The role of marine flora and microbiota in carbon sequestration: A comparative review with terrestrial flora

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Abstract. Carbon sequestration represents the removal of atmospheric CO_2 and its conversion into stable carbon pools, a cornerstone of climate change mitigation strategies. While terrestrial ecosystems (especially forests, peatlands, and grasslands) have long been recognized for their carbon storage capabilities, marine ecosystems are emerging as equally, if not more, critical in regulating global carbon dynamics. This comparative review synthesizes current knowledge on marine carbon sequestration mechanisms, contrasting them with those operating on land. We examine three principal ocean-based carbon sinks: (i) the biological pump, whereby phytoplankton (including diatoms, coccolithophores, and picocyanobacteria) photosynthesize and export carbon to the deep ocean, sequestering an estimated 0.9-2.6 Pg C annually on centennial timescales; (ii) the microbial loop, where bacteria and archaea degrade and transform organic carbon, producing recalcitrant dissolved organic carbon that may persist for millennia; and (iii) blue carbon habitats (mangroves, seagrass meadows, and salt marshes), which store substantial carbon in biomass and sediments, often rivaling tropical forests in per-hectare sequestration efficiency. By contrast, terrestrial vegetation annually fixes ~120 Gt C, with net sequestration estimated at ~10-20 Gt C, but its stability is constrained by disturbances such as deforestation, wildfires, pest outbreaks, and soil erosion. While terrestrial ecosystems currently dominate total carbon uptake, they occupy only ~30 % of Earth's surface and remain vulnerable to rapid release under climatic and anthropogenic pressures. The review highlights: (a) the greater spatial extent and potential long-term stability of marine carbon sinks; (b) the nutrient-limited nature and ecological risks associated with ocean fertilization; (c) significant knowledge gaps in deep-sea microbial sequestration; and (d) threats to blue carbon habitats from coastal development and rising seas. We conclude that future climate strategies must integrate oceanic carbon sinks alongside terrestrial restoration, emphasizing marine flora and microbiota as essential agents in the global carbon budget and sustainable climate mitigation.
Key Words: biological pump, blue carbon ecosystems, carbon cycling, carbon sequestration, climate mitigation, comparative review, mangroves, marine flora, microbial loop, phytoplankton, seagrass meadows, terrestrial vegetation.

Introduction. Carbon sequestration, the process by which carbon dioxide (CO_2) is removed from the atmosphere and stored in a stable form, is central to climate change mitigation strategies. While terrestrial forests have long been recognized as significant carbon sinks (Petrescu-Mag et al 2023, 2024), increasing scientific attention has turned to the oceans, which cover over 70% of the Earth's surface. Marine flora (including macroalgae and phytoplankton) and microbial communities play a crucial, though often underappreciated, role in the global carbon cycle. This review compares the carbon sequestration potential of marine ecosystems, especially their microscopic components, with that of terrestrial flora, highlighting mechanisms, scale, permanence, and limitations.

Oceanic Carbon Sequestration: Mechanisms and Contributors

Phytoplankton and the biological pump. Marine phytoplankton, including diatoms, dinoflagellates, and cyanobacteria, are responsible for a significant portion of global photosynthesis, forming the base of the oceanic biological carbon pump. Through photosynthetic activity, these organisms convert atmospheric CO_2 into organic carbon. When phytoplankton die or are consumed, a fraction of their carbon-rich biomass sinks into the deep ocean, where it can be sequestered for centuries to millennia, effectively removing CO_2 from the atmosphere for long periods (Jiao et al 2014; Zhang et al 2017; Prasad et al 2021; Nowicki et al 2022; Ricour et al 2023; Zhao et al 2024) (Figure 1).

• Estimated annual CO_2 fixation by phytoplankton: Approximately 45–50 gigatons, with global carbon export via the biological pump estimated at 10.2 Pg C (gigatons) per year (Prasad et al 2021; Nowicki et al 2022).

