Different Roles of Mangrove Ecosystems and Their Significance

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Abstract Mangrove forests, covering ~167,000–181,000 km^2 across 123 countries, are among the most carbon-dense and functionally diverse ecosystems on Earth. Their capacity to sequester 5.5–6.5 Mg C ha^{-1} year^{-1} in deltaic settings and store up to 2200 Mg C ha^{-1} in carbonate soils underscores their disproportionate role in global climate mitigation. Beyond carbon regulation, mangroves attenuate wave energy by as much as 99% over 500 m of forest, preventing an estimated US$65 billion in annual flood damages and safeguarding more than 15 million people worldwide. Yet, despite these services, ~35% of global mangrove cover has been lost in recent

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decades, largely driven by aquaculture expansion, coastal development, and deforestation for timber and fuelwood. This chapter argues that mangrove conservation must be reframed not simply as an ecological priority but as an urgent global imperative for climate adaptation and socio-economic stability. By synthesizing ecological functions, socio-economic benefits, and valuation frameworks, we demonstrate that the erosion of mangrove resilience directly undermines fisheries that support millions of households, coastal infrastructure protection, and cultural heritage embedded in local communities. At the same time, fragmented research and policy silos have limited effective interventions, particularly in Asia where 36% of global losses have occurred. We contend that sustaining mangroves requires integrated strategies that align ecological restoration with local livelihood security and international climate commitments. Incorporating advances in remote sensing, economic valuation, and community-led conservation, this synthesis highlights pathways for embedding mangrove ecosystem services into adaptive governance and global sustainability agendas. Given their dual role in climate mitigation and disaster risk reduction, safeguarding mangroves represents a decisive opportunity to couple.

Keywords Carbon regulation · Mangrove conservation · Mangrove resilience · Adaptive governance

1 Introduction

Mangrove ecosystems represent one of the most ecologically significant and functionally diverse coastal biomes, uniquely positioned at the interface of terrestrial and marine systems (Giri et al., 2011). These intertidal forests have been dominated by salt-tolerant tree species, serve as critical buffers against coastal erosion, mitigate the impacts of storm surges and sea-level rise, and regulate global biogeochemical cycles (Blankespoor et al., 2017; Sunkur et al., 2023). Their ability to sequester substantial amounts of carbon has positioned them as key components of blue carbon ecosystems, reinforcing their role in climate change mitigation. Beyond their ecological significance, mangroves sustain millions of coastal inhabitants by providing essential resources such as timber, fuelwood, fisheries, and medicinal products, while also supporting traditional livelihoods and cultural practices (Giri et al., 2008). However, despite their invaluable services, mangrove forests are experiencing significant declines due to deforestation, habitat degradation, and climate change-induced stressors. The urgency of their conservation necessitates a comprehensive understanding of their ecological, socio-economic, and adaptive functions.

Mangroves are distributed across tropical and subtropical coastlines in over 123 countries (Cummings & Shah, 2018), covering an estimated 167,000 to 181,000 km^2 globally (Fig. 1) (Giri et al., 2011). Their distribution can be broadly categorized into two major biogeographic zones: the western zone, encompassing the Atlantic

