Discover Oceans

Review

Mechanisms, processes, and implications of blue carbon sequestration and pollution control for climate change mitigation

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Abstract
Mangroves, seagrass beds, and salt marshes are examples of blue carbon ecosystems that are essential to the global carbon cycle because they store atmospheric CO2 in biomass and sediments. In order to assess the biogeochemical processes, sequestration rates, and environmental factors that control carbon storage and emissions in these ecosystems, this study summarizes data from peer-reviewed research published over the previous 20 years. Seagrass and salt marsh systems sequester 30–218 g C m^{-2} yr^{-1} and 150–250 g C m^{-2} yr^{-1}, respectively, whereas mangroves have considerable belowground carbon storage (up to 1,023 Mg C ha^{-1}) supported by anoxic, sulfate-reducing sediments and vertical accretion rates of 3–10 mm yr^{-1}. Additionally, we evaluate carbon-loss mechanisms that might turn blue carbon sinks into net carbon sources, such as sediment erosion, methane generation, and oxidation after disturbance. Sea level rise, nitrogen loading, hydrological changes, and pollution are some of the factors that affect carbon stability and sequestration effectiveness. Our research as a whole shows that while restoration can recover 50–90% of depleted carbon stocks over several decades, intact blue carbon ecosystems significantly contribute to climate mitigation. These results highlight the significance of protecting coastal ecosystems and incorporating blue carbon solutions into frameworks for carbon offsets, pollution management, and climate adaption.

Keywords Blue carbon sequestration · Climate change mitigation · Coastal ecosystems · Mangroves · Carbon storage · Marine ecosystems

1 Introduction

1.1 Overview of blue carbon sequestration

Blue carbon sequestration refers to the process of capturing and storing large amounts of carbon dioxide from the atmosphere over hundreds to thousands of years in coastal and marine ecosystems, such as mangroves, seagrass meadows, and salt marshes [1]. This mechanism is crucial for reducing the effects of climate change by lowering the amount of greenhouse gases in the atmosphere and improving blue carbon storage by maintaining healthy marine ecosystems.

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Numerous studies have been conducted to determine the potential of blue carbon sequestration as a natural method of mitigating carbon emissions. These studies have clarified the factors influencing carbon sequestration rates and the capacity of different coastal ecosystems to store carbon [2]. Furthermore, blue carbon sequestration contributes to the resilience of coastal ecosystems and offers additional benefits, such as habitat preservation and improved water quality. Research has been conducted to evaluate the viability and efficacy of implementing blue carbon projects to reduce greenhouse gas emissions and adapt to climate change. The formation and burial of carbon, along with the rates of erosion, decomposition, and export, all impact the landscape's blue carbon reserves. The opposing processes of export, erosion, and decomposition within these ecosystems and their productivity make them vulnerable to climate change [1]. The literature review on blue carbon sequestration provides an in-depth discussion of the concept, its significance in minimizing the impact of global warming, and the various approaches and outcomes relevant to its application. It offers a thorough understanding of the concept, its importance in combating climate change, and the most recent research findings and implementation strategies. This review emphasizes the crucial role of blue carbon sequestration as a natural solution for mitigating carbon emissions in marine and coastal areas. In summary, the literature review offers a comprehensive overview of blue carbon sequestration.

1.2 Importance of blue carbon in climate change mitigation

The role of blue carbon in climate change mitigation has become interesting research in recent years. Coastal and marine systems, such as mangroves, seagrasses, and salt marshes, are key components of blue carbon ecosystems. These ecosystems can sequester and store significant amounts of carbon dioxide, thus helping to mitigate the increasing emissions of CO_2 into the atmosphere. By sequestering carbon, blue carbon ecosystems contribute to reducing the amount of CO_2 in the atmosphere and ultimately help to mitigate climate change. Additionally, the management and conservation of blue carbon ecosystems is essential for maximizing their carbon sequestration potential. Resource managers rely on best-management practices that have historically included protecting and restoring vegetated coastal habitats to promote the sequestration of blue carbon. However, it is now recognized that catchment-level approaches are also necessary to optimize coastal blue carbon sequestration. These catchment-level approaches involve considering a range of environmental variables that influence blue carbon sequestration, such as warming, carbon dioxide levels, water depth, nutrients, runoff, bioturbation, physical disturbances, and tidal exchange. By understanding these environmental variables and their impacts on blue carbon sequestration, three potential management strategies have been identified to maximize coastal blue carbon sequestration: reducing anthropogenic nutrient inputs, reinstating top-down control of bioturbator populations, and restoring hydrology. Overall, the literature highlights the importance of blue carbon ecosystems in climate change mitigation. Blue carbon ecosystems, such as mangroves, seagrasses, and saltmarshes, play a crucial role in climate change mitigation by sequestering and storing significant amounts of carbon dioxide. This carbon sequestration helps to reduce CO_2 levels, Greenhouse Gas Emissions, and enhance the coastal in the atmosphere and contributes to efforts to mitigate climate change [3, 4].

2 Review methodology

This review was prepared as a structured narrative synthesis focusing on the mechanisms, processes and implications of blue carbon sequestration and pollution control in coastal and marine ecosystems, including mangroves, salt marshes, seagrass meadows, marine microbes and algae. A literature search was conducted in Web of Science, Scopus and PubMed, complemented by targeted searches in Google Scholar and by screening the reference lists of key papers, covering publications from 2000 to 2024 in order to capture contemporary understanding of blue carbon dynamics and their responses to climate and anthropogenic drivers. Search terms were combined using Boolean operators and included phrases such as blue carbon, mangrove carbon storage, seagrass carbon burial, salt marsh carbon sequestration, marine carbon cycle, microbial carbon pump, coastal sediment carbon and pollution control in blue carbon ecosystems. Only peer reviewed articles, reviews and book chapters in English were considered, while grey literature, conference abstracts and non reviewed reports were excluded. Studies were included if they quantified carbon stocks or sequestration rates in mangroves, salt marshes, seagrasses or associated sediments, examined microbial or algal processes contributing to marine carbon fixation and storage, analysed physical, chemical or biological mechanisms underpinning carbon burial, assessed environmental or anthropogenic drivers such as climate, hydrology, nutrient loading, land use change, pollution, habitat degradation or sea level rise, or evaluated restoration, management or policy interventions in blue carbon ecosystems. Titles and abstracts were screened for relevance and full texts of potentially eligible studies were examined in detail, with non relevant or purely conceptual works removed. For each included study, information was extracted where available on ecosystem type and location, dominant species, study design, methods used to quantify carbon stocks or fluxes, reported values for biomass or sediment carbon, rates of sequestration or burial, key drivers and pressures, and any restoration or management actions. Owing to heterogeneity in ecosystem types, methods and reporting units, a formal meta analysis was not attempted; instead, findings were grouped into thematic domains aligned with the structure of the review, including ecosystem specific mechanisms of carbon capture and storage, biological and physico chemical processes supporting sequestration, environmental and anthropogenic controls, measurement and monitoring approaches and implications for climate mitigation and pollution control, and patterns were compared qualitatively across regions and taxa. Study quality was considered qualitatively based on clarity of methods, sampling design, analytical techniques and treatment of uncertainty, with greater weight given to work using established approaches such as sediment coring with depth resolved carbon analysis, radiometric dating, gas flux measurements and validated remote sensing products. The review is subject to several limitations, including restriction to English language literature, methodological differences in sampling depth and analytical protocols that complicate comparison of carbon stock estimates, and an uneven evidence base with more data for mangroves and temperate salt marshes than for many tropical seagrasses or microbially mediated processes; these limitations are acknowledged when interpreting the findings and in identifying knowledge gaps and priorities for future research.

3 Coastal ecosystems as blue carbon sinks (Table 1)

3.1 Mangroves: carbon storage and sequestration mechanisms

Coastal ecosystems, particularly mangroves, have been identified as important "blue carbon" sinks as it capture carbon within aquatic environments such as mangroves and seagrass meadows [5]. Several studies have focused on the carbon storage and sequestration mechanisms of mangroves. Mangroves have been identified as important exporters of both organic and inorganic carbon. This carbon export is facilitated through processes such as tides, which can transport dissolved and particulate organic carbon to adjacent coastal ecosystems. Furthermore, the amount of carbon stored in mangrove soils can vary widely, with values ranging from 0.1 to 40% of soil dry weight. . A highly variable proportion of this carbon is derived from mangroves, as organic matter is transported by tides from various adjacent habitats and land-based sources, as well as other marine environments. One important aspect to consider is the potential for mangroves to act as both carbon sinks and sources [6]. A significant amount of biomass is distributed belowground by mangroves in the form of intricate and dense root systems, such as prop roots, pneumatophores, and fine roots. These roots significantly contribute to soil organic carbon stores and continuously deliver organic matter to sediments. 50–70% of the carbon stored in mangroves comes from belowground biomass [5]. Deep carbon-rich soils are maintained by root turnover and deposition. Because mangrove sediments are usually oxygen-poor and wet, anoxic conditions are created that inhibit the microbial breakdown of organic materials. Microbial processes like fermentation and sulfate reduction, which both mineralize carbon more slowly than aerobic routes, take over when there is less oxygen available. Because of this, organic matter in mangrove soils breaks down three to ten times more slowly than in upland soils [7]. The conversion of mangrove forests to aquaculture ponds can release such large amounts of carbon to the atmosphere that these emissions may be up to 50 times higher than the carbon that intact mangrove forests would normally sequester. Deforestation and hydrological changes are examples of disturbance events that can raise CO2 emissions to levels 10–40 times greater than intact mangroves' normal sequestration rates [8]. Mineral deposits carried by rivers, waves, and tides are captured by mangrove roots. This encourages the burial of organic debris and the accumulation of vertical sediment. Mangroves can collect surface elevation at rates greater than 10 mm annually in sediment-rich areas, allowing for ongoing carbon burial and resilience to moderate sea-level rise [9]. High amounts of lignin, tannins, and other polyphenolic chemicals that withstand microbial degradation can be found in mangrove leaves, roots, and woody materials. These chemically resistant substances improve the long-term retention of organic carbon in sediments by slowing breakdown [10]. Through tidal exchange, mangrove habitats export significant volumes of particulate organic carbon (POC) and dissolved organic carbon (DOC) into nearby estuaries and coastal seas. Beyond the mangrove canopy, some of this exported carbon is

Table 1 Mangroves, salt marshes, and seagrasses, including their carbon capture capabilities, origin, mechanisms, unique features, ecological significance, and potential biotechnological applications

