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TOPICAL REVIEW

Modelling mangrove social-ecological systems – a review

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Abstract

Mangrove social-ecological systems (SES) involve the dynamic relationships between mangrove ecosystems and human communities that depend on and influence these environments. This article explores progress in biophysical and socio-economic modelling approaches by selecting 74 peer-reviewed studies published up to April 2024. Selected documents show that 32% of studies adopt integrated modelling, 26% use empirical methods, 23% employ GIS-based techniques and 19% use a mixed approach. Data sources include remote sensing (46%), primary and secondary databases (26%), survey data (21%), and various models (7%). Key tools for mangrove SES modelling include mental or conceptual models like DPSIR, integrated assessment models, Actor-Network models, Motivation and Ability and Sustainable Livelihood frameworks, and ecosystem management models. Progress in understanding human-nature interactions within mangrove ecosystems comes from integrated approaches combining ecological and socio-economic factors in the analysis. Challenges, however, remain, including the need for high-resolution spatial and temporal data, improved modelling of complex feedback mechanisms between ecological and social components, and more effective integration of local stakeholder knowledge and perspectives into model design and decision-making processes. This review emphasises the critical role played by collaboration among scientists, policymakers, and local communities to enhance mangrove ecosystem resilience and sustainability. To address the challenges, we propose a generalised conceptual model developed upon the studied literature, with a specification for Bangladesh, to facilitate exchanges, synergies and integration in future research and applications to preserve mangrove ecosystem services amid growing environmental and socio-economic pressures.

1. Introduction

Mangrove forests in tropical and subtropical coastal regions are vital ecosystems that provide numerous ecological and socioeconomic benefits (Kumar *et al* 2021). They are among the most productive and biologically significant ecosystems because they supply multiple goods and services to society and benefit coastal and marine systems (Giri *et al* 2011). Mangroves are highly productive ecosystems, sequestering more carbon than tropical forests and offering coastal protection from natural disasters (Giri 2021). Despite their importance, global mangrove extent has declined by 3.4% between 1996 and 2020, from 152,604 km^2 to 147,359 km^2 (Bunting *et al* 2022). This loss is primarily due to deforestation for agriculture and aquaculture expansion (Bunting *et al* 2022).

Mangrove ecosystems exhibit distinct ecotypes with varying distribution and species composition (Urrego *et al* 2009), which is based on environmental conditions such as flooding levels, salinity, and soil depth, primarily categorised as fringe, riverine, and basin forests (Ewel *et al* 1998). Mangroves demonstrate specialised adaptations and trait plasticity, including salt-tolerance mechanisms, efficient water use for photosynthesis, and structural modifications such as pneumatophores and salt glands (Lovelock *et al* 2016, Madhavan *et al* 2024), allowing them to tolerate these environmental conditions (Feller *et al* 2010). Different species exhibit varying levels of salt tolerance, which influences their distribution along salinity gradients. For instance, *Sonneratia alba* demonstrates broader salt tolerance compared to *S. lanceolata*, but at the cost of reduced growth potential in low-salinity conditions (Ball and Pidsley 1995). These species-specific responses are crucial for understanding the ecosystem functions and services, as well as for understanding the conservation and restoration efforts (Madhavan *et al* 2024).

The diversity and complexity of mangrove ecosystems and the numerous ecological and social processes involved require a holistic approach. Several reviews have been conducted on social-ecological systems (De Vos *et al* 2019, Li *et al* 2020, Wang *et al* 2022, Liu *et al* 2023, Lejano and Stokols 2024, Xu *et al* 2024), mangrove ecosystem extent (Rahman *et al* 2024), and ecosystem services (Getzner and Islam 2020, Mitra 2020, Bimrah *et al* 2022). However, no comprehensive review has systematically addressed mangrove social-ecological systems.

Academics and development experts are increasingly turning to modelling to encourage collaboration and learning among diverse groups, thus improving decision-making (Bousquet and Le Page 2004, Barnaud *et al* 2008, Verburg *et al* 2016, Voinov *et al* 2016, Schlüter *et al* 2019). Creating models that accurately represent the complexity of social-ecological systems (SES), while offering valuable insights at relevant management scales, remains a significant conceptual and methodological challenge (Elsawah *et al* 2017). SES modelling is often criticised for not considering broader contexts, operating on too large a scale (Mahony 2015, Steger *et al* 2021), simplifying complex processes into abstract quantities (Taylor 2005, Hulme 2011, Dempsey 2016), or overlooking the interests and capabilities of end-users. These critiques highlight the need for a more comprehensive integration of transdisciplinary and co-production processes in SES modelling. Although researchers have begun developing conceptual frameworks for the transdisciplinary application of SES models (Schlüter *et al* 2019), there are still theoretical and practical gaps.

Overall, integrated SES modelling provides a holistic view essential for balancing ecological integrity with human needs and ensuring the sustainability of mangrove ecosystems and the communities they support. Holistic modelling of mangrove SESs is crucial for several reasons. Firstly, it can comprehensively explain how human activities and natural processes interact within these environments, enabling more effective conservation and management strategies. For example, models can predict the impacts of coastal development on mangrove health and fishery yields, helping policymakers implement sustainable development practices. Secondly, such models can identify potential threats and resilience factors, guiding interventions to enhance ecological and community resilience. For instance, models might reveal how climate change-induced sea level rise could affect mangrove distribution and the livelihoods of communities dependent on them, leading to proactive measures like the restoration of degraded areas and the development of alternative livelihoods. Finally, mangrove SES models can provide quantitative information to compare alternative strategies or future scenarios, thus supporting decisions about SES management. For example, an integrated (ecological and social) model can compare the expected outcomes of alternative management measures in future scenarios and facilitate the identification of preferred solutions.

Mangroves are complex, adaptive systems that vary across space and time (Hagger *et al* 2022). Therefore, the spatial and dynamic notion of mangrove SES is essential (Yando *et al* 2021). Spatial modelling captures differences in ecosystem conditions, land use, and governance across locations, while dynamic modelling accounts for ecological changes, human-nature feedback, and policy adaptations over time (Dahdouh-Guebas *et al* 2021). Together, they help understand system resilience, identify risks or tipping points, and guide more effective, context-specific management and conservation strategies

Considering the above gaps, this review offers a thorough overview and critical analysis of the methods used to study mangrove social-ecological systems. The approaches examined - statistical, empirical, geospatial, and mixed methods - each present unique strengths and limitations. Based on this analysis, we identify key challenges, including limited high-resolution data, inadequate representation of complex feedback, and insufficient integration of local stakeholder knowledge. To address these issues, we propose a generalised conceptual model, with a specific application to Bangladesh, to guide future research and promote the sustainable management of mangrove ecosystem services amid growing environmental and socio-economic pressures

2. Approaches used for review

2.1. Search strategy

This review adopted the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines (Page *et al* 2021). The PRISMA statement allows readers to identify author bias and systematically replicate the review methods using explicit reporting steps. The literature search for the review used the Scopus database with the search string 'TITLE-ABS-KEY' and the Web of Science Core Collection database with the search string 'Topic'. We performed basic searches using two different search terms linked by the 'AND' and

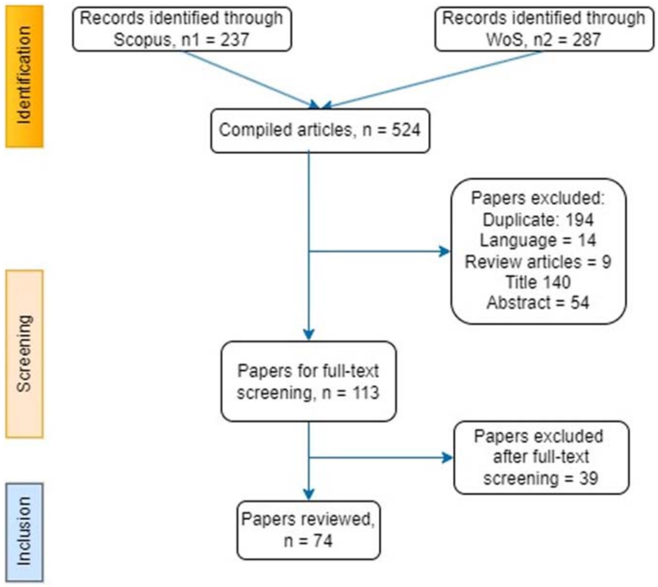

Figure 1. Diagram illustrating the steps followed in the article screening process based on the PRISMA method.

