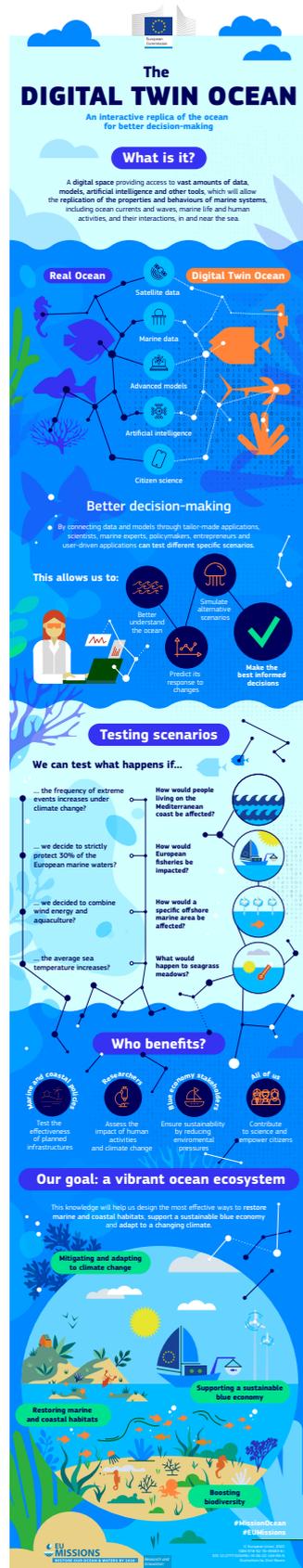
Digital twins thus provide the ability to make informed operational, management, and policy decisions for the real twin



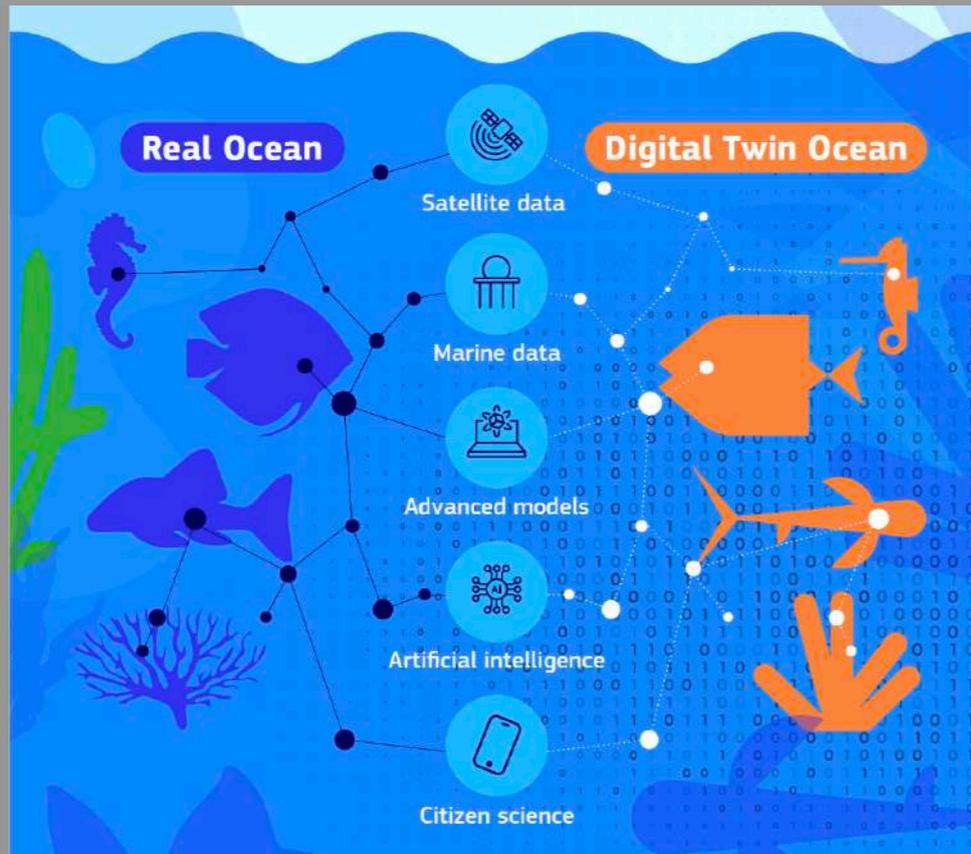
Digital Twins of the Ocean II

This connection between the digital twin and the real one requires a well-formulated interface between the digital twin, environmental data, and the user

User interaction is therefore an essential function that is embedded in the design of digital twins, including visualisation, user-driven data transformation and data-science tools



Digital Twins of the Ocean III



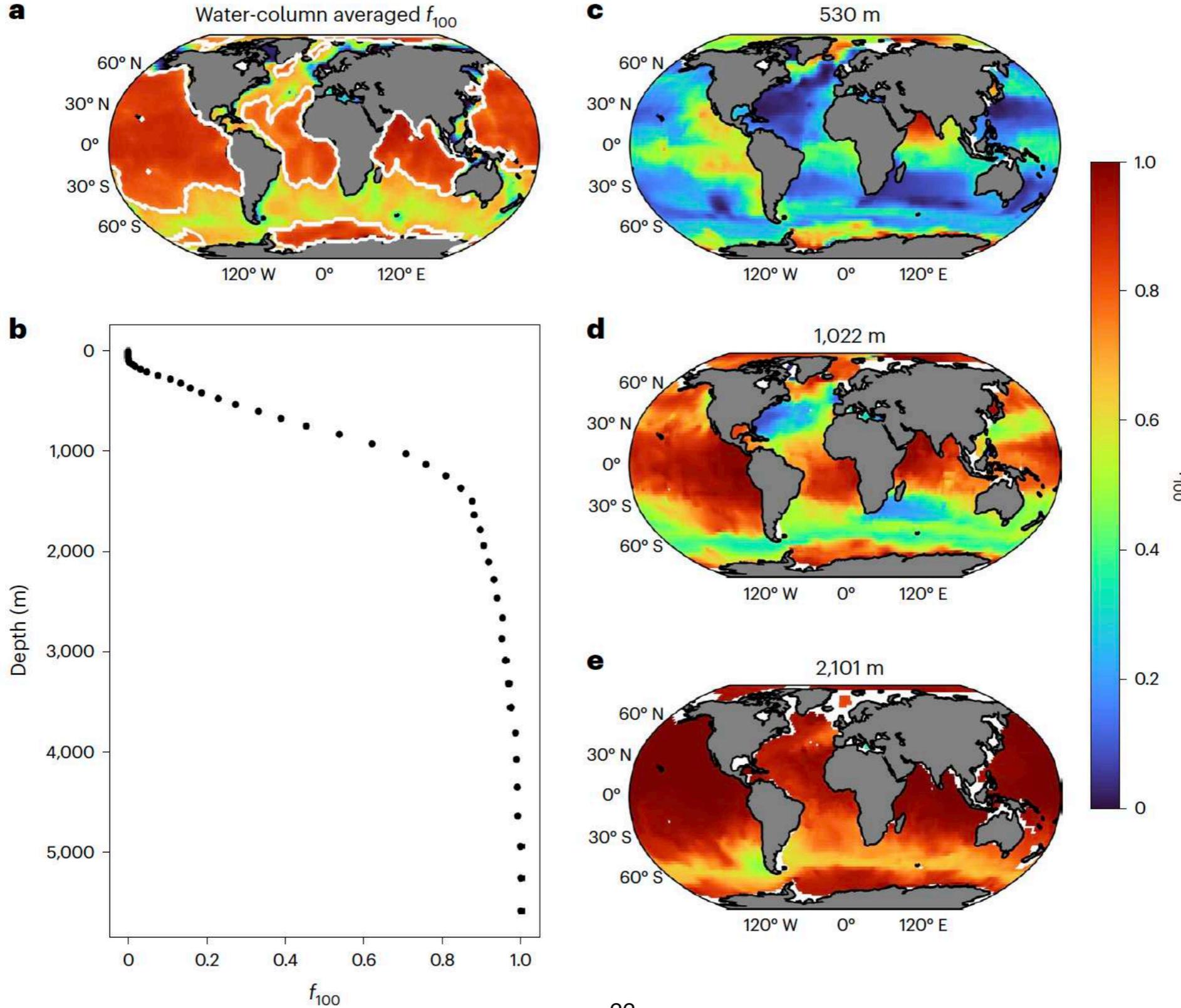
Prof. Visbeck



What are questions that DTO can answer now and in the future?

Physics

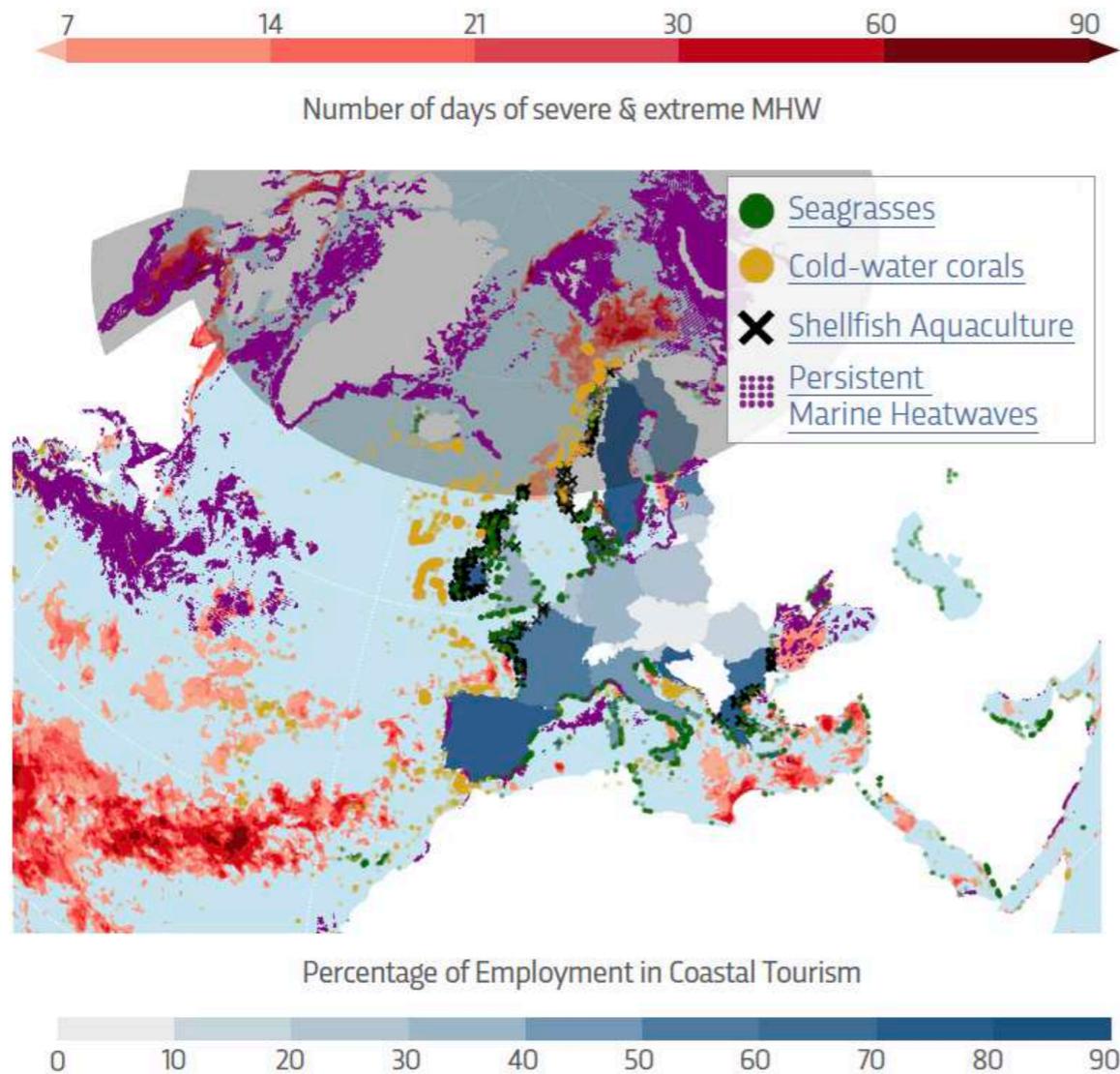
Geographic and vertical distributions of the fraction of a water parcel that will remain in the ocean for ≥ 100 years (f_{100})



Marine heatwaves

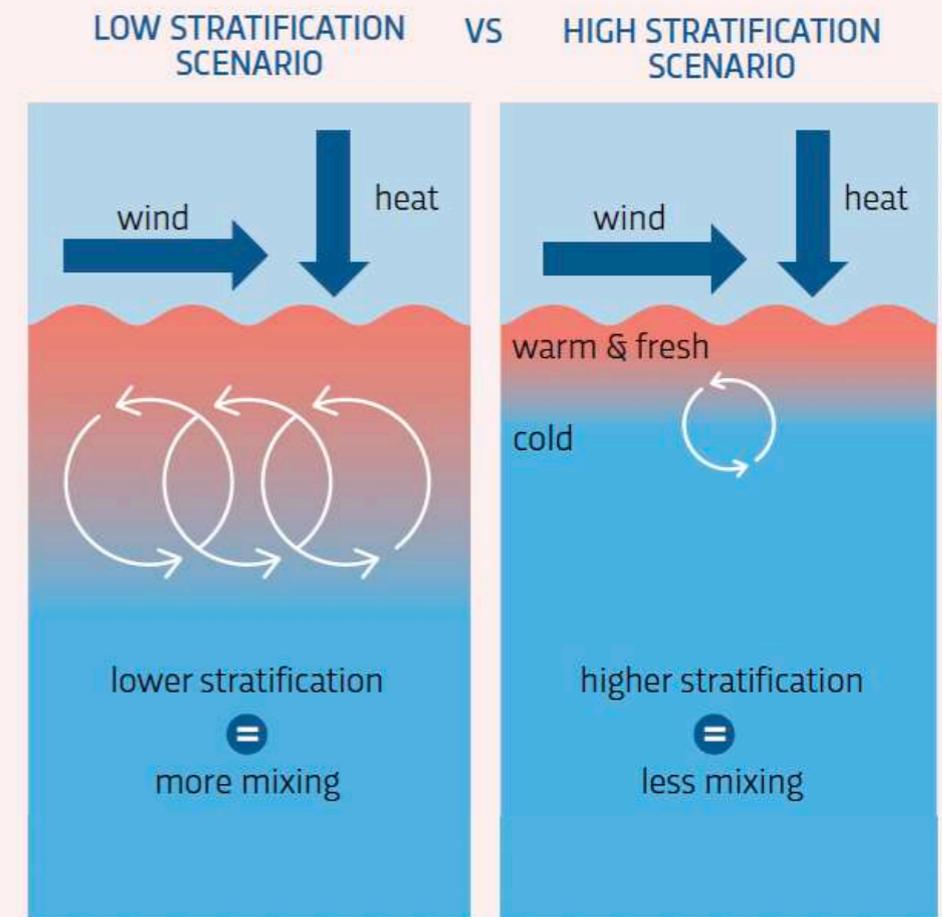


THE IMPACTS OF MARINE HEATWAVES ON THE ECONOMY



ABOVE: Cumulated number of marine heatwave days lasting 5 days or more in 2024, with percentage of employment in coastal tourism in 2017. Persistent heatwaves (in purple) are intense and long-lasting MHWs (> 38 days & > 2.3°C). Grey area is temporally ice-covered and may be less accurate for marine heatwave detection. Adapted from: von Schuckmann et al., 2025. Copernicus Ocean State Report 9

