

A SYSTEMATIC REVIEW OF MANGROVE RESILIENCE TO CLIMATE VARIABILITY

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ABSTRACT: This systematic literature review synthesizes recent research on the resilience of mangroves in response to climate variability. Mangroves play a crucial role in coastal protection, carbon sequestration, and biodiversity conservation. However, climate variability, including extreme weather events, sea level rise, and changing precipitation patterns, poses significant challenges to mangrove ecosystems. Using Covidence for article selection and analysis, this study investigates the relationship between climate variability and mangrove resilience. This study employed the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines to ensure methodological accuracy and transparency. A search of the Scopus database (2014–2024) identified $n = 223$ records, which after screening and eligibility assessment, resulted in $n = 44$ studies included in the final synthesis. The review identified sea level rise, extreme weather events, and altered sediment dynamics as the primary climate-related stressors affecting mangrove resilience, while vegetation structure, species composition, and recovery capacity emerged as the most frequently used resilience indicators. This review concludes that strengthening mangrove resilience requires integrated socio-ecological strategies that combine ecological processes with adaptive governance, sediment management, and community-based adaptation. Addressing research gaps through geographically and interdisciplinary approaches will be crucial for enhancing the role of mangroves in climate adaptation and sustainable coastal management. The findings underscore the importance of mangroves in relation to the global Sustainable Development Goals (SDGs), particularly SDGs 13 (Climate Action), 14 (Life Below Water), and 15 (Life on Land).

Keywords: Mangrove resilience, climate variability, coastal ecosystems, socio-ecological adaptation, systematic review

RESUMO: Esta revisão sistemática da literatura sintetiza pesquisas recentes sobre a resiliência dos manguezais em resposta à variabilidade climática. Os manguezais desempenham um papel crucial na proteção costeira, no sequestro de carbono e na conservação da biodiversidade. No entanto, a variabilidade climática, incluindo eventos climáticos extremos, elevação do nível do mar e mudanças nos padrões de precipitação, impõe desafios significativos aos ecossistemas de manguezais. Utilizando o Covidence para a seleção e análise dos artigos, este estudo investiga a relação entre variabilidade climática e resiliência dos manguezais. O estudo empregou as diretrizes Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) para garantir rigor metodológico e transparência. A busca na base de dados Scopus (2014–2024) identificou $n = 223$ registros, dos quais, após as etapas de triagem e avaliação de elegibilidade, resultaram em $n = 44$ estudos incluídos na síntese final. A revisão identificou a elevação do nível do mar, os eventos climáticos extremos e a alteração da dinâmica sedimentar como os principais fatores de estresse relacionados ao clima que afetam a resiliência dos manguezais, enquanto a estrutura da vegetação, a composição de espécies e a capacidade de recuperação emergiram como os indicadores de resiliência mais frequentemente utilizados. Esta revisão conclui que o fortalecimento da resiliência dos manguezais requer estratégias socioecológicas integradas que combinem processos ecológicos com governança adaptativa, manejo sedimentar e adaptação baseada na comunidade. A superação das lacunas de pesquisa por meio de abordagens geográficas e interdisciplinares será crucial para ampliar o papel dos manguezais na adaptação climática e na gestão costeira sustentável. Os resultados destacam a importância dos manguezais em relação aos Objetivos de Desenvolvimento Sustentável (ODS) globais, particularmente os ODS 13 (Ação Climática), 14 (Vida na Água) e 15 (Vida Terrestre).

Palavras-chave: Resiliência de manguezais, variabilidade climática, ecossistemas costeiros, adaptação socioecológica, revisão sistemática

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1. INTRODUCTION

Mangroves are intertidal forest ecosystems distributed across tropical and subtropical coastlines, occupying approximately 140,260 km² globally (Bunting *et al.*, 2022) and providing critical ecological and socio-economic services. They are widely recognized for their multifunctionality in preserving coastal ecosystems and significantly contributing to protection from natural hazards by dissipating wave energy, stabilizing sediments, and buffering storm surges (Menéndez *et al.*, 2020; Zhang *et al.*, 2022). Despite their global importance, mangroves are experiencing significant decline due to both anthropogenic pressures and climate-related stressors (Friess *et al.*, 2019; Goldberg *et al.*, 2020). Their capacity to mitigate climate variability, such as sea-level rise, tropical storms, and tidal anomalies, depends strongly on ecological processes, including sediment accretion and hydrodynamic interactions (Gijsman *et al.*, 2021; Menéndez *et al.*, 2020; Zhang *et al.*, 2022). However, when sea level rise surpasses natural sedimentation rates, mangroves face ecological collapse (Lovelock *et al.*, 2015). In addition, climatic variables such as temperature and precipitation significantly influence mangrove growth and health, while extreme events, including cyclones and droughts, often trigger large-scale dieback (Allen *et al.*, 2021; Silva *et al.*, 2022). Therefore, the resilience of mangroves to such disturbances is critical, as these ecosystems function as natural barriers that reduce coastal erosion and flooding risks, thereby protecting coastal communities (Mugilan *et al.*, 2024).

The presence of mangroves is integral to achieving several of the United Nations' Sustainable Development Goals (SDGs), particularly SDG 13 (Climate Action), SDG 14 (Life Below Water), and SDG 15 (Life on Land). These ecosystems provide numerous benefits that enhance climate resilience and promote biodiversity conservation, which are crucial in the face of ongoing environmental challenges (Gijsman *et al.*, 2021). Sustainable coastal management frameworks are increasingly recognizing the value of preserving mangroves and other critical habitats as natural defenses, while supporting biodiversity and mitigating climate change (Rumondang *et al.*, 2024; Xavier *et al.*, 2022). Integrating ecological considerations into coastal development and urban planning is crucial to maintain these ecosystem services (Martínez *et al.*, 2025). Collaborative management approaches, particularly those engaging local stakeholders in restoration efforts, have been shown to enhance both ecological recovery and community resilience (Hasan *et al.*, 2022). Sustainable coastal management relies on striking

a balance between ecological integrity and the socio-economic realities of the communities that depend on these ecosystems.

