

Different Roles of Mangrove Ecosystems and Their Significance

Md Rezaul Karim, Md. Shamim Reza Saimun, Md Shydul Amin,
Md. Sahinur Islam Fahim, Fahmida Sultana, Dhananjay Barman,
Sanjeev Kumar Srivastava, Sharif A. Mukul,
and Mohammed A. S. Arfin-Khan

Abstract Mangrove forests, covering ~167,000–181,000 km² 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

M. R. Karim

Institute of Forestry and Conservation, John H. Daniels Faculty of Architecture, Landscape, and Design, University of Toronto, Toronto, ON, Canada

M. S. R. Saimun · M. S. Amin · M. S. I. Fahim · M. A. S. Arfin-Khan (✉)

Department of Forestry and Environmental Science, School of Agriculture and Mineral Sciences, Shahjalal University of Science and Technology, Sylhet, Bangladesh
e-mail: khan-for@sust.edu

F. Sultana

Department of Forestry and Environmental Science, School of Agriculture and Mineral Sciences, Shahjalal University of Science and Technology, Sylhet, Bangladesh

Department of Biosciences, Faculty of Science and Engineering, Swansea University, Swansea, UK

D. Barman

ICAR—Central Research Institute for Jute and Allied Fibers, Kolkata, India

S. K. Srivastava

School of Science, Technology and Engineering (SSTE), University of the Sunshine Coast, Sippy Downs, QLD, Australia

S. A. Mukul

School of Science, Technology and Engineering (SSTE), University of the Sunshine Coast, Sippy Downs, QLD, Australia

Department of Environment and Development Studies, United International University, Dhaka, Bangladesh

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

31 **Keywords** Carbon regulation · Mangrove conservation · Mangrove resilience ·
32 Adaptive governance

33 1 Introduction

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

49 Mangroves are distributed across tropical and subtropical coastlines in over 123
50 countries (Cummings & Shah, 2018), covering an estimated 167,000 to 181,000 km²
51 globally (Fig. 1) (Giri et al., 2011). Their distribution can be broadly categorized
52 into two major biogeographic zones: the western zone, encompassing the Atlantic

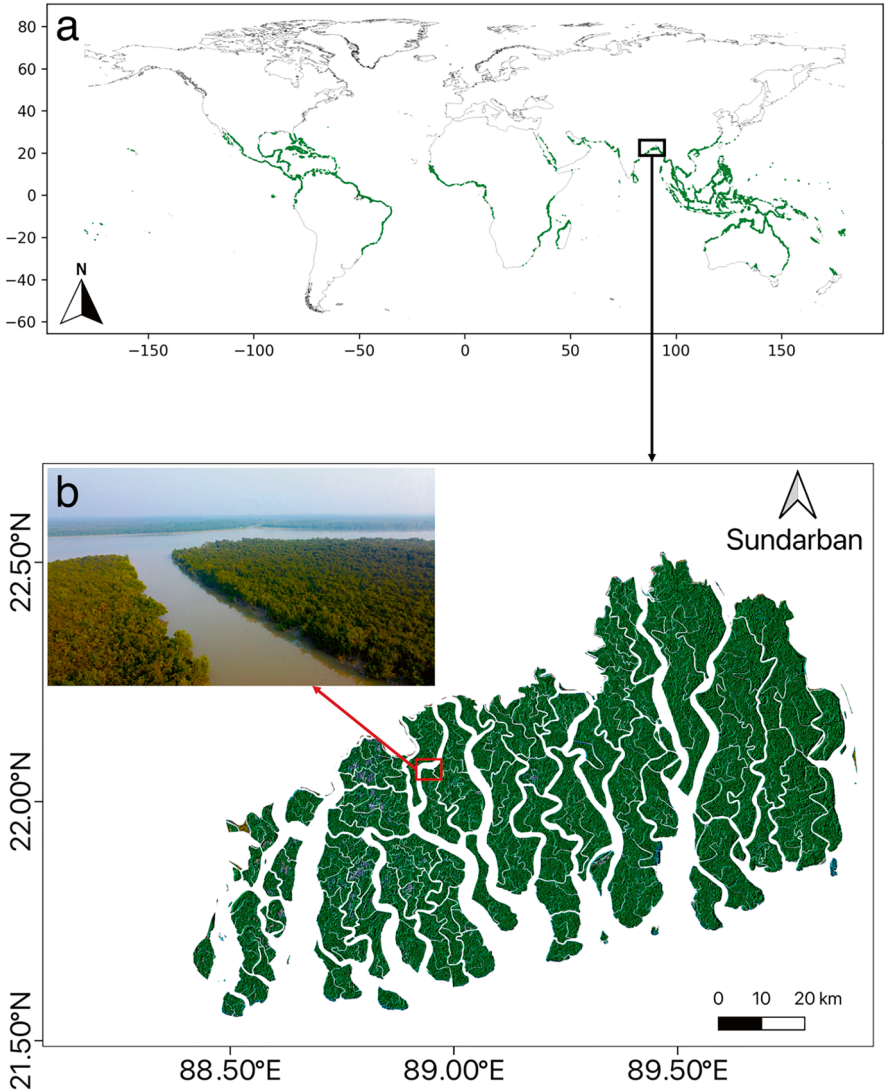


Fig. 1 (a) Global distribution of mangrove forests derived from Earth observation data. Mangrove extent was mapped using the Global Land Survey (GLS) dataset and the Landsat archive, with approximately 1000 Landsat scenes classified through a hybrid supervised–unsupervised digital image classification 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