Table 1. Inclusion and exclusion criteria for reviewing the studies.

Criteria	Inclusion	Exclusion
Context	Only records containing all selected keywords were retained	Records containing only one keyword or unrelated to the search were discarded
Language	Records published in English only were considered	Records published in other languages were excluded
Types of study	Peer-reviewed articles, conference proceedings	Review articles, editorial materials, and book chapters
Study focus	Records with mangrove ecosystem modelling	Research focuses on areas other than forest ecosystems in the mangrove ecosystems.
Access	Records with a specific direct link for access were considered	Records with broken and no direct link were excluded

'OR' connectors. Initially, pre-search was carried out in the Web of Science core database (WoS) and Scopus on April 28, 2024, using the keywords '(mangrove*) and (spatial) and (dynamic*) and (soci* ecologi* system*) and (model*)' 237 articles were found in Scopus and 287 in Web of Science.

2.2. Screening process

For an article to be eligible for data extraction, the criteria considered are shown in table 1. After screening for duplicates, language, review articles, titles, and abstracts, 113 articles were selected for full-text analysis. Finally, after full-text reading, 74 articles were retained for information extraction (figure 1).

2.3. Development of a review framework

A framework was developed to review mangrove modelling literature, following Bipa *et al* (2023), which includes the following sections: (i) general information, including authors, years of publication, journal, and document type; (ii) introductions, including aims, study area, geographical location, study types, and sectors; (iii) methodological information, including methods, models, tools, data, variables, etc, used in the article and study sectors; (iii) result-based information, including land use change, ecosystem services, social-ecological systems, management strategies as well as research gaps and conclusions addressed in the selected studies. The main elements of the frameworks and the respective considerations have been shown in table 2.

2.4. Data extraction

Information extracted from the studies through full-text review following the framework was compiled in a synoptic table developed in MS Excel. After synthesising the information, graphs and tables were prepared using MS Excel to describe the current knowledge on mangrove ecosystem modelling with a particular emphasis on the methodology used in the studies and whether social and ecological variables were considered. Following Quevedo *et al* (2023)Articles were also reviewed and categorised to investigate which component of the DPSIR

Table 2. Review framework for the modelling of mangrove ecosystems.

Criteria of the framework		Description
Type of information	Label	Information to be recorded from the reading of the papers
General information	Authors	List the first three authors; add '*et al*' if more than three authors
	Title	Article's title
	Year	Publication year
	Journal	Name of the journal
	Publisher	Name of the publisher
	Document type	Article, book chapter, conference paper
Introductions	Aims	Purpose of the study
Methodology	Study area	Location
	Geographical location	Geographic scale of study
	Study type	Type of study: Empirical, geospatial and modelling
	Sector	Please write the article's wording to address mangrove ecosystem modelling: SES, ES, biodiversity, ecosystem management, C stock, LULC, mangrove dynamics, climate change, ecosystem management etc
	Methods	Study approaches used in the study
	Models	What model is used
	Model type	Types of models used in the study
	Tools	Software and analytical tools used in the study
	Data	Primary or secondary
	Data period	Period of the data set used in the study
	Data sources	Publicly available data sources or not
	Ecological variable	Ecological and environmental variables are considered
	Social variable	Social variables considered in the study
	Climate scenarios	Whether climate scenarios are considered
	Policy scenarios	Whether any other scenarios are considered
Findings	Key findings	A summary of the conclusions derived from the study
Conclusion	Research gap	Future research direction addressed
Comments		If a reviewer has any comments

framework was addressed by the studies. A word cloud was generated for the included studies to represent the most frequent terms visually. The analysis was based on the abstracts since they concisely include the most frequently used keywords in aims, methods, findings and conclusions. Finally, based on the literature review, we drafted a general conceptual model of mangrove SES based on the DPSIR framework, which was proposed as a reference framework for future studies.

3. Summary of the review

3.1. Analysis of abstracts

The word cloud generated from the reviewed abstracts of the selected articles highlights several key themes and concepts frequently addressed in the literature (Appendix A). Prominent among these are 'climate,' 'management,' 'forest,' 'ecosystem,' 'coastal,' and 'carbon,' indicating a strong focus on environmental management and conservation. Terms like 'services,' 'land,' 'change,' 'future,' 'spatial,' and 'modelling' suggest an emphasis on the spatial analysis and modelling of ecosystems, with a particular interest in forecasting future changes and impacts. 'Sundarbans' appears prominently, hinting at specific regional studies or case studies related to this unique ecosystem. Other notable words include 'drivers,' 'conservation,' 'sustainable,' 'value,' 'analysis,' and 'data,' reflecting the diverse methodologies and considerations in ecological research, such as socio-economic factors, sustainability, and the valuation of ecosystem services. Overall, the word cloud depicts a comprehensive engagement with various aspects of environmental science, mainly focusing on climate change, ecosystem management, and the importance of integrating spatial data and modelling in research.

3.2. Overview of the research

The Scopus and WoS searches revealed records dating back to 2000, as shown in figure 2. Most of the studies were conducted from 2019 onwards, with the peak number of publications occurring in 2022, followed by 2020, 2021, and 2019 (figure 2(A)). Geographically, in figure 2(B)), the literature on mangrove modelling is unevenly distributed, but with a clear focus on Asia, where most of the articles originated (73.85%), followed by 8% each in the Americas and Africa. The highest number of studies reviewed was conducted in Indonesia (16.9%),

