Science-Policy Brief for the UN Multistakeholder Forum on Science, Technology and Innovation for the SDGs, 8 May 2025

Integrating Oceanic Carbon Sequestration Strategies as High-Impact STI Solutions for SDGs 13, 14 and 17

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Abstract

Coastal acidification, driven by anthropogenic carbon dioxide (CO_2) increase in the atmosphere and exacerbated by wastewater discharge and other human activities, threatens marine biodiversity and the ocean's capacity to mitigate climate change. Emerging scientific evidence highlights microbial carbon pump (MCP) enhancement and related, synergistic strategies as transformative solutions to increase oceanic carbon sequestration while advancing Sustainable Development Goals (SDGs) 13 (Climate Action), 14 (Life Below Water) and 17 (Global Partnerships). Key findings include: 1) Ocean alkalinity enhancement could be a feasible and practical solution when implemented at wastewater treatment plants (WWTPs) by optimizing microbial processing and adding alkaline minerals to effluents, which are now often discharged at pH as low as 6.0; 2) aquaculture could be transformed into a climate-resilient carbon sink by a concept of BCMS that optimizes the synergistic effects of the biological carbon pump (BCP), carbonate counter pump (CCP) in high-pH environments, microbial carbon pump (MCP), and solubility carbon pump (SCP); and enhancing the microbial carbon sink in coastal seas via reduced terrestrial fertilization is achievable. Policy recommendations are: 1) revise WWTPs' pH standards by raising the lower limit of effluent pH from 6.0 to ~8.0 to mitigate acidification, lower carbon emission, and restore microbial functions, 2) scale frameworks to incentivize sea-farming systems that combine carbon sequestration with economic benefits, and 3) apply a Land-Sea Nutrient Modulation strategy to amplify the MCP by reducing chemical fertilization on land and stabilizing coastal carbon sequestration. These recommendations provide high-impact STI solutions by transforming anthropogenic liabilities (e.g., eutrophication, hypoxia, acidification) into ecological and economic assets and enhance mitigation of atmospheric CO_2 at gigaton scale annually.

Introduction

As the world confronts the existential threat of climate change, humanity faces a universal challenge demanding unprecedented global cooperation. The Paris Agreement stands as a historic milestone in climate governance, yet the 2023 COP 28 Global Stocktake exposed critical gaps in meeting temperature targets, while COP 29 (2024) reinforced the urgency of enhanced funding and multilateral action to secure a livable future. Amid this imperative, the ocean emerges not only as a linchpin of Earth's climate system but also as a vulnerable ally in need of urgent stewardship.

The ocean regulates planetary climate dynamics while sustaining human development, storing 93% of planetary CO_2 and absorbing 40% of CO_2 emissions from fossil fuel use since the Industrial Revolution. Over the past 150 years, it has also captured 90% of excess heat from anthropogenic warming (Friedlingstein et al., 2023). Yet these vital services come at a cost: increased sea surface temperature, acidification, and deoxygenation threaten marine ecosystems, triggering cascading ecological crises. With terrestrial resources dwindling and populations rising, the ocean has become a critical frontier for addressing climate change, resource scarcity, and sustainable development.