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

66 The resilience of mangrove ecosystems is attributed to their remarkable physio-
67 logical and structural adaptations, which enable them to thrive in saline, water-
68 logged, and anoxic conditions (Kumari & Rathore, 2021). These adaptations include
69 aerial root systems, salt-excreting mechanisms, and viviparous propagules, all of
70 which contribute to their survival in fluctuating coastal environments (Naskar &
71 Palit, 2015). However, regional variations in environmental conditions and human-
72 induced pressures result in differing patterns of degradation and restoration poten-
73 tial. While extensive research has been conducted on mangrove ecology and
74 conservation, much of the existing literature is fragmented, often focusing on iso-
75 lated ecological or socio-economic aspects. Recent advances in remote sensing
76 have provided complementary global and regional assessments of mangrove extent,
77 dynamics, and degradation trajectories (e.g., Lu & Wang, 2021; Tran et al., 2022),
78 which offer important spatial baselines. This chapter seeks to bridge these gaps by
79 presenting an integrative perspective that encompasses the ecological functions,
80 socio-economic roles, and conservation imperatives of mangroves. Unlike conven-
81 tional reviews that emphasize either biodiversity conservation or economic valua-
82 tion, this chapter highlights the interconnectedness of these dimensions, emphasizing
83 how mangrove resilience is intrinsically linked to human well-being and climate
84 adaptation strategies.

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

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

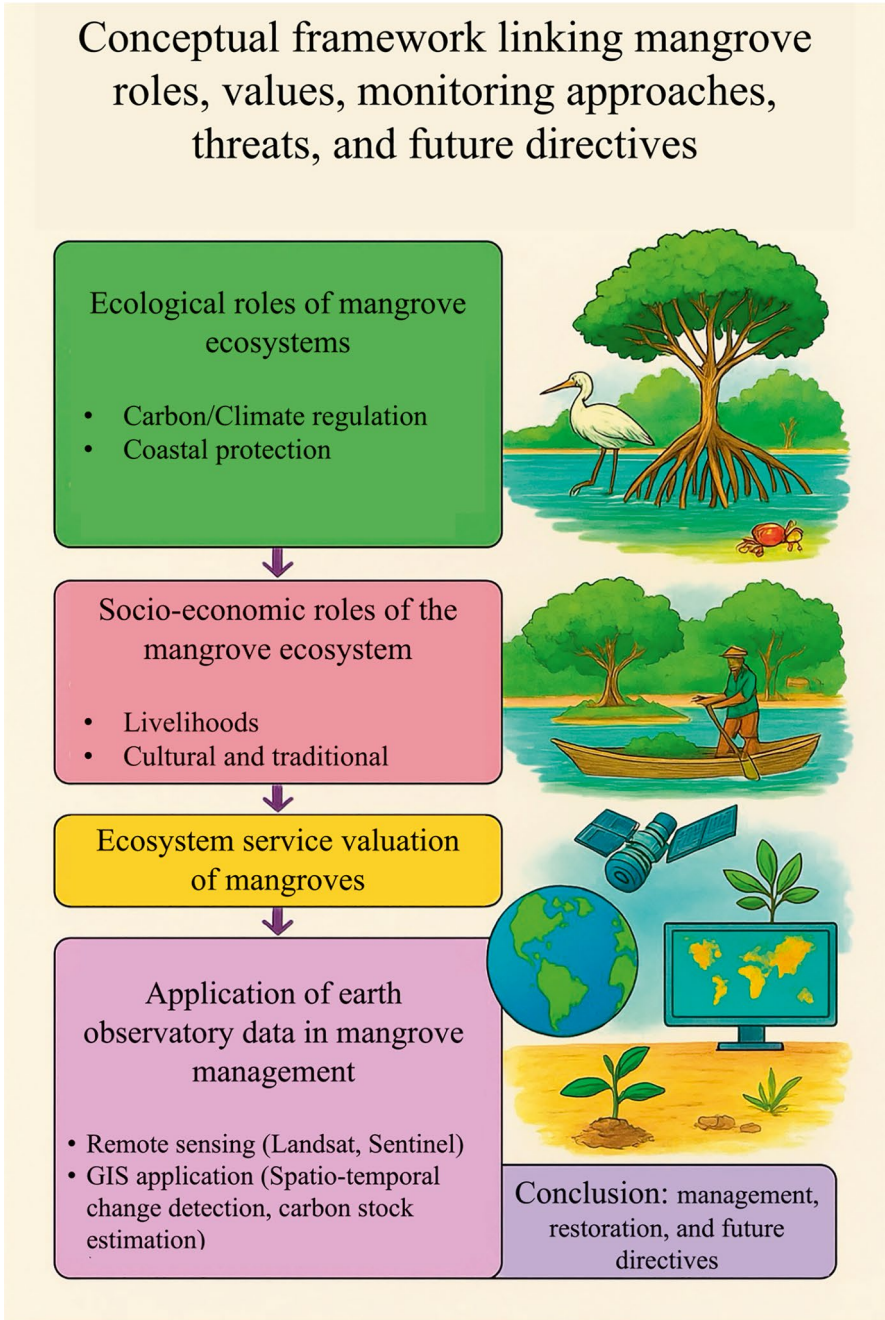


Fig. 2 Conceptual framework illustrating the ecological roles, socio-economic values, monitoring approaches, threats, and future directives of mangrove ecosystems

98 Earth observation (EO) and GIS-based monitoring approaches, and finally manage-
99 ment, restoration, and future perspectives. This sequential organization underscores
100 the interconnected nature of mangrove ecosystem services, pressures, and conserva-
101 tion strategies.