Marine vegetation	Amount of carbon capture	Type of carbon captured	Origin place	Mechanism	Uniqueness	Ecological significance	Biotechnological applications	References
Mangroves	Approximately 6.4 GT of CO_2 stored annually	Organic and Inorganic (CO_2 and sediment)	Coastal tropical and subtropical regions	Photosynthesis and sediment trapping	High root density that traps sediments and stores carbon	Protects coastlines, supports marine life	Potential in carbon sequestration projects and coastal protection	[88]
Salt Marshes	Approximately 3.7 GT of CO_2 stored annually	Organic and Inorganic (CO_2 and sediment)	Coastal temperate and subtropical regions	Photosynthesis and sediment accretion	High nutrient absorption and filtration capacity	Acts as a buffer against coastal erosion, supports biodiversity	Potential in carbon offset projects and water filtration systems	[35, 37]
Seagrasses	Approximately 83 million metric tons of CO_2 sequestered annually	Inorganic (CO_2) and Organic carbon	Shallow coastal waters worldwide	Photosynthesis and organic carbon burial	Ability to sequester carbon in anoxic sediments	Critical habitat for marine species, stabilizes sediments	Used in habitat restoration and carbon sequestration efforts	[89]

sequestered in nearshore sediments. According to studies, mangroves preserve a substantial amount of carbon burial in their soils while acting as DOC exporters [11]. On centennial to millennial periods, mangrove sediments can build up deep, organic-rich layers (typically more than one meter), creating peat deposits that store carbon. Mangroves sustain vertical accretion rates that enable them to keep up with sea level rise when there is an adequate supply of sediment, further improving carbon preservation [12]. Sulfate reduction is the predominant terminal electron-accepting activity in saline, anoxic mangrove sediments. A greater percentage of organic matter stays buried in the sediment because sulfate-reducing bacteria mineralize carbon less effectively than aerobic microorganisms [10].

3.2 Salt marshes: role in carbon sequestration and coastal protection

Salt marshes also play an important role in mitigating climate change and providing protection against coastal hazards. They are among the most productive ecosystems, capable of sequestering and storing large amounts of carbon [13]. Cook-Patton et al. [14] state that salt marshes can store up to 10 times more carbon per unit area than terrestrial ecosystems through processes such as photosynthesis and sediment trapping. Moreover, salt marshes provide important coastal protection by reducing wave energy and acting as a buffer against storm surges and flooding. Other natural carbon removal processes, notably seaweed ecosystems and proposed non-biologic marine CO_2 removal techniques, have smaller climate mitigation impacts. Salt marshes, along with other coastal wetlands species such as mangroves and seagrass meadows, are highly effective in carbon sequestration and can significantly contribute to global carbon mitigation efforts.

Several studies have highlighted the importance of salt marshes as carbon sinks and their role in mitigating climate change. Salt marshes can sequester carbon at rates comparable to tropical rainforests. The carbon sequestration potential of salt marshes is influenced by various factors, such as sediment availability and tidal range [15]. Additionally, the protection and enhancement of coastal salt marshes can help to reduce the impacts of sea-level rise and coastal erosion. Under favorable conditions, salt marshes have been found to keep pace with fast rates of sea-level rise by trapping sediments and building up their elevation. In contrast, salt marshes located in areas with high wave exposure and limited sediment availability may struggle to keep up with sea-level rise and face the risk of submergence. Therefore, it is necessary to protect and restore salt marshes to maximize their carbon sequestration potential and enhance their resilience in the face of climate change and rising sea levels [13].

3.3 Seagrasses: carbon accumulation and ecosystem services

Seagrasses are aquatic angiosperms, it is also important to maintain the coastal ecosystem. They are taxonomically restricted to two families, 12 genera, and 55 species, all of which evolved from land predecessors that returned to the sea approximately 100 million years ago during the Cretaceous [16]. Seagrass meadows are recognized as global hotspots for carbon storage, with higher soil carbon accumulation compared to terrestrial soils. Carbon accumulation in seagrasses has been a subject of research due to its importance in understanding the role of seagrass meadows in carbon sequestration and climate change mitigation. According to a study by (Duarte et al.) seagrass meadows have been found to store twice as much carbon as terrestrial forests. In addition to carbon storage, seagrass meadows provide habitat and a nutritional base for a diverse range of species including finfish, shellfish, waterfowl, and herbivorous mammals. Several studies have explored the spatial variability of soil carbon storage in seagrass meadows. A survey conducted in 17 Australian seagrass meadows revealed that soil carbon storage varies spatially with factors such as seagrass species and water depth. Furthermore, studies have shown that the proximity to shore and hydrodynamic properties of the area also affect soil organic carbon storage in seagrass meadows. Seagrass meadows are highly productive ecosystems with substantial soil carbon storage. According to a study, seagrass meadows were found to have varying spatial distribution of soil carbon storage, influenced by factors such as seagrass species and water depth [2]. Another important aspect of seagrass meadows in carbon accumulation is their role as exporters of both organic and inorganic carbon [2]. Nutrient supply from roots allows seagrasses to continue accumulating carbon even in nutrient-poor waters. Seagrasses also play a significant role in nutrient cycling, sediment stabilization, and water quality improvement.

3.4 Marine bacteria: photosynthetic carbon fixation in marine environments

In the marine environment, the microbial carbon pump (MCP), biological pump (BP), and microbially induced carbonate precipitation (MICP) are the primary drivers of carbon collection, transformation, and transport (Table 2). The breakdown of particulate organic matter (POM), cell death, and interspecies interactions are how marine microorganisms contribute to the synthesis of refractory dissolved organic carbon (RDOC), as highlighted by the MCP process. phytoplankton changed the structure of the bacterioplankton community in various water layers. *Prochlorococcus* was found to predominate over *Synechococcus* and picoeucaryotes in a study of marine picophytoplankton and their distribution patterns in the West Pacific. *Prochloroco ccus* abundance was negatively correlated with nutrient concentrations, while temperature and salinity were closely correlated with the spatial variation in the picophytoplankton community, suggesting the significance of picophytoplankton in contributing to the C pool in the oligotrophic ocean [17].

3.5 Algae: carbon fixation and atmospheric CO_2 reduction

The predominant primary producers in the coastal zone are micro and macro algae, however, these organisms generally do not thrive in ecosystems that are thought to store significant amounts of organic carbon. Nonetheless, reports have indicated the existence of algal carbon in the deep sea and sediments, where it is successfully removed from the atmosphere (Table 3). These results taken together imply that algae may be a significant source of the carbon stored in deep ocean and marine sediments. There are two primary ways that algal material gets transported to the deep ocean and sediments: it drifts via underwater canyons, or algal trash that is negatively buoyant sinks. The deep sea is used for exporting around 90% of this sequestration, with the remaining 10% being buried in coastal sediments. This estimate is higher than the amount of carbon stored in coastal ecosystems supported by angiosperms- seagrass meadows, salt marshes, and mangroves, marine macroalgae [18]. Numerous research conducted in the last few years has clarified how important it is to ascertain if microalgae growing techniques can lower CO_2 emissions. Microalgae are thought to create half of the oxygen in the atmosphere and use CO_2 to develop photo autotrophically at the same time. Microalgae are good candidates for CO_2 removal because they develop at considerably faster rates than normal forestry, agriculture, and aquatic plants, and they fix CO_2. Due to their energy-saving architecture, these microbes are ten times more efficient at fixing CO_2 using solar energy than terrestrial plants [19].

4 Mechanisms of blue carbon sequestration

4.1 Biological processes

4.1.1 Photosynthesis

The process of photosynthesis is complex and heavily regulated. Solar energy harvesting, excitation energy transfer, energy conversion, electron transfer from water to $NADP^+$, ATP synthesis, and a sequence of enzyme processes that assimilate carbon dioxide and manufacture carbohydrates are all included in this process (Fig. 1a). Because the fundamental ideas of photosynthesis were established by the middle of the twentieth century and the specific mechanisms have subsequently been clarified, photosynthesis holds a special place in the history of plant science [20]. The necessity to increase total photosynthesis and production is imperative due to the scarcity of arable land and the growing human population. Light absorption is the first step of oxygenic photosynthesis. Next comes light-excited energy transfer to the reaction centers, primary photochemistry, electron and proton transport, ATP and NADPH production, and CO_2 fixation (the Hatch–Slack cycle and the Calvin–Benson cycle). The existence of two light reactions and two photosystems connected by an electron transport chain (the Z-scheme), the chemiosmotic hypothesis for ATP synthesis, the water oxidation clock for oxygen evolution, the steps involved in carbon fixation, and finally the various mechanisms of regulatory processes, such as "state transitions" and "non-photochemical quenching" of the excited state of chlorophyll a, are process some of the discoveries related to this process [21] (Fig. 1b).

4.1.2 Carbon fixation

The primary path for organic carbon to enter the biosphere is autotrophic carbon fixation that is an essential phase in the biogeochemical carbon cycle. Once thought to be the only carbon-fixation mechanism, the Calvin–Benson–B–Bassham pathway is mostly found in plants, algae, and certain bacteria, primarily cyanobacteria (Fig. 2). More study into previously unrecognized ancient carbon-fixation routes in taxonomically and phylogenetically diverse microorganisms has been spurred by the discovery of a new carbon-fixation mechanism in sulfurous green bacteria

Table 2 The ecological significance of the bacteria, the type of carbon captured (organic vs. inorganic), and their potential applications in biotechnology or environmental science

Marine bacteria	Amount of carbon capture	Type of carbon captured	Origin place	Mechanism	Uniqueness	Ecological significance	Biotechnological applications	References
Prochlorococcus	Estimated to sequester 4 GT of CO2 per year	Inorganic (CO2)	Global oceans (tropical and subtropical)	Photosynthesis (Oxygenic)	Smallest and most abundant photosynthetic organism	Major contributor to global oxygen production	Potential in bioengineering for carbon sequestration	[90]
Synechococcus	Estimated to sequester 0.7 GT of CO2 per year	Inorganic (CO_2)	Global oceans	Photosynthesis (Oxygenic)	High genetic diversity and adaptability	Supports marine food webs	Potential in biofuels and bioproducts	[91]
Pelagibacter ubique	Significant, but not well quantified	Organic carbon	Oceans worldwide	Aerobic respiration	Simplest known free-living bacterium	Major role in marine carbon cycling	Model organism for minimal cellular life	[92]
Vibrio natriegens	Potentially high (due to rapid growth)	Organic carbon	Coastal marine environments	Aerobic and anaerobic respiration	Fastest known growth rate among bacteria	Important in nutrient recycling in coastal areas	Used in synthetic biology and biotechnology for rapid growth	[93]
Marinobacter hydrocarbonoclasticus	Contributes to carbon sequestration through hydrocarbon degradation	Organic carbon	Oil-contaminated marine environments	Hydrocarbon degradation (alkane oxidation)	Specialized in degrading hydrocarbons	Key player in bioremediation of oil spills	Application in bioremediation and environmental cleanup	[94]