The concept of mangrove resilience provides a fundamental framework for analyzing the effects of climate variability. It is defined as the capacity of an ecosystem to resist, recover from, and adapt to climate-induced disturbances while preserving its essential functions and services, including increased sea levels, a higher probability of catastrophic storms, and shifts in salinity levels (Alongi, 2015; Friess *et al.*, 2019; Portela, 2025; Ward *et al.*, 2016). Resilience is influenced by multiple factors, such as biodiversity, ecological interactions, and local environmental conditions (Dong *et al.*, 2023; Smith *et al.*, 2022). In this study, resilience encompasses the ecological aspects of mangroves' responses to climate variability and the climate indicators that drive mangrove resilience. Diverse species responses to climate variability, referred to as response diversity, may improve ecosystem resilience, encouraging functional continuity even during stress (Feit *et al.*, 2021). Studies demonstrate that terrain attributes, including bedrock and soil composition, have a substantial influence on ecosystem reactions to climatic variability (Dong *et al.*, 2023).

Mangroves demonstrate resilience through mechanisms such as sediment trapping, land-building processes, and rapid recolonization following disturbance, allowing them to maintain ecosystem functions despite stress (Alongi, 2015). Their resilience is strengthened by the preservation of ecological connectivity, genetic diversity, and local community management, reducing vulnerability to climatic extremes (Dahdouh-Guebas *et al.*, 2005). However, human-induced pressures, including deforestation and coastal development, reduce mangrove resilience, making them more vulnerable to climate-related degradation (Friess *et al.*, 2019). Environmental stressors, such as significant rainfall-induced flooding, can reduce groundwater salinity, which has been demonstrated to enhance the growth of particular mangrove species (Li *et al.*, 2022). This explains the ever-changing relationship between mangrove health and local hydrological conditions, indicating that changes in freshwater supply can enhance the ecosystem's resilience. Freshwater ecosystems are vulnerable to fluctuations in temperature and precipitation, requiring management solutions customized to local ecological contexts to enhance resilience (Portela, 2025; Rivers-Moore & Dallas, 2022). Studies showing increased resilience in mangrove ecosystems subjected to such fluctuations highlight the importance of understanding local environmental conditions to improve conservation methods (Li *et al.*, 2022). A comprehensive framework is necessary

to integrate ecological processes with adaptive governance, restoration strategies, and climate adaptation policies, thereby ensuring the ongoing provision of essential services, including coastal protection, carbon sequestration, and biodiversity conservation, in the face of climate variability (Lee *et al.*, 2014; Ward *et al.*, 2016).

Recent studies have increasingly explored mangrove ecosystems through review and synthesis approaches, addressing topics such as ecosystem services, carbon dynamics, vulnerability to sea-level rise, and restoration strategies (Alongi, 2008; Friess *et al.*, 2019; Sasmito *et al.*, 2020). However, these studies often focus on specific dimensions of mangrove systems, particularly biophysical processes or localized case studies, without explicitly integrating climate variability as a central driver of resilience. As a result, existing syntheses remain fragmented and lack a comprehensive framework that connects climatic drivers, ecological responses, and socio-institutional mechanisms. This limitation constrains a holistic understanding of mangrove resilience and its variability across regions. Therefore, a more integrative and systematic synthesis is needed to bridge these gaps and advance the understanding of mangrove resilience within a coupled socio-ecological context.

This study aims to establish a fundamental basis for investigating the relationship between climate variability and mangrove resilience. It synthesizes and critically evaluates recent research examining how mangrove ecosystems respond to climatic variability and related stressors. To guide this synthesis, the review is structured around the following research questions: (1) What are the drivers of mangrove resilience? (2) What methods have been employed to assess mangrove resilience under climatic variability? (3) How do mangroves respond to climate variability? (4) What research gaps remain concerning the interactions between climate variability and mangrove ecosystems? Together, these questions provide a structured framework for synthesizing existing knowledge and identifying opportunities for future research. This study contributes by systematically identifying and classifying the factors influencing mangrove resilience across both biophysical and socio-institutional dimensions, while proposing an empirically grounded typology of response pathways, including resistance, recovery, and dieback. This approach advances current understanding from a predominantly biophysical perspective toward a more integrated socio-ecological framework, supporting more effective and sustainable coastal management strategies.

2. METHODS

2.1 Search Strategy

This study followed the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines, which provide a structured and transparent framework to enhance reproducibility and methodological rigor (Rethlefsen *et al.*, 2021). The literature search was conducted using the Scopus database (accessed on November 28, 2024), as it offers comprehensive coverage of peer-reviewed environmental and interdisciplinary journals. The search was limited to articles published between 2014 and 2024. This time frame was chosen to reflect the most recent advances in mangrove resilience research, particularly the growing emphasis on climate variability, extreme events, and integrated socio-ecological methods. It also indicates a movement in the literature from primarily biophysical viewpoints to more interdisciplinary and policy-relevant frameworks.

To capture the relevant scope, the following Boolean string was applied: mangrove AND climat* AND resilience AND NOT carbon. This formulation was designed to focus on the relationship between mangrove resilience and climate variability, while excluding studies that primarily addressed carbon dynamics, thereby avoiding bias toward mitigation research and maintaining an emphasis on adaptation and ecological resilience. The literature search initially identified a total of $n = 223$ records from the Scopus database. After the removal of duplicates and limitation of document type and language, $n = 181$ unique records remained for the screening stage. During title and abstract screening, $n = 121$ records were excluded for not meeting the predefined inclusion criteria. Subsequently, $n = 60$ full-text articles were assessed for eligibility, of which $n = 16$ were excluded due to reasons such as lack of direct relevance to mangrove resilience, methodological limitations, or insufficient focus on climate variability. Finally, $n = 44$ studies met all criteria and were included in the qualitative synthesis, forming the basis for this systematic literature review. The detailed process is summarized in the PRISMA flow diagram (Figure 1).

2.2 Screening and Eligibility

All search results were imported into Covidence software to facilitate screening and overall reference management. Covidence has become one of the most widely used platforms for conducting systematic literature reviews, particularly in health sciences, environmental studies, and social sciences, because it streamlines study selection, data extraction, and quality assessment (Babineau, 2014; Haby *et al.*, 2024; Harrison *et al.*,

2020). Its increasing adoption across disciplines demonstrates its reliability and efficiency in supporting transparent and reproducible review processes. Duplicate records were removed, and a two-stage screening process was performed: (1) title and abstract screening, followed by (2) full-text screening. Studies were included if they explicitly addressed research examining mangrove ecosystems, concentrating on coastal regions in tropical and subtropical climates, and research examining mangroves impacted by climate variability, including sea level rise. Exclusion criteria encompassed articles focusing exclusively on blue carbon storage and stressors unrelated to climate, such as pollution, that do not pertain to sea level rise and mangrove resilience, studies not peer-reviewed, and non-English publications. Table 1 outlines the detailed inclusion and exclusion criteria.

