

Microbial Ecology

- Study of the interactions of microorganisms with their environment (including organic matter), each other, and plant and animal species (other organisms) —> symbioses, biogeochemical cycles, climate change
 - Atmosphere as a microbial environment
 - Biogeochemical cycles in the environment (including pollution)
 - Anthropocene and Climate Change

ATNOSPHERE

The atmospheric ecological niche



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

One Atmosphere that we all breath



Diverse aerosol particles Atmospheric aerosols are a collection of small liquid droplets and/or solid particles suspended in air Microbes exchange: 6 × 10⁴ and 1.6 > 10⁷ microbes per m² of ocean per day



Patterns of microbial diversity and abundance in the atmosphere



Factors affecting atmospheric microbial transport and macroecological outcomes



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



Biophysical role of atmospheric microorganisms in ice nucleation



• And what about pathogens?



BIOGEOCHEMICAL CYCLES

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

Madsen, 2011

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

Biogeochemical processes

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

Process Nature of process		Typical habitat	
Carbon cycle			
Photosynthesis	Light-driven CO ₂ fixation into biomass	Ow, Fw, FwS, C	Ds
C respiration	Oxidation of organic C to CO ₂	All	
Cellulose decomposition	Depolymerization, respiration	SI	
Methanogenesis	CH ₄ production	Sw, FwS, Os	
Aerobic CH ₄ oxidation	CH ₄ becomes CO ₂	All)5
Anaerobic CH ₄ oxidation	CH ₄ becomes CO ₂	Os	, 200
			sen
Biodegradation			lad
Synthetic organic compounds	Decomposition, CO ₂ formation	All	2
Petroleum hydrocarbons	Decomposition, CO ₂ formation	All	
Fuel additives (MTBE)	Decomposition, CO ₂ formation	SI, Sw, Gw	
Nitroaromatics	Decomposition, CO ₂ formation	SI, Sw, Gw	
Pharmaceuticals, personal care products	Decomposition	SI, Sw, Gw	
Chlorinated solvents	Compounds are dechlorinated through respiration in anaerobic habitats	SI, Sw, Gw	

As, arsenic; C, carbon; CH_4 , methane; CO_2 , carbon dioxide; Fe, iron; FeS, iron sulphide; Fw, freshwater; FwS, freshwater sediment; Gw, groundwater; H_2 , hydrogen; Hg, mercury; Hg²⁺, mercuric ion; MTBE, methyl tertiary butyl ether; N₂, nitrogen; NH₃, ammonia; NH₄⁺, ammonium; NO₂⁻, nitrite; NO₃⁻, nitrate; Os, ocean sediments; Ow, ocean waters; S⁰, elemental sulphur; S²⁻, sulphide; SI, soil; SO₄²⁻, sulphate; Sw, sewage; U, uranium.

Biogeochemical processes

Nitrogen cycle



nna ogon oyolo			
N ₂ fixation	N ₂ gas becomes NH ₃	SI, Ow	
NH_4^+ oxidation	NH_3 becomes NO_2^- , NO_3^-	SI, Sw	
Anaerobic NH_4^+ oxidation	NO_2^- and NH_3 become N_2 gas	Sw, Os	
Denitrification	$\mathrm{NO_3^-}$ is used as an electron acceptor and converted to $\mathrm{N_2}$ gas	SI, Sw	
Sulphur cycle			10
S_2 oxidation	S^{2-} and S^{0} become SO_{4}^{2-}	Os, FwS	200
SO ₄ ²⁻ reduction	$SO_4^{\ 2^-}$ is used as an electron acceptor and converted to S^0 and S^{2^-}	Os, Sw, Gw	sen,
Other elements			lads
H ₂ oxidation	H_2 is oxidized to H^+ , electrons reduce other substances	Sw, SI, Os, FwS	2
Hg methylation and reduction	Organic Hg is formed and Hg ²⁺ is converted to Hg	FwS, Os	
(per)chlorate reduction	Oxidants in rocket fuel and other sources are converted to chloride	Gw	
U reduction	U oxyanion is used as an electron acceptor; therefore immobilized	Gw	
As reduction	As oxyanion is used as an electron acceptor; therefore toxicity is diminished	FwS, Gw	
Fe oxidation, acid mine drainage	FeS ores are oxidized, strong acidity is generated	FwS, Gw	

As, arsenic; C, carbon; CH_4 , methane; CO_2 , carbon dioxide; Fe, iron; FeS, iron sulphide; Fw, freshwater; FwS, freshwater sediment; Gw, groundwater; H_2 , hydrogen; Hg, mercury; Hg^{2+} , mercuric ion; MTBE, methyl tertiary butyl ether; N_2 , nitrogen; NH_3 , ammonia; NH_4^+ , ammonium; NO_2^- , nitrite; NO_3^- , nitrate; Os, ocean sediments; Ow, ocean waters; S⁰, elemental sulphur; S²⁻, sulphide; SI, soil; SO_4^{-2-} , sulphate; Sw, sewage; U, uranium.