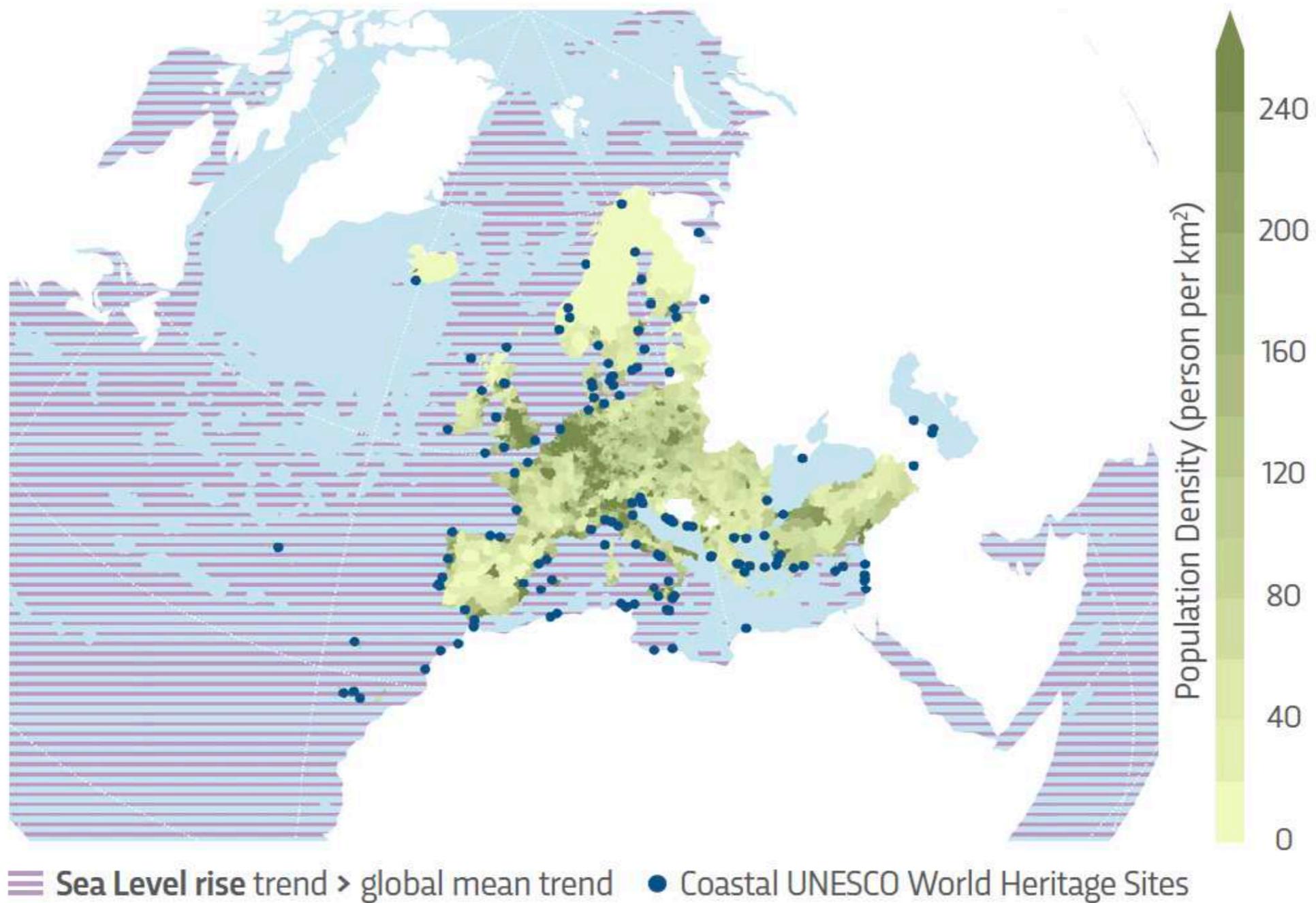
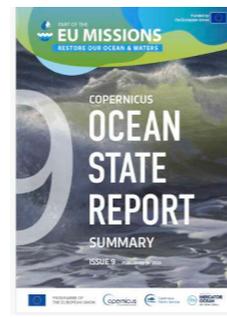
Multiple overlapping factors, including an abnormally cold spring, an unusually fresh surface layer, high levels of heat transfer between the atmosphere and ocean, and low wind speeds led to reduced mixing between ocean layers and an intense surface heatwave in July.



ABOVE: Stratification is the natural separation of horizontal ocean layers due to heat and salinity. On the left, lower stratification leads to more mixing. On the right, higher stratification leads to less mixing and higher surface temperatures. Adapted from: Soontiens et al., 2025. Copernicus Ocean State Report 9

Geology

Sea-level rising



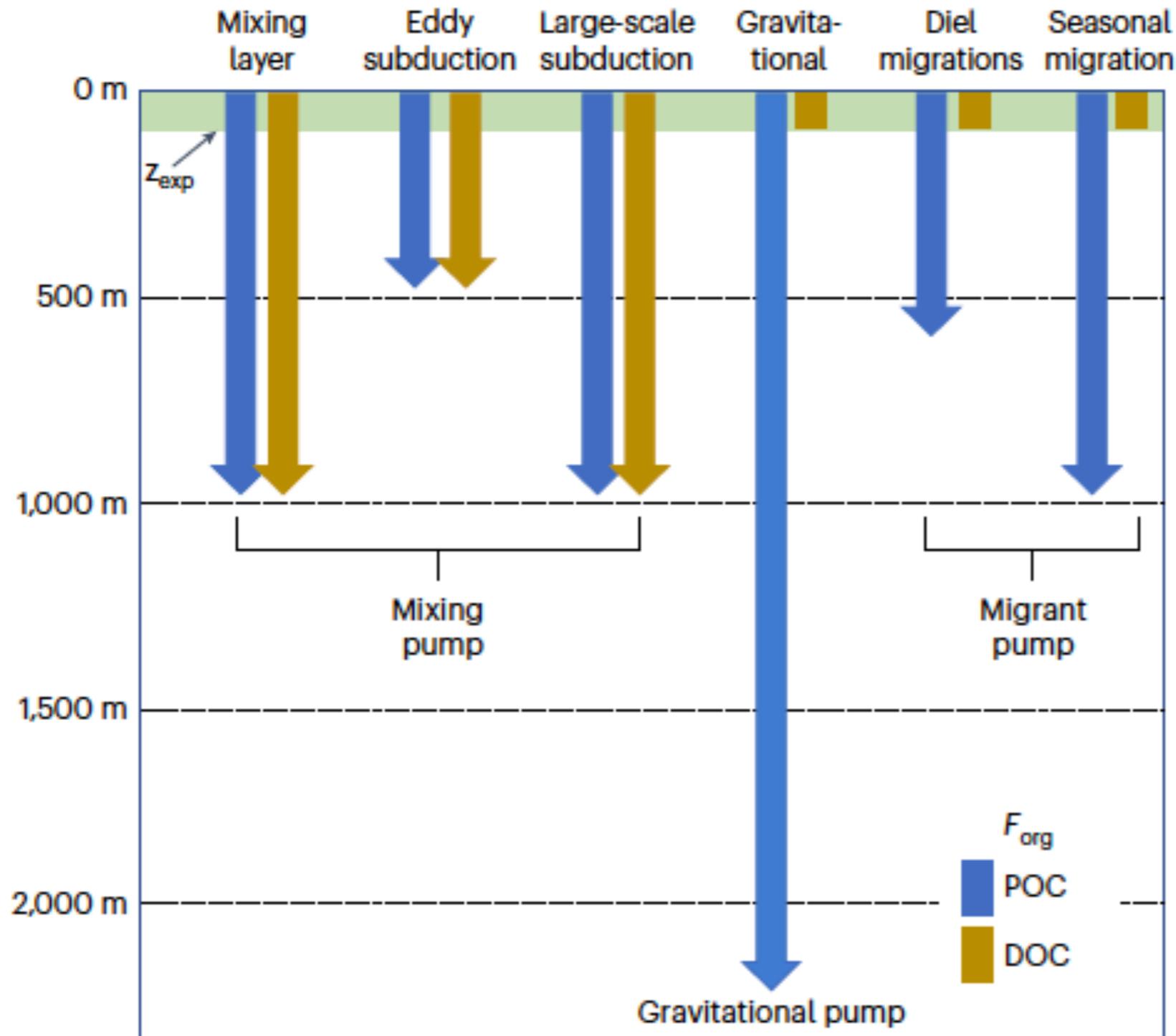
ABOVE: Population density in European countries in 2023. Dark blue dots show coastal UNESCO heritage sites. Adapted from: von Schuckmann et al., 2025. Copernicus Ocean State Report 9

Ocean-Carbon

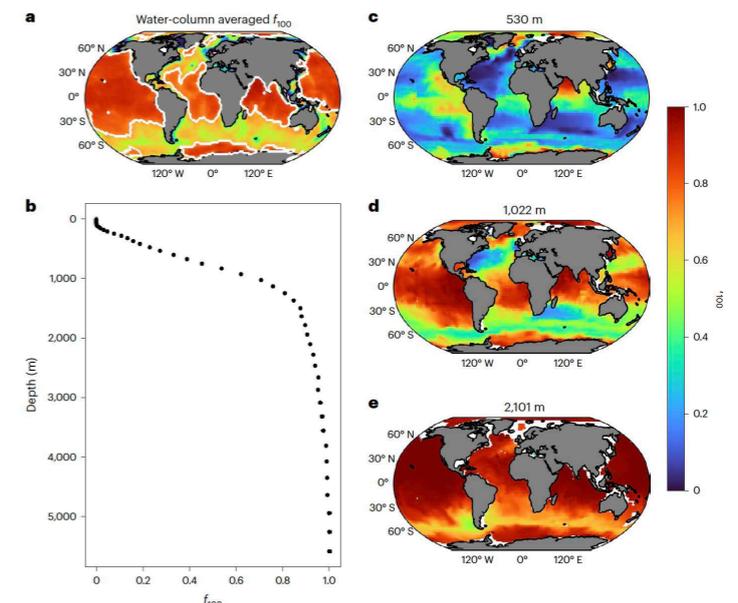
**Physics-Chemistry-
Biology**

Schematic illustration of the carbon export and sequestration mechanisms of the biological pump

Maximum depths of POC and DOC vertical BCP fluxes



- MCPs (missing)
- POC → DOC (refractory)
- Microscale action of organic matter degradation/respiration



Triple planetary crisis:
Climate Change
Biodiversity Loss
Pollution



THE OCEAN'S GREATEST CHALLENGES



GLOBAL WARMING

90%

of the excess heat caused by greenhouse gas emissions is absorbed by the ocean.



MARINE
BIODIVERSITY AT RISK

10%

of assessed marine species are at risk of extinction.



OVERFISHING AND
FOOD SECURITY

Over

37%

of global fish stocks are overexploited¹.



PLASTIC POLLUTION

Between

8 AND 14

million tonnes of plastic end up in the ocean each year.



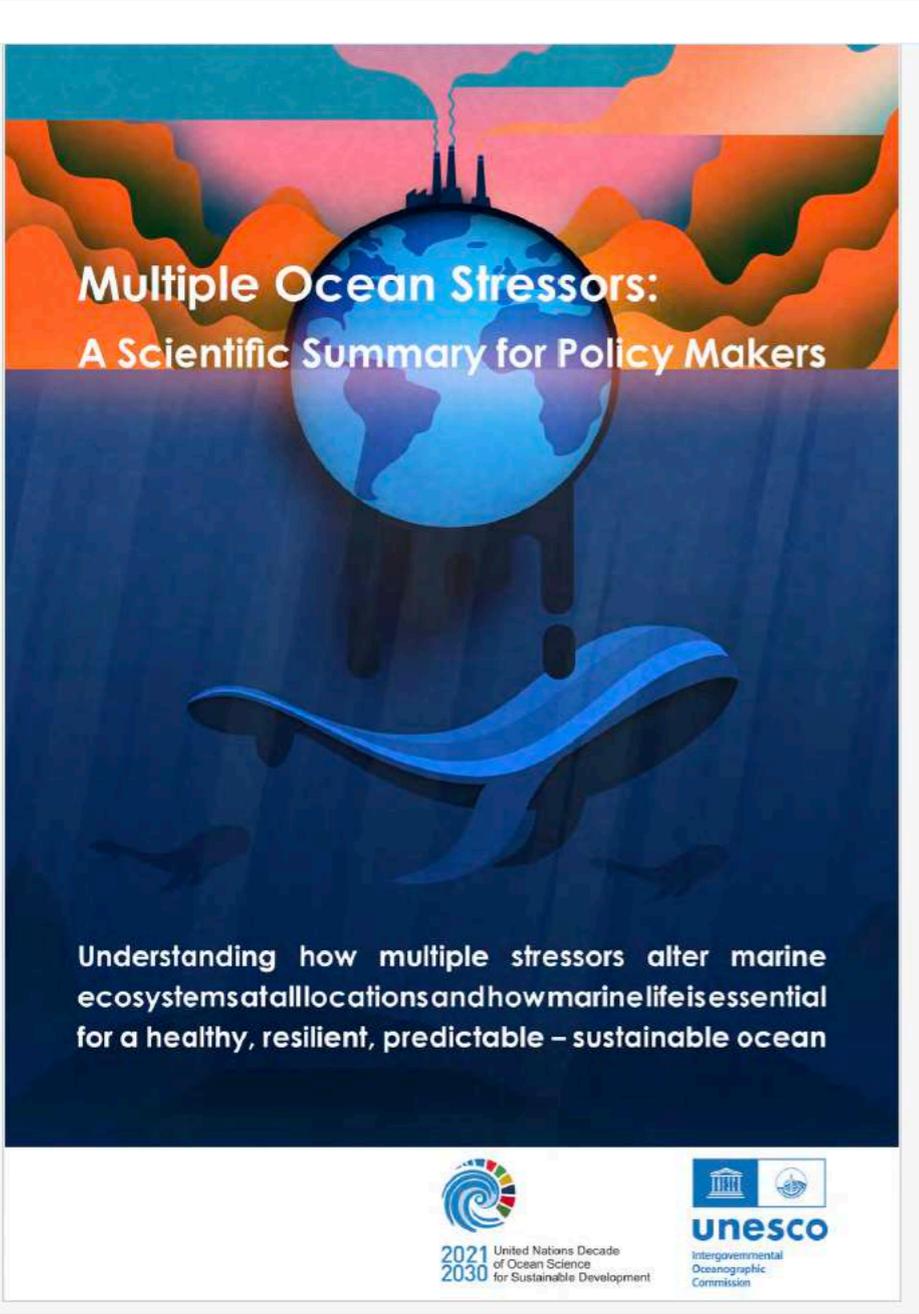
MARITIME TRANSPORT

3%

of global greenhouse gas emissions come from maritime transport.