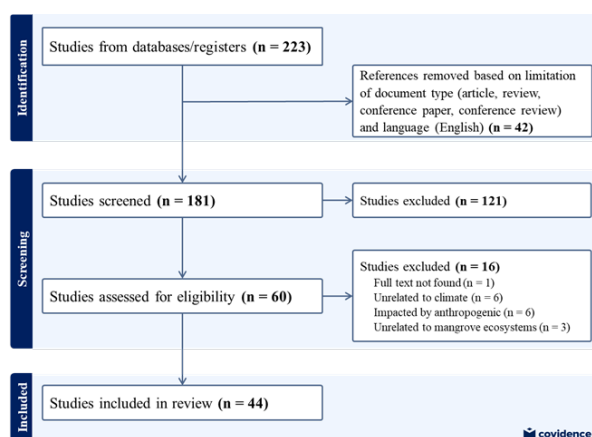


Figure 1. PRISMA flow diagram.

Table 1. Inclusion and exclusion criteria.

Criteria	Inclusion	Exclusion
Publication years	2014–November 2024	Any study outside these dates
Language	English	Other language
Type of article	Journal article, journal review, conference paper, conference review	Book chapter, unpublished research, PhD theses, reports
Study focus	Article mentioned about mangrove resilience and climate variability	Article focused on blue carbon storage in mangroves and stressors unrelated to climate
Geographical area of interest	Research in tropical and subtropical coastal areas affected by climate variability	Research conducted beyond coastal regions

2.3 Data Extraction

Data extraction was carried out systematically using a standardized coding sheet developed in Covidence. In the data extraction phase, a structured framework was applied to ensure the systematic collection of relevant variables from each included study. The extracted information encompassed bibliographic details such as year of publication, name of journal, and DOI, as well as the aim of the study and the research type. Contextual variables were also documented, including country or location, climate regions, and the type of climate variability examined. Ecological dimensions were captured by identifying mangrove species, ecological indicators measured, and mangrove responses to climate variability, while methodological aspects included the research methodology, climate indicators measured, and data processing tools utilized. Furthermore, the analysis considered key findings, and underlying drivers of mangrove resilience. The extraction component enabled the identification of cross-cutting patterns and established a foundation for synthesizing knowledge on mangrove resilience to climate variability.

2.4 Data Synthesis

The extracted data were synthesized through qualitative content analysis to identify recurring themes, knowledge gaps, and emerging trends. Findings were then interpreted within the broader framework of sustainability and coastal management, highlighting the adaptive capacity of mangrove ecosystems in mitigating climate-induced risks. The synthesis aimed to establish an integrative understanding of how mangrove resilience contributes to disaster risk reduction and supports sustainable development pathways in coastal zones.

3. RESULTS AND DISCUSSION

3.1 Patterns and Characteristics of the Reviewed Literature

The literature review identified 44 papers for the final analysis. These articles encompass studies concerning mangrove resilience related to climatic variability conducted during the past decade. The selected studies cover diverse geographical regions, employ various research approaches, and address multiple dimensions of mangrove resilience, providing a broad basis for subsequent analysis. Figure 2 illustrates the historical trends in publications addressing mangrove resilience under climate variability between 2014 and 2024. The figure demonstrates a relatively modest level of research activity during

the early years (2014–2017), with annual outputs ranging from one to three publications. A slight increase is observed in 2018, followed by a temporary decline in 2019. Research productivity intensified again in 2020, reaching five publications, and remained relatively stable through 2021–2023, with four to five publications per year. By 2024, research on mangrove resilience to climate variability has seen a significant increase in publication production, indicating increased attention and research engagement with this field of study. This underscores the heightened focus on the topic within coastal management, which integrates nature-based solution (NBS) considerations and, in this case, is viewed through a climatic perspective.

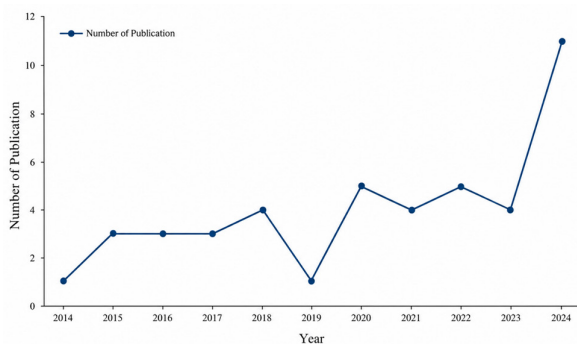


Figure 2. Recent publication trends on mangrove resilience under climate variability (2014–2024).

Further research on the multifaceted benefits of NBS remains critical, particularly as coastal regions are increasingly affected by the compounded effects of climate change and urbanization (Kindeberg *et al.*, 2023; Wu & Barrett, 2022). Policymakers and coastal managers are encouraged to embrace NBS not only as standalone solutions but as integral parts of comprehensive coastal management frameworks that prioritize sustainability and community engagement (van der Meulen *et al.*, 2023; Yahia *et al.*, 2024). This approach aligns with global trends that advocate for holistic and adaptive management practices, leveraging natural processes for long-term viability (Knight, 2024; Sutton *et al.*, 2023). The integration of NBS in coastal management demonstrates significant potential for enhancing environmental resilience and is increasingly recognized as a necessary adaptation to the vulnerabilities posed by climate change.

To further understand the spatial emphasis of existing research, the reviewed articles were categorized based on their regional and climatic focus. Figure 3 shows the geographical distribution of the 44 reviewed studies across different regions and climate zones. The United States (US) accounts for the largest share (8 studies),

followed by Colombia and the Caribbean Sea, as well as global-scale studies (6 each). Southeast and East Asia represent another key focus (5 studies). The distribution highlights a predominant emphasis on tropical regions, with fewer contributions addressing subtropical areas. This pattern may be partially influenced by using English-language publications as a selection criterion, which could contribute to the overrepresentation of English-speaking countries in the dataset.

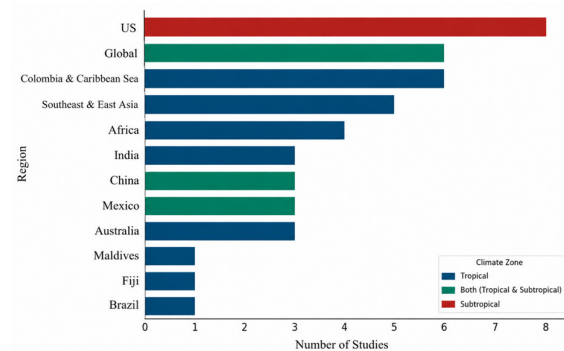


Figure 3. Geographical distribution of reviewed studies on mangrove resilience to climate variability by climate zone.

