

The Role of Blue Carbon in Climate Change Mitigation: A Review

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KEY WORDS

Blue carbon; Carbon sequestration;
Circular economy; Climate change
mitigation; Coastal ecosystems;
Mangroves; Measurement, Reporting
and Verification (MRV); Salt marshes;
Seagrass meadows; Sustainable
Development Goals.

ABSTRACT

Blue carbon ecosystems comprising mangroves, seagrass meadows, and salt marshes that have garnered substantial scientific and policy attention as nature-based solutions for climate change mitigation, owing to their exceptional capacity for atmospheric carbon dioxide sequestration and long-term organic carbon storage. This review synthesizes current knowledge on the role of blue carbon in climate change mitigation, with a focus on sequestration mechanisms, ecosystem diversity, global carbon stocks, anthropogenic and climatic threats, and relevant policy frameworks. These coastal vegetated ecosystems capture atmospheric CO₂ through photosynthesis and efficiently store it in both living biomass and anoxic sediments, where anaerobic conditions substantially reduce microbial decomposition rates, enabling carbon residence times spanning centuries to millennia. Despite occupying a relatively limited global surface area, blue carbon ecosystems contribute disproportionately to marine carbon burial relative to many terrestrial systems. Anthropogenic pressures including coastal development, land-use change, pollution, and aquaculture expansion in conjunction with climate-driven stressors such as accelerating sea-level rise and ocean warming, are placing these ecosystems under intensifying threat. The degradation and loss of blue carbon habitats not only diminish their future sequestration potential but also triggers the release of previously stored carbon stocks, thereby converting natural carbon sinks into net greenhouse gas sources. This review further examines the role of blue carbon within global climate governance frameworks, particularly its integration into Nationally Determined Contributions (NDCs) under the Paris Agreement, voluntary carbon markets, and emerging blue carbon financing mechanisms.

Critical knowledge gaps persist in carbon accounting methodologies especially for macroalgal systems as well as in the permanence and verifiability of sequestered carbon stocks under changing climatic conditions. Advancing standardized measurement, reporting, and verification (MRV) protocols, alongside robust governance and conservation frameworks, is essential for maximizing the climate mitigation potential of blue carbon ecosystems. This review underscores the necessity of mainstreaming blue carbon into integrated coastal zone management, Sustainable Development Goal (SDG) frameworks, and international climate policy to support global decarbonization trajectories.

1 Introduction

The concept of blue carbon encompasses the carbon fluxes and stocks sequestered within coastal and marine ecosystems, primarily salt marshes, mangroves, and seagrass beds which are distinguished by their capacity to capture and store carbon at rates disproportionate to their spatial extent. First formally articulated by Nellemann et al. (2009) in a landmark UNEP report, the blue carbon concept has since evolved into a recognized discipline within climate science and environmental policy. These ecosystems are increasingly recognized as powerful nature-based climate solutions (NbCS), capturing atmospheric CO₂ and sequestering it in both living biomass and long-lived sedimentary deposits.

The Intergovernmental Panel on Climate Change (IPCC) defines blue carbon as all organically driven carbon fluxes and storages in marine systems amenable to human management, thereby positioning coastal vegetated ecosystems as potentially accountable components of national greenhouse gas inventories. Strategies for climate change mitigation and carbon stock conservation at local, national, and global scales should therefore incorporate blue carbon ecosystems as integral components of comprehensive mitigation portfolios.

Climate change denotes sustained variations in temperature and atmospheric systems that threaten the viability of life on Earth. The present crisis is exerting economic pressure through the accelerated degradation of marine biodiversity and associated habitats. (Bindoff et al., 2019). Current atmospheric CO₂ concentrations have surpassed 420 ppm, levels not recorded in at least 800,000 years of paleoclimate records, while mean global surface temperatures have risen approximately 1.1°C above pre-industrial baselines (IPCC, 2023). The latest IPCC Synthesis Report (2023) underscores that maintaining warming below 1.5°C will require immediate, deep, and sustained reductions in greenhouse gas emissions across all sectors, supplemented by carbon dioxide removal strategies (Bandh et al., 2023).

As shown in figure 1 below, although the coastal blue carbon ecosystems occupy only 2% of the total ocean's surface area, they hold more than half of the carbon storage potential in marine sediments. This is due to their capacity to rapidly sequester carbon much more quickly than trees in forest ecosystems; therefore, they are highly valued for combating climate change. (Goldberg et al., 2020). While much scientific and political attention has historically focused on terrestrial forests and renewable energy transitions, the ocean's capacity to sequester and store carbon has remained comparatively underappreciated in mainstream climate policy. Blue carbon ecosystems, which collectively occupy approximately 2% of the global ocean surface area, are estimated to account for over 50% of marine sediment carbon burial, representing a storage efficiency that is unmatched among natural ecosystems (McLeod et al., 2011; Ash et al., 2024; Kaur et al., 2025). Their carbon sequestration rates on a per-unit-area basis are estimated to be 10–40 times greater than

those of tropical terrestrial forests (Pendleton et al., 2012; Duarte et al., 2022).

The three principal blue carbon ecosystem types are: (1) mangrove forests, comprising tropical and subtropical intertidal woody vegetation; (2) seagrass meadows, consisting of submerged angiosperms in shallow coastal waters; and (3) salt marshes, herbaceous communities occupying temperate intertidal zones. In addition to these canonical systems, macroalgal (seaweed) ecosystems have increasingly been recognized as potentially significant contributors to oceanic carbon cycling, although their formal inclusion in blue carbon accounting frameworks remains contested due to methodological challenges in quantifying export pathways (Krause-Jensen & Duarte, 2016; Ricart et al., 2022).