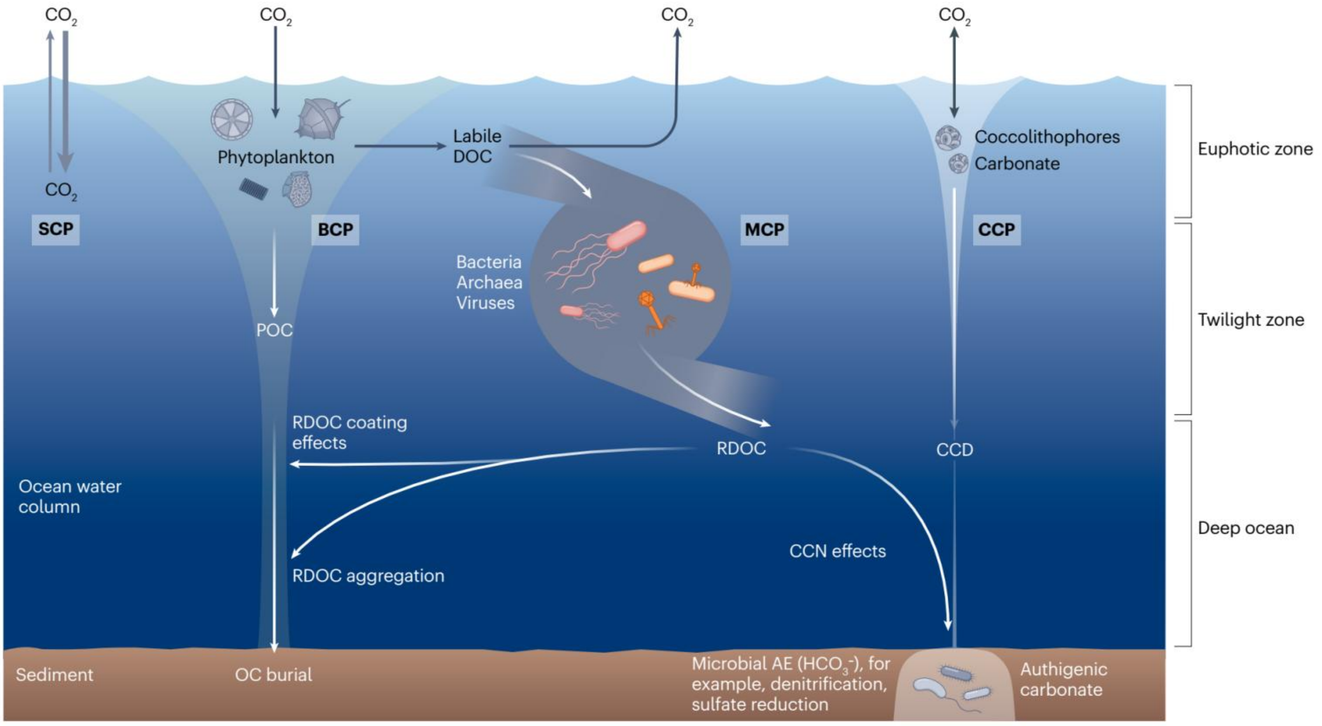

Fig. 1. Marine carbon cycling and the major processes and mechanisms involved. BCP = biological carbon pump; CCP = carbonate counter pump; MCP = microbial carbon pump; SCP = solubility carbon pump. (Jiao et al., 2024).

The ocean's role in regulating Earth's climate is anchored in carbon sequestration mechanisms: including the known biological carbon pump (BCP), carbonate counter pump (CCP), and solubility carbon pump (SCP) as well as the newly recognized microbial carbon pump (MCP) (Fig. 1). These processes collectively govern the exchange, storage, and cycling of carbon between the atmosphere and the ocean, forming the basis of marine carbon sequestration science. While these pumps are well-established in marine science, their natural capacities and process rates are insufficient to meet Paris Agreement targets. In particular, the specific shortcomings of each carbon pump—such as the rapid decline in efficiency with depth in BCP, the opposing interactions in the CCP, the need for optimal conditions to strengthen the MCP, and the inconsistent reliance on partial CO_2 pressure (pCO_2) in SCP—must be addressed by integrating these processes. By combining their strengths to offset individual weaknesses, their synergistic potential can be maximized.

MCP, first proposed in Jiao et al. (2010) represents a paradigm shift in understanding marine carbon sequestration. Unlike the BCP, which relies on vertical carbon export, the MCP can take place at any depths and produce recalcitrant dissolved organic carbon (RDOC) resistant to degradation for millennia, making a vast reservoir of hundreds gigatons of carbon (Jiao et al., 2010, 2024) (Fig. 1). The MCP is the foundation of the Global Ocean Negative Carbon Emissions (Global ONCE) Program endorsed in 2022 by the UN Ocean Decade (UNESCO-IOC, 2021). Global ONCE focuses on linking BCP and CCP with MCP, and SCP into a BCMS comprehensive approach that exemplifies science-driven nature-based solutions, offering scalable, low-risk pathways to achieve net-negative emissions. By bridging fundamental science and innovative engineering, the BCMS illuminates a path toward harnessing the ocean's full potential in the climate crisis.

This briefing report reaffirms our commitment to the UN Ocean Decade's outcomes — "a predicted, accessible, and inspiring ocean"— by translating cutting-edge science into actionable policy and community-led stewardship. Together, we strive to position the ocean as a cornerstone of climate resilience, intergenerational equity, and a net-zero future. By bridging science, policy, and innovation, Global ONCE embodies the United Nations' call for "transformative action through co-designed, solutions-oriented science" (UNESCO-IOC, 2021) — proving that the ocean, when stewarded wisely, can be humanity's greatest ally in securing a sustainable future.