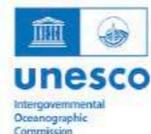
NICE FRANCE
3-6 June 2025





Multiple Ocean Stressors: A Scientific Summary for Policy Makers

Understanding how multiple stressors alter marine ecosystems at all locations and how marine life is essential for a healthy, resilient, predictable – sustainable ocean



Box 1. Definitions to remember

Drivers: Environmental properties (e.g. temperature) and ecological processes (e.g. grazing pressure) that influence marine life and its productivity and diversity. Drivers can be natural or anthropogenic forces that cause beneficial or detrimental effects. For example, temperature determines growth rates but excessive temperature causes stress and eventually mortality.

Healthy ocean: The ocean is healthy if and only if it is resilient, productive, and diverse.

Stressors: Environmental properties or ecological processes, which at a certain threshold (e.g. excess nutrient supply or over-harvesting) results in detrimental effects to marine life. Stressors, individually or collectively, are directly responsible for a range of significant harmful changes to the biological components, patterns, and relationships in natural systems.

How do we know?

npj | ocean sustainability

Article



<https://doi.org/10.1038/s44183-025-00108-7>

Strengthening the seascape of global environmental assessments to support ocean sustainability

 Check for updates

Juliette Jacquemont^{1,8}✉, Tanya Brodie-Rudolph^{2,8}✉, Leopoldo Cavaleri Gerhardinger^{3,7},
Joachim Claudet⁴, Hans-Otto Pörtner⁵ & Françoise Gaill^{4,6}



<https://doi.org/10.1038/s44183-025-00108-7>

Strengthening the seascapes of global environmental assessments to support ocean sustainability

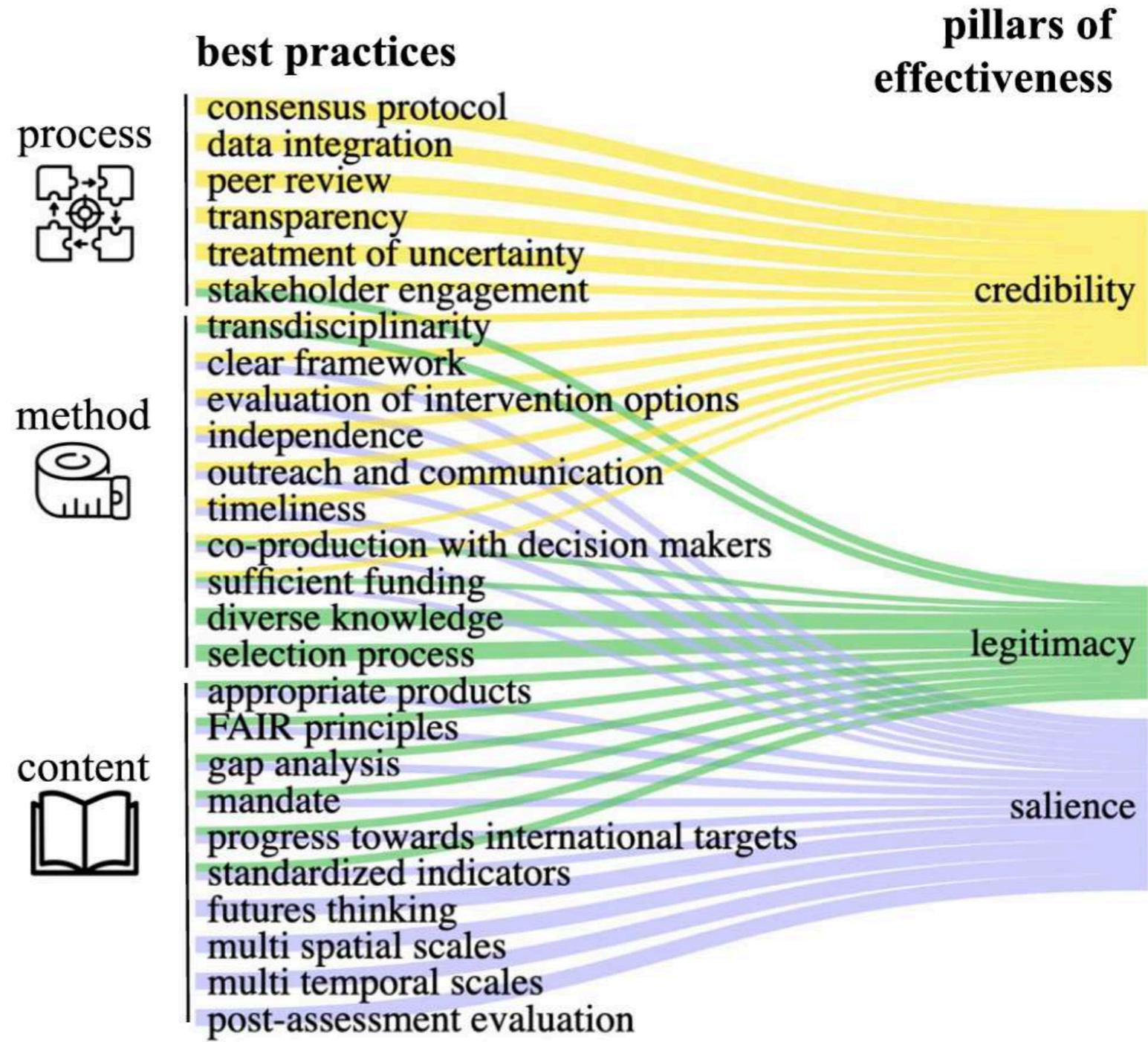


Fig. 1 | Best practices contributing to the legitimacy, credibility, and salience of Global Environmental Assessments. Links connecting best practices to two (resp. three) pillars of effectiveness are twice (resp. three-fold) thinner than links connecting best practices to a single pillar. Definitions of best practices are provided in Supplementary Table S2.

Primary literature (data structured papers)

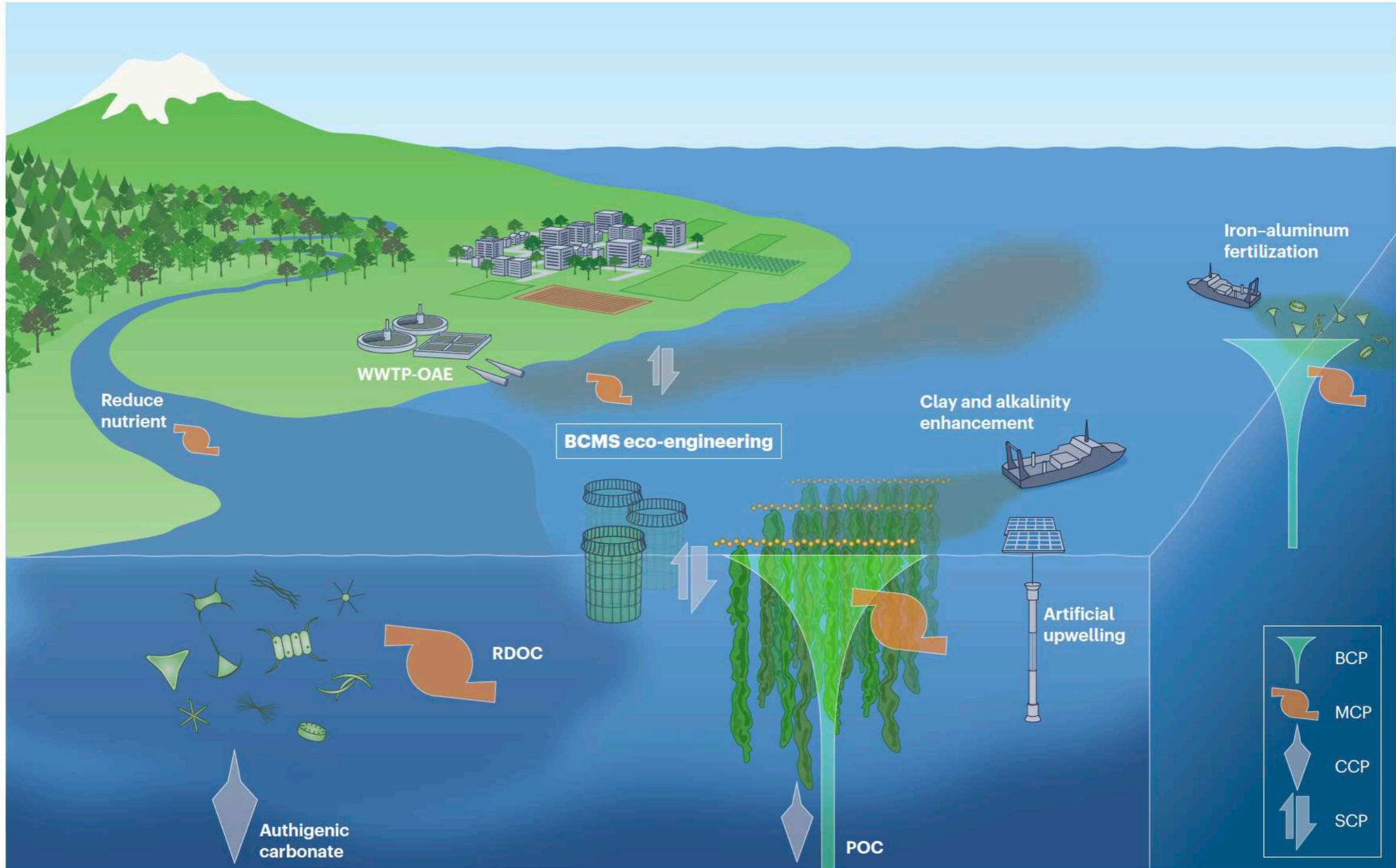
Versus

Grey literature included material published online, such as blogs, opinion pieces, project briefs and mission statements, in addition to more traditional grey literature material, such as technical reports, white papers, guidelines and policy documents

Carbon sequestration strategies

An integrated approach for maximum carbon sequestration in the ocean

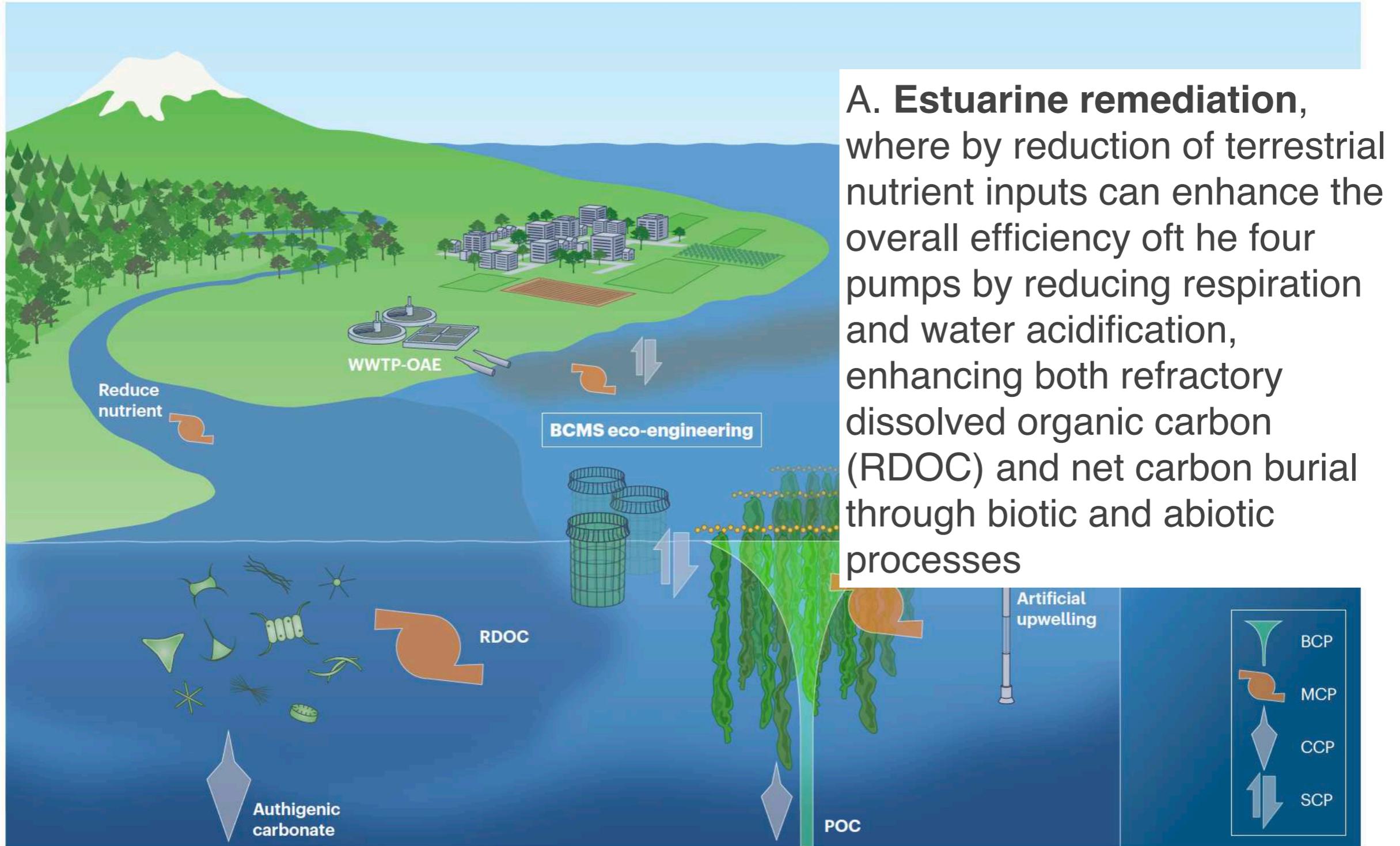
Jiao et al., 2024



Biological carbon pump (BCP), the carbonate counter pump (CCP), the microbial carbon pump (MCP) and the solubility carbon pump (SCP)