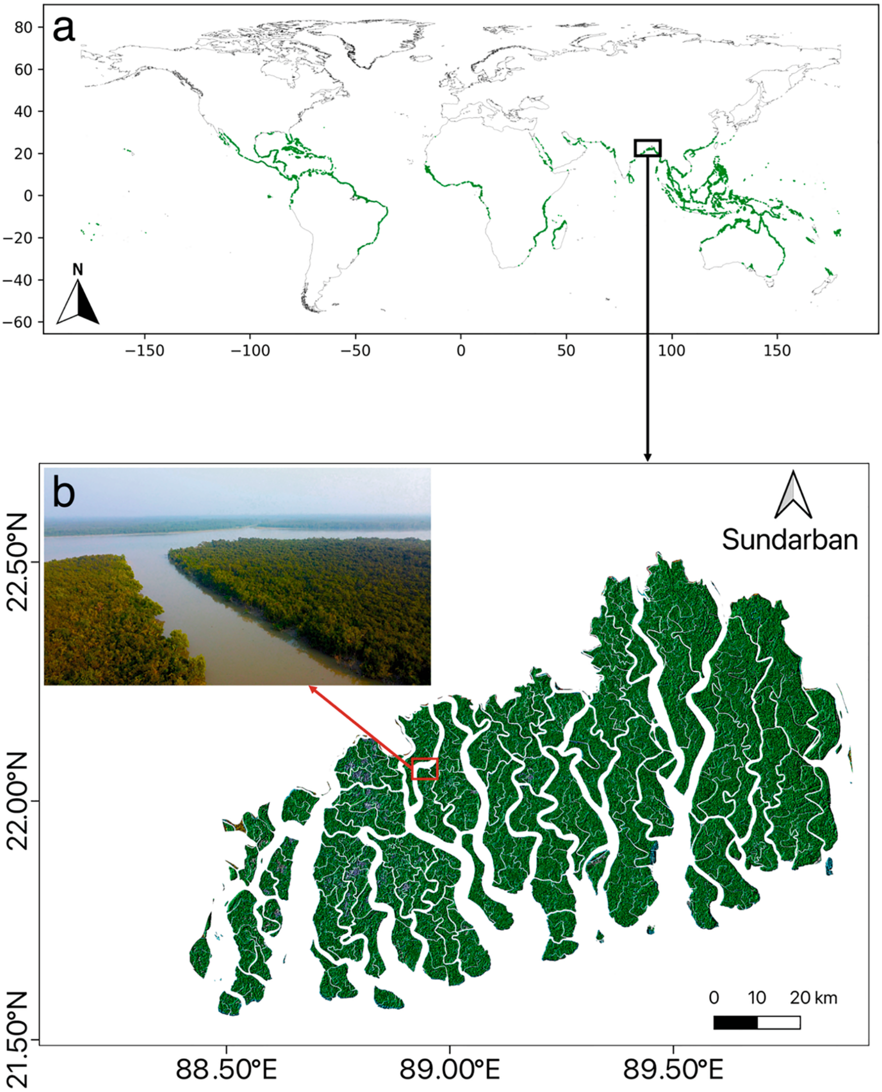

Fig. 1 (**a**) Global distribution of mangrove forests derived from Earth observation data. Mangrove extent was mapped using the Global Land Survey (GLS) dataset and the Landsat archive, with approximately 1000 Landsat scenes classified through a hybrid supervised–unsupervised digital image classification approach. Mangrove forests are shown in green, and country boundaries are delineated in black. (**b**) The Sundarbans, the world's largest contiguous mangrove forest, illustrated in high resolution using ESRI Sentinel-2 land cover data. The inset shows a drone image of a major river confluence with tidal channels within the Sundarbans, captured on 25 December 2021

coasts of the Americas and Africa, and the eastern zone, which includes the Indian Ocean and Indo-Pacific regions. The eastern zone harbors the highest species diversity, particularly in Southeast Asia, which accounts for nearly one-third of the world's mangrove cover (Gerona-Daga & Salmo III, 2022). In contrast, mangroves in the Americas, though extensive, exhibit lower species richness, dominated by a few genera such as *Rhizophora*, *Avicennia*, and *Laguncularia* (Moreira, 2020). The Sundarbans, spanning Bangladesh and India, represent the world's largest contiguous mangrove forest, providing a habitat for numerous endangered species, including the Bengal tiger (*Panthera tigris*) (Sarker et al., 2016). Despite their vast expanse, mangrove forests continue to decline, with approximately 35% of global mangrove cover lost in the past few decades due to anthropogenic pressures, including land reclamation for aquaculture, urban expansion, and pollution (Richards et al., 2020).

The resilience of mangrove ecosystems is attributed to their remarkable physiological and structural adaptations, which enable them to thrive in saline, waterlogged, and anoxic conditions (Kumari & Rathore, 2021). These adaptations include aerial root systems, salt-excreting mechanisms, and viviparous propagules, all of which contribute to their survival in fluctuating coastal environments (Naskar & Palit, 2015). However, regional variations in environmental conditions and human-induced pressures result in differing patterns of degradation and restoration potential. While extensive research has been conducted on mangrove ecology and conservation, much of the existing literature is fragmented, often focusing on isolated ecological or socio-economic aspects. Recent advances in remote sensing have provided complementary global and regional assessments of mangrove extent, dynamics, and degradation trajectories (e.g., Lu & Wang, 2021; Tran et al., 2022), which offer important spatial baselines. This chapter seeks to bridge these gaps by presenting an integrative perspective that encompasses the ecological functions, socio-economic roles, and conservation imperatives of mangroves. Unlike conventional reviews that emphasize either biodiversity conservation or economic valuation, this chapter highlights the interconnectedness of these dimensions, emphasizing how mangrove resilience is intrinsically linked to human well-being and climate adaptation strategies.

By synthesizing contemporary research with emerging findings on mangrove adaptation to climate change, this chapter provides a comprehensive discussion on the different roles of mangrove ecosystems and their significance. It explores the mechanisms through which mangroves persist in dynamic environments and the sociopolitical frameworks that govern their conservation. In this chapter, case studies and infographics are incorporated, providing tangible insights into successful restoration initiatives and policy interventions. Moreover, the urgent need for sustainable mangrove management to safeguard these critical ecosystems for future generations is emphasized in this chapter, integrating scientific evidence with real-world conservation strategies.