The significance of coastal ecosystems in global climate policy gained formal recognition through the 2015 Paris Agreement, and successive IPCC assessment cycles have progressively elevated the mitigation importance of blue carbon (IPCC, 2019, 2022, 2023). Notwithstanding this growing recognition, substantial challenges persist in translating blue carbon science into effective and scalable policy implementation. Key barriers include inadequate standardization of MRV protocols, incomplete global mapping of blue carbon habitats, and persistent uncertainties regarding the long-term permanence of stored carbon under projected climate scenarios (Macreadie et al., 2021).

This review adopts a structured narrative approach to synthesize current knowledge on blue carbon sequestration mechanisms, ecosystem-level carbon dynamics, global stocks and fluxes, ecological and socioeconomic co-benefits, prevailing threats, policy frameworks, and future research priorities. The review is intended to serve as a comprehensive reference for researchers, policymakers, and coastal resource managers engaged in advancing blue carbon science and implementation.

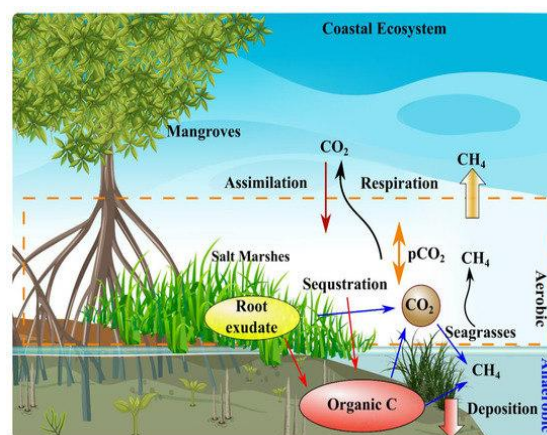


Fig. 1: Role of blue carbon ecosystems in mitigation of climate change (Gao et al. 2016).

2 Methodology of Literature Selection

2.1 Type of Review

This study is a structured narrative review, designed to provide a comprehensive synthesis of current scientific knowledge on the role of blue carbon ecosystems in climate change mitigation. Unlike systematic meta-analysis, this approach allows for the qualitative integration of diverse evidence types including experimental studies, global syntheses, modelling analyses, and policy assessments while maintaining analytical rigor and thematic coherence. The narrative framework was guided by a predefined set of thematic domains to ensure systematic coverage of key topics.

2.2 Literature Databases and Search Strategy

A comprehensive multi-database literature search was conducted using several academic databases and institutional repositories, including Scopus (Elsevier), Web of Science (Clarivate Analytics), PubMed (National Library of Medicine), Google Scholar, IPCC report archives, UNEP and FAO institutional repositories, and The Blue Carbon Initiative. The search strategy employed Boolean operators to combine primary and secondary keyword clusters relevant to blue carbon ecosystems and climate change mitigation. Primary search terms included “blue carbon,” “coastal carbon sequestration,” “mangrove carbon,” “seagrass carbon,” “salt marsh carbon,” and “macroalgae blue carbon.” These were further combined with secondary terms such as “carbon permanence,” “sediment carbon storage,” “nutrient cycling,” “greenhouse gas emissions,” “climate change mitigation,” “nature-based solutions,” “Nationally Determined Contributions,” “carbon markets,” “MRV protocols,” “circular economy,” and “Sustainable Development Goals.” In addition, regional and applied search terms including “Indo-Pacific mangroves,” “coastal blue economy,” “blue carbon policy,” “blue bonds,” and “payment for ecosystem services” were incorporated to capture geographically relevant and policy-oriented literature.

2.3 Inclusion and Exclusion Criteria

The inclusion criteria comprised peer-reviewed research articles, systematic reviews, and authoritative grey literature published between 1990 and 2026, including reports from organizations such as the IPCC (2019; 2022; 2023), UNEP (2021), FAO, and the World Bank (2023). Studies included if they addressed carbon sequestration, carbon storage, or carbon flux measurements within mangroves, seagrasses, salt marshes, or macroalgal ecosystems. In addition, policy analyses and governance frameworks related to blue carbon within national or international climate agreements were considered, alongside studies examining ecosystem services, socioeconomic co-benefits, environmental threats, and restoration outcomes associated with coastal blue carbon ecosystems. Only literature published in English was included in the review. Conversely, studies focused exclusively on freshwater or deep-ocean carbon systems without direct relevance to coastal ecosystems were excluded. Geographically isolated case studies lacking broader applicability were also omitted unless they provided important regional insights or illustrative context. Furthermore, conference

abstracts, non-peer-reviewed commentaries, and opinion-based articles lacking supporting scientific data were excluded, as were duplicate studies reporting identical datasets without presenting novel analyses or interpretations.

2.4 Literature Time Range and Volume

The primary literature search covered publications from 1990 to March 2026, with particular emphasis on studies published between 2019 and 2026 to capture the most recent advances in blue carbon science and policy. A total of approximately 180 sources were initially identified, of which 95 were selected for inclusion.

3 Mechanisms of Carbon Sequestration in Blue Carbon Ecosystems

Blue carbon ecosystems sequester carbon through a combination of biological, chemical, and physical processes that operate across both biomass and sediment compartments. These processes collectively distinguish coastal vegetated ecosystems from terrestrial carbon sinks in terms of sequestration efficiency, carbon longevity, and biogeochemical stability.

Mangroves, seagrass beds, and salt marshlands are examples of coastal stagnated ecosystems that use photosynthesis to absorb atmospheric carbon dioxide and transform it into organic carbon that is stored in plant tissues (Duarte *et al.*, 2020; Macreadie *et al.*, 2021). Long-term carbon storage is improved when a substantial amount of this carbon is later moved belowground into roots and rhizomes. (Alongi, 2020). Recent evidence indicates that belowground carbon allocation in mangroves can account for 60–80% of total ecosystem net primary production, with fine root turnover representing a critical pathway for sediment carbon inputs (Adame *et al.*, 2021).