An integrated approach for maximum carbon sequestration in the ocean

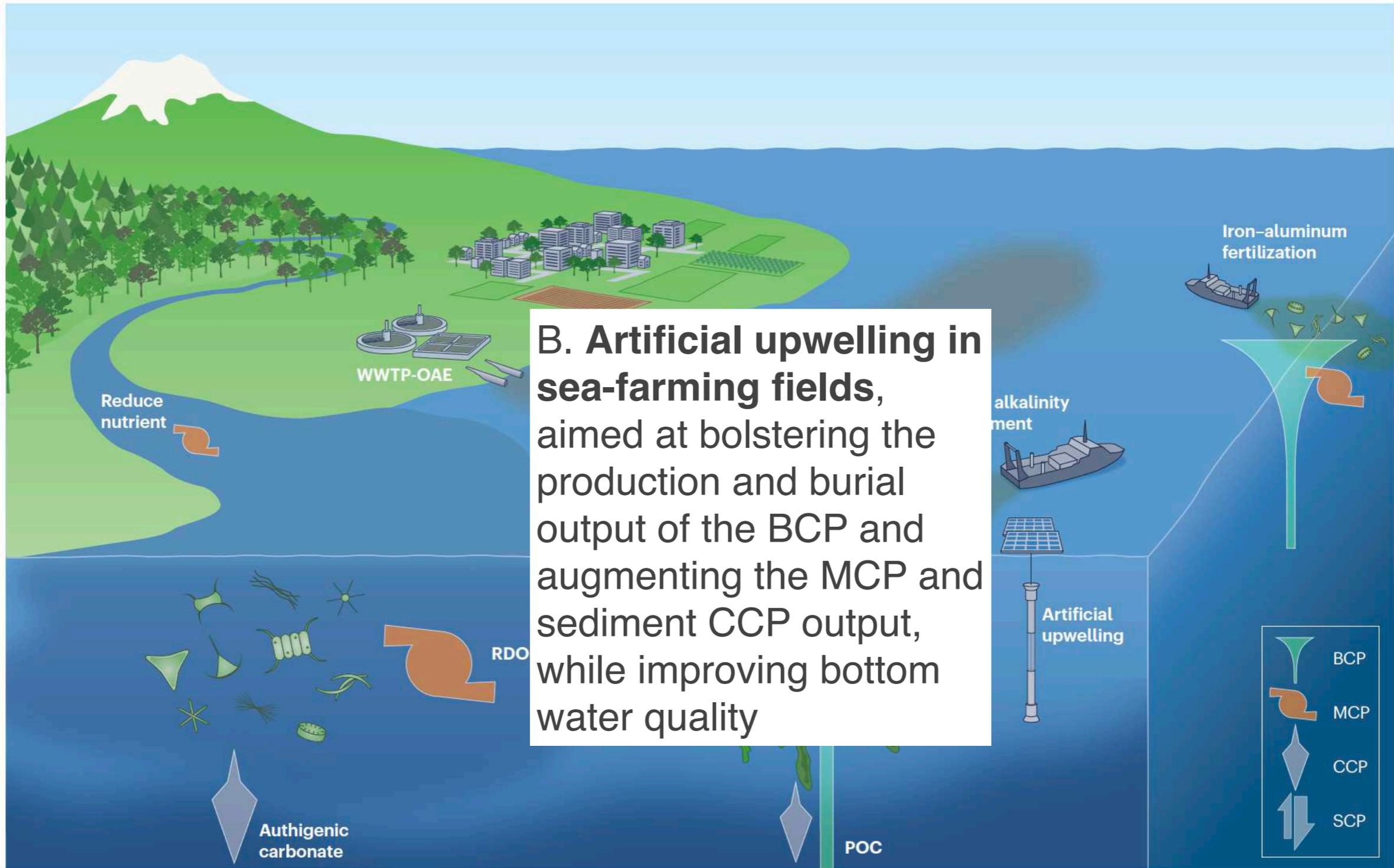
Jiao et al., 2024



Biological carbon pump (BCP), the carbonate counter pump (CCP), the microbial carbon pump (MCP) and the solubility carbon pump (SCP)

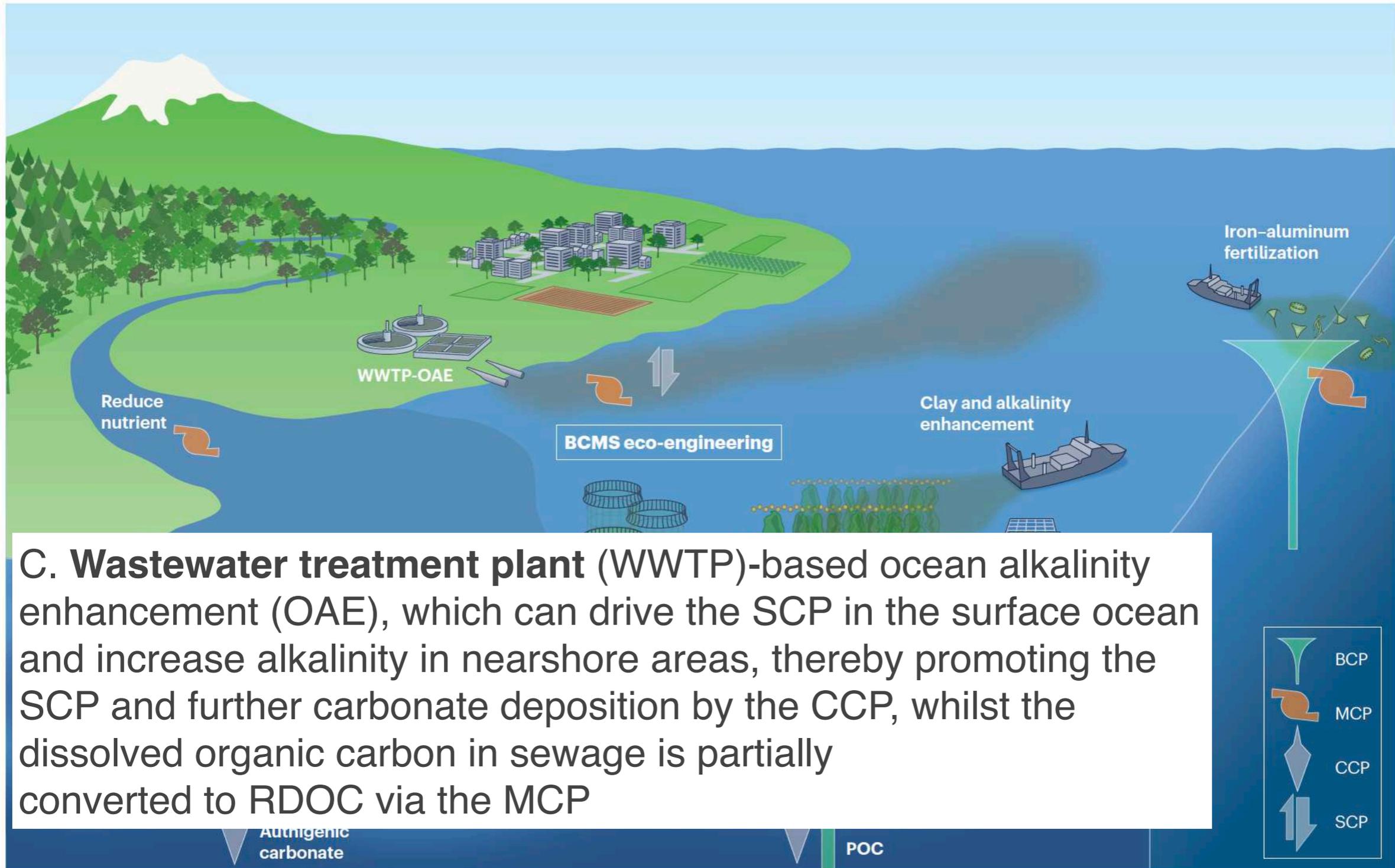
An integrated approach for maximum carbon sequestration in the ocean

Jiao et al., 2024



Biological carbon pump (BCP), the carbonate counter pump (CCP), the microbial carbon pump (MCP) and the solubility carbon pump (SCP)

An integrated approach for maximum carbon sequestration in the ocean

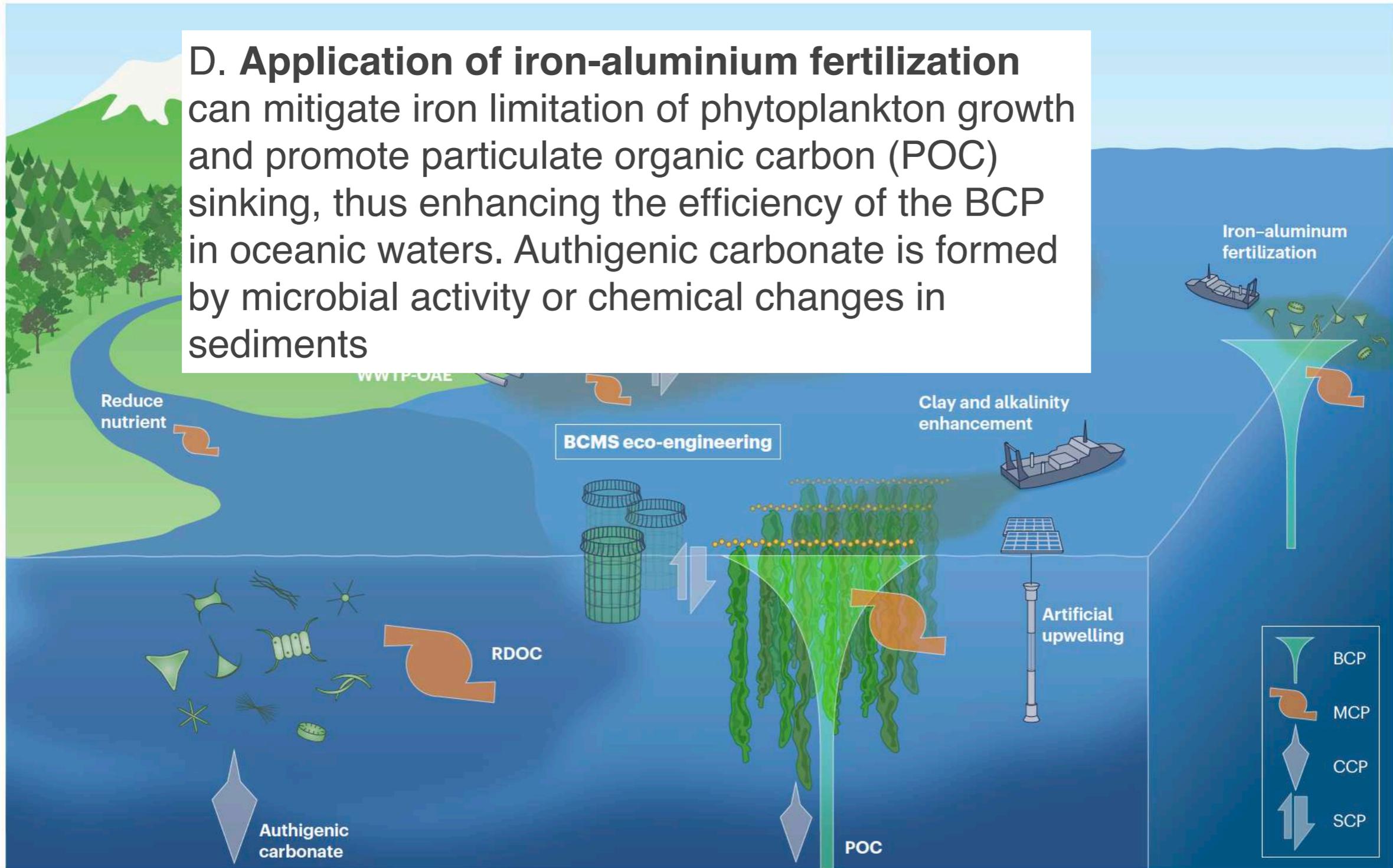


Jiao et al., 2024

Biological carbon pump (BCP), the carbonate counter pump (CCP), the microbial carbon pump (MCP) and the solubility carbon pump (SCP)

An integrated approach for maximum carbon sequestration in the ocean

D. Application of iron-aluminium fertilization can mitigate iron limitation of phytoplankton growth and promote particulate organic carbon (POC) sinking, thus enhancing the efficiency of the BCP in oceanic waters. Authigenic carbonate is formed by microbial activity or chemical changes in sediments