To provide a coherent framework for this chapter, a conceptual flowchart (Fig. 2) is presented, illustrating the progression from mangrove ecological functions, through anthropogenic and climate-related threats, to socio-economic implications,

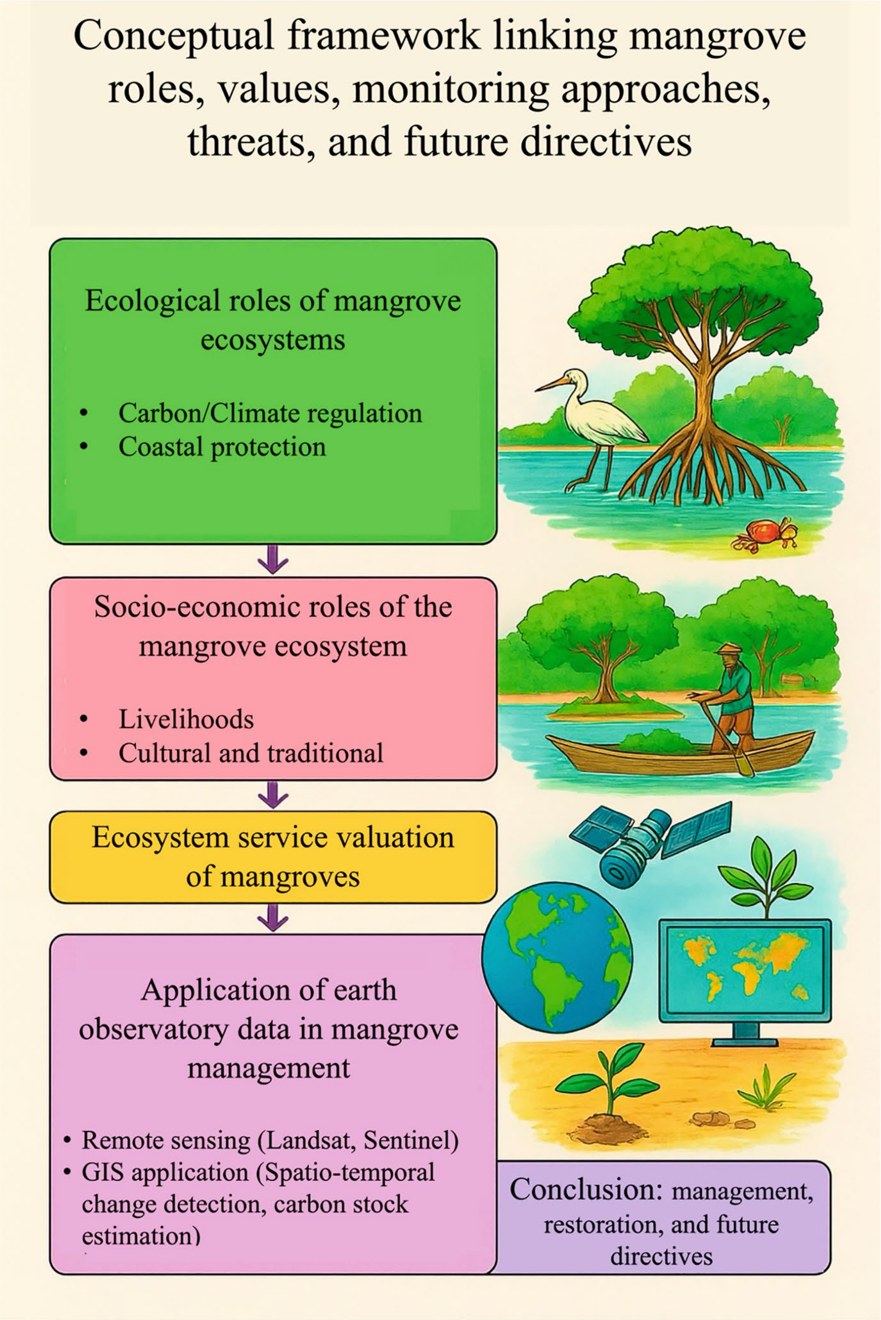

Fig. 2 Conceptual framework illustrating the ecological roles, socio-economic values, monitoring approaches, threats, and future directives of mangrove ecosystems

Earth observation (EO) and GIS-based monitoring approaches, and finally management, restoration, and future perspectives. This sequential organization underscores the interconnected nature of mangrove ecosystem services, pressures, and conservation strategies.

2 Ecological Roles of Mangrove Ecosystems

Mangrove ecosystems provide a diverse array of ecological services that are vital to both the environment and human societies. These roles can be broadly categorized into three main aspects: carbon/climate regulation, coastal protection and disaster mitigation, and biodiversity hotspots. Each of these roles underscores the unique and indispensable value of mangroves in maintaining ecological balance and supporting human livelihoods.

2.1 Carbon/Climate Regulation

Among the most effective carbon sinks on Earth, mangrove forests are playing a crucial role in climate regulation through carbon sequestration and long-term storage. As blue carbon ecosystems, they store significant amounts of carbon in both biomass and sediments, with their capacity far exceeding that of many terrestrial forests (Choudhary et al., 2024). The unique anaerobic conditions in mangrove soils slow the decomposition of organic matter, allowing carbon to accumulate over centuries to millennia (Dasat & Sam, 2022).

