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Review Article

Mangrove restoration and blue carbon potential in Odisha: Bridging ecosystem services with climate resilience

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Abstract: Mangrove ecosystems along Odisha's coastline act as frontline defenses against climate volatility, shielding communities and supporting rich biodiversity. This study synthesizes 25 years of research (2000–2025) and employs the InVEST model to assess ecological restoration outcomes, including carbon capture, water quality gains, and future climate risks. Field data indicate sequestration rates of 7.3–10.9 tonnes of carbon per hectare annually. Projections reveal that, by 2030, optimized restoration could add 1.55 million tonnes of carbon (5.7 Mt CO_2), while ongoing degradation risks re-releasing over 2 million tonnes. Scenario modeling to 2050 highlights resilience thresholds: moderate emissions support net uptake (+0.85 Tg C), whereas high-emission pathways reverse the trend (–0.45 Tg C). Restoration practices also reduce sediment runoff by 25 % and nutrient loading by 8 %, improving coastal water quality. Cyclone-buffering valuation in Kendrapara estimates avoided damages between USD 4,335–43,352 per hectare. Governance analysis uncovers fragmented institutional roles as a barrier, while women-led Village Mangrove Councils improve sapling survival by 30 %, showcasing inclusive stewardship. To scale success, Odisha must embed mangrove targets in climate policy, adopt MRV-compliant carbon accounting, engage voluntary markets, and implement adaptive planting methods using raised beds and salt-tolerant species. This place-based model offers replicable restoration pathways for tropical coastal deltas globally, aligning ecological restoration with climate resilience and social equity.

Keywords: Biodiversity, ecosystem services, climate resilience, coastal ecosystems, carbon sequestration, Odisha coast, sustainability

Introduction

Mangrove forests rank among the world's most carbon-dense ecosystems, with total ecosystem carbon stocks averaging 856 ± 32 Mg C ha^{-1}, 85 % of which is stored belowground (Kauffman et al., 2020). In

India, mangroves extend over 4 992 km² (≈ 0.15 % of land area), of which Odisha hosts 259.1 km² (≈ 5.2 % of national cover) as of 2023 (FSI, 2023). Surprisingly, 81 % of Odisha's mangroves are concentrated in Bhitarkanika National Park, leaving much of its 480 km coastline exposed to cyclones, saline intrusion, and erosion (Kumar et al., 2010). Recent MISHTI (Mangrove Initiative for Shoreline Habitats & Tangible Incomes) programme interventions delivered a net gain of 2.55 km² over two years, yet these restored sites remain under-represented in carbon accounting and resilience planning. Scientific integration of Odisha's restoration into national NDCs and blue carbon frameworks is still limited. Stem-only sequestration rates of 7.34 t C ha^{-1} yr^{-1} in the Mahanadi delta (Agarwal et al., 2017) are omitted from policy targets, while legal protection coexists with > 70 % of littoral households depending on mangrove resources for subsistence (Tapaswini et al., 2020). Although Ecological Mangrove Restoration and Fishbone Channel Systems show promise in Balasore and Bhadrak, long-term success hinges on hydrology-based site selection, community monitoring, and MRV integration (OFSDS, 2013; CIFOR-ICRAF, 2025). This paper addresses the below questions with reasonable numbers and facts to back them up. What is the carbon sequestration potential of Odisha's mangroves under optimized restoration compared to business-as-usual? Modelling suggests that by 2030, restoration could sequester about 1.55 Tg C (≈5.69 Tg CO_2), while disturbance pathways risk emissions of 2.16 Tg C (≈7.93 Tg CO_2). Field studies in Bhitarkanika further show stem-only sequestration rates of 10.92 t C/ha/yr (≈40.08 t CO_2/ha/yr), underscoring the high per-hectare potential. How do restoration pathways affect sediment and nutrient retention, and thus water quality? Restoration scenarios are projected to reduce sediment export by up to 24.9% and nutrient export by 7.6%, highlighting tangible co-benefits for coastal water systems. Which governance and community-led models best enable scalable, equitable restoration? Evidence from Odisha shows that women-led and village-led initiatives have successfully managed nurseries and planting programs, ensuring survival and stewardship across districts such as Balasore and Jagatsinghpur. Hydrology-first ecological mangrove restoration (EMR) approaches, supported by state and national programs, provide a scalable technical pathway. How can Odisha's blue carbon efforts align with national and international climate finance mechanisms? The state's Climate Budgeting framework and SAPCC already create a finance-ready architecture, while national schemes like MISHTI and GCF-backed projects offer channels for blended finance. A proposed 84 km² restoration program by 2030 is estimated to cost ~USD 100 million and generate ~2,200 FTE job-years, strengthening the case for investability and just transition narratives. Unlike prior single-service assessments, this study integrates a PRISMA-based systematic review of 39 peer-reviewed studies and other studies from government websites or government press release with spatial modelling via InVEST v3.8.0 and governance analysis. It offers the first comprehensive blueprint for scaling Odisha's mangrove restoration as a nature-based climate solution.

Methodology

To capture the state of knowledge on mangrove restoration and blue carbon in Odisha, we conducted a systematic literature search across four major databases: Web of Science (v6.5), Scopus (2025 release), PubMed, and Google Scholar (Kumar, 2025). The search was restricted to publications between January 2000 and June 2025 to encompass both early restoration studies and recent advances in blue carbon science. Authors have used a combination of targeted keywords, including "Odisha mangrove restoration", "blue carbon India", "ecosystem services mangroves", and "InVEST mangrove modeling". Reference lists of relevant articles were also screened to identify additional sources. The review process followed the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines (Moher et al., 2009; Page et al., 2021), ensuring transparent documentation of inclusion and exclusion criteria. A total of 250 records were initially identified across the four databases. After removing 40 duplicates, 210 unique records were screened at the title and abstract level, of which 140 were excluded for irrelevance. Seventy full-text articles were then assessed for eligibility, and 31 were excluded: 10 due to focus on regions outside Odisha, 9 for insufficient empirical data, and 12 because they were non–peer-reviewed sources. Ultimately, 39 peer-reviewed studies were included in the synthesis, supplemented by 11 additional sources from government websites and official press releases. As illustrated in Figure 1, this process narrowed the initial 250 records to a final set of 50 studies forming the evidence base for this review.

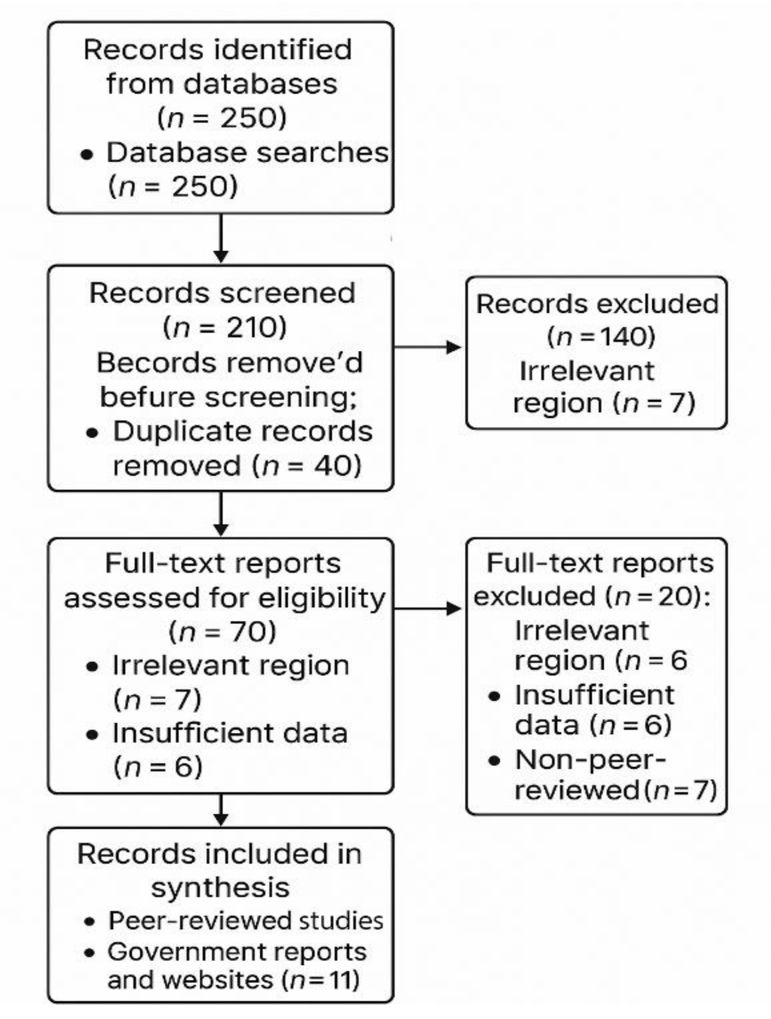

Figure 1: Prisma flow diagram shows the flow of records through identification, screening, eligibility, and inclusion

Although 210 records were initially reviewed at the title/abstract stage, only 50 studies passed all inclusion filters and were formally cited in this paper. The larger screening number reflects the breadth of literature canvassed; the final count of 50 represents those that met our rigorous criteria for data quality and relevance. Two independent reviewers extracted information on study location, restoration methods, ecosystem-service metrics, and governance models. Discrepancies were resolved by consensus. We assessed each paper's methodological rigor using a modified CASP checklist, evaluating sampling design, model validation, and reporting completeness.