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



- 3. All substrates and products must ultimately be cycled
- 4. Biological processes are paired
- 5. Photoautotrophic microorganisms are responsible for about half of CO_2 fixation and O_2 production on Earth
- 6. Heterotrophic microorganisms are responsible for much of the return reaction: the oxidation of organic matter back into CO₂
- The temporal and spatial separation of photoautotrophy and heterotrophy in the global environment drives the biological sequestration of carbon, the reduction of atmospheric CO₂, and the maintenance of elevated atmospheric and oceanic O₂
- Chemoautotrophic microorganisms also fix CO₂ and, together with anaerobic heterotrophic metabolisms, carry out diverse chemical transformations including the fluxes of nitrogen and sulphur to and from biologically available states

Across scale integration of biogeochemistry aka microbial metabolism

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

Ultimately, this disequilibrium is maintained by constant influx of radiant energy from the sun, and constant efflux of heat and reduced materials (e.g. CH₄, H₂S, H₂) from the Earth's core

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

Madsen, 2011

Key microbially driven redox transformations



Microbial interaction with organic matter



Azam and Malfatti, 2007 Nature Reviews Microbiology 10:782

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

Carbon cycle



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



Figure 21.4 Seasonal flares of methane bubbling from methane hydrates. Methane hydrates in shallow coastal sediments are sensitive to seasonal changes in bottom water temperature. Flares of methane bubbles are observed when water temperatures warm by as little as $1-2^{\circ}$ C.

Redox cycle for Carbon

- Autotrophic processes CO₂—> organic matter
- Heterotrophic processes: organic matter -> CO₂



Interconnected cycles on Earth



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

Microbes are master recyclers

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

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

Mercury cycle

• Hg⁰ (volatile) elemental mercury major form in the atmosphere, photochemically oxidized to Hg²⁺

Long-range

atmospheric

- Toxicity: Hg⁰~Hg²⁺ <CH₃Hg⁺ & CH₃-Hg-CH₃ (volatile)
- CH₃Hg⁺ bioaccumulated and biomagnificated in trophic levels
- In anaerobic sediment $Hg^{2+} \rightarrow CH_3Hg^+$ by sulphate-reducing and iron-reducing bacteria





Photochemical and other oxidations

Chemical pollution



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

Microbial metabolisms on Earth

- 1. Life on Earth depends on the evolution of non-equilibrium redox chemistry of the intertwined C, H, O, N, P, S
- 2. All organisms derive energy for growth and maintenance by moving electrons from a substrate to a product
- 3. All substrates and products must ultimately be cycled
- 4. Biological processes are paired

Microbial metabolic pathways during Earth history: *anoxygenic world*



Molecules listed horizontally (HS–, S0, CH4, NH4+, H2O, CH2O, Exred) are reduced substrates, molecules listed vertically (SO42–, CO2, NO3–, O2, Exox) are oxidized substrates, and N2 is an intermediate and atmospheric reservoir of unreactive nitrogen

Microbial metabolic pathways during Earth history: *oxygenic world*

heterotrophy

b Exploiting the atmosphere and ocean, -500 to 800 mV



Present microbial metabolic pathways



A, ammonification; AP, anoxygenic photosynthesis; AR, aerobic respiration; AU, autotrophy; D, denitrification; EO, other elements oxidation; ER, other elements reduction (EO and ER include Fe and Mn oxidation and reduction); H, heterotrophy; M, methanogenesis; MO, methane oxidation/methanotrophy; N/AO, nitrification/ammonia oxidation; NF, nitrogen fixation; OP, oxygenic photosynthesis; SDO, sulfide oxidation; SO, sulfur oxidation; SR, sulfur reduction; STR, sulfate reduction

CLIMATE: Anthropocene and climate change

Climate, Climate Change and Microbes

- Climate is the general weather over a long period (>30 years)
- Climate can include rainfall, temperature, snow or any other weather condition
- Earth climate system comprises five **components**:
 - The atmosphere
 - The biosphere (living things)
 - The cryosphere (ice, such as sea ice, glaciers, ice sheets and permafrost)
 - The hydrosphere (water on, under or above the Earth's surface, such as oceans, lakes, rivers and clouds)
 - The lithosphere (the Earth's crust)
- Climate system can change because of either 1. internal variability (e.g., natural variation of climate components) or external forcings (e.g., variations in the Earth's orbit or the output from the Sun, volcanoes and human activities)
- **Climate change**: intense droughts, water scarcity, severe fires, rising sea levels, flooding, melting polar ice, catastrophic storms and declining biodiversity