2.1.1 Mechanisms of Carbon Sequestration

Mangrove ecosystems regulate climate through three primary mechanisms: atmospheric carbon uptake and biomass accumulation, sediment carbon burial, and outwelling to marine ecosystems. First, mangrove trees actively capture atmospheric CO_2 through photosynthesis, subsequently storing carbon in both above-ground (leaves, stems, and branches) and below-ground (roots) biomass (Choudhary et al., 2024). Research indicates that mangrove forests exhibit an average net primary production of 226 g C m^2 $year^{-1}$, a rate that exceeds that of many terrestrial forests. This high productivity contributes significantly to global carbon sequestration efforts (Mcleod et al., 2011; Tang et al., 2018).

Second, unlike terrestrial ecosystems, mangroves store a substantial portion of their carbon stock in waterlogged, anoxic soils, which create conditions that markedly slow organic matter decomposition (Choudhary et al., 2024). As a result, 50–90% of total carbon in mangrove ecosystems is retained within sediments for extended periods. Moreover, due to the influence of regional hydrological dynamics, species composition, and sedimentation rates, carbon burial rates in these ecosystems vary from 0.17 to 4.3 Mg C ha^{-1} $year^{-1}$ (Kelleway et al., 2017a, 2017b; Lamont et al., 2020). This long-term carbon storage in mangrove sediments plays a dynamic role in mitigating atmospheric CO_2 concentrations and buffering the effects of climate change.

Lastly, through the outwelling process, organic carbon is exported to adjacent marine ecosystems, resulting in significant contribution to the broader carbon cycle. This mechanism facilitates the transfer of mangrove-derived organic material to seagrass meadows and offshore sediments, where it is further sequestered (Hemminga et al., 1994; Chen et al., 2017). Empirical studies have reported that up to 83% of the carbon buried in seagrass beds in proximity to mangroves originates from these coastal forests (Potouroglou et al., 2017). This relationship highlights the role of mangroves as critical components of coastal carbon dynamics, emphasizing their importance in sustaining global blue carbon stocks.

2.1.2 Regional Variability in Carbon Sequestration

Environmental conditions such as tidal hydrodynamics, soil characteristics, and species composition drive the carbon dynamics, resulting in different sequestration rates in different mangrove ecosystems (Table 1). The following table presents a comparison of global mangrove ecosystems in terms of carbon sequestration efficiency:

2.2 Coastal Protection and Disaster Mitigation

Mangrove ecosystems function as natural coastal defenses, reducing the impact of extreme weather events, mitigating erosion, and stabilizing shorelines. Their dense root networks dissipate wave energy, trap sediments, and prevent shoreline retreat, making them essential for coastal resilience in the face of climate change (Marois & Mitsch, 2015; Gijsman et al., 2021). Previous literature has shown that mangrove forests can mitigate wave energy by up to 99% across a 500-m-wide forest, resulting significant decrease in coastal vulnerability to storm surges and flooding (McIvor et al., 2012). One of the primary mechanisms is named wave energy dissipation, through which mangroves reduce disaster risk. Mangrove forests act as wave breakers; the velocity of waves passing through them is gradually reduced by friction from trunks, aerial roots, and pneumatophores. Research indicates that mangroves lower wave height by 13–66% over a 100-m stretch, with larger and denser forests providing greater protection (McIvor et al., 2012). In addition to wave attenuation, mangroves act as storm surge buffers, reducing both the extent and severity of coastal flooding (Montgomery et al., 2019). For example, regions

Table 1 Global variation in mangrove soil organic carbon (SOC) storage across different coastal environmental settings (CES)

Mangrove ecosystem	Carbon sequestration (Mg/ha/year)	Total carbon stock (Mg/ha)	Role in climate mitigation
Deltaic (Amazon, Caravelas, etc.)	5.5–6.5	400–800	High sediment input supports rapid SOC accumulation, but past estimates overestimated SOC by 86%
Estuarine (Florida Coastal Everglades, Costa Rica)	3.5–5.0	900–1500	Tidal influence enhances soil aeration, reducing decomposition, leading to high SOC stability
Carbonate (Karstic, Bahamas, Pacific Atolls)	4.0–5.5	1200–2200	Peat-dominated soils store 50% more SOC than previously estimated, making these settings key blue carbon reservoirs
Bedrock (Brazil, Caribbean, SE Asia)	2.5–3.5	600–1000	Limited sediment supply reduces sequestration rates, but long-term carbon storage potential remains significant
Lagoonal (West Africa, SE Asia, Central America)	3.0–4.5	700–1100	Moderate SOC retention with a mix of marine and riverine carbon sources
Composite (Mixed River & Wave, Indo-Pacific, Gulf of Mexico)	4.0–6.0	1000–1800	Dynamic sediment processes enhance carbon burial efficiency, with stable SOC pools