102 **2 Ecological Roles of Mangrove Ecosystems**

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

109 **2.1 Carbon/Climate Regulation**

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

117 **2.1.1 Mechanisms of Carbon Sequestration**

118 Mangrove ecosystems regulate climate through three primary mechanisms: atmo-
119 spheric carbon uptake and biomass accumulation, sediment carbon burial, and out-
120 welling to marine ecosystems. First, mangrove trees actively capture atmospheric
121 CO₂ through photosynthesis, subsequently storing carbon in both above-ground
122 (leaves, stems, and branches) and below-ground (roots) biomass (Choudhary et al.,
123 2024). Research indicates that mangrove forests exhibit an average net primary pro-
124 duction of 226 g C m² year⁻¹, a rate that exceeds that of many terrestrial forests. This
125 high productivity contributes significantly to global carbon sequestration efforts
126 (McLeod et al., 2011; Tang et al., 2018).

127 Second, unlike terrestrial ecosystems, mangroves store a substantial portion of
128 their carbon stock in waterlogged, anoxic soils, which create conditions that mark-
129 edly slow organic matter decomposition (Choudhary et al., 2024). As a result,
130 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 CO₂ 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 146

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: 151

2.2 Coastal Protection and Disaster Mitigation 152

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; Gijssman 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 in 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 167

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)

168 with mangrove forests wider than 1 km experienced 24% lower economic losses
 169 from hurricanes compared to areas with degraded mangroves in Central America
 170 (Del Valle et al., 2020). Mangroves contribute to socio-economic resilience by safe-
 171 guarding infrastructure, agricultural land, and fisheries, besides their biophysical
 172 functions. By ensuring sustainable livelihoods through resources such as timber,
 173 fish, and other marine products while simultaneously serving as crucial carbon
 174 sinks, mangroves play critical roles in the coastal zone of several regions.
 175 Economically, their protective functions are substantial, with estimates suggesting
 176 that mangroves help prevent approximately \$65 billion in annual flood-related
 177 damages and shield over 15 million people globally from coastal hazards (Menéndez
 178 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 (<i>Panthera tigris</i>)	Apex predator; maintains ecological balance	Tourism, cultural value, conservation importance	Habitat and prey availability within mangrove ecosystems	Ghosh et al. (2015)
Mud crab (<i>Scylla</i> 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 (<i>Lutjanus argentimaculatus</i>)	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 (<i>Avicennia germinans</i>)	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 (<i>Palaemon</i> spp.)	Important detritivore; contributes to nutrient cycling	Aquaculture, shrimp farming	Breeding and juvenile habitats in mangrove swamps	Solari et al. (2017)
Saltwater crocodile (<i>Crocodylus porosus</i>)	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 (<i>Crassostrea</i> spp.)	Filter feeder; water quality improvement	Fisheries, shellfish industry	Thrives on mangrove roots and substrates	Chacin et al. (2025)
Herons and egrets (<i>Ardeidae</i> 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

179

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

180
181
182
183
184

185 structural complexity, including aerial roots and dense canopies, offers refuge and
186 feeding grounds for a wide array of marine organisms, enhancing coastal productiv-
187 ity and ecosystem stability.

188 Mangroves not only sustain aquatic ecology and marine biodiversity but also
189 make a substantial contribution to terrestrial biodiversity, especially in areas where
190 they coexist alongside tropical forests. Specialized species have evolved in response
191 to the distinct environmental conditions of mangrove ecosystems, characterized by
192 high salinity, waterlogged soils, and anoxic conditions (Alvarenga et al., 2015; Perri
193 et al., 2023). Mangrove forests like the Sundarbans provide habitat and prey for
194 apex predators like the Bengal tiger (*Panthera tigris*) (Loucks et al., 2010; Ghosh
195 et al., 2015). The biological link between these coastal forests and neighboring eco-
196 systems is further highlighted by the fact that migratory bird species, such as herons
197 and egrets, rely on mangroves for both nesting and foraging (Zakaria & Rajpar,
198 2015; Kelleway et al., 2017b).

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

209 **3 Socio-economic Roles of Mangrove Ecosystem**

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

217 **3.1 Livelihood**

218 For millions of coastal residents, mangrove resources provide a primary means of
219 sustenance and economic stability. Fisheries, aquaculture, and the harvesting of
220 crabs, mollusks, and honey contribute significantly to household incomes, particu-
221 larly 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.

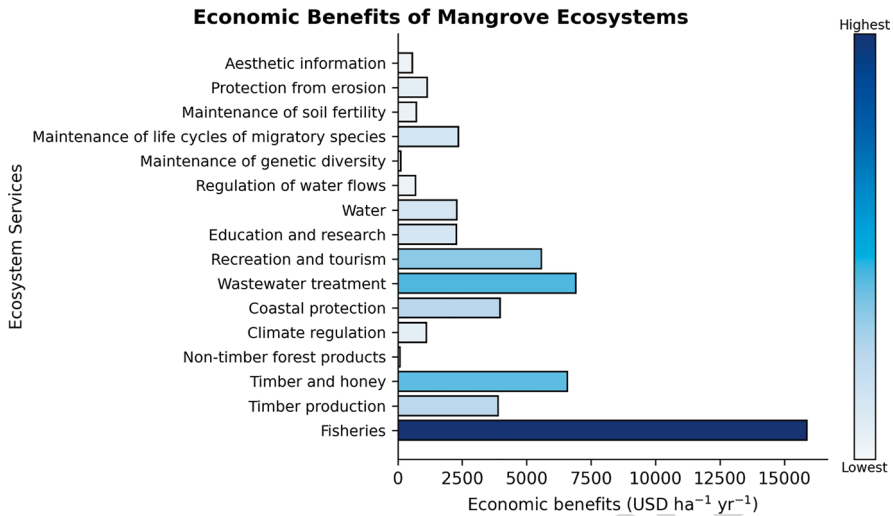


Fig. 3 Economic benefits of mangrove ecosystems, comparing restored and natural mangrove ecosystems across various ecosystem services. The bar length represents the total economic value (USD ha⁻¹ year⁻¹) associated with each ecosystem service. The color gradient reflects the range of values from lowest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