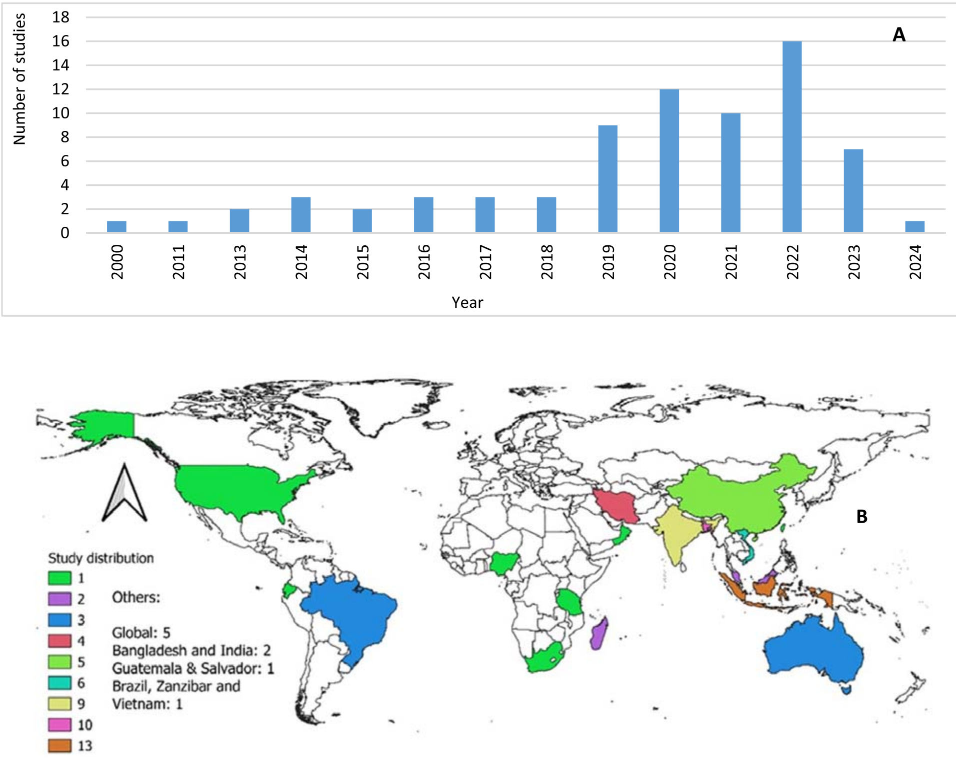

Figure 2. Number of mangrove ecosystem modelling records per year (A), country-wise distribution map of the studies (B).

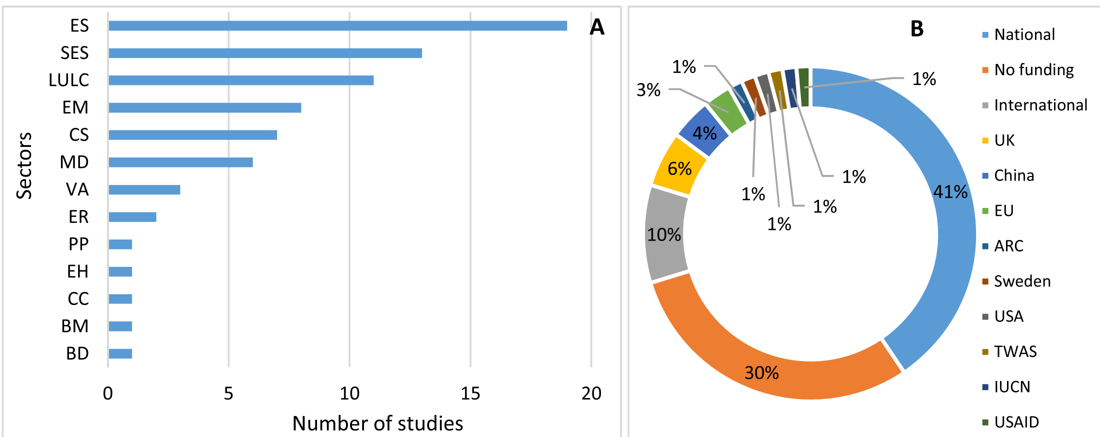

Figure 3. Number of mangrove ecosystem modelling records as per research sector-wise distribution (A) and based on funding sources (B). Note: ES: ecosystem services; SES: social-ecological systems; LULC: land use land cover change; EM: ecosystem management: CS: carbon storage, MD: mangrove dynamics; VA: vulnerability assessment; ER: ecosystem response; PP: primary production; EH: ecosystem health; CC: climate change; BM: mangrove biomass; and BD: mangrove biodiversity.

followed by India (13.9%), Bangladesh (12.3%), China (7.7%), Iran (6.2%), and Vietnam (6.2%). This is reflective of the fact that the most significant proportion of global mangrove forests is in Indonesia.

Figure 3(A) categorises the studies based on their focus within the broader field of mangrove ecosystems. It provides insights into the primary interests and specialisations of researchers, thus revealing that the highest number of studies focus on ecosystem services (19), followed by social-ecological systems (13), land use and land cover change (11), and mangrove ecosystem management strategies (8). Understanding the funding landscape is crucial for recognising potential biases and identifying areas of concentrated financial support. Figure 3(B) categorises the studies based on their funding sources, highlighting that 41% of the total studies have national funding sources. In comparison, 10% of studies are carried out with support from international bodies, with additional support from non-governmental organisations and other entities.

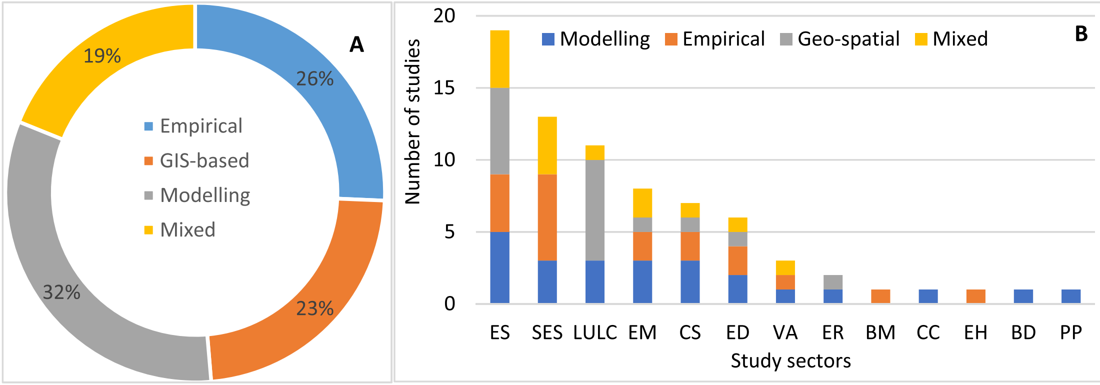

Figure 4. Number of records on research approaches (A) and sector-wise approaches (B), for mangrove ecosystem research. Figure F represents the evolution of different models used for the studies. Note: ES: ecosystem services; SES: social-ecological systems; LULC: land use land cover change; EM: ecosystem management: CS: carbon storage, ED: mangrove dynamics; VA: vulnerability assessment; ER: ecosystem response; BM: mangrove biomass; CC: climate change; EH: ecosystem health; BD: mangrove biodiversity; and PP: primary production.

The findings (presented in figures 2(A), (B) and 3(A), (B)) indicate a dynamic and evolving field of mangrove ecosystem modelling that has significantly grown over recent years, particularly since 2019. This review reveals that Asia is the main research hub, with countries like Indonesia, India, and Bangladesh contributing most of the studies. This geographical concentration reflects the distribution of mangrove forests and highlights regional research priorities and funding influences.

3.3. Research approaches and data sources

Out of the 74 studies reviewed, approximately 32% (24 studies) utilised an integrated modelling approach incorporating both biophysical and socio-economic dimensions, followed by 26% applying empirical methods, with 74% incorporating models as research tools. Additionally, 23% employed GIS-based approaches, 59% included models as research tools, while 19% adopted a mixed-method approach, as illustrated in figure 4(A). Among the empirical and GIS-based approaches, research on mangrove ecosystems primarily utilised statistical analysis, spatial analysis, ecological modelling, and habitat modelling. Regarding mangrove social-ecological systems (SES), the highest number, 11 studies, utilised empirical approaches, with only two studies employing modelling approaches. For ecosystem services, out of 19 studies, seven each were based on modelling and empirical approaches, while five utilised a geospatial approach. Among the 11 studies on land use and land cover change (LULC), seven utilised a geospatial approach and four employed modelling techniques (figure 4(B)).