Unlike most terrestrial systems, blue carbon ecosystems are distinguished by their capacity to trap and stabilize organic matter within anoxic sediments. Oxygen-limited (anaerobic) conditions inhibit heterotrophic microbial decomposition, enabling carbon to persist in sediments for centuries to millennia (Pendleton *et al.*, 2012). Radiocarbon dating of mangrove sediment profiles has confirmed the presence of organic carbon deposited more than 5,000 years before present at depth, attesting to the extraordinary temporal stability of blue carbon stocks (Breithaupt *et al.*, 2012; Macreadie *et al.*, 2021). Additionally, hydrodynamic processes facilitate the import and accumulation of allochthonous (externally derived) carbon from adjacent systems, further augmenting burial rates (Serrano *et al.*, 2021). The interaction between high net primary productivity, efficient particle sedimentation, and suppressed decomposition renders blue carbon ecosystems among the most effective natural carbon sinks per unit area on Earth (Macreadie *et al.*, 2021).

4 Types of Blue Carbon Ecosystems

Following are the types of blue carbon ecosystems that exhibit distinct structural, functional, and biogeochemical characteristics that collectively underpin their role as globally significant carbon reservoirs. Together, these ecosystems occupy an estimated 46–79 Mha globally, storing between 8.6 and 15.7 Pg C in sediment profiles alone (Table 2).

4.1 Mangrove Forests

Mangrove forests occupy tropical and subtropical intertidal zones, characterized by dense woody vegetation with aerating root structures (pneumatophores, prop roots, and knee roots) that facilitate gas exchange under waterlogged conditions (Alongi, 2020). These ecosystems store large quantities of carbon both in above-ground biomass and in deep sediment profiles (Sanderman et al., 2018). Mangroves are the most carbon-dense of the three canonical blue carbon ecosystems on a per-unit-area basis, with soil organic carbon stocks in the top metre averaging 386 Mg C ha⁻¹ globally and reaching up to 1,000 Mg C ha⁻¹ in Indo-Pacific peat mangroves (Adame et al., 2021; Goldberg et al., 2020). Recent studies from South and Southeast Asia, including assessments of Indian mangrove systems, highlight the critical role of sediment properties and tidal regime in governing carbon storage variability at regional scales (Ash et al., 2024; Antony et al., 2025).

4.2 Seagrass Meadows

Seagrass meadows are distributed across shallow coastal and estuarine waters on all continents except Antarctica, comprising approximately 72 species of submerged angiosperms (McKenzie et al., 2020). Despite their relatively modest global spatial extent (30–60 Mha), seagrass meadows contribute disproportionately to marine carbon burial through both autochthonous production and the trapping of allochthonous organic matter (Duarte et al., 2020; Serrano et al., 2021). Recent global assessments estimate that seagrass meadows sequester between 41 and 83 Tg C yr⁻¹, storing an average of 48–296 Mg C ha⁻¹ in sediments. However, seagrass meadows are also among the most rapidly declining coastal habitats globally, with an estimated 7% loss per decade since the 1990s attributed primarily to anthropogenic water quality degradation and coastal disturbance (McKenzie et al., 2020).

4.3 Salt Marshes

Salt marshes, predominantly distributed in temperate estuarine and intertidal zones, support herbaceous halophytic vegetation including *Spartina*, *Salicornia*, and *Phragmites* species, and are highly efficient at accumulating organic-rich sediments (McLeod et al., 2011).

5 Blue Carbon: Advancing Climate Change Mitigation and the Circular Economy

Blue carbon contributes not only to climate change mitigation but also holds potential as a biomass feedstock for biofuel production. Furthermore, it serves as a key intermediate in the circular carbon dioxide (CO₂) cycle. The significance of littoral bionetworks has amplified because of the degradation of global bionetworks carried by anthropological activities such as terrestrial use change, desertification, fossil-fuel ingestion etc. Blue carbon serves as powerful natural solutions within both climate change mitigation and the circular economy by sequestering atmospheric carbon at unparalleled rates while providing renewable biomass that can be cycled back into sustainable production systems. These coastal systems provide long-term climate mitigation and lower atmospheric CO₂ concentrations by using photosynthesis to absorb and store carbon in wet, anaerobic sediments for millennia (McLeod et al., 2011; IPCC, 2019). Concurrently, their biomass can be utilized in circular economic models to replace carbon-intensive materials, reduce waste, and create regenerative loops that minimize environmental impact. Examples of this include using seaweed for biofuels, bioplastics, animal feed, and biofertilizers (Duarte et al., 2022; Froehlich et al., 2019). We improve carbon storage and coastal resilience. encourage sustainable resource use.

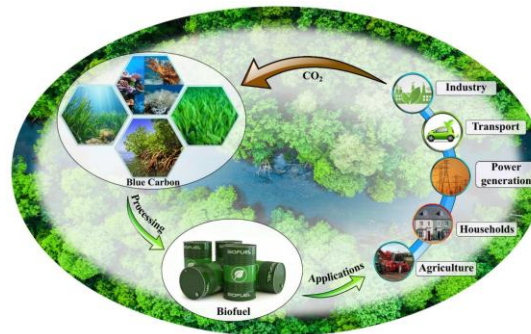


Fig. 2: Blue carbon role in climate change vindication and circular economy (Bandh et al. 2023)

6 Comparative Carbon Sequestration Rates Across Ecosystems

Blue carbon ecosystems achieve exceptional carbon-sequestration through several interconnected mechanisms. As in table 1 unlike terrestrial forests where carbon is primarily stored in living biomass vulnerable to disturbance, coastal ecosystems confiscate most carbon (70-90%) in below-ground sediments under anaerobic conditions that melodramatically slow disintegration (McLeod et al., 2011). This fundamental difference in carbon storage architecture renders blue carbon ecosystems far less vulnerable to rapid carbon loss through fire and drought, though they remain susceptible to disturbance through sea-level inundation, erosion, and anthropogenic drainage.