Table 3 Marine algae, with their carbon capture capabilities, origin, mechanisms, unique features, ecological significance, and potential biotechnological applications

Marine algae	Amount of carbon capture	Type of carbon captured	Origin place	Mechanism	Uniqueness	Ecological significance	Biotechnological applications	References
Prochlorococcus (Microalgae)	Estimated to sequester 4 GT of CO2 per year	Inorganic (CO2)	Global oceans (tropical and subtropical)	Photosynthesis (Oxygenic)	Smallest and most abundant photosynthetic organism	Major contributor to global oxygen production	Potential in bio-engineering for carbon sequestration	[90]
Synechococcus (Microalgae)	Estimated to sequester 0.7 GT of CO_2 per year	Inorganic (CO_2)	Global oceans	Photosynthesis (Oxygenic)	High genetic diversity and adaptability	Supports marine food webs	Potential in biofuels and bioproducts	[91]
Phaeodactylum tricornutum (Microalgae)	Not well quantified	Inorganic (CO_2)	Coastal regions worldwide	Photosynthesis (Diatom)	Ability to thrive in varying salinities	Key player in nutrient cycling	Used in biofuels and omega-3 fatty acid production	[95]
Chlorella vulgaris (Microalgae)	High potential in controlled environments	Inorganic (CO_2)	Freshwater and marine environments	Photosynthesis	High growth rate and protein content	Important in global carbon cycle	Widely used in food supplements and biofuel production	[96]
Macrocystis pyrifera (Macroalgae)	Estimated to sequester 1.7 GT of CO2 per year	Inorganic (CO_2)	Coastal areas, particularly in the Pacific Ocean	Photosynthesis (Oxygenic)	Fastest growing macroalgae species	Provides habitat for marine life	Used in alginate production and bioenergy	[97]
Sargassum (Macroalgae)	High carbon sequestration potential in the Sargasso Sea	Inorganic (CO_2)	Sargasso Sea and other warm waters	Photosynthesis	Forms large floating mats, unique among macroalgae	Supports diverse marine ecosystems	Potential for biofuel production and carbon sequestration	[98]
Ulva lactuca (Macroalgae)	Moderate to high, particularly in nutrient-rich waters	Inorganic (CO_2)	Coastal regions worldwide	Photosynthesis	Known as "sea lettuce," fast-growing	Plays a role in eutrophication processes	Used in food, fertilizers, and bioremediation	[99]

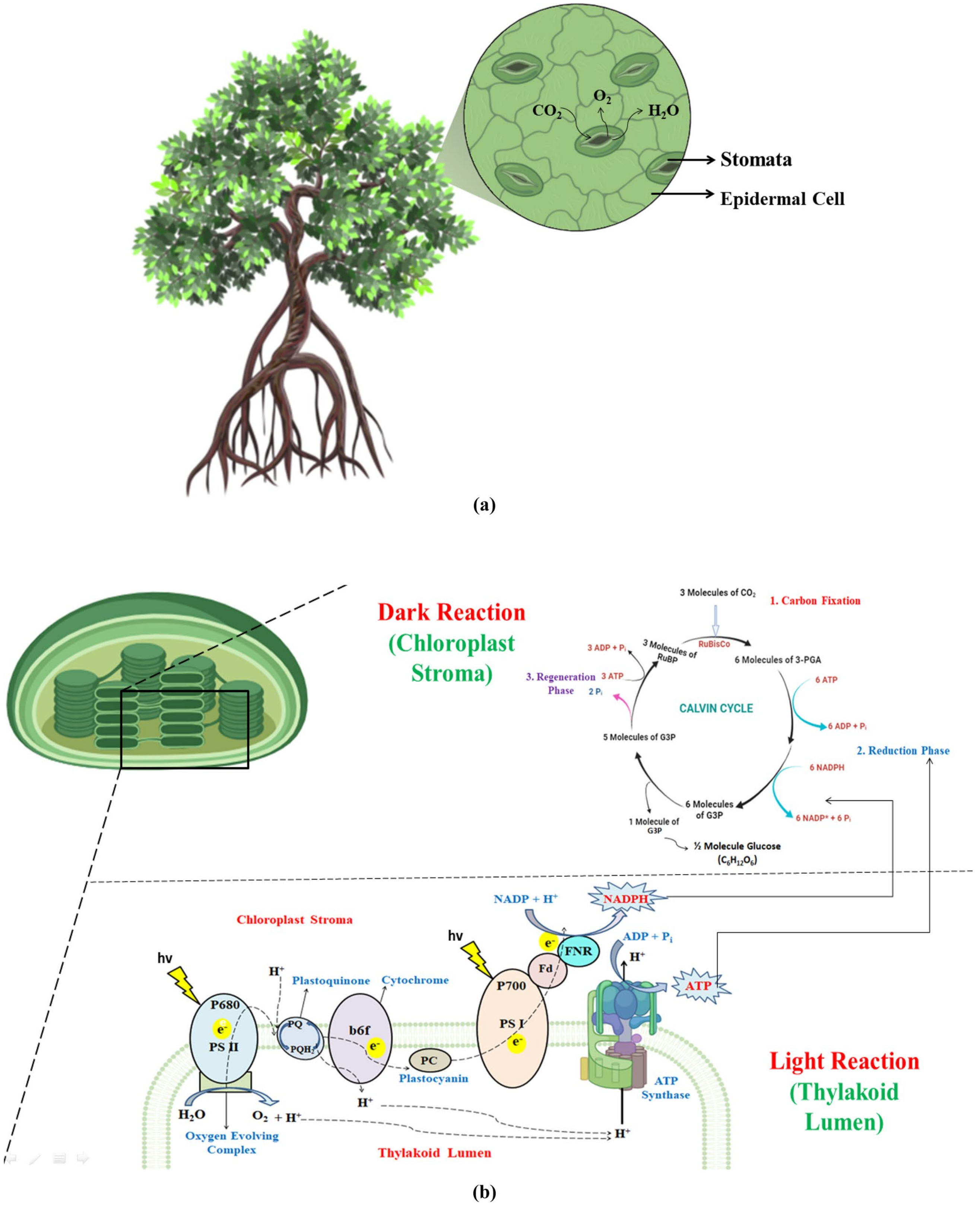

Fig. 1 **a** CO_2 consumption in Mangrove trees via leaves stomata, **b** Photosynthetic electron transport (Light reaction) and carbon sequestration (Dark Reaction) mechanism in plants [25]

nearly two decades ago [22]. After oxygen, hydrogen, and helium, carbon is the most common element on Earth. It is believed to function as a building block for the synthesis of organic compounds, which include nucleic acids, proteins, carbohydrates, and lipids and are necessary for life. This element is the foundation of Earth's biogeochemical cycles and supplies energy to whole ecosystems. Carbon fixing is linked to the influx of inorganic carbon into the biosphere. The process via which autotrophic carbon fixation transforms inorganic carbon into biomass is directly linked to the primary generation of organic molecules.

Obtaining inorganic carbon from the surroundings and supplying the chloroplast with CO_2 and HCO3-. HCO3-transporters and CO_2 channels on the plasma membrane and chloroplast envelope, as well as CAs in the periplasmic space (CAH1 and perhaps CAH8) and a CA in the cytoplasm (CAH9), would be the components of this portion of the CCM. The second component of the suggested strategy that uses the pH gradient across the thylakoid membrane to generate significant amounts of HCO3- in the chloroplast stroma. The putative HCO3-transporter on the thylakoid membrane and the CAs found in the chloroplast stroma (CAH6) and thylakoid lumen (CAH3) comprise this portion of the CCM.LCI1, HLA3, BST 1–3 are potential Ci transport proteins. CAH1, CAH3, CAH4/5, CAH6 and CAH8 are Carbonic Anhydrases; PGA- Phosphoglyceric Acid. Courtesy: [23–25].

The cyanobacterial CCM functions through the cooperation of several components. These constituents may be categorized based on their roles in the intracellular build-up of Ci, such as the entities involved in CO_2 absorption and bicarbonate transport, as well as those that involved in CO_2 consumption and elevation inside the carboxysomes. The CO_2 that is created from HCO_{3-} in carboxysomes and crosses cell envelopes by diffusion via aquaporins or via the so-called CO_2 uptake systems, which include NDH-1 complexes situated on the thylakoid membrane, is converted to HCO_{3-} in the cytoplasmic pool (Fig. 3) [26–30].

4.1.3 Decomposition

Litter fall plays a significant role in the nutrient cycle in forest ecosystems, which controls the uptake of soil organic matter (SOM), nutrient input and outflow, replenishment of nutrients, preservation of biodiversity, and other ecosystem processes. Therefore, for sustainable forest management (SFM), a thorough understanding of the cycle's primary processes, litterfall production and its rate of decomposition are essential. Despite these facts, our understanding of tropical forest ecosystems is still restricted, necessitating much more research. The lack of knowledge based on research, particularly in tropical forest ecosystems, may be one of the reasons behind the ignorance of the function of plant litter in the forest ecosystem for sustainable forest management, especially in tropical forest landscapes [31]. The term "litter" describes the

