frontiers | Frontiers in Marine Science

TYPE Editorial
PUBLISHED 06 September 2022
DOI 10.3389/fmars.2022.1018397

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OPEN ACCESS

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SPECIALTY SECTION
This article was submitted to Aquatic Microbiology, a section of the journal Frontiers in Marine Science

RECEIVED 13 August 2022
ACCEPTED 23 August 2022
PUBLISHED 06 September 2022

CITATION
He Z, Lin L, Wang X, Qin W and Zhang C (2022) Editorial: Carbon storage by marine microorganisms for carbon neutrality. *Front. Mar. Sci.* 9:1018397. doi: 10.3389/fmars.2022.1018397

Editorial: Carbon storage by marine microorganisms for carbon neutrality

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KEYWORDS

marine microorganism, carbon storage, carbon degradation, dissolved organic matter, greenhouse gas emission, algal-bacterial interaction, microbe-DOM-environment

Editorial on the Research Topic
Carbon storage by marine microorganisms for carbon neutrality

Carbon (C) neutrality is the urgent and ultimate goal of mitigating the anthropogenic greenhouse gas (GHG) emissions associated with global climate challenges. As the ocean is the largest active C reservoir on Earth, marine microorganisms play important roles in the global C cycle. For example, marine microorganisms can remove carbon dioxide (CO_2) from the atmosphere by C sequestration processes, and reduce methane (CH_4) emissions through their interactions with the environment, especially dissolved organic matter (DOM). However, how marine microorganisms interact with DOM to realize C sequestration remains unclear. In the marine ecosystem, the capture, transformation, and transport of C are mainly driven by the biological pump (BP) (Honjo et al., 2014), microbial carbon pump (MCP) (Jiao et al., 2010), and microbially induced carbonate precipitation (MICP) (Macreadie et al., 2017). The MCP mechanism emphasizes the contribution of marine microorganisms to recalcitrant dissolved organic carbon (RDOC) production through the degradation of particulate organic matter (POM), cell death, and interspecies interactions (Jiao et al., 2010). The BP, MCP and MICP altogether may work cooperatively to drive efficient C sequestration and storage in marine environments, thereby mitigating global climate change.

The Research Topic "*Carbon Storage by Marine Microorganisms for Carbon Neutrality*" presents five publications in *Frontiers in Microbiology* and *Frontiers in Marine Science*, providing new insights into our understanding of marine microbial community diversity and functions, biotic interactions (e.g., macrophyte-phytoplankton, algae-bacteria, bacteria-fungi), microbe-DOM interactions, and possible C storage mechanisms in marine ecosystems. Marine macrophytes (e.g., seagrasses, macroalgae) are important primary producers, and serve a variety of ecosystem functions such as biogeochemical cycling of C, nitrogen (N) and phosphorus (P) through macrophyte-microbe interactions (Egan et al., 2013; Human et al., 2015; Xie et al., 2017), and mitigation of global climate change through blue carbon sequestration (Duarte et al., 2018). In this Research Topic, Chen et al. analyzed the diversity and composition of epiphytic bacterial and fungal communities from 11 types of macroalgae and 2 types of seagrasses. The results indicate that macrophyte host phylogeny influences the bacterial community structure, while geographic differences mainly shape the fungal community structure. C metabolizing bacteria and fungi are enriched in the epiphytic environment of marine macrophytes. Also, phytoplankton are widely distributed in the ocean and contribute importantly to C sequestration *via* the BP (Honjo et al., 2014). Zhao et al. found distinct species-specific algae-bacteria relationships in different water layers, being more pronounced in the mesopelagic and bathypelagic zones than in the euphotic zone. A laboratory experiment further showed that phytoplankton reshaped the bacterioplankton community structure in different water layers. In a study of marine picophytoplankton (e.g., *Prochlorococcus*, *Synechococcus*, picoeucaryote) and their distribution patterns in the West Pacific, *Prochlorococcus* was found to dominate over *Synechococcus* and picoeucaryotes, and the abundance of *Prochlorococcus* was negatively correlated with nutrient concentrations, while temperature and salinity were closely correlated with the spatial variation in the picophytoplankton community, highlighting the importance of picophytoplankton in contributing to the C pool in the oligotrophic ocean (Wang et al.). To further understand bacterial transformation and processing of DOM in aquatic ecosystems, three bacteria (*Roseobacteria* sp., *Marinobacter* sp., and *Bacillus* sp.) were selected to investigate the processing of DOM and lysate organic matter (LOM) from the marine diatom *Skeletonema dohrnii*. The results showed that such epiphytic bacteria were able to process DOM and LOM, and convert them into more complex refractory dissolved organic matter (RDOM) (Liu et al.). In addition, in this Research Topic, Ma et al. reviewed current knowledge and future exploration of thermophilic microorganisms from submarine hydrothermal environments as a valuable source of thermostable tolerant carbonic anhydrases, highlighting their potential applications for rapid CO_2 capture in the marine ecosystem.