Table 1: Comparative carbon sequestration pathways in terrestrial versus coastal ecosystems. Coastal systems sequester most carbon in anaerobic deposits where putrefaction charges are orders of magnitude slower than in aerobic terrestrial soils. (Fourqurean et al. 2012; Alongi 2014; Howard et al. 2017; IPCC 2019; Macreadie et al., 2021; Adame et al., 2021).

Ecosystem Type	Mean Carbon Sequestration Rate (Mg C ha ⁻¹ yr ⁻¹)	Carbon Stock in Sediments (Mg C ha ⁻¹)	Global Area (Mha)	Estimated Global Sequestration (Tg C yr ⁻¹)
Mangroves	2.26 ± 0.39	386-1,024	13.7-15.2	31-34
Seagrasses	1.38 ± 0.38	48-296	30-60	41-83
Salt Marshes	1.94 ± 0.42	255-598	2.2-4.0	4-8
Tropical-Forests	2.8 ± 0.5	120-250 (biomass only)	1,760	4,928
Temperate Forests	1.4 ± 0.3	90-200 (biomass only)	1,040	1,456

7 Biological and Geochemical Processes

The superior sequestration capacity of blue carbon ecosystems stems from multiple complementary processes:

High Primary Productivity: Like tropical rainforests but concentrated in smaller biomass, mangroves and seagrasses have net primary production rates of 500–2,500 g C m⁻² yr⁻¹. (Chandrani et al., 2025)

Sediment Trapping and Stabilization: By slowing water flow, intricate root systems encourage the deposition of mineral and organic particles. According to Krauss et al. (2014), mangrove pneumatophores can increase sedimentation rates by up to 10 mm yr⁻¹ by reducing water velocity by 50–90%.

Anaerobic Conditions: Within millimeters of the surface, wet sediments turn anoxic, which inhibits heterotrophic respiration. Although it happens, methanogenesis usually happens at speeds 10–100 times slower than aerobic breakdown (Fourqurean et al. 2012).

Allochthonous Carbon Capture: A large amount of carbon is imported by blue carbon ecosystems from nearby systems. For example, plankton and macroalgal-detritus generated elsewhere provide seagrass meadows with 27–88% of their sediment carbon (Kennedy et al., 2010).

Carbonate Production: Although it has complicated biogeochemical ramifications, certain seagrasses and related solidifying organisms make calcium carbonate, which is an additional carbon storage mechanism (Saderne et al., 2019).

8 Timescales of Carbon Storage

Blue carbon sequestration's longevity is entirely distinct from terrestrial ecosystems. Whereas forests' carbon cycle exists over

decades and centuries, coastal sediment carbon can remain trapped for thousands of years. Radiocarbon analysis indicates that carbon in mangrove sediments is older than 5,000 years at depths (Breithaupt et al., 2012). Such longevity is due to:

Chemical Recalcitrance: The formation of stable humic substances from organic matter that are resistant to microbial degradation.

Mineral Protection: Association of organic carbon with mineral particles, particularly clays, forming organo-mineral-complexes.

Sulfate Reduction: In marine sediments, sulfate reduction produces sulfide that can bind with organic matter, further slowing decomposition.

9 Global Carbon Stocks and Fluxes

Organic carbon is stored abundantly in vegetation as well as sediments within blue carbon ecosystems, which act as major sinks for carbon globally. Sediment deposition through time is one method by which coastal ecosystems provide a substantial subsidy towards global carbon storage (Macreadie et al., 2021).

Mangroves rank among the densest carbon forests in tropical regions, with carbon density being exceptionally high compared to that found in terrestrial forests on a per unit area basis (Alongi, 2020). Similarly, seagrass meadows and salt marshes contribute meaningfully to global carbon burial despite their limited spatial degree (Duarte et al., 2020). These ecosystems are estimated to sequester carbon at rates up to 10–40 times greater than terrestrial forests (Pendleton et al., 2012).

However, these ecosystems' global distribution and potential to store carbon differ based on anthropogenic, climatic, and geographic factors. Accurately estimating global blue carbon stocks continues to be hampered by uncertainties in measuring methods, spatial mapping, and long-term monitoring (Sanderman et al., 2018). Recent syntheses provide updated estimates of global blue carbon stocks and fluxes (Table 2). Despite their limited spatial extent, blue carbon ecosystems represent globally significant carbon reservoirs.

Table 2: Global distribution of major-blue carbon ecosystems showing concentration in tropical and temperate-coastal zones. (Alongi 2014; Fourqurean et al. 2012; IPCC 2019; Macreadie et al., 2021)

Parameter	Mangroves	Seagrasses	Salt Marshes	Total
Global Area (Mha)	13.7-15.2	30-60	2.2-4.0	46-79
Carbon Stock (Pg C)	4.0-6.4	4.2-8.4	0.4-0.9	8.6-15.7
Annual Sequestration (Tg C yr ⁻¹)	31-34	41-83	4-8	76-125
Equivalent CO ₂ (Mt CO ₂ yr ⁻¹)	114-125	150-304	15-29	279-458
Historical Loss (%)	30-50	29	25-50	~30-40
Current Emissions from Loss (Tg C yr ⁻¹)	9.6-24.0	11-33	0.5-2.0	21-59

10 Geographic Variability and Hotspots

Blue carbon distribution and sequestration rates show significant geographic variability driven by climatic, oceanographic, and geomorphic factors:

Indo-Pacific Region: Contains approximately 50% of global mangrove area and exhibits the highest carbon sequestration rates ($2.5\text{--}3.5 \text{ Mg C ha}^{-1} \text{ yr}^{-1}$) because of the wide tidal variations and ideal growth conditions (Alongi, 2014). Recent assessments from Southeast Asian nations, including Indonesia, Malaysia, and the Philippines, document exceptionally high carbon densities in peat-forming mangrove systems, with implications for regional NDC targets.