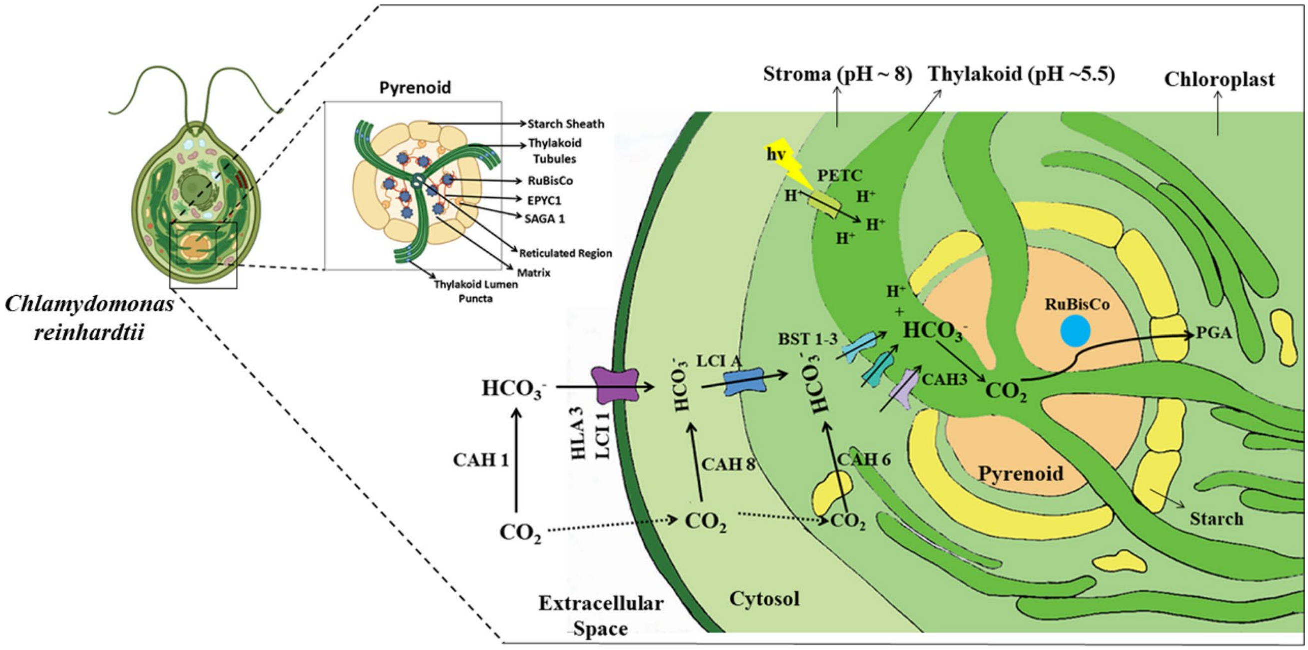

Fig. 2 Structure and Carbon Concentrating Mechanism (CCM) of *Chlamydomonas reinhardtii* with its Pyrenoid

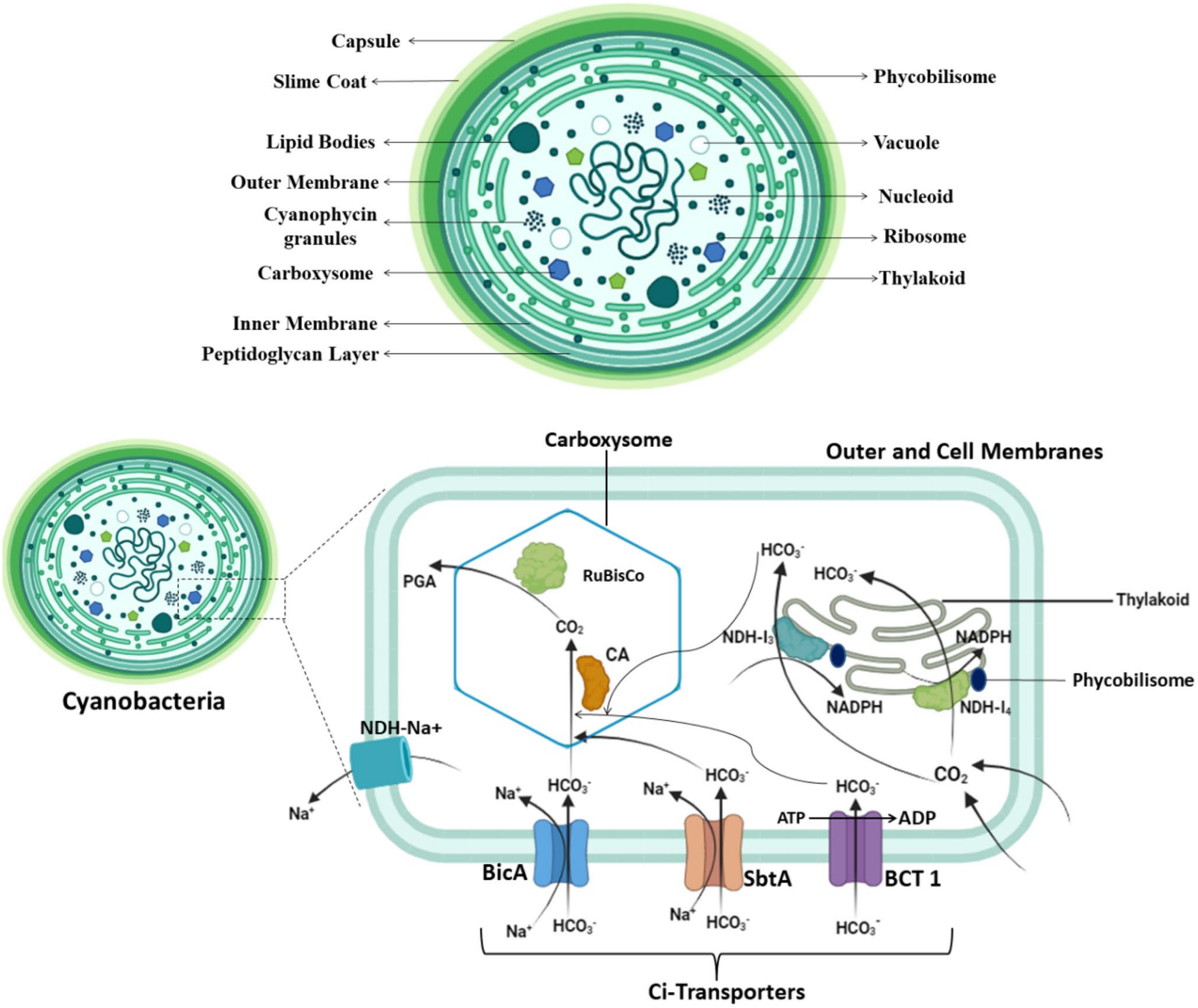

Fig. 3 **a** Structure and CO_2 concentration mechanism of Cyanobacteria (*Synechocystis sp)*

decomposing matter that results from a plant's death and decay, such as falling leaves, detritus, dead branches, blooms, fruits, and withered roots. Wetland habitats serve as a link between aquatic and terrestrial ecosystems and are crucial to the process of climate change on a global scale. Degradation of litter is the main source of carbon for wetlands, and their carbon cycle is an essential component of the global carbon balance. Plant breakdown is a significant mechanism that controls the net production of nutrients in an ecosystem. It has physical, chemical, and biological impacts [32]. Litter decomposition influences the microbial community structure, soil physicochemical qualities, organic matter abundance, and content of wetland sediments. It also affects the moisture, light, and temperature conditions necessary for the growth of nearby plants. Plant decomposition in wetlands needs further research, despite the fact that plant litter in woods, grasslands, and meadows has been the subject of several studies. Because of their unique features of wet-dry alternation and sedimentation, wetlands are unique natural settings of land–water interactions that are home to extremely intricate litter plant breakdown. Wetland plant litter decomposition is crucial to the system's material cycle, energy flow, and information transfer. This system differs from terrestrial and aquatic ecosystems in that it is more influenced by land–water interactions, such as dry–wet alternation, water accumulation conditions, sedimentation behavior and characteristics, etc. It is a crucial step in the energy and nutrient cycles of wetlands and plays a significant role in preserving the ecosystem's ability to operate.

4.2 Physical processes

4.2.1 Sedimentation in coastal blue carbon ecosystems

Sedimentation in coastal blue carbon ecosystems refers to the delivery, trapping and accumulation of mineral and organic particles within vegetated intertidal and shallow subtidal habitats such as mangroves, salt marshes and seagrass meadows. In these systems, plant canopies slow water flow and enhance the deposition of fine sediments and organic matter, promoting vertical accretion and burial of organic carbon in waterlogged, often anoxic soils, which is a central mechanism of blue carbon sequestration. Although much of the classical sedimentation literature focuses on freshwater reservoirs and their storage capacity [33, 34], similar physical principles govern sediment transport and deposition in coastal wetlands, where sediment supply and trapping capacity determine shoreline stability, the ability of ecosystems to keep pace with sea level rise, and the longevity of their soil carbon stocks [35–37]. Understanding how hydrodynamics, catchment land use and climate driven changes in sediment supply alter these coastal sedimentation processes is therefore critical for predicting the resilience and future contribution of blue carbon ecosystems to climate change mitigation. Sedimentation is the process by which the sediment particles in a reservoir separate from their source and end up deposited as suspended and bed loads. Because capacity and reservoir life have a special relationship, sedimentation is a crucial quantity in fluvial hydraulics because it gives a device's likelihood of being employed as a capacity prediction device in all storage zones. More specifically, sediment yield defined as the amount of sediment discharged through a river outlet per unit catchment area per unit time determines how much sediment will settle in a given reservoir . Because the sediment yield in the catchment is dependent on soil erosion, this is another crucial factor. Since soil erosion, sediment yield, and sedimentation into the reservoir are three parameters that directly or indirectly affect a reservoir's life, efforts have been made to relate them to lessen the issue associated with the number of sediment particles that eventually deposit into the reservoir after being eroded from the catchment [33]. Natural and impounded reservoirs lose some of their storage capacity and lifespan over time due to sediment deposition at the bottom of the reservoirs. This has negative effects on the ecosystem due to deteriorating water quality and biodiversity loss, as well as significant effects on the production of food, energy, water, and reservoir maintenance expenses. According to estimates from around the world, sedimentation causes between 0.5 and 1% of the annual loss of water storage. The capacity of the world's water storage is predicted to drop by more than 50% by the year 2100 [34].

4.2.2 Carbon burial

Carbon burial is a central mechanism through which blue carbon ecosystems act as long term carbon sinks. In vegetated coastal habitats such as mangroves, salt marshes and seagrass meadows, organic carbon produced within the canopy and imported from adjacent systems is trapped, deposited and progressively buried in waterlogged, often anoxic sediments, removing it from short term exchange with the atmosphere. In mangrove forests, a large fraction of total ecosystem carbon is stored below ground: 50–70 percent of the carbon stock is held in roots and soils, which can form deep, organic rich deposits over centennial to millennial timescales[5]. Anoxic, sulphate reducing conditions in mangrove sediments slow microbial decomposition, causing organic matter to break down three to ten times more slowly than in upland soils, which greatly enhances the proportion of carbon that remains buried [7, 10]. Recurrent root production, litter input and vertical accretion allow mangrove soils to reach thicknesses greater than one metre, forming peat like layers that preserve large quantities of carbon and help these ecosystems keep pace with moderate sea level rise where sediment supply is sufficient [11, 12].