257 **4 Ecosystem Service Valuation of Mangroves**

258 Ecosystem service valuation is a fundamental tool for quantifying the ecological,
 259 economic, and social benefits provided by mangroves (Fig. 3). These intertidal forests
 260 deliver a wide array of services, categorized into provisioning, regulating, and
 261 cultural services. Among provisioning services, fisheries rank as the most valuable,
 262 with an average estimated value of 17,090 USD per hectare per year, reflecting their
 263 critical role as nurseries for commercially important fish and crustacean species
 264 (Mukherjee et al., 2014). Wood and timber resources, essential for fuel and construction
 265 in many developing countries, are another key provisioning service, though often
 266 undervalued at approximately 247 USD per hectare per year (Mukherjee et al., 2014).
 267 Mangroves offer significant regulating services, particularly in coastal protection by
 268 buffering storm surges and mitigating erosion, valued at 8459 USD per hectare per year.
 269 They are also highly effective in carbon sequestration, storing 1023 Mg C per hectare,
 270 surpassing other tropical forest ecosystems (Donato et al., 2011).
 271

272 Despite their vital ecological function, services like bioremediation of pollutants
 273 and protection from salt intrusion are rarely represented in economic assessments,
 274 leaving significant gaps in understanding their full value. Cultural services such as
 275 ecotourism and aesthetic appreciation provide additional socio-economic benefits,
 276 particularly in regions where mangroves attract visitors. However, these services
 277 remain underrepresented in valuation exercises, especially in developing countries
 278 where community livelihoods heavily depend on mangrove ecosystems. The disparity
 279 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

320 areas for erosion, sea-level rise, and anthropogenic encroachment (Youssef et al.,
321 2021). Carbon stock estimation using EO-derived biomass models informs carbon
322 credit and payment-for-ecosystem-service programs, while spatial prioritization
323 tools support restoration planning, protected area design, and policy enforcement
324 (Le et al., 2021).

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

334 **6 Major Threats and Consequences**

335 Mangrove ecosystems face escalating threats driven by both anthropogenic activi-
336 ties and environmental changes (Table 3). Over the past five decades, approximately
337 35% of global mangrove coverage has been lost (Gouvêa et al., 2022), with Asia
338 contributing 36% of these losses (Yousefi & Naderloo, 2022). The primary drivers
339 of mangrove degradation include coastal development, aquaculture expansion, and
340 deforestation for timber and fuelwood. Coastal infrastructure projects such as
341 resorts, ports, and dams disrupt natural hydrological flows, resulting in increased
342 soil erosion, altered salinity, and habitat fragmentation. Aquaculture, particularly
343 large-scale shrimp farming, has converted up to 52% of mangrove forests globally
344 in recent decades, with Indonesia, Vietnam, and Bangladesh among the most
345 affected regions (Bhowmik et al., 2022).

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

353 Pollution from industrial discharge, agricultural runoff, and oil spills further
354 degrades mangrove habitats, impairing their water filtration capacity and leading to
355 biodiversity loss. Additionally, eutrophication—driven by excessive nutrient
356 input—stimulates harmful algal blooms that suffocate mangrove roots and reduce
357 photosynthetic efficiency (Sarkar & Sarkar, 2018; Tsikoti & Genitsaris, 2021). The
358 combined impacts of these threats not only compromise the ecological integrity of
359 mangrove forests but also diminish their capacity to deliver vital ecosystem ser-
360 vices, 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.

372 Despite their critical ecological and economic roles, mangrove forests are
 373 increasingly threatened by deforestation, habitat conversion, pollution, and climate
 374 change. Addressing these challenges requires integrated conservation strategies,
 375 including habitat restoration, sustainable resource management, and policy inter-
 376 ventions informed by ecological and socio-economic research. Given their resil-
 377 ience and capacity for regeneration, targeted conservation initiatives, coupled with
 378 community engagement and adaptive governance, can enhance their long-term
 379 sustainability.

380 Moving forward, bridging knowledge gaps and implementing science-based
 381 policies that recognize the full value of mangrove ecosystem services will be essen-
 382 tial. Collaboration among ecologists, policymakers, and local communities will
 383 ensure conservation efforts align with socio-economic priorities, balancing environ-
 384 mental protection with human development. By safeguarding mangroves, we not
 385 only preserve critical coastal ecosystems but also contribute to global climate stabili-
 386 ty and long-term resilience.