When this distribution is further considered in relation to the global extent of mangrove forests, a notable imbalance becomes evident. The United States, despite having a relatively smaller share of global mangrove coverage, shows the highest research output, whereas regions with extensive mangrove ecosystems, such as Southeast Asia, are comparatively underrepresented. This indicates a spatial mismatch between ecological importance and research effort, suggesting that scientific output is influenced more by research capacity, funding availability, and institutional infrastructure than by the actual distribution of mangrove ecosystems (Bunting *et al.*, 2022; Friess *et al.*, 2019).

Although mangrove ecosystems have been widely studied, the relatively limited number of selected studies in this review reflects the specificity of the search criteria, which focused exclusively on research explicitly addressing mangrove resilience in relation to climate variability. As a result, a substantial body of literature addressing other aspects, such as blue carbon, biodiversity, or general ecosystem services, was excluded. At the same time, this outcome also points to a gap in the literature, particularly in studies that explicitly integrate climate variability within resilience frameworks. Therefore, the limited number of studies should be interpreted not only as a methodological constraint but also as an indication of emerging research needs in this field. Such variations further highlight the need for more

geographically balanced and thematically integrated research efforts to ensure that assessments of mangrove resilience accurately represent global diversity. In addition to spatial disparities, it is also important to examine how research themes and methodological approaches have evolved over time.

Table 2 further illustrates the temporal evolution of research types and aims in mangrove resilience studies under climate variability. Early studies (2014–2016) primarily focused on fundamental resilience mechanisms and sea-level rise, often employing review articles, global syntheses, and paleo-based reconstructions to establish a baseline understanding. This focus gradually shifted during the mid-phase (2017–2020) toward disturbance ecology and regional-scale impacts, with increased use of longitudinal analyses, genetic diversity studies, and ecosystem modeling. These approaches reflect a growing emphasis on understanding ecosystem responses to climate extremes and environmental variability at finer spatial and temporal scales. In the most recent period (2021–2024), research has expanded into more integrative and applied domains, including socio-ecological adaptation and predictive risk modeling. Studies in this phase increasingly incorporate adaptive management, vulnerability assessment, disaster resilience, and policy-oriented strategies. This progression indicates a clear transition from predominantly biophysical and descriptive approaches toward more interdisciplinary and solution-oriented frameworks. It highlights the growing need to bridge ecological science with governance and policy to effectively address accelerating climate risks in coastal environments.

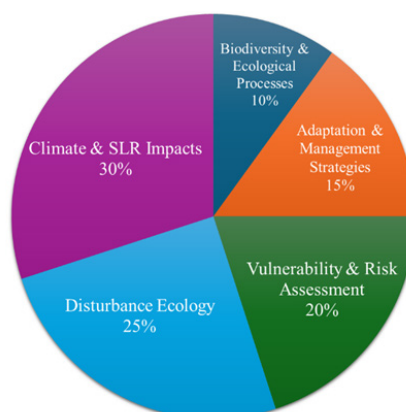


Figure 4. Distribution of research aims of reviewed studies.

A synthesis of research aims and types was conducted across the 44 articles reviewed in this study. Figure 4 shows the distribution of research aims. Overall, most studies focus on the impacts of climate change and sea-level rise, with an emphasis on resilience mechanisms and accretion processes (Alongi, 2015; Friess *et al.*, 2019). Many articles examine disturbance ecology, particularly ecological responses of mangroves to cyclones, hurricanes, and other extreme events (Sasmito *et al.*, 2020; Ward *et al.*, 2016). Additional studies address vulnerability and risk assessment by integrating ecological, spatial, and socio-ecological perspectives, reflecting the complexity of climate impacts. These patterns indicate a growing research emphasis on understanding not only the ecological sensitivity of mangroves to climate-related disturbances, but also their adaptive capacity

Table 2. Temporal shifts in research types and aims on mangrove resilience to climate variability

Year	Number of Studies	Representative Research Types	Representative Research Aims
2014	1	Review article	Resilience & sea-level rise (SLR) mechanisms
2015	3	Empirical paleo-reconstruction, remote sensing	Climate change impact assessment, proxy-based SLR estimation
2016	3	Global synthesis, indicator-based quantitative assessment	Cyclone disturbance recovery, regional vulnerability & resilience
2017	3	Longitudinal ecological study, remote sensing	Climate extremes & range dynamics, SLR & climate change simulation
2018	4	Genetic diversity analysis, Longitudinal field study	Disturbance ecology, Historical SLR & resilience limits
2019	1	Paleoecological reconstruction	Historical drought resilience
2020	5	Field experiment & modeling, field-based survey	Ecosystem connectivity & resilience, sedimentation & vegetation influence
2021	4	Case study, quantitative palaeoclimate analysis	Adaptive management, ecological impact of extremes
2022	4	Global remote sensing and statistics, predictive modeling	Cyclone impact quantification, Sediment accretion resilience
2023	4	Field study, geospatial modeling	Future vulnerability hotspots, long-term vulnerability assessment
2024	12	Empirical observation, field experimentation, remote sensing, mixed methods	Climate resilience strategies, cyclone/tsunami resistance, policy-oriented risk

and contribution to long-term coastal resilience. Recent research increasingly emphasizes the management and policy relevance of adaptive strategies, highlighting the implementation of nature-based solutions to enhance coastal resilience.

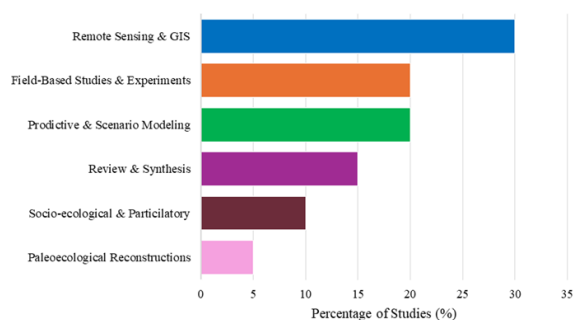


Figure 5. Distribution of research types based on methodological approaches across reviewed studies.

The distribution of methodologies, as illustrated in Figure 5, demonstrates the diversification of approaches in mangrove and coastal resilience research and the growing integration of ecological, spatial, and socio-political dimensions. The research types are classified based on the primary methodological approach employed in each study, rather than the research objectives, to ensure consistency across diverse study designs. The results indicate a clear dominance of empirical approaches, with remote sensing and GIS-based analyses, predictive and scenario modeling, and field-based experiments representing the core of the field.

