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The Existence of Blue Carbon and its Prospective Role in the Preservation of Carbon Stocks and the Mitigation of Climate Change

Milind Girkar [a*], Santosh Kunjir [a], Saiprasad Bhusare [b] and Sagar Gorakh Satkar [c]

[a] College of Fishery Science, Udgir - 413 517, Dist. Latur, Maharashtra, India.
[b] ICAR-Central Institute of Fisheries Education, Mumbai- 400 061, India.
[c] Faculty of Fisheries, Kerala University of Fisheries and Ocean Studies, Panangad, Kochi, Kerala- 682506, India.

Authors' contributions

This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.

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Review Article

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ABSTRACT

The substantial rise in carbon emissions can be attributed to the initiation of the industrial revolution in the 17th century. The increase in global temperature is linked to higher concentrations of atmospheric carbon dioxide. The anticipated increase in international sea levels is predicted to affect a considerable portion of the world's population significantly. The susceptibility of blue carbon ecosystems to climate change prompts inquiries regarding their capacity to operate effectively in the future while simultaneously delivering ecological advantages to coastal communities, including

**Corresponding author: E-mail: milindgirkar21@gmail.com;*

climate change adaptation. The primary emphasis of the study was on blue carbon, a term used to describe the process of carbon sequestration in coastal and marine ecosystems to mitigate the dangers associated with climate change.

Keywords: Blue carbon; coastal and marine carbon sequestration; climate change; mitigation.

1. INTRODUCTION

"Blue Carbon" has altered in concept and practice in recent years. Nellmann et al. (2009) used the "blue carbon" that UNEP published first. Oceans and coastal environments contain "blue carbon." It includes ecosystems, animals, and biological processes that collect atmospheric carbon and move it to sediments or deep waters. Martin and Lutz (2014) elaborate on this idea. The seas store and transfer around 93% of the world's carbon dioxide. They also contain almost half of living marine species' biological carbon, according to Nellemann et al. (2009). Sabine et al. [1] discovered that the oceans absorb and store 20–35% of atmospheric carbon dioxide. Many scientists are studying natural carbon sequestration and storage methods.

Human activities global CO2 buildup, which adds to global warming, inspired this study. Coral reefs, mangroves, seagrass meadows, tidal marshes, dune systems, and salt marshes are coastal and marine ecosystems. NOAA [2,71-76] recognizes these ecosystems as major global carbon sinks with a higher carbon storage capacity per unit area and a quicker carbon sequestration rate than tropical forests. Hamilton [3] revealed that terrestrial ecosystems with significant CO2 burial convert 20 times more carbon into biomass via photosynthesis than boreal and tropical forests. This makes these ecosystems vital carbon reserves on Earth. Vegetated coastal habitats may store atmospheric carbon dioxide for years or decades [66-70]. This requires organic carbon buildup in stems, branches, leaves, and roots. Carbon builds up in oxygen-depleted sediments supported by plant rhizomes as dead plant matter accumulates. Coastal environments are very productive and vital to biodiversity. These habitats help fish reproduce and safeguard coastal regions from storms [47-55].

When measuring the blue carbon ecosystem, endogenous and external carbon sources must be distinguished [4]. Geographic coordinates show where indigenous carbon is created and stored. Photosynthesis converts carbon dioxide from the atmosphere or aquatic environments into plant structures, including leaves, stems, roots, and rhizomes, increasing plant biomass. Significant plant biomass is used for anaerobic breakdown, sequestering carbon in sedimentary deposits [56-61].

Allochthonous carbon is generated in one place and then transferred to another, where it accumulates. Variable environments are present every day in blue carbon ecosystems [77-83]. Wave action, tidal pressures, and coastal currents carry sand and organic carbon from surrounding ecosystems, on land or offshore. Their sophisticated root systems and canopies traverse sediment, storing carbon in the region [62-65].

The review aims to explain blue carbon ecosystems and their carbon sequestration capacities across kinds.