Table 1. Input data layers for InVEST v3.8.0 scenario modelling of Odisha's mangrove ecosystem services.

Dataset	Purpose	Source	Resolution
LULC rasters (2023 & 2030)	Baseline & restoration scenarios	Kadaverugu et al., (2022); FSI (2023)	30 m
Biophysical carbon pools	Aboveground, belowground, soil, litter	Banerjee et al., (2020); Kauffman et al., (2020)	–
DEM (SRTM v4.1)	Elevation model for SDR/NDR	USGS	30 m
Rainfall erosivity (IMD 2019–21)	R-factor for SDR	IMD	30 m
Runoff coefficients by LULC	C/P tables for SDR & NDR	Local water-quality surveys	–

Module	Key Parameters
CBC	analysis year = 2030; economic_analysis = False
SDR	flow accum threshold ≥ 1,000 upstream pixels
NDR	flow accum threshold ≥ 1,000; subsurface_flow = False

To assess future vulnerabilities, we developed a "Climate Stress" pathway for 2050 by updating land-cover projections, rainfall erosivity, and sea-level rise parameters within InVEST v3.8.0. Land-use/land-cover (LULC) rasters for 2050 were derived from CLUE-GP simulations that incorporated projected population and economic drivers. Rainfall erosivity (R-factor) was increased by 10% under RCP4.5 and 20% under RCP8.5 to represent intensifying storm events. Sea-level rise allowances of 0.50 m (RCP4.5) and 0.75 m (RCP8.5), based on regional projections from NASA's AR6 Sea Level Projection Tool (National Aeronautics and Space Administration, 2023), resulted in the inundation of approximately 8% and 14% of current mangrove extent, respectively, which were reclassified as “open water” in the LULC layers. All other model parameters, including flow-accumulation thresholds and carbon pool settings, were held constant to isolate the effects of climate stressors.

We tested the robustness of Δ Carbon projections by varying carbon pool values and rainfall erosivity (R-factor) by ±10 % independently. These inputs represent major drivers of sequestration and hydrological stress in InVEST v3.8.0. Results reaffirm resilience under RCP4.5 and vulnerability under RCP8.5 even across uncertainty bounds (see Supplementary Table S2).

Model calibration and validation were undertaken to ensure robustness of the InVEST outputs. Sediment and nutrient retention modules were calibrated against local soil-survey data from the Odisha Forest Sector Development Society (OFSDS, 2013), providing site-specific parameterization. Carbon sequestration estimates from the Coastal Blue Carbon (CBC) model were validated by comparing InVEST outputs with field-measured stem flux rates (Banerjee et al., 2020; Mishra et al., 2021) and soil-core carbon inventories, thereby aligning modelled projections with empirical observations.

From the 39 peer-reviewed papers and supplementary government sources, we distilled six illustrative case studies that best captured the diversity of Odisha’s mangrove restoration experience. Selection was guided by four criteria: the availability of measured carbon-flux or biodiversity-recovery data; the inclusion of economic valuations of cyclone buffering; the presence of clear governance or co-management descriptions; and coverage across key coastal zones such as Bhitarkanika, the Mahanadi delta, and the Rushikulya estuary. Together, these case studies provide a representative cross-section of ecological, economic, and institutional dimensions, offering grounded insights into both the opportunities and challenges of scaling mangrove restoration in Odisha.

Our analytical approach combined multiple methods to integrate ecological, governance, and policy dimensions of mangrove restoration. A narrative synthesis was used to link restoration techniques such as Ecological Mangrove Restoration (EMR) and fishbone channel systems with their observed outcomes for carbon sequestration, sediment retention, and nutrient regulation. Governance dynamics were examined through thematic coding, which identified barriers such as sectoral silos alongside enabling factors like women-led Village Mangrove Councils (VMCs). To compare alternative futures, we developed tabular assessments of scenario projections, carbon fluxes, and cost–benefit figures, allowing for transparent evaluation of trade-offs. Finally, a gap analysis was conducted to map under-restored estuarine zones and to highlight shortfalls in monitoring, reporting, and verification (MRV) relative to policy targets. Together, these methods provided a structured framework for assessing both the ecological effectiveness and institutional feasibility of scaling mangrove restoration in Odisha.

We applied PRISMA guidelines and a modified CASP appraisal to ensure robust evidence synthesis (Supplementary Table 2). A formal PROSPERO registration was not pursued because its scope is currently limited to health and clinical intervention reviews, rendering environmental and ecosystem-service assessments ineligible. In addition, strict project timelines, and the urgent need to inform policy decisions precluded real-time registration. To maintain transparency and methodological rigor, we adhered fully to PRISMA 2020 standards, published our complete search strings and screening criteria in the Supplementary Materials.

Status of mangrove restoration in Odisha

Recent assessments indicate that Odisha's mangrove cover has increased by 1.0%, representing a net gain of 2.55 km² and bringing the total area to 259.06 km² (FSI, 2023). While Bhitarkanika National Park continues to account for the majority of this extent, approximately 81%, restoration initiatives are now being extended to other coastal districts, including Balasore, Bhadrak, Jagatsinghpur, and Puri. The NIDM Coastal Vulnerability Atlas (2024) highlights that nearly 22% of the state's 480 km coastline, with Kendrapara and Jagatsinghpur most affected, falls into the "highly vulnerable" category due to cyclone exposure and salinization. These patterns emphasize the importance of directing restoration towards degraded and unprotected coastal stretches to strengthen ecological resilience. Multi-temporal Landsat analysis shows Odisha's mangrove cover rose from 18 573.5 ha in 1990 to 23 871.5 ha by 2015, a 28 % gain, yet spatial gaps persist in non-protected estuaries (Roy et al., 2019). Floristic surveys across six estuaries (Subarnarekha to Gopalpur) document 61 mangrove and associate taxa, highlighting severe fragmentation outside Bhitarkanika (Panda et al., 2013). Government-backed restoration follows the OFSDS Technical Manual (2013), employing Ecological Mangrove Restoration (EMR) and Fishbone Channel Systems. These methods have been implemented in Balasore and Bhadrak in collaboration with Village Mangrove Councils (VMCs). A CIFOR-ICRAF (2025) technical report details monitoring stations in Bhitarkanika National Park that measure vegetation structure, sediment accretion, and carbon fluxes to refine restoration protocols. In Odisha's mangrove restoration scenarios, spatial modeling using InVEST v3.8.0 (Kadaverugu et al., 2022) projects contrasting outcomes under business-as-usual and optimistic restoration pathways (Table 1). Under the disturbance scenario, mangroves would release 2.16 Tg C (−7.93 Tg CO_2) by 2030, whereas optimized restoration leads to a sequestration of 1.55 Tg C (+5.69 Tg CO_2). Restoration also reduces sediment export by 24.9 % and nutrient export by 7.6 % compared to current conditions.These findings support prioritizing mangrove restoration in Odisha's coastal planning and integrating blue-carbon values into national strategies. Model projections under contrasting management scenarios are summarized in Table 2.

Table 2: InVEST v3.8.0 projections for Odisha's mangrove restoration scenarios by 2030. "Reference" indicates baseline export under current management. Carbon is converted to CO_2 using the factor 3.67 t CO_2 per t C (IPCC, 2006). Source: Kadaverugu et al., (2022).

Scenario	Carbon Outcome (Tg C)	Carbon Outcome (Tg CO_2)	Sediment Exchange Change (%)	Nutrient Export Change (%)
Disturbance	-2.16	-7.93	0 % (baseline)	Reference

Optimistic Restoration	+1.55	+5.69	-24.9	-7.6

Full model inputs, spatial parameters, and version details are provided in Supplementary Table S1.

