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A roadmap for Ocean Negative Carbon Emission eco-engineering in sea-farming fields

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Carbon neutralization has become a significant, inevitable, and urgent strategy for both adaptation and mitigation of global warming caused by anthropogenic CO_2 emissions, and its environmental consequences such as ocean acidification. However, the reduction of anthropogenic CO_2 emissions often conflicts with economic development. In contrast, environmentally-friendly negative carbon emissions can be a way of killing two birds with one stone, capturing carbon dioxide and ensuring economic development, and therefore become imperative to achieve carbon-neutral goals.

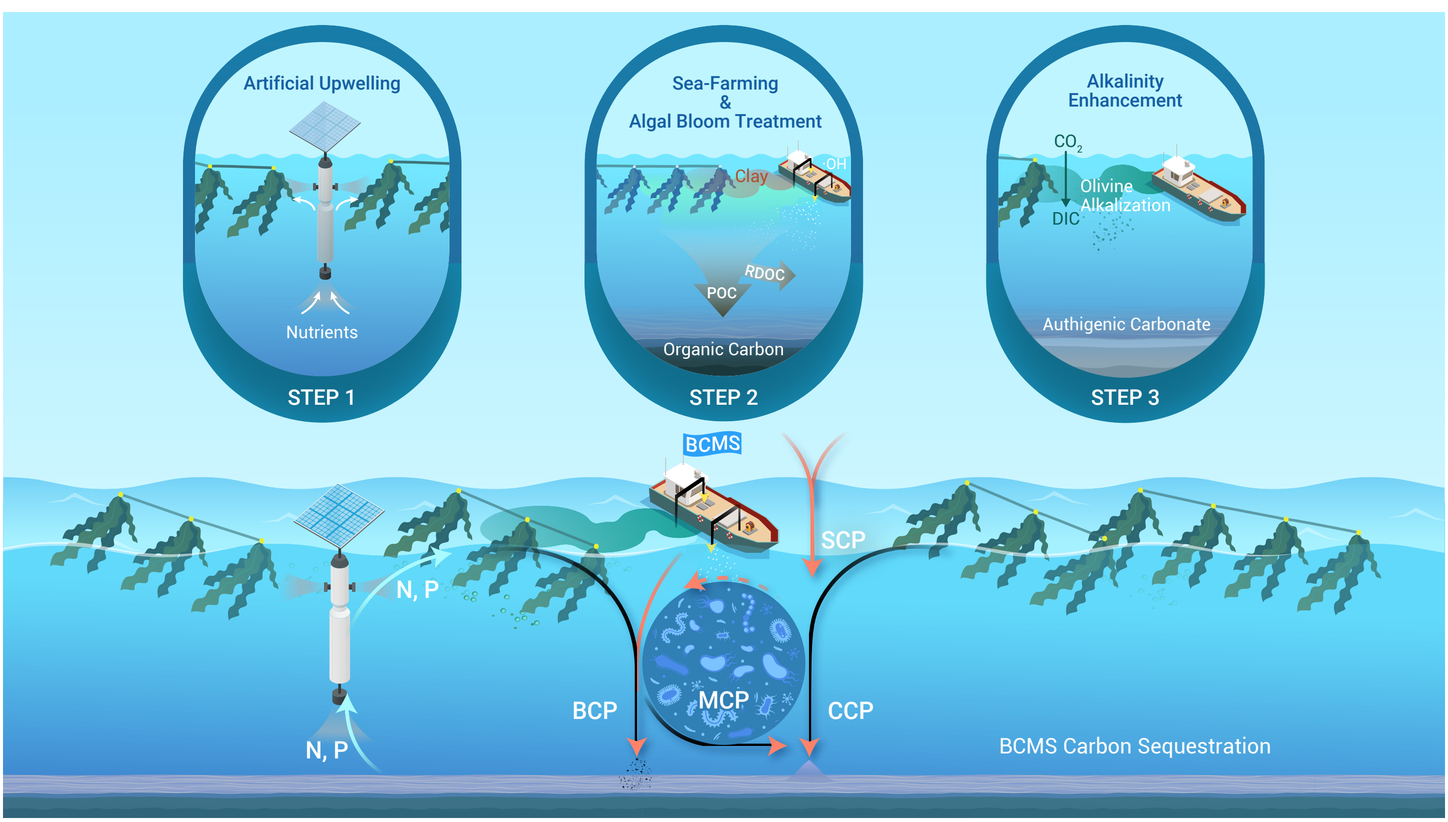

Figure 1. An illustration of the BCMS ecoengineering approaches POC: Particulate Organic Carbon, RDOC: Refractory Dissolved Organic Carbon, N,P: Nitrogen and phosphorus.

The ocean, as the largest active carbon reservoir, has great potential for negative carbon emissions. However, since the ocean has stored 93% of the world's CO_2, further negative carbon emissions remain a formidable challenge. On top of that, both the approaches and implementation fields should be appropriate and must comply with the UN Conventions on the Law of the Sea, and the International Maritime Organization London Convention and Protocol.

Sea-farming, being a low cost and high productivity manner, is a well-developed marine industry, and is further promoted nowadays by the UN given that the world food needs are under pressure of 8 billion world population. However, rapid and over-intensive sea-farming developments entail a series of environmental risks and problems, such as eutrophication, deoxygenation, acidification in the bottom water, and potential harmful microalgal blooms in the surface water.

