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Unlocking Blue Carbon: Harnessing Coastal Ecosystems for Effective Climate Change Mitigation

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Blue carbon ecosystems, which include mangroves, tidal marshes, and seagrass meadows, play a crucial role in the global carbon cycle by acting as significant carbon sinks. These ecosystems are essential for mitigating climate change, especially as the world moves towards a low-carbon economy. This article provides an in-depth exploration of the mechanisms, potential, and challenges associated with blue carbon ecosystems. It also discusses the impacts of climate change on these ecosystems, evaluates current policies and measures aimed at their conservation and restoration, and highlights the need for international cooperation to protect these vital resources.

Introduction

The oceans are often referred to as the blue beating heart of our planet, serving as the largest natural carbon sink known. As the world transitions towards a low-carbon economy, the removal of atmospheric carbon dioxide through bio sequestration becomes increasingly critical to keep global warming below 2˚C (Sheikh *et al*., 2014). Among the most efficient systems for bio sequestration are the vegetated coastal habitats, commonly referred to as Blue Carbon Ecosystems (BCEs). Despite occupying only 0.2 per cent of the ocean surface, these ecosystems contribute to 50 per cent of the total carbon buried in marine sediments, with the capacity to accumulate carbon without reaching saturation and to store it in sediments over millennial timescales (Chmura *et al.* 2003).

Understanding Blue Carbon

The Intergovernmental Panel on Climate Change (IPCC) defines blue carbon as all biologically driven carbon fluxes and storage in marine systems that can be managed. The primary focus is on rooted vegetation in coastal zones, such as tidal marshes, mangroves, and seagrasses. These ecosystems have a high carbon burial rate per unit area and are capable of storing carbon in their soils and sediments. The carbon storage capacity in the soils of marine angiosperm habitats can reach up to 1000 tC/ha, far exceeding the storage potential of most terrestrial ecosystems (Nellemann and Corcoran, 2009).

The Role of Blue Carbon in Climate Change Mitigation

Climate change is the most pressing environmental issue of the 21st century, dominating international conferences, meetings, and agreements. Human activities have caused approximately 1°C of global warming since pre-industrial times, and this warming could exceed 1.5°C as early as 2030 (IPCC Special Report on 1.5°C). The impact of climate change on all living organisms is profound, necessitating the adoption of various mitigation strategies, such as afforestation, reforestation, and the development of renewable energy resources.

Blue carbon storage emerges as one of the most important strategies for mitigating climate change. The term "blue carbon" was coined to describe the disproportionately large contribution of coastal vegetated ecosystems to global carbon sequestration. The role of blue carbon in climate change mitigation and adaptation has gained international prominence, with a focus on understanding how climate change affects carbon accumulation in mature BCEs and during their restoration.

Major Components of Blue Carbon Ecosystems

Mangroves: Mangroves are tropical forests that grow at the land-sea interface and are frequently flooded by tidal water. These ecosystems are among the most carbon-rich, with an average annual carbon sequestration rate estimated between 6 and 8 Mg CO2e/ha, which is two to four times higher than that observed in mature tropical forests. Mangroves contribute significantly to carbon sequestration, and their degradation can lead to substantial carbon emissions. The importance of mangroves is particularly evident in countries like India, where regions such as Sundarbans, Mahanadi, and Krishna Godavari are rich in mangrove cover (Suresh *et al*., 2017).

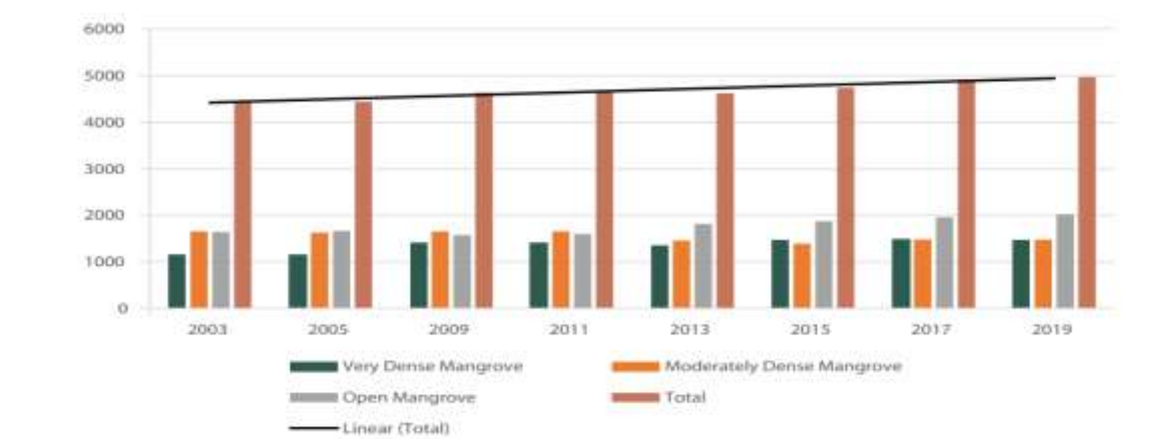

Fig. 1: Status of mangrove cover since 2003-2019 in India (FAO, 2020)

Table 1: Carbon stocks in mangrove forests of different states (Suresh *et al*., 2017).

