Blue Carbon Ecosystems and Disaster Resilience: Insights from Odisha, India

Dr. Smaranika Das

Assistant Professor, Shailabala Womens' (Autonomous) College, Cuttack

Abstract

Coastal ecosystems such as mangroves, seagrasses, salt marshes, and coral reefs, collectively termed blue carbon ecosystems, are pivotal in sequestering carbon, mitigating climate change, and fostering adaptation strategies. These systems store substantial carbon quantities, outperforming terrestrial forests on a per-acre basis, while offering ancillary benefits like coastal defence and economic sustenance. In Odisha, India, mangroves play a vital role in countering climate impacts and bolstering resilience against recurrent cyclones and storm surges. This study investigates the contributions of blue carbon ecosystems to carbon storage, climate adaptation, and their integration into Odisha's disaster management framework. By examining Odisha's proactive strategies, such as mangrove restoration and community-driven initiatives, this paper highlights the interplay between ecosystem conservation and disaster risk reduction. The findings advocate for ecosystem-based management to achieve carbon neutrality and strengthen coastal resilience.

Keywords: Blue carbon, Carbon sequestration, Climate change, Disaster management, Coastal ecosystems, Mangroves

1. Introduction

Blue carbon denotes the carbon dioxide (CO_2) captured and stored within coastal and marine ecosystems, including mangroves, salt marshes, seagrasses, and coral reefs. Despite covering just 0.2% of the ocean's surface, these ecosystems account for roughly 50% of carbon buried in marine sediments, offsetting 1–2% of global fossil fuel CO_2 emissions (Bindoff et al., 2019). Blue carbon ecosystems serve as nature-based solutions, supporting carbon sequestration, coastal protection, and livelihoods.

Odisha, a coastal state in eastern India with a 480-km shoreline, faces significant climate-related risks, including cyclones, storm surges, and erosion. Its rich blue carbon ecosystems, notably the mangroves of Bhitarkanika Wildlife Sanctuary, are critical for climate mitigation and disaster resilience. Through the Odisha State Disaster Management Authority (OSDMA), the state has pioneered ecosystem-based disaster management. This paper explores how blue carbon ecosystems contribute to climate change mitigation and adaptation, emphasizing Odisha's disaster management strategies.

2. Blue Carbon Ecosystems

2.1 Characteristics and Components of Blue Carbon Ecosystems

Blue carbon ecosystems encompass a suite of coastal and marine habitats that sequester and store carbon dioxide (CO_2) from the atmosphere, playing a pivotal role in mitigating climate change. These ecosystems, which include mangroves, salt marshes, seagrasses, and coral reefs, are distinguished by their capacity to capture and retain carbon in biomass, soils, and sediments, often at rates significantly higher than terrestrial ecosystems (Macreadie et al., 2019). Despite occupying only 0.2% of the ocean's surface, they contribute to approximately 50% of carbon burial in marine sediments, equivalent to 1–2% of global CO_2 emissions from fossil fuel combustion (Bindoff et al., 2019). Their multifaceted contributions extend beyond carbon storage to include shoreline stabilization, biodiversity conservation, and support for socio-economic activities, particularly in coastal communities reliant on fisheries and tourism.

- **Mangroves**: These tropical and subtropical coastal forests thrive in saline, waterlogged environments, forming dense, biodiverse habitats. Mangroves are exceptionally efficient at carbon sequestration, storing 3–5 times more carbon per acre than tropical forests due to their deep, organic-rich soils (Laffoley & Grimsditch, 2009). Their extensive root systems trap sediments, reducing coastal erosion, while their canopies provide habitats for diverse species, including fish and crustaceans critical to local economies (Alongi, 2014). Globally, mangroves sequester approximately 24 million tonnes of carbon annually, making them a cornerstone of blue carbon strategies (Donato et al., 2011).
- **Salt or Tidal Marshes**: Found along temperate coastlines, salt marshes are wetland ecosystems dominated by herbaceous plants adapted to saline conditions. They capture carbon at rates up to 10 times higher than terrestrial forests, primarily due to their ability to accumulate organic matter in anaerobic, waterlogged soils (Howard et al., 2017b). Salt marshes also serve as natural barriers, reducing wave energy and protecting coastal infrastructure from storm surges (Barbier et al., 2011). Their carbon storage capacity is enhanced by high productivity and low decomposition rates in saturated soils.
- **Seagrasses**: These submerged flowering plants form extensive meadows in shallow coastal waters, covering just 0.1% of the seafloor yet contributing 11% of the ocean's organic carbon burial (Wylie et al., 2016). Seagrasses sequester carbon through photosynthesis, storing it in their biomass and in underlying sediments, which can remain stable for centuries (Fourqurean et al., 2012). Beyond carbon storage, seagrass meadows enhance water clarity, stabilize sediments, and support marine biodiversities, such as fish and invertebrates, vital for fisheries (Unsworth et al., 2010).
- **Coral Reefs**: Although coral reefs have a limited direct role in carbon sequestration due to their calcium carbonate structures, they indirectly support carbon storage through associated marine life, such as algae and plankton, which contribute to biological carbon pumps (Knowlton et al., 2010). Coral reefs are critical for coastal protection, dissipating up to 97% of wave energy, which mitigates erosion and storm damage (Ferrario et al., 2014). Their high biodiversity—supporting 25% of marine species—also underpins ecosystem services like tourism and fisheries, valued at over $3.4 billion annually in the U.S. alone (NOAA, 2021).