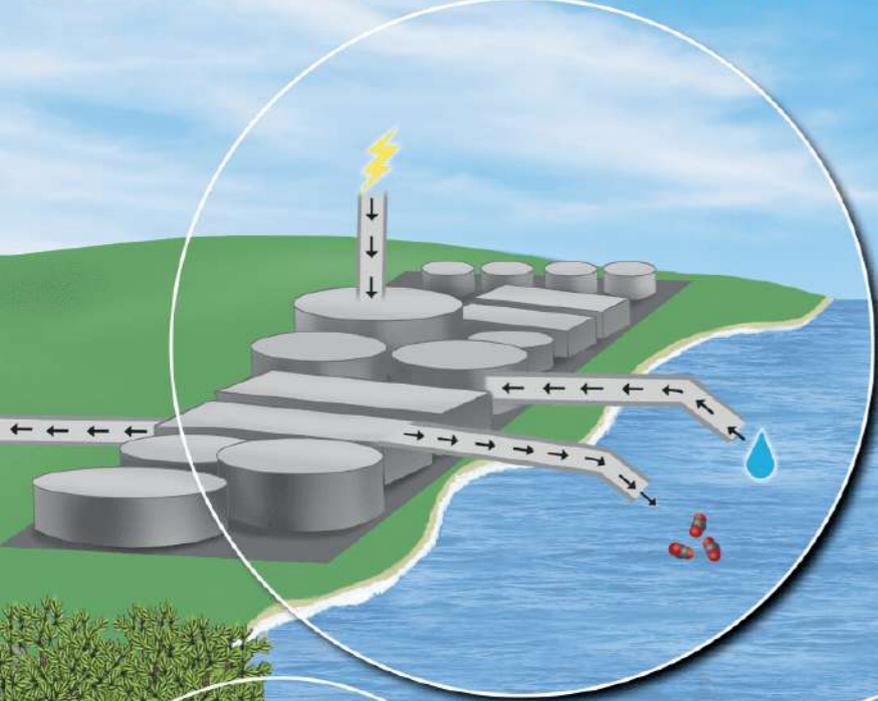


Jiao et al., 2024

Biological carbon pump (BCP), the carbonate counter pump (CCP), the microbial carbon pump (MCP) and the solubility carbon pump (SCP)

OCEAN-BASED CARBON DIOXIDE REMOVAL

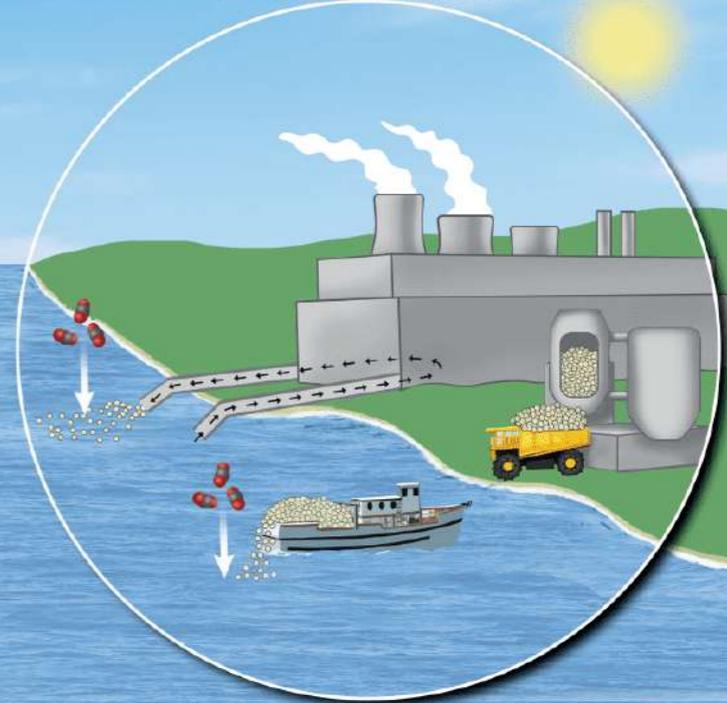
ELECTROCHEMICAL OCEAN CARBON DIOXIDE REMOVAL



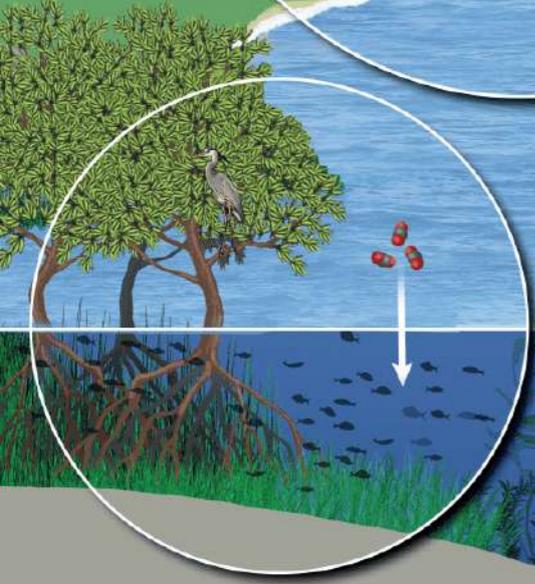
DEEP SEA STORAGE



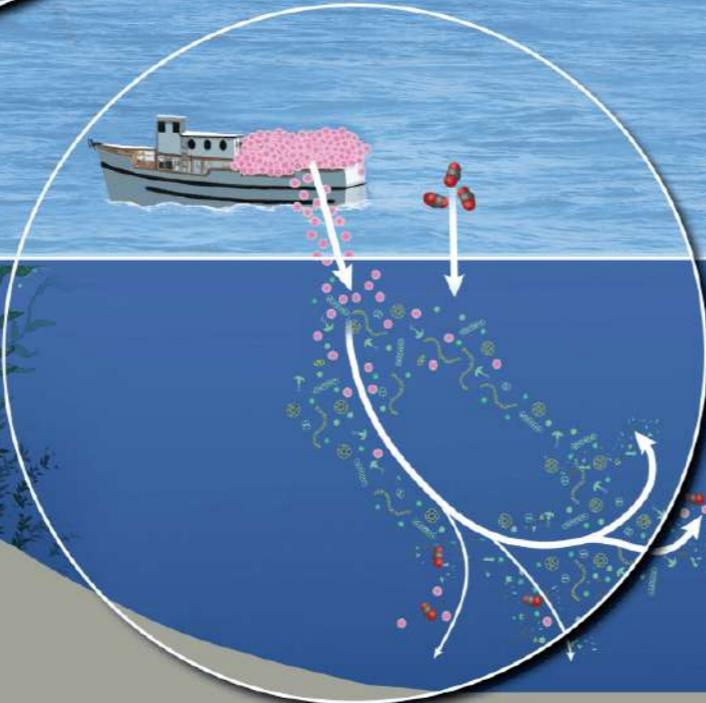
OCEAN ALKALINITY ENHANCEMENT



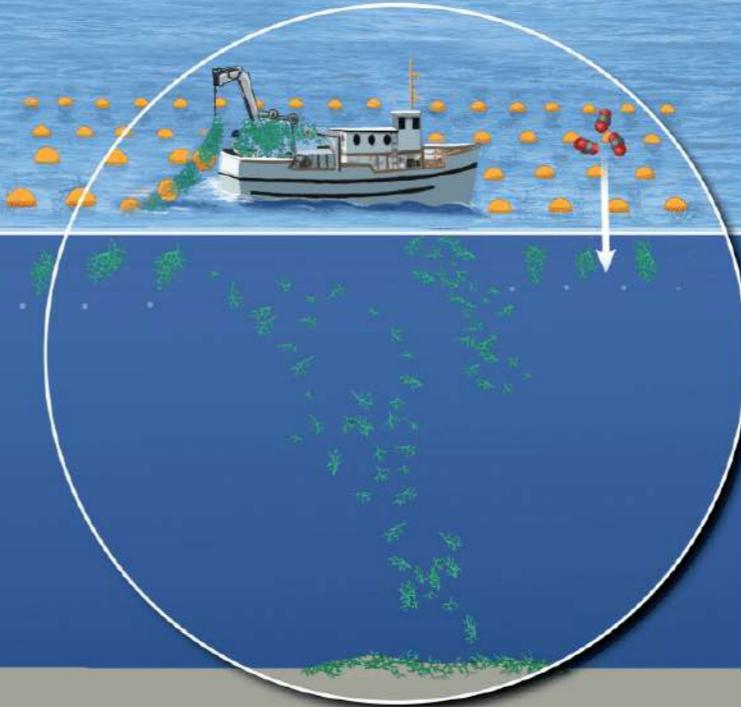
RESTORING LIVING BLUE CARBON



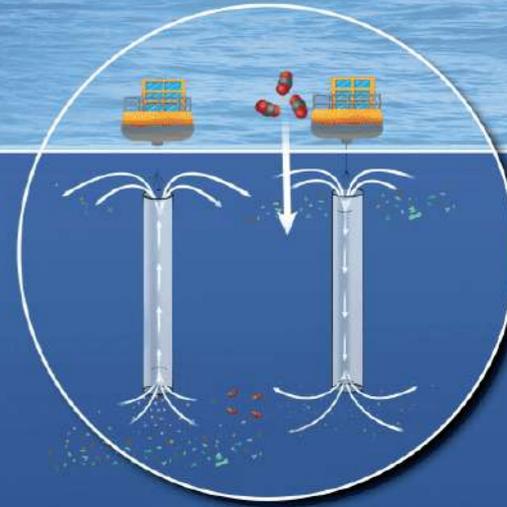
MICROALGAE CULTIVATION



MACROALGAE CULTIVATION AND CARBON SEQUESTRATION



ARTIFICIAL UPWELLING AND DOWNWELLING



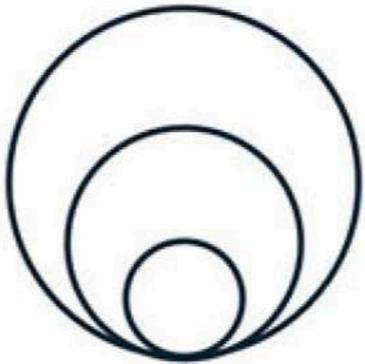
Rewilding/Restoration

Rewilding was presented by its pioneers as the large-scale restoration of wilderness

3 key attributes: large core reserves (such as protected areas); landscape connectivity (linkages and corridors to connect species populations and habitats); and re-establishment of keystone species (often apex predators or large herbivores)

Key:

-  Habitat restoration
-  Spatial protection
-  Repairing ecological linkages
-  Reduction of human pressures
-  Consideration of land-based influences
-  Climate change focused
-  Social factors
-  Broad rewilding, ecosystem restoration
-  Reference conditions
-  Political intervention
-  Evidence of success, best practice

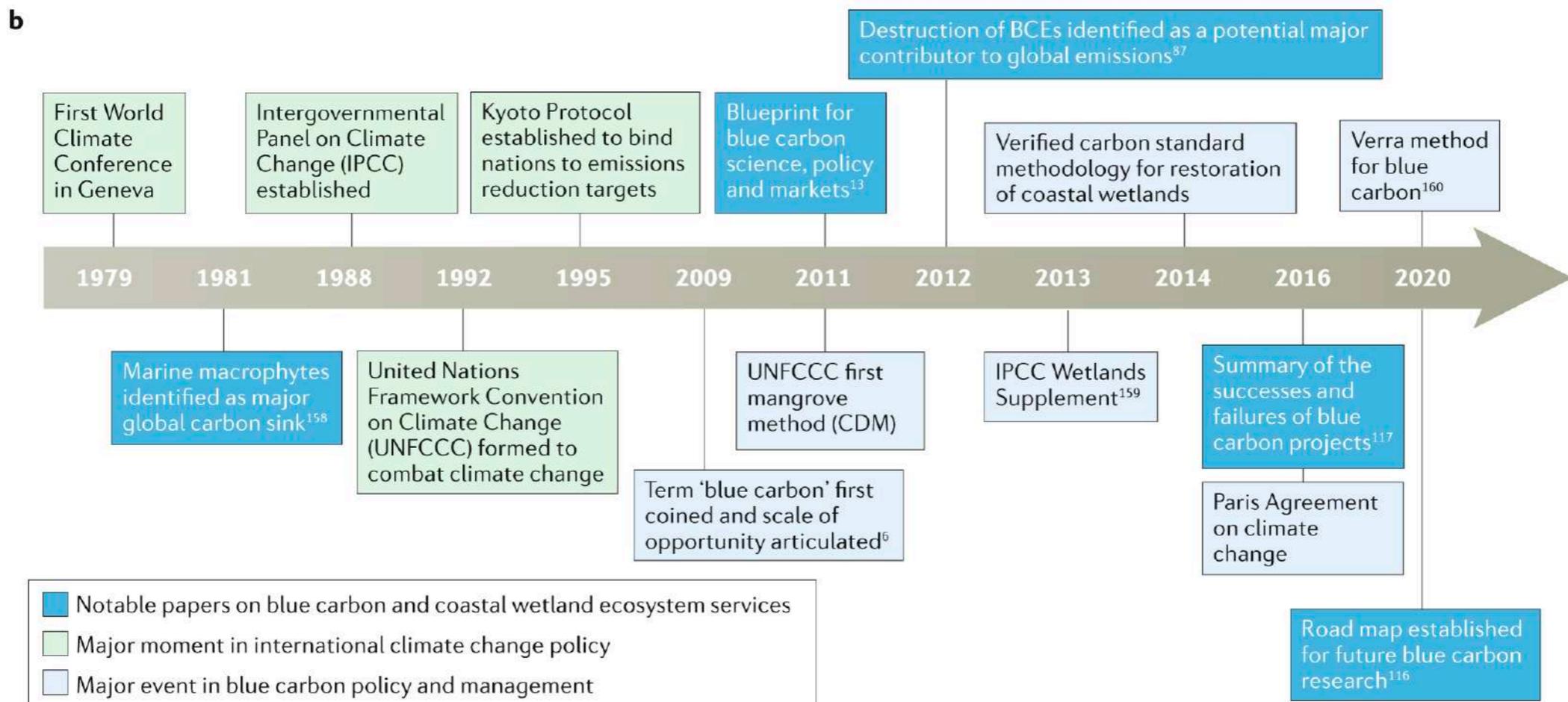
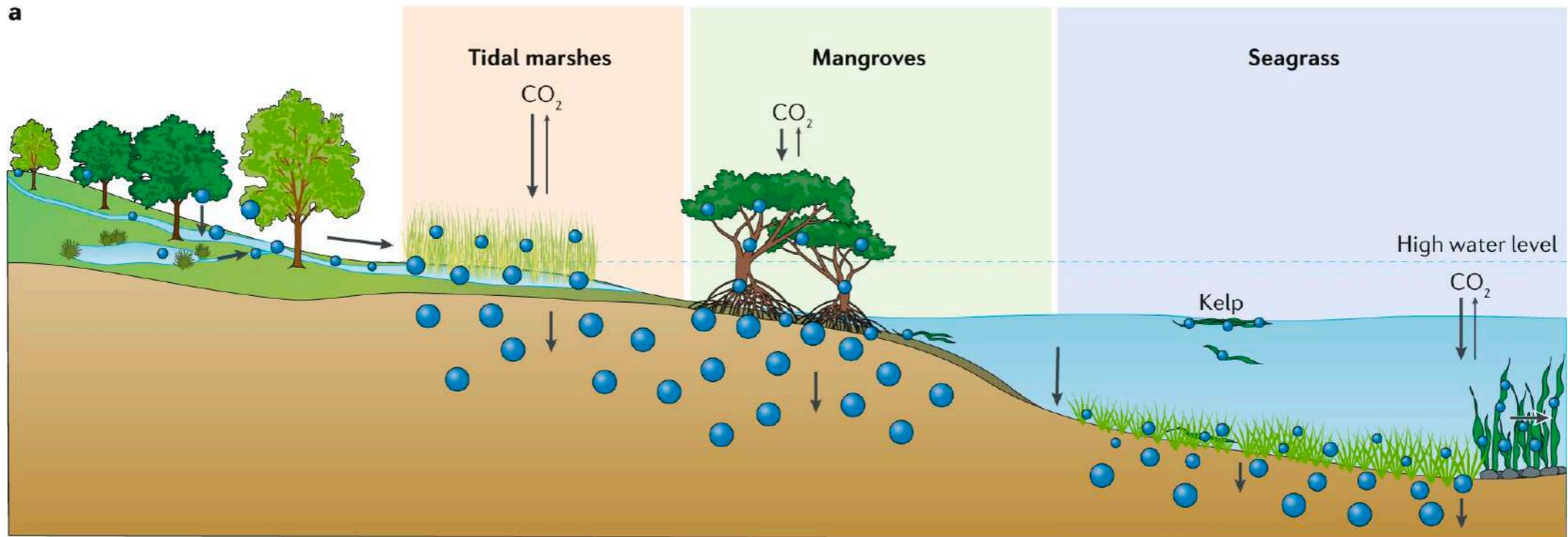