Salt marshes and seagrass meadows show similar patterns of efficient carbon burial. Salt marshes are among the most productive ecosystems and can store up to ten times more carbon per unit area than many terrestrial systems, largely through rapid primary production and effective trapping and burial of suspended sediments and organic matter [13, 14]. Under favourable conditions of sediment supply and tidal range, marshes can maintain vertical accretion rates that keep pace with sea level rise, thereby preserving and expanding their soil carbon stores [15]. Seagrass meadows are likewise recognised as global hotspots for carbon storage, with soil carbon accumulation that can exceed that of many terrestrial forests. Their dense root and rhizome mats stabilise sediments and promote the long term retention of organic carbon below ground, and global syntheses indicate that seagrass meadows may store roughly twice as much carbon as terrestrial forests on a per area basis [16].

At the global scale, inland waters such as lakes and reservoirs also represent important sites of organic carbon burial. A synthesis by Mendonça et al. [38] estimated that lakes and reservoirs bury around 0.15 Pg C yr^{-1} (range 0.06–0.25 Pg C yr^{-1}), with approximately 40 percent of this burial occurring in reservoirs, and with relatively higher burial rates in warm, dry climates (Fig. 4).

When these inland water values are considered alongside typical burial rates reported for mangroves, salt marshes and seagrass meadows, it becomes clear that vegetated coastal blue carbon ecosystems, although smaller in global area, rank among the most efficient natural environments for carbon burial on a per area basis. The combination of high primary production, persistent sediment accumulation and anoxic subsurface conditions allows them to sequester and preserve large amounts of carbon over long timescales, complementing the burial occurring in lakes and reservoirs and underscoring their relevance in global carbon budgets and climate change mitigation.

4.2.3 Bioturbation on carbon storage

The mixing of soils and sediments by living things through ingesting, burrowing, and plant root growth is known as bioturbation. This process affects the environment's structure and nutrient cycling by upending the initial layers and changing the sediment's physical and chemical characteristics. It is a prime illustration of an ecosystem engineering technique that has been crucial to the development of life [39]. Crabs' burrowing activities speed up the breakdown of trash and the movement of silt from the surface to deeper horizons. An average of 87% of the daily mangrove litter fall in Thailand is removed by crabs by ingestion or burial; the removal rate is negatively connected with inundation time and favourably correlated with the number of crab burrows. Ocypodid crabs in Japan remove organic debris three times more quickly than weathering and mineralization. As a result, crab bioturbation is essential to bio-geomorphological processes. Lugworms and bivalves bioturbate the sediment in salt marshes and seagrass beds, controlling porewater exchange, burial depth, and sediment mixing [40, 41].

4.2.4 Carbon cycling

About half of all photosynthesis occurs in the modern ocean, and the ocean's principal source of organic matter is what drives the ocean's carbon cycle. Because of its net consumption of atmospheric CO_2 and net release of molecular oxygen, the ocean thus has a significant impact on the chemistry and redox status of the atmosphere. Initially, it was estimated that around 25% of the primary production of the ocean was transported to the interior by the biological carbon pump (BCP) (below the euphotic zone). Later estimates changed this number to 10–15% for gravitational sinking, with an

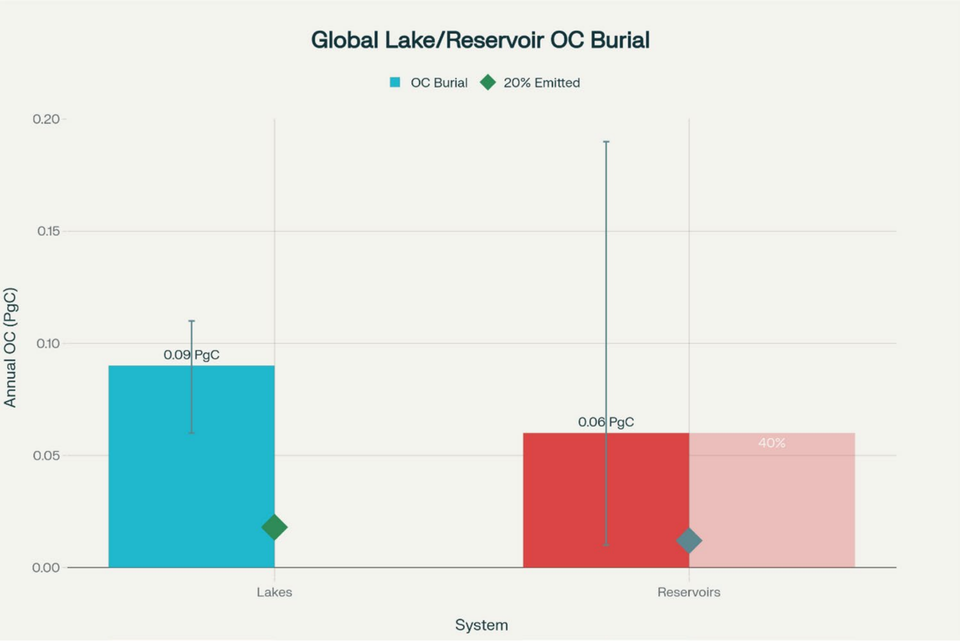

Fig. 4 Schematic figure representing the global and regional carbon burial in lakes and reservoirs chemical processes

additional 5% each for passive transport by water motion and active transport by vertical migrators. When carbon is carried to the deep ocean (> 1000 m), it is stored for periods ranging from > 100 years to 1000 years (i.e., the deepwater residency time) [42]. Marine sediments include around 0.3% of the primary output of the ocean. Part of these sediments eventually create a significant store of organic matter that endures in rock formations for hundreds of millions of years (Fig. 5).

4.2.5 Biogeochemical transformations

Our knowledge of the biogeochemical history of the ocean and its connection to the evolution of the Earth system as a whole has advanced significantly in the last few decades. According to the conventional theory of atmospheric and oceanic oxygenation, oxygen oases would have formed in microbial mats and possibly in the surface ocean beneath a decreasing atmosphere following the emergence of oxygenic photosynthesis at some point during the Archean Eon [43]. Our understanding of the ocean's biogeochemical history and its relationship to the evolution of the Earth system has advanced rapidly in recent decades. Within the conventional framework for explaining the oxygenation of the atmosphere and seas, it was acknowledged that oxygen oases would have developed in microbial mats and maybe in the surface ocean beneath a decreasing atmosphere following the emergence of oxygenic photosynthesis at some point during the Archean Eon. Rivers contain physiologically and photochemically reactive sources of DOM that are both autochthonous (made inside a system) and allochthonous (generated outside a system). Additionally, interaction processes such priming promote the breakdown and bioavailability of DOM [44] (Fig. 6).

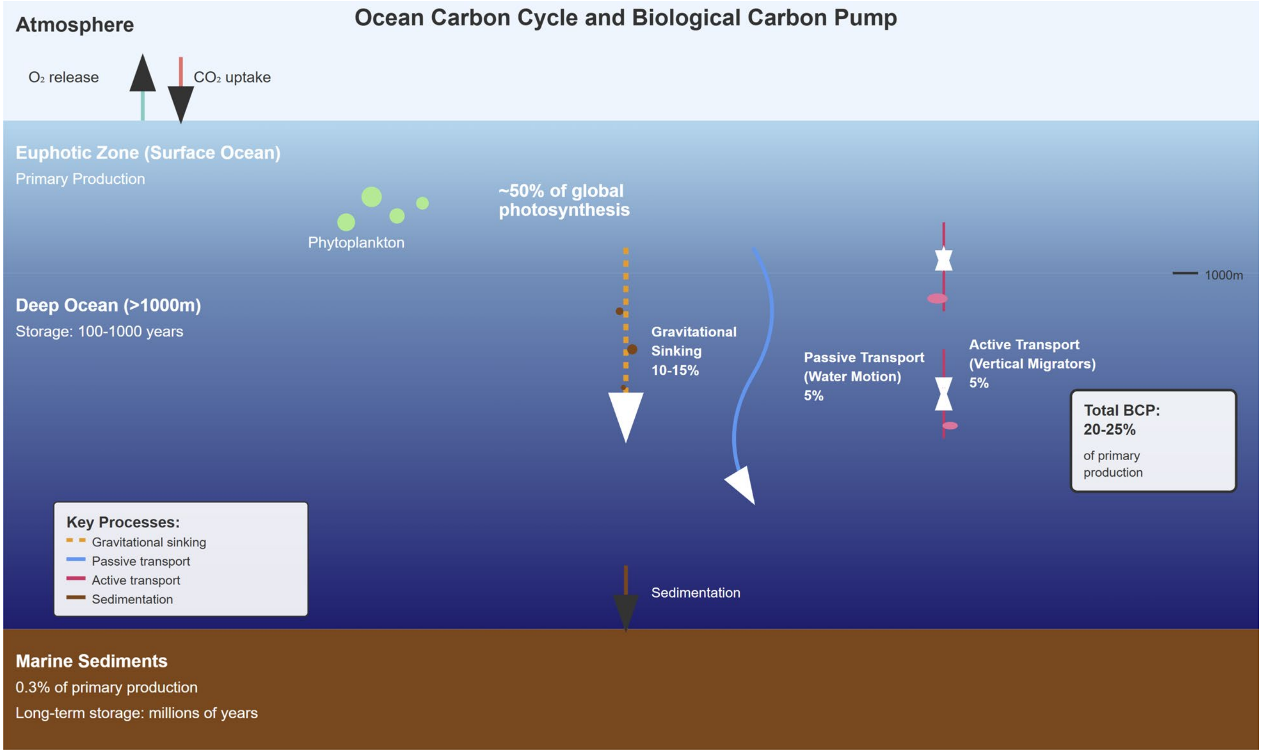

Fig. 5 Schematic representation of the ocean's biological carbon pump (BCP) showing the three main transport mechanisms that transfer organic carbon from the euphotic zone to the deep ocean and sediments