2. MATERIALS AND METHODS

The study involved a comprehensive review of the current literature on blue carbon-rich ecosystems. This study utilized several databases, including reputable sources such as SpringerLink, ScienceDirect, Google Scholar, Scopus, Springer, and Web of Science. A thorough literature review was conducted using a combination of criteria, including topics such as blue carbon ecosystems and their carbon sequestration capabilities, seagrass meadows contribute to marine carbon sequestration, Carbon sequestration in mangrove forests, role of marine vegetation on the oceanic carbon cycle, Seagrass restoration enhances “blue carbon” sequestration, ocean warming and acidification, and macroalgal blooms trigger the breakdown of seagrass blue carbon.

2.1 Threats and Challenges Faced by Ecosystems

In conclusion, blue carbon-rich ecosystems are vital for carbon emission mitigation. The blue carbon ecosystem is vulnerable to threats from natural and human activities, reducing carbon sequestration and retention capacity.

2.2 Anthropogenic Threats Due to Urbanization

Various findings show that human actions considerably affect climate change. The fast economic expansion and growing populations of many countries have led to the purposeful use of fossil fuels and infrastructure building, especially in coastal areas. Remote sensing has shown that land use and land cover changes have degraded coastal ecosystems, notably mangrove ecology. Diverse land uses for economic growth are replacing mangroves. Nguyen et al. [5] examined Vietnam's Kien Giang coast's peripheral mangrove extent and neighbouring land usage. The research examined mangrove size changes over time using four Landsat TM photos. The study shows that mangroves shrank by 2.7% from 1989 to 1992 and 2.1% annually from 2003 to 2006. From 1992 to 2003, mangrove size increased by 0.7% per year. According to the report, shrimp farms were the main driver of mangrove loss.

2.3 Effects of Rising Sea Levels

The increasing rate of sea level rise presents an added risk to the stability of blue carbon ecosystems. "Coastal squeeze" is a phenomenon attributed to rising sea levels, primarily impacting wetlands adjacent to steep terrain or developed beaches [6]; (Chmura 2013). A significant number of prominent urban centres across many nations are situated along coasts that were once inhabited by indigenous coastal ecosystems. Urban development along coastal areas restrict the inland expansion of wetlands, while the seaward boundary is anticipated to recede.

Salt marshes need help adapting to the changing environment caused by the rapid rise in sea levels and their relatively slow sediment accumulation rate. Therefore, the size of this environment will gradually decrease.

2.4 Natural and Artificial Disasters

Both natural and human-caused disasters can rapidly and significantly alter the blue carbon environment. Two significant events, the 2004 Indian Ocean tsunami [7] and the 2013 storm surge by Super Typhoon Haiyan (Primavera et al., 2016), demonstrate the devastating potential of natural processes. Large-scale oil spills caused by maritime accidents, like those in Panama in the 1980s, negatively impact affected ecosystems and coastal communities [8]. Cochard et al. [7] visually depicted the risks of event occurrence over time and its consequences for property and human life. The identified hazards can potentially cause immediate and long-term impacts on coastal ecosystems.

2.5 Coastal and Marine Carbon Sequestration

2.5.1 Mangroves

Mangrove forests provide food, energy, and habitats for diverse fauna, sediment, and carbon sequestration and sometimes help mitigate coastal erosion from tsunamis and tropical cyclones [9]. In the previous 50 years, nearly 50% of mangrove forests have been degraded despite their advantages to humans [10]. The economic worth of mangrove forests makes their decline significant. Urbanization, aquaculture, mining, and unsustainable wood, fish, crustacean, and shellfish exploitation are the main drivers of this impact. Mangroves economically outperformed coral reefs, continental shelves, and the open sea [11]. A growing coastal population and increased demand for non-wood forest products like small timber, fodder, and fuelwood are to blame for India's decline in mangrove ecosystems. Effective management and conservation are needed to meet local demands to conserve and responsibly use the ecosystem and forest resources. Mangrove-rich nations take steps to preserve and control their resources. Gujarat must restore its mangrove ecosystems via direct seeding, raised bed plantations, and fishbone channel plantings. The Andhra Pradesh Forest Department created Eco-development Committees and Van Samrakshan Samitis to collaborate on mangrove projects. Regular training sessions help preserve mangroves. Protection, restoration, regeneration, and management have been used to maintain Maharashtra's mangrove ecology and biodiversity. *Avicennia officinalis, Morindacitrifolia, Rhizophora mucronata, Sonneratia alba, Bruguiera cylindrica, Heritieralittoralis, Phoenix paludosa,* and *Ceriops tagal* are common Indian mangrove species. Mangrove woodlands produce carbon, like humid tropical forests. Mangroves have better below-to-above carbon mass ratios than terrestrial plants and allocate more carbon to belowground carbon. Large soil storage regions and decomposing root systems store most mangrove carbon. Mangroves are the most incredible carbon density biome, with 937 tC ha^{-1} effective carbon. Additionally, they boost sediment accretion rates to 5 mm annually and carbon burial to 174 $gC/m^2/yr$.