Regional or international scale
County or national scale
Local or project scale

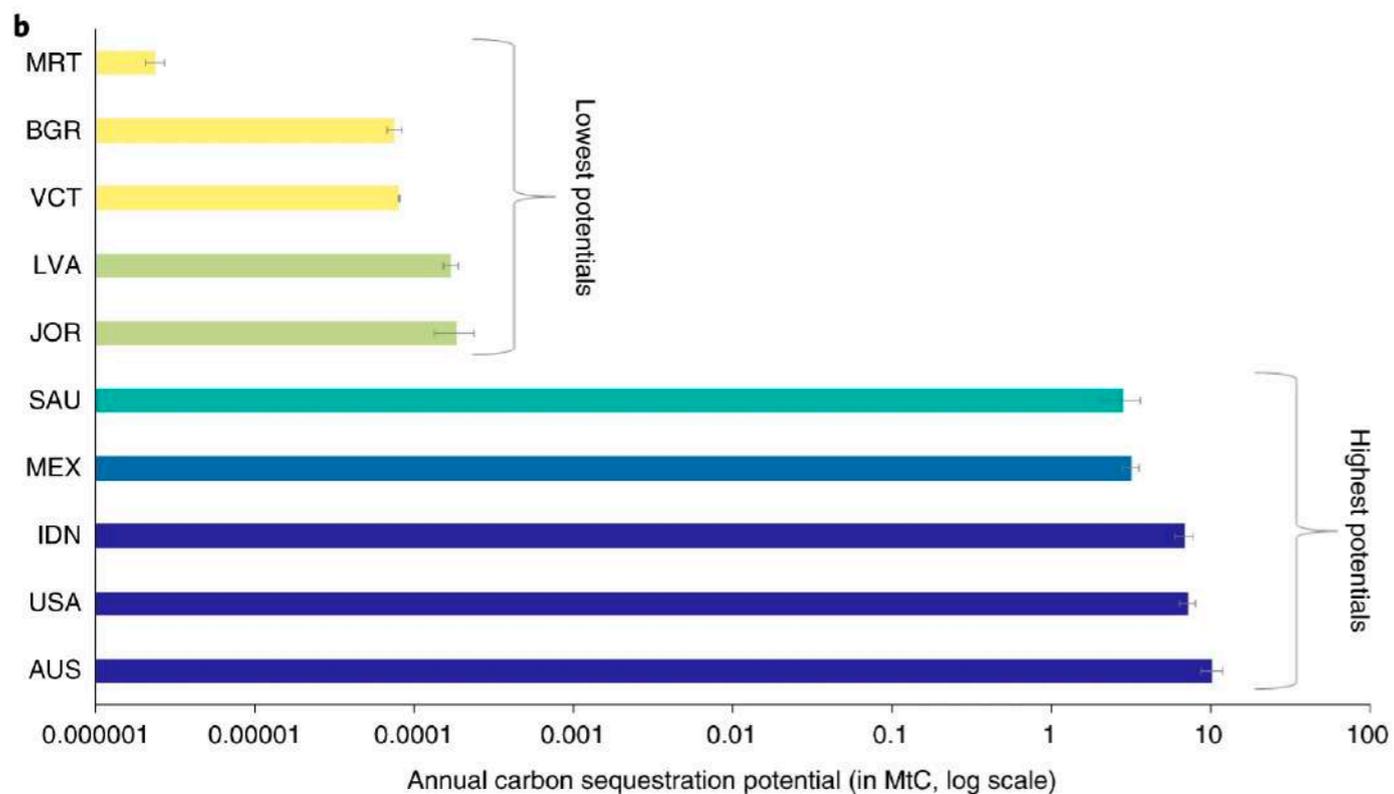
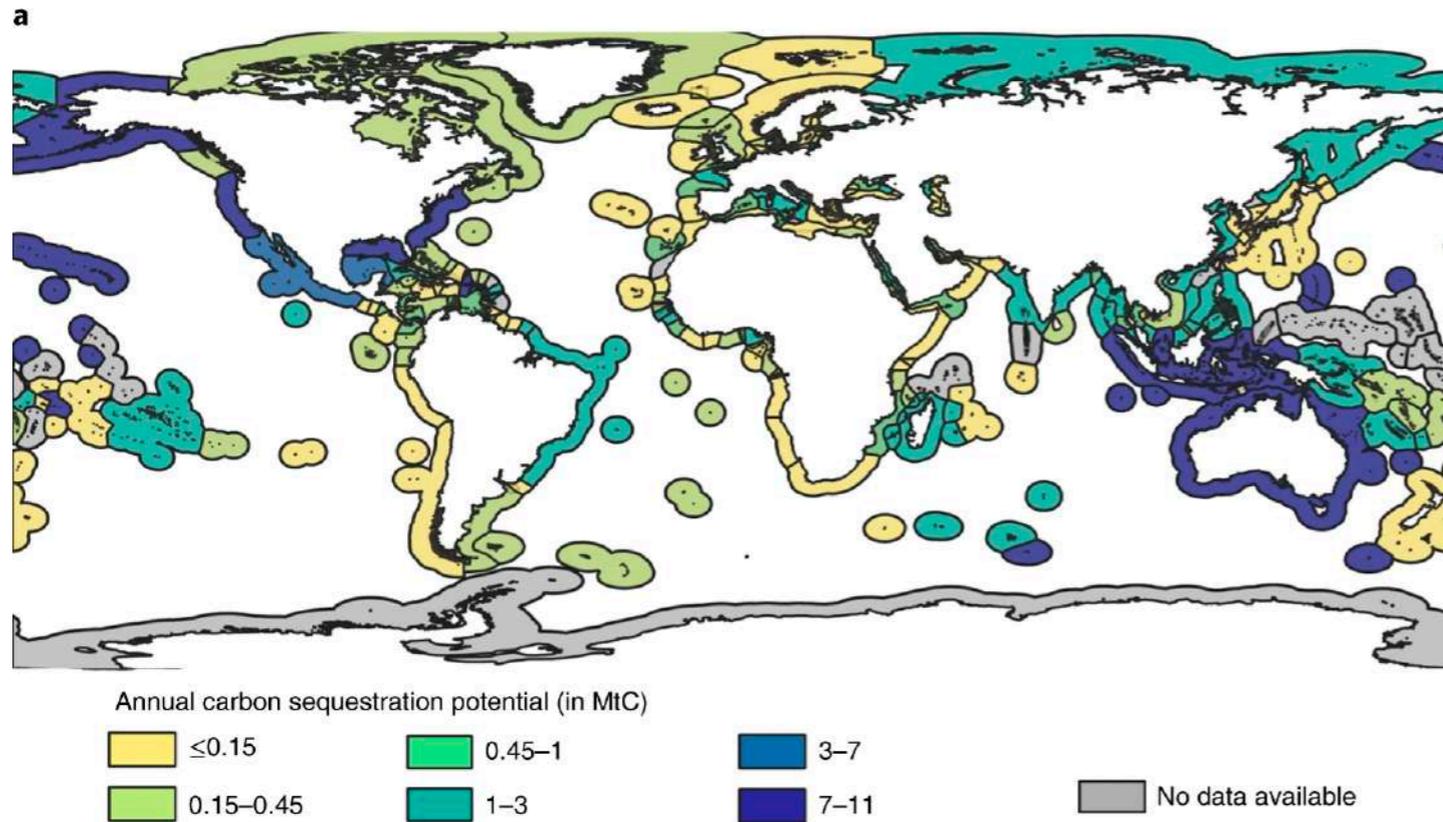
Restoration for Blue Carbon

<https://www.thebluecarboninitiative.org/>

Blue carbon ecosystems (BCEs), including mangrove forests, seagrass meadows and tidal marshes, store carbon and provide co-benefits such as coastal protection and fisheries enhancement



Global map of mean annual blue carbon sequestration potentials by country



b, Bar chart of the five countries with the largest and smallest mean annual blue carbon sequestration potentials. Mean national carbon sequestration potentials are based on spatial ecosystem coverages and mean global net sequestration rates, both per ecosystem type.

Error bars in **b** represent ± 1 s.e.m. of global carbon sequestration rates. MRT, Mauritania; BGR, Bulgaria; VCT, Saint Vincent and the Grenadines; LVA, Latvia; JOR, Jordan; SAU, Saudi Arabia; MEX, Mexico; IDN, Indonesia; USA, United States; AUS, Australia

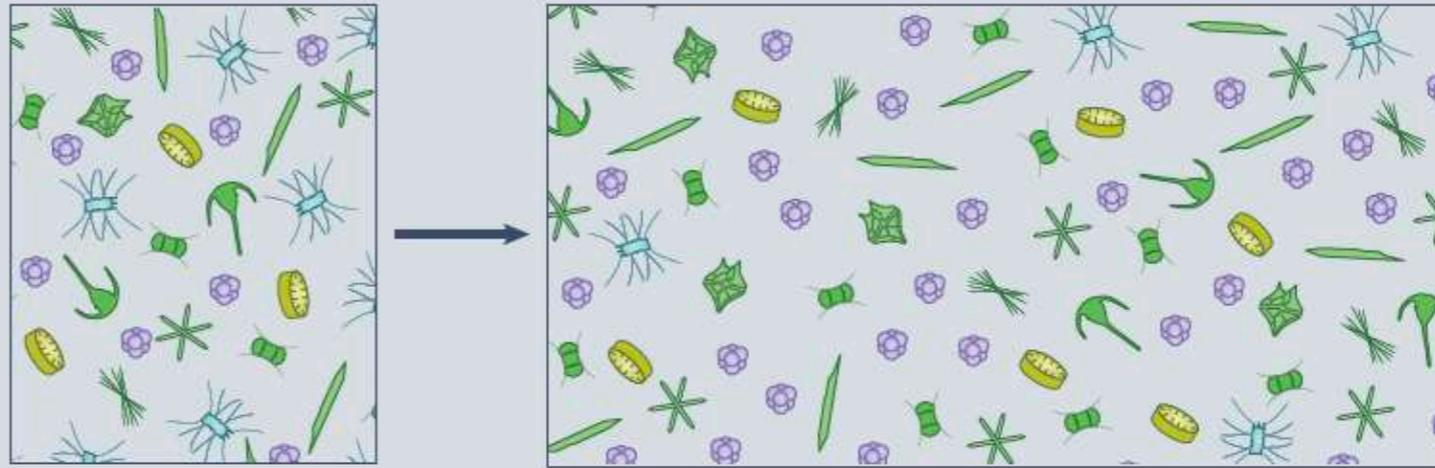
Carbon dioxide removal (CDR)

CDR

Boyd et al., 2022

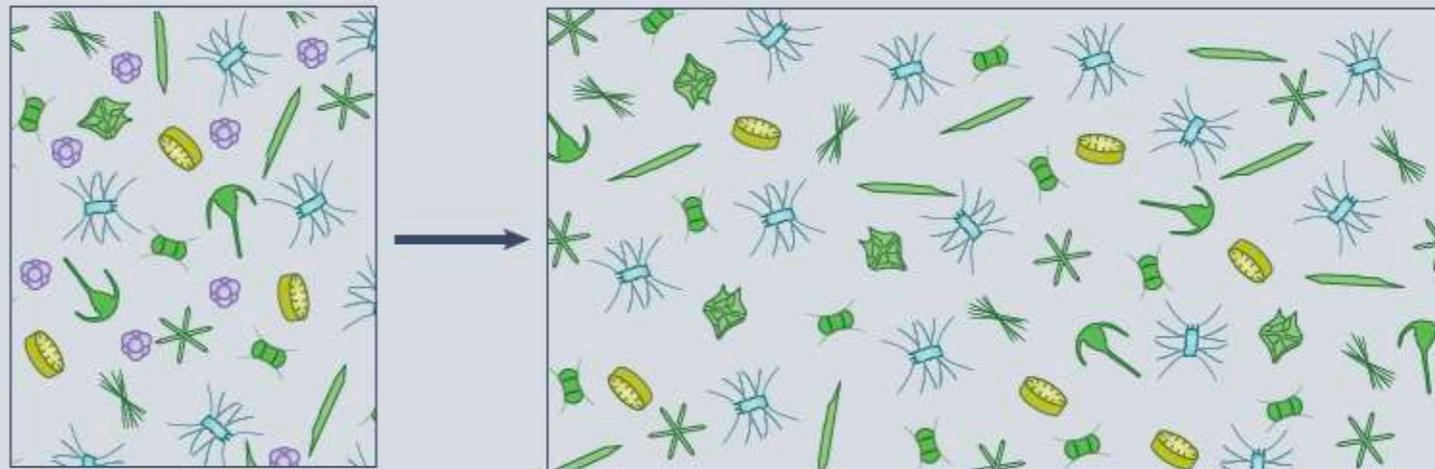
a

Ocean alkalinity enhancement (OAE)