States	Area (ha)	Biomass (Mt)			C Stocks (Mt)
		AGB	BGB	Total	
Andra Pradesh	35,200	2.46	0.64	3.10	1.55
Goa	2,200	0.154	0.040	0.194	0.097
Gujarat	1,08,500	7.41	1.92	9.34	4.67
Karnataka	300	0.021	0.005	0.026	0.013
Maharastra	18,600	1.30	0.33	1.64	0.821
Orissa	22,200	1.56	0.404	1.96	0.980
Tamilnadu	3,900	0.273	0.071	0.314	0.1722
West Bengal	21,500	15.10	3.92	19.03	9.51
Andaman &Nicobar	61,700	4.32	1.12	5.44	2.72
Pondicherry	100	0.007	0.001	0.008	0.004
Kerala	600	0.042	0.010	0.052	0.026
Daman & Diu	156	0.010	0.002	0.013	0.006
Grand Total	**4,66,256**	**32.68**	**8.49**	**41.18**	**20.59**

The estimated total biomass in mangrove forests in India was 41.2 million tons of which above ground biomass was 32.68 Mt and 8.49 Mt of belowground biomass. West Bengal with 19.03 Mt has high stocking of biomass followed by Gujarat (9.34 Mt) and Andaman & Nicobar Islands (5.44 Mt). Total carbon stock found to be – 20.59 (Suresh *et al.*, 2017).

- **Aboveground biomass (AGB) - AGB** = ρ*exp (–1.349+1.980*ln D) + 0.207*(ln)) ^2–0.0281(ln (D))^3). (Chave et al., 2005)
- **Belowground biomass (BGB)** = 26 per cent of the AGB. Fifty percent of biomass is assumed to be Carbon.

Seagrass Meadows: Seagrass meadows are essential coastal ecosystems that provide numerous ecosystem services, including carbon storage. Globally, seagrass ecosystems are declining at a rate of about 5 per cent per year due to anthropogenic stresses, which could lead to the release of large amounts of stored carbon. Restoration of seagrass meadows is crucial to re-establish lost carbon stores and sinks. These meadows cover only 0.1per cent of the world's ocean floor yet account for 10–18per cent of the total oceanic carbon burial, accumulating carbon at rates of 48 to 112 Tg C/yr. (Suresh *et al.*, 2017)

Salt Marshes: Tidal marshes, coastal wetlands with deep soils formed by the accumulation of mineral sediment and organic material, are critical for carbon sequestration. These ecosystems have an annual carbon sequestration rate of 6 to 8 Mg CO2e/ha, similar to mangroves. Tidal marshes provide critical habitat for marine species and act as buffers for coastal communities, absorbing energy from storms and preventing erosion. However, they are rapidly disappearing due to coastal development, agriculture, and rising sea levels. (Suresh *et al.*, 2017)

Global Distribution and Potential of Blue Carbon Ecosystems

Blue carbon ecosystems are distributed globally, with significant coverage in Asia, Central and South America, and North America. These ecosystems, although limited in area, have immense potential for carbon sequestration. Estimates suggest that BCEs could sequester up to 700 million tons of CO2 annually, which represents about 22 per cent of India's annual carbon emissions. However, the ongoing degradation and loss of these ecosystems threaten this potential (Christine Bertram *et al.*, 2021).

The global distribution of blue carbon ecosystems reveals that mangroves are most prevalent in Asia, Central, and South America, while seagrass meadows are widespread in North America and South Asia. Despite their importance, blue carbon ecosystems are among the most endangered on the planet, with annual losses ranging from 0.5 to 3per cent depending on the ecosystem type. (Christine Bertram *et al*., 2021)

Global Distribution of Blue Carbon (Christine Bertram *et al*., 2021)

