Ground-Based Techniques in Mangrove Monitoring and Management

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Abstract Mangroves provide a wide range of ecosystem services, including coastal protection, biodiversity conservation, and fisheries support. While offering cultural and recreational benefits to local communities, they also play a crucial role in climate regulation and nutrient cycling. Despite their immense importance, mangrove ecosystems around the world are disappearing at an alarming rate. To safeguard this

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critical coastal ecosystem, effective management and continuous monitoring are essential. Ground-based monitoring techniques play a crucial role by providing high-resolution, site-specific data that complement remote sensing technologies, offering detailed insights into mangrove health, dynamics, and resilience. This chapter presents an overview of ground-based approaches to mangrove management and monitoring, emphasizing their significance; the key biological, physical, chemical, and social parameters involved; important methodological considerations; and the challenges associated with their application. While ground-based monitoring faces challenges such as limited accessibility, high resource demands, and environmental risks, it remains indispensable for the long-term conservation and management of mangroves. By combining these techniques with community engagement and technological innovation, stakeholders can develop robust strategies to strengthen mangrove resilience and ensure the sustainable management and protection of this imperiled ecosystem.

Keywords Biogeochemical process · Climate change · Ecosystem services · Livelihood dependence · Mangrove forest

1 Introduction

Mangroves are coastal ecosystems that occur in the intertidal zones of tropical and subtropical regions worldwide (Fig. 1; Spalding et al., 2010). Globally, they cover about 15 million hectares across 118 countries, accounting for nearly 15% of the world's coastlines (IUCN, 2024; Giri et al., 2011; Table 1). Mangrove ecosystems are characterized by the presence of "true mangroves," i.e., plant species that are specially adapted to saline environments, featuring unique traits such as

Fig. 1 Map showing the global distribution of mangroves (in black). Source: UNEP-WCMC (https://data.unep-wcmc.org; accessed on 15 June 2024)

Table 1 Mangrove distribution by region

Region	Share of global mangroves (%)	Major countries
Asia	42	Indonesia, Malaysia, Thailand
Africa	21	Mozambique, Kenya, Tanzania
North and Central America	15	Mexico, Belize, USA (Florida)
Australia and Oceania	12	Australia, Papua New Guinea
South America	10	Brazil, Colombia, Venezuela

pneumatophores (aerial roots), prop roots, and salt-excreting leaves (Biswas & Biswas, 2019; Lugo & Snedaker, 1974, Table 2).

Mangrove ecosystems provide a wide range of critical ecosystem services (Ho & Mukul, 2021). They act as natural barriers, protecting coastlines from cyclones, tsunamis, and storm surges (Mohammed et al., 2024; Costanza et al., 2008). They also play a significant role in carbon storage and sequestration (Hamilton & Friess, 2018; Donato et al., 2011), contribute to water quality regulation (Romañach et al., 2018), and serve as critical breeding and nursery habitats for numerous fish and wildlife species (zu Ermgassen et al., 2025). Beyond their ecological functions, mangroves also support local livelihoods by providing resources such as food, fuel, timber, construction materials, and opportunities for ecotourism (Friess et al., 2019).

Despite their immense ecological and socio-economic importance, mangroves are disappearing at a rate faster than that of tropical rainforests (Thomas et al., 2017). According to the first global assessment of mangroves under the IUCN Red List of Ecosystems, more than half of the world's mangrove ecosystems are currently at risk of collapse (Fig. 2; IUCN, 2024). The primary drivers of mangrove loss include coastal infrastructure development, aquaculture, conversion of land for agriculture, climate change, and sea-level rise (Leal & Spalding, 2024; Mukul et al., 2019, 2020a). Between 2000 and 2016, over half of global mangrove loss was attributed to land-use change, mainly the conversion of mangrove areas into aquaculture and agricultural lands, with the majority of these losses concentrated in six Southeast Asian countries (FAO, 2023; Goldberg et al., 2020).

Given their critical role in carbon sequestration, coastal protection, biodiversity conservation, and community livelihoods, the sustainable management and effective monitoring of mangroves are imperative to safeguard these vital ecosystems from ongoing and future threats (Friess et al., 2024; Schmitt & Duke, 2015). Ground-based techniques are essential for providing detailed, localized, and highly accurate data for the assessment and management of mangroves and for complementing remote sensing and aerial data (Misiukas et al., 2021).