The table summarizes estimated carbon sequestration rates, total carbon stocks, and their role in climate mitigation. Data highlight the influence of geomorphological and hydrological processes on SOC variability, with carbonate settings storing more carbon than previously estimated and deltaic settings showing past overestimations. Estimates are based on a global compilation of field measurements integrated into an eco-geomorphological modeling framework (Rovai et al., 2018)

with mangrove forests wider than 1 km experienced 24% lower economic losses from hurricanes compared to areas with degraded mangroves in Central America (Del Valle et al., 2020). Mangroves contribute to socio-economic resilience by safeguarding infrastructure, agricultural land, and fisheries, besides their biophysical functions. By ensuring sustainable livelihoods through resources such as timber, fish, and other marine products while simultaneously serving as crucial carbon sinks, mangroves play critical roles in the coastal zone of several regions. Economically, their protective functions are substantial, with estimates suggesting that mangroves help prevent approximately $65 billion in annual flood-related damages and shield over 15 million people globally from coastal hazards (Menéndez et al., 2020).

Table 2 Key species associated with mangrove ecosystems, highlighting their ecological roles, economic importance, and dependence on mangrove habitats

Species	Ecological role	Economic importance	Dependence on mangroves	Source
Bengal tiger (*Panthera tigris*)	Apex predator; maintains ecological balance	Tourism, cultural value, conservation importance	Habitat and prey availability within mangrove ecosystems	Ghosh et al. (2015)
Mud crab (*Scylla* spp.)	Keystone species; ecosystem engineer, food source	Fishing industry, culinary value, local livelihoods	Spawning and nursery grounds in mangrove areas	Lee (1998); Pati et al. (2023)
Mangrove snapper (*Lutjanus argentimaculatus*)	Predatory fish; maintains marine food web	Fisheries, important for local economies	Habitat in mangrove roots and estuarine areas	Aburto-Oropeza et al. (2009); Sandilyan and Kathiresan (2012)
Black mangrove (*Avicennia germinans*)	Critical to ecosystem structure; primary producer	Timber, fuelwood, medicinal uses, ecological services	Fundamental role in mangrove forest structure and regeneration	Satyanarayana et al. (2012); Friis and Killilea (2024)
Palaemonid shrimp (*Palaemon* spp.)	Important detritivore; contributes to nutrient cycling	Aquaculture, shrimp farming	Breeding and juvenile habitats in mangrove swamps	Solari et al. (2017)
Saltwater crocodile (*Crocodylus porosus*)	Apex predator, maintains balance in ecosystems	Tourism, cultural significance	Nesting and feeding habitats in mangrove forests	Semeniuk et al. (2011); Hanson et al. (2015)
Mangrove oyster (*Crassostrea* spp.)	Filter feeder; water quality improvement	Fisheries, shellfish industry	Thrives on mangrove roots and substrates	Chacin et al. (2025)
Herons and egrets (*Ardeidae* spp.)	Birds that control invertebrate and fish populations	Ecotourism, biodiversity indicator species	Nesting, roosting, and foraging within mangrove habitats	Etezadifar et al. (2010); Gopi and Pandav (2011); Ghasemi et al. (2012)

Mangroves support a diverse range of organisms, from apex predators to keystone species, contributing to ecosystem stability, fisheries, and ecotourism

2.3 *Biodiversity Hotspot*

Mangrove ecosystems are globally recognized as biodiversity hotspots (Table 2), providing critical habitats for over 1400 mangrove-affiliated species, including fish, crustaceans, mollusks, and birds (Rodrigues et al., 2004). These forests serve as nurseries and breeding grounds for 30–50% of commercially important fish species, playing an essential role in sustaining global fisheries (Cau et al., 2020). Their structural complexity, including aerial roots and dense canopies, offers refuge and feeding grounds for a wide array of marine organisms, enhancing coastal productivity and ecosystem stability.

Mangroves not only sustain aquatic ecology and marine biodiversity but also make a substantial contribution to terrestrial biodiversity, especially in areas where they coexist alongside tropical forests. Specialized species have evolved in response to the distinct environmental conditions of mangrove ecosystems, characterized by high salinity, waterlogged soils, and anoxic conditions (Alvarenga et al., 2015; Perri et al., 2023). Mangrove forests like the Sundarbans provide habitat and prey for apex predators like the Bengal tiger (*Panthera tigris*) (Loucks et al., 2010; Ghosh et al., 2015). The biological link between these coastal forests and neighburing ecosystems is further highlighted by the fact that migratory bird species, such as herons and egrets, rely on mangroves for both nesting and foraging (Zakaria & Rajpar, 2015; Kelleway et al., 2017b).