In terms of data sources, many of the studies (46%) relied on aerial/satellite data, followed by primary and secondary databases (26%), survey data (21%), and data from various models (7%) (figure 5(A)). As shown in figure 5(B), sector-wise utilisation of data types indicated that all four data types were used in ecosystem services research. For land use land cover change, social-ecological systems, carbon stocks, and mangrove ecosystem management, three datasets (remote sensing, databases, and survey data) were utilised. However, only one type of data was employed for ecosystem response: biomass, climate change, ecosystem health, mangrove biodiversity, and primary production.

3.4. Models and tools

Appendix B provides a summary of the application of various models in mangrove ecosystem research, outlining their background methods and data utilisation, the tools and platforms employed for model execution, consideration of variables, the different sectors where the models are utilised, and the focus of the study on various components of the DPSIR framework. Among the studies, 18 used outcome-based models such as DPSIR, 12 used process-based models like the coastal blue carbon model in InVEST, and 24 employed models as research tools, including various statistical models. Predominantly, conceptual models like the DPSIR model (Quinn *et al* 2017, Rahman *et al* 2020, Ahmed *et al* 2021, Mahardika *et al* 2023), integrated assessment models (Marcinko *et al* 2021), Actor-Network model (Ainurrohmah *et al* 2023), mental models (Furman *et al* 2021), motivation and ability framework and sustainable livelihood framework (Nguyen *et al* 2020), and ecosystem management models (Rumondang *et al* 2024) are commonly utilised for mangrove social-ecological systems. The data types utilised in mangrove ecosystem research include stakeholders' opinions, field survey data, and satellite remote sensing data such as Landsat, Sentinel, SPOT, Shuttle Radar Topography Mission (SRTM), IKONOS, digital elevation model (DEM), Moderate Resolution Imaging Spectroradiometer (MODIS), Advanced Very-High-Resolution Radiometer (AVHRR), and global databases like Mangrove Watch, as well as

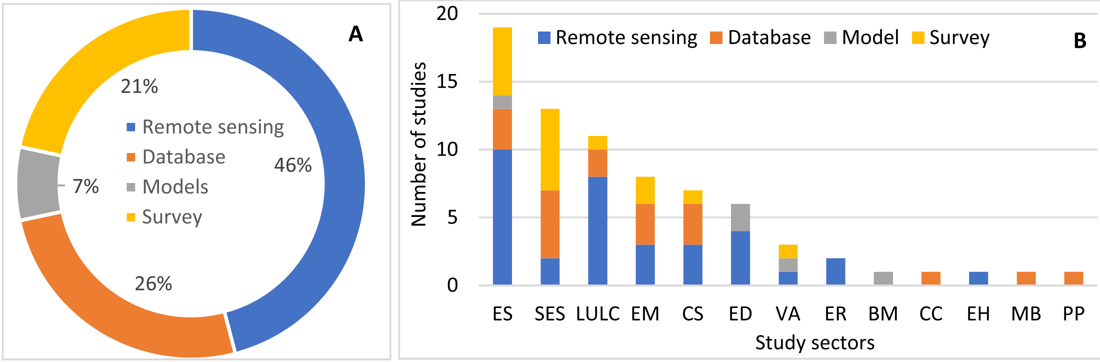

Figure 5. Number of records on types of data used (C) and sector-wise data types (D) for mangrove ecosystem research. Figure F represents the evolution of different models used for the studies. Note: ES: ecosystem services; SES: social-ecological systems; LULC: land use land cover change; EM: ecosystem management: CS: carbon storage, ED: mangrove dynamics; VA: vulnerability assessment; ER: ecosystem response; BM: mangrove biomass; CC: climate change; EH: ecosystem health; BD: mangrove biodiversity; and PP: primary production.

modelled data like WorldClim BioClim, International Best Track Archive for Climate Stewardship, and Community Climate System Model-4 data.

Tools more frequently used in mangrove ecosystem modelling encompass the InVEST model, ARIES model, ArcGIS, QGIS, ENVI, IDRISI, ERDAS Imagine, NVivo, and R programming, among others. Regarding the inclusion of studies in different components of the DPSIR framework based on their aims and objectives, over 50% of the studies encompass the STATE component. Notably, studies by Mahardika *et al* (2023), Ahmed *et al* (2021), Rahman *et al* (2020), and (Quinn *et al* 2017) encompass all components of the DPSIR framework.

In terms of research approaches, the review shows that while integrated modelling (32% of studies) and empirical methods (26%) are commonly used, there is still a notable gap in studies addressing the social dimensions of mangrove ecosystems. For example, while ecosystem services receive considerable attention, only a few studies apply modelling approaches to social-ecological systems. This observation suggests that, compared to other fields, mangrove research might benefit from more balanced attention between biophysical data and socio-economic factors.

Figure 6(A) illustrates the distribution of papers across various modelling approaches employed in mangrove ecosystem research. Approximately 20% of the studies utilised regression models, followed by around 15% using different conceptual models such as DPSIR, integrated assessment models, and actor-network models. Each of the three models, the coastal blue carbon model, support vector machine, and Markov chain—cellular automata, was utilised by 7% of the studies. In contrast, the Random Forest Model, Species Distribution Model, and ecosystem services valuation model each accounted for 5% of the studies. Additionally, nine models—KiWi model, total economic valuation framework, motivation and ability framework and sustainable livelihood framework, Burkhard model, EVDT model, hydrodynamic model, hotspot model, mental model, and contingent valuation model, were each used only once throughout the study period. This graph provides insight into the most frequently employed models, shedding light on their popularity and perceived effectiveness in the field, and offers a comparative perspective on their usage. Figure 6(B) depicts the evolution of different models over time, outlining researchers' introduction and adoption of new models. This graph showcases the progression and diversification of modelling techniques, illustrating the timeline for the introduction of models such as the KiWi model, species distribution model, ecosystem services valuation model, various regression models, and conceptual models like DPSIR, integrated assessment models, cascade models, and actor-network models. Some models were used repeatedly throughout the studied period, such as different speciation of regression models, multi-criterial decision method, cellular automata—markov chain simulation, RAPMangrove model, DPSIR model, ecosystem services valuation model, random forest model, support vector machine, and species distribution model. Conversely, models like the KiWi model, Burkhard model, LARS-WGS model, among others, were utilised only once. This suggests either the discontinuation of their use (as seen with the KiWi model used in 2000 and not after that) or the initiation of their use in mangrove ecosystem research (for instance, the actor-network model used for mangrove social-ecological systems in 2022 by Ainurrohmah *et al* (2023). Among the 74 reviewed studies, 48 studies were found to consider the components of the DPSIR framework, of which the highest number of studies were under the component state (25%), followed by 21% of the studies that considered both state and impact components in their studies (figure 6(C)). Out of 74 studies, more than 50% were carried out on biophysical domains of the mangrove ecosystems, followed by around 30% with their research focus on biophysical and social domains (figure 6(D)).