This chapter provides an overview of the rationale for mangrove management and monitoring, emphasizing the importance of ground-based approaches. It discusses the key biological, physical, and chemical processes that are essential for effective mangrove monitoring and management, including human dimensions, main methodological considerations, and the challenges associated with ground-based monitoring and management of mangroves.

Table 2 List of true mangrove species

Family	Species
Acanthaceae	*Avicennia alba*
	Avicennia germinans (black mangrove)
	Avicennia marina
	Avicennia officinalis
Combretaceae	*Laguncularia racemosa* (white mangrove)
	Lumnitzera littorea
	Lumnitzera racemosa
Lythraceae	*Sonneratia alba*
	Sonneratia apetala
	Sonneratia caseolaris
	Sonneratia griffithii
	Sonneratia ovata
Rhizophoraceae	*Bruguiera cylindrica*
	Bruguiera exaristata
	Bruguiera gymnorhiza
	Bruguiera hainesii
	Bruguiera parviflora
	Bruguiera sexangula
	Ceriops australis
	Ceriops decandra
	Ceriops tagal
	Kandelia candel
	Kandelia obovata
	Rhizophora apiculata
	Rhizophora harrisonii
	Rhizophora mangle (red mangrove)
	Rhizophora mucronata
	Rhizophora racemosa
	Rhizophora stylosa
Arecaceae (Palms)	*Nypa fruticans* (special mangrove palm)
Malvaceae	*Heritiera fomes*
	Heritiera littoralis
	Hibiscus tiliaceus
Rubiaceae	*Scyphiphora hydrophylacea*
Euphorbiaceae	*Excoecaria agallocha*
	Excoecaria indica
Plumbaginaceae	*Aegialitis annulata*
	Aegialitis rotundifolia

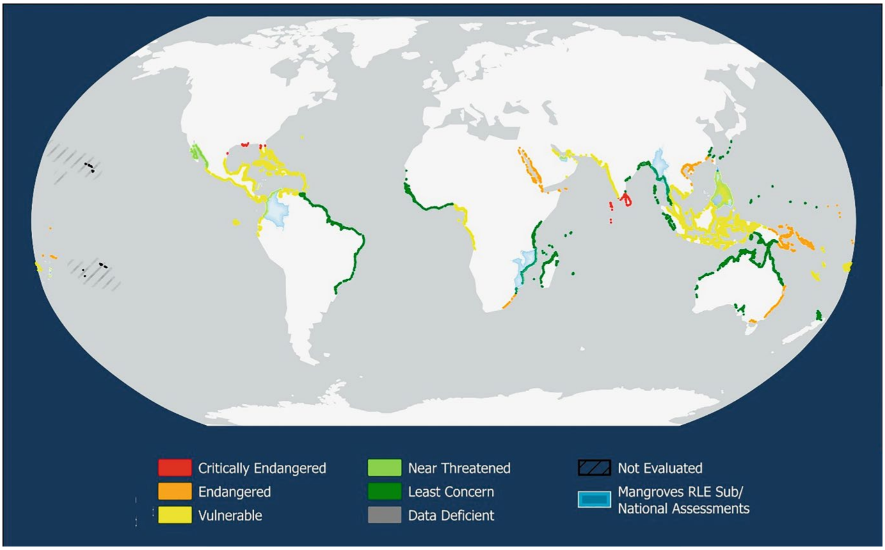

Fig. 2 Global red list of mangrove ecosystems. Source: Modified after IUCN (2024)

Fig. 3 Vertical (left) and horizontal (right) representation of a mangrove ecosystem. Photo credits: Sharif A. Mukul

2 The Rationale for Mangrove Management and Monitoring

The objective of mangrove management typically falls into several key categories: sustainable timber production, conservation of forests and wildlife habitats, coastal and shoreline protection, ecological restoration, and support of essential ecological functions such as soil stabilization, site protection, and carbon sequestration (Akram et al., 2023). The rationale for managing mangroves may also vary depending on the position or type of mangrove forest (Schmitt & Duke, 2015). For instance, as shown in Fig. 3, fringe mangrove forests play a vital role in protecting shorelines, and riverine forests are especially important for supporting plant and animal productivity, while basin or interior mangroves serve as key nutrient sinks and sources of wood products (Ewel et al., 1998).