• Net biological carbon sequestration (export to deep ocean): Recent estimates suggest 0.9–2.6 Pg C per year is sequestered for at least 100 years, with the gravitational pump (mainly zooplankton fecal pellets and sinking phytoplankton aggregates) responsible for about 70% of total export (Nowicki et al 2022; Ricour et al 2023).

• Key contributors: Diatoms (noted for their silica shells), coccolithophores (with calcium carbonate plates), and picocyanobacteria such as Prochlorococcus are major contributors to the biological pump and oceanic carbon sequestration (Jiao et al 2014; Zhang et al 2017; Prasad et al 2021; Nowicki et al 2022; Zhao et al 2024).

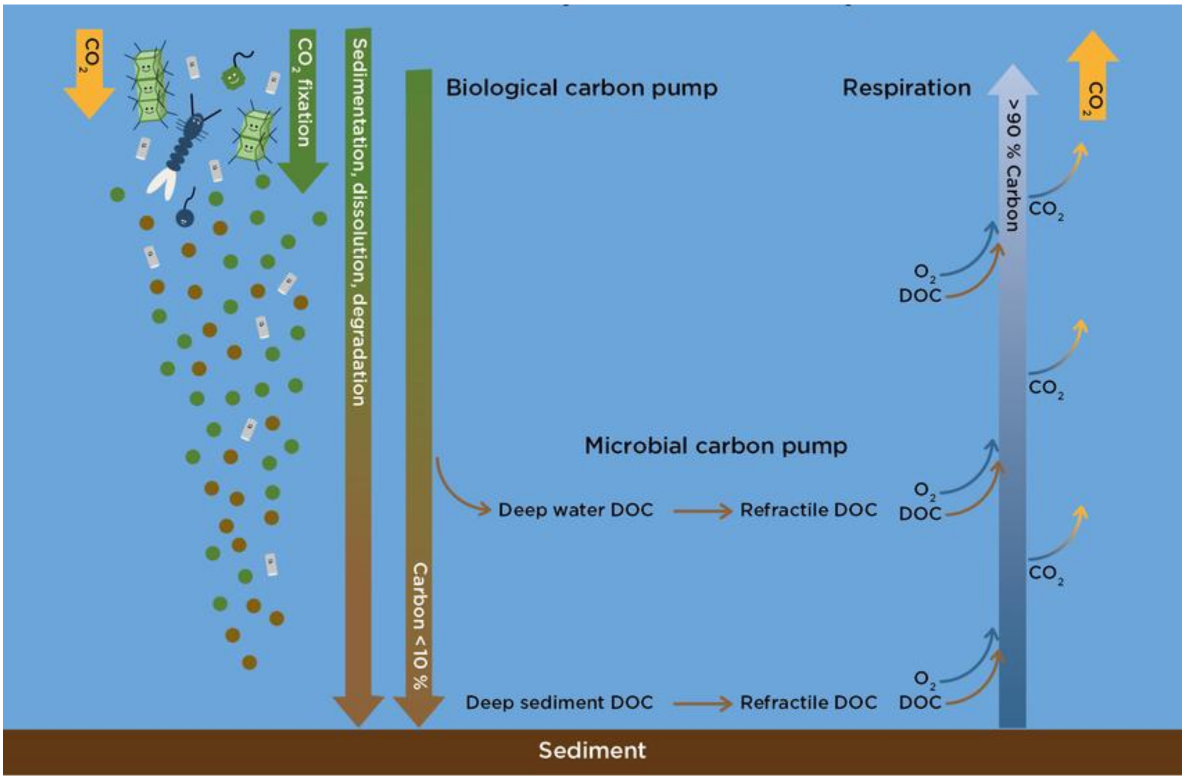

Figure 1. Oceanic carbon cycle and carbon sequestration (Wikner et al 2023).

Microbial loop and carbon cycling. Marine bacteria and archaea degrade organic matter and play a role in transforming and remineralizing carbon. Some microbes also contribute to carbonate precipitation and the production of recalcitrant dissolved organic carbon (RDOC), which can persist in the ocean for millennia. Additionally, certain marine archaea and deep-sea microbes participate in methane oxidation and carbon fixation in aphotic zones (Zhang et al 2022; Li et al 2024; Gilabert et al 2025).