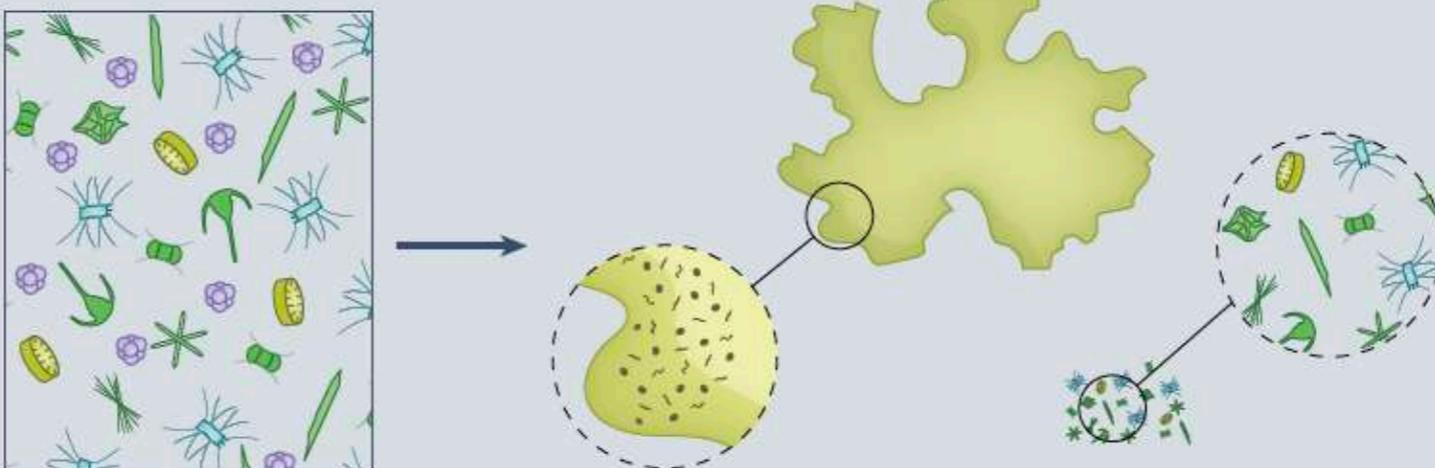
b

Ocean iron fertilization (OIF)



c

Ocean afforestation

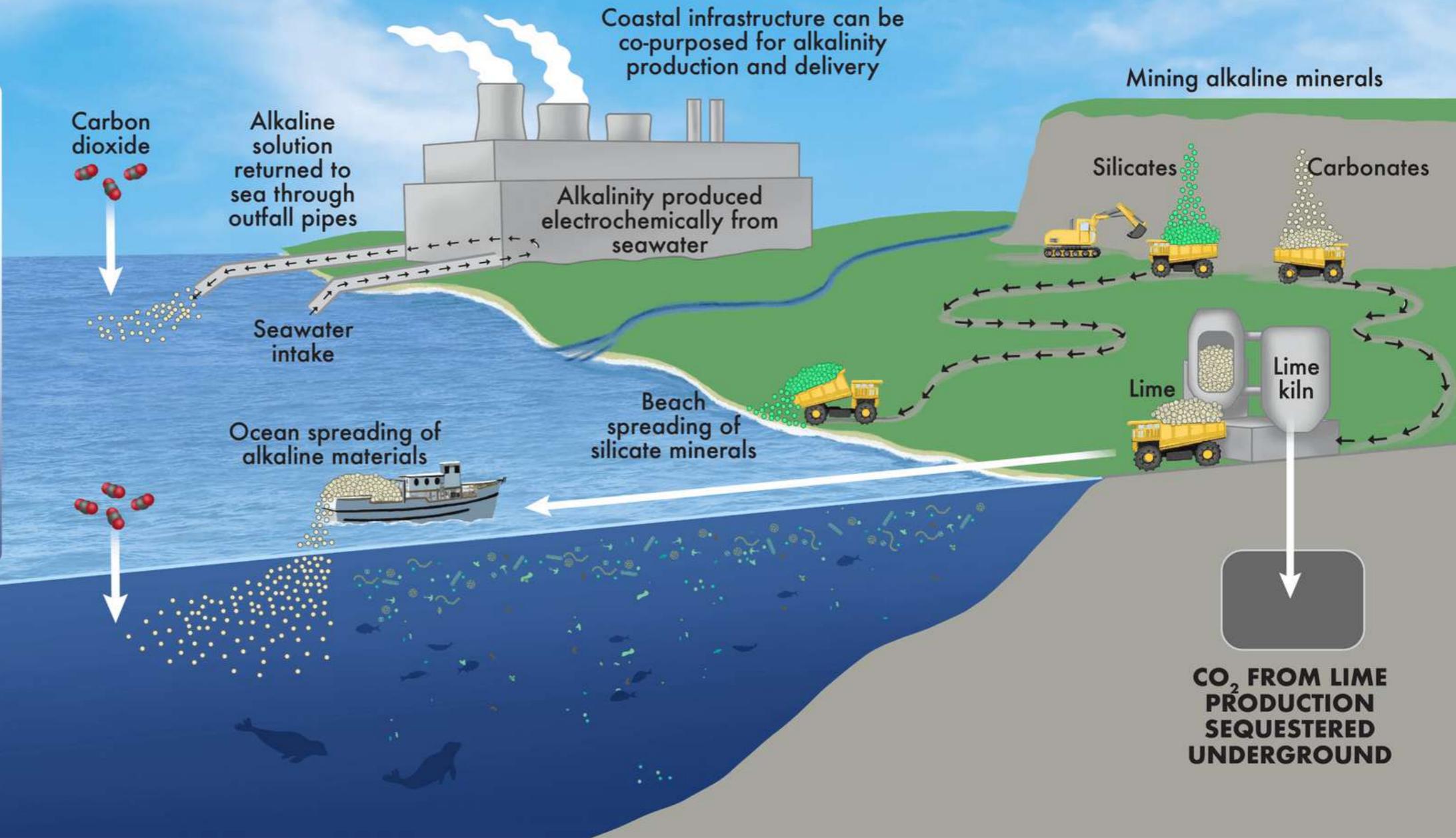


At basin scales, to populate what some proponents refer to as 'ocean deserts' (<https://www.theintrepidfoundation.org/t/seaweed-regeneration>) with coastal macroalgae attached to free-drifting platforms

OCEAN ALKALINITY ENHANCEMENT

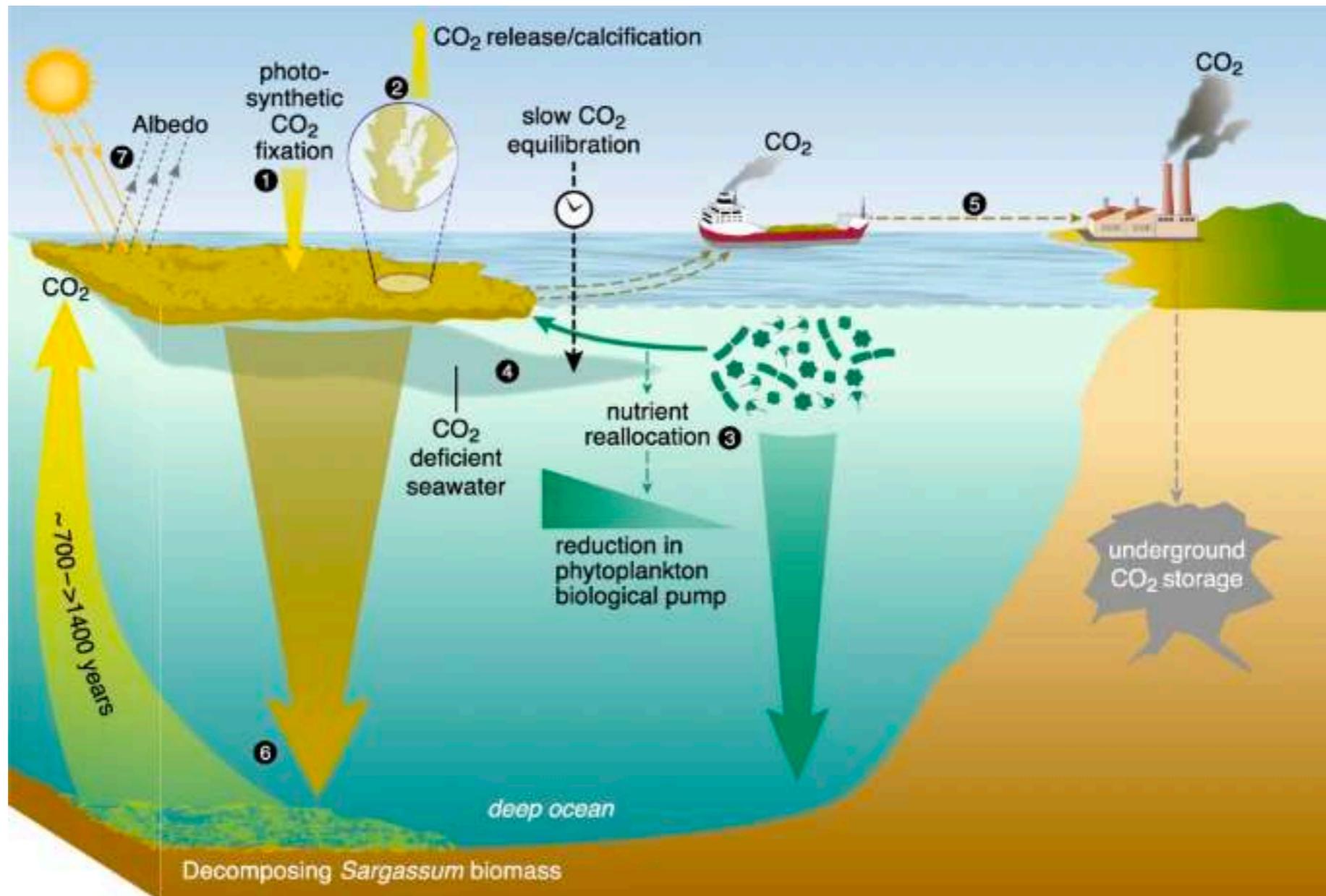
CARBON DIOXIDE IN SEAWATER + ALKALINITY = CARBON STORED IN THE OCEAN AS BICARBONATE

The diagram shows a chemical reaction where carbon dioxide (CO_2) and water (H_2O) combine with alkaline materials to form bicarbonate storage. The reaction is represented by a tree-like structure with CO_2 and H_2O at the top, branching down to 'Alkaline materials' on the right and 'Bicarbonate storage' at the bottom. Molecular models of CO_2 , H_2O , and bicarbonate ions are shown.



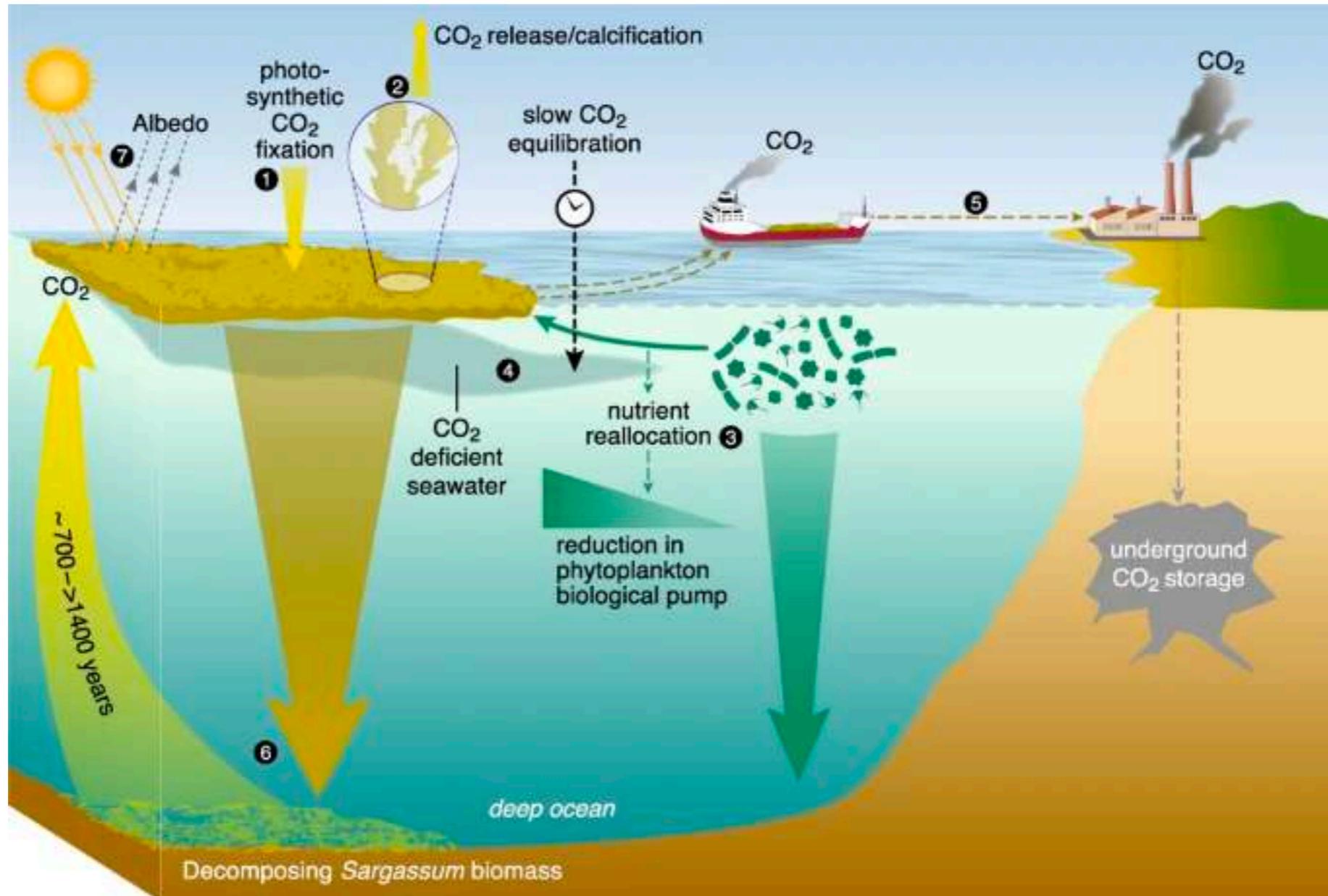
CO_2 FROM LIME PRODUCTION SEQUESTERED UNDERGROUND