Climate stress projections by 2050

Authors have evaluated mangrove performance under moderate (RCP4.5) and high-emission (RCP8.5) pathways by 2050. Projected changes in carbon, sediment, and nutrient dynamics are summarized in Table 3.

Table 3: InVEST v3.8.0 projections for a "Climate Stress" scenario by 2050, under moderate (RCP4.5) and high-emissions (RCP8.5) pathways. Carbon is converted to CO_2 using 3.67 t CO_2/t C.

Scenario	Δ Carbon (Tg C)	Δ Carbon (Tg CO_2)	Sediment Export Δ (%)	Nutrient Export Δ (%)
RCP 4.5 (2050)	+0.85	+3.12	-18.3	-5.4
RCP 8.5 (2050)	-0.45	-1.65	-10.1	-2.7

Under moderate climate forcing (RCP4.5), optimized restoration continues to deliver measurable benefits, with mangroves projected to sequester approximately 0.85 Tg C by 2050. However, co-benefits for sediment and nutrient retention decline by about 5–7% relative to the 2030 optimistic restoration pathway, reflecting the growing influence of climate stressors. In contrast, under high-emissions conditions (RCP8.5), projected sea-level rise and storm intensification outpace restoration gains: mangroves shift from a carbon sink to a net source (−0.45 Tg C), while sediment export reduction falls below 15% and nutrient retention is further weakened. A critical tipping point emerges when inundation exceeds roughly 12% of the forest area (corresponding to sea-level rise >0.7 m) and rainfall erosivity increases beyond 15%, at which stage dieback in low-lying zones outweighs growth and accretion. These results highlight both the resilience limits of Odisha's mangroves and the urgency of coupling restoration with ambitious climate mitigation. Authors have tested the robustness of Δ Carbon projections by varying carbon pool values and rainfall erosivity (R-factor) by ±10 % independently. These inputs represent major drivers of sequestration and hydrological stress in InVEST v3.8.0. Results reaffirm resilience under RCP4.5 and vulnerability under RCP8.5 even across uncertainty bounds (Supplementary Table S2).

Blue carbon sequestration potential of Odisha's mangroves

The blue carbon potential of Odisha's mangroves lies at the heart of their ecological and climate significance. Beyond their role as protective coastal buffers, these forests function as long-term carbon sinks, storing organic matter in both biomass and deep sediments. In this section, we trace how restoration and protection efforts enhance that capacity, linking local ecological processes to broader climate commitments. By situating Odisha's mangroves within the wider discourse on blue carbon, the discussion moves from site-level dynamics to their contribution in shaping resilient coastlines and informing climate finance pathways.

Modelled ecosystem service scenarios: Mangrove ecosystems are globally renowned for their high blue-carbon density, especially in sediment-accumulating coastal environments. Although Odisha's mangroves cover just 259.1 km² (FSI, 2023), they store outsized carbon stocks thanks to diverse species assemblages, optimal hydrology, and active restoration. Recent modelling by Kadaverugu et al., (2022) applied InVEST v3.8.0 to two scenarios through 2030 (Table 1). Under a Business-as-Usual disturbance scenario, Odisha's mangroves are projected to release approximately 2.16 Tg of carbon (≈ −7.93 Tg CO_2), underscoring the vulnerability of these ecosystems to ongoing pressures. By contrast, an Optimistic Restoration pathway could sequester 1.55 Tg of carbon (≈ +5.69 Tg CO_2) by 2030, while simultaneously reducing sediment export by nearly 25% and nutrient export by 7.6% relative to baseline conditions. These outputs highlight the dual role of scaled mangrove restoration as both a climate-mitigation strategy and a natural water-quality regulator, reinforcing its value as a cost-effective, multi-benefit intervention for Odisha's coastal resilience.

Field-measured carbon fluxes: Mishra et al., (2021) used high-resolution mapping to show that northern mangrove patches (Kendrapara, Bhadrak) hold 3.4–4.1 Tg C in biomass and soils. They recommend mixed, salt-tolerant species over casuarina monocultures for greater resilience and carbon yield. Further, Banerjee et al. (2020) report stem-only fluxes of 10.9 t C ha^{-1} yr^{-1} (≈40 t CO_2 ha^{-1} yr^{-1}) in Bhitarkanika, excluding soil and litter pools, suggesting true rates are substantially higher. However, not all restoration efforts have succeeded. For instance, in the Rushikulya estuarine zone, a state-led restoration initiative launched in 2019 under CAMPA aimed to reintroduce *Avicennia officinalis* and *Bruguiera gymnorhiza*. However, the project failed to consider the site's altered hydrology due to upstream sandbar formation and channel constriction. As a result, over 80% of the saplings perished within two monsoon cycles, and the area reverted to mudflat. CIFOR-ICRAF (2025) flagged this as a case where site–species mismatching and inadequate pre-restoration diagnostics led to resource loss and local disillusionment. The project lacked community monitoring mechanisms, and no corrective replantation has occurred to date. When evaluated against global benchmarks, Odisha's mangrove ecosystems demonstrate a distinctly superior carbon sequestration performance. While the global average for mangrove carbon uptake is estimated at ~6.0 t C/ha/year, and the IPCC Tier 1 default value is just ~3.5 t C/ha/year, field measurements from Odisha consistently report fluxes in the range of 7.3 to 10.9 t C/ha/year, with a mean of approximately 9.1 t C/ha/year. This places Odisha's mangroves among the top-performing blue carbon sinks worldwide, surpassing both global means and IPCC conservative estimates. When converted to CO_2-equivalents, the annual uptake reaches up to 33.4 t

CO_2/ha/year, nearly threefold higher than Tier 1 values (Figures 2 and 3). This strong performance not only validates Odisha's restoration strategy but also underscores the importance of region-specific field data for accurate national and international climate accounting.

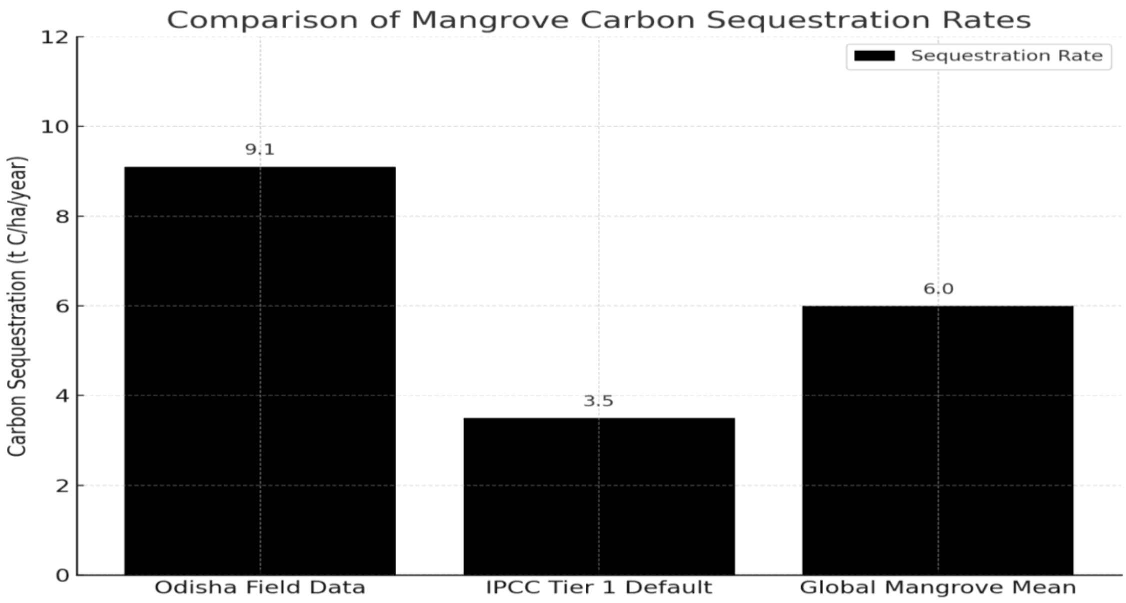

Figure 2: Comparative carbon sequestration rates (in t C/ha/year) between Odisha field measurements, global mangrove averages, and the IPCC Tier 1 default. Odisha's fluxes significantly exceed global norms, highlighting their high restoration value