Objectives of mangrove management change over time and may include specific goals such as coastal protection through coastal green belt or offsetting carbon emissions (Schmitt & Duke, 2015). Historically, the primary objective was on afforestation for silviculture, emphasizing coastal stabilization and timber production to support industries like pulp and paper manufacturing (Iftekhar & Islam, 2004). Over time, greater attention shifted toward the ecological functions of mangroves, including their role as wildlife habitats, coastal protection, contributors to pelagic food webs, and providers of livelihoods for coastal communities (Friess et al., 2019; Stubbs & Saenger, 2002). More recently, mangroves have been managed as cost-effective, nature-based solutions for enhancing climate resilience, acknowledged for their capacity to sequester atmospheric carbon more rapidly than other tropical ecosystems and their capacity to endure rising sea levels (Mukul et al., 2020b; Krauss et al., 2014).

Mangroves grow in different hydrogeomorphic settings, such as river-, tide-, wave-dominated, or interior mangrove forests, and rainfall, temperature, and freshwater supply also affect mangrove growth (Biswas & Biswas, 2019). Figure 4 presents a generalized decision-making flowchart that can guide mangrove management processes. The primary objective of any mangrove management strategy should be to protect and conserve existing mangrove ecosystems while minimizing the disturbances driving their loss. This approach is often more efficient and more cost-effective than efforts focused solely on planting new mangroves (Leal & Spalding, 2024). Alongside legal protection, local communities play a vital role in safeguarding mangrove forests from degradation and loss (Datta et al., 2012). Raising awareness and actively involving local stakeholders in mangrove management can further strengthen conservation outcomes (Walters et al., 2008).

In areas where mangroves have been present in the past, it is important to distinguish between sites that have been degraded since the loss of mangrove cover and those that remain relatively intact. Based on this distinction and having determined that planting is necessary, three different types of mangrove planting can be employed: reforestation, rehabilitation, and restoration (Schmitt & Duke, 2015). Additionally, afforestation is used in areas where mangroves did not previously grow (Siddiqi, 2001).

Because species distribution is closely tied to specific site conditions, careful attention must be given first to selecting a suitable planting site, followed by choosing the appropriate species and the most effective planting technique for that location (Lewis & Brown, 2014). Planting can be carried out using seeds, propagules, or seedlings, and site selection should be guided by an analysis of historical changes and natural processes (Schmitt & Duke, 2015). Historical data helps clarify coastal dynamics, such as patterns of accretion and erosion, and supports the selection of species that naturally thrived in the area prior to human disturbance (Lewis & Brown, 2014). This process should be complemented by observing natural regeneration, which signals that a site is suitable for mangrove growth and provides valuable insights into appropriate species choices and planting methods (Siddiqi, 2001).