Additionally, these habitats promote fine particle buildup. The forest's worldwide carbon storage capacity is 1% (13.5 gt $year^{-1}$) from mangroves. Due to their closeness to the shore, coastal habitats contribute 14% to the global marine carbon cycle. Disruptions in mangrove carbon reserves may boost gas emissions significantly. Despite REDD+ and Blue Carbon uncertainties and hurdles, mangroves may be regenerated and restored [12]. Methodological issues restrict mangrove forest primary production assessment. The credible calculations of Duarte *et al.* [13] show that mangroves create more carbon than other primary producers in estuarine and marine environments.

Understanding mangroves long-term importance requires considering their carbon storage capability in mitigating climate change. Scientists increasingly believe that passive and active carbon dioxide storage and absorption technologies are needed to minimize greenhouse gas (GHG) emissions [14]. Mangrove carbon storage has often been overlooked, leading to overestimation and underestimation. This study aims to analyze mangroves carbon sequestration and worldwide effects impartially [15].

2.5.2 Seagrasses

Seagrasses are angiosperms that thrive in coastal environments with high salinity, displaying vigorous growth. These seagrasses are classified into four separate plant families: *Zosteraceae, Hydrocharitaceae, Posidoniaceae* and *Cymodoceaceae*. All of these families are categorized under the taxonomic order *Alismatales*. There are 58 species of seagrass, which fall into 12 other genera. These animals are present in all continent's coastal seas except Antarctica. Seagrass meadows have a low carbon content in their above-ground biomass.

However, many carbon resources are typically stored underground through long-lasting root systems, including below-ground biomass. Seagrass meadows develop sub-surface structures called "mattes" from their root systems, which play a crucial role in carbon storage. The seagrass meadow undergoes elevation increase near the water's surface due to the gradual accumulation of organic materials.

Seagrass meadows are being explored as a nature-based blue carbon sequestration method because they can lessen the impacts of climate change and offset carbon emissions while posing little danger. While seagrass carbon burial does not compensate for the carbon emissions caused by using fossil fuels in the past, it significantly contributes to reaching carbon neutrality in the present carbon cycle.

2.5.3 Macroalgae

Macroalgae dominate rocky shorelines and vegetated coastal ecosystems globally. These species occupy coastal locations on all continents, from the intertidal zone to depths with much less light than the surface [20,21]. By producing food, pharmaceuticals, and biofuels, macroalgae help coastal ecosystems. They also provide marine creatures with habitats, feeding grounds, and breeding grounds [22,23]. Macroscopic algae like pelagic sargassum may drift in open oceans and adhere to coastlines. Blue carbon macroalgae is currently debated [24]. According to multiple research [25,26,21,27], macroalgae are essential to marine carbon sequestration. Kruse-Jensen and Duarte (2016) estimate that the global net primary production is 1,826,561 TgC, with 199,820 TgC of carbon stored throughout 3.21 million square kilometres.

Table 1. Carbon sequestration by mangrove forests and coastal habitats worldwide

Habitat	Area (10^{12} m^2)	Sequestration rate ($gC\ m^{-2}\ year^{-1}$)	Global carbon sequestration ($Tg\ year^{-1}$)
Mangroves	0.14 (0.5%)	174	24 (14%)
Salt marshes	0.22 (0.8%)	150	33 (20%)
Seagrasses	0.3 (1.1%)	54	16 (10%)
Estuaries	1.1 (4.0%)	45	50 (30%)
Shelves	26 (93.6%)	17	44 (26%)
Total			167

Data source- (Matsu, [16]; Berger et al., [17]; Kennedy et al., [18]; Cai, [19]) Macroalgae like kelp prefer rocky or sandy grounds, unlike seagrasses, which limit carbon storage. The productive deep sea and surrounding seagrass meadows store organic carbon, benefiting these ecosystems [28-30]. Researchers have shown that macroalgal bloom bacteria and seagrass frond degradation reduce carbon storage in seagrasses [31]. Climate change will enhance green and golden macroalgal tides [32,33,34]. The complex relationship between seagrasses and macroalgae and its impact on carbon sequestration needs more investigation.