Australia: Home to the world's largest seagrass meadow (Shark Bay: $\sim 4,300 \text{ km}^2$) and significant mangrove systems, representing around 5–10% of global blue carbon stocks.

Indonesia: Contains 20–23% of global mangrove area but suffers the highest-loss rates ($52,000 \text{ ha yr}^{-1}$ between 2000–2012), making it both a critical-reservoir and emission source (Richards & Friess, 2016).

South Asia: Emerging evidence from India highlights the underappreciated carbon sequestration potential of Sundarbans and western Indian mangrove systems, with sediment carbon stocks varying significantly with salinity gradients and tidal exposure (Ash et al., 2024; Antony et al., 2025; Lincoln et al., 2023).

Atlantic Temperate Regions: Salt marshes-dominate, with particularly high carbon density in accreting systems with high sediment-supply (Chmura et al., 2003).

11 The Seaweed Dimension

Macroalgal ecosystems represent a potentially massive but poorly quantified carbon pool. Global seaweed primary-production is estimated at 1.5 Pg C yr^{-1} , with approximately 153 Tg C yr^{-1} exported to deep ocean sediments (Krause-Jensen & Duarte, 2016). Seaweed carbon differs from traditional blue carbon in several ways:

Lack of Sedimentary Storage: Most seaweed grows on hard-substrates rather than accumulating sediments.

Export Pathways: Carbon sequestration principally occurs through export of detritus to deep ocean or coastal sediments.

Scalability: Cultivation potential offers anthropogenic improvement opportunities unavailable for natural coastal ecosystems. (Chmura et al., 2003).

12 Blue Carbon: A Potential Resource for Biofuel Production

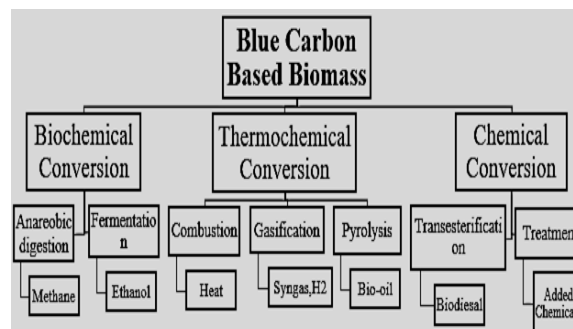


Fig. 3: Flow Chart of Blue Carbon biomass as a Potential Source for Biofuel Production.

Blue carbon ecosystems are particularly seaweed and mangrove biomass present a highly promising and sustainable source for biofuel production, contributing a renewable energy pathway that aligns with both climate change mitigation and circular economy principles. In terms of being used in various methods of biofuel production, macroalgae or seaweed are highly suited because of their high carbohydrate content and fast growth process, as well as their ability to grow in absence of freshwater or arable land. The figure highlights the various ways in which blue carbon biomass can be converted into methane using anaerobic digestion, ethanol using fermentation, heat via direct combustion, syngas and hydrogen through gasification, bio-oil by pyrolysis, and biodiesel through transesterification (Rosentreter et al., 2021). Such biofuels will cut down on greenhouse emissions and improve energy security by converting marine biomass into renewable fuel sources that can serve as replacements for fossil fuels (Fig. 3).

More importantly, harvesting seaweed for biofuels would not create conflict between growing food crops and also will not lead to changes in land use which results in GHG emission, but may actually offset carbon sequestration when sustainably combined with agriculture which stores carbon in marine sediments and deep oceanic reservoirs (Duarte et al., 2013; Froehlich et al., 2019). Moreover, the nutrient rich deposits from biofuel processing can be recycled as biofertilizers or animal feed, closing nutrient loops and enhancing the sustainability of coastal agroecological systems. By harnessing blue carbon biomass for biofuels, we can instantaneously advance decarbonization, promote marine ecosystem restoration, and support coastal-blue economies making it a critical component of the global renewable energy.

13 Blue Carbon and the Sustainable Development Goals

The conservation, restoration, and sustainable management of blue carbon ecosystems contribute meaningfully to multiple Sustainable

Development Goals, underscoring their relevance beyond the climate science community (Hilmi et al., 2021; Macreadie et al., 2021). Key SDG linkages include:

SDG 13 (Climate Action): Blue carbon ecosystems such as mangroves, seagrasses, and salt marshes play a critical role in climate change mitigation through carbon sequestration and long-term carbon storage, while also enhancing coastal resilience to climate-related hazards.

SDG 14 (Life Below Water): The protection and restoration of coastal and marine ecosystems support marine biodiversity, improves fisheries productivity, and maintains ecological balance in coastal environments.

SDG 15 (Life on Land): Blue carbon conservation contributes to the preservation of biodiversity and ecosystem integrity by protecting habitats that support numerous terrestrial and aquatic species.

SDG 1 (No Poverty) and SDG 8 (Decent Work and Economic Growth): Sustainable management of blue carbon ecosystems supports livelihoods through fisheries, ecotourism, aquaculture, and other nature-based economic activities, particularly in vulnerable coastal communities.