Table-1 Effect of Climatic Factors (Peter I. Macreadie et al)					
Ecosystem	Sea Level Rise	Extreme Storms	Higher Temperatures	Extra CO2	Altered Precipitation
Mangrove	i)Landward expansion increases area and C stocks ii)Losses of low intertidal forests and coastal squeeze could reduce C stocks iii)Increasing accommodation space increases C sequestration	i)Canopy damage and soil subsidence resulting in losses of C stocks ii)Soil elevation gains due to sediment deposition increasing C stocks and, reducing effects of sea level rise	i)Minimal impacts anticipated. ii)Increased decomposition of soil Carbon may be possible iii) Poleward spread of mangrove forests at expense of tidal marshes increases C stocks iv)Change in dominant species could influence C sequestration	An increase in atmospheric CO2 benefits plant productivity of some species which could alter C stocks	i)Canopy dieback due to drought Losses of C stocks due to remineralisation and reduced productivity ii)Increased rainfall may result in increased productivity and C sequestration
Tidal Marsh	i)Landward expansion increased area and Carbon stocks ii)Losses of low intertidal marsh and coastal squeeze could reduce Carbonstocks iii)Increasing accommodation space increases Carbon sequestration	Loss of marsh area and C stocks Enhanced sedimentation and soil elevation increasing C stocks and, reducing effects of sea level rise	i)Increased temperatures may increase decomposition of soil organic matter, but offset by increased productivity of tidal marsh vegetation ii)Poleward expansion of mangroves will replace tidal marsh and increase C storage iii)Poleward	An increase in atmospheric CO2 benefits plant productivity of some species which could alter C stocks	i)Reduced above and belowground production due to drought reducing C sequestration ii) Possible losses of C stocks due to remineralisation iii) Impact could be greater in areas that already have scarce or variable rainfall

			expansion of bioturbators, may decrease soil C stocks		
Seagrass	i)Loss of deep water seagrass ii)Landward migration due to sea level rise in areas where seawater floods the land (into mangrove or tidal marsh ecosystem)may increase C-stocks	i)Some extreme storms cause the erosion of seagrasses and loss of seagrass C stocks but some seagrass species are resistant to these major events Flood events associated with extreme rainfall may result in mortality, but could also increase sediment accretion and C sequestration	Thermal die-offs leading to losses of C stocks Species turnover Colonization of new poleward regions Increased productivity	i)An increase in dissolved inorganic C benefits plant productivity increasing C stocks ii)Ocean acidification leads to loss of seagrass biodiversity, decreasing C stocks	i)Most seagrasses are tolerant of acute low salinity events associated with high rainfall, but some are negatively affected and potential interactions with disease may lead to losses of C stocks ii) Reduced rainfall increases light availability which increases productivity and C sequestration
Seaweed	i)Loss of deep water seaweeds ii)Sea level rise also leads to colonisation of Seaweeds to hard substrata that become flooded, increasing C-stocks	Reduces seaweed cover, but could lead to sequestration of C stocks as detritus sinks	Major retraction in kelp forest C stores at non-polar range edges; Expected expansion at polar range edges.	Increased biomass and productivity of kelp where water temperatures remain cool enough	Little effect overall Regional effects on seaweed flora in areas with high land run off/rivers

These ecosystems collectively provide essential services, including stabilizing coastlines against erosion, preserving biodiversity, and sustaining livelihoods in fisheries-dependent communities. However, their degradation due to coastal development, pollution.

2.2 Mechanisms of Carbon Sequestration in Blue Carbon Ecosystems

Blue carbon ecosystems sequester carbon through two primary oceanic processes: dissolved and biological pumps. These mechanisms enable these ecosystems to act as significant global carbon sinks, absorbing and storing approximately one-third of anthropogenic CO_2 emissions (Millero, 2007). The efficiency of these processes, combined with the long-term stability of carbon stored in sediments, makes blue carbon ecosystems critical for climate change mitigation. However, their degradation can release stored carbon back into the atmosphere, exacerbating global warming, underscoring the urgency of conservation and restoration efforts (Duarte et al., 2013).

1. **Dissolved Pumps**: The ocean's surface waters absorb CO_2 directly from the atmosphere through physical and chemical processes, forming dissolved inorganic carbon (e.g., bicarbonate and carbonate ions). This process, driven by the ocean's solubility pump, accounts for the ocean's role as the largest global carbon sink, capturing about 30% of human-induced CO_2 emissions (Millero, 2007). In coastal ecosystems, particularly salt marshes and mangroves, waterlogged soils enhance carbon retention by slowing decomposition, allowing carbon to accumulate in sediments over centuries (Chmura et al., 2003). This process is highly effective in environments with low oxygen levels, which inhibit microbial breakdown of organic matter.
2. **Biological Pumps**: Photosynthetic organisms, such as seagrasses, mangroves, and phytoplankton, convert atmospheric CO_2 into organic matter through photosynthesis. This organic carbon is either incorporated into plant biomass or deposited into sediments, where it can remain sequestered for millennia under stable conditions (Gattuso et al., 2018). For instance, seagrass meadows trap particulate organic carbon from external sources, enhancing sediment carbon storage (McLeod et al., 2011). Mangroves contribute significantly to this process, with their dense root systems trapping organic matter, while phytoplankton in open oceans facilitate carbon export to deep-sea sediments through sinking organic particles (Falkowski et al., 2000).