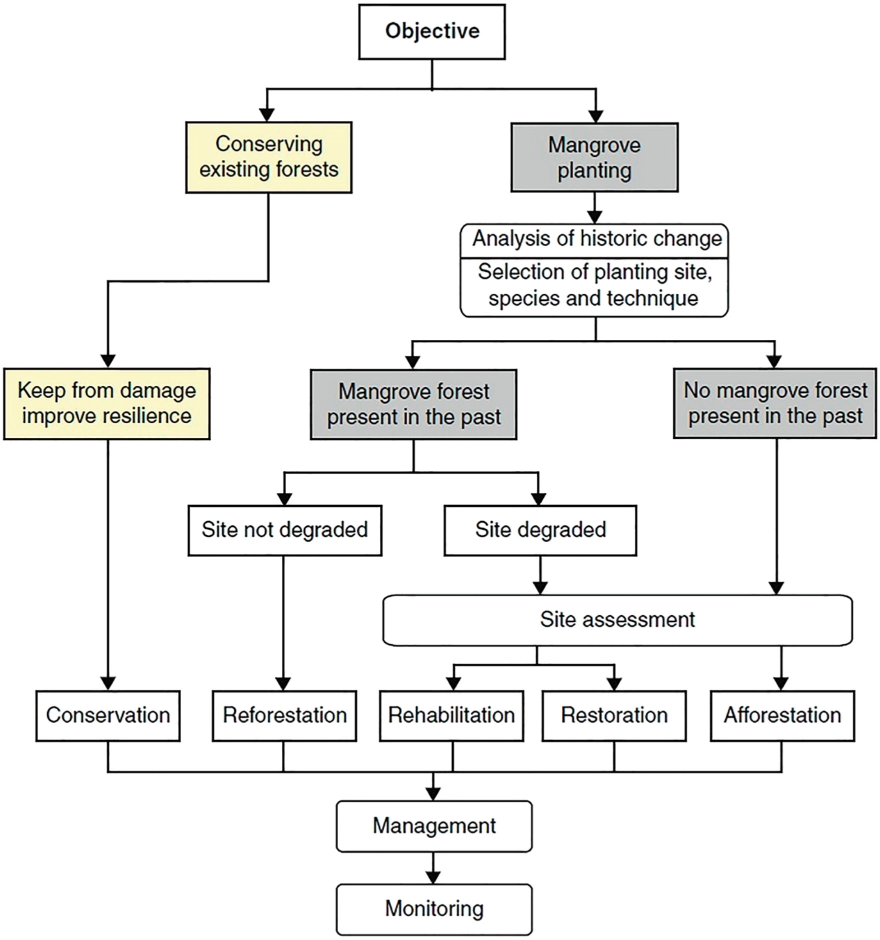

Fig. 4 Decision-making flow chart for mangrove management. Source: Modified after Schmitt and Duke (2015)

Mangrove forests have a strong capacity for natural regeneration following disturbances (Siddiqi, 2001). In areas where mangroves have been destroyed or degraded, a thorough site assessment is required to determine whether interventions such as soil or hydrological restoration are necessary before planting (Lewis & Brown, 2014). Whenever possible, rehabilitation approaches that promote natural regeneration should be prioritized (Schmitt & Duke, 2015). However, in cases where habitat loss or degradation is so severe that natural processes are insufficient for recovery, tailored, site-specific, and cost-effective rehabilitation or restoration methods must be implemented (Lewis & Brown, 2014).

Large-scale afforestation is typically undertaken to establish mangrove forests on treeless mudflats or newly accreted lands (Siddiqi, 2001). In such areas, afforestation requires specialized and carefully designed planting techniques. After planting, seedlings must be protected from human disturbances, such as destructive fishing practices and grazing by cattle or sheep (Schmitt & Duke, 2015). In some locations, additional protection from wave action may also be necessary. Once mangroves are established, they must be effectively managed and safeguarded from human activities such as felling or conversion to other land uses. Traditionally, these management and protection efforts have been overseen by government forestry departments.

Mangrove monitoring refers to the systematic collection of data and the processing of this data into information about the condition, health, and status of mangrove forests (Schmitt & Duke, 2015). It also helps to understand why changes are occurring. Ground-based monitoring of mangroves involves direct, on-site assessments of this ecosystem using appropriate approaches. While recent technological advancements, such as the availability of satellite imagery, artificial intelligence, remote sensing, and machine learning, have provided new opportunities for monitoring mangroves, ground-based data remains essential (Wang et al., 2025).

3 Considerations for Ground-Based Management and Monitoring of Mangroves

Mangrove ecosystems are shaped by a complex interplay of biological, physical, and chemical processes that sustain their structure, function, and resilience (Lugo & Snedaker, 1974). The ecological integrity of these ecosystems is maintained through the synergistic interaction of these processes, which operate across various spatial and temporal scales (Fig. 5). In addition to these natural dynamics, human dimensions—including anthropogenic pressures such as disturbances and local dependence on mangrove resources—play a significant role in influencing mangrove health and stability (Biswas et al., 2009). Disruption of any of these interconnected components, whether ecological or human-driven, can compromise the functionality of mangroves and the vital ecosystem services they provide (Schmitt & Duke, 2015). Therefore, a comprehensive understanding of these processes is essential for the effective monitoring and management of mangrove ecosystems, as outlined in the sections that follow.

3.1 Biological Processes

Biological processes in mangrove ecosystems are essential for sustaining productivity, maintaining biodiversity, and ensuring resilience to environmental change (Lugo & Snedaker, 1974). Primary production, driven by mangrove trees, algae, and epiphytic organisms, supports both local consumers and the export of energy and