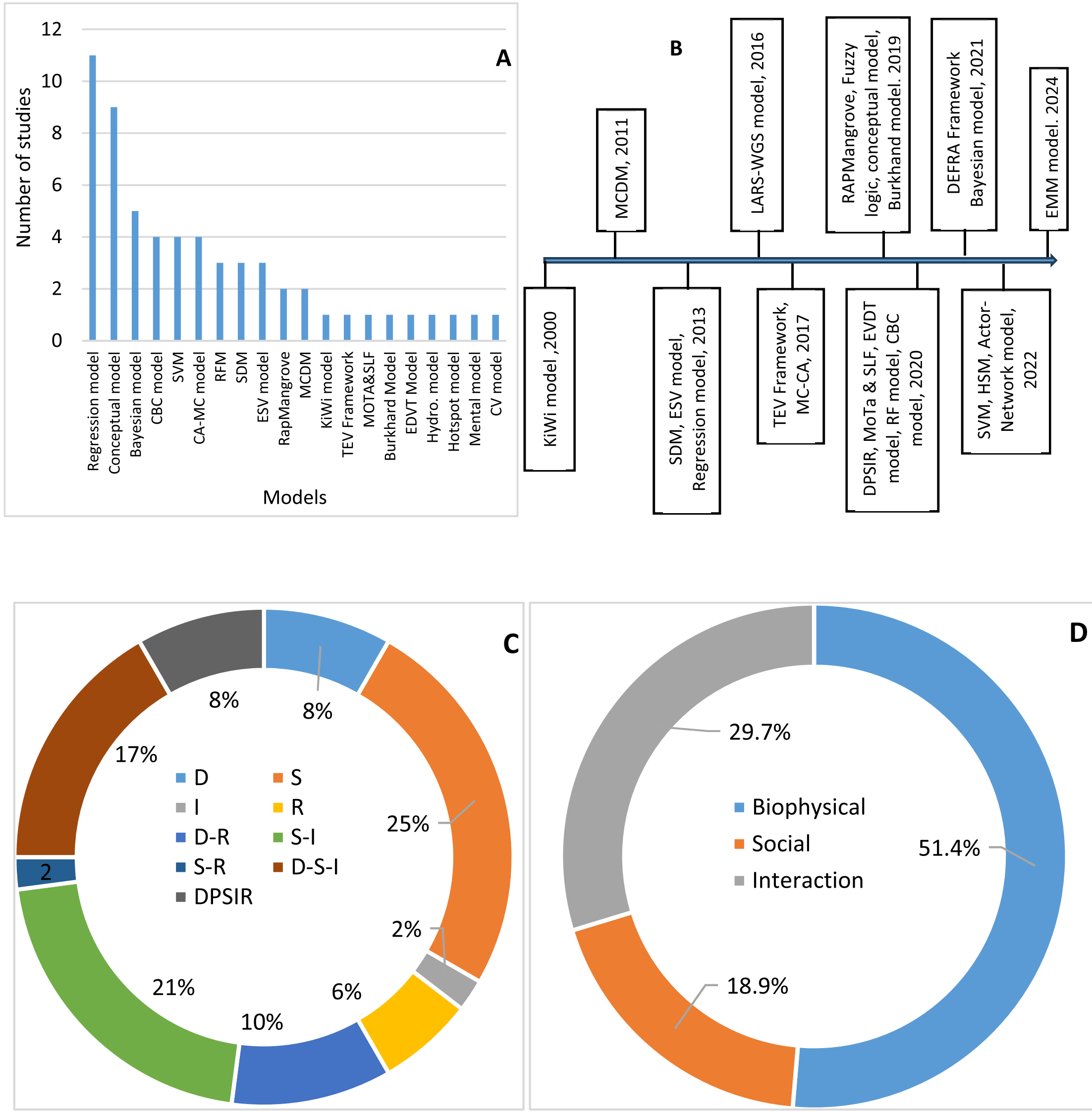

Figure 6. Number of records on models used for mangrove ecosystem research (A), the evolution of different models used for the studies (B), per cent of records under various components of DPSIR framework (C) and domains of the studies (D). Different speciation of regression models includes linear modelling, ordinary least square, generalised additive models, and multinomial logit models. In contrast, conceptual models include DPSIR, integrated assessment models, cascade models, concept models, and actor-network models. Note: CBC: coastal blue carbon; SVM: support vector machine; CA-MC: cellular automata–Markov chain; RFM: random forest model; SDM: species distribution model; ESV: ecosystem services valuation; MCDM: multi-criteria decision model; CV: coastal vulnerability model.

The findings demonstrate a diverse use of models and data types. Compared with earlier periods, there is a clear trend toward more integrated and sophisticated approaches that combine empirical methods, GIS-based techniques, and various modelling frameworks. Frequent use of models like the DPSIR framework, integrated assessment models, and various regression models indicates a trend toward adopting more robust and multifaceted analytical tools. When compared to previous research trends in environmental modelling, there is a noticeable shift toward integrating remote sensing data with stakeholder opinions and survey data, which enriches the contextual understanding of both ecological processes and human impacts.

3.5. Key issues emerging from modelling studies

Appendix C summarises key issues emerging from the reviewed studies. Firstly, the global decline in mangrove extent; secondly, the resulting loss of ecosystem services and their economic value, and thirdly, impacts on carbon stocks and climate change.

Using Global Mangrove Watch (GMW) data, (Bunting *et al* 2022) reported a 5245 km^2 (3.4%) decline in global mangrove forests from 1996 to 2020, with losses most pronounced in lower latitudes and areas of intense human activity. Similar trends were reported in Bangladesh (Hasan *et al* 2020), India (DasGupta *et al* 2019), Malaysia (Khuzaimah *et al* 2013), and Indonesia. Nevertheless, future projections show potential poleward expansion of mangroves in temperate zones, irrespective of RCP scenarios (Cavanaugh *et al* 2019, Gouvêa *et al* 2022). Coastal erosion, particularly in the Sundarbans, is a dominant natural driver of mangrove loss, worsened by reduced sediment supply and sea-level rise (Giri and Long 2016, Bunting *et al* 2022). Human-induced pressures, such as conversion for agriculture, aquaculture, and urban infrastructure (e.g., roads, ports, oil facilities), further intensify degradation, especially in Southeast Asia (Agbagwa and Ndukwu 2014, Goldberg *et al* 2020).

Economic valuation studies show that supporting and regulating services of mangroves have the highest value. In the Indian Sundarbans, Sannigrahi *et al* (2020) estimated habitat services at USD 30,780/ha and regulating services at USD 20,212/ha. However, overall service values are declining due to degradation, with Malaysia's mangrove services dropping from USD 0.81 million in 2000 to USD 0.43 million in 2020 (Khuzaimah *et al* 2013).

Globally, mangroves store an estimated 6.17 Pg of organic carbon, representing 17% of tropical marine carbon stocks (Alongi 2023). When foregone sequestration is included, emissions from mangrove loss may reach 2391 Tg CO_2 eq by 2100, increasing to 3392 Tg CO_2 eq. Species-specific studies (Rahman *et al* 2015) show that forests dominated by *Heritiera fomes* store more carbon than others.

3.6. Research gaps

Modelling mangrove SES is vital for understanding the interactions between ecological processes and human activities. However, several key limitations affect the proposed models' accuracy and usefulness for decision-making.