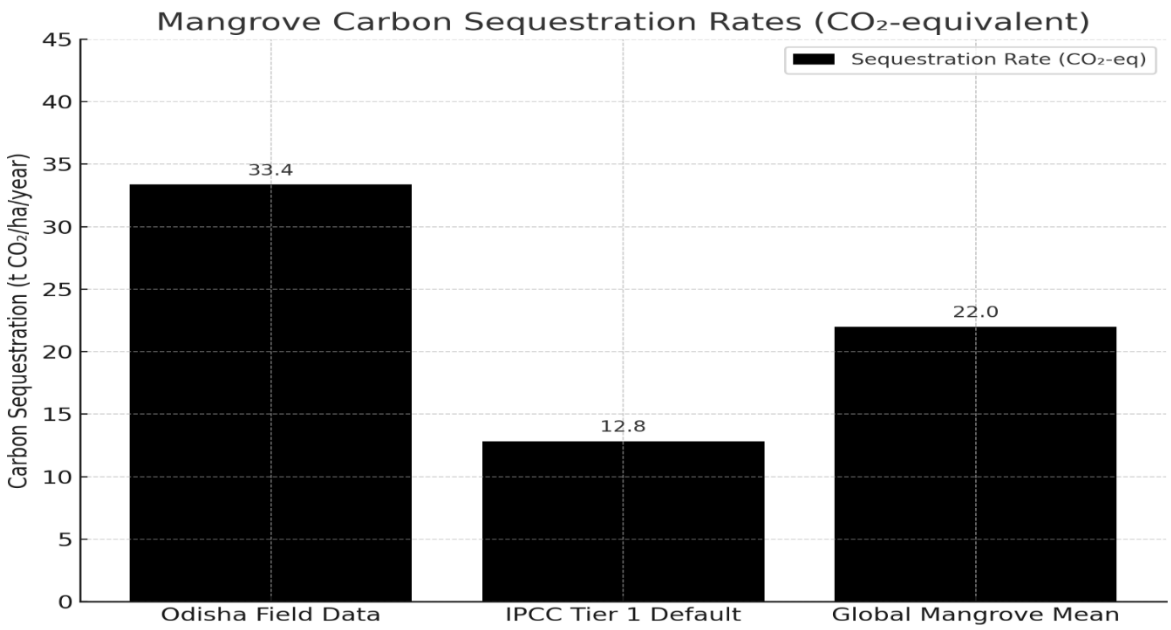

Figure 3: Estimated annual carbon sequestration rates by mangroves expressed in CO_2-equivalents (t CO_2/ha/year). Odisha's mangroves show nearly 3× higher carbon uptake than the IPCC Tier 1 default value, emphasizing their role in national and global climate mitigation strategies

Field measurements show Odisha's mangroves sequester 7.3–10.9 t C ha^{-1} yr^{-1} (≈27–40 t CO_2 ha^{-1} yr^{-1}), substantially exceeding the global average (~6.0 t C ha^{-1} yr^{-1}; ~22 t CO_2 ha^{-1} yr^{-1}) and the IPCC Tier 1 default (3.5 t C ha^{-1} yr^{-1}; ≈12.8 t CO_2 ha^{-1} yr^{-1}) (Figures 2 and 3).

Underutilized estuarine systems: Mishra et al., (2024) identified South Odisha estuaries (Rushikulya, Bahuda) as carbon-rich but under-restored zones due to policy gaps and anthropogenic pressures. They propose public–private restoration partnerships and community planting to establish new carbon sinks, linking restoration to climate-finance and local livelihoods. Collectively, these modelled and empirical studies position Odisha's mangroves, and adjacent estuaries, as strategic nature-based climate solutions. Strengthening their integration into NDCs and carbon-finance mechanisms remains an urgent next step.

Cyclone buffering and coastal resilience

The protective role of Odisha's mangroves extends beyond their ecological functions to the frontline of disaster risk reduction. Acting as natural barriers, they absorb storm surges, reduce wind velocity, and stabilize shorelines, thereby lessening the impact of recurrent cyclones on vulnerable communities. In this section, we explore how the structure and distribution of mangrove forests contribute to coastal resilience, showing how restoration and expansion can transform fragile stretches of coastline into buffers that safeguard both livelihoods and ecosystems.

Cyclone exposure and mangrove role: Odisha's 480 km coastline experiences near-annual cyclone landfalls, especially in Kendrapara, Jagatsinghpur, and Ganjam, heightening the need for natural buffers (Mohapatra et al., 2025). Mangrove ecosystems in these zones serve as green infrastructure that attenuates storm surges, reduces wind energy, and stabilizes shorelines, thus protecting lives and assets. Mangrove ecosystems in Odisha provide vital storm-buffering and coastal protection services, echoing global findings on nature-based resilience. Studies show that estuarine vegetation can significantly reduce surge height, wave energy, and erosion, safeguarding vulnerable communities (Barbier et al., 2011). Mangroves and hybrid infrastructure models offer cost-effective alternatives to hard engineering, enhancing ecosystem stability while supporting local livelihoods (Sutton-Grier et al., 2015). These benefits underscore the need to prioritize mangrove restoration in integrated coastal resilience planning.

Economic valuation of storm protection: A landmark study by Das, (2021) estimated that during the 1999 super cyclone, each hectare of mangrove in Kendrapara averted USD 4,335–43,352 in household damages. This protection value exceeds twice the opportunity cost of deforestation and is ~20× greater than alternative land uses, underlining mangrove conservation's high cost-effectiveness.

Recovery dynamics and case studies: NIDM, (2025) shows that mangrove-backed areas exhibit both static resilience (lower damage) and dynamic resilience (faster recovery) in low-elevation coastal villages. Ecological monitoring in Bhitarkanika National Park, led by CIFOR-ICRAF, confirms that mixed-species belts, especially *Avicennia marina* + *Rhizophora mucronata*, achieve the greatest surge attenuation owing to their complex root-canopy structure (CIFOR-ICRAF, 2023). Odisha's mangrove ecosystems have repeatedly demonstrated their capacity to mitigate cyclone impacts. Kumari et al., (2023) report that intact sanctuary mangroves cut immediate coastal forest damage by > 30 % in storms. The National Cyclone Risk Mitigation Project, (2014) documented up to 50 % reductions in flooding and structural losses during Cyclone Phailin. Post–Cyclone Yaas, (2021) data confirm lower surge heights and wind speeds in mangrove-protected zones (NIDM, 2021). Recent events (Fani, 2019; Amphan, 2020; Dana, 2024) further illustrate how mangrove belts reduce surge penetration and shoreline erosion, cementing their role in Odisha's resilience planning. In Bhadrak and Kendrapara, disaster risk reduction infrastructure, cyclone shelters and elevated roads, was constructed near or within CRZ-I buffer zones occupied by mangroves. While State Disaster Management Authority cited urgent needs post-Cyclone Phailin, the projects bypassed EIA norms and encroached into ecologically sensitive belts. Local panchayats and Village Mangrove Councils were not consulted. This case exemplifies how well-intentioned infrastructure projects can undermine ecological resilience if not aligned with CRZ and Integrated Coastal Zone Management (ICZM) frameworks (NIDM, 2021; Mohapatra et al., 2025).

Biodiversity recovery and ecosystem services

The regeneration of mangroves in Odisha is not only about restoring tree cover but about reviving the intricate web of life that thrives within these ecosystems. As degraded patches recover, they provide habitat for fish, crustaceans, and bird species, strengthening local food webs and sustaining coastal livelihoods. In this section, the focus shifts to how biodiversity recovery underpins a wider range of ecosystem services—from fisheries support and nutrient cycling to shoreline stabilization—demonstrating that restoration delivers benefits far beyond carbon storage or storm protection.

