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Deep-Sea ecosystems and their role in biogeochemical cycles and carbon sequestration

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Abstract

Deep-sea ecosystems have transitioned from being perceived as biological deserts and geochemically inactive to being recognized as major players in regulating Earth's biogeochemical cycles and long-term carbon storage. They include various ocean-floor environments, such as abyssal plains, hydrothermal vents, cold seeps, seamounts, and hadal trenches, each with its own microbial and faunal communities that promote nutrient cycling and organic matter decomposition. The process of deep-ocean carbon storage is multistep. It includes the sinking of particulate organic carbon from surface waters, microbial carbon fixation, and burial of the organic material in sediments over geological timescales. Recent research has shown that deep-sea inhabitants are actively involved in nutrient remineralization, methane oxidation, and the stabilization of carbon-rich compounds, thereby influencing global climate dynamics. Nevertheless, the security of these processes is put at risk by trawling, mining, plastic pollution, and changes in ocean chemistry associated with warming. As human activities push into deeper oceans, gaining a thorough understanding of biological interactions, sediment processes, and carbon fluxes is essential. This review compiles existing knowledge of deep-sea ecosystem services, identifies uncertainties in carbon budget calculations, and suggests the need for improved monitoring using autonomous observation systems and high-resolution modeling. The preservation of deep-sea areas is hence a key factor not only for supporting biodiversity but also for maintaining their crucial role in regulating Earth's climate.

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Introduction

Deep-sea ecosystems lie beneath the continental shelf in the oceans, covering the bathyal, abyssal, and hadal zones, where there is total darkness and pressure is exceptionally high. Still, the life forms in these areas are very varied, including microscopic organisms in the soil, larger invertebrates, and fish living near the bottom. The ecological processes in these areas depend heavily on the supply of organic matter and minerals from the surface waters and the coastal regions. According to (Smith Jr *et al.*, 2009), the deep ocean is a habitat with distinct conditions, where temperature changes, the supply of particulate organic carbon, and the water-solubility of nutrients can significantly alter biological activity. It was once assumed that these areas were dead zones, but they turned out to play a significant role in the cycle of surface productivity and the long-term storage of carbon in sediments.

The biogeochemical cycles in the ocean determine the fate and transport of major elements such as carbon, nitrogen, sulfur, and oxygen. Most of these processes involve microbes, benthic fauna, and sediments. (Thurber *et al.*, 2014) noted that deep-sea inhabitants are responsible for nutrient remineralization, chemosynthetic production, and the detoxification of organic debris, which together make the seafloor a primary contributor to the chemical stability of the entire ocean. The food web structure (Rowe and Pariente, 2012) presented illustrates how particles falling to the ocean floor are consumed, decomposed, and eventually incorporated into complex trophic pathways. In polar regions, water mass formation further promotes the transfer of dissolved inorganic carbon to the ocean floor, with (Hoppema, 2004) pointing to the Weddell Sea as a particular site for long-term sequestration.

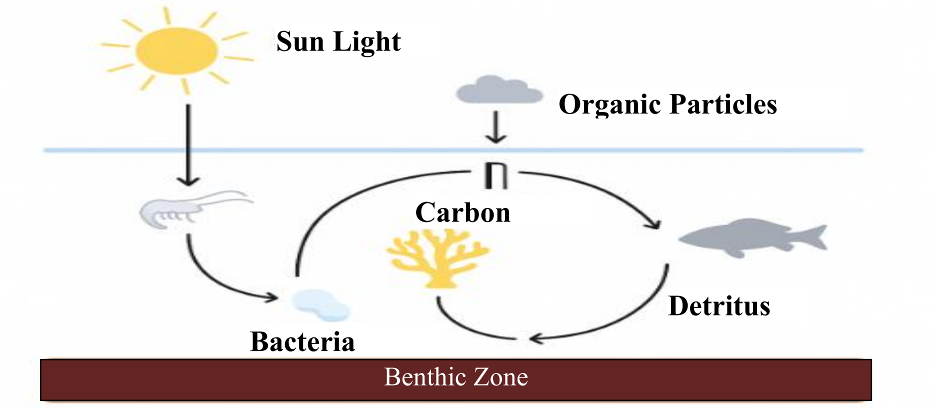

Figure 1: Conceptual framework of deep-sea ecosystems

The interconnected flow of energy and carbon within deep-sea ecosystems commences with sunlight and primary production at the surface, as illustrated in Figure 1, and continues with the descent of organic matter and particles to deeper strata. Advanced consumer systems in the deep sea, including certain shrimp, fish, and benthic invertebrates, derive sustenance from falling detritus and dead organisms. In addition to bacterial carbon recycling, organic material stored within the ecosystem is later entombed in deep-sea sediments, thus facilitating long-term carbon sequestration within the benthic zone. These processes and their interactions illustrate the role of biological activity, sediment processes, and microbial decomposition in shaping the carbon cycle in the deep ocean.