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





Observed warming

Contributions to warming based on two complementary approaches











Defining the beginning of the Anthropocene



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

SL

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

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)

CO₂ trends on our planet



https://keelingcurve.ucsd.edu/







http://www.thefosterlab.org/blog

Planetary Boundaries



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

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

Human pressure must be included in understanding Earth System

Foci of human induced changes on Earth

Rockström, J., Steffen, W., Noone, K., Persson, Å., et.al. 2009. A safe operating space for humanity. Nature 461: 432-475

Human Impact on Environmental Microbial Ecology

- Pollution (heavy metals, hydrocarbons, plastics)
- Land use changes (deforestation, agriculture)
- Climate change (temperature, CO₂ levels, ocean acidification)
- Antibiotic resistance genes in the environment (AMR spread via One Health)

Microbes and Climate Change

Cavicchioli et al. 2019



- In marine environments, microbial primary production contributes substantially to CO2 sequestration
- Marine microorganisms also recycle nutrients for use in the marine food web and in the process release CO2 to the atmosphere
- In a broad range of terrestrial environments, microorganisms are the key decomposers of organic matter and release nutrients in the soil for plant growth as well as CO₂ and CH₄ into the atmosphere

Biogeochemical processes

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Compounds are dechlorinated through respiration in anaerobic habitats

SI, Sw, Gw

SI, Sw, Gw

SI, Sw, Gw

SI, Sw, Gw

Decomposition, CO₂ formation

Decomposition, CO₂ formation

Decomposition

Fuel additives (MTBE)

Chlorinated solvents

Pharmaceuticals, personal

Nitroaromatics

care products

Biogeochemical processes

Nitrogen cycle			
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Microbial aquatic ecosystems and climate, I

- Rising temperature —> biological processes, reduce water density and thereby stratification and circulation—> organismal dispersal and nutrient transport
- Precipitation, salinity and winds also affect stratification, mixing and circulation
- Nutrient inputs from air, river and estuarine flows also affect microbial community composition and function, and climate change affects all these physical factors
- By fixing carbon and nitrogen, and remineralizing organic matter, marine microorganisms form the basis of ocean food webs and thus global carbon and nutrient cycles
- The sinking, deposition and burial of fixed carbon in particulate organic matter to marine sediments is a key, long-term mechanism for sequestering CO₂ from the atmosphere
- The balance between regeneration of CO₂ and nutrients via remineralization versus burial in the seabed determines the effect on climate change
- Oceans have acidified by ~0.1 pH units since preindustrial times, with further reductions of 0.3–0.4 units predicted by the end of the century

Microbial aquatic ecosystems and climate, II

- Marine phytoplankton perform half of the global photosynthetic CO₂ fixation (net global primary production of ~50 Pg C per year, petagram= 10¹⁵g) and half of the oxygen production despite amounting to only ~1% of global plant biomass
- In comparison with terrestrial plants, marine phytoplankton are distributed over a larger surface area, are exposed to less seasonal variation and have markedly faster turnover rates than trees (days versus decades)
- Phytoplankton respond rapidly on a global scale to climate variations.
- Chemolithoautotrophic archaea and bacteria fix CO₂ under dark conditions in deep ocean waters and at the surface during polar winter
- Oxygen minimum zones (OMZs) have expanded in the past 50 years as a result of ocean warming, which reduces oxygen solubility
- OMZs are global sinks for reactive nitrogen, and microbial production of N₂ and N₂O accounts for ~25–50% of nitrogen loss from the ocean to the atmosphere
- OMZs are the largest pelagic methane reservoirs in the ocean and contribute substantially to open ocean methane cycling
- Ocean warming, acidification, eutrophication and overuse (for example, fishing, tourism) together cause the decline of coral reefs and mangroves

Carbon export deep ocean and climate change

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

Microbial terrestrial ecosystems and climate, I

- There is ~100-fold more terrestrial biomass than marine biomass, and terrestrial plants account for a large proportion of Earth's total biomass
- Terrestrial plants perform roughly half of net global primary production
- Soils store ~2,000 billion tonnes of organic carbon, which is more than the combined pool of carbon in the atmosphere and vegetation
- Plants remove CO₂ from the atmosphere through photosynthesis and create organic matter that fuels terrestrial ecosystems
- Conversely, autotrophic respiration by plants (60 Pg C per year) and heterotrophic respiration by microorganisms (60 Pg C per year) release CO₂ back into the atmosphere (balance)