Findings and Issues

1. Revising the Wastewater Discharge pH Standard: A Practical Measure for Mitigation of Coastal Acidification and Climate Change

Over the past century, the average pH of surface seawater has decreased from 8.2 to 8.1, corresponding to 30% change in acidity that has already caused gradual disruption of the marine carbonate equilibrium system. This lowering of pH (referred to as acidification) alters the physiology and survival of calcifying organisms, such as corals and shellfish, drawing widespread concern from both scientific communities and society. However, the ecological aftermath of wastewater discharge has long been overlooked due to its presumable small footprint. In fact, it is often a more severe driver of coastal acidification than rising atmospheric CO_2 levels, as the pH of the effluent from wastewater treatment plants (WWTPs) is often as low as pH 6.0 (some countries have pH values even 5.5), which equates to hydrogen ion concentrations +150 times higher than in natural seawater (pH 8.0-8.1), severely impacting the metabolic functions of marine microorganisms (Fig. 2). These disruptions cascade through food chains, threaten fisheries, and impose persistent pressures on the sustainability of marine ecosystems.

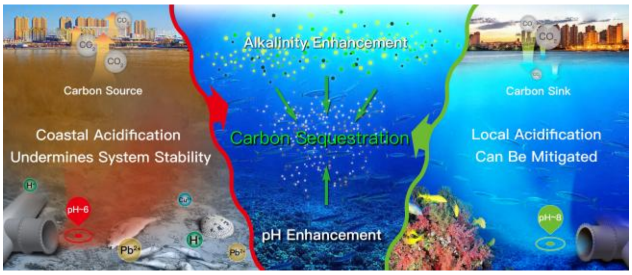

Fig. 2. Turning coastal wastewater treatment plants into ocean negative carbon emission engines by alkalinizing wastewater to pH 8.0-8.1, adopted from Meng and Jiao, (2025).

2. Harnessing Sea-Farming Ecosystems: A Strategic Pathway to Climate Mitigation and Marine Sustainability

Sea-farming is a well-developed marine industry that is promoted by the UN because world food needs are under pressure from Earth's > 8 billion human population. However, intensive sea-farming developments entail a series of environmental risks and problems, such as eutrophication, deoxygenation, acidification of bottom water, and potential harmful algal blooms in surface water. These challenges demand innovative, scalable interventions to transform marine aquaculture industries into pillars of climate resilience (Fig. 3).

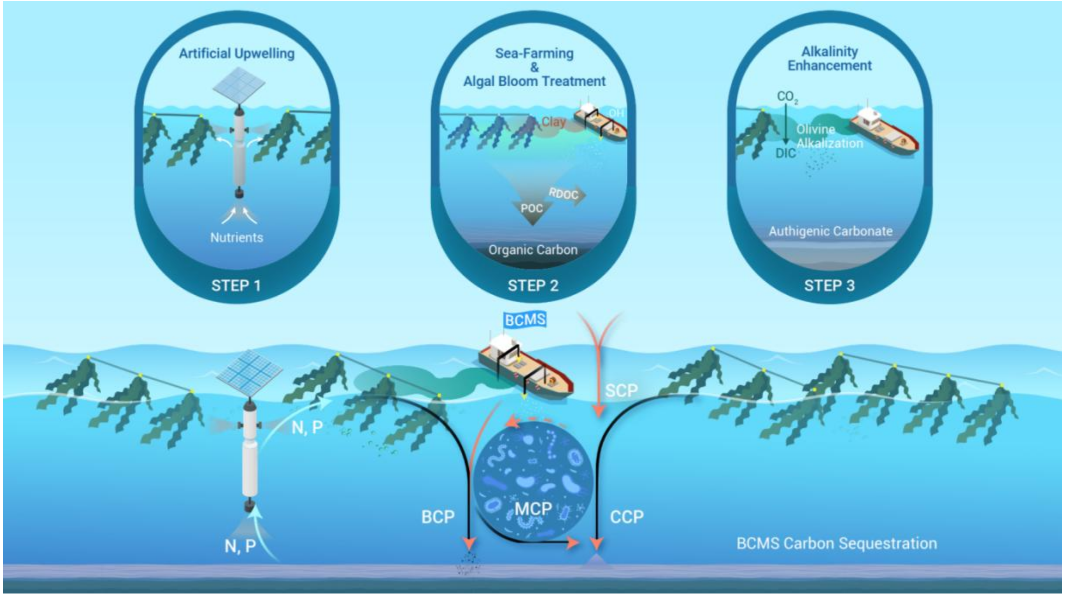

Fig. 3. A roadmap for Ocean Negative Carbon Emission eco-engineering in sea-farming fields (Jiao et al., 2023).