In addition to its economic significance, mangrove biodiversity supports a variety of businesses, including tourism, aquaculture, fisheries, and the harvesting of non-timber forest products. Both domestic and international seafood markets greatly benefit from commercially valuable species, such as mud crabs (*Scylla* spp.) and mangrove snappers (*Lutjanus argentimaculatus*). Furthermore, filter-feeding species like mangrove oysters (*Crassostrea* spp.) improve water quality while sustaining shellfish industries, and saltwater crocodiles (*Crocodylus porosus*) attract ecotourism revenue (Dame, 1993; Layman et al., 2014). The safeguarding of mangrove biodiversity is therefore crucial for both the long-term viability of these economic benefits as well as for preserving the integrity of the ecosystem.

3 Socio-economic Roles of Mangrove Ecosystem

Beyond their ecological significance, mangrove forests play a crucial role in sustaining livelihoods and preserving cultural heritage in coastal regions. These dynamic ecosystems support diverse economic activities, from fisheries and aquaculture to ecotourism and small-scale industries. At the same time, they hold deep cultural and spiritual value for many indigenous and local communities. However, the extent to which people benefit from these forests varies, shaped by economic dependency, regional traditions, and community awareness.

3.1 Livelihood

For millions of coastal residents, mangrove resources provide a primary means of sustenance and economic stability. Fisheries, aquaculture, and the harvesting of crabs, mollusks, and honey contribute significantly to household incomes, particularly in rural settlements where alternative employment opportunities are scarce. A study conducted in Myanmar involving over 185 households showed that 43% of households generated their income through selling forest products (Aye et al., 2019). Small-scale enterprises centered around mud crab (*Scylla* spp.) farming, shrimp aquaculture, and beekeeping have emerged as profitable ventures, enhancing financial resilience for coastal communities (Mirera et al., 2014; Hua et al., 2025). Additionally, livestock grazing in mangrove areas provides a supplementary source of income, particularly in regions where agricultural land is limited (Ahouangan et al., 2022). However, despite these benefits, economic disparities exist. In some areas, a negative correlation between ecosystem services and community well-being has been observed, largely due to unsustainable resource extraction, economic instability, and the lack of diversified income sources.

A shift toward sustainable economic models can help balance conservation and economic needs. Encouraging responsible aquaculture, adding value to mangrove-derived products, and integrating eco-friendly enterprises into local economies can enhance both community well-being and the long-term sustainability of these ecosystems.

3.2 Cultural/Traditional

Across many coastal societies, mangroves hold deep cultural and historical importance. From traditional fishing techniques and folklore to religious practices, these forests are woven into the identity of local communities. In certain regions, they are even regarded as protective natural barriers against storms and tidal surges, reinforcing their spiritual significance. Beyond their role in tradition, these coastal forests provide recreational and aesthetic benefits, fostering ecotourism and nature-based cultural activities. A study in the Hara Biosphere Reserve which is a key mangrove area, shows that 81.2% of visitors are willing to pay for access, indicating people's attraction to this ecosystem including birdwatchers, researchers, and visitors seeking immersive experiences in nature (Dehghani et al., 2010). The rise of boat tours, wildlife excursions, and eco-cultural festivals has not only increased environmental awareness but also generated revenue for local economies. However, the degree to which mangroves remain embedded in cultural practices varies. Urbanization and industrial development have led to a decline in traditional knowledge and reduced direct engagement with these forests in some communities (Rangel et al., 2024). Preserving this cultural heritage requires proactive efforts, such as community-led conservation programs, integration of traditional ecological knowledge in resource management, and promotion of sustainable ecotourism initiatives.

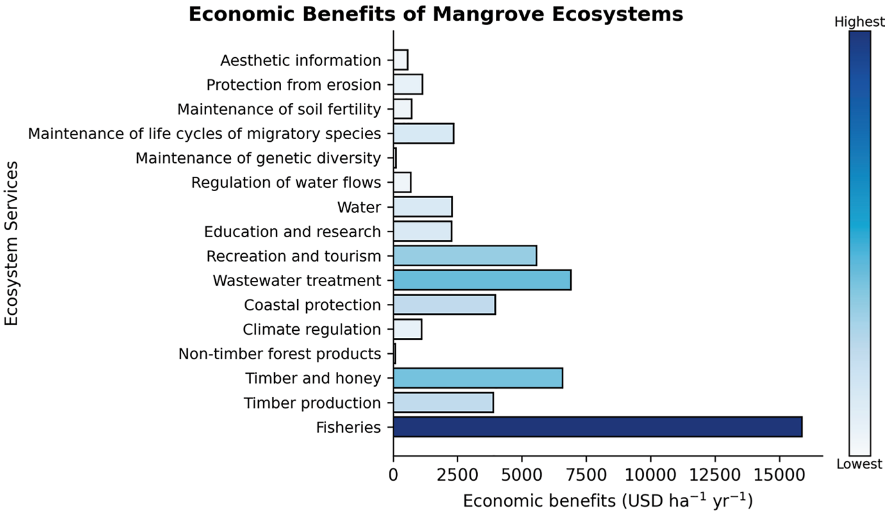

Fig. 3 Economic benefits of mangrove ecosystems, comparing restored and natural mangrove ecosystems across various ecosystem services. The bar length represents the total economic value (USD ha^{-1} year^{-1}) associated with each ecosystem service. The color gradient reflects the range of values from lowest to highest. Data source: (Su et al., 2021)