Faunal & floral recovery: Odisha's mangroves harbour 21 true mangrove taxa and > 270 bird species (many migratory), (Rasquinha, 2024) {moved citation inside sentence} underscoring their biodiversity value. In Bhitarkanika, the Mahanadi delta, and Devi estuary, replanting has driven partial returns of key taxa (*Heritiera fomes*, *Sonneratia apetala*, *Rhizophora mucronata*), enhancing canopy structure and nesting sites (Shyamal, 2023). Restored belts support endangered fauna like Olive Ridley turtles' mass-nest at Gahirmatha (Mishra et al., 2022), and Bhitarkanika remains India's largest wild saltwater crocodile (*Crocodylus porosus*) stronghold (Palei et al., 2021). Intensive surveys in the Mahanadi delta recorded 61 true mangrove taxa and flagged rare species' loss in non-protected blocks, underscoring urgent restoration needs (Panda et al., 2013; Nayak et al., 2016). In Puri district, near the Chilika lagoon fringe, state-funded afforestation under CAMPA prioritized fast-growing monocultures such as *Casuarina equisetifolia* for rapid coverage and erosion control. However, ecological assessments by CIFOR-ICRAF and local academic partners highlighted the poor salinity tolerance and biodiversity compatibility of Casuarina in brackish zones. Survival rates were low, and the plantations failed to support avian or aquatic species. In contrast, native species like *Avicennia marina* and *Rhizophora mucronata* showed higher survival and ecosystem service delivery in pilot plots. This mismatch between top-down plantation goals and ecological suitability delayed biodiversity recovery and eroded local participation in replantation drives (CIFOR-ICRAF, 2023; Srikanthan et al., 2024). In Jagatsinghpur's Kujang block, afforestation funds under CAMPA and the State Plan were directed toward planting *Casuarina equisetifolia* in intertidal zones classified as CRZ-I. Despite warnings from ecologists about poor survival in saline soils and low biodiversity value, the plantations proceeded without a site suitability assessment. Within two years, most stands failed, and the few surviving trees provided minimal faunal support or shoreline stabilization. The plantation was later declassified from the “restored” category in the district’s forest cover audit. Local Village Mangrove Councils had no role in planning or monitoring, revealing the pitfalls of top-down, area-focused afforestation metrics (Dhal et al., 2023; CIFOR-ICRAF, 2025).

Ecosystem services (provisioning & regulation): Srikanthan et al., (2024) report that over 60% of Bhitarkanika households rely on restored mangroves for fuelwood, honey, and fish, while flood buffering and nutrient cycling secure downstream water quality. Mixed-species stands surpass monocultures on biodiversity metrics and salinity tolerance. Sediment and nutrient retention by creek-fringe roots reduces siltation and eutrophication in shrimp ponds and fisheries (Kadaverugu et al., 2022). Despite these gains, biodiversity recovery remains uneven. South Odisha’s Rushikulya and Bahuda estuaries still lack true mangroves and exhibit low faunal turnover, driven by policy gaps and development pressures (Mishra et al., 2024). Bridging these deficits demands targeted species-to-site matching, strengthened community co-management, and monitoring protocols for richness, canopy closure, and wildlife return. Divergent mandates and roles, from the Forest Department’s MISHTI & EMR implementation and Fisheries Department’s aquaculture leasing, to Revenue Offices adjudicating tenure, disaster authorities funding hard infrastructure, and community VMCs leading local planting, create conflicts over buffer zones, resource access, and policy alignment that undermine cohesive mangrove restoration (Table 4).

Table 4: Stakeholder role, responsibility and conflict matrix in mangrove restoration in Odisha

Stakeholder	Mandated Role / Responsibility	Current Role in Restoration	Observed Conflicts / Challenges
Odisha Forest Department (DFO, PCCF)	Lead agency for forest protection and afforestation under Indian Forest Act and CAMPA guidelines	Implementation of MISHTI, EMR pilots, and afforestation drives	Overlaps with Fisheries Dept over CRZ buffer zones; delays in afforestation due to tenure disputes
Odisha Department of Fisheries & ARD	Regulate inland and brackish water aquaculture; manage fishing communities	Promotes aquaculture near estuaries, grants leases for ponds	Conflicts with Forest Dept in mangrove buffer areas; expansion of shrimp farms into potential restoration zones
Revenue Department / Tehsildar Offices	Maintain land records, approve land use	Adjudicate land ownership (especially	Disputed tenure in degraded mangrove areas

	conversion, manage village commons	in disputed deltaic lands)	(e.g., Kujang, Erasama); forest clearance delays
Odisha State Disaster Management Authority (OSDMA)	Coordinate cyclone response and infrastructure resilience	Funding cyclone shelters; supports natural buffers in coastal plans	Limited integration of mangroves in DRR plans; prefers hard infrastructure (embankments, seawalls)
Panchayati Raj Institutions (PRI)	Local governance of development, forest committees, and NRM projects	Interface with Joint Forest Management and VMCs	Lack of ecological awareness and capacity; some PRIs back shrimp farms for revenue
NGOs / CSOs (e.g., APOWA, Pragati)	Facilitate community engagement, restoration planning, training	Promote women-led Village Mangrove Councils, raise saplings, site selection	Limited access to official funds; not recognized as formal partners in MISHTI/REDD+ processes
CIFOR-ICRAF, Academic Institutions	Research, baseline mapping, MRV frameworks, ecosystem modeling	Provide carbon flux data, species mix advice, and GIS-based restoration maps	Lack of sustained collaboration with state agencies; research not always translated into policy
Local Communities / VMCs	Traditional users of coastal resources; informal land stewards	Plantation, protection, and monitoring in select sites (e.g., Rajnagar)	Inconsistent compensation; limited access to carbon benefits; gender gaps persist despite promising women-led models

Socio-ecological conflicts and restoration governance

Mangrove restoration in Odisha unfolds within a complex social landscape where ecological priorities often intersect with community needs and development pressures. Conflicts emerge around land use, access to resources, and competing visions of coastal management, making governance a central determinant of restoration outcomes. In this section, the focus shifts to how inclusive governance frameworks, community participation, and policy alignment can transform potential points of tension into opportunities for collaboration, ensuring that restoration is both ecologically effective and socially equitable.

Socio-ecological drivers of conflict: Mangrove restoration in Odisha unfolds within a landscape of competing conservation goals, subsistence needs, and rapid land-use change. In Bhitarkanika and the Mahanadi delta, shrimp aquaculture, port expansion, and agricultural encroachment drive mangrove loss, exacerbated by cyclones and saltwater intrusion (Dhyani et al., 2023). These pressures force trade-offs between legal protection and livelihoods, especially in villages where over 70% of households depend on mangroves for fuelwood, fodder, or fish.

Fragmented governance: Sectoral silos, among forestry, fisheries, agriculture, disaster management, and local bodies, hamper coherent mangrove policy. A notable conflict occurred in the Rajnagar block of Kendrapara district, where the Forest Department initiated mangrove afforestation on intertidal estuarine zones under the Joint Forest Management scheme. Simultaneously, the Fisheries Department had approved shrimp aquaculture leases to private operators in overlapping areas under the Brackish Water Fisheries Policy.