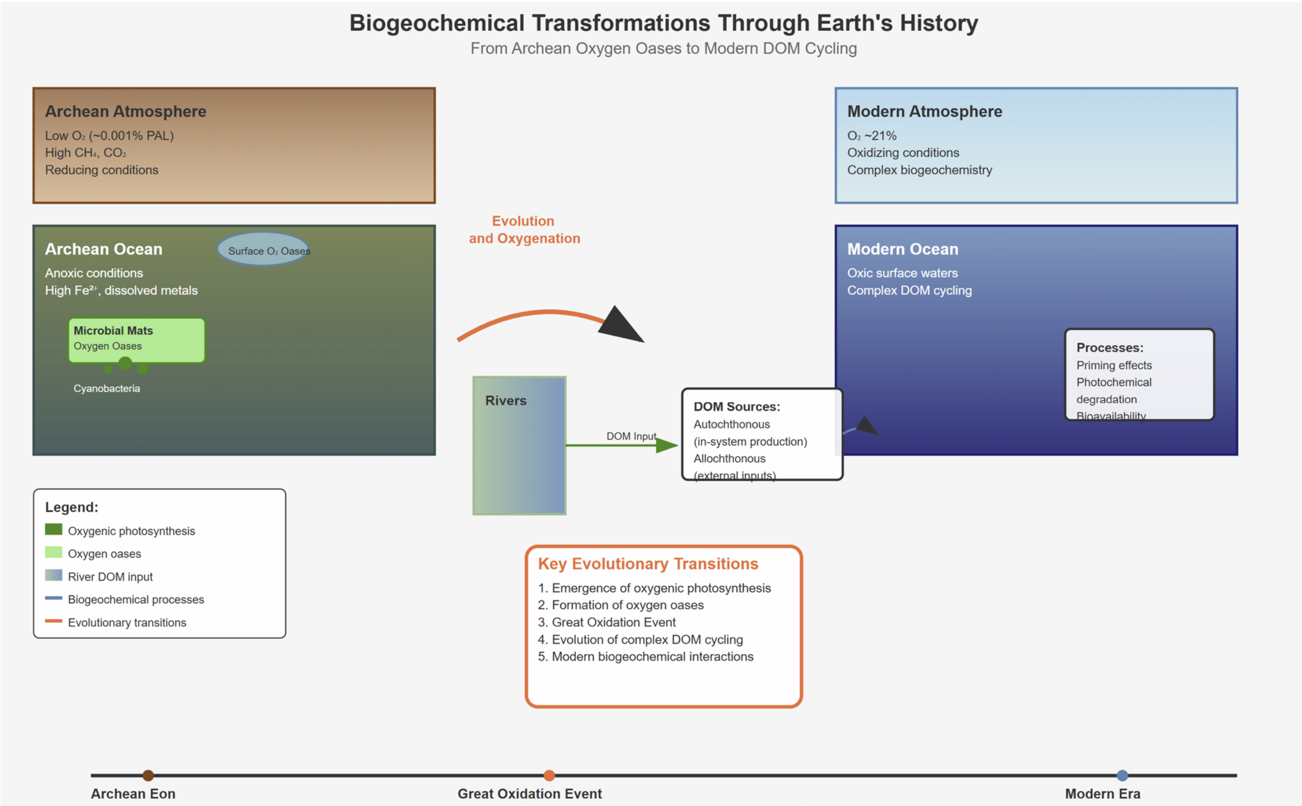

Fig. 6 Evolution of ocean biogeochemistry from Archean oxygen oases to modern dissolved organic matter (DOM) cycling. The figure illustrates the dramatic transformation from early localized oxygenation events during the Archean Eon to the complex biogeochemical interactions characterizing contemporary ocean systems. River inputs now provide both autochthonous and allochthonous DOM sources, with interaction processes such as priming promoting enhanced breakdown and bioavailability of organic matter

5 Factors influencing blue carbon sequestration

5.1 Environmental drivers

5.1.1 Climate

Research on enhancing our knowledge of the global carbon (C) cycle and measuring the pools and fluxes that make up this cycle has exploded in recent years. This has occurred because it is evident that human activity is significantly disrupting the carbon cycle, which has the effect of changing the climate and potentially having detrimental effects on terrestrial ecosystems [45]. Although it is evident that the greatest terrestrial pool is found Jonesin the soil, we are still unsure of the exact magnitude, worldwide distribution, and fluxes of carbon. This is especially true for grassland environments, where up to 98% of the total carbon store is stored underground. Terrestrial carbon makes up around two thirds of underground space, and turnover rates there are often substantially lower than those of aboveground carbon. According to reports, ongoing climate changes impact forest vegetation's prospective distribution and carbonsequestration potential (CSP). Temperature rises and precipitation decreases greatly impact the structure, functions, dynamics, and distribution of forest vegetation; these changes in turn impact the carbon sequestration potential (CSP) of forest vegetation. Several studies have shown that changes in the distribution of forest vegetation due to recent climate change have an impact on carbon cycling and CSP [46]. Carbon storage in blue carbon ecosystems is greatly influenced by climate-related factors, including temperature, precipitation, storm frequency, and sea level rise. For instance, high temperatures hasten the breakdown of salt marsh and mangrove sediments, decreasing the stability of soil carbon in tropical areas [5]. Long-term buried carbon reserves may be lost as a result of seagrass meadow erosion brought on by stronger storms [47]. On the other hand, by encouraging vertical sediment accretion and peat formation, moderate sea-level rise can improve carbon burial in mangroves [48]. In the Mediterranean, extreme drought episodes have been demonstrated to lower primary production and raise mortality in seagrasses like *Posidonia oceanica*, resulting in decreases in carbon stocks [49].

To enhance scientific decision making and policy planning, an evaluation of the possible distribution of forest vegetation and an assessment of its CSP are required.

5.1.2 Hydrology

Climatic conditions affect the hydrological processes and also the dynamics of carbon (C) in forest ecosystems. The hydrological conditions that control the carbon balance in forest ecosystems are affected by changes in temperature and rainfall. These changes are particularly significant in forest wetlands where hydrology plays a crucial role in the accumulation and consumption of C [50]. While forest wetlands act as sinks for atmospheric C, they may also contribute to terrestrial GHG emissions (CH and CO_2). Understanding the consequences of climate variability on forest hydrology and the C balance in these ecosystems requires consideration of the relative GHG emissions of upland and forest wetlands. Should the Inter-tropical Convergence Zone (ITCZ) alter its yearly cycles, numerous wetlands' regional hydrological patterns and carbon dynamics will be affected. Significant alterations to these crucial carbon stocks would follow from this. Carbon burial is directly impacted by hydrology, which also regulates groundwater exchange, sediment transport, salinity gradients, and tidal inundation. According to Kelleway et al. [51], hydrological connection in mangroves raises sediment deposition rates from less than 2 mm yr^{-1} in limited systems to more than 10 mm yr^{-1} in open tidal habitats. Root production and the retention of organic matter are impacted by changes in salinity and tidal regimes brought about by climate change, such as changing rainfall patterns and sea level rise. Tidal amplitude, which ranges from 50 to 250 g C m^{-2} yr^{-1} depending on inundation frequency, has a high correlation with carbon accumulation rates in salt marshes [35, 37]. Seagrass photosynthetic capability is determined by hydrological clarity,decreased water clarity due to climate-enhanced runoff reduces meadow persistence and carbon fixation. Seasonal pulsing hydrology plays an important role in many tropical wetlands. This can be due to watershed activity, orographic characteristics, or the ITCZ's monsoonal pulses. This is shown in both the annual and the 30-year hydrological patterns of Okavango Delta, Southern Africa [52].

5.1.3 Nutrient availability

Nutrient availability is a key regulator of productivity and carbon storage in blue carbon ecosystems such as mangroves, salt marshes and seagrass meadows. In these habitats, moderate inputs of nitrogen and phosphorus can stimulate primary production, increase belowground biomass and root turnover, and thereby enhance the amount of organic matter entering and being buried in the sediments [36]. Nutrient enrichment in mangrove forests has been shown to increase growth and litter fall, which can translate into higher soil carbon accumulation where anoxic conditions slow decomposition . Similarly, nutrient supply influences seagrass shoot density, leaf area and root rhizome development, all of which affect the capacity of meadows to trap particles and store carbon in their underlying sediments [36, 53]. However, excessive nutrient loading from agriculture, wastewater or urban runoff can have adverse effects by promoting algal blooms, reducing water clarity, smothering vegetation and accelerating decomposition and greenhouse gas emissions, which may offset some of the gains in carbon sequestration [53]. Understanding these contrasting responses is therefore essential for managing nutrient inputs so that they support the productivity and long term carbon storage of blue carbon ecosystems rather than driving their degradation.

5.2 Anthropogenic pressures

5.2.1 Land use change

Land use change in the coastal zone is one of the most direct and visible pressures on blue carbon ecosystems. Mangroves, salt marshes and seagrass meadows are frequently cleared or fragmented to make space for ports, harbours, marinas, seawalls and land reclamation schemes. In many deltas and estuaries, mangrove forests have been removed to build container terminals, navigation channels and coastal roads, which not only eliminates aboveground biomass but also exposes organic rich soils to erosion and oxidation, leading to substantial carbon losses [8]. The removal of vegetation and construction of embankments and hard coastal defences alters tidal exchange and wave energy, reducing the capacity of these systems to trap sediments and maintain vertical accretion, and thereby undermining their role as long term carbon sinks [15, 36].

Tourist and residential development in the coastal fringe can have similar effects. Hotel complexes, waterfront housing schemes and associated infrastructure are often built on former mangrove or salt marsh areas, or on seagrass covered shallows that are dredged to create boat access. Such developments usually involve infilling, dredging and levelling that permanently convert vegetated wetlands into built surfaces, causing immediate loss of biomass carbon and triggering rapid decomposition of previously buried organic matter as soils are drained and aerated [8, 53]. In several regions, mangroves have also been widely converted to aquaculture ponds, particularly for shrimp and fish farming, which replaces a diverse natural forest with a simplified production system and releases a large fraction of stored soil carbon over relatively short time scales [5].

Industrial growth along coasts adds another layer of pressure. Factory construction, industrial estates, power plants and refineries are often sited on low lying coastal land for ease of access and discharge. Building and operating these facilities can require extensive land reclamation, canalisation and alteration of river mouths, which change salinity regimes, sediment delivery and water quality in adjacent blue carbon habitats [36]. Thermal discharges, wastewater and accidental spills can further degrade mangroves, salt marshes and seagrass meadows, reducing plant cover and increasing erosion of carbon rich soils. Together, these different forms of land use change demonstrate how coastal construction, urban and tourism development and industrial expansion can directly and indirectly erode the carbon storage capacity of blue carbon ecosystems, and highlight the importance of integrating blue carbon conservation into coastal land use planning, environmental regulation and climate policy [8, 53].