4 Ecosystem Service Valuation of Mangroves

Ecosystem service valuation is a fundamental tool for quantifying the ecological, economic, and social benefits provided by mangroves (Fig. 3). These intertidal forests deliver a wide array of services, categorized into provisioning, regulating, and cultural services. Among provisioning services, fisheries rank as the most valuable, with an average estimated value of 17,090 USD per hectare per year, reflecting their critical role as nurseries for commercially important fish and crustacean species (Mukherjee et al., 2014). Wood and timber resources, essential for fuel and construction in many developing countries, are another key provisioning service, though often undervalued at approximately 247 USD per hectare per year (Mukherjee et al., 2014). Mangroves offer significant regulating services, particularly in coastal protection by buffering storm surges and mitigating erosion, valued at 8459 USD per hectare per year. They are also highly effective in carbon sequestration, storing 1023 Mg C per hectare, surpassing other tropical forest ecosystems (Donato et al., 2011).

Despite their vital ecological function, services like bioremediation of pollutants and protection from salt intrusion are rarely represented in economic assessments, leaving significant gaps in understanding their full value. Cultural services such as ecotourism and aesthetic appreciation provide additional socio-economic benefits, particularly in regions where mangroves attract visitors. However, these services remain underrepresented in valuation exercises, especially in developing countries where community livelihoods heavily depend on mangrove ecosystems. The disparity between expert-based assessments and monetary valuations highlights the need for inclusive valuation frameworks that recognize the plurality of benefits mangroves provide. It is also important to recognize the limitations of economic valuation itself. Many non-market services, particularly cultural, spiritual, and relational values, are inherently difficult to monetize and risk being undervalued or overlooked in purely monetary frameworks (Hejnowicz & Rudd, 2017). Over-reliance on market-based estimates can therefore bias decision-making toward easily quantified services, potentially marginalizing benefits that are equally critical for local communities and long-term sustainability. Such comprehensive approaches can better inform policy decisions, improve conservation incentives, and promote sustainable management of mangrove ecosystems.

5 Application of Remote Sensing and GIS in Mangrove Management

Advances in Earth observation (EO) and geographic information systems (GIS) have primarily transformed mangrove monitoring, providing robust tools to quantify ecosystem extent, structure, dynamics, and vulnerability at multiple spatial and temporal scales. Global-scale datasets, such as the Global Mangrove Forest Cover (Hamilton & Casey, 2016) and the Hansen Global Forest Change (GFC) dataset (Hansen et al., 2013), have enabled consistent mapping of mangrove distribution and long-term loss trends. More recently, the Global Mangrove Watch (GMW) integrates multi-sensor satellite data to provide near-real-time monitoring of mangrove extent, allowing for high-resolution assessments of deforestation, degradation, and restoration trajectories (Bunting et al., 2022). These datasets provide essential baselines for assessing ecosystem services and informing climate mitigation strategies, particularly in the context of blue carbon accounting.

Remote sensing platforms offer complementary capabilities for detailed mangrove characterization. Optical sensors such as Landsat (Hemati et al., 2021) and Sentinel-2 (Misra et al., 2020) facilitate multidecadal change detection, canopy phenology monitoring, and biomass estimation, while MODIS data supports large-scale temporal analyses of productivity and greenness of mangroves (Ishtiaque et al., 2016). High-resolution commercial satellites, including PlanetScope, enable localized mapping for mangrove management interventions with carbon stock estimation (Purnamasari et al., 2021), whereas LiDAR and synthetic aperture radar (SAR) provide three-dimensional structural information, canopy height, and aboveground biomass estimates even under cloud-prone conditions (Kaasalainen et al., 2015). Hyperspectral sensors further allow species-level discrimination, supporting biodiversity assessments and ecological niche mapping.

GIS-based analyses extend the utility of EO data by integrating spatial layers to model mangrove vulnerability, carbon stock distribution, and ecosystem service provisioning (Kuenzer & Tuan, 2013). Change detection algorithms, spatial overlay analyses, and hydrodynamic modeling have been employed to identify high-risk areas for erosion, sea-level rise, and anthropogenic encroachment (Youssef et al., 2021). Carbon stock estimation using EO-derived biomass models informs carbon credit and payment-for-ecosystem-service programs, while spatial prioritization tools support restoration planning, protected area design, and policy enforcement (Le et al., 2021).

Collectively, these Earth observation and GIS approaches provide a quantitative, spatially explicit framework that bridges ecological assessment with management action. By integrating multi-source satellite data and geospatial analyses, practitioners can identify degradation hotspots, monitor recovery trajectories, evaluate ecosystem service flows, and implement evidence-based conservation strategies. The convergence of remote sensing, GIS, and ecological modeling thus underpins contemporary mangrove management, offering scalable solutions to safeguard these critical coastal ecosystems under accelerating anthropogenic and climate pressures.