Remote sensing, in particular, emerges as the most widely employed technique, reflecting its capacity to provide long-term, large-scale insights into mangrove and coastal dynamics.

Predictive ecological modeling and scenario-based approaches further highlight the field's forward-looking orientation, allowing researchers to assess potential futures under varying climate and sea-level rise trajectories. Field-based studies and controlled experiments complement these remote analyses by generating site-specific evidence on ecological mechanisms and resilience processes. Parallel to these empirical approaches, a considerable share of the literature draws on review and synthesis methods, which play a pivotal role in consolidating dispersed findings into integrative knowledge frameworks. Moreover, socio-ecological and participatory approaches, though less frequent, signal an increasing awareness of the necessity to link ecological science with community-based adaptation and governance strategies. Paleoecological reconstructions, however, being a minor percentage, yield essential long-term insights into mangrove responses to historical climate variability, thereby providing significant baselines for understanding current and future changes.

3.2 Drivers of Mangrove Resilience

A multi-dimensional approach is essential for accurately evaluating and improving mangrove resilience in considering projected climate variability and change. In this study, mangrove resilience is determined by four primary dimensions: biophysical, geomorphological-hydrological, climatic, and socio-institutional. The interaction among biophysical and species-level traits, geomorphological and hydrological settings, climatic and environmental variability, and socio-institutional and governance dimensions, as summarized in Table 3, collectively shapes resilience outcomes.

As outlined in Table 3, sediment dynamics and hydrological connectivity (geomorphological-hydrological dimension) play a

Table 3. Categories of drivers influencing mangrove resilience. Note: ENSO = El Niño–Southern Oscillation; IOD = Indian Ocean Dipole; PDO = Pacific Decadal Oscillation; AMO = Atlantic Multidecadal Oscillation.

Category	Key Drivers Identified
Biophysical and species-level traits	Root productivity and morphology; species-specific physiological adaptations (e.g., salinity tolerance, redox adjustment, salt excretion in <i>Avicennia germinans</i>); canopy structure; tree size and wood traits; regeneration dynamics (propagule dispersal, epicormic resprouting); structural redundancy; prior exposure and life stage
Geomorphological and hydrological settings	Sediment supply and accretion; tidal flushing; elevation capital; geomorphic context; hydrological buffering (lagoons); freshwater inflow and connectivity; storm-driven deposition; migration space availability
Climatic and environmental variability	Sea-level rise; drought severity; storm frequency and intensity; freeze thresholds; temperature anomalies; historical climate patterns; ENSO, IOD, PDO, AMO oscillations; regional climate stability; ocean-land buffering (e.g., nocturnal canopy warming)
Socio-institutional and governance dimensions	Anthropogenic pressures (urbanization, land use change, population density, encroachment); adaptive governance; policy support; protected area coverage; spatial connectivity; monitoring and enforcement; community engagement; knowledge integration; sustainable livelihoods

key role in facilitating adaptation to sea-level rise, while species-specific traits and canopy structure (biophysical dimension) influence tolerance to climatic extremes. In addition, climatic variability, including sea-level rise and extreme events, acts as a key external driver, while the effectiveness and inclusivity of governance and management practices (socio-institutional dimension) critically determine whether resilience is strengthened or weakened.

This review conceptualizes the drivers of mangrove resilience as stemming from climate variability. Table 4 organizes these drivers into major themes, including gradual processes such as sea-level rise and temperature anomalies, as well as episodic disturbances, including tropical cyclones, hurricanes, and compound extreme events. This structure clarifies the synthesis and highlights the primary climatic drivers influencing mangrove dynamics. It also demonstrates the range of stressors addressed in the literature, supporting a comprehensive understanding of the interactions between climate variability and mangrove resilience.

Analysis of 44 studies indicates that sea-level rise, examined in 21 studies, and tropical cyclones or hurricanes, examined in 17 studies, are the most frequently investigated climate

drivers affecting mangrove ecosystems. Researchers often assess these drivers both independently and in conjunction with additional stressors, such as storm surge, salinity intrusion, and precipitation variability. Temperature-related factors, including warming anomalies and extreme cold events, were linked to physiological thresholds and changes in mangrove distribution in 12 studies. Precipitation and hydrological changes, addressed in 14 studies, were also identified as critical, particularly in relation to flooding, salinity balance, and freshwater availability. Large-scale climatic oscillations, such as the El Niño-Southern Oscillation (ENSO), Indian Ocean Dipole (IOD), Pacific Decadal Oscillation (PDO), and Atlantic Multidecadal Oscillation (AMO), were identified in 9 studies as key modulators of multiple hazards, influencing droughts, storms, and rainfall extremes. Only four studies examined compound extreme events, such as tsunamis and wind-wave energy events, which, despite their rarity, pose significant risks to mangrove resilience. Overall, the literature addresses gradual drivers, such as sea-level rise, temperature warming, and rainfall variability, as well as episodic high-intensity hazards, including cyclones and hurricanes. In contrast, compound and cascading extreme events remain insufficiently explored.

Table 4. Climate variability category addressed in mangrove resilience studies.