Afforestation



Bach et al., 2021

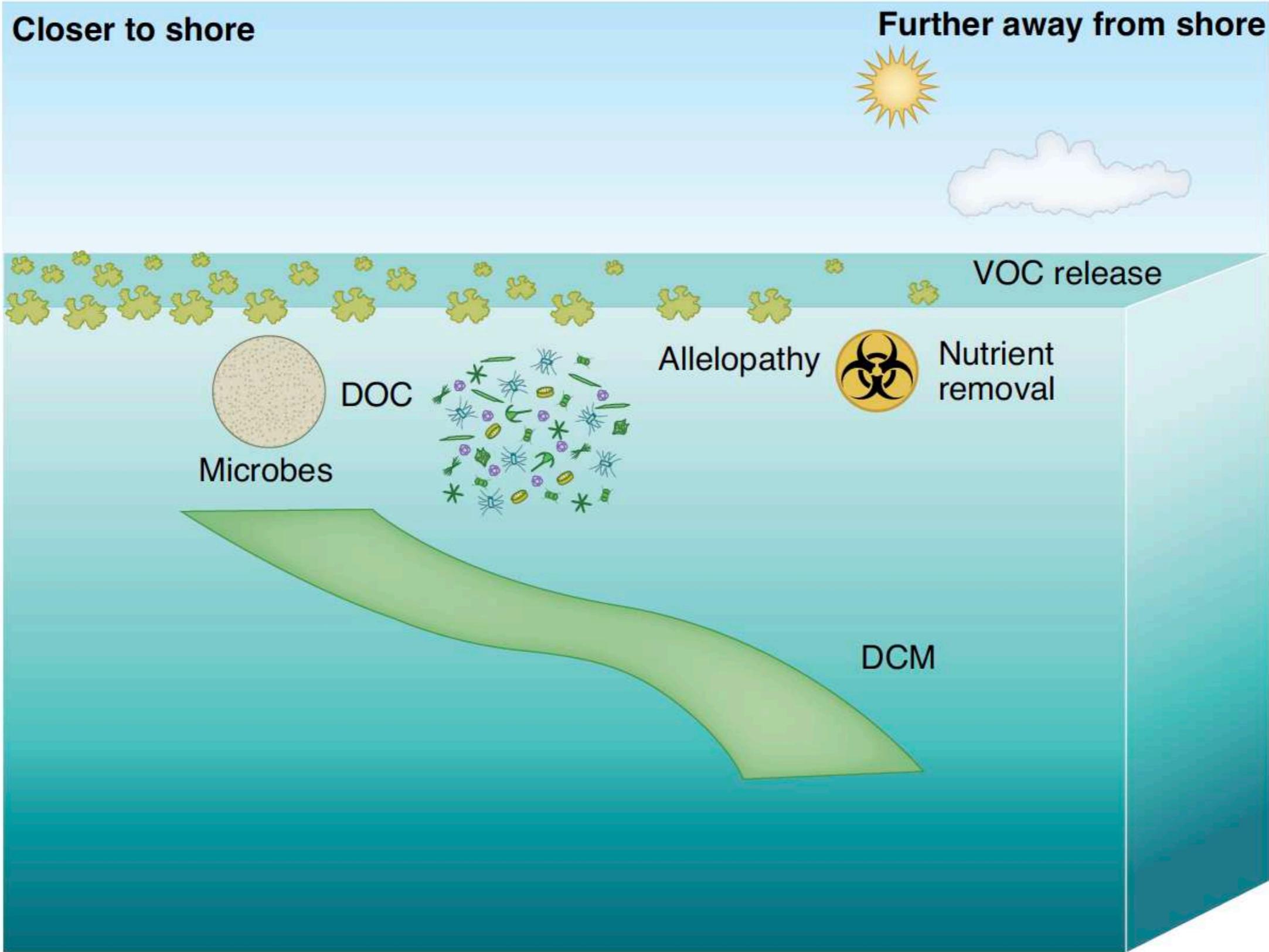
1. Photosynthetic carbon fixation by *Sargassum* consumes CO₂ dissolved in seawater
2. *Sargassum* provides habitat for epibiontic encrusting organisms to calcify, thereby generating CO₂ through complicated feedbacks in the seawater carbonate system
3. Nutrients taken up by *Sargassum* become unavailable for phytoplankton thereby reducing the natural carbon sequestration by phytoplankton
4. CO₂ deficient seawater (driven by photosynthesis) can be subducted below the surface layer before it fully equilibrates with atmospheric CO₂



Bach et al., 2021

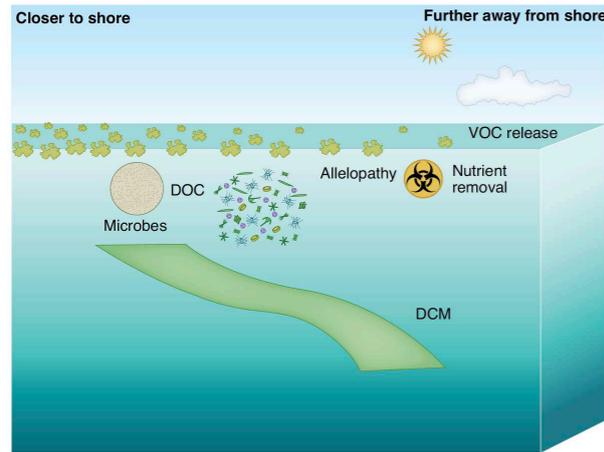
5. *Sargassum* biomass can be harvested and transported to shore and used for Bioenergy with Carbon Capture and Storage (BECCS) causing CO₂ discounts
6. Alternatively, *Sargassum* could be deposited on the seafloor but a large fraction of the respired *Sargassum* carbon would come back to surface on centennial-millennial timescales
7. *Sargassum* increases albedo at the sea surface but could also induce complicated indirect albedo effects of unknown sign and magnitude

Potential ecological consequences of the offshore transport and dispersal of macroalgal rafts



Potential ecological consequences of the offshore transport and dispersal of macroalgal rafts

Boyd et al., 2022



Ocean afforestation side effects may have direct and indirect influences on offshore food webs

Direct effects include **allelopathy** (that is, **chemical ecological competition between macroalgae and microalgae (green cells)**, represented by a chemical hazard symbol) and **coastal microbial colonization of oceanic waters originating from the macroalgal biome** (denoted by the stippled disc symbol)

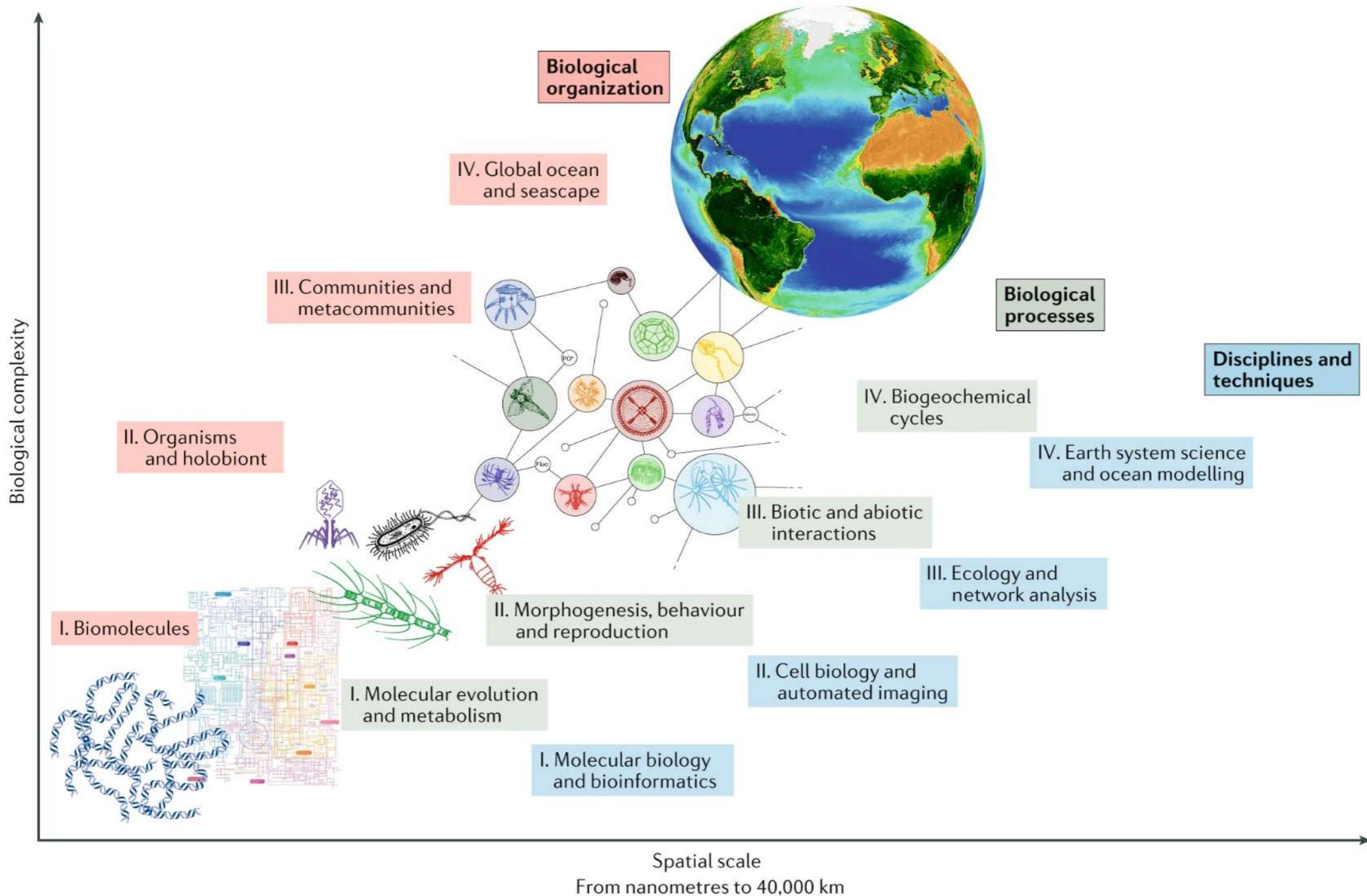
Indirect effects include alteration of seawater properties (**nutrient removal**), **release of macroalgal DOC** (impacts on oceanic microbes) and VOCs (cloud symbol), altered light climate (reflectance) and underwater light penetration

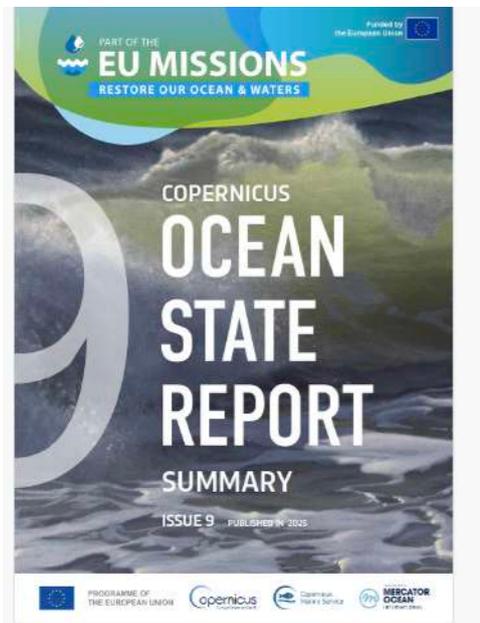
Research into the **implications of VOC release** for lower atmosphere processes is a major unknown

Reduced light penetration in the water column due to shading from macroalgal rafts may impact the location and functioning of the DCM, denoted by the green subsurface layer, deepening offshore due to a higher density of macroalgal rafts (more underwater shading)

The DCM is a subsurface niche set jointly by underwater irradiance levels and subsurface nutrient supply

Ecosystems biology and integrative analyses of the global oceans





OCEAN STATE

Current health of the ocean

HUMAN PRESSURES

Pollution, greenhouse gas emissions and overexploitation

SOCIETAL HARMS

Escalating costs from ocean-related disasters

PROTECTION EFFORTS

Actions to protect and preserve the ocean

OPPORTUNITIES FOR HUMANITY

Blue economy sectors and ecosystem services



The sea is rising. Its level has increased globally by 23 cm since 1901



Fossil fuel CO₂ emissions are rising including a 2.7% increase from shipping



Global losses from tropical storms and floods hit US\$ 102 billion



Global protected areas hit 8.34% but efforts are still needed



Marine animal food production reached a record 115 million tonnes



The ocean reached its highest recorded temperatures



Unsustainable fishing hits 37.7% while 75% of large vessels go untracked



Insurance premium costs incurred by maritime activities grew by 5.9%



Multilateral ocean governance advances



The marine-derived health market is growing amid high inequity



1,677 marine species are threatened with extinction



Rising human and climate pressures threaten ocean habitats globally



9,002 migrants lost their lives at sea



Equity rises as a driving force in global ocean conservation



US\$ 2.6 trillion ocean economy powers 134 million jobs



The 4th major coral bleaching record event hit the ocean



Plastic pollution is rising but still no global system to monitor and assess it



US\$ 250 billion health cost and 1,200 species affected by marine plastic pollution



Ocean literacy is gaining global momentum



Small-scale fisheries support 88% of marine harvest jobs and US\$ 51.8 billion

THE END