First, reliable data on mangrove structure, function, and ecosystem services are often lacking due to limited monitoring, inaccessible locations, and environmental variability (Hagger *et al* 2022). Integrating remote sensing, field data, expert input, and rigorous uncertainty analysis is essential to improve model reliability. Second, models must simplify complex ecological and social interrelationships and feedback (Dahdouh-Guebas *et al* 2021), but this can result in inaccurate predictions and a poor representation of system dynamics. Third, mangrove systems operate across multiple spatial and temporal scales. Inappropriate scaling can lead to flawed insights - fine-scale models may miss broader trends, while large-scale models can overlook local nuances (Brosse *et al* 2025). Fourth, including dynamic human dimensions - like local governance, economic drivers, and cultural practices - is complex, but critical (Cruz Portorreal *et al* 2024). Many models fail to reflect these social realities adequately, limiting their relevance for community-level management. Fifth, long-term observational data are scarce, making model validation difficult (Berger *et al* 2008), thus leading to high uncertainty in model outcomes and limited confidence in predictions. Finally, although models are powerful tools for policy and planning, their limitations must be communicated (Mukherjee *et al* 2014). Transparent reporting of model assumptions and uncertainties is vital for informed decision-making.

4. A general conceptual model for mangrove SES

To address the limitations described above, we formulated a general conceptual model that can be used as a framework for future studies on mangrove social-ecological systems, particularly for developing modelling approaches in collaboration with stakeholders and policy/decision makers. The objective was to delineate the essential features of social-ecological systems, the interrelationships among the main system elements, and their associated ecosystem services to demonstrate how these pivotal aspects should be incorporated into ecosystem assessments to guide evidence-based policy and management decisions. The proposed model utilises the DPSIR framework (Gari *et al* 2015, Roy *et al* 2023). Drawing on the work of Quevedo *et al* (2023), Ahmed *et al* (2021), and other contributors, the general conceptual model was specified for mangrove ecosystem services and social-ecological systems in the coastal region of Bangladesh, highlighting the key characteristics of various components within the framework, as reported in figure 7 and in the text below.

4.1. Drivers and pressures

Within coastal mangrove ecosystems, commonly identified natural drivers encompass climate change, sea level rise, hydrological fluctuations, and anthropogenic factors include land use alterations, coastal development, rapid urbanisation, and population growth (Mateus and Campuzano 2008, Lewison *et al* 2016), with associated activities such as agriculture, fisheries, aquaculture, tourism, port operations, export processing zones, and solid waste management. Land use changes, particularly in agriculture and aquaculture, emerge as primary drivers affecting mangrove ecosystems (Hossain *et al* 2021). These drivers and activities in coastal regions exert pressure on mangrove ecosystem dynamics, leading to overexploitation, deforestation, pollution, erosion, salinity intrusion, coastal alteration, etc.

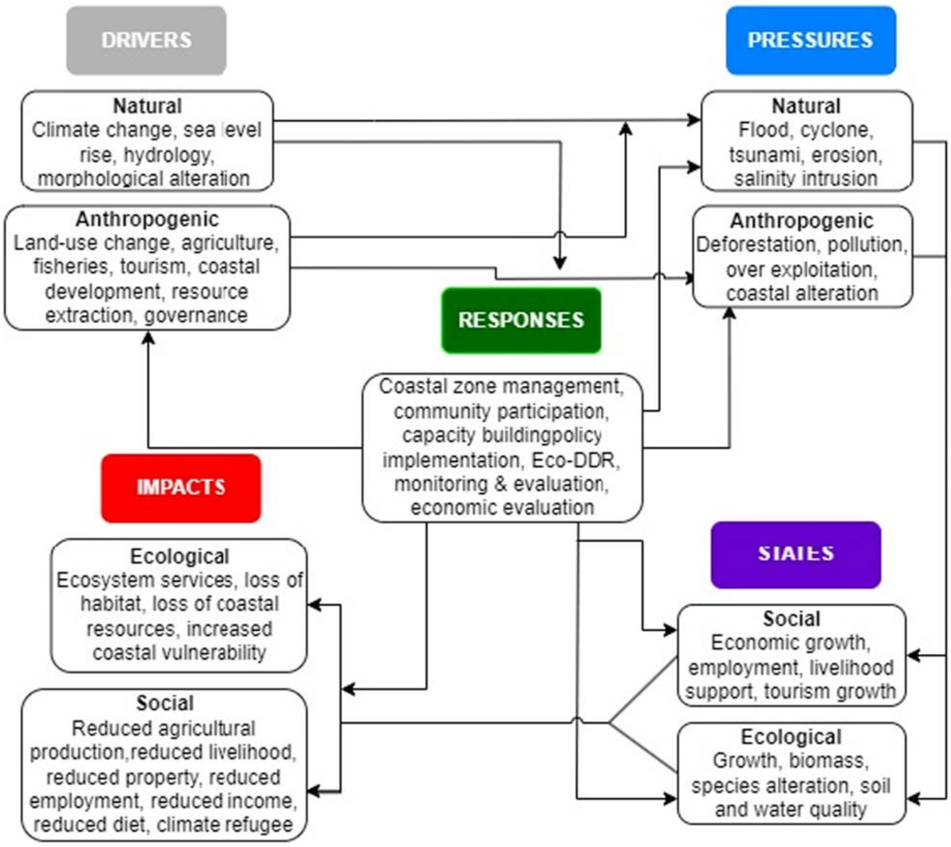

Figure 7. Conceptual model of the mangrove socio-ecological system drafted through this review work. Although the general model is drafted for the mangrove ecosystem in the coastal regions of Bangladesh, it can be adapted for any coastal ecosystem, such as salt marshes, seagrass, or coral reefs, in any area of the world.

4.2. States and impacts

Ahmed *et al* (2021) have identified vegetation density, fuelwood collection, fish and crab catch, and honey and wax production as pivotal variables reflecting the ecological state of mangroves in Bangladesh's coastal regions. However, producing fuelwood, fish, crabs, honey, and wax indicates goods provided by coastal ecosystems, causing changes in these factors to signify impacts. Additionally, soil and water quality within the mangroves are essential indicators of the coastal ecosystem's state. Works by Ataullah *et al* (2017), Zafar *et al* (2015), Rahaman *et al* (2013), and Islam *et al* (2004) shed light on the soils and water quality of mangrove areas.

Overall, the ecological and social impacts identified predominantly relate to the loss or reduction of provisioning, regulating, and supporting services (figure 7). Key environmental impacts include habitat loss, biodiversity decline, depletion of tangible and intangible resources, changes in ecosystem services (Sarker *et al* 2024) and heightened vulnerability in coastal regions. Consequently, social impacts encompass diminished livelihood support, reduced income and employment opportunities, and increased climate refugees, as many coastal countries are already experiencing (Abdullah-Al-Mamun *et al* 2017). This situation underscores the urgent need for a comprehensive management plan inspired by multiple objectives that can be framed within the Sustainable Development Goals of U.N. Agenda 2030 (Lee *et al* 2016).

4.3. Responses

Quevedo *et al* (2023) have categorised the response strategies available for managing mangrove social-ecological systems into five groups: (i) reforestation and monitoring, (ii) management-related responses such as Integrated Coastal Zone Management, (iii) Integrated Water Resources Management, and Community-Based Management, (iv) capacity development responses such as training and awareness programs, policy-related responses like the Coastal Zone Policy (2005), and (v) other responses such as ecosystem-based disaster risk reduction.

Shampa *et al* (2023) reviewed existing management strategies for sustainable coastal zone management in Bangladesh. The Government of Bangladesh has initiated several endeavours for mangrove ecosystem management, including the Coastal Zone Policy (2005), Integrated Coastal Zone Management (ICZM), Coastal

Development Strategy (2006), Bangladesh Delta Plan 2100, Char Development and Settlement Program, National Adaptation Plan, among others.