5.2.2 Pollution

The world's air quality is declining and posing a serious threat to human and environmental health due to the fast urbanization, industrialization, and overuse of transportation. These factors also release different types of air pollutants into the atmosphere. It is well recognized that vegetation can improve air quality by storing CO2, reducing the activity of urban heat islands, and trapping air pollutants on leaves. Carbon dioxide (CO2) is taken up by trees during photosynthesis, and they store it as biomass. Given the speed at which air pollutants are piling up in the earth's atmosphere, it is imperative that their effects on different kinds of vegetation be examined holistically. The purpose of this study is to review the body of knowledge regarding the effects of different air pollutants on various types of vegetation and to pinpoint research gaps in order to better guide future investigations [54]. This study also covers various vegetation types and their effects on Carbon sequestration rates, as well as air pollution scenarios. By capturing, changing, and holding onto different contaminants in their sediments and biomass, blue carbon ecosystems also contribute significantly to pollution control. Heavy metals (such as Pb, Cd, and Zn), hydrocarbons, and persistent organic pollutants can attach to organic matter and become immobilized in anoxic soils because mangrove and salt marsh root systems slow water flow and promote the deposition of suspended particles [55, 56]. Similarly, seagrass meadows reduce the movement of microplastics and fine particles into coastal waters by trapping them [57]. These ecosystems also enhance nutrient removal through plant uptake and microbial processes such as denitrification, which lowers excess nitrogen and improves water quality [58]. By stabilizing sediments and preserving favorable biogeochemical conditions, blue carbon ecosystems indirectly enhance carbon sequestration by holding onto contaminants and preventing their further dissemination. Plastics and microplastics are increasingly recognised as important pollutants in blue carbon ecosystems. Mangrove root networks, salt marsh vegetation and dense seagrass canopies can trap floating and suspended plastic debris, causing these habitats to act as sinks where microplastics accumulate in surface sediments and biota rather than being transported offshore . This trapping can contribute to local pollution control by retaining plastics near the coast, but it also raises concerns about physical stress on organisms, ingestion by invertebrates and fish, and potential changes to sediment structure, porosity and microbial activity that may influence organic carbon burial and greenhouse gas fluxes [57]. Understanding how plastics and microplastics interact with vegetation, sediments and microbial communities in mangroves, salt marshes and seagrass meadows is therefore essential for assessing both the pollution control function and the long term carbon storage capacity of blue carbon ecosystems.Researchers and policymakers wishing to conduct additional research or understand the effects of air pollutants on the rate of carbon sequestration will find this review the literature to be very helpful.

5.2.3 Habitat degradation

Habitat degradation is a major pathway through which the carbon storage capacity of blue carbon ecosystems is reduced. Mangrove forests, salt marshes and seagrass meadows are often cleared or fragmented to accommodate coastal construction and land reclamation, including ports, harbours, marinas, roads and urban or tourism developments. Such activities remove aboveground biomass and disturb organic rich soils, exposing them to erosion and oxygen and thereby accelerating decomposition and release of stored carbon to the atmosphere [5, 8]. In many regions, mangroves have been converted to aquaculture ponds, industrial estates or factory zones, which further alters hydrology and sediment delivery and prevents natural regeneration [15, 36]. Seagrass meadows are damaged by dredging, boat traffic, propeller scarring and marina development, which increase turbidity, reduce light penetration and cause large scale loss of vegetation and associated sediment carbon stores [36, 53]. Chemical pollution adds an additional pressure, as nutrient rich agricultural and urban runoff promotes eutrophication and algal blooms, while industrial discharges introduce heavy metals and hydrocarbons that impair plant growth, reduce canopy cover and increase erosion of carbon rich soils [53]. Together, these construction related and chemical stressors illustrate how habitat degradation directly undermines the integrity of blue carbon ecosystems and erodes their role as long term carbon sinks. This study expands on that idea of regenerative design [59]. It looks into the ways that habitat provisioning and carbon sequestration in architecture might work together to lessen or even reverse the effects of the built environment on climate change and biodiversity loss.

5.3 Ecological interactions

5.3.1 Biotic relationships

It is clear that biota are essential to the cycle of carbon in both land and water. As a result of fundamental physiological processes, biota-mediated carbon cycling describes how CO_2 is converted into organic matter (OM) by primary producers (plants, algae, and autotrophic prokaryotes) and how CO_2 (or CH_4) is released by dissimilatory processes like respiration by consumers (mostly animals), microbial decomposers (fungi, bacteria, and archaea), and primary producers. In addition to these direct effects on the carbon cycle mediated by the biota, biotic interactions among producers, consumers, and decomposers can also affect the rate of assimilatory and dissimilatory processes, leading to indirect effects on the carbon cycle mediated by the biota. For example, by controlling the microbial availability of oxygen, nutrients, and labile substrates through plant–microbe interactions in the rhizosphere of wetland and terrestrial environments and through phytoplankton–microbe interactions on OM aggregates of aquatic environments, primary producers can significantly influence the rate of microbial OM decomposition [60]. Through trophic cascades, consumers in turn impose top-down control over primary producers and serve as conduits for the movement of carbon within and between ecosystems. Although the physiological processes of biota are widely recognized as important for carbon cycling and constitute the fundamental component of current Earth system models, this is not the case for biotic interactions, which are either not represented at all or are represented in a very simplified manner in carbon cycle modeling approaches.

5.3.2 Species composition

The climate changes in forest areas are reduced by storing the carbon. Approximately 45% of terrestrial carbon is stored in forests worldwide, containing 2.4 Pg C annual net sink. One third of Germany's land surface, or 11 million hectares, is covered by forests, which store over 2.5 Pg C in above- and belowground carbon stocks (soils up to 90 cm deep, or 224 Mg C ha^{-1}). Forest carbon fluxes and stocks, however, vary both temporally and geographically. Local carbon stores and fluxes can be influenced by site factors such as soil qualities and climate, species composition, stand age, and management techniques. In Germany, for instance, mature beech forests retain more carbon than comparable spruce forests. Environmental conditions and management techniques may also have an impact on the amount of carbon in various pools, including deadwood, soil, and aboveground biomass. For example, a study conducted in Belgium found that increased precipitation, lowered temperatures, and higher clay content all enhance the amount of carbon accumulated in the soil. The estimation of carbon fluxes is highly problematic due to the numerous drivers of carbon dynamics, particularly in mixed (species-mixed) deciduous forests [61]. Traditional methods for examining carbon fluxes, like forest inventories and eddy covariance (EC) measurements, have limitations in the geographical domain and need costly implementations. Usually, only smaller plots and forest stands that provide accessibility in terms of density can be used for forest inventories. EC measurements are restricted to uniformly level terrain and well-turbulent air conditions.

Under ideal circumstances, an area spanning several hundred meters can be represented by EC readings. Carbon storage capacity is significantly influenced by species composition. *Rhizophora spp*. and other mangrove plants with thick, highly productive root systems store more carbon below ground than species with less developed root systems [5]. While tiny, quickly developing species like *Halophila ovalis* show less long-term carbon storage, huge species like *Posidonia oceanica* may store carbon in deep rhizome mats for centuries in seagrass environments. Due to substantial root deposition, salt marshes dominated by *Spartina alterniflora* often retain more soil carbon than marshes with mixed halophytic species [62].

5.4 Sea-level rise (SLR) and blue carbon sequestration

For blue carbon (mangroves, salt marshes, and seagrasses), sea level rise (SLR) poses a double-edged sword: moderate SLR can increase carbon sequestration by encouraging wetland growth and sediment trapping, but rapid SLR can overwhelm these systems, resulting in erosion, vegetation loss, increased decomposition, and higher greenhouse gas (GHG) emissions (methane, nitrous oxide), ultimately reducing their capacity to mitigate climate change and possibly turning them into carbon sources. Although vertical accretion and landward migration provide adaptation, SLR jeopardizes these essential coastal carbon sinks, resulting in difficult trade-offs between carbon storage and coastal defense with dire consequences for vulnerable coastlines around the world [63]. According to the IPCC Sixth Assessment Report WGII 2022, one of the main factors influencing the long-term carbon sequestration capacity of coastal blue carbon ecosystems is SLR [64–66]. SLR affects ecosystem movement, hydrological connection, vertical accretion, and sediment deposition, all of which affect an ecosystem's capacity to sustain or increase carbon burial rates. Moderate SLR rates encourage vertical peat development and sediment trapping in mangroves. Mangroves can accumulate soil at rates of 3–10 mm yr^{-1} when there is a sufficient supply of sediment, which enables them to continue storing carbon and keep up with increasing sea levels. However, mangroves may drown when SLR surpasses accretion capacity, which would result in the loss of vegetation and the release of previously stored soil carbon [67]. When the supply of sediment is high, SLR enhances tidal flooding and promotes the formation of organic matter in salt marshes [68]. While marshes with low sediment inputs suffer from erosion, edge retreat, and carbon loss, wetlands that sustain vertical accretion rates can promote carbon burial. SLR modifies water depth and light availability in seagrass meadows. While excessive depth decreases photosynthesis and carbon fixation, which results in decreases in meadow extent and sediment carbon stocks, moderate SLR may increase habitat in some regions [69]. In general, under climate-driven sea-level change, the equilibrium between SLR and vertical accretion determines whether blue carbon ecosystems act as carbon sinks or turn into carbon sources.

5.5 Restoration and its benefits for sediment carbon sequestration

It has been demonstrated that restoring salt marshes, mangroves, and seagrass beds improves sediment carbon sequestration. Ecosystem restoration is acknowledged by the IPCC sixth assessment WGII report as a significant natural option that can boost ecosystem resilience and carbon burial . Restoration speeds up vegetation regeneration, sediment trapping, root biomass production, and long-term carbon burial, according to recent meta-analyses and field investigations [70, 71]. Restoration of mangroves are increasing through canopy cover and root formation, hydrological reconnection, planting, or natural recruitment enhance sediment stability and organic carbon storage. Restored mangroves frequently recover a significant portion of natural biomass and soil carbon stocks over decades, according to meta-analyses and long-term syntheses [70, 72]. In many situations, planted or restored mangroves can recover significant portions of ecosystem carbon stocks in less than 20 years, while recovery rates vary depending on site circumstances and technique [72, 73]. In seagrass restroring, sediment deposition is improved and sediment resuspension is decreased by active restoration techniques like seed broadcasting and plug planting. According to a number of field studies, recovered seagrass meadows can achieve carbon accumulation rates in the tens of g C m^{-2} yr^{-1} within 10 years [74, 75]. Depending on local conditions, recorded early recovery rates are typically in the range of ~ 20–40 g C m^{-2} yr^{-1}. Rehabilitation of salt marshes where rapid sediment accumulation and organic matter burial are frequently the results of controlled realignment and tidal reconnection. Large carbon accumulation has been documented in case studies (such as managed realignment sites) in the initial years following restoration; however, full recovery to comparable natural marsh stocks may take longer and is site-dependent [76–78]. Therefore, restoration is a beneficial nature-based climate action that increases the potential for sequestering carbon along the coast. However, the amount and timing of carbon recovery vary depending on the geomorphic context, sediment supply, restoration technique, and time since restoration.