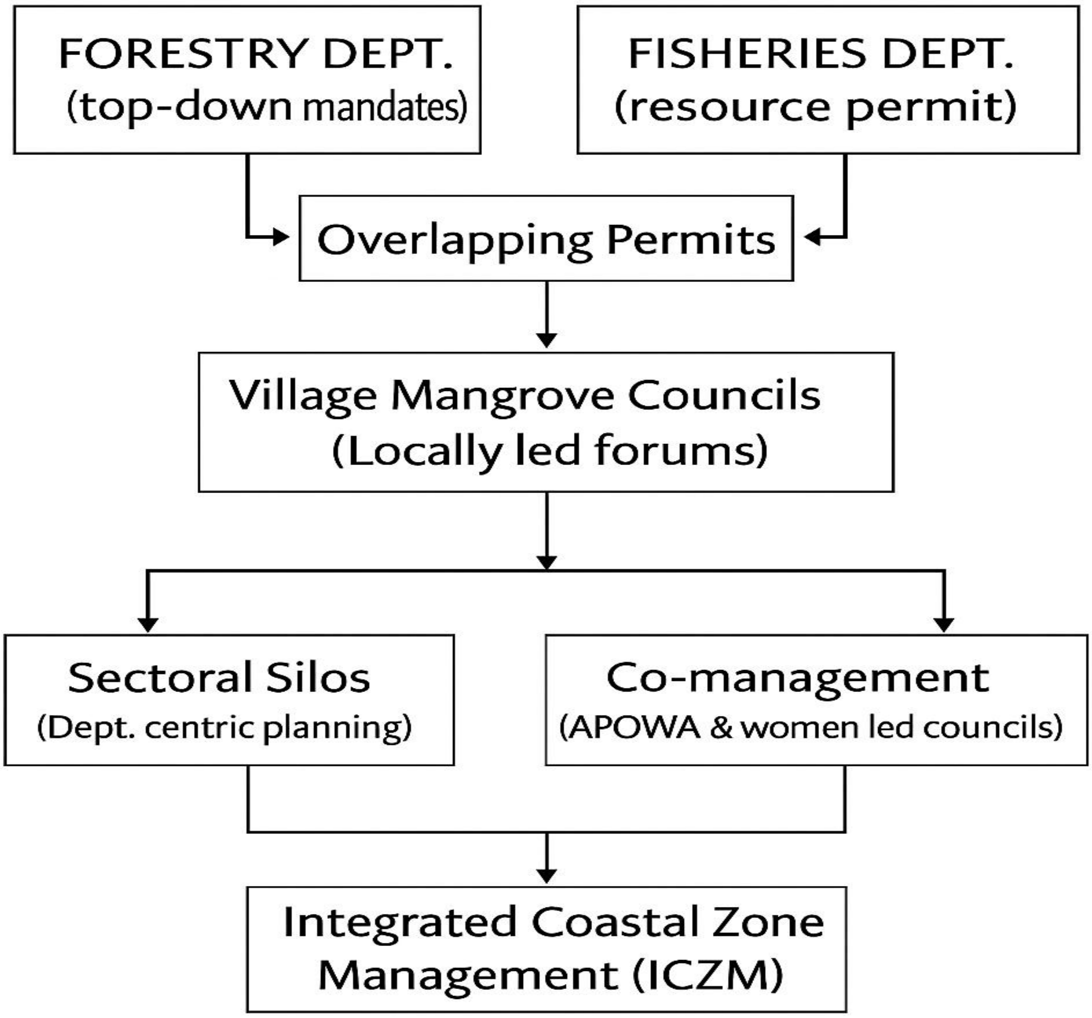

Figure 4: Governance flowchart illustrating how overlapping sectoral mandates (Forestry vs. Fisheries) converge through Village Mangrove Councils to diverge into sectoral-silo planning or community co-management, ultimately feeding into an integrated coastal zone management (ICZM) approach

This resulted in overlapping land claims, destruction of newly planted mangroves, and legal ambiguity over site jurisdiction. Local Village Mangrove Councils (VMCs) lacked the authority to mediate, and restoration goals were undermined despite both sectors acting under separate policy mandates. The absence of a district-level restoration planning cell or integrated coastal zone management framework exacerbated the conflict, illustrating the cost of siloed governance (GIZ–Wetlands International, 2023; Dhal et al., 2023). Dhal et al., (2023) also report that Odisha lacks functioning District Wetland Committees, inter-agency coordination mechanisms, and unified restoration protocols aligned with SDG goals. The institutional shift from fragmented permits to integrated coastal governance is depicted below (Figure 4). Community-led mangrove restoration in Odisha reflects broader governance insights from global and India-specific studies. Berkes, (2004) emphasizes that co-management is not a fixed institutional structure but a flexible, adaptive process rooted in shared responsibility and local knowledge. Complementing this, Chhatre and Agrawal (2009) show that decentralized forest governance, with rule-making autonomy and community ownership, can simultaneously deliver carbon storage and livelihood benefits. These frameworks underscore the importance of empowering Village Mangrove Councils and aligning restoration with bottom-up governance for sustained ecological and social outcomes.

Community co-management models: Community-based schemes demonstrate viable governance alternatives. The APOWA programme in Kendrapara and Basantpur shows that Village Mangrove Councils, particularly those led by women, can resolve land-use disputes, manage planting sites, and diversify incomes through mushroom farming and SRI rice cultivation (APOWA, 2013). Tapaswini et al. (2020) find that over 70% of Mahanadi delta households rely on mangroves for fuelwood, fodder, and fish, underscoring the necessity of community engagement for lasting restoration. These insights call for integrated co-management frameworks, performance-linked incentives, and sustained community stewardship to harmonize restoration with local livelihoods. Authors have applied narrative synthesis to link restoration techniques (EMR, Fishbone) with carbon, sediment, and nutrient outcomes. This thematic coding approach addresses the social-ecological reporting gaps identified in Southeast Asian mangrove studies (Gerona-Daga and Salmo, 2022), particularly around community-level governance. Subsequently, we coded governance barriers (sectoral silos) and enablers (women-led VMCs).

Policy recommendations and future directions

The trajectory of mangrove restoration in Odisha now hinges on how effectively science, governance, and finance can be aligned to sustain long-term outcomes. Building on the ecological and social insights outlined earlier, this section turns toward the policy measures needed to embed restoration within state and national climate strategies. It highlights opportunities to strengthen institutional coordination, integrate blue carbon into finance mechanisms, and ensure that community participation remains central to decision-making. By framing restoration as both an ecological necessity and a development priority, the discussion points toward future directions that can secure resilience, equity, and climate relevance for Odisha's coastal landscapes.

Mainstream restoration in climate governance: Embedding mangrove restoration into Odisha's climate governance requires moving beyond project-level interventions to formal policy integration. This can be achieved by incorporating explicit mangrove targets into the State Action Plan on Climate Change (SAPCC) and aligning them with relevant Sustainable Development Goals, particularly SDGs 13, 14, and 15. To ensure accountability, measurable indicators should be established for key functions such as carbon sequestration, cyclone buffering, and biodiversity resilience, drawing on emerging frameworks like those proposed by CIFOR-ICRAF (2025). At the national scale, restoration goals must also be synchronized with India's Nationally Determined Contributions (NDCs), supported by monitoring, reporting, and verification (MRV) protocols that comply with international carbon accounting standards. Together, these steps would position mangrove restoration as a central pillar of Odisha's climate strategy while enhancing its visibility in global climate finance and policy arenas.

Strategic expansion and blue carbon financing: Scale restoration beyond Bhitarkanika's 80%-dominant cover by targeting open zones in Balasore, Bhadrak, Jagatsinghpur, and Puri. Leverage EMR and Fishbone Channel Systems to enhance hydrological connectivity and increase sapling survival (OFSDS, 2013), Tap into carbon markets: restoring 84 km² could yield ~USD 1 million in credits by 2030 (CEEW, 2023), conditional on establishing transparent project pipelines and third-party verification.

Strengthening governance and adaptive monitoring: A meaningful transition from top-down afforestation programs to inclusive co-management requires placing communities at the center of mangrove governance. Strengthening Village Mangrove Councils (VMCs) through targeted capacity building, access to microfinance, and performance-based incentives has already shown promise in Odisha (APOWA, 2013), and offers a pathway to more durable stewardship. Scaling up women-led councils is particularly critical, as these groups have consistently demonstrated higher sapling survival rates and stronger local protection of restored sites. To ensure that restoration remains adaptive and evidence-based, monitoring systems should be co-developed with academic partners such as IIT Kharagpur, OUAT, and CIFOR-ICRAF, drawing on tools like rSETs, permanent vegetation plots, and carbon flux baselines. Together, these mechanisms create the foundation for data-driven course correction while embedding accountability within community structures. Table 5 outlines the specific actions, lead agencies, timelines, and key performance indicators required to operationalize these recommendations and scale up mangrove restoration across Odisha.

Table 5: "Q" denotes calendar quarter: Q1 = Jan–Mar, Q2 = Apr–Jun, Q3 = Jul–Sep, Q4 = Oct–Dec. KPI = Key Performance Indicator

Action	Lead Agency	Timeline	KPI
Embed mangrove targets into Odisha SAPCC	Odisha Ministry of Environment, Forest &	Q1 2026	SAPCC published with explicit mangrove area and sequestration targets

	Climate Change (MoEFCC)		
Finalize MRV-compliant carbon-accounting protocols	OUAT & CIFOR-ICRAF	Q3 2026	Protocol document published; 3 VMCs trained
Establish District Restoration Cells in Kendrapara, Jagatsinghpur, Balasore & Bhadrak	Odisha Forest Department	Q4 2026	Four fully operational Restoration Cells
Pilot voluntary carbon-credit project for 50 ha of restored mangroves	Odisha Forest Department & Verra	Q2 2027	50 ha registered; first credits issued
Launch coastal-resilience dashboard (R Shiny) with scenario toggles	OUAT GIS Lab & Odisha State Disaster Mitigation Authority	Q4 2027	Dashboard live; 2 scenario modules active