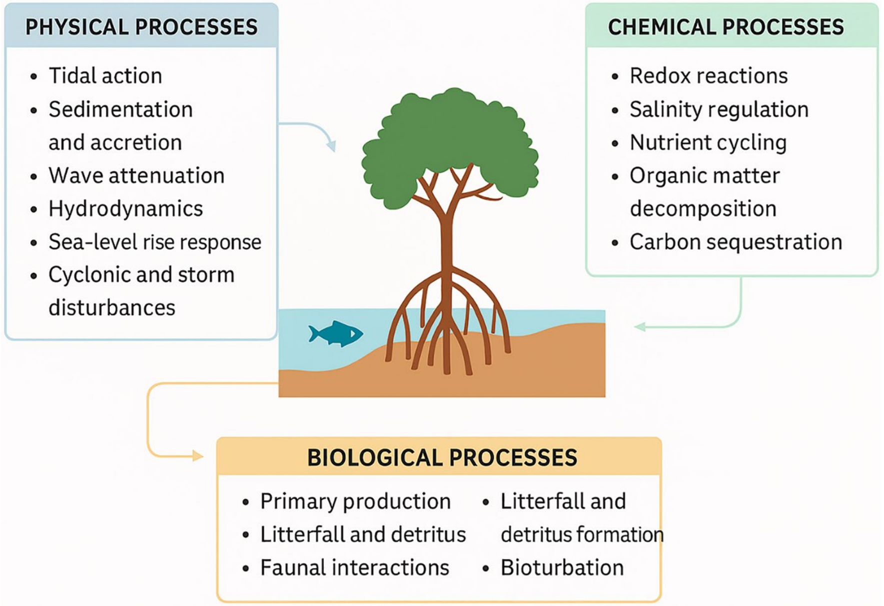

Fig. 5 The interplay of physical, chemical, and biological processes in the mangrove ecosystem

nutrients to adjacent ecosystems (Alongi, 2002). Litterfall and detrital pathways provide organic material that fuels microbial decomposition and detritivore food webs (Twilley et al., 1992). Faunal interactions and bioturbation, carried out by organisms such as crabs, mollusks, and polychaetes, play crucial roles in sediment aeration, nutrient cycling, and organic matter turnover (Kristensen, 2008). Their burrowing activities enhance oxygen penetration and stimulate microbial processes in otherwise anoxic sediments. Symbiotic relationships, such as nitrogen-fixing bacteria associated with mangrove roots, further contribute to nitrogen inputs in these typically nutrient-poor coastal environments (Kristensen et al., 2008). Finally, mangrove regeneration is shaped by recruitment, seedling establishment, and species interactions, which together drive successional dynamics and determine zonation patterns within mangrove forests (Siddiqi, 2001).

3.2 Physical Processes

Physical processes in mangroves shape their zonation patterns, habitat formation, and interactions with neighboring ecosystems such as seagrass beds and coral reefs. These processes are largely driven by hydrodynamics, geomorphology, and climatic forces. For example, tidal action regulates inundation patterns, sediment deposition, and nutrient fluxes across the intertidal zone (Alongi, 2009). Tidal exchange also plays a crucial role in oxygenating mangrove soils and maintaining salinity gradients within the water column. Meanwhile, sediment dynamics in mangroves enhance sediment trapping and vertical accretion, contributing to land-building processes that help buffer against sea-level rise (Krauss et al., 2014). The dense root networks of mangroves attenuate wave energy, stabilize shorelines, reduce coastal erosion, and promote further sediment deposition (Mazda et al., 1997). Additionally, storms and cyclonic disturbances can reshape mangrove stands by altering sediment profiles and clearing vegetation, triggering successional processes that influence ecosystem recovery (Duke, 2001).

3.3 Chemical Processes

Chemical processes in mangrove ecosystems are largely shaped by anaerobic soil conditions and tidal influences, playing a central role in the mangroves' contribution to global biogeochemical cycles (Kristensen et al., 2008). Mangroves help regulate salinity through specialized physiological adaptations, such as salt exclusion at the roots, salt secretion via specialized glands, or salt storage within vacuoles (Lugo & Snedaker, 1974). The sediments in mangrove systems are typically anoxic, fostering reduction reactions like sulfate reduction, methanogenesis, and denitrification, all of which influence nutrient dynamics and availability (Alongi, 1994). In addition, nitrogen cycling—including ammonification, nitrification, and denitrification—occurs within both the sediments and rhizosphere, further regulating nitrogen availability (Kristensen et al., 2008). Phosphorus cycling is primarily governed by adsorption-desorption processes involving iron and aluminum oxides in the sediments. Another key chemical process is the decomposition of organic matter, where mangrove leaf litter and woody debris break down through microbial activity, releasing dissolved organic carbon and nutrients that sustain detrital food webs (Alongi, 2002). Importantly, mangrove soils act as major carbon sinks, with the long-term burial of organic carbon under anaerobic conditions significantly contributing to "blue carbon" storage (Mukul et al., 2020b).