SDG 2 (Zero Hunger): Healthy coastal ecosystems enhance food security by sustaining fisheries resources and supporting nutrient cycling essential for marine productivity.

SDG 6 (Clean Water and Sanitation): Mangroves, seagrasses, and salt marshes improve water quality by filtering pollutants, trapping sediments, and reducing nutrient runoff into coastal waters.

The alignment of blue carbon with the SDG agenda provides a compelling rationale for embedding blue carbon considerations within Voluntary Local Reviews, National Biodiversity Strategies and Action Plans (NBSAPs), and Integrated Coastal Zone Management (ICZM) frameworks. This cross-sectoral integration is essential for ensuring that blue carbon investments generate co-benefits that extend beyond carbon mitigation to encompass broader sustainable development objectives

14 Ecological And Economic Perspectives of Blue Carbon

The increasing prominence of blue carbon in scientific and policy discussions underscores the necessity of advancing carbon sequestration rate assessment capabilities. (Macreadie *et al.*, 2017). Ocean sequestered carbon, or "blue carbon" deposits, are vulnerable to anthropogenic threats. These hazards must be acknowledged and weighed against the advantages of maintaining these carbon drawdown systems in order to build a sustainable economy.

Despite weak coordination among governments, communities, and the private sector, better definition of blue carbon ecosystems and

recognition of their socio-economic vulnerabilities in IPCC reports could promote collaboration toward sustainable outcomes that reduce ecological and economic impacts of climate change. Blue Carbon's potential to help develop sustainable management frameworks by including it into strategies for carbon-conservation and mitigation from both an ecological & economic standpoint. (Siikamäki et al., 2012)

15 Blue Carbon Global Frameworks

The blue carbon classifications increase climate justification strategies as bionetworks store long-term carbon. In international contracts on climate change such as the United Nations Framework Convention on Climate Change and Kyoto Protocol The same frameworks are documented. It assists nations in meeting their pollution reduction targets and observing to the Nationally Appropriate Contributions of the Paris Agreement. The blue carbon program is being funded locally through the establishment of clean development tools.

Advancing Blue Carbon through the international initiative recognized as the foremost global program of its kind, created through a corporation between the Intergovernmental Oceanographic Commission of UNESCO and the IUCN. Its primary purpose is to address climate change by preserving and rehabilitating ocean bionetworks. To support this mission, the International Blue Carbon Scientific Working Group has developed comprehensive guidelines covering blue carbon assessment and monitoring, standardized data collection and quality declaration methods, field survey protocols, as well as conservation tactics and management practices. The International Blue Carbon Policy working group is enthusiastic to integrating blue carbon developments into the UNFCCC and the CBD. It formulates financial support, and other policy programs and guides needed for research, projects, and policy priorities.

NDCs for climate change mitigation and adaptation have included blue carbon ecosystems because of their role in growing coastal vulnerability to climate change and weather catastrophes. Ecosystem based approaches to flood administration provide considerable benefits. Mangrove forests alone are estimated to deliver annual flood protection valued at around US \$65 billion, helping decrease flood risk for almost 15 million people (Lovelock et al., 2017; Beck et al., 2018; Narayan et al., 2019). However, coastal ecosystems within the Coral Triangle such as mangroves, seagrass meadows, and salt marshlands are highly vulnerable to sea-level intensification and are increasingly threatened by the impacts of climate change (Saderne *et al.*, 2019).

The fragility of blue carbon organizations in delta regions, such as that seen on oceanic islands and ring-shaped coral reefs also hurt from rising sea levels and amplified wave heights. Significant carbon dioxide discharges are caused by the global loss of coastal surroundings when carbon in plants and deposits is disturbed and crystallized to carbon dioxide. The deterioration of the surviving ecosystems has reduced their ability to provide additional

environmental services and buffer climate change. However, blue carbon ecosystems and initiatives to safeguard them have not yet been incorporated into climate change regulations. Acidification, currents, anoxia, precipitation, increasing sea levels, storm frequency, and other environmental changes are causing coastal regions to be destroyed at a critical rate worldwide owing to abrupt changes in coastal development and poor management of coastal ecosystems (Chandrani, *et al.*, 2025)

Although blue carbon has gained increasing consideration in recent years, practical implementation and full incorporation of related strategies and policy measures remain limited. Many countries have not yet established or adopted climate and carbon policies specifically targeting coastal carbon ecosystems. However, some early-stage mitigation initiatives have begun to integrate coastal blue carbon habitats, highlighting their growing gratitude in climate action efforts.

16 Seaweeds Dimensions in Blue Carbon Ecosystem and their Role in Climate Change Mitigation

By accumulating CO₂ through rapid growth (up to 30 cm/day) and sequestering carbon as debris falls to deep seas or coastal deposits, seaweed stops climate change by capturing around 173 million tons of CO₂ annually. They are, nonetheless, less studied than seagrass beds or mangroves. They enhance biodiversity, reduce coastal erosion, buffer ocean acidity, and provide carbon-negative applications like biofuels. However, their survival is threatened by storms and warmer seas (e.g., 40% loss in Tasmania) (Doo *et al.*, 2020). Scaling up sustainable farming and enhancing carbon tracking methods are necessary to maximize their worldwide potential while avoiding ecological effect. Despite any uncertainties, seaweed offers a unique, scalable climate cure because of their production and many benefits as illustrated in figure 4.