Blue carbon ecosystems. Coastal vegetated habitats (mangroves, salt marshes, and seagrass meadows) are often referred to as blue carbon ecosystems due to their high carbon sequestration capacity:

• Mangroves: Up to 1,000 Mg CO_2/ha stored in biomass and sediments (Schile et al 2017; Macreadie et al 2019; Yin et al 2023; Ding et al 2025).

• Seagrass meadows: Globally sequester ~27.4 Tg CO_2/year (Macreadie et al 2019; Yin et al 2023).

• Salt marshes: Sequester ~210 g CO_2/m^2/year on average (Macreadie et al 2019; Yin et al 2023).

These ecosystems trap both organic and inorganic carbon in sediments, offering long-term storage that can rival or exceed that of tropical forests per unit area (Macreadie et al 2019; Yin et al 2023).

Terrestrial Carbon Sequestration: Strengths and Constraints. Terrestrial plants, particularly forests (Oroian et al 2023), are key components of the global carbon cycle:

• Annual CO_2 fixation by terrestrial vegetation: ~120 gigatons (Sheikh et al 2014).

• Net terrestrial carbon sequestration: ~10-20 gigatons per year (Sheikh et al 2014; Bar-On et al 2025).

• Main contributors: Tropical forests, boreal forests, peatlands (Sheikh et al 2014; Nolan et al 2021; Bar-On et al 2025).

However, terrestrial carbon sinks are vulnerable to disturbance and climate feedbacks. Deforestation, wildfires, pest outbreaks, and increasing temperatures can rapidly release stored carbon back into the atmosphere (Peñuelas 2022; Yumashev et al 2022; Yuan et al 2024). Additionally, soil carbon is sensitive to land-use change and erosion (Yumashev et al 2022; Rodriguez et al 2023; Liang & Zhu 2021; Oroian et al 2024ab) (Table 1).

Table 1

The role of marine flora and microbiota in carbon sequestration - comparative insights

Attribute	*Marine flora & microbiota*	*Terrestrial flora*
Primary productivity	~45-50 Gt C/year (phytoplankton)	~120 Gt C/year
Long-term sequestration	Deep ocean storage for millennia	Soil and biomass storage (decades-centuries)
Stability of carbon sink	More stable in deep sea; less vulnerable to fire/deforestation	Vulnerable to anthropogenic and climatic disturbances
Spatial extent	70% of Earth's surface (oceans)	30% of Earth's surface (land)
Ecosystem examples	Phytoplankton, seagrasses, mangroves	Forests, grasslands, peatlands
Limitations	Carbon sequestration efficiency is nutrient-limited; some carbon remineralized before burial.	Land competition, degradation, finite expansion potential.

Limitations and Emerging Opportunities

- **Ocean iron fertilization** has been proposed to boost phytoplankton growth, but ecological risks and ethical concerns limit its implementation.
- **Marine microbial carbon sequestration** is underexplored due to sampling challenges and limited understanding of deep-sea processes.
- **Blue carbon habitats** are threatened by coastal development, pollution, and sea-level rise, necessitating protection and restoration.

Meanwhile, terrestrial reforestation and afforestation efforts face land-use constraints and require decades to centuries for full carbon storage potential.

Conclusions. Marine flora and microbiota, though largely invisible, are vital to Earth's carbon balance. Phytoplankton-driven biological pumps, blue carbon ecosystems, and microbial transformations make the ocean not only a vast carbon reservoir but also an active agent in atmospheric CO_2 regulation. While terrestrial ecosystems fix more carbon annually, oceanic processes offer more stable, long-term sequestration and occupy a larger portion of the planet. Future climate strategies must consider the ocean as an indispensable ally in carbon mitigation, balancing restoration of terrestrial ecosystems with marine conservation and innovation in ocean-based solutions.

Conflict of Interest. The authors declare that there is no conflict of interest.

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