2.5.4 Microalgae

Marine conditions include coastal areas, open seas, equatorial and polar regions, surface waters, and the deep ocean containing microalgae. Microalgae collect and sequester carbon globally due to their wide dispersion. You must recognize that they can only absorb and retain so much carbon, particularly in oligotrophic marine habitats. Blue carbon plants and macroalgae sequester more carbon than microalgae (1.2%–2.4%). This supports a rapid carbon cycle due to herbivore grazing [27]. Gao et al. [35] and Schippers et al. [37] found that ocean warming and acidity may increase primary output. These factors may interact with other environmental variables and lower ocean primary production. Therefore, their combined impacts must be considered [35,37]. Gregg and Rousseaux [38] and Kulk et al. [39] reveal a drop in primary phytoplankton output over the previous several decades. This loss is projected at 0.8 PgC yearly, or 2.1% per decade. Warming and stratification may reduce nutrient availability, which is the main culprit. Ocean warming also boosts heterotrophic microbial activity, remineralizing fixed carbon. Cavan et al. [40] argue that this may reduce ocean carbon sequestration. Food enrichment increases organic carbon synthesis and decreases MCP activity. Jiao et al. [41] discovered that this might increase CO2 emissions and decrease DOC production. Thus, iron fertilization and other approaches to promote phytoplankton carbon sequestration need further effort. The intricacy of oceanic biological pumps, marine carbon pumps (MCP), and changing climates cause this phenomenon. Numerous studies have warned against geoengineering and ocean fertilization [42,43]. Large-scale microalgae cultures in open ponds or closed photobioreactor (PBR) systems may be able to store carbon because they proliferate in nutrient-rich environments [44,45]. This approach has little acceptance due to land acquisition and cultural issues.

2.5.6 Tidal salt marsh

A tidal salt marsh is a coastal ecological habitat in the upper intertidal zone between terrestrial land and saline or open salt water. This habitat frequently experiences tidal inundation. The ecosystem consists mainly of dense clusters of low shrubs, grasses, and herbaceous plants that can withstand high salinity levels. Salt marshes are intertidal ecosystems widely distributed in temperate areas and can be found along sheltered coastlines ranging from subarctic to tropical regions. In salt marshes, carbon is stored in anaerobic sediments, which prevents its breakdown and subsequent release of carbon dioxide into the atmosphere. Intertidal ecosystems, such as salt marshes, depend on sediment accumulation and elevation changes to mitigate the effects of rising sea levels. A positive correlation exists between the total carbon stock in salt marshes and the collection of anaerobic deposits beneath them. Bridgham, Megonigal, Keller *et al.* [46] state that methane is a greenhouse gas (GHG) with a potency 25 times higher than carbon dioxide. Freshwater marshes commonly exhibit this characteristic. Salt marshes have saline conditions that effectively inhibit natural methane production, significantly reducing methane emissions within these ecosystems.

2.5.7 Coral reefs

Coral reefs protect against storms and cyclones, reduce coastal erosion, and provide fish breeding and nursery grounds. Coral reefs contribute $100 million in ecological benefits worldwide. Climate change increases ocean temperatures and acidity, bleaching coral reefs. Climate change, natural catastrophes, and human activity quickly diminish coral reefs worldwide. The current theory is that coral reefs are carbon sources. Coral reef restoration is necessary because these ecosystems house creatures engaged in many carbon cycles. The intricate carbon transfer pathway in coral ecosystems has drawn scientific interest. Research is needed to establish coral reef carbon sources and sinks. Coral reefs are not carbon-budgeted. However, their impact on blue carbon, directly and indirectly, must be acknowledged.