3.4 Human Dimensions

The human dimensions of mangroves encompass the complex social, cultural, and economic relationships between coastal communities and these vital ecosystems (Biswas et al., 2009). Mangroves provide a diverse array of ecosystem services, including fisheries, timber, fuelwood, non-timber forest products (NTFPs), coastal protection, and ecotourism opportunities, upon which millions of people worldwide depend for their livelihoods and well-being (Sarkar et al., 2024; Fig. 6). Therefore, the effective management and monitoring of mangroves must account for socio-economic factors and actively engage local communities in decision-making to ensure both ecological sustainability and community benefits (Datta et al., 2012).

Fig. 6 Mangroves provide key non-timber products like *Nypa* palm (left) and support ecotourism (right), as seen in the Sundarbans forest, where both generate important revenue and showcase the ecosystem's rich biodiversity. Photo credits: Sharif A. Mukul

4 Ground-Based Approaches for Monitoring and Managing Mangroves

Ground-based approaches play a crucial role in effective mangrove monitoring and management by providing detailed, site-specific information. These approaches include field-based surveys to assess forest structure, species composition, biomass, and regeneration status, as well as monitoring of soil and water parameters such as salinity, nutrient levels, and sedimentation (Bosire et al., 2008; Lugo & Snedaker, 1974). Participatory monitoring, involving local communities and stakeholders, enhances the accuracy and relevance of data collection by integrating traditional ecological knowledge and local observations (Walters et al., 2008). Ground-based methods also support adaptive management by enabling regular assessments of human pressures, such as harvesting intensity, land-use changes, and pollution, which are critical for designing locally appropriate conservation and restoration strategies (Datta et al., 2012). When combined with socio-economic data, these field-based approaches provide a holistic framework for managing mangroves in ways that balance ecological health with community needs (Biswas et al., 2009).

Ground-based techniques are also essential for validating and calibrating remote sensing data. Field measurements—such as vegetation density, species identification, and canopy structure—provide critical ground-truth information that improves the accuracy of satellite or aerial imagery analysis (Maurya et al., 2021). By integrating ground-based and remote sensing approaches, the overall effectiveness and precision of mangrove monitoring have significantly improved (Karsch et al., 2023). Recent technological advancements have further improved ground-based monitoring, with tools like handheld GPS units, drones, and mobile apps enabling more efficient data collection and real-time reporting. For instance, drones can capture high-resolution images of mangrove areas, while mobile apps allow field teams to record and upload data directly to centralized databases, streamlining both analysis and management efforts.

4.1 Field-Based Surveys and Sampling

Field surveys and sampling are the cornerstone of ground-based mangrove monitoring and management, providing essential, on-the-ground data. These activities involve direct observations and measurements of vegetation, fauna, soil, water parameters, and biogeochemical processes (Fig. 7). Key components include:

- **Biodiversity surveys:** Recording the presence and abundance of mangrove flora and fauna—including fish, crabs, birds, predators, and prey—to assess species composition, diversity, and ecological interactions (Mukul et al., 2019).
- **Vegetation assessment:** Measuring tree height, diameter at breast height (DBH), species composition, and canopy cover from representative plots of different size and shape to evaluate mangrove forest health, biomass, and carbon storage potential (Mukul et al., 2020b).
- **Seedling recruitment:** Monitoring the density and distribution of mangrove seedlings to gauge regeneration potential and forest recovery capacity (Siddiqi, 2001).
- **Phenology monitoring:** Tracking seasonal changes in flowering, fruiting, and leaf development to better understand mangrove life cycles and reproductive patterns in the face of climate or salinity change (Siddiqi, 2001).
- **Soil sampling:** Analyzing soil properties such as salinity, pH, organic matter content, and nutrient levels, which are critical for understanding growth conditions and detecting stressors like pollution or sediment imbalance (Twilley et al., 1992).
- **Sedimentation and erosion monitoring:** Using techniques such as sediment traps, erosion pins, and marker horizons to measure sediment deposition and

Fig. 7 Snapshots from field surveys conducted in the Sundarbans mangrove forest of Bangladesh. Photo credits: Sharif A. Mukul

erosion rates, helping assess the effects of coastal development, sea-level rise, and storm events on mangrove stability (Bhargava & Friess, 2022).