3. Enhancing the Microbial Carbon Sink in Coastal Seas via Reduced Terrestrial Fertilization

Fertilizer use on land is a major source of nitrogen and phosphorus nutrients to waterways. As a result, rivers and estuaries each year transport 400 Mt of organic carbon, 54 Mt of nitrogen and 8.5 Mt of phosphorus to the ocean. The anthropogenic nutrient discharge enhances algal and dissolved organic carbon production disrupting microbial carbon processing, increasing respiration and exacerbating CO_2 emissions (Fig. 4a). This challenge calls for rebalancing land-sea nutrient flows to transform coastal waters into durable carbon sinks (Fig. 4b).

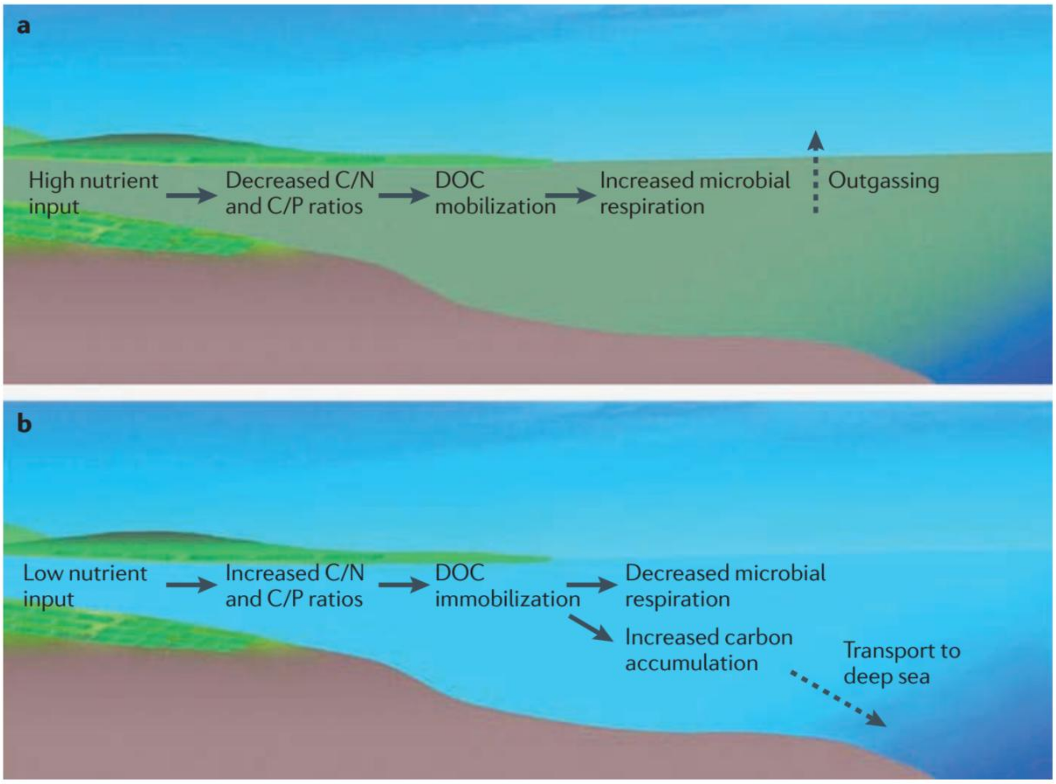

Fig. 4. Microbial carbon processing scenarios under different environmental conditions. Panel A. Microbial respiration of dissolved organic carbon (DOC) is mobilized by enhanced terrestrial nutrient input. Panel B. Microbial carbon sequestration is enhanced by reducing terrestrial nutrient input (Jiao et al. 2011).

Policy and Science Recommendations

1. Mandating Regulatory Actions on Wastewater pH

Based on scientific evidence, we propose to revise the pH standards and increase the lower pH limit for WWTP effluent discharge from 6.0 to 8.0. This adjustment would not only aid in phosphate recovery, heavy metal detoxification and ecosystem restoration but also enhance coastal CO_2 absorption and sequestration capacity. Such a measure offers a tangible lever to safeguard underwater biodiversity (SDG 14) and advance cross-sector collaboration (SDGs 13 and 17), thereby supporting the sustainable development of coastal ecosystems.

Effective implementation of these measures would transform WWTPs from CO_2 emission sources into CO_2 sinks. By discharging alkalinized wastewater into the ocean, WWTPs could enable large-scale atmospheric CO_2 removal and contribute to net ocean negative carbon emissions. Such a shift would use existing technology and infrastructure to catalyze tangible new productive forces, pioneer innovative industrial models, and provide a robust mechanism for advancing the vision of a global community with a shared future.