Climate Variability Category	Examples	Number of Articles (n=44)	Source
Sea-level rise (SLR)	Historical SLR, projected SLR (Representative Concentration Pathways (RCP)/ Shared Socioeconomic Pathways (SSP), subsidence, sediment supply, salinity intrusion)	21	Agraz-Hernández <i>et al.</i> , 2022; Allen <i>et al.</i> , 2021; Cinco-Castro and Herrera-Silveira, 2020; Ding <i>et al.</i> , 2024; Duncan <i>et al.</i> , 2018; Dutta Roy <i>et al.</i> , 2024; Ellison and Strickland, 2015; Gijnsman <i>et al.</i> , 2021; Guo <i>et al.</i> , 2018; Hens <i>et al.</i> , 2018; Huang <i>et al.</i> , 2020; Krauss <i>et al.</i> , 2014; Li <i>et al.</i> , 2022; Liang <i>et al.</i> , 2023; Maina <i>et al.</i> , 2021; McKee <i>et al.</i> , 2020; Parkinson and Wdowinski, 2022; Sardar and Samadder, 2023; Srivastava <i>et al.</i> , 2015; Urrego <i>et al.</i> , 2019; Ward <i>et al.</i> , 2023
Temperature variability	Warming trends (+1.5–2°C), long-term anomalies, extreme cold/freezing events	12	Bonilla-Roman & Acuña-Guzman, 2024; Cinco-Castro & Herrera-Silveira, 2020; Feehan <i>et al.</i> , 2024; Flower <i>et al.</i> , 2017; Huang <i>et al.</i> , 2020; Li <i>et al.</i> , 2022; Liang <i>et al.</i> , 2023; Mo <i>et al.</i> , 2023; Osland <i>et al.</i> , 2015, 2017; Urrego <i>et al.</i> , 2019; Xu <i>et al.</i> , 2016
Precipitation & Hydrological variation	Rainfall variability, drought cycles, runoff patterns, flooding (freshwater & seawater)	14	Agraz-Hernández <i>et al.</i> , 2022; Andrieu <i>et al.</i> , 2020; Cinco-Castro & Herrera-Silveira, 2020; Flower <i>et al.</i> , 2017; Galeano <i>et al.</i> , 2017; Hens <i>et al.</i> , 2018; Li <i>et al.</i> , 2022; Maina <i>et al.</i> , 2021; Sewilam <i>et al.</i> , 2024; Srivastava <i>et al.</i> , 2015; Sunkur <i>et al.</i> , 2024; Touza <i>et al.</i> , 2021; Urrego <i>et al.</i> , 2019; Ward <i>et al.</i> , 2016
Tropical cyclones & Hurricanes	Cyclone Eline (2000), Hurricanes Hugo, Irma, Maria, North Atlantic TCs, storm surges, wind intensity	17	Allen <i>et al.</i> , 2021; Andrieu <i>et al.</i> , 2020; Bennion <i>et al.</i> , 2024; Bonilla-Roman & Acuña-Guzman, 2024; Carruthers <i>et al.</i> , 2024; Cohen <i>et al.</i> , 2024; Hens <i>et al.</i> , 2018; Hill <i>et al.</i> , 2024; Imbert, 2018; Li <i>et al.</i> , 2022; Liang <i>et al.</i> , 2023; Macamo <i>et al.</i> , 2016; McKee <i>et al.</i> , 2020; Mo <i>et al.</i> , 2023; Odériz <i>et al.</i> , 2020; Peereman <i>et al.</i> , 2022; Ward <i>et al.</i> , 2023
Large-scale climatic oscillations	ENSO, IOD, PDO, AMO, Indian Ocean Dipole, El Niño & La Niña	9	Agraz-Hernández <i>et al.</i> , 2022; Allen <i>et al.</i> , 2021; Galeano <i>et al.</i> , 2017; Gijnsman <i>et al.</i> , 2021; Kathirvelpandian <i>et al.</i> , 2024; Maina <i>et al.</i> , 2021; Srivastava <i>et al.</i> , 2015; Touza <i>et al.</i> , 2021; Urrego <i>et al.</i> , 2019
Compound extreme events	Tsunamis, extreme tides, wind-wave energy events, multi-hazard combinations	4	Cramer <i>et al.</i> & Ellison, 2022; Ding <i>et al.</i> , 2024; Dutta Roy <i>et al.</i> , 2024; Peereman <i>et al.</i> , 2022

3.3 Mangrove Responses to Climate Variability

A review of 44 studies identifies five primary mangrove response pathways, as summarized in Table 5. The pathways are: (1) resistance to disturbance through structural and physiological buffering; (2) recovery through regrowth, resprouting, and increased sediment or elevation; (3) reorganization through species turnover and altered stand structure; (4) range shifts, including landward migration or retreat, determined by elevation and available space; and (5) threshold responses that result in partial or widespread dieback under compound or persistent stress.

Mangrove resilience pathways are diverse, but the combined effects of climatic, geomorphic, ecological, and anthropogenic drivers fundamentally determine their trajectories. Resistance is supported by ecological factors, such as species-specific physiological traits and wood structure, as well as by geomorphic factors, including elevation and buffered microclimates. These drivers enable mangroves to withstand stress with minimal canopy loss. For example, species-specific resistance has been observed in multiple contexts: *Avicennia germinans* demonstrated higher adult survival and resprouting capacity compared to juveniles under extreme cold stress (Osland *et al.*, 2015), while *Avicennia marina* and *Rhizophora mucronata* exhibited differential recovery following cyclone Eline, with sheltered sites showing greater resilience (Macamo *et al.*, 2016). Similarly, root productivity and soil elevation feedback contribute to buffering effects against sea-level rise and storm surges (Krauss *et al.*, 2014). Complementing these empirical findings, previous study highlights that wood density and root architecture in species such as *Rhizophora mangle* and

Avicennia germinans play a decisive role in minimizing uprooting and canopy damage during storms (Alongi, 2015).

Recovery processes, such as resprouting, canopy infill, and sediment-driven elevation gain, are closely linked to geomorphic and hydrological drivers, including sediment supply, connectivity, and storm deposition. For instance, *Avicennia germinans* adults exhibited resprouting capacity following extreme cold stress in the Gulf of Mexico (Osland *et al.*, 2015), while root productivity and storm-induced sedimentation enhanced vertical accretion in several regions (Galeano *et al.*, 2017; Gijsman *et al.*, 2021; Imbert, 2018; Krauss *et al.*, 2014; Li *et al.*, 2022; McKee *et al.*, 2020; Parkinson & Wdowinski, 2022; Urrego *et al.*, 2019; Ward *et al.*, 2016). However, recovery potential is often contingent on hydrological connectivity, as illustrated by differences in recovery between sheltered and exposed sites after cyclone Eline in Mozambique (Macamo *et al.*, 2016). This pattern aligns with broader evidence showing that fragmented or embanked mangrove areas tend to display delayed or incomplete regrowth (Cinco-Castro & Herrera-Silveira, 2020; Parkinson & Wdowinski, 2022; Sewilam *et al.*, 2024; Ward *et al.*, 2016).

Reorganization reflects adaptive restructuring, where ecological drivers such as species turnover and regeneration dynamics interact with climatic disturbances, including hurricanes, droughts, and sea-level rise. This process often manifests as shifts in species dominance, altered recruitment patterns, and modified structural configurations. For example, life stage-dependent responses in *Avicennia germinans* revealed that adult trees resprouted more effectively than juveniles after extreme cold stress, reshaping population structure (Osland *et al.*, 2015). Similarly, post-cyclone assessments in Mozambique

Table 5. Concise typology of mangrove response pathways to climate variability.