Deep-sea carbon sequestration is an essential factor in regulating atmospheric greenhouse gas levels. The "biological pump," as described by (Longhurst, 1991), removes organic carbon from the surface waters and stores it in deeper layers, where it gets either consumed, respired, or buried. In addition, chemosynthetic microbes fix inorganic carbon directly from seawater, forming a primary energy source independent of sunlight; (Molari, Manini and Dell'Anno, 2013) showed that dark carbon fixation can sustain benthic functioning even in areas with very low organic input. Natural sequestration helps stabilize the climate, but human activities can disrupt the ecological balance. (Seibel and Walsh, 2001) cautioned that CO_2 injection and other geo-engineering methods could lead to negative impacts on the deep-sea fauna that are already less tolerant to rapid chemical changes. The findings of (Thurber *et al.*, 2014) indicate that protecting deep-sea processes is key to ensuring we receive ecological services and that the ocean continues to be a long-term carbon sink.

This paper has five main sections. In the first section, the importance of the deep-sea ecosystems and their biogeochemical connections were introduced, along with the paper scope. In the second section, environmental factors and deep-sea habitat biodiversity are described. The third section outlines the main biogeochemical cycles, emphasizing primary production, microbe and human activity, and impact shifts interlinked with the cycles. The fourth section describes carbon sequestration with a focus on models and their evaluation approaches. The final section summarizes the main points and suggests deep-sea ecosystems biogeochemical cycles research and conservation efforts.

Characteristics of Deep-Sea Ecosystems

The deep-sea ecosystems are characterized by the physical conditions that are mainly opposite to those of the upper ocean (Bruno and Muraleedaran, 2025). The temperatures are nearly zero, there is no sunlight, and the hydro-static pressure increases by approximately one atmosphere for every ten meters. However, life continues to make its way through trenches, seamounts, and cold seeps. Microbial and faunal communities have devised ways of normal metabolism that even at such high pressures would be lethal to shallow-water creatures. (Zhang *et al.*, 2022) noted that the deep-sea sediments contain a rich variety of microbial taxa which can endure these harsh conditions by utilizing energy in the form of metabolic pathways that are very efficient and adapted to low energy supply. Such bacteria not only participate in the decomposition of organic matter but also in the nitrogen, sulfur, and carbon cycling under the layers of several kilometers of water. The diversity of deep-sea environments is less in their numbers but unexpectedly rich in unique species. The organisms include the incredible fish that can tolerate a lot of pressure, as well as sponges, worms, and though invisible, there is also a presence of gelatinous zooplankton. According to the study of (Wishner and Gowing, 1992), deep-sea zooplankton are major players in the vertical carbon pathway, they are the ones that not only consume sinking particles but also help in the redistribution of organic matter throughout the water column. The sponge's corruption was considered an important factor in the ecosystem: (Hanz *et al.*, 2022) presented evidence of sponge reefs giving rise to great impacts on nitrogen removal and dissolved carbon assimilation in biotic hot spots. Sediment is also the location where the terrestrial organic matter brought from the land by rivers is still retained, but according to (Kandasamy and Nagender Nath, 2016), the burial processes along the coastline to the deep ocean are still unclear with regard to many aspects. One of the main characteristics that determine the ecology of the deep ocean is its dependence on the chemosynthesis production. At cold seeps, hydrothermal vents, and methane-laden sediments, bacteria and archaea receive their energy from inorganic compounds instead of sunlight. These microorganisms are the primary producers in the food chains that provide energy for mussels, tubeworms, shrimps, and other specialized animals. (Honjo *et al.*, 2014) characterized this biological pump as a leading route for carbon export and its conversion to deeper layers. The organic matter quality deposited at the seabed, basically, controls the speed of the respiration or burial process. (Mayor *et al.*, 2012) reported that the cycling of carbon in sediments is prolonged when the materials coming in are resistant, thus turning the depositional areas into long-term storage sites. Moreover, one of the significant roles that viruses play in the ecosystem is the subtle but important control of certain processes (Dixit and Raje, 2024; Danovaro *et al.*, 2008). In 2008, Danovaro and his team observed that viruses through lysis contributed to the recycling of organic compounds which are then used as the main source of energy for microbial production in the case of benthic communities. Through ongoing and more extensive research, (Zhang *et al.*, 2025) conclude that at a global level, viruses are the main regulators of the microbial transformation of carbon that eventually leads to the situations where carbon is either respired or trapped in sediments for very long periods.