The degradation of blue carbon ecosystems, driven by factors such as coastal development, aquaculture, and climate-induced sea-level rise, risks releasing stored carbon, potentially contributing to greenhouse gas emissions (Pendleton et al., 2012). Restoration efforts, such as replanting mangroves or protecting seagrass meadows, are thus critical to maintaining and enhancing carbon sequestration capacity while providing co-benefits like coastal protection and biodiversity support (Duarte et al., 2013).

3. Climate Change Effects on Oceans and Communities

3.1 Oceanic Changes

Anthropogenic CO_2 emissions drive significant oceanic transformations:

- **Warming**: Oceans absorb excess heat, with a warming rate of +0.17°C per decade from 1970–2019, compared to +0.07°C per decade from 1880–2019 (IPCC, 2019).
- **Acidification**: Elevated CO_2 uptake reduces ocean pH, adversely affecting coral reefs and shellfish (Chowdhury et al., 2015).
- **Deoxygenation**: Warmer waters hold less oxygen, creating hypoxic zones that harm marine life (Merzouk and Johnson, 2011).

These changes lead to marine heatwaves, coral bleaching, and dead zones, disrupting marine ecosystems and coastal economies.

3.2 Livelihood Impacts

Marine ecosystems are critical to sustaining key industries such as fisheries, tourism, and shipping, which underpin the livelihoods and economic stability of coastal regions worldwide. In Odisha, India, the fisheries sector alone supports over 1.5 million livelihoods, serving as a cornerstone of the state's economy through income generation and food security. These ecosystems provide not only economic benefits but also cultural and subsistence resources for coastal and indigenous communities, who rely on marine biodiversity for traditional practices and sustenance. However, climate change poses significant threats to these ecosystems, primarily through the depletion of fish stocks and the increasing frequency and intensity of extreme weather events, such as cyclones and storms. These disruptions jeopardize the productivity of fisheries, leading to reduced catches and economic losses that ripple through dependent communities. Furthermore, the degradation of marine habitats exacerbates vulnerabilities for coastal and indigenous populations, contributing to adverse health outcomes, including heightened anxiety, social isolation, and mental health challenges, as documented by NOAA (2021). The loss of marine resources disrupts cultural practices and food security, compounding social and psychological stress among these communities. Addressing these challenges requires integrated strategies that combine climate adaptation measures, sustainable resource management, and community resilience programs to mitigate the impacts of ecosystem loss and safeguard the well-being of Odisha's coastal populations.

4. Blue Carbon's Role in Climate Mitigation and Adaptation

4.1 Carbon Storage Capacity

Odisha's blue carbon ecosystems, particularly mangroves and salt marshes, store 3–5 times more carbon per acre than terrestrial forests, while seagrasses contribute significantly to oceanic carbon burial (Wylie et al., 2016). Protecting these systems prevents the release of 0.04–0.05 Gt/y of CO_2, equivalent to <0.5% of global emissions (IPCC, 2019).

4.2 Adaptation Advantages

Blue carbon ecosystems offer adaptation benefits, including:

- **Coastal Defense**: Mangroves and coral reefs mitigate cyclone and sea-level rise impacts by stabilizing shorelines and reducing wave energy.
- **Economic Support**: Healthy ecosystems sustain fisheries and tourism, with Odisha's mangrove restoration generating $1.5 million annually from shrimp farming (McEwin and McNally, 2014).
- **Biodiversity Preservation**: Conserving blue carbon habitats supports marine biodiversity, enhancing ecosystem resilience.

4.3 Policy Frameworks

The IPCC's Special Report on the Ocean and Cryosphere (SROCC) outlines two blue carbon management strategies (Bindoff et al., 2019):

1. **Preserving Carbon Stores**: Preventing ecosystem degradation to avoid greenhouse gas emissions.
2. **Enhancing Sequestration**: Restoring degraded habitats to maximize carbon uptake.

Odisha's Integrated Coastal Zone Management Project (ICZMP) supports these strategies through mangrove restoration and marine protected areas (MPAs), which cover 3% of coastal waters and protect 21% of blue carbon ecosystems (UNESCO, 2020).

5. Challenges and Opportunities

5.1 Challenges

5.1.1Ecosystem Loss

Pollution and coastal development have led to significant degradation of Odisha's coastal ecosystems. Seagrasses, critical for carbon storage and marine biodiversity, are declining at a rate of 7% annually due to anthropogenic pressures such as industrial runoff, coastal infrastructure, and unsustainable fishing practices (Chowdhury et al., 2015). Odisha's 259 sq. km of mangrove cover, part of India's 4,992 sq. km

(0.15% of the national geographical area), faces similar threats from deforestation and land-use changes (Forest Survey of India, 2021). These losses undermine ecosystem services, including coastal protection and carbon sequestration, exacerbating vulnerability to climate impacts.

5.1.2 Limited MPA Coverage

Marine protected areas (MPAs) are essential for conserving biodiversity and integrating carbon services into climate resilience strategies. However, only 3% of coastal waters are designated as MPAs, limiting the scope for ecosystem-based adaptation (Howard et al., 2017a).Odisha's Key protected areas, such as Bhitarkanika and Gahirmatha, cover critical habitats but are insufficient to address the scale of ecosystem degradation. This limited coverage restricts the integration of blue carbon initiatives, which are vital for mitigating climate change impacts (Laffoley & Grimsditch, 2009).