Blue carbon ecosystems-mangroves, seagrasses, salt marshes, and emerging seaweed systems stand as some of the most powerful, efficient, and immediately available nature-based solutions to the global climate crisis. They are positioned not just as biological assets but also as essential elements of global climate mitigation portfolios due to their unmatched ability to capture and store atmospheric carbon dioxide at rates far higher than terrestrial forests. But it is impossible to exaggerate how urgent it is to safeguard and restore them. Coastal development, the growth of aquaculture, pollution, and the direct effects of climate change, such as rising sea levels and hotter oceans, pose a serious and growing danger to these ecosystems (Beaumont *et al.*, 2014). A twin climatic disaster is represented by the deterioration and loss of blue carbon habitats: the quick release of centuries to millennia of stored carbon, turning essential sinks into major emission sources, and the loss of future carbon sequestration potential (Fig. 6) (Chandrani, *et al.*, 2025)

Blue carbon ecosystems are essential to meeting the goals of the Paris Agreement and keeping global warming to 1.5°C, according

to overwhelming scientific evidence. Their importance goes well beyond carbon. They offer vital adaptation services, protecting coasts from erosion and storms, bolstering global fisheries, preserving biodiversity, filtering pollutants, and maintaining the way of life and cultural customs of millions of coastal residents.

Dimensions of seaweed in blue carbon ecosystem and their role in climate change mitigation

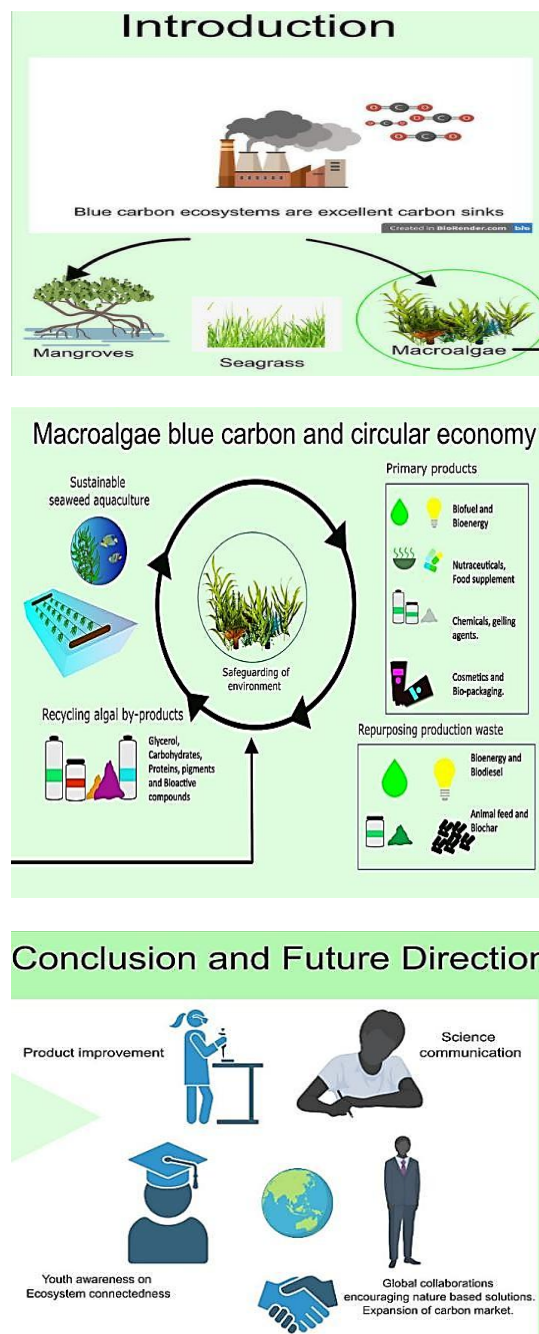


Fig. 4: Dimensions of seaweeds in blue carbon ecosystem and their role in climate change mitigation (Chandrani, *et al.*, 2025)

By Converting biomass into sustainable biofuels, bioplastics, and fertilizers, blue carbon's incorporation into the circular economy increases its value and creates regenerative economic loops that lessen waste and reliance on fossil fuels. The flexibility stresses utilizing blue carbon is an entire strategy towards social equity, sustainable economic development, and environmental durability in contrast to a particular climate change mitigation strategy. (Friess *et al.*, 2019).

Nonetheless, achieving this requires radical steps from various perspectives. For instance, there is a need for credible standard methods to monitor, evaluate, and confirm blue carbon stocks and fluxes to minimize confusion and strengthen the faith in the carbon market. Additionally, policymakers should incorporate blue carbon approaches promptly in national adaptation strategies, marine 3D management schemes, and Nationally Determined Contributions (NDCs) through novel financial mechanisms such as carbon credits, blue bonds, and payment for ecological services. Equally vital is the acknowledgment and empowerment of local and indigenous communities as the custodians of ecosystems in conservation and rehabilitation undertakings. Lastly, there is a necessity for international collaboration through platforms such as the International Blue Carbon initiative to facilitate information exchange, resource mobilization, and implementation of transboundary protection schemes.

The relation between blue carbon and the circular economy makes it an even more potent sustainable solution that incorporates carbon sequestration alongside renewable energy, reduced waste, and resource efficiency. Overall, this perspective makes blue carbon not just a climate mitigation strategy but also a catalyst for sustainable development.

We must focus on blue carbon in terms of climate policies and funding initiatives to ensure that we have a sustainable and prosperous future. Safeguarding our blue carbon heritage is crucial to the survival of life on Earth. Overall, this perspective makes blue carbon not just a climate mitigation strategy but also a catalyst for sustainable development.

17 Threats and Challenges

Natural and human activities are both threatening blue carbon ecosystems despite the significance of these ecosystems from ecological and climatic perspectives. Pollution, expansion of aquaculture, change in land use, and coastal development have resulted in extensive loss and destruction of these habitats globally (Friess *et al.*, 2019). Rising sea levels, ocean warming, and extreme weather events due to climate change are some of the ways through which climate change amplifies these threats (IPCC, 2022).