2.6 Sandy Beaches and Dunes

The five major Andaman-Nicobar Islands are part of India's 8391 km coast. This coastal area borders 13 states and territories. The National Center for Coastal Research (2018) reports that 33% of the nation's coastline has eroded, losing 2156 km. The coastline has increased by 1941 km, or 29%. The reasons above raise worries about coastal ecosystems, emphasizing the need to restore them quickly. The effects of coastal dune vegetation on greenhouse gas concentrations have received less attention than its role in coastal protection, water purification, and enjoyment. Sandy beaches and dunes provide carbon sequestration, entertainment, and coastal defence on 33% of ice-free coasts globally. Wind, waves, sedimentary processes, and plant responses form dynamic interface ecosystems. By entrapping wind-driven sand, burial-tolerant plants like dune grasses help vegetate coastal dunes. Foredunes and beaches against wave overtopping and floods need dune grasses. Sand buildup and stability are facilitated over time. Foredunes reduce greenhouse gas emissions by sequestering carbon in their vegetation and sand. The role of dunes in coastal ecosystems is essential.

Sand-covered beaches and dunes defend against coastal storms and cyclones, decreasing climate change's impacts. Post-tsunami research shows that dunes are more effective natural defences than shelter belts and mangroves. Biological coastal defence systems must be improved rather than artificial interventions to manage the expected sea level increase successfully. These ecosystems collect and store atmospheric carbon dioxide, among other benefits. Coastal forests and dunes like Ipomoea, Spinifex, and Palmyra may store carbon in the sand as carbon sinks.

2.7 Ecological and Economic Aspects of Blue Carbon

Assessing carbon sequestration rates and long-term sustainability is crucial as Blue Carbon becomes increasingly important to researchers and politicians [24]. The SROCC does not adequately address the human-induced risks to preserving Blue Carbon reserves, which are the carbon stored in marine ecosystems. Recognizing and thoroughly evaluating the risks of maintaining carbon drawdown mechanisms is crucial to establishing a long-lasting and sustainable economy. Increased collaboration among governments, local communities, and the business sector is imperative. The IPCC is assumed to have examined and recorded the sensitivity of Blue Carbon habitats to human-caused changes and that these habitats have been accurately identified. These tools can help achieve sustainable goals, reduce economic and environmental burdens, and address the impacts of climate change.

2.8 Need to Conserve Coastal Ecosystems

Coastal development and land-use modification threaten mangroves, tidal salt marshes, seagrasses, coral reefs, sandy beaches, and dunes. Sediments are discharged into the air or water when vegetation is destroyed, and land is dredged or drained for profit. Mangrove tree removal for shrimp ponds, tidal marsh emptying for agriculture, and seagrass bed dredging are frequent coastal activities worldwide. Carbon combines with oxygen in the sediment, releasing carbon dioxide and other greenhouse gases (GHGs) into the atmosphere and ocean. These acts harm biodiversity, ecological services, and CO2 emissions. Conservation of mangrove forests, coral reefs, and seagrasses might aid global climate change efforts. Cyclone "Amphan" caused significant damage in eastern India, particularly West Bengal, in May 2020. Mangroves near the coast may have been protected to avoid losses.

Ocean conservation and climate protection might meet the Nationally Determined Contribution targets. This impoverished area has few major institutions with specialized skills and resources to collect essential information. Governments usually administer Ocean conservation, although its impacts may cross boundaries. A comprehensive literature analysis and stakeholder engagement underpin our approach to promoting carbon sequestration via maritime environmental protection.

3. CONCLUSION

The importance of protecting and restoring coastal ecosystems for addressing climate change and fulfilling global goals is growing. The world is interested in Blue Carbon's CO2 reduction potential. Blue carbon ecosystems facilitate and adapt to climate change, making them crucial to global response. India must engage with the UNFCCC to fulfill its NDCs and fight climate change. Nationally, promoting coastal habitats' carbon storage is vital. Beyond coastal regions, international, national, and state governments may use blue-carbon ecosystems to combat climate change and benefit the environment and economy. This may be done via cooperative policy measures. Carbon dioxide may be sequestered by millions of metric tons of mangrove forests. Thus, the Indian government must emphasize these efforts' preservation and growth. Preserving blue carbon habitats is crucial for long-term carbon sequestration and reducing land use change emissions. Data deficiencies must be addressed to determine Blue Carbon's Paris Agreement contribution. Sustainable development and human well-being benefit from marine and coastal ecosystem conservation. These ecosystems help humans adapt to global warming and reduce its impacts. Nationally Determined Contributions should emphasize coastal habitats in countries with vast coastlines.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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