387 References

- 388 Aburto-Oropeza, O., et al. (2009). Recruitment and ontogenetic habitat shifts of the yellow snap-
 389 per (*Lutjanus argentiventris*) in the Gulf of California. *Marine Biology*, 156(12), 2461–2472.
 390 <https://doi.org/10.1007/s00227-009-1271-5>
- 391 Ahouangan, B. S. C. M., et al. (2022). Ruminant keeping around mangrove forests in Benin (West
 392 Africa): Herders' perceptions of threats and opportunities for conservation of mangroves.
 393 *Discover Sustainability*, 3(1), 13. <https://doi.org/10.1007/s43621-022-00082-x>
- 394 Akram, H., et al. (2023). Mangrove health: A review of functions, threats, and challenges associ-
 395 ated with mangrove management practices. *Forests*, 14(9). <https://doi.org/10.3390/f14091698>
- 396 Alvarenga, D. O., et al. (2015). Cyanobacteria in mangrove ecosystems. *Biodiversity and
 397 Conservation*, 24(4), 799–817. <https://doi.org/10.1007/s10531-015-0871-2>
- 398 Arévalo-Mejía, R., et al. (2020). A baseline assessment of hydrologic alteration degree for the
 399 Mexican catchments at gauged rivers (2016). *Science of the Total Environment*, 729, 139041.
 400 <https://doi.org/10.1016/j.scitotenv.2020.139041>
- 401 Arias-Ortiz, A., et al. (2021). Losses of soil organic carbon with deforestation in mangroves of
 402 Madagascar. *Ecosystems*, 24(1), 1–19. <https://doi.org/10.1007/s10021-020-00500-z>
- 403 Asbridge, E., et al. (2015). Mangrove response to environmental changes predicted under varying
 404 climates: Case studies from Australia. *Current Forestry Reports*, 1, 178–194
- 405 Aye, W. N., et al. (2019). Contribution of mangrove forest to the livelihood of local communities in
 406 Ayeyarwaddy region, Myanmar. *Forests*. <https://doi.org/10.3390/f10050414>
- 407 Bhowmik, A. K., et al. (2022). Global mangrove deforestation and its interacting social-ecological
 408 drivers: A systematic review and synthesis. *Sustainability*. <https://doi.org/10.3390/su14084433>
- 409 Bindiya, E. S., Sreekanth, P. M., & Bhat, S. G. (2023). Conservation and management of mangrove
 410 ecosystem in diverse perspectives. In S. T. Sukumaran & T. R. Keerthi (Eds.), *Conservation
 411 and sustainable utilization of bioresources* (pp. 323–352). Springer Nature Singapore. https://doi.org/10.1007/978-981-19-5841-0_13
- 412 Blankespoor, B., Dasgupta, S., & Lange, G.-M. (2017). Mangroves as a protection from storm
 413 surges in a changing climate. *Ambio*, 46(4), 478–491
- 414 Bunting, P., et al. (2022). Global mangrove extent change 1996–2020: Global mangrove watch
 415 version 3.0. *Remote Sensing*, 14(15). <https://doi.org/10.3390/rs14153657>

- Cau, A., et al. (2020). The nursery role of marine animal forests. In S. Rossi & L. Bramanti (Eds.), *Perspectives on the marine animal forests of the world* (pp. 309–331). Springer International Publishing. https://doi.org/10.1007/978-3-030-57054-5_10
- Chacin, D. H., Bell, S. S., & Stallings, C. D. (2025). Red mangrove (*Rhizophora mangle*) roots serve as additional valuable habitat for the eastern oyster (*Crassostrea virginica*) in a subtropical estuary. *Journal of Experimental Marine Biology and Ecology*, 583, 152083. <https://doi.org/10.1016/j.jembe.2025.152083>
- Chen, G., et al. (2017). Mangroves as a major source of soil carbon storage in adjacent seagrass meadows. *Scientific Reports*, 7(1), 42406.
- Choudhary, B., Dhar, V., & Pawase, A. S. (2024). Blue carbon and the role of mangroves in carbon sequestration: Its mechanisms, estimation, human impacts and conservation strategies for economic incentives. *Journal of Sea Research*, 199, 102504. <https://doi.org/10.1016/j.seares.2024.102504>
- Cummings, A. R., & Shah, M. (2018). Mangroves in the global climate and environmental mix. *Geography Compass*, 12(1), e12353.
- Dame, R. (1993). Bivalve filter feeders and estuarine and coastal ecosystem processes: Conclusions. In R. F. Dame (Ed.), *Bivalve filter feeders* (pp. 565–569). Springer Berlin Heidelberg.
- Dasat, G. S., & Sam, C. E. (2022). Carbon sequestration and the enzymic latch mechanism in red, black and white mangrove soils of Florida USA. *World Journal of Advanced Research and Reviews*, 13(3), 421–430. <https://doi.org/10.30574/wjarr.2022.13.3.0235>
- De Lacerda, L. D., Borges, R., & Ferreira, A. C. (2019). Neotropical mangroves: Conservation and sustainable use in a scenario of global climate change. *Aquatic Conservation: Marine and Freshwater Ecosystems*, 29(8), 1347–1364.
- Dehghani, M., et al. (2010). Recreation value of Hara Biosphere Reserve using willingness-to-pay method. *International Journal of Environmental Research*, 4(2), 271–280. <https://doi.org/10.22059/ijer.2010.19>
- Del Valle, A., et al. (2020). Mangroves protect coastal economic activity from hurricanes. *Proceedings of the National Academy of Sciences*, 117(1), 265–270.
- Donato, D. C., et al. (2011). Mangroves among the most carbon-rich forests in the tropics. *Nature Geoscience*, 4(5), 293–297.
- Etezadifar, F., et al. (2010). Breeding success of western reef heron in Hara Biosphere Reserve, Persian Gulf. *Waterbirds*, 33(4), 527–533.
- Ferreira, A. C., Borges, R., & de Lacerda, L. D. (2022). Can sustainable development save mangroves? *Sustainability*, 14(3), 1263.
- Friis, G., & Killilea, M. E. (2024). Mangrove ecosystems of the United Arab Emirates. In J. A. Burt (Ed.), *A natural history of the Emirates* (pp. 217–240). Springer Nature Switzerland. https://doi.org/10.1007/978-3-031-37397-8_7
- Gerona-Daga, M. E. B., & Salmo, S. G., III. (2022). A systematic review of mangrove restoration studies in Southeast Asia: Challenges and opportunities for the United Nation's Decade on Ecosystem Restoration. *Frontiers in Marine Science*, 9, 987737.
- Ghasemi, S., et al. (2012). Relative abundance and diversity of waterbirds in a Persian Gulf mangrove forest, Iran. *Tropical Zoology*, 25(1), 39–53.
- Ghosh, A., et al. (2015). The Indian Sundarban mangrove forests: History, utilization, conservation strategies and local perception. *Diversity*, 7, 149–169. <https://doi.org/10.3390/d7020149>
- Gijssman, R., et al. (2021). Nature-based engineering: A review on reducing coastal flood risk with mangroves. *Frontiers in Marine Science*, 8, 702412.
- Giri, C., et al. (2008). Mangrove forest distributions and dynamics (1975–2005) of the tsunami-affected region of Asia. *Journal of Biogeography*, 35(3), 519–528.
- Giri, C., et al. (2011). Status and distribution of mangrove forests of the world using earth observation satellite data. *Global Ecology and Biogeography*, 20(1), 154–159. <https://doi.org/10.1111/j.1466-8238.2010.00584.x>