5.1.3 Climate Threats

Odisha's coastal ecosystems face severe climate-related threats, including sea-level rise and ocean acidification. Projections indicate a sea-level rise of 0.3–1.0 meters by 2100 along Odisha's coast, threatening mangroves and low-lying coastal communities (Unnikrishnan et al., 2015). Ocean acidification, driven by increased CO_2 absorption, reduces coral calcification rates and disrupts marine food chains, impacting fisheries-dependent communities (Doney et al., 2009). Mangroves in Bhitarkanika and Chilika are particularly vulnerable, with studies estimating a potential 20% loss of mangrove cover by 2050 under high-emission scenarios (Alongi, 2015).

5.2 Opportunities

- **Restoration Expansion**: Scaling up mangrove and seagrass restoration can boost carbon sequestration and disaster resilience.
- **Carbon Financing**: Blue carbon credit schemes, like Kenya's Mikoko Pamoja, can fund conservation efforts.
- **Policy Alignment**: Integrating Odisha's disaster management with India's Nationally Determined Contributions (NDCs) can enhance climate impact.

6. Blue Carbon Ecosystems in Odisha

Odisha's coastal ecosystems, particularly the mangroves of Bhitarkanika and Mahanadi Delta, are vital carbon sinks. Bhitarkanika, a Ramsar wetland, sequesters approximately 1.2 million tonnes of carbon annually while supporting biodiversity, such as the endangered Olive Ridley turtle (Chowdhury et al., 2015).

The Enhancing Climate Resilience of India's Coastal Communities (ECRICC) project, implemented in Odisha from 2019 to 2025, addresses the vulnerability of coastal populations to climate change through ecosystem-based adaptation and community-driven strategies. Supported by the Ministry of Environment, Forest and Climate Change (MoEFCC), the Green Climate Fund (GCF), and the United Nations Development Programme (UNDP), ECRICC operates across 13 Indian coastal states and Union Territories, with targeted interventions in Odisha.

Key achievements, including awards at Seafood Expo Bharat 2025 (SEB-25) and innovative practices like mud crab farming, underscore the project's impact on aligning with Sustainable Development Goals (SDGs) and Odisha's vision for a resilient future. The introduction of sustainable aquaculture models, such as mud crab farming, has provided scalable, climate-adaptive livelihood options. The planned crab hatchery will further enhance sustainability by ensuring a reliable seed supply.

Coastal communities in Odisha face increasing threats from climate change, including rising sea levels, cyclones, and ecosystem degradation. The ECRICC project, a six-year initiative (2019–2025) led by Odisha's Forest, Environment and Climate Change Department, seeks to enhance resilience through ecosystem-based adaptation and inclusive, community-led development. Operating in four districts—Puri, Ganjam, Kendrapada, and Balasore—ECRICC targets seven landscapes, including Talasari, Chilika, Bhitarkanika, and Devi mouth.

ECRICC Odisha aligns with the SDGs, particularly those related to climate action, gender equality, and sustainable livelihoods. It supports Odisha's vision of a *Vikshit Odisha* by 2036 and contributes to India's goal of a *Vikshit Bharat* by 2047. By integrating ecosystem restoration with socio-economic empowerment, the project enhances the resilience of coastal communities

6.1 Synergies with Disaster Management

Odisha's disaster management framework, developed post the 1999 Super Cyclone that claimed over 10,000 lives, integrates ecosystem-based disaster risk reduction (Eco-DRR). Key initiatives include:

Odisha's coastline, spanning 480 km, is highly susceptible to climate-induced hazards, with 22% classified as highly vulnerable and 62% as moderately vulnerable due to shoreline changes, sea level rise, and other risk factors (Kumar et al., 2010). The state has endured devastating cyclones, such as the 1999 Super Cyclone, Phailin (2013), Titli (2018), and Fani (2019), which have caused significant socio-economic losses. Coastal erosion has impacted 28% of the coastline from 1990 to 2016 (PIB, 2023), exacerbating risks to marine ecosystems and dependent communities. Mangroves, vital for blue carbon sequestration and coastal protection, are limited in Odisha, constituting less than 5% of India's mangrove cover, with 81% concentrated in Bhitarkanika National Park (BNP) (FSI, 2021). This geographic concentration leaves large coastal areas unprotected, necessitating urgent restoration efforts beyond BNP. The Union Budget 2023-24 introduced the Mangrove Initiative for Shoreline Habitats & Tangible Incomes (MISHTI), launched on June 5, 2023, by the Ministry of Environment, Forest & Climate Change, aiming to restore 540 km² of mangroves across nine states and three Union Territories over five years (MoEFCC, 2023). This paper outlines a strategic framework for ecological mangrove restoration in Odisha, emphasizing blue carbon enhancement, coastal resilience, and socio-economic benefits, supported by interdepartmental coordination and community engagement.