Degradation of blue carbon ecosystems causes emission of greenhouse gases since it reduces their ability to absorb carbon and releases the sequestered carbon into the atmosphere (Pendleton *et al.*, 2012). Other barriers include the lack of sufficient scientific

understanding, poor monitoring of these ecosystems, and differences in carbon accounting practices (Macreadie *et al.*, 2021).

In addition to that, economic challenges like lack of knowledge and poor governance can also be blamed on the failure to restore blue carbon ecosystems on a larger scale. These challenges require solutions where scientific investigations will have to be coupled with strategy formation and social interaction (Friess *et al.*, 2019).

18 Policy and Management

There is an increasing level of global interest regarding the role of blue carbon ecosystems within climate policy formulation. Blue carbon ecosystems have gained importance as nature-based solutions for climate change mitigation and adaptation (IPCC, 2022). Coastal ecosystems' incorporation in Nationally Determined Contributions (NDCs) is supported by international treaties such as the Paris Agreement, which mentions them as important strategies for achieving climate goals (UNEP, 2021).

Some examples of efficient management strategies include the protection of existing habitats, rehabilitation of damaged ecosystems, and utilization of sustainable coastal development approaches (Macreadie *et al.*, 2021). Market-based strategies like carbon credits and blue carbon financing not only provide opportunities for conservation but also make significant impacts on the socioeconomic condition of coastal regions (UNEP, 2021).

The policy frameworks should facilitate interdisciplinarity in their formation, which can be achieved by integrating social, economic, and ecological dimensions. Enhanced governance would be required for the long-term sustainability of blue carbon ecosystems, and better monitoring along with increased engagement among stakeholders would be necessary (IPCC, 2022).

19 Knowledge Gaps and Future Research Directions

Contempt was another feature of progress in blue carbon research, and there are still several knowledge gaps that impede its comprehensive implementation in climate change mitigation policies. The biggest issue is carbon accounting and especially with seaweed-based systems, sequestration pathways like export of biomass to Deep Ocean are hard to measure and prove. Moreover, standardized procedures of measuring, reporting, and verifying (MRV) blue carbon remain in their infancy, thus restricting their successful inclusion in world carbon markets (Pendleton *et al.*, 2012).

Moreover, it is still not completely known how stable sequestered carbon can be in a changing climate. Exposure of the sediment to environmental stressors like the warming and acidification of the ocean, and extreme weather events can influence the carbon storage in the sediment and the ecosystem resilience. Therefore, more long-term and experimental studies are necessary to better evaluate these impacts (Saderne *et al.*, 2019).

The other significant gap in research is the lack of comprehensive implementation of socio-economic variables such as governance systems, involvement of communities, and fair distribution of benefits. Even though blue carbon projects hold a promising future as economic prospects, its application should be socially inclusive, sustainable, and equitable in terms of benefits distribution to the stakeholders (Sanderman *et al.*, 2018; Duarte *et al.*, 2020).

Moreover, the potential of macroalgae (seaweeds) as a scalable blue carbon solution needs to be explored further, specifically, in terms of lifecycle analysis, ecological effects of massive cultivation, and the ethics of carbon sequestration in the ocean.

The next steps in research should focus on:

- Construction of regular MRV systems.
- Three-dimensional mapping and high-resolution of the blue carbon pillars.
- Climate flexible valuations of coastal ecosystems.
- Sustainable models of seaweed farming.
- Policy combination and economic estimate studies.
- The need to fill these gaps will be essential in transforming the blue carbon science into effective climate action (Chandrani *et al.*, 2025).

20 Conclusion

Blue carbon ecosystems including mangroves, seagrass meadows, salt marshes, and macroalgal systems, are highly efficient natural carbon sinks that contribute significantly to climate change mitigation. Owing to high primary productivity and efficient long-term carbon burial in anoxic sediments, these systems sequester atmospheric carbon dioxide at rates that often surpass those of terrestrial forests on a per-unit-area basis. Beyond carbon storage, they deliver essential ecosystem services such as coastal protection, shoreline stabilization, nutrient cycling, water purification, fisheries support, and biodiversity maintenance.

Despite their importance, blue carbon ecosystems are under increasing pressure from anthropogenic and environmental stressors. Coastal development, land-use conversion, pollution, and expanding aquaculture are major drivers of habitat loss and degradation. In addition, climate-related impacts including sea-level rise, ocean warming, acidification, and extreme weather events further accelerate ecosystem decline. The degradation of these habitats reduces future carbon sequestration capacity and can release previously stored sedimentary carbon, thereby contributing to greenhouse gas emissions.

Blue carbon is increasingly recognized in international climate policy frameworks, including the Paris Agreement, Nationally

Determined Contributions (NDCs), voluntary carbon markets, and Sustainable Development Goal (SDG) implementation. However, its effective integration remains limited by several challenges, particularly the lack of standardized Measurement, Reporting, and Verification (MRV) systems, uncertainties in global carbon stock estimation, limited understanding of long-term carbon permanence, and incomplete inclusion of macroalgal systems in formal carbon accounting methodologies.

Future progress requires strengthened interdisciplinary research, improved global monitoring and spatial mapping, and the development of standardized, science-based carbon accounting frameworks. Effective policy integration, innovative climate financing mechanisms, and the active engagement of coastal communities will be essential for scaling conservation and restoration efforts.

Overall, blue carbon ecosystems represent a highly effective nature-based solution for climate change mitigation and coastal resilience. Their protection and restoration should be prioritized within global climate and coastal management strategies to support long-term environmental sustainability and sustainable development.

Ethical Considerations & Conflict of Interest

All authors confirm originality and no potential conflict of interest was reported.

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