5. Conclusion

This review presents a comprehensive survey of the current state-of-the-art modelling approaches for mangrove social-ecological systems. The paper highlights the need for robust modelling frameworks to address the challenges facing mangrove ecosystems, such as habitat loss from climate change and human activities.

Based on the review of the studies, the following critical research gaps have been identified. First, existing models lack integration between ecological and hydrodynamic processes. Second, limited access to field data hampers model validation, underscoring the need for comprehensive, site-specific datasets. Third, human-environment interactions are often underrepresented, despite their significant impact on mangrove dynamics. Lastly, current models tend to oversimplify complex feedback, calling for the adoption of advanced approaches like agent-based and coupled biophysical models to reflect system complexity better. Addressing current limitations through better data, interdisciplinary integration, and transparent communication is key to developing robust, decision-supportive models for mangrove SES.

Addressing these research gaps will advance the development of more robust and reliable mangrove models, facilitating better-informed management and conservation efforts for these vital coastal ecosystems. A conceptual model has been developed to address these gaps. This provides a framework for studying mangrove social-ecological systems, particularly in coastal Bangladesh, and can be adapted for other ecosystems globally. It highlights the drivers, pressures, states, and impacts affecting mangroves, emphasising the need for incorporating ecosystem services into evidence-based policy and management decisions. Response strategies include reforestation, integrated management approaches, capacity development, and various policy initiatives the Government of Bangladesh implemented, aiming for sustainable coastal ecosystem management.

This review contributes in a diverse way by critically examining the existing modelling landscape. First, they highlight the regional particularity and the impact of funding configurations on research directions. Second, the review is helpful for constructing new research methodologies as it traces the progression of modelling methods from simpler regression modelling to more sophisticated frameworks like the actor-network model. Third, the interrelationship between land use and land cover change, social-ecological systems, and ecosystem services with contemporary threats driven by climate change, sea level rise, and broader global changes remains to be explored. The insights from this review consolidate the existing knowledge base and set a direction for future investigations, facilitating evidence-based decision-making concerning the conservation and sustainable management of mangrove social-ecological systems amidst global change.

Data availability statement

No new data were created or analysed in this study.

Appendix A. Word cloud analysis of abstracts for reviewed papers

Figure A1. Word cloud for keywords extracted from the literatures.

Appendix B. Summary of models, methods, tools, data types, sectors and variables used for mangrove ecosystem research

Models	Methods	Tools	Data types	Sectors	Variables	Temporal scale	DPSIR component	References
Ecosystem management model	ANP, AHP, Kendall's coefficient of concordance	SuperDecisions software		SES			S, R	(Rumondang *et al* 2024)
DPSIR	Descriptive qualitative analysis		Survey, spatial data, database	SES, ES		1984–2013	D, P, S, I, R	(Quinn *et al* 2017, Rahman *et al* 2020, Ahmed *et al* 2021, Mahardika *et al* 2023, Quevedo *et al* 2023)
Coastal blue carbon model	Spatially explicit analysis	InVEST	Database, spatial data	ES, CS	Forest cover change, C sequestration, soil C stock	1988–2020	D, R	(de Paula Costa *et al* 2022, Hernández-Blanco *et al* 2022, Rosa *et al* 2022)
Coastal vulnerability model		InVEST	Spatial data	ES	C sequestration, C stock, flooding and erosion	1998–2014	D	(Sannigrahi *et al* 2020, Hernández-Blanco *et al* 2022)
Regression model	Seascape matrix, plant matrix, vegetation indices,	ArcGIS, ERDAS Imagine, SIMCA-P, ENVI, R programming	Database, field survey	LULC, VA, ES, EH	Soil organic carbon stock		D, S, I	(Quisthoudt *et al* 2013, Ishtiaque *et al* 2016, Wang *et al* 2018, Hashim

(Continued.)

Models	Methods	Tools	Data types	Sectors	Variables	Temporal scale	DPSIR component	References
								et al 2020, Mafi-Gholami et al 2020a, 2020b, Asplund et al 2021, Sarker et al 2021)
RAPMangrove	Monte Carlo Simulation, AHP	Expert choice software	Database	MS	Ecological, social, economic, institutional, technological		R	(Santoso and Nugraha 2019, Sukuryadi et al 2021)
Bayesian model	Stable isotope analysis, trait-trait matrix, trait-environment matrix	R programming	Field survey	ES, PP		2008–2014	S	(Sarker et al 2021, Tachas et al 2021)
MCDM	Questionnaire survey, Spatial multi-criteria analysis			LULC, VA	CO_2, RH, Temperature, SRL, rainfall, alien invasive sp, pollution input	1987–2002	S, I	(Omo-Irabor et al 2011, Akhbar et al 2022)
ESV model	NDVI, AVI, ANN, KNN, LDA, MLC, GBT, DT	InVEST, ARIES		ES			S	Sannigrahi et al 2019b Khuzaimah et al 2013, Sannigrahi et al 2019a
SVM	Regression analysis	ArcGIS	Spatial data	CS	Soils organic carbon stock	1988–2018	S, I	(Sannigrahi et al 2019b, 2019c, Zhu et al 2021, Datta et al 2022, Meng et al 2022)
RFM	Regression analysis	ArcGIS	Spatial data	CS	Soils organic carbon stock	1988–2018	S	(Zhu et al 2020, 2021, Meng et al 2022)
MC-CA model	AHP, Transparency probability matrix	SPSS, R programming	Databasen Spatial data	LULC, ES		1987–2016	S, I	(Supriatna et al 2018, Trialfhianty et al 2022)
Fuzzy logic		FCMWizard, ArcGIS, MAKESENSE	Spatial data	MS			D, R	(Singh et al 2019, Mafi-Gholami et al 2020a, 2021)
IAMs	Selected SDG analysis, policy analysis	Draw.ai	Database	SES				(Marcinko et al 2021)
EVDT model	NDVI	Python	Spatial data	ES		1975–2019	S, I	(Reida and Wood 2020)
ES elasticity model			Database	ES	Provisioning, regulating and cultural services	Monthly data 2018	I	(Nurokhmah et al 2019b)
LARS-WGS model	GCM strategy	ENVI, ArcGIS	Database	CC			D	(Etemadi et al 2016)
Hotspot model	NDVI	ArcGIS	Spatial data	VA		2001–2015	D	(Hussain and Islam 2020)
MOTA and SLF			Survey data	SES			S	(Nguyen et al 2020)
Burkhand model			Survey	ES	ES capacity, availability, ES Demand	Monthly data 2018	S	(Nurokhmah et al 2019a)

(Continued.)

Models	Methods	Tools	Data types	Sectors	Variables	Temporal scale	DPSIR component	References
SDM		Maxent, ArcGIS	Spatial data, model data	LULC, ED	Climatic, oceanographic, and environmental variables	1950–2020	D, S	(Quisthoudt et al 2013, Ghayoumi et al 2022)
Habitat suitability model	Continuity and momentum equation, Habitat suitability index	Hydrodynamic model SRH-2D	Database	MS			R	(Shih et al 2022)
TEV Framework			Database	ES			S	(Abdullah-Al-Mamun et al 2017)
CLUE-S model	EVI, logistic regression, SVM and RFM algorithm	R programming	Spatial data	MS	Land use, mangrove distribution variables	1987–2017	S	(Zhu et al 2021)

*DPSIR—Driver-Pressure-State-Impact-Response, MCDM—Multi-Criterial Decision Method, ESV—Ecosystem Services Valuation, SVM—Support Vector Machine Model, SDM—Species Distribution Model, RFM—Random Forest Model, MC-CA –Monte Carlo Cellular Automata, IAM—Integrated Assessment Model, ARIES - ARtificial Intelligence for Environment & Sustainability, EVDT - Environment-Vulnerability-Decision-Technology, MOTA—Motivation and Ability, SLF—Sustainable Livelihood Framework, ANP—Analytical Network Process, AHP—Analytical Hierarchical Process, NDVI—Normalized Difference Vegetation Index, AVI—Advanced Vegetation Index, ES—mangrove ecosystem services, LULC—land use land cover change in the mangrove forests, SES—mangrove social ecological systems, CS—carbon stock in mangrove ecosystems, MS—management strategies for adopted mangrove forests, ED—mangrove ecosystem dynamics, VA—mangrove vulnerability assessments, ER—mangrove ecosystem responses to drivers and pressures, BM—mangrove biomass, CC—climate change, EH—mangrove ecosystem health, BD—mangrove biodiversity and PP—primary production. abbreviation.