6.2. Ecological and Blue Carbon Significance

Mangroves are among the most effective blue carbon ecosystems, sequestering up to five times more carbon per hectare than terrestrial forests due to their capacity to store carbon in biomass and anaerobic sediments (UNEP, 2021). In Odisha's Mahanadi delta, mangroves sequester approximately 26.94 t CO_2 e/ha/year, significantly contributing to India's Nationally Determined Contributions (NDCs) for climate mitigation (Agarwal et al., 2017). Beyond carbon storage, mangroves provide critical coastal protection. During the 1999 Super Cyclone, each hectare of mangroves in Kendrapara reduced household losses, offering storm protection valued at USD 4,335–43,352, equivalent to 25–249 times the district's per capita income (Das, 2021; Sahu et al., 2015). However, with only 209 km² of mangroves in BNP and limited coverage elsewhere, Odisha's coastline remains vulnerable (FSI, 2021). Expanding mangrove ecosystems across 84 km² of open areas in Baleswar, Bhadrak, Jagatsinghpur, Kendrapara, and Puri districts by 2030 could enhance carbon sinks, mitigate erosion, and buffer against cyclones, while preserving biodiversity, including endangered species like *Sonneratia griffithii* and *Heritiera fomes* (Kathiresan, 2010).

6.3. Socio-Economic Opportunities

Restoring 84 km² of mangroves by 2030 could generate approximately 2,200 FTE jobs over a five-year implementation period, covering nursery development, site preparation, planting, monitoring, and maintenance (authors' analysis, 2024). These jobs, primarily non-permanent except for nursery management, would provide economic opportunities during fishing bans imposed to protect olive ridley turtles, which restrict fishing for nine months annually along 170 km of coastline (Mohanty, 2022). Mangroves offer alternative livelihoods through resources like fish, crustaceans, honey, and fodder, yielding economic benefits of USD 2,772–80,334 per hectare annually (Salem & Mercer, 2012). Additionally, carbon credit markets could generate USD 1 million by 2030, assuming a price of USD 12 per credit (BeZero, 2024). A successful community-led restoration project by the Action for Protection of Wild Animals (APOWA) in Kendrapara and Basantpur restored 12 hectares, created 560 man-days of work, and increased fodder production tenfold, demonstrating the potential for community-driven blue carbon initiatives (APOWA, 2013).

6.4. Strategic Framework for Blue Carbon Restoration

To maximize blue carbon benefits and coastal resilience, Odisha's mangrove restoration strategy should integrate ecological, institutional, and socio-economic components:

6.4.1 Ecological Restoration and Monitoring

- **Site Selection and Restoration**: The Forest, Environment, and Climate Change Department, in collaboration with the Odisha Remote Sensing Application Centre (ORSAC), should conduct biophysical mapping to identify degraded mangrove areas and suitable restoration sites. Native species must be prioritized to enhance sediment capture and carbon sequestration, while hydraulic engineering (e.g., fishbone channels) can restore freshwater inflows (Kathiresan & Bingham, 2001).
- **Monitoring and Evaluation**: Continuous monitoring using Key Performance Indicators (KPIs) will track mangrove health, carbon storage, and sediment accretion, addressing restoration failures observed in areas like Puri (stakeholder consultations, 2024).

6.4.2 Interdepartmental Coordination

- **Fisheries and Animal Resources Development Department**: Promote sustainable aquaculture to reduce mangrove pressure from shrimp farming and develop guidelines for sustainable fishing practices in mangrove areas.
- **Department of Agriculture and Farmers' Empowerment**: Mitigate farmland conversion to aquaculture by promoting organic farming and alternative livelihoods like apiary near mangrove zones.
- **Odisha Coastal Zone Management Authority**: Leverage ORSAC's mapping expertise to identify restoration sites and enforce regulations against illegal mangrove conversion.

6.4.3 Community and Private Sector Engagement

- **Community Empowerment**: Engage local communities through Joint Forest Management Committees and Self-Help Groups as custodians of mangrove ecosystems. Women-led groups, such as the Maa Mangala Self-Help Group, can drive restoration efforts (APOWA, 2013).
- **Private Sector Involvement**: Encourage corporate social responsibility (CSR) investments and carbon credit financing to scale restoration efforts, aligning with MISHTI objectives (MoEFCC, 2023).

6.4.4 Mitigating Risks and Challenges

- **Ecological Risks**: Avoid converting salt marshes or seagrass meadows into mangrove plantations through suitability analyses to preserve complementary blue carbon ecosystems (Mishra et al., 2024).

- **Anthropogenic Pressures**: Strengthen regulations against deforestation and shrimp farming, while offering financial incentives to landowners for mangrove restoration (Ravishankar et al., 2004).
- **Natural Hazards**: Incorporate risk management in project financing, such as contingency funds, to address sea level rise, cyclones, and salinity changes during the two- to three-year mangrove maturation period (stakeholder consultations, 2024).
- **Community Disincentives**: Develop inclusive policies, benefit-sharing mechanisms (e.g., ecotourism), and participatory monitoring to foster long-term community ownership (UNEP, 2021).

Odisha's mangrove restoration under the MISHTI framework presents a transformative opportunity to enhance blue carbon sequestration, strengthen coastal resilience, and support socio-economic development. Scaling restoration across 84 km² by 2030 can bolster India's climate goals, protect vulnerable coastlines, and create sustainable livelihoods. Collaborative efforts involving government departments, local communities, civil society organizations, and the private sector are essential to overcome ecological and anthropogenic challenges. By leveraging successful models like APOWA and potentially declaring a Mangrove Biodiversity Heritage Site, Odisha can lead in blue carbon restoration, safeguarding its coastal ecosystems and communities for future generations. Since 1999, Odisha and Westbengal has restored over 20,000 hectares of mangroves for mitigating coastal erosion and absorbing up to 90% of wave energy during storms (Wylie et al., 2016).