Biogeochemical Cycles in Deep-Sea Ecosystems

Role of Phytoplankton in Primary Production and Nutrient Cycling

The deep sea may be in total darkness but it gets its energy from the surface layers of the ocean where phytoplankton carry out the process of photosynthesis. These tiny plants convert CO2 to organic matter and at the same time they take up nutrients such as nitrate, phosphate, and silica from the water. The death of phytoplankton or their consumption by zooplankton leads to a situation where the biomass is partly converted to particulate organic matter which takes a long time to sink from the upper water column to the bottom. This phenomenon which is referred to as "marine snow" is the main way in which energy moves from the surface waters to the deep sea bottom areas of the ocean and trenches. Very little of this rain actually reaches the sea floor at depths of 4,000–6,000 m but still it is enough to support the life of benthic communities. The seasonal influx of phytodetritus often triggers a short-term increase in the feeding of worms, brittle stars, and other mobile detritivores. The surface nutrient uptake is directly affected by phytoplankton growth and thus any change in surface productivity—for instance, warming-induced stratification—has a direct impact on the amount of organic material entering the deep sea.

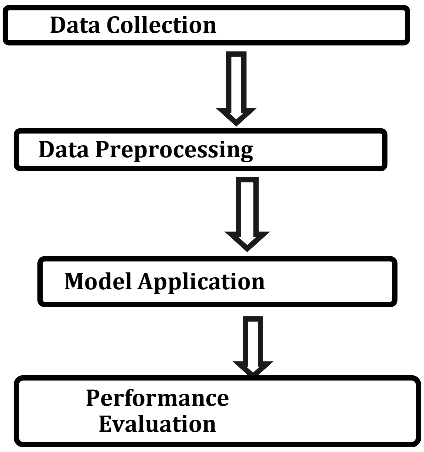

Figure 2: Workflow or data processing pipeline

Figure 2 outlines the described workflow for the proposed data processing pipeline which begins with collecting data from primary and secondary sources and proceeds with data preprocessing steps like cleaning, normalization, and feature extraction. The data is then processed and input into the chosen computational or machine learning model to create predictions or other analytical results. At the end, system performance is assessed to evaluate the results based on the defined metrics for accuracy, reliability, and robustness.

Importance of Microbial Communities in Nutrient Recycling and Decomposition

Microbial assemblages are all over the place in the seabed to the totality of a carbon transformation once the organic debris gets settled. When oxygen is plentiful, aerobic bacteria break down proteins, carbohydrates, and lipids very quickly to produce dissolved nutrients that are diffused back into the bottom waters. In places with less or no oxygen, the microbes rely on alternative pathways for respiration—nitrate, sulfate, or metal oxides as electron acceptors. These slower pathways lead to the organic remains being buried for long periods in the sediments. Besides the action of microbes, the Archaea and fungi living deep in the ocean are also involved in the breakdown process of the slowest to decay substances like lignin-rich fragments that have been transported from land. Besides decomposition, microbes are also in charge of regulating the cycling of nitrogen and sulfur; they gradually change reduced compounds into forms that allow plankton growth as they return to the upper layers of the ocean. Since direct measurement is tricky, modeling is the method that gives us the most insight into how matter is transformed at such a depth. One simplified representation is based on two key rates: microbial respiration and sediment burial. If F(t) is the organic flux arriving on the seabed at time t,

$$R(t) = k_1 \cdot F(t) \qquad (1)$$

k_1 is the constant responsible for the respiration efficiency. The burial process through deeper sediment layers is where

$$B(t) = k_2 \cdot \big(F(t) - R(t)\big) \qquad (2)$$

k_2 is the parameter that shows the portion of non-respired matter which is going to be buried. A simple algorithm to predict yearly carbon sequestration would:

- get daily estimates of organic flux,
- use the respiration rates modified by temperature,
- deduct carbon respired from the total input,
- total up B(t) during the year for the whole sequestration.

Human Impact on Biogeochemical Processes through Deep-Sea Mining and Other Activities

Human disturbances have an increasingly adverse effect on the natural cycles. The application of deep-sea mining has led to a great disturbance of the sediment layers that have been kept sealed for ages, thus enormously exposing the carbon that has been stored to oxygen and the process of re-mineralization. Once the layers that trap carbon are mixed with the layers above, the respiration of microbes gets faster, and the release of dissolved inorganic carbon occurs, which, otherwise, would have been buried permanently. The same disturbances are caused when pipelines are installed, cables are laid, and when trawlers operate, all these activities lead to the breaking of habitat complexity and the elimination of the organisms that are responsible for the processing of the materials that have settled. Reduced, over a period of time, microbial activity and loss of benthic fauna are the natural biological mechanisms that strengthen and regulate nutrient recycling being weak now. Carbon burial efficiency changes can be very minor from year to year, but if the disruption is cumulative it is possible that the deep ocean loses its role as a long-term sink in the global carbon system as a result of decreased impact on carbon reservoirs.