Response pathway	Typical field/ remote sensing indicators	When it occurs	Typical outcomes
Resistance	Minimal canopy loss; stable normalized difference vegetation index (NDVI)/evapotranspiration (ET); low uprooting	Steep/elevated, buffered microclimates; mature stands	Short-term persistence with limited functional loss
Recovery	Resprouting, lateral infill, gradual NDVI/ET rebound; storm-delivered sediments	Moderate events; adequate sediment supply/connectivity	Structural rebuild; elevation maintained
Reorganization	Species turnover; altered canopy height/biomass; changed litterfall/propagules	Post-hurricane/drought heterogeneous settings	New dominant species; modified ecosystem functions
Range shift	Inland edge advance; retreat at seaward edge; marsh-mangrove ecotone movement	SLR with available upland space; warming at cold margins	Landward migration; fragmentation where constrained
Threshold/dieback	Large NDVI drop; stable carbon isotope (^{13}C) and intrinsic water-use efficiency (IWUE) changes; elevation loss; mass mortality	Compound extremes; accelerating SLR; chronic human pressure	Dieback, functional collapse, slow/failed recovery

documented differential recovery among *Avicennia marina*, *Rhizophora mucronata*, and *Bruguiera gymnorrhiza*, leading to altered species composition across sheltered and exposed sites (Macamo *et al.*, 2016). In Fiji, mangrove zonation reorganized through landward migration of *Rhizophora stylosa* in response to relative sea-level rise (Ellison & Strickland, 2015). Over longer timescales, interactions between sediment supply, soil elevation change, and regeneration processes drive shifts in ecosystem functioning and resilience (Krauss *et al.*, 2014). Such reorganizations suggest resilience at the ecosystem level, buffering against total collapse, but they also entail trade-offs, including reductions in biodiversity and altered provisioning services (Galeano *et al.*, 2017; Imbert, 2018; Urrego *et al.*, 2019).

Range shifts are primarily driven by climatic forces, particularly sea-level rise and temperature increases, but they are critically moderated by geomorphic settings and constrained by anthropogenic pressures. Landward migration of mangroves has been widely documented in multiple regions. For instance, in Fiji, relative sea-level rise has triggered landward retreat of species such as *Rhizophora stylosa* (Ellison & Strickland, 2015), while in the Gulf of Mexico, warming winters reduced freeze frequency, enabling *Avicennia germinans* to expand poleward into salt marsh zones (Osland *et al.*, 2015). A similar poleward expansion has also been observed at marsh-mangrove ecotones in Australia, consistent with broader climate warming trends (Alongi, 2015). Geomorphic feedback, including sediment supply and elevation gain, strongly influences whether mangroves can track sea-level rise through vertical or lateral shifts (Krauss *et al.*, 2014). Conversely, in arid and densely populated coasts such as western India, rising temperatures interact with land-use change to alter mangrove distribution and constrain potential migration pathways (Srivastava *et al.*, 2015). In urbanized Southeast Asia, hard infrastructure such as seawalls has blocked natural landward migration, leading instead to coastal squeeze, fragmentation, and heightened vulnerability (Lovelock *et al.*, 2015).

Threshold responses occur when climatic extremes interact with persistent anthropogenic stress, driving ecosystems beyond resilience limits. Large-scale dieback has been reported in northern Australia, where extreme drought, coupled with heatwaves, led to the mortality of over 7,000 hectares of mangroves (Duke *et al.*, 2017). In Mozambique, Cyclone Eline caused severe structural damage and incomplete recovery in exposed stands, highlighting how extreme storms can push mangrove ecosystems beyond recovery thresholds (Macamo

et al., 2016). In subtropical USA, juvenile *Avicennia germinans* experienced widespread mortality following freeze events, contrasting with the survival of adults, which suggests life-stage-specific thresholds (Osland *et al.*, 2015). In India, interacting pressures from sea-level change and land-use modification have exacerbated declines in mangrove density (Srivastava *et al.*, 2015), while in Fiji, relative sea-level rise combined with limited sediment supply has led to persistent elevation deficits and landward retreat (Ellison & Strickland, 2015). More broadly, global syntheses show that threshold responses are rarely the result of climate drivers alone, but are compounded by geomorphic constraints, governance gaps, altered hydrology, and land-use pressures (Alongi, 2015; Krauss *et al.*, 2014).

Mangroves rely on both natural geomorphic settings and human management for effective resilience. Adaptive governance, sediment management, and conserving landward migration corridors are crucial for supporting resilience as climate variability intensifies. Evidence from the reviewed studies indicates that ecological processes, such as resprouting, species turnover, and vertical accretion, are fundamentally influenced by geomorphic factors, including elevation, sediment supply, and hydrological connectivity (Ellison & Strickland, 2015; Krauss *et al.*, 2014; Osland *et al.*, 2015). However, the persistence of these natural buffering mechanisms is increasingly dependent on anthropogenic interventions. Cases from India and Mozambique illustrate how land-use change, embankments, and exposure to extreme storms constrain recovery and accelerate vulnerability (Macamo *et al.*, 2016; Srivastava *et al.*, 2015). This underscores that resilience is not only an ecological attribute but also a socio-ecological outcome shaped by management and policy. Strengthening resilience, therefore, requires integrating climate-adaptive governance, proactive sediment and hydrological management, and the protection of landward migration corridors to prevent coastal squeeze (Alongi, 2015; Lovelock *et al.*, 2015). Together, these measures ensure that mangrove ecosystems can reorganize, recover, and persist under intensifying climate variability while continuing to provide critical biodiversity and ecosystem services.

3.4 Research gap

This synthesis identifies several critical gaps in the current understanding of the interactions between climate variability and mangrove ecosystems. Geographically, research is unevenly distributed, with concentrations in the United States, Southeast and East Asia, Colombia, the Caribbean, and parts of Africa,

while evidence from Australia, South America, and small Pacific islands remains limited, constraining the global generalizability of findings. A clear zonal disparity is also evident between tropical and subtropical regions. Tropical mangrove systems, particularly in Southeast Asia and the Caribbean, dominate the literature, reflecting their high biomass, biodiversity, and vulnerability to sea-level rise. By contrast, subtropical ecosystems represent a much smaller proportion of studies, leaving major gaps in understanding how mangroves at climatic margins respond to variability and extremes, such as resilience thresholds, poleward range expansion, and sensitivity to cold events. This scarcity of evidence in transitional zones weakens the ability to capture cross-latitude dynamics of resilience.

Our findings further show that sea-level rise and storms are the most frequently studied climatic drivers (Table 4). Correspondingly, the most commonly reported response pathways include range shifts in response to sea-level rise and recovery or dieback in response to storms (Table 5). This indicates that the research community has primarily focused on responses to gradual long-term changes and large-scale episodic disturbances. While such focus has generated important insights, it leaves other critical drivers, such as droughts, heat stress, and compound or cascading events, comparatively underexplored.