Achieving these milestones will require a phased, overlapping approach: MoEFCC can finalize mangrove targets through stakeholder workshops before the end of this year to feed into the Q1 2026 SAPCC update. Simultaneously, OUAT and CIFOR-ICRAF should begin drafting MRV protocols and deliver initial VMC training by early 2026 to stay on track for the Q3 2026 deadline. The Odisha Forest Department can leverage existing district offices and recruit core staff mid-2026, ensuring four fully operational Restoration Cells by Q4 2026. For the carbon-credit pilot, kicking off baseline surveys and engaging Verra immediately will satisfy the registry's 18–24-month validation window and make the Q2 2027 target attainable. Finally, OUAT's GIS Lab and OSDMA can prototype the dashboard this year using historical hazard data, iterating with user feedback to secure a robust Q4 2027 launch. With dedicated funding, streamlined inter-agency coordination, and adaptive management, this revised timeline is ambitious yet realistic. Likewise, to mitigate potential delays in carbon credit registration, early engagement with carbon certifying bodies such as Verra, along with the pre-identification of a pilot site adhering to methodological readiness, will be essential. For milestones at risk of slippage (e.g., MRV protocol finalization, dashboard deployment), the adoption of interim outputs, such as beta-stage deliverables or draft standards, can sustain procedural momentum and stakeholder confidence. To address uncertainties inherent in third-party validation and cross-institutional workflows, a structured contingency window of one to two calendar quarters should be embedded in the project design. Furthermore, rather than sequential rollout, a parallel training model targeting at least ten Village Mangrove Councils will facilitate more scalable MRV deployment and enhance long-term programmatic absorptive capacity for carbon-financed restoration.

Odisha in the global blue carbon discourse

Benchmarking Odisha's carbon stocks: Although covering just 259 km², Odisha's mangroves match many larger sites in carbon density. Kauffman et al., (2020) report TECS of 79–2,208 Mg C ha^{-1} (mean 856 ± 32 Mg C ha^{-1}), 85% belowground. Stem-flux studies in Bhitarkanika (10.9 t C ha^{-1} yr^{-1}) and the Mahanadi delta (7.3 t C ha^{-1} yr^{-1}) equate to ~27–40 t CO_2 ha^{-1} yr^{-1}, aligning with global TECS rates. India-wide syntheses (Sahu et al., 2016; Banerjee et al., 2020; Akhand et al., 2022) confirm Odisha as a blue-carbon hotspot.

Leveraging international frameworks: Odisha can strengthen its restoration agenda by engaging with global initiatives that provide monitoring, reporting, and verification (MRV) tools, technical guidance, and access to finance. Platforms such as the UN Blue Carbon Initiative and the Mangrove Alliance for Climate (MAC) offer standardized MRV frameworks, capacity-building opportunities, and dedicated finance windows to support large-scale blue carbon projects (Mangrove Alliance for Climate, 2023; Schindler Murray et al., 2023). In parallel, voluntary carbon standards such as Verra and Plan Vivo, along with mechanisms like REDD+, create pathways for Odisha to translate its site-specific datasets into results-based payments. By aligning local restoration outcomes with these international standards, the state can unlock new finance channels while ensuring that its projects meet globally recognized benchmarks for credibility and impact (Pendleton et al., 2012; Schindler Murray et al., 2023).

Cost-efficiency and investment potential: Restoration costs (~USD 2,000–3,500 ha^{-1} for EMR and Fishbone) undercut many tropical benchmarks (CEEW, 2023). With co-benefits, storm protection, biodiversity, livelihoods, Odisha stands out as a prime blue-carbon investment. Integrating state protocols into voluntary standards and spotlighting VMC-led co-management can mobilize climate finance and set a model for tropical deltas (Pendleton et al., 2012; Kauffman et al., 2020).

Aligning with COP27 and REDD+ mechanisms: At COP27 (Nov 2022), MAC launched with India, Sri Lanka, Australia, Japan, Spain, and others, advocating mangrove inclusion in national REDD+ strategies (Press Information Bureau, 2022). The UN-REDD Programme offers phased support, readiness, implementation, results-based payments, and MRV guidance (UN-REDD Programme, 2023). Aligning Odisha's MRV data (Bhitarkanika, Mahanadi, Devi) with these frameworks can unlock REDD+ and voluntary finance streams. Overall, Odisha's high sequestration benchmarks, cost-efficiency, and robust co-benefits position it as a leader in the global blue carbon arena. Its next step: harmonize state protocols with international standards to secure scalable climate finance.

Discussion

Climate co-benefits of restoration: Odisha's mangroves have expanded modestly in recent years, with a net gain of 2.55 km² since 2015 bringing the total cover to 259.06 km², and this growth signals important climate and resilience benefits. Modelling suggests that under optimistic restoration scenarios, these ecosystems could sequester substantial amounts of carbon by 2030, while field measurements confirm consistently high fluxes in the range of 7.3–10.9 t C ha^{-1} yr^{-1} (equivalent to roughly 27–40 t CO_2 ha^{-1} yr^{-1}). Beyond their role as carbon sinks, mangroves also provide measurable protection from extreme events, with studies showing more than 0.8 m of storm surge attenuation and avoided damages exceeding USD 4,000 per hectare. Taken together, these co-benefits position Odisha's mangroves as both natural climate solutions and frontline coastal defences, underscoring the urgency of scaling restoration and protection efforts.

Governance innovation and social inclusion: Mangrove loss in Odisha continues to be shaped by a combination of human and natural pressures, including the expansion of shrimp farms, port development, agricultural encroachment, recurrent cyclones, and saltwater intrusion. Addressing these drivers requires solutions that are both ecological and social in design. Community co-management has already demonstrated its effectiveness, with women-led Village Mangrove Councils improving sapling survival rates by nearly 30 % through stronger local stewardship and protection. At the policy level, embedding mangrove metrics into the State Action Plan on Climate Change (SAPCC) and India's NDCs would ensure that restoration outcomes are formally recognized within climate governance frameworks. Complementary measures such as designating Biodiversity Heritage Sites for threatened species like *Heritiera fomes* and *Sonneratia griffithii*, alongside the establishment of MRV pipelines for carbon finance, would further strengthen the institutional and financial foundations needed to scale restoration. Together, these interventions create a pathway that links local action with national and global commitments, ensuring that Odisha's mangroves are safeguarded as both ecological assets and climate solutions. In Jagatsinghpur district's Devi estuarine zone, the Forest Department's replantation efforts stalled when the Revenue Department refused to designate target areas as forest land. Although ecologically suited for mangroves, the parcels were classified as "government wasteland" or "unclassified land," requiring legal notification under Section 4 of the Indian Forest Act. This delay prevented fund utilization under CAMPA and excluded the site from REDD+ pipelines, highlighting how jurisdictional disconnects impede time-sensitive restoration (Dhal et al., 2023).

Scaling up with adaptive management: Scaling mangrove restoration in Odisha requires a structured pathway that integrates technical rigor, institutional coordination, and research partnerships. On the technical side, hydrological diagnostics and species–salinity matching provides the foundation for site-appropriate restoration, ensuring that interventions are ecologically viable and resilient over time. To operationalize these efforts, District Restoration Cells staffed with ecologists, GIS specialists, and community leads can serve as decentralized hubs, supported by real-time dashboards that track canopy cover, carbon flux, and biodiversity indicators. Complementing these institutional mechanisms, research partnerships with IIT Kharagpur, OUAT, and CIFOR-ICRAF can embed adaptive monitoring through rSETs and eddy-covariance networks, generating the data needed for course correction and long-term accountability. Together, these elements create a pathway that moves restoration from isolated projects toward a scalable, evidence-driven program capable of delivering both ecological and social resilience. Scenario modelling reveals that under high-emission pathways (RCP8.5), restoration gains may be reversed due to increased runoff erosivity and submergence stress. Mangrove forests often recover from cyclonic disturbances unless compounded by secondary factors like hydrological disruption or sediment erosion (Krauss & Osland, 2020). However, elevation collapse following peat degradation can induce regime shifts from forest to mudflat, as documented in Everglades case studies (Osland et al., 2020), underscoring the need for hybrid restoration strategies in low-lying zones.

Research gaps in carbon accounting: Advancing mangrove restoration in Odisha also depends on addressing critical knowledge gaps that limit the precision of monitoring and long-term carbon accounting. Greater clarity is needed on turnover and deposition rates within deep alluvial sediments, as these processes underpin the stability of belowground carbon pools. High-resolution remote sensing tools must be developed to capture belowground biomass dynamics, complementing field-based assessments. In parallel, sediment core chronologies and RSET-based elevation change measurements are essential for reconstructing long-term carbon accumulation and tracking ecosystem resilience under changing hydrological regimes. Filling these gaps will not only strengthen the scientific foundation of restoration but also enhance Odisha's credibility in MRV systems, thereby securing its eligibility for durable carbon crediting and climate finance.