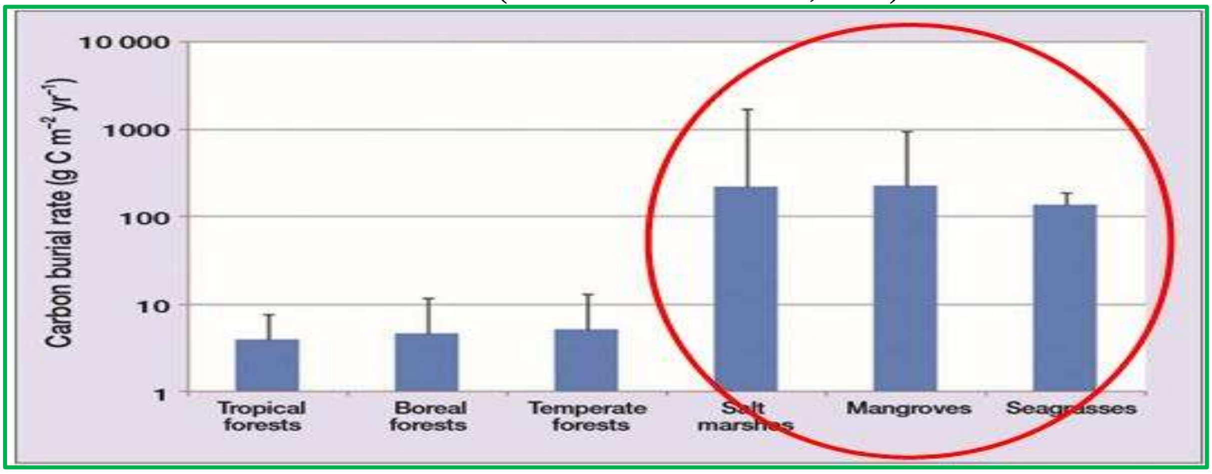

Fig. 2. Carbon burial rate in different ecosystems

Impact of Climate Change on Blue Carbon Ecosystems

Climate change has a profound impact on blue carbon ecosystems. Increased temperatures, rising sea levels, and extreme weather events can lead to increased plant mortality, shifts in species composition, and degradation of these ecosystems. For instance, seagrasses may experience altered growth rates and shifts in distribution due to temperature stress, while mangroves may see changes in species composition and a reduction in productivity. These changes not only reduce the ability of BCEs to sequester carbon but also result in the release of stored carbon, exacerbating global warming (Gilman *et al.*, 2008).

Challenges and Opportunities in Blue Carbon Conservation

Conservation Challenges: Despite their critical role in climate change mitigation, blue carbon ecosystems face numerous threats, primarily driven by human activities. Aquaculture, agriculture, mangrove forest exploitation, pollution, and coastal development are common drivers of BCE degradation. Climate change is expected to exacerbate these effects, leading to further loss of these vital ecosystems. Additionally, blue carbon is not directly addressed in international climate agreements like the Paris Agreement, which limits the scope of policy interventions. There is also a significant knowledge gap regarding the geographical extent and carbon sequestration capacity of these ecosystems.

Opportunities for Conservation: The conservation and restoration of blue carbon ecosystems offer significant opportunities for climate change mitigation. Policies and financial mechanisms, such as the Blue Carbon Initiative (BCI) and the Global Mangrove Alliance, are being developed to mobilize resources for the protection of BCEs. These initiatives aim to promote the sustainable management and restoration of coastal ecosystems through international cooperation. India has taken steps to protect its coastal ecosystems through the Coastal Regulation Zone (CRZ) and the Integrated Coastal Zone Management (ICZM) programs. These initiatives focus on conserving critical habitats, promoting sustainable development, and enhancing the resilience of coastal communities.

Economic Measures to Safeguard Blue Carbon Ecosystems: Economic instruments such as carbon taxes, fines, and emission trading systems (ETS) can play a crucial role in protecting blue carbon ecosystems. Carbon taxes or pricing mechanisms internalize the external costs of greenhouse gas emissions, encouraging polluters to adopt cleaner technologies. The ETS allows emitters to trade greenhouse gas permits, providing an economic incentive to reduce emissions. Results-based climate finance (RBCF) is another mechanism that rewards companies for achieving pre-determined climate-related targets, such as emission reductions. This approach can catalyze private sector investment in climate projects, including those focused on blue carbon conservation. The carbon market can be divided into two types: a mandatory carbon market and a voluntary carbon market, where the voluntary carbon market is a complement to the mandatory carbon market (Hua and Dong, 2019). The mandatory carbon market requires regulators to issue annual carbon quota to companies, which can be obtained through auctions or as free. If a company's annual carbon emissions exceed its quota, it must purchase the quota through the carbon market, and conversely, it can sell its excess quota. Among the various carbon trading mechanisms, carbon cap trading has become the focus of the current global carbon trading system. Scholars have also studied the impact of carbon cap trading on firms' green investments, emission reduction, and production decisions. However, with the growth of the carbon trading market, carbon allowances and emission rights have taken on financial attributes and become part of the firm assets, i.e., carbon assets (Zhang *et al.*, 2021). In 2016, with support from the Chinese government, carbon asset renting (CR) became a new type of carbon financial product in the carbon trading market. CR is a commercial activity based on carbon emissions trading that is used to reduce greenhouse gas emissions or increase carbon sink capacity. It is expected to help companies generate additional revenue and reduce financial burdens. It is worth emphasizing that there are relatively few existing studies on carbon asset renting.

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