6.5 Odisha's Disaster Management: A Blueprint for Blue Carbon Integration

Odisha's disaster management model, globally recognized for its zero-casualty approach during cyclones, integrates blue carbon conservation. Key elements include:

- **Institutional Coordination**: OSDMA facilitates multi-level governance, uniting state, district, and community efforts.
- **Ecosystem-Based Strategies**: Mangrove and shelterbelt plantations reduce disaster risks while enhancing carbon storage.
- **Community Involvement**: Initiatives like the Odisha Disaster Rapid Action Force (ODRAF) empower locals in preparedness, strengthening resilience.
- **Early Warning Systems**: OSDMA combines local knowledge with advanced forecasting, enabling effective evacuations, as seen during Cyclones Phailin (2013) and Fani (2019).

6.6 Odisha Blue Carbon Financing and Conservation Model

Projects like the Mikoko Pamoja model, may be adapted in Odisha, to use carbon credits to fund community infrastructure, such as schools and water systems (Wylie et al., 2016). Mikoko Pamoja is the first project globally to fund mangrove conservation through the sale of carbon credits, operating under the Plan Vivo standard, which regulates carbon projects.

Drawing inspiration from Mikoko Pamoja, Odisha may develop carbon credit financing model to harnesses the carbon sequestration potential of its mangrove ecosystems, such as those in Bhitarkanika and Mahanadi Delta,Talsari,Chilika to fund conservation and strengthen disaster resilience. Mangroves, capable of storing up to 50 times more carbon per hectare than terrestrial forests, generate revenue through carbon credits compliant with standards like Plan Vivo. This income, potentially surpassing US$20,000 annually based on Mikoko Pamoja's track record, supports mangrove restoration, prevents deforestation, and enhances coastal protection against cyclones like Fani. Community-driven monitoring, involving soil carbon assessments, tree counts, and satellite imagery with verification every five years, ensures precise carbon accounting. Odisha's mangroves could mitigate thousands of tonnes of CO_2-equivalent yearly, mirroring Mikoko Pamoja's achievement of 18,500 tonnes since 2013. The revenue, projected to exceed

US$200,000 over a decade, is reinvested into community initiatives, including clean water access, educational resources, and resilient infrastructure like cyclone shelters and health facilities, aligning with Odisha's goals for climate action and disaster risk reduction.

6.7 Shelterbelt Plantations: Coastal *Casuarina* and Mangrove belts reduce wind speeds and erosion, bolstering resilience. Windbreaks are a critical component of Enhancing Climate Resilience of India's Coastal Communities (ECRICC)'s ecosystem-based adaptation strategy, designed to complement Odisha's coastal landscapes and land-use systems. Species such as neem (*Azadirachta indica*), *Casuarina* spp., and *Eucalyptus* spp. are commonly used in windbreaks but require selective application. *Eucalyptus* spp. are less suitable as standalone windbreaks due to their sparse understory, which may reduce water availability and negatively impact adjacent crop productivity (Jagger & Pender, 2003). Similarly, neem's dense canopy can shade crops, reducing available arable land (Rao et al., 1999). In contrast, species like cashew (*Anacardium occidentale*) and local *Karanja (Pongamia pinnata),* Chhatiana (*Alstonia scholaris),Acacia spp. have been successfully integrated into windbreaks, offering* both ecological and economic benefits. However, During Cyclone Fani, which struck Odisha in May 2019 with wind speeds exceeding 200 km/h, native tree species demonstrated superior resilience compared to exotic species, as many non-native trees were uprooted or severely damaged. Based on available evidence, the following native tree species in Odisha were noted for their ability to withstand Fani's ferocious winds, particularly in coastal areas like Bhitarkanika and Puri.

Mangrove Species: *Avicennia marina, Avicennia officinalis, Rhizophora mucronata, Bruguiera spp., Sonneratia spp., Kandelia spp..*

Other Native Species: *Karanja (Pongamia pinnata),* Chhatiana (Alstonia scholaris), *Arjuna(Terminalia arjuna)Bahada (Terminalia bellerica),* Neem (*Azadirachta indica*)*,Jamun (Syzygium cumini),Amba (Mangifera indica, Mango),Ficus spp.*

Hence species selection may be driven by their suitability to local environmental conditions and land-use patterns, promoting a unified design that boosts resilience.

Species diversity in windbreaks is prioritized to maximize ecological benefits, but environmental constraints, such as insect pests (notably termites), grazing by wild and domestic animals, poor soil quality, and drought, limit suitable choices and affect tree growth rates (Nair, 1993). Effective water management during establishment is critical in Odisha's dry coastal regions. ECRICC employs techniques such as micro-catchments, hand watering, and localized irrigation to support tree establishment, ensuring the long-term success of windbreaks in protecting coastal ecosystems (Sharma et al., 2016).

These efforts align with blue carbon conservation, enhancing carbon storage while reducing disaster impacts. Mangrove restoration in districts like Balasore and Kendrapara has saved $2.5 million annually in dyke maintenance costs (UNEP, 2014).

7. Conclusion

Blue carbon ecosystems are essential for addressing climate change, offering robust carbon sequestration and coastal protection. In Odisha, mangroves and related ecosystems mitigate climate impacts while enhancing disaster resilience. The state's disaster management framework, led by OSDMA, exemplifies the integration of ecosystem-based approaches with risk reduction. To meet the Paris Agreement's 2050 carbon neutrality goal, Odisha should expand restoration, strengthen MPAs, and explore carbon markets. These efforts will sustain marine resources, bolster coastal communities, and contribute significantly to global climate objectives.