Based on these studies as mentioned above and other existing literatures, we propose a conceptual framework to summarize biotic interactions on the DOM through the microbial loop and microbially-driven DOM degradation and transformation by the MCP mechanism (Figure 1). First, marine microorganisms interact with each other and with macroorganisms to form complex networks through food webs (e.g., the degradation of macroorganism-derived DOM). The necromass from those macroorganisms and microorganisms may sink to the seabed and C may, thereby, be sequestered from upper waters. Second, microbially-driven DOM degradation may result in diverse products, including labile dissolved organic carbon (LDOM), which is mainly used by microorganisms and produces CO_2 and/or CH_4. CO_2 may be re-fixed by autotrophic or chemo-autotrophic microorganisms (Dyksma et al., 2016; Vasquez-Cardenas et al., 2020; Taubert et al., 2022), and more importantly, a recent study indicates that CH_4 may be re-transformed into DOM (Yang et al., 2020). A part of such DOM may be used by marine microorganisms and

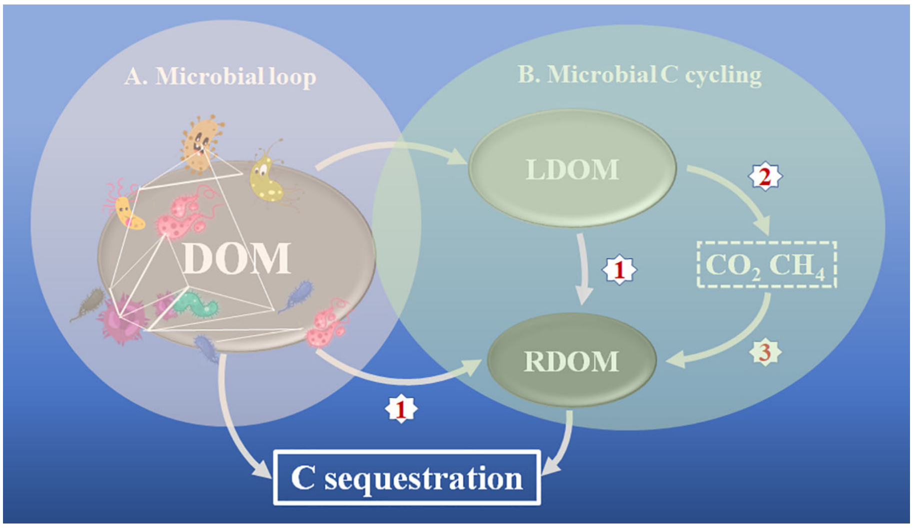

FIGURE 1
A conceptual framework for understanding C sequestration mechanisms in the marine ecosystem. **(A)** Biotic interactions are shown as complex networks between marine organisms (including macro-organisms and micro-organisms) affecting DOM dynamics. C sequestration is mainly driven by the biological pump (BP) mechanism. **(B)** Microbially-driven DOM degradation and transformation are largely explained by the microbial carbon pump (MCP) mechanism. The red numbers (1, 2 and 3) indicate possible future strategies for enhancing C sequestration in the marine ecosystem. DOM, dissolved organic matter; LDOM, labile dissolved organic matter; RDOM, refractory dissolved organic matter.

further transformed into RDOC, or RDOM by the MCP mechanism for C sequestration. A comprehensive understanding of those mechanisms, especially microorganism-DOM interactions, is necessary for us to develop efficient technologies for increasing C storage in the marine ecosystem. In the future, several strategies may enhance C sequestration (Figure 1). These may include (1) the enhancement of RDOM formation by the selection of microbial taxa/genes for efficient transformation of DOM and LDOM into RDOM (McCarren et al., 2010; Osterholz et al., 2015; Lechtenfeld et al., 2015); (2) the reduction of CH_4 emissions by inhibiting CH_4 production (Huang et al., 2009) or strengthening CH_4 oxidation (Sivan et al., 2014; Egger et al., 2015); and (3) the re-transformation of CO_2 and CH_4 into organic C (Dyksma et al., 2016; Yang et al., 2020). The implementation of such strategies for increasing C sequestration in marine ecosystems calls for the urgent development of innovative science and technology in microbial ecology, microbiome engineering and geoengineering.

Author contributions

ZH drafted this manuscript; LL, XW, WQ and CZ edited it. All authors contributed to the article and approved the submitted version.

Funding

This work was supported by the Southern Marine Science and Engineering Guangdong Laboratory (Zhuhai) (313022002, SML2020SP004 and 311021006), and by the National Natural Science Foundation of China (91951207 and 31770539).

Conflict of interest

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