6 Major Threats and Consequences

Mangrove ecosystems face escalating threats driven by both anthropogenic activities and environmental changes (Table 3). Over the past five decades, approximately 35% of global mangrove coverage has been lost (Gouvêa et al., 2022), with Asia contributing 36% of these losses (Yousefi & Naderloo, 2022). The primary drivers of mangrove degradation include coastal development, aquaculture expansion, and deforestation for timber and fuelwood. Coastal infrastructure projects such as resorts, ports, and dams disrupt natural hydrological flows, resulting in increased soil erosion, altered salinity, and habitat fragmentation. Aquaculture, particularly large-scale shrimp farming, has converted up to 52% of mangrove forests globally in recent decades, with Indonesia, Vietnam, and Bangladesh among the most affected regions (Bhowmik et al., 2022).

Deforestation for timber and fuelwood extraction accounts for 26% of mangrove loss, driven by local demand for construction materials and energy sources (Ferreira et al., 2022). Beyond human-induced pressures, climate change exacerbates mangrove vulnerability through rising sea levels, increased storm intensity, and shifts in precipitation patterns, which alter species composition and productivity. The rise in sea level, projected to reach 1.5–2.5 m by 2099, poses a significant threat to low-lying mangrove forests, particularly in deltaic regions (Akram et al., 2023).

Pollution from industrial discharge, agricultural runoff, and oil spills further degrades mangrove habitats, impairing their water filtration capacity and leading to biodiversity loss. Additionally, eutrophication—driven by excessive nutrient input—stimulates harmful algal blooms that suffocate mangrove roots and reduce photosynthetic efficiency (Sarkar & Sarkar, 2018; Tsikoti & Genitsaris, 2021). The combined impacts of these threats not only compromise the ecological integrity of mangrove forests but also diminish their capacity to deliver vital ecosystem services, including coastal protection, carbon sequestration, and fishery support.

Table 3 Major anthropogenic and natural threats to mangrove ecosystems and their associated ecological consequences

Threat category	Major threats	Consequences	Reference
Anthropogenic	Coastal development	Habitat fragmentation, erosion, altered hydrology	Arévalo-Mejía et al. (2020); Vousdoukas et al. (2020)
	Deforestation for timber	Reduction in carbon storage, habitat degradation	Lee et al. (2019); Arias-Ortiz et al. (2021)
	Pollution (industrial and agricultural runoff)	Water quality degradation, eutrophication, biodiversity loss	Tsikoti and Genitsaris (2021); Tekman et al. (2022); Bindiya et al. (2023)
	Biological invasion	Altered species composition, competition with native species	Mandal et al. (2022)
Natural	Climate change and sea-level rise	Coastal erosion, habitat loss, salt intrusion, altered species composition	Godoy et al. (2018); De Lacerda et al. (2019); Li et al. (2022)
	Storm surges and cyclones	Physical destruction, increased soil salinity, vegetation mortality	Hoppe-Speer et al. (2011); Asbridge et al. (2015)
	Tidal inundation	Waterlogging, sedimentation changes, reduced seedling recruitment	Xie et al. (2020)
	Temperature fluctuations	Range shifts, altered growth patterns, species mortality	Li et al. (2022)
	Coastal development	Habitat fragmentation, erosion, altered hydrology	Akram et al. (2023)

Effective mitigation strategies require integrated management approaches that address both direct human pressures and the broader impacts of climate change.

7 Conclusion

Mangrove ecosystems are among the most functionally diverse and ecologically vital coastal biomes, providing essential services such as carbon sequestration, coastal protection, biodiversity support, and socio-economic benefits. Their role as blue carbon reservoirs underscores their significance in climate mitigation, while their ability to attenuate wave energy and buffer storm surges highlights their importance as natural coastal defenses. Additionally, mangroves serve as nurseries for commercially valuable marine species and support millions of coastal livelihoods, reinforcing the link between ecosystem integrity and human well-being.

Despite their critical ecological and economic roles, mangrove forests are increasingly threatened by deforestation, habitat conversion, pollution, and climate change. Addressing these challenges requires integrated conservation strategies, including habitat restoration, sustainable resource management, and policy interventions informed by ecological and socio-economic research. Given their resilience and capacity for regeneration, targeted conservation initiatives, coupled with community engagement and adaptive governance, can enhance their long-term sustainability.

Moving forward, bridging knowledge gaps and implementing science-based policies that recognize the full value of mangrove ecosystem services will be essential. Collaboration among ecologists, policymakers, and local communities will ensure conservation efforts align with socio-economic priorities, balancing environmental protection with human development. By safeguarding mangroves, we not only preserve critical coastal ecosystems but also contribute to global climate stability and long-term resilience.

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