Innovative financing and partnerships: Scaling mangrove restoration in Odisha will depend on innovative financing models that combine multiple streams of support. A blended finance approach—drawing on public grants, carbon credit revenues, and philanthropic contributions—can provide both stability and flexibility for long-term programs. Linking restoration to the wider Blue Economy further diversifies opportunities, with climate-smart aquaculture, community-based ecotourism, and sustainable non-timber products such as honey and handicrafts offering pathways for local income generation alongside ecological gains. To coordinate these efforts, multi-sector stakeholder platforms and task forces are essential, enabling joint planning across government agencies, research institutions, private investors, and community organizations. Together, these strategies create a financing architecture that is both resilient and inclusive, ensuring that mangrove restoration is embedded within broader economic and social development agendas.

Implications of 2050 climate-stress scenario: By incorporating a 2050 climate-stress scenario, we reveal clear resilience thresholds: beyond moderate warming (RCP4.5), mangroves still deliver net gains but at reduced efficiency, whereas under RCP8.5 they cross into net carbon loss. These insights underscore the urgency of coupling restoration with climate adaptation measures. The under mentioned themes should be encouraged:

1. Adaptive Management: Prioritize restoration in higher-elevation fringing zones to buffer against projected inundation.
2. Species Selection: Emphasize *Avicennia marina* and *Sonneratia apetala*, which tolerate prolonged submergence and salinity swings.
3. Hybrid Solutions: Combine EMR with engineered micro-elevations (e.g., fishbone + elevated berms) to maintain root-substrate contacts under higher water levels.

Sensitivity tests further support these thresholds: even when carbon pool or storm erosivity inputs are varied ±10 %, mangroves remain net sinks under RCP4.5 and net sources under RCP8.5 (see Table S2). The robustness of these thresholds is further supported by ensemble-based rainfall erosivity projections (Panagos et al., 2022) and satellite-derived erosivity estimates in data-poor regions (Emberson, 2023), which confirm intensification trends under RCP8.5. Forest carbon modeling studies (Fuller et al., 2025) also advocate for sensitivity testing of carbon pool assumptions to improve policy relevance.

Future research directions

Pilot comparative restoration trials: Establishing long-term monitoring plots is essential to evaluate the comparative effectiveness of different restoration approaches, including Ecological Mangrove Restoration (EMR), fishbone channel systems, and emerging microtopography designs. These plots should be tracked over a period of at least five years to capture trends in sapling survival, biomass accumulation, soil carbon burial, and species diversity, thereby providing a robust evidence base for adaptive management. In parallel, testing species–site matching through trait-based recovery indices can help refine planting prescriptions, ensuring that restoration strategies are tailored to local ecological conditions. Together, these efforts will generate the empirical insights needed to optimize restoration design, strengthen resilience, and guide future scaling of mangrove recovery in Odisha.

Cross-regional governance comparisons: Developing agent-based models offers a powerful way to capture the complex interactions among forestry departments, fisheries, and community councils across deltaic systems such as Odisha, the Sundarbans, and the Mekong. By simulating these dynamics, it becomes possible to test how different policy levers—ranging from permit harmonization to incentive schemes—shape restoration outcomes and influence pathways for conflict resolution. To ensure that these models remain grounded in local realities, stakeholder workshops should be convened to validate underlying assumptions and co-design governance scenarios. This participatory approach not only strengthens the credibility of the models but also creates a shared platform for envisioning restoration strategies that are both ecologically effective and socially legitimate.

Next-generation monitoring approaches: Advancing monitoring capacity in Odisha's mangroves will require the integration of cutting-edge remote sensing and field-based technologies. Deploying UAV-LiDAR and terrestrial laser scanning in pilot sites can generate sub-meter resolution maps of canopy structure and aboveground biomass, providing a detailed baseline for restoration assessment. Complementing these spatial datasets, paired RSET installations and eddy-covariance flux towers enable real-time monitoring of carbon dynamics, sediment processes, and water-level fluctuations, offering insights into both ecological function and climate resilience. At the landscape scale, time-series imagery from Sentinel and Planet platforms can be leveraged to validate InVEST projections and to detect early warning signals of mangrove degradation or loss. Together, these tools establish a robust, multi-scale monitoring framework that links local restoration outcomes to regional and global reporting systems.

Socio-economic and livelihood assessments: Assessing the socio-economic impacts of mangrove restoration requires systematic evaluation across households and communities. Longitudinal surveys in villages managed by Village Mangrove Councils (VMCs) can provide critical insights into how restoration influences income diversification, patterns of resource use, and shifts in gender equity over time. Complementing these household-level assessments, cost–benefit analyses comparing restoration with gray infrastructure over 10–20-year horizons can capture the economic value of avoided cyclone damages and long-term resilience gains. In addition, both market and non-market valuation of ecosystem services—ranging from honey and fisheries to carbon credits—should be explored under different governance models to reveal how benefits are distributed and sustained. Together, these approaches create a comprehensive framework for demonstrating the economic and social returns of mangrove restoration, strengthening the case for its integration into policy and finance agendas.

Integrated scenario modelling under climate and land-use change: Extending InVEST scenarios to 2050 provides an opportunity to explore how Odisha's mangroves may respond under different climate and land-use futures. By integrating Representative Concentration Pathways (RCPs) with projected land-use change from models such as CLUE or GLOBIOM, these scenarios can capture both climatic and socio-economic drivers of change. Coupling carbon, sediment, and nutrient modules with projections of cyclone frequency further allows for the assessment of resilience trade-offs, highlighting where ecological gains may be offset by increasing disturbance risks. From this integrated analysis, it becomes possible to identify "no-regret" restoration portfolios—strategies that consistently deliver co-benefits for climate mitigation, biodiversity conservation, and local livelihoods regardless of future uncertainty. Such an approach strengthens the evidence base for long-term planning and positions Odisha's mangrove restoration as a robust climate adaptation and mitigation strategy.

Limitations and uncertainties

Although this review provides a broad synthesis of Odisha's mangrove restoration and blue carbon potential, several uncertainties remain that limit the precision of current assessments. Belowground carbon stocks are still poorly sampled, raising the likelihood that total sequestration is underestimated. Model outputs from InVEST, while useful, operate on annual timesteps and simplified hydrological assumptions, thereby overlooking the influence of seasonal floods, droughts, and groundwater dynamics. Similarly, the reliance on 30-m land-cover maps risks misclassifying narrow or fragmented mangrove stands, while the exclusion of non-English studies, grey literature, and local newspaper reports may have omitted valuable community-level insights. Stakeholder interviews, concentrated in only three districts, also provide a partial view of social perspectives. Addressing these gaps through deeper soil sampling, higher-frequency ecological monitoring, finer-scale mapping, and broader social surveys will be essential to strengthen future assessments and to guide more robust, inclusive restoration planning.

Conclusion and recommendations

Odisha's mangrove ecosystems, though modest in extent, represent a disproportionately powerful asset for climate mitigation, coastal resilience, and biodiversity conservation. Recent initiatives such as MISHTI and the adoption of ecological restoration techniques have begun to reverse losses, adding new cover and demonstrating the potential of science-based interventions. Model projections and field data alike confirm that these forests are among the world's most efficient carbon sinks, while also reducing sediment and nutrient runoff, buffering cyclone impacts, and sustaining iconic species like Olive Ridley turtles and saltwater crocodiles. Together, these co-benefits position Odisha as a global hotspot for blue carbon and nature-based coastal protection. Yet challenges remain. Fragmented governance, socio-ecological trade-offs, and under-restored estuarine zones continue to limit the scale of impact. At the same time, community-led approaches—particularly women-led Village Mangrove Councils—have shown how local stewardship can align ecological restoration with livelihood gains, improving sapling survival and creating tangible social benefits. These examples highlight the importance of embedding restoration within inclusive governance frameworks that balance conservation goals with community needs. Looking ahead, Odisha is well placed to lead in blue carbon conservation if it can bridge on-ground progress with policy and finance. Priorities include harmonizing monitoring with international MRV standards, mobilizing carbon finance through credits and climate funds, and embedding mangrove targets into state climate and SDG plans. By combining scientific best practices, participatory governance, and innovative financing, Odisha can scale its mangrove restoration into a model of climate-smart, equitable coastal resilience—securing both community well-being and ecological heritage.

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