Carbon Sequestration in Deep-Sea Ecosystems

Role of Deep-Sea Sediments in Storing Organic Carbon

Deep-sea sediments are the ultimate repository of organic matter from the upper ocean. As particles sink to the ocean floor, most of them are either consumed or refreshed in the water column, but a certain quantity still comes down to the seabed. The moment they are buried under layers of more mud, clay and minerals, the organic carbon gets separated from the oxidation process and can be held up for hundreds of years. Burial efficiency usually varies with the sedimentation rate, oxygen penetration, and microbial activity. A simplified measure of how much carbon gets trapped is the Carbon Burial Efficiency (CBE), which is expressed as:

$$CBE = \frac{C_{buried}}{C_{input}} \times 100 \qquad (3)$$

where C_{buried} represents the amount of carbon that is maintained underneath the actively disturbed surface layer and C_{input} is the annual quantity coming in. The practice of having fine-grained sediments or low-oxygen conditions that last for a very long time, generally implies a higher CBE value.

Contribution of Deep-Sea Ecosystems to Global Carbon Budgets

Even though the deep ocean is far away, it still has a definite influence on the global carbon budget. Organic particles that do not get remineralised become buried in the sediment and hence are not included in the atmospheric exchange. In order to measure this contribution at regional levels, scientists often use sediment cores, particle traps, and numerical models. One of the most common performance metrics used is Annual Carbon Sequestration Rate (ACSR):

$$ACSR = \frac{\sum_{t=1}^{n} C_{buried}(t)}{A} \qquad (4)$$

where t indicates the time (days or months) and A the seafloor area under consideration. Using software programs such as MATLAB, Python-SciPy, R-OceanPack, or ArcGIS, one can thus interpolate burial rates, create hotspot maps, and perform comparisons of time-series data.

Possibility for Acquiring More Carbon from the Atmosphere via Conservation and Restoration

Conservation tactics like the banning of deep-sea trawling or mining in specific areas not only protect the sediment but also prevent the carbon particles already buried in the sediment from being exposed. Restoration methods concentrate on the safeguarding of sponge grounds, coral mounds, and microbial mats which in turn trap the organic material. One simple metric for performance evaluation is Sequestration Stability Index (SSI), wherein the carbon retention before the disturbance is compared with that after the disturbance:

$$SSI = \frac{C_{after}}{C_{before}} \qquad (5)$$

A threshold >1 means that retention has improved, while <1 means that there has been a carbon loss. Tools such as HYCOM, COMSOL Multiphysics, or ROMS can be used to run simulations for testing the impact of disturbance on the burial rates.

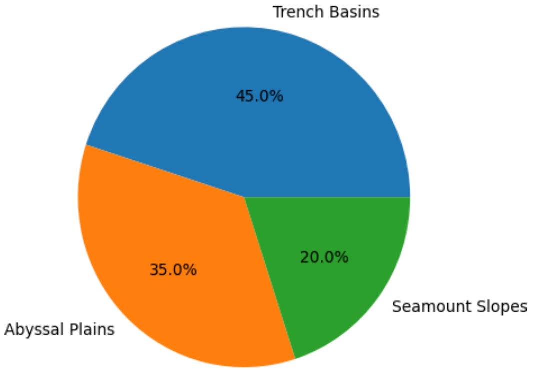

Figure 3: Carbon burial distribution across major deep-sea habitats

Figure 3 shows the proportional contributions of three key deep-sea environments, trench basins, abyssal plains, and seamount slopes, to total organic carbon burial. The pie chart illustrates how trench basins lead in carbon storage because of high sedimentation rates and consistent deposition of organic matter. Abyssal plains and seamount slopes add smaller but still important amounts. By presenting carbon burial as percentages instead of raw values, the figure reveals differences across deep-ocean landscapes. It also shows that the ability of deep-sea ecosystems to store carbon varies and is strongly affected by geomorphology, hydrodynamics, and sediment composition.

Conclusion

Multiple research advances indicate that deep-sea ecosystems are becoming more influential than previously thought in driving and balancing the global cycling of carbon and nutrients. Observational data from these isolated ecosystems trigger transformative active and passive regulation of carbon cycling and nutrient turnover. Evidence of carbon entrapment and the retention of organic matter in the deep-sea sediments indicate long-term vaulting of carbon. This long-term retention of vault carbon is becoming more necessary as industrialized nations lock down carbon and as global warming passes the tipping point. Deep-sea mines pose incentives of industrialized nations. Deep-sea mining and extraction of other seabed resources lead to the presumed rapid alteration of regulation systems that have taken millennia to stabilize. Future conservation measures that attempt to maintain the deep-sea ecosystems as safely buffered systems will need the integration of the most recent monitoring systems and ultra-conservative environmental restrictions. Knowledge of the active and passive deep-sea ecosystems will aid in providing scientifically sound carbon management policies. Ignoring the carbon management value of the deep sea is shrinking global biodiversity and undermining climate initiatives.

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