- **Water quality monitoring:** Measuring parameters such as salinity, temperature, dissolved oxygen, turbidity, and nutrient concentrations to understand water conditions influencing mangrove ecosystems (Kristensen et al., 2008). Regular monitoring of water also helps detect pollution sources, including agricultural runoff and industrial discharges, and their impacts on mangrove health.

4.2 Permanent Sample Plots

Establishing permanent plots is a common ground-based technique for long-term mangrove monitoring. These fixed plots are repeatedly surveyed over time to document changes in vegetation structure, species composition, and overall ecosystem dynamics. By tracking key indicators such as growth rates, regeneration, and mortality, permanent plots offer valuable insights into how mangrove forests respond to environmental changes and help predict their future under the influence of drivers such as climate variability, natural disturbances, and species interactions (Misiukas et al., 2021).

4.3 Socio-economic Surveys

Socio-economic surveys explore how mangroves support local livelihoods through traditional and commercial uses, such as harvesting NTFPs, fisheries, and honey production (Sarkar et al., 2024). These surveys help capture the diverse human benefits derived from mangroves and inform management strategies that are tailored to local contexts and community needs (Datta et al., 2012). Mangrove economic value, however, varies depending on valuation methods, the types of ecosystem services assessed, and local socio-economic contexts (Himes-Cornell et al., 2018). Some assessments even use composite indicators like "saved wealth" (avoided damage to property and income) and "saved health" (reduced risk of disease, injury, or death) to estimate the broader adaptation and resilience benefits provided by mangroves (Vo et al., 2012). For instance, coastal mangroves play a critical role in attenuating wave energy, reducing storm surge impacts, and preventing shoreline erosion—services that can be quantified using such approaches (Akber et al., 2018). In addition, mangroves generate substantial revenue through ecotourism, offering opportunities for local employment and environmental education. Socio-economic surveys can offer valuable insights for understanding not only the direct and indirect benefits of ecotourism but also visitors' willingness to pay for specific ecosystem services, helping guide sustainable tourism development and conservation efforts (Saha & Mukul, 2022).

4.4 Community-Based Monitoring (CBM)

Engaging local communities in mangrove monitoring is a powerful ground-based approach (Walters et al., 2008). Local knowledge and participation enhance data collection efforts and foster a sense of ownership and responsibility for mangrove conservation (Datta et al., 2012). CBM often includes activities like mangrove planting, clean-up drives, and awareness campaigns.

5 Challenges in Ground-Based Mangrove Management and Monitoring

Despite its many benefits, ground-based monitoring and management of mangroves face several significant challenges. One of the primary difficulties is accessibility, as mangrove ecosystems are often located in remote, isolated, or difficult-to-reach coastal zones, making fieldwork logistically complex and time-consuming (Halder et al., 2021). These activities are also highly resource-intensive, requiring substantial investments of time, labor, specialized skills, and financial resources to conduct surveys, sampling, and data collection effectively. Additionally, field teams working in mangrove environments are often exposed to environmental hazards, including extreme weather, unstable terrain, strong tidal currents, and encounters with potentially dangerous wildlife. Security concerns also arise, particularly in remote or less-monitored areas where the presence of armed groups, pirates, or ferocious animals may pose serious threats to field personnel, sometimes necessitating the use of armed guards or specialized protection measures to ensure safe operations.

6 Conclusion

Ground-based techniques are indispensable for effective monitoring and management of mangrove ecosystems. Despite the rapid advancements in remote sensing technologies, field-based observations provide irreplaceable, fine-scale data on species composition, forest structure, regeneration status, soil and hydrological conditions, and anthropogenic pressures. These techniques—ranging from simple plot surveys and transect measurements to more advanced methods such as soil sampling and sediment monitoring—offer critical ground-truthing for interpreting remotely sensed data and are essential for understanding ecological processes that cannot yet be fully captured from above. Furthermore, ground-based approaches play a crucial role in participatory monitoring of mangroves, engaging local communities and stakeholders, and integrating traditional ecological knowledge into management practices. This not only improves the accuracy and relevance of monitoring outcomes but also fosters local stewardship and enhances the sustainability of conservation efforts in mangroves. Integrating ground-based methods with modern geospatial tools in a complementary, hybrid monitoring framework also holds promise for delivering more comprehensive, multi-scale assessments of mangrove health and change. As mangroves continue to face mounting pressures from climate change and sea-level rise, robust ground-based monitoring will remain a cornerstone of efforts to protect this invaluable coastal ecosystem.

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