6 Measurement and assessment of blue carbon stocks

6.1 Techniques for quantifying carbon stocks in coastal ecosystems

Mangroves are critically important forested wetlands that play key ecological and economic roles, boasting the highest carbon density of all terrestrial ecosystems. Due to their immense carbon stocks and their value in coastal protection, the preservation and restoration of mangroves have been suggested as effective strategies to combat climate change. Understanding and quantifying carbon stocks in coastal ecosystems is vital for comprehending the role of these environments in carbon sequestration and climate regulation. The advent of remote sensing, particularly through lidar technology, has transformed the assessment of aboveground biomass in coastal vegetation such as mangroves. Lidar remote sensing offers detailed 3D structural data, enabling precise estimation of biomass even in challenging and inaccessible terrains. Fatoyinbo et al. [79] demonstrated the efficacy of remote sensing in the Zambezi River delta, highlighting its potential for large-scale evaluations of carbon stocks in coastal forests.

Meanwhile, direct soil sampling and analysis remain fundamental technique for quantifying soil organic carbon stocks. Studies like those by Jäger et al. [80] stress the significance of field-based assessments in coastal wetlands like the Venice Lagoon. This approach involves gathering soil samples at various depths and analyzing them for carbon content, yielding insights into carbon storage and accumulation rates in coastal soils. Assessing blue carbon stocks, which refers to carbon stored in coastal sediments, requires sediment sampling and analysis. The significance of accurate measurements of sediment carbon was emphasized by Rogers et al. [81], especially considering the consequences of sea level rise. When sediment coring is paired with laboratory analysis, significant information on the potential for long-term carbon storage and sequestration in coastal ecosystems can be gained. Moreover, carbon stocks across large areas and diverse ecosystem types can be computed through carbon budgeting that makes use of Geographic Information Systems (GIS) and ecological models. Breithaupt et al. [82] showcased the use of spatial modeling to estimate carbon burial rates in tidal wetlands, advancing our understanding of carbon dynamics and storage capacities in coastal environments.

Integrated studies that combine multiple techniques, such as remote sensing, field surveys and modeling, offer holistic assessments of carbon stocks in coastal ecosystems. The global significance of blue carbon stored in coastal vegetation was highlighted through mangrove carbon stock assessments conducted in Indonesia [83]. These methodologies collectively contribute to a comprehensive understanding of carbon dynamics in coastal ecosystems, providing essential data for informed decision-making in climate change mitigation and ecosystem management. Mangroves and other coastal habitats need to be protected and restored in order to absorb carbon dioxide, maintain biodiversity, and protect coastal residents from environmental dangers.

6.2 Challenges and considerations in blue carbon monitoring and inventory

Coastal and marine habitats such as mangroves, seagrass beds, and tidal marshes are examples of blue-carbon ecosystems. These ecosystems’ ability to absorb and store atmospheric carbon dioxide is essential for controlling the global carbon cycle. However, accurately monitoring and assessing blue carbon stocks pose numerous challenges due to the complexity of these habitats and their interactions with environmental factors [5]. Research highlights various difficulties associated with monitoring and inventorying blue carbon. One major challenge is the spatial variability of carbon stocks across different ecosystem types. For example, carbon stored in mangroves can vary greatly based on factors like tree species, age, and environmental conditions such as salinity and tides. Seagrass meadow biomass and carbon storage are dependent on a number of factors, including depth, light levels, and sediment qualities.

The requirement for standard procedures for data collection and analysis in various blue carbon ecosystems is another crucial factor to take into account. It might be difficult to compare studies and locations due to differences in carbon stock estimations resulting from variations in sampling methodology and measuring techniques. Establishing robust, standardized protocols that consider habitat-specific characteristics is crucial for generating reliable data on blue carbon stocks [15].

Additionally, scaling up field measurements to estimate regional or global blue carbon stocks is challenging. While field assessments provide valuable local-scale data, extrapolating these findings to larger areas requires integrating remote sensing and modeling techniques. Remote sensing tools like satellite imagery and LiDAR can provide essential information on habitat extent and structure, aiding in scaling up carbon stock estimates [36].

Accounting for temporal dynamics in blue carbon ecosystems is another significant challenge. These habitats are susceptible to natural and human-induced disturbances such as storms, sea-level rise, and coastal development, which can affect carbon sequestration rates and ecosystem stability over time. Long-term monitoring is essential to capture temporal variability in blue carbon stocks and understand the impacts of environmental changes [84].

7 Implications for climate change mitigation

7.1 Blue carbon offsetting: potential contributions to global carbon budgets

Blue carbon ecosystems, which include mangroves, seagrasses, and tidal marshes, are highly valuable for mitigating climate change through their ability to capture and store carbon. Research indicates that these ecosystems can make substantial contributions to global carbon budgets, especially through initiatives focused on blue carbon offsetting. Blue carbon offsetting involves assessing the amount of carbon stored in coastal and marine habitats and using this stored carbon to compensate for greenhouse gas emissions elsewhere. Protecting and restoring blue carbon ecosystems can help countries and organizations achieve carbon neutrality and meet climate goals. Studies show that blue carbon habitats sequester carbon at rates comparable to terrestrial forests, with mangroves alone estimated to capture up to 42 million tons of carbon annually worldwide [85]. This underscores the significant carbon sequestration potential of these ecosystems.

Moreover, blue carbon projects offer additional benefits beyond carbon mitigation, including coastal protection, biodiversity conservation, and support for fisheries. These multiple advantages enhance the appeal of blue carbon offsetting as a strategy for climate change mitigation. But to completely profit from blue carbon offsetting, several problems need to be overcome, such as accurately measuring and tracking blue carbon stocks, addressing geographical and temporal changes, and ensuring the permanence of carbon storage [15]. Blue carbon offsetting presents a promising approach for mitigating climate change by harnessing the carbon sequestration capabilities of coastal and marine ecosystems. As research progresses and methodologies improve, blue carbon offsetting initiatives can play an increasingly important role in global efforts to combat climate change.

7.2 Policy and management strategies for enhancing blue carbon sequestration

For blue carbon ecosystems to be preserved and their capacity for carbon sequestration to be enhanced, policies that protect and restore these environments must be put into place. This involves establishing marine protected areas (MPAs) and enforcing regulations to prevent the depletion of mangroves and seagrass beds. Restoration initiatives, such as replanting mangroves and rehabilitating degraded seagrass meadows, also play a key role in boosting blue carbon sequestration [15]. Incorporating incentive mechanisms into policy frameworks is another effective strategy to promote the conservation and restoration of blue carbon ecosystems. This may include offering financial incentives to landowners or communities for preserving mangroves and seagrass beds or integrating blue carbon projects into carbon offset markets or climate finance mechanisms [36]. Integrated coastal management is essential for considering the role of blue carbon in climate regulation. This approach involves integrating blue carbon considerations into coastal zone planning, infrastructure development, and fisheries management to ensure sustainable ecosystem practices that support carbon sequestration [53].

Robust reporting and monitoring systems are necessary for the efficient tracking and assessment of policy activities. This includes developing standardized protocols for measuring carbon stocks and conducting regular assessments to inform adaptive management strategies [5]. International collaboration is vital for addressing transboundary challenges associated with blue carbon management. This involves sharing best practices, exchanging scientific knowledge, and developing harmonized policy frameworks to promote blue carbon sequestration on a global scale (IPCC 2019).

7.3 Integration of blue carbon into climate change mitigation and adaptation plans

Incorporating blue carbon into climate strategies is increasingly valued for enhancing coastal resilience and reducing greenhouse gas emissions. Research emphasizes integrating blue carbon ecosystems like mangroves, seagrasses, and tidal marshes into climate action plans.Blue carbon integration involves recognizing these ecosystems' role in capturing and storing carbon, supporting emission reduction targets in national and international climate strategies [64, 65].

Additionally, blue carbon ecosystems act as natural coastal defenses against sea-level rise and storms, enhancing resilience and protecting vulnerable communities [15]. Successful integration requires interdisciplinary collaboration and policy coherence, aligning marine and coastal management with climate policies to maximize benefits [15].

8 Future directions and research needs

Emerging technologies are transforming blue carbon sequestration efforts in coastal and marine ecosystems. Remote sensing tools such as satellite imagery and LiDAR allow for large-scale monitoring and mapping, facilitating the identification of key areas for conservation [79]. Advancements in molecular biology are uncovering the genetic diversity of blue carbon species, providing insights that inform restoration strategies aimed at increasing resilience to climate change impacts [86]. Innovative restoration techniques like assisted natural regeneration and bioengineering are being developed to restore ecosystem functions and enhance carbon sequestration capacity [87]. To support these efforts, innovative financing mechanisms such as blue carbon offset programs incentivize investment in conservation projects. These mechanisms play a crucial role in scaling up efforts to protect and restore blue carbon habitats [85]. Considering all of this, these tools and methods support blue carbon projects and provide a significant contribution to climate change adaptation and mitigation for scientists, professionals, and decision-makers.

9 Summary

Blue carbon ecosystems such as mangroves, seagrass meadows and tidal marshes play a central role in climate mitigation by capturing atmospheric carbon dioxide and burying organic carbon in long lived coastal sediments. Their dense vegetation and complex root and rhizome systems slow water flow, trap fine particles and support anoxic soils, which together promote long term carbon storage and help these habitats keep pace with sea level rise. At the same time, these ecosystems act as natural filters that retain nutrients, heavy metals, hydrocarbons and plastics in their sediments and biomass, providing an important local pollution control service for coasts affected by agriculture, urbanisation and industry. This review synthesises current knowledge on the mechanisms that underpin carbon sequestration and pollutant trapping in blue carbon systems, the environmental and human drivers that threaten their stability and the implications for climate policy, coastal management and restoration. Protecting and restoring mangroves, seagrass meadows and tidal marshes is therefore critical not only for sustaining their contribution to global carbon budgets but also for maintaining their role as natural buffers that improve water quality and support coastal resilience.

Author contributions **Y.D.:** conceptualization, review and editing **; M.S and N.I.:** Resources, supervision **; K.S and M.H.:** software, validation **; S.I and J.J.:** Writing original draft preparation **; I.R and R.M.:** Visualization, review **. All authors have read and agreed to the published version of the manuscript.**

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