Under such circumstances, the Global Ocean Negative Carbon Emissions (ONCE) program (https://www.global-once.org), endorsed by the United Nations Decade of Ocean Science for Sustainable Development, has proposed a comprehensive eco-engineering approach， which integrates the well-known biological carbon pump (BCP) and the carbonate counter pump (CCP), and the newly established microbial carbon pump (MCP),[1] as well as the "unmanageable" solubility carbon pump (SCP) into a comprehensive "BCP-CCP-MCP-SCP (BCMS)" approach, just like the Business-Continuity-Management-System (BCMS). We here propose a road map for the BCMS approach. As illustrated in Figure 1, this ONCE roadmap is based on systematic measures, starting with solar energy-driven artificial upwelling as an internal ecosystem regulation solution, followed by further scientific intervention measures to simultaneously increase carbon sequestration capabilities and mitigate potential environmental impacts (Figure 1).

BCMS STEP 1, Intelligent artificial upwelling to enhance carbon fixation

Artificial upwelling can bring up nutrients from deep water to the surface water for enhancement of photosynthesis, and the consequent downwelling can drag high oxygen surface water down to the subsurface for mitigation of hypoxia and acidification. Ideally, solar energy powered artificial upwelling would enhance nutrient supply during the daytime fitting the photosynthesis rhythm and the growth of primary producers, and would stop during the night to avoid excessive dissolved inorganic carbon (DIC).

Artificial upwelling should be implemented in legal sites. Grounded in the United Nations Convention on the Law of the Sea and the London Convention, seaweeds culture fields would be the right place for BCMS practice. An intelligent operation of the artificial upwelling can maintain a nutrient-DIC balance, ensuring optimal and efficient seaweed growth without release of CO_2, which can be achieved through solar radiation based automatic adjustment of upwelling flux and rhythm.

BCMS STEP 2, Controlling algal blooms and enhancing carbon sequestration

Once the microalgal bloom occurs, the microalgal cells can be treated by inactivation processing at proper scales. E.g., bloom cells can be exposed to hydroxyl radicals (•OH) that effectively breaks the DNA strands of the microalgal cells while keeping their cell walls intact,[2] ensuring no intracellular organic matter and no extra dissolved organic carbon is released during the BCP process. Meanwhile MCP is well developed in seaweeds culture area,[3] favoring the aggregation of the dead cells and therefore enhancing BCP efficiency.

In the controlled areas of intentional upwelling, on-site floating photobioreactors can be applied for cultivation of specific microalgae such as marine *Chlorella sp*. for high population densities to generate "Green Water".[4] Continuous supply of large quantities of microalgae not only produces sufficient dissolved oxygen and food for aquaculture animals but also offers a countermeasure to bead harmful blooms. Up on needed, flocculants can be introduced to aggregate and settle the microalgal cells down to the seafloor for long term burial.

In case microalgal bloom spreads, the cells can be flocculated and settled with modified clay which can also reduce the release rate of dissolved inorganic phosphorus (P).[5] Dissolved organic carbon could be immobilized for uptake due to the enlarged C/P ratio, leading to the accumulation of recalcitrant dissolved organic matter through the MCP. Consequently, carbon sequestration efficiency is enhanced for both the BCP and the MCP.

BCMS STEP 3, Integrating the unmanageable SCP with BCP, CCP and MCP toward maximum complex carbon sequestration

Enhancing seawater alkalinity simultaneously with clay addition can secure both organic and inorganic carbon sequestration in the water column and sediment. Olivine with the main ingredients of Mg_2SiO_4, an effective alkaline mineral for CO_2 removal (Eq. 1), can chelate 4 moles of CO_2 per mole of olivine. More importantly, the CO_2 is captured and stored in the form of bicarbonate (Eq. 1), which is a major component of total alkalinity. This makes the alkaline addition an efficient approach for the enhancement of ocean alkalinity, which could significantly decrease surface seawater pCO_2 and promote CO_2 uptake from the atmosphere, enhancing the SCP efficiency.

$$Mg_2SiO_4 \bullet (\text{Olivine}) + 4CO_2 + 4H_2O = 2Mg^{2+} + 4HCO_3^- + H_4SiO_4 \quad (1)$$

Moreover, the use of olivine minerals could also supply extra nutrients including silicate and iron to promote the growth of micro/macroalgae. Consequently, the elevated seawater pH resulting from the enhanced micro/macroalgal photosynthesis drives the SCP to accelerates CO_2 absorption from the atmosphere into the sea, making the SCP a "manageable" approach for ONCE.

In the seabed, the metabolic activities of anaerobic methanotrophic archaea, nitrogen reduction and sulfate-reduction bacteria can not only contribute to the MCP but also enhance the concentration of bicarbonate alkalinity, promoting the combination of microbial mats/biofilm with Mg^{2+} and /or Ca^{2+} ions to induce carbonate deposition. The effective formation of carbonates-microbial mats/biofilm precipitation would then turn the CCP counter pump to be an effective pump for ONCE.

Closing remark

A comprehensive BCMS-based ONCE eco-engineering roadmap is proposed here towards achieving the twin goals of enhancement of carbon sink alongside remediation of the ecosystem. BCMS would be best implemented in sea-farming fields. This ONCE roadmap is theoretically riskless, environmentally friendly, sustainable, and efficient by using specialized measures, including photosynthesis rhythm-fit artificial upwelling, specifically designed DNA-inactivation hydroxyl radical treatment, modified clay sedimentation of organic matter, as well as natural minerals mediated water alkalinity enhancement. BCMS could become a forward-looking best practice for MRV (Measurement, Reporting, and Verification) based ONCE eco-engineering.

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DECLARATION OF INTERESTS

The authors declare no competing interests.