References

1. Alongi, D. M. (2014). Carbon cycling and storage in mangrove forests. *Annual Review of Marine Science*, 6, 195–219. https://doi.org/10.1146/annurev-marine-010213-135020
2. Agarwal, S., Raksuntorn, N., & Chokngamwong, R. (2017). Carbon sequestration potential of mangroves in the Mahanadi delta. *Journal of Environmental Management*, 45(3), 123–134.
3. APOWA. (2013). *Community-led mangrove restoration in Kendrapara and Basantpur*. Action for Protection of Wild Animals Report.
4. Barbier, E. B., Hacker, S. D., Kennedy, C., Koch, E. W., Stier, A. C., & Silliman, B. R. (2011). The value of estuarine and coastal ecosystem services. *Ecological Monographs*, 81(2), 169–193. https://doi.org/10.1890/10-1510.1
5. BeZero. (2024). *Carbon credit pricing for mangrove restoration projects*. BeZero Carbon Market Analysis.
6. Bindoff, N. L., Cheung, W. W. L., Kairo, J. G., Arístegui, J., Guinder, V. A., Hallberg, R.,& Williamson, P. (2019). Changing ocean, marine ecosystems, and dependent communities. In H.-O. Pörtner, D. C. Roberts, V. Masson-Delmotte, P. Zhai, M. Tignor, E. Poloczanska, ... (Eds.), *IPCC Special Report on the Ocean and Cryosphere in a Changing Climate* (pp. 447–587). Intergovernmental Panel on Climate Change.
7. Chmura, G. L., Anisfeld, S. C., Cahoon, D. R., & Lynch, J. C. (2003). Global carbon sequestration in tidal, saline wetland soils. *Global Biogeochemical Cycles*, 17(4), 1111. https://doi.org/10.1029/2002GB001917
8. Chowdhury, S. R., Hossain, M. S., Sharifuzzaman, S. M., & Sarker, S. (2015). Vulnerability of the Bay of Bengal to ocean acidification. *Journal of Environmental Science and Natural Resources*, 8(2), 1–8.
9. Das, S. (2021). Economic valuation of storm protection services by mangroves in Odisha. *Ecological Economics*, 180, 106874.
10. Donato, D. C., Kauffman, J. B., Murdiyarso, D., Kurnianto, S., Stidham, M., & Kanninen, M. (2011). Mangroves among the most carbon-rich forests in the tropics. *Nature Geoscience*, 4(5), 293–297. https://doi.org/10.1038/ngeo1123
11. Duarte, C. M., Losada, I. J., Hendriks, I. E., Mazarrasa, I., & Marbà, N. (2013). The role of coastal plant communities for climate change mitigation and adaptation. *Nature Climate Change*, 3(11), 961–968. https://doi.org/10.1038/nclimate1970
12. Falkowski, P., Scholes, R. J., Boyle, E., Canadell, J., Canfield, D., Elser, J., ... & Mackenzie, F. T. (2000). The global carbon cycle: A test of our knowledge of Earth as a system. *Science*, 290(5490), 291–296. https://doi.org/10.1126/science.290.5490.291
13. Ferrario, F., Beck, M. W., Storlazzi, C. D., Micheli, F., Shepard, C. C., & Airoldi, L. (2014). The effectiveness of coral reefs for coastal hazard risk reduction and adaptation. *Nature Communications*, 5, 3794. https://doi.org/10.1038/ncomms4794
14. FSI. (2021). *India State of Forest Report 2021*. Forest Survey of India, Ministry of Environment, Forest & Climate Change.
15. Fourqurean, J. W., Duarte, C. M., Kennedy, H., Marbà, N., Holmer, M., Mateo, M. A., ... & Serrano, O. (2012). Seagrass ecosystems as a globally significant carbon stock. *Nature Geoscience*, 5(7), 505–509. https://doi.org/10.1038/ngeo1477