- 468 Godoy, M. D. P., de Andrade Meireles, A. J., & de Lacerda, L. D. (2018). Mangrove response
469 to land use change in estuaries along the semiarid coast of Ceará, Brazil. *Journal of Coastal*
470 *Research*, 34(3), 524–533.
- 471 Gopi, G. V., & Pandav, B. (2011). Nest space partitioning among colonial nesting waterbirds at
472 Bhitarkanika Mangroves, India. *World Journal of Zoology*, 6(1), 61–72.
- 473 Gouvêa, L. P., et al. (2022). Global impacts of projected climate changes on the extent and above-
474 ground biomass of mangrove forests. *Diversity and Distributions*, 28(11), 2349–2360.
- 475 Hamilton, S. E., & Casey, D. (2016). Creation of a high spatio-temporal resolution global database
476 of continuous mangrove forest cover for the 21st century (CGMFC-21). *Global Ecology and*
477 *Biogeography*, 25(6), 729–738. <https://doi.org/10.1111/geb.12449>
- 478 Hansen, M. C., et al. (2013). High-resolution global maps of 21st-century forest cover change.
479 *Science*, 342(6160), 850–853. <https://doi.org/10.1126/science.1244693>
- 480 Hanson, J. O., et al. (2015). Feeding across the food web: The interaction between diet, movement
481 and body size in estuarine crocodiles (*Crocodylus porosus*). *Austral Ecology*, 40(3), 275–286.
- 482 Hejnowicz, A. P., & Rudd, M. A. (2017). The value landscape in ecosystem services: Value, value
483 wherefore art thou value? *Sustainability*, 9(5). <https://doi.org/10.3390/su9050850>
- 484 Hemati, M., et al. (2021). A systematic review of Landsat data for change detection applications:
485 50 years of monitoring the earth. *Remote Sensing*, 13(15). <https://doi.org/10.3390/rs13152869>
- 486 Hemminga, M. A., et al. (1994). Carbon outwelling from a mangrove forest with adjacent seagrass
487 beds and coral reefs (Gazi Bay, Kenya). *Marine Ecology-Progress Series*, 106, 291.
- 488 Hoppe-Speer, S. C. L., et al. (2011). The response of the red mangrove *Rhizophora mucronata*
489 Lam. to salinity and inundation in South Africa. *Aquatic Botany*, 95(2), 71–76.
- 490 Hua, H. H., et al. (2025). A comparative analysis of livelihood sustainability among farmers
491 in Ca Mau Province, Vietnam: A case study of organic mangrove–shrimp and rice–shrimp
492 farming systems. *Cogent Social Sciences*, 11(1), 2451736. [https://doi.org/10.1080/2331188](https://doi.org/10.1080/23311886.2025.2451736)
493 [6.2025.2451736](https://doi.org/10.1080/23311886.2025.2451736)
- 494 Ishtiaque, A., Myint, S. W., & Wang, C. (2016). Examining the ecosystem health and sustainability
495 of the world's largest mangrove forest using multi-temporal MODIS products. *Science of the*
496 *Total Environment*, 569–570, 1241–1254. <https://doi.org/10.1016/j.scitotenv.2016.06.200>
- 497 Kaasalainen, S., et al. (2015). Combining lidar and synthetic aperture radar data to estimate forest
498 biomass: Status and prospects. *Forests*, 6(1), 252–270. <https://doi.org/10.3390/f6010252>
- 499 Kelleway, J. J., et al. (2017a). Geochemical analyses reveal the importance of environmental
500 history for blue carbon sequestration. *Journal of Geophysical Research: Biogeosciences*, 122(7),
501 1789–1805.
- 502 Kelleway, J. J., et al. (2017b). Review of the ecosystem service implications of mangrove encroach-
503 ment into salt marshes. *Global Change Biology*, 23(10), 3967–3983.
- 504 Kuenzer, C., & Tuan, V. Q. (2013). Assessing the ecosystem services value of Can Gio Mangrove
505 Biosphere Reserve: Combining earth-observation- and household-survey-based analyses.
506 *Applied Geography*, 45, 167–184. <https://doi.org/10.1016/j.apgeog.2013.08.012>
- 507 Kumari, A., & Rathore, M. S. (2021). Roles of mangroves in combating the climate change. In
508 *Mangroves: Ecology, biodiversity and management* (pp. 225–255).
- 509 Lamont, K., et al. (2020). Thirty-year repeat measures of mangrove above-and below-ground bio-
510 mass reveals unexpectedly high carbon sequestration. *Ecosystems*, 23, 370–382.
- 511 Layman, C. A., et al. (2014). Provision of ecosystem services by human-made structures
512 in a highly impacted estuary. *Environmental Research Letters*, 9(4), 44009. [https://doi.](https://doi.org/10.1088/1748-9326/9/4/044009)
513 [org/10.1088/1748-9326/9/4/044009](https://doi.org/10.1088/1748-9326/9/4/044009)
- 514 Le, N. N., et al. (2021). Learning from multimodal and multisensor earth observation dataset for
515 improving estimates of mangrove soil organic carbon in Vietnam. *International Journal of*
516 *Remote Sensing*, 42(18), 6866–6890. <https://doi.org/10.1080/01431161.2021.1945158>
- 517 Lee, S. Y. (1998). Ecological role of grassid crabs in mangrove ecosystems: A review. *Marine and*
518 *Freshwater Research*, 49(4), 335–343.
- 519 Lee, S. Y., et al. (2019). Better restoration policies are needed to conserve mangrove ecosystems.
520 *Nature Ecology & Evolution*, 3(6), 870–872. <https://doi.org/10.1038/s41559-019-0861-y>