2. Scaling Nature-Based Solutions by the Integrative BCMS Approach

Here we propose a novel BCMS approach that integrates the biological carbon pump (BCP), carbonate counter pump (CCP), microbial carbon pump (MCP) and solubility carbon pump (SCP) to convert sea-farming waters into efficient carbon sinks while mitigating potential environmental impacts:

- Artificial upwelling that enhances primary production (carbon fixation) while alleviating subsurface acidification and hypoxia through oxygen-rich downwelling.

- Algal bloom control and carbon sequestration enhancement by targeted hydroxyl radical (·OH) treatments to inactivate harmful blooms by breaking down DNA but keeping cells intact, without releasing organic carbon. Concomitantly, well-developed practices in seaweed cultivation favor the MCP and the aggregation of dead intact cells, enhancing BCP efficiency.

- Alkalinity enhancement integrated with the carbon pumps that would boost seawater alkalinity to accelerate CO_2 absorption while transforming the CCP into a durable process for carbon sequestration into seabed sediments by driving carbonate deposition.

The implementation of BCMS-based eco-engineering in sea-farming fields has the potential to optimize achievement of the twin goals of enhancing carbon sequestration while ensuring sustainable ecosystem. This ocean negative carbon emissions roadmap is generally low risk, environmentally friendly, sustainable, and achieves efficiency by using specialized measures, including photosynthesis rhythm-fit artificial upwelling, specifically designed DNA-inactivation hydroxyl radical treatment, and modified clay sedimentation of organic matter. BCMS could become a forward-looking best practice for carbon dioxide removal ecoengineering. By renovating sea-farming into carbon-sink systems, BCMS transforms economic liabilities into assets, enhancing carbon sequestration and bolstering productivity. This shift aligns with the "Business-Continuity-Management-System" ethos, ensuring ecological and economic resilience.

3. Applying a Land-Sea Nutrient Modulation (LSNM) Strategy

This strategy amplifies MCP by reducing chemical fertilization on land, thereby stabilizing coastal carbon sequestration through three targeted interventions:

- Optimization of terrestrial fertilization to restore stoichiometric balance in the coastal ocean by lowering riverine nutrient fluxes to increase carbon/nutrient (C/N, C/P) ratios. Higher C/N ratios promote microbial production of recalcitrant DOC (RDOC) via storage polymers like polyhydroxyalkanoates, shifting microbial metabolism to carbon immobilization. Control of competing effects (Norbisrath et al., 2022) will foster optimization.

- Integrate riverine DOC export with deep-sea carbon sequestration by minimizing nutrient-driven respiration in estuaries so that surface-derived RDOC can be stabilized for long-term deep water oceanic storage, thus extending the MCP's climate mitigation potential.

Implementation of LSNM leverages policy-driven agricultural reforms to curb fertilizer overuse. This approach transforms coastal waters from CO_2 sources into verifiable carbon sinks and turns nutrient pollution liabilities into RDOC assets, supporting carbon sequestration schemes while restoring marine health. LSNM harmonizes terrestrial practices with marine microbial ecology. Reduced eutrophication mitigates algal blooms and hypoxia, while enhanced RDOC production offers scalable climate benefits. This strategy bridges science and policy, fostering resilience in both agricultural and marine sectors under a unified sustainability framework.

4. Strengthening Science-Policy Interfaces

   - Establish an ONCE Knowledge Hub: Co-led by IOC-UNESCO and UNDESA, this platform will share best practices, environmental risk assessment frameworks, data (e.g., ONCE Digital Twins), and training for policymakers.

   - Enhance monitoring: Deploy AI-driven sensors to track RDOC and acidification trends, feeding into the UN Ocean Decade's predictive frameworks.

5. Promoting Global Equity and Capacity Building

   - Prioritize vulnerable regions: Allocating ONCE funds to SIDS and coastal LDCs for wastewater retrofits and building RDOC production capacity.

   - Science diplomacy: Launch a UN Coalition on Ocean-Aligned STI to harmonize marine carbon strategies with the 2030 Agenda.

By leveraging STI-driven strategies—MCP, BCMS, and WWTP alkalinization—this briefing provides a roadmap to transform coastal ocean industries into scalable carbon sinks while advancing SDGs 14 and 17. Immediate action on wastewater standards and RDOC scaling can secure a proportion of the Paris Agreement's carbon gap in addition to improving the coastal environment, proving that science-policy synergy is key to a sustainable future.

Acknowledgments

This policy brief was supported by the Global Ocean Negative Carbon Emissions program. The following people provided valuable contributions: Tingwei Luo, Yabing Meng, Xi Lu, Anyi Hu, and Yang Liu, Research Center for Ocean Negative Carbon Emissions, Xiamen; Jihua Liu, Shandong University.

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