Microbial terrestrial ecosystems and climate, II

- Forests cover ~30% of the land surface, contain ~45% of terrestrial carbon, make up ~50% of terrestrial primary production and sequester up to 25% of anthropogenic CO2
- Grasslands cover ~29% of the terrestrial surface
- Non-forested, arid and semiarid regions (47%) are important for the carbon budget and respond differently to anthropogenic climate change than forested regions
- Lakes make up ~4% of the non-glaciated land ares and shallow lakes emit substantial amounts of CH₄
- Peat (torba decomposed plant litter) covers ~3% of the land surface and, due to plant productivity exceeding decomposition, intact peatlands function as a global carbon sink and contain ~30% of global soil carbon
- In permafrost, the accumulation of carbon in organic matter (remnants of plants, animals and microorganisms) far exceeds the respiratory losses, creating the largest terrestrial carbon sink —> Climate warming of 1.5–2 °C (relative to the global mean surface temperature in 1850–1900) is predicted to reduce permafrost by 28–53% (compared with levels in 1960–1990) thereby making large carbon reservoirs available for microbial respiration and greenhouse gas emissions

Microbial terrestrial ecosystems and climate

- In peatlands, decay-resistant litter (for example, antimicrobial phenolics and polysaccharides of *Sphagnum* mosses) inhibits microbial decomposition, and water saturation restricts oxygen exchange and promotes the growth of anaerobes and release of CO₂ and CH₄
 - Increased temperature and reduced soil water content caused by climate change promote the growth of vascular plants (ericaceous shrubs) but reduce the productivity of peat moss
 - Changes in plant litter composition and associated microbial processes (for example, reduced immobilization of nitrogen and enhanced heterotrophic respiration) are switching peatlands from carbon sinks to carbon source
- According to the World Bank (World Bank data on agricultural land), nearly 40% of the terrestrial environment is devoted to agriculture —> this proportion is predicted to increase, leading to substantial changes in soil cycling of carbon, nitrogen and phosphorus, among other nutrients

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

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

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

Elevated CO₂ —> an increase in carbon below ground due to increases in plant growth, with corresponding increases in soil microbial biomass and shifts in community composition. In the long term,SOC may decompose at a faster rate than it is formed.

White lines indicate increased microbial activity

Increased temperature —> in loss of SOC, shifts in bacterial and/or archaeal compositions and decreases in fungal abundance. **Permafrost thaw** results in a deepening of the seasonally thawed active layer and an increase in microbial degradation of SOC. Viruses have been detected in thawed permafrost and have been implicated in carbon cycling. Depending on landscape hydrology, methanogens in wetter and more anaerobic areas can generate CH₄.

Drought —> in less decomposition of SOC, lower microbial biomass and less CO₂ production. Surviving bacteria may produce molecules to retain cell turgor (osmolytes) and/or enter a dormant physiological state (as represented by a change in shape of the red cell). Under drought, fungal hyphae can be better suited to bridge disconnected soil pores and serve as a fungal highway for other microbial cells.

Increased precipitation can increase water saturation and anaerobic soil zones. Here, a case for wetting dry soil when there is a sudden increase in water and nutrient availability , which may cause some cells to burst (as shown by the burst red cell) and serve as a substrate for other cells to become more active (white lines by blue cells indicate increased activity), respire and produce CO₂ (Birch effect); there can also be some community shifts.

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

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

Human footprint on microbes

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

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

Philippot et al., 2023

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

Soll erosio

Philippot et al., 2023

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

Philippot et al., 2023

Microbial pathogens and climate change

Cavicchioli et al. 2019

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

Microbes and Climate

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.

Mitigation of carbon dioxide (CO₂), methane (CH₄), and nitrous oxide (N₂O)

- Geoengineering solutions to stock CO₂
- Managing landfill CH₄ emission —> coupling with bioreactors for new product production or heat and designing new landfill with methanotrophs
- Reducing CH₄ emission from cattle (rumen microbes)—> changing societal culture for raising livestock
- Sequestering C via CH₄ from wastewater treatment facilities —> pyrolytic conversion
- NOx mitigation, N₂O is a product of ammonia oxidation in oxic conditions, in anoxic condition is produced by coupling NO reduction to oxidation od edonors (Fe, S, organics by the denitrifies) —> estuaries, soils, <u>landfills</u>, <u>wastewater bioreactors —>to force efficient denitrification</u>

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

2021 United Nations Decade of Ocean Science for Sustainable Development

Decade Motivation: reverse the cycle of decline in ocean health

2021 United Nations Decade of Ocean Science for Sustainable Development

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

The Decade Warbon sinks in major biomes (SI Appendix, Table 1). Grey areas indicate regions dominated by agricultureal innovation in ocean science needed to deliver key societal outcomes:

• A clean ocean where sources of pollution are identified and removed

• A safe ocean where people are protected from ocean hazards

• A healthy and resilient ocean where marine ecosystems are mapped and protected

• A sustainably harvested and productive ocean ensuring the provision of food supply

• A predictable ocean where society has the capacity to understand current and future ocean conditions

• A transparent ocean with open access to data, information and technologies

1. A roadmap for rapid decarbonization

Rockström et al., 2017

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

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

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

Rockström et al., 2021

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