- Li, X., et al. (2022). Correlations between photosynthetic heat tolerance and leaf anatomy and climatic niche in Asian mangrove trees. *Plant Biology*, 24(6), 960–966. 521
522
- Loucks, C., et al. (2010). Sea level rise and tigers: Predicted impacts to Bangladesh's Sundarbans mangroves. *Climatic Change*, 98(1), 291–298. <https://doi.org/10.1007/s10584-009-9761-5> 523
524
- Lu, Y., & Wang, L. (2021). How to automate timely large-scale mangrove mapping with remote sensing. *Remote Sensing of Environment*, 264, 112584. <https://doi.org/10.1016/j.rse.2021.112584> 525
526
527
- Mandal, B., Ganguly, A., & Mukherjee, A. (2022). A review for understanding the reasons of vanishing Sundari tree *Heritiera fomes* Buchanan-Hamilton from Sundarban mangroves. *Environment and Ecology*, 39(4), 813–817. ISSN 0970-0420. 528
529
530
- Marois, D. E., & Mitsch, W. J. (2015). Coastal protection from tsunamis and cyclones provided by mangrove wetlands—A review. *International Journal of Biodiversity Science, Ecosystem Services & Management*, 11(1), 71–83. 531
532
533
- McIvor, A. L., et al. (2012). *Storm surge reduction by mangroves* (2) (p. 35). The Nature Conservancy and Wetlands International. Retrieved from <http://www.naturalcoastalprotection.org/documents/storm-surge-reduction-by-mangroves> 534
535
536
- Mcleod, E., et al. (2011). A blueprint for blue carbon: Toward an improved understanding of the role of vegetated coastal habitats in sequestering CO₂. *Frontiers in Ecology and the Environment*, 9(10), 552–560. 537
538
539
- Menéndez, P., et al. (2020). The global flood protection benefits of mangroves. *Scientific Reports*, 10(1), 4404. 540
541
- Mirera, D. O., Ochiewo, J., & Munyi, F. (2014). Social and economic implications of small-scale mud crab (*Scylla serrata*) aquaculture: The case of organized community groups. *Aquaculture International*, 22(4), 1499–1514. <https://doi.org/10.1007/s10499-014-9762-x> 542
543
544
- Misra, G., Cawkwell, F., & Wingler, A. (2020). Status of phenological research using Sentinel-2 data: A review. *Remote Sensing*, 12(17). <https://doi.org/10.3390/rs12172760> 545
546
- Montgomery, J. M., et al. (2019). Attenuation of storm surges by coastal mangroves. *Geophysical Research Letters*, 46(5), 2680–2689. 547
548
- Moreira, N. M. (2020). *Mangroves of Latin America*. Grupo Compas. p-211. ISBN 9789978251591. 549
- Mukherjee, N., et al. (2014). Ecosystem service valuations of mangrove ecosystems to inform decision making and future valuation exercises. *PLoS One*, 9(9), e107706. 550
551
- Naskar, S., & Palit, P. K. (2015). Anatomical and physiological adaptations of mangroves. *Wetlands Ecology and Management*, 23(3), 357–370. 552
553
- Pati, S. G., et al. (2023). Impacts of habitat quality on the physiology, ecology, and economical value of mud crab *Scylla* sp.: A comprehensive review. *Water*. <https://doi.org/10.3390/w15112029> 554
555
556
- Perri, S., et al. (2023). Salinity-induced limits to mangrove canopy height. *Global Ecology and Biogeography*, 32(9), 1561–1574. <https://doi.org/10.1111/geb.13720> 557
558
- Potouroglou, M., et al. (2017). Measuring the role of seagrasses in regulating sediment surface elevation. *Scientific Reports*, 7(1), 11917. 559
560
- Purnamasari, E., Kamal, M., & Wicaksono, P. (2021). Comparison of vegetation indices for estimating above-ground mangrove carbon stocks using PlanetScope image. *Regional Studies in Marine Science*, 44, 101730. <https://doi.org/10.1016/j.risma.2021.101730> 561
562
563
- Rangel, J. M. L., do Nascimento, A. L. B., & Ramos, M. A. (2024). The influence of urbanization on local ecological knowledge: A systematic review. *Journal of Ethnobiology and Ethnomedicine*, 20(1), 106. <https://doi.org/10.1186/s13002-024-00747-z> 564
565
566
- Richards, D. R., Thompson, B. S., & Wijedasa, L. (2020). Quantifying net loss of global mangrove carbon stocks from 20 years of land cover change. *Nature Communications*, 11(1), 4260. <https://doi.org/10.1038/s41467-020-18118-z> 567
568
569
- Rodrigues, A. S. L., et al. (2004). Global gap analysis: Priority regions for expanding the global protected-area network. *BioScience*, 54(12), 1092–1100. [https://doi.org/10.1641/0006-3568\(2004\)054\[1092:GGAPRF\]2.0.CO;2](https://doi.org/10.1641/0006-3568(2004)054[1092:GGAPRF]2.0.CO;2) 570
571
572