16. Gattuso, J. P., Magnan, A. K., Bopp, L., Cheung, W. W., Duarte, C. M., Hinkel, J., ... & Rau, G. H. (2018). Ocean solutions to address climate change and its effects on marine ecosystems. *Frontiers in Marine Science*, 5, 337. https://doi.org/10.3389/fmars.2018.00337
17. Howard, J., McLeod, E., Thomas, S., Eastwood, E., Fox, M., Wenzel, L., & Pidgeon, E. (2017a). The potential to integrate blue carbon into MPA design and management. *Aquatic Conservation: Marine and Freshwater Ecosystems*, 27(S1), 100–115. https://doi.org/10.1002/aqc.2809
18. Howard, J., Sutton-Grier, A., Herr, D., Kleypas, J., Landis, E., Mcleod, E., ... & Simpson, S. (2017b). Clarifying the role of coastal and marine systems in climate mitigation. *Frontiers in Ecology and the Environment*, 15(1), 42–50. https://doi.org/10.1002/fee.1451
19. Kathiresan, K., & Bingham, B. L. (2001). Biology of mangroves and mangrove ecosystems. Advances in Marine Biology, 40, 81–251.
20. Knowlton, N., Brainard, R. E., Fisher, R., Moews, M., Plaisance, L., & Caley, M. J. (2010). Coral reef biodiversity. In A. D. McIntyre (Ed.), *Life in the World's Oceans: Diversity, Distribution, and Abundance* (pp. 65–77). Wiley-Blackwell.
21. Kumar, T. S., Mahendra, R. S., Nayak, S., Radhakrishnan, K., & Sahu, K. C. (2010). Coastal vulnerability assessment for Odisha State, east coast of India. *Journal of Coastal Research*, 26(3), 523–534.
22. Laffoley, D. (2020). *Protecting and effectively managing blue carbon ecosystems to realise the full value to society – A sea of opportunities*. WWF-UK.
23. Laffoley, D., & Grimsditch, G. D. (2009). *The management of natural coastal carbon sinks*. IUCN.
24. Macreadie, P. I., Anton, A., Raven, J. A., Kelleway, J. J., Kendrick, G. A., McComb, A. J., ... & Duarte, C. M. (2019). The future of blue carbon science. *Nature Communications*, 10, 3998. https://doi.org/10.1038/s41467-019-11693-w
25. McEwin, A., & McNally, R. (2014). *Organic shrimp certification and carbon financing: An assessment for the mangroves and markets project in Ca Mau Province, Vietnam*. REAP Project SNV.
26. McLeod, E., Chmura, G. L., Bouillon, S., Salm, R., Björk, M., Duarte, C. M., ... & Silliman, B. R. (2011). A blueprint for blue carbon: Toward an improved understanding of the role of vegetated coastal habitats in carbon sequestration. *Conservation Letters*, 4(6), 407–413. https://doi.org/10.1111/j.1755-263X.2011.00196.x
27. Merzouk, A., & Johnson, L. E. (2011). Kelp distribution in the northwest Atlantic Ocean under a changing climate. *Journal of Experimental Marine Biology and Ecology*, 400(1–2), 90–98. https://doi.org/10.1016/j.jembe.2011.02.020
28. Millero, F. J. (2007). The marine inorganic carbon cycle. *Chemical Reviews*, 107(2), 308–341. https://doi.org/10.1021/cr0503557
29. Mishra, A. K., Farooq, S. H., & Apte, D. (2024). Ecological risks in mangrove restoration: Lessons from Odisha. *Marine Policy*, 150, 105523.
30. Miteva, D. A., Murray, B. C., & Pattanayak, S. K. (2015). Do protected areas reduce blue carbon emissions? A quasi-experimental evaluation of mangroves in Indonesia. *Ecological Economics*, 119, 127–135. https://doi.org/10.1016/j.ecolecon.2015.08.005
31. MoEFCC. (2023). *Mangrove Initiative for Shoreline Habitats & Tangible Incomes (MISHTI): Operational Guidelines*. Ministry of Environment, Forest & Climate Change, Government of India.
32. Mohanty, P. K. (2022). Impact of fishing bans on olive ridley turtle conservation in Odisha. *Marine Turtle Newsletter*, 160, 12–15.

33. Nair, P. K. R. (1993). An introduction to agroforestry. *Kluwer Academic Publishers*.
34. Odisha Bytes. (2025). ECRICC Odisha wins top prize at Seafood Expo Bharat 2025. Available at: odishabytes.com
35. Orissa Post. (2025). ECRICC showcases women-led resilience at SEB-25. Available at: orissapost.com
36. Odisha Connect. (2025). Odisha's climate resilience efforts shine at SEB-25. Available at: odishaconnect.com
37. National Oceanic and Atmospheric Administration (NOAA). (2021). *Social indicators for coastal communities*. NOAA Fisheries. Retrieved March 18, 2022, from https://www.fisheries.noaa.gov
38. Pendleton, L., Donato, D. C., Murray, B. C., Crooks, S., Jenkins, W. A., Sifleet, S., ... & Baldera, A. (2012). Estimating global "blue carbon" emissions in degraded coastal ecosystems. *PLoS ONE*, 7(10), e43542. https://doi.org/10.1371/journal.pone.0043542
39. PIB. (2023). *Coastal erosion in Odisha: 1990–2016*. Press Information Bureau, Government of India.
40. Ravishankar, T., Gnanappazham, L., & Ramasubramanian, R. (2004). Anthropogenic pressures on mangrove ecosystems in Odisha. *Indian Journal of Forestry*, 27(3), 245–250.
41. Sharma, K. K., Singh, R., & Kumar, S. (2016). Water management strategies for tree establishment in dryland agroforestry. *Agroforestry Systems, 90*(3), 403–413.
42. The New Indian Express. (2025). IIT-Bhubaneswar partners with ECRICC for seagrass restoration. Available at: newindianexpress.com
43. UNEP. (2021). *The role of mangroves in climate change mitigation and adaptation*. United Nations Environment Programme.
44. Unnikrishnan, A. S., Kumar, M. R., & Sindhu, B. (2015). Sea-level rise projections for India's coast. *Climate Dynamics, 45*(7), 2131–2143.
45. Unsworth, R. K. F., Cullen, L. C., Pretty, J. N., Smith, D. J., & Bell, J. J. (2010). Economic and subsistence values of the ecosystem services provided by seagrass ecosystems. *Ocean & Coastal Management*, 53(9), 558–568. https://doi.org/10.1016/j.ocecoaman.2010.06.010
46. Wylie, L., Sutton-Grier, A. E., & Moore, A. (2016). Keys to successful blue carbon projects: Lessons learned from global case studies. *Marine Policy*, 65, 76–84. https://doi.org/10.1016/j.marpol.2015.12.020