Appendix C. Summary findings based on reviewing records on mangrove ecosystem research

Sector	Impacts	References
Mangrove extent	Land use increased from 3,375 ha in 1988 to 3,764 ha in 2018	(Rosa et al 2022)
	An increasing trend was observed for mangrove forest	(Datta et al 2022)
	Mangrove forests decreased by 2168.3 ha from 1987 to 2020	(Nguyen et al 2022)
	Mangrove area increased slowly under a natural growth scenario (NGS) (4460 ha), decreased significantly under an economic development scenario (EDS) (2704 ha) and increased significantly under a mangrove protection scenario (MPS) (5456 ha) by 2037.	(Zhu et al 2021)
	In 2005, mangrove areas were 14.08 ha, in 2005 area increased to 25.99 ha but in 2019, area again decreased to 15.22 ha, with overall increase of 1.14 ha.	(Martuti et al 2020)
	Mangrove area increased by 5.5% from 1995 to 2014.	(Wang et al 2018)
	2.7 sq km of mangrove forest area increased from 1984 to 2017	(Cohen et al 2018)
	2.72% in 2000 to 4.40% in 2020 and forests lands are decreasing proportionally	(Liang et al 2022)
	Present mangrove extent is 12780 km^2 and RCP 2.6 showed higher increase (17.29%) than RCP 8.5 (15.77%)	(Gouvêa et al 2022)
	SRF has been degraded significantly in a negative manner (4773.02 ha yr^{-1}) (about 18.53% for TR of the total share of land area) in 1989–2009.	(Hasan et al 2020)
	From 1986 to 2917, mangrove area changed in Khamir (−800 ha), Tiab (620 ha) and Jask (−95 ha) wit an overall loss of 275 ha	(Mafi-Gholami et al 2020b)
	27.3% of the Indian Sundarbans went under landuse transition. 3.72% of the forest will be declined in BAU scenario but 4.67% will be gained in Green scenario by 2030.	(DasGupta et al 2019)
	Mangrove area significantly decreases 7,241.77 Ha (9.75%)	(Supriatna et al 2018)
	Mangrove forest decreased from 1246 ha in 2000 to 1152 ha in 2010 and for 2020, the change is predicted to 1058 ha.	(Khuzaimah et al 2013)
Ecosystem Services Valuation	Total economic value for the mangrove ecosystem in Batu Bara Regency, Indonesia is $60,056,390,237.60.	(Rumondang et al 2024)

(Continued.)

Sector	Impacts	References
	Restoration could generate approximately AU$12 million to AU$103.5 million	(de Paula Costa *et al* 2022)
	Habitat service: 30780 (US$/ha), nutrient cycling: 12626 (US$/ha), gas regulation: 7224.81 (US$/ha), water regulation: 347.81 (US$/ha), raw material production: 777.82 (US$/h)) and waste treatment: 13.57 (US$/ha)	(Sannigrahi *et al* 2020)
	mangrove ecosystem (US$19144.9 million/year in the Indian Sundarbans	(Sannigrahi *et al* 2020)
	total revenue for for provisioning services USD 488033/year and regulating services USD 945231 / year	(Nurokhmah *et al* 2019b)
	The value for forest area decreased from USD 808707.61 in 2000 to USD 747697.56 in 2010; its value is predicted to be USD 429017.44 in 2020.	(Khuzaimah *et al* 2013)
Carbon sequestration / Carbo stock	Restoration could accumulate over 7 million t of CO_2e by 2135.	(de Paula Costa *et al* 2022)
	Carbon stocks in the mangroves of the city of Santos increased 29%	(Rosa *et al* 2022)
	Net carbon sequestration was approximately 925,393 Mg CO2e and 287,130 Mg CO_2e, in Santos and Sao Vicente	(Rosa *et al* 2022)
	Carbon stock was estimated to be 703,181 Mg C (with a mean density of 192 Mg C/ha)	(Meng *et al* 2022)
	The highest SOC (4400.52 Mg/ha) was in 0–20 cm and gradually decreased over the depth.	(Datta *et al* 2022)
	Dense mangrove patches have the highest SOC of 248.92 Mg/ha and the lowest in Casuarina plantations (2.78 Mg/ha)	(Datta *et al* 2022)
	Average carbon stock in mangrove 86 Mg C ha	(Asplund *et al* 2021)
	The global mean C stock for mangroves is estimated to be 6.17 Pg C_{org}, constituting17% of total tropical marine C stock.	(Alongi, 2020)
	Global emissions from mangrove loss are projected to reach 2391 Tg CO_2 eq by 2100 and 3392 Tg CO_2 eq considering deforestation rate of 1.5 Mg C ha^{-1} $year^{-1}$.	(Adame *et al* 2021)
	Total biomass increased from 23270.43 to 39819.03 tons	(Zhu *et al* 2020)
	AGB increased by 7.2% and above-ground carbon increased from 57 to 79 t C/ha from 1995 to 2014.	(Wang *et al* 2018)
	TB in its current stage is 9.4 t/ha; TB in RCP 2.6, RCP 4.5, RCP 6.0 and RCP 8.5 is 7.3, 12.1, 11.7 and 17.8 t/ha.	(Wang *et al* 2017)
	Heritiera fomes dominated forest types store more ecosystem carbon (360.1 Mg C/ha) than other vegetation types and low saline zone part of the Sundarbans showed the highest carbon stock (336.09 Mg C/ha)	(Rahman *et al* 2015)
Others	Land conversion followed by coastal erosion are the highest priority issues and Rehabilitation and conservation of mangrove areas is the highest solution priority.	(Rumondang *et al* 2024)
	21.85 sq.km for the species *Avecennia marina* will be reduced at RCP 8.5 by 2080	(Ghayoumi *et al* 2022)
	PFTs height is more affected by salinity	(Sarker *et al* 2021)
	29.5% loss of its current total productivity under the highest stress scenario mainly associated with community-wide decreases (36%) in height by 2050	(Sarker *et al* 2021)
	14.1% extreme safe zone is increased from 2001 to 2015 and extremely vulnerable zone increased 4.1% at the same time, although 4.3% stable zone also decreased	(Hussain and Islam 2020)
	Mangrove is exposed to sea level rise followed by drought, runoff change and temperature.	(Mafi-Gholami *et al* 2020a)
	NPP increased significantly during the first half period (1982–1999), but significantly declined during the second period (2000–2017).	(Sannigrahi *et al* 2020)
	The most species-rich mangrove communities are restricted to the northern upstream habitat.	(Sarker *et al* 2019)

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