- 573 Rovai, A. S., et al. (2018). Global controls on carbon storage in mangrove soils. *Nature Climate*
574 *Change*, 8(6), 534–538. <https://doi.org/10.1038/s41558-018-0162-5>
- 575 Sandilyan, S., & Kathiresan, K. (2012). Mangrove conservation: A global perspective. *Biodiversity*
576 *and Conservation*, 21(14), 3523–3542. <https://doi.org/10.1007/s10531-012-0388-x>
- 577 Sarkar, S. K., & Sarkar, S. K. (2018). Algal blooms: Potential drivers, occurrences and impact. In
578 *Marine algal bloom: Characteristics, causes and climate change impacts* (pp. 53–109).
- 579 Sarker, S. K., et al. (2016). Are we failing to protect threatened mangroves in the Sundarbans world
580 heritage ecosystem? *Scientific Reports*, 6(1), 21234.
- 581 Satyanarayana, B., et al. (2012). A socio-ecological assessment aiming at improved forest resource
582 management and sustainable ecotourism development in the mangroves of Tanbi Wetland
583 National Park, The Gambia, West Africa. *Ambio*, 41(5), 513–526. <https://doi.org/10.1007/s13280-012-0248-7>
- 584 Semeniuk, V., et al. (2011). The saltwater crocodile, *Crocodylus porosus* Schneider, 1801, in the
585 Kimberley coastal region. *Journal of the Royal Society of Western Australia*, 94(2), 407.
- 586 Solari, P., et al. (2017). Antennular morphology and contribution of aesthetascs in the detection
588 of food-related compounds in the shrimp *Palaemon adspersus* Rathke, 1837 (Decapoda:
589 Palaemonidae). *The Biological Bulletin*, 232(2), 110–122.
- 590 Su, J., Friess, D. A., & Gasparatos, A. (2021). A meta-analysis of the ecological and economic out-
591 comes of mangrove restoration. *Nature Communications*, 12(1), 5050. <https://doi.org/10.1038/s41467-021-25349-1>
- 592 Sunkur, R., et al. (2023). Mangroves' role in supporting ecosystem-based techniques to reduce
593 disaster risk and adapt to climate change: A review. *Journal of Sea Research*, 196, 102449.
- 594 Tang, J., et al. (2018). Coastal blue carbon: Concept, study method, and the application to ecologi-
595 cal restoration. *Science China Earth Sciences*, 61, 637–646.
- 596 Tekman, M., et al. (2022). *Impacts of plastic pollution in the Oceans on marine species, biodiversity*
597 *and ecosystems*. WWF Germany. <https://doi.org/10.5281/zenodo.5898684>
- 598 Tran, T. V., Reef, R., & Zhu, X. (2022). A review of spectral indices for mangrove remote sensing.
599 *Remote Sensing*, 14(19). <https://doi.org/10.3390/rs14194868>
- 600 Tsikoti, C., & Genitsaris, S. (2021). Review of harmful algal blooms in the coastal Mediterranean
601 Sea, with a focus on Greek waters. *Diversity*. <https://doi.org/10.3390/d13080396>
- 602 Vousdoukas, M. I., et al. (2020). Sandy coastlines under threat of erosion. *Nature Climate Change*,
603 10(3), 260–263. <https://doi.org/10.1038/s41558-020-0697-0>
- 604 Xie, D., et al. (2020). Mangrove diversity loss under sea-level rise triggered by bio-morphodynamic
605 feedback and anthropogenic pressures. *Environmental Research Letters*, 15(11), 114033.
- 606 Yousefi, M., & Naderloo, R. (2022). Global habitat suitability modeling reveals insufficient habitat
607 protection for mangrove crabs. *Scientific Reports*, 12(1), 21713.
- 608 Youssef, Y. M., et al. (2021). Natural and anthropogenic coastal environmental hazards: An inte-
609 grated remote sensing, GIS, and geophysical-based approach. *Surveys in Geophysics*, 42(5),
610 1109–1141. <https://doi.org/10.1007/s10712-021-09660-6>
- 611 Zakaria, M., & Rajpar, M. N. (2015). Assessing the Fauna diversity of Marudu Bay mangrove
612 Forest, Sabah, Malaysia, for future conservation. *Diversity*, 7, 137–148. <https://doi.org/10.3390/d7020137>
- 613
- 614