Thematically, most studies emphasize biophysical and climatic processes, while socio-institutional dimensions, including governance, community-based adaptation, and policy integration, remain insufficiently addressed. Another important gap lies in the integration of multi-scalar perspectives: paleoecological records, contemporary monitoring, and predictive modeling are seldom combined, yet such integration is essential for projecting future resilience trajectories. Moreover, limited research addresses the interactions between climatic variability and anthropogenic pressures, such as land-use change, aquaculture expansion, or coastal infrastructure development, which may amplify vulnerability and constrain natural adaptive capacities. Addressing these research gaps requires more geographically inclusive, interdisciplinary, and socio-ecological approaches to comprehensively capture how mangrove ecosystems respond and adapt to intensifying climate variability.

3.5 Limitations of the study

Despite its contributions, this review has several limitations. The spatial and temporal distribution of studies is uneven, with underrepresentation in regions such as Australia, South America, and small Pacific islands, limiting global

generalizability. Methodological heterogeneity and the predominance of descriptive approaches restrict opportunities for meta-analysis and quantitative synthesis. In addition, the graphical representations presented in this study are primarily descriptive and may not fully capture complex relationships between variables, such as interactions between biophysical, climatic, and socio-institutional drivers.

The reliance on English-language, peer-reviewed literature and the exclusive use of the Scopus database may also have led to the omission of relevant local or regionally indexed studies. In addition, the exclusion of the keyword carbon, although intended to avoid bias toward mitigation studies, may have overlooked research that frames resilience through carbon-related indicators, despite the inherent link between resilience and carbon dynamics. Finally, most studies emphasize biophysical drivers, while governance, policy, and community-based adaptation remain comparatively neglected.

Despite these limitations, this review provides an integrative synthesis that highlights key gaps in the understanding of mangrove resilience under climate variability, particularly the limited integration of climatic, ecological, and socio-institutional dimensions. This contribution is essential for supporting more comprehensive and policy-relevant resilience frameworks. Overall, the findings should be interpreted as indicative rather than universal, while underscoring the need for more inclusive, interdisciplinary, and socio-ecological research on mangrove resilience in support of global sustainability agendas, particularly SDG 13 (Climate Action), SDG 14 (Life Below Water), and SDG 15 (Life on Land).

4. CONCLUSIONS

This systematic review demonstrates that mangrove resilience to climate variability is shaped by interconnected biophysical, geomorphological, climatic, and socio-institutional drivers, with sea-level rise, tropical cyclones, precipitation anomalies, and large-scale oscillations such as ENSO emerging as the most influential stressors. Mangroves respond through pathways of resistance, recovery, reorganization, range shifts, and threshold dynamics, yet these adaptive capacities are increasingly constrained by anthropogenic pressures, including land-use change, fragmentation, and coastal infrastructure. Across the reviewed studies, a consistent pattern emerges in which resilience is governed by the interaction between environmental stressors and ecosystem adaptive capacity, highlighting the

importance of integrated system-level understanding. The findings highlight that resilience is not solely an ecological attribute, but a socio-ecological outcome that requires integrated strategies to safeguard sediment and hydrological processes, protect migration corridors, and strengthen adaptive governance. However, significant gaps remain, particularly in the limited integration of climatic drivers with socio-institutional processes and the underrepresentation of certain geographical regions. Addressing geographic and disciplinary gaps through interdisciplinary and inclusive research will be essential to enhance the role of mangroves as natural buffers against climate extremes, thereby supporting biodiversity, ecosystem services, and the achievement of global sustainability goals, particularly SDGs 13, 14, and 15. These insights underline the need for more application-oriented and policy-relevant research to support effective climate adaptation and coastal management strategies.

AUTHOR'S CONTRIBUTION

Anies Ma'rufatin: Conceptualization, Methodology, Formal Analysis, Writing - Original Draft, and Writing - Review & Editing. Novian Andri Akhirianto: Writing - Review & Editing, Data Curation, and Validation. Khusnul Setia Wardani: Supervision and Data Curation. Amalia Nurwijayanti: Software, Methodology, and Validation. Farikhotul Chusnayah: Investigation, Resources, and Methodology. Favian Mavazi Giska Putra: Methodology and Visualization.

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REFERENCES

Agraz-Hernández, C. M., Chan-Keb, C. A., Muñoz-Salazar, R., Pérez-Balan, R. A., Vanegas, G. P., Manzanilla, H. G., Osti-Sáenz, J., & del Río Rodríguez, R. (2022). Pore Water Chemical Variability and Its Effect on Phenological Production in Three Mangrove Species under Drought Conditions in Southeastern Mexico. *Diversity*, 14(8). <https://doi.org/10.3390/d14080668>

Allen, K. J., Verdon-Kidd, D. C., Sippo, J. Z., & Baker, P. J. (2021). Compound climate extremes driving recent sub-continental tree mortality in northern Australia have no precedent in recent centuries. *Scientific Reports*, 11(1). <https://doi.org/10.1038/s41598-021-97762-x>

Alongi, D. M. (2008). Mangrove forests: resilience, protection from tsunamis, and responses to global climate change. *Estuarine, Coastal and Shelf Science*. <https://www.sciencedirect.com/science/article/pii/S0272771407003915>

Alongi, D. M. (2015). The Impact of Climate Change on Mangrove Forests. *Current Climate Change Reports*, 1(1), 30-39. <https://doi.org/10.1007/s40641-015-0002-x>

Andrieu, J., Lombard, F., Fall, A., Thior, M., Ba, B. D., & Dieme, B. E. A. (2020). Botanical field-study and remote sensing to describe mangrove resilience in the Saloum Delta (Senegal) after 30 years of degradation narrative. *Forest Ecology and Management*, 461. <https://doi.org/10.1016/j.foreco.2020.117963>

Babineau, J. (2014). Product Review: Covidence (Systematic Review Software). *Journal of the Canadian Health Libraries Association / Journal de l'Association Des Bibliothèques de La Santé Du Canada*, 35(2), 68. <https://doi.org/10.5596/c14-016>

Bennion, V., Hill, J. W., & Lovelock, C. E. (2024). Mangrove Surface Elevation Loss after Tree fall during Extreme Weather. *Wetlands*, 44(8). <https://doi.org/10.1007/s13157-024-01868-7>

Bonilla-Roman, Y. N., & Acuña-Guzman, S. F. (2024). Resilience of an Urban Coastal Ecosystem in the Caribbean: A Remote Sensing Approach in Western Puerto Rico. *Earth (Switzerland)*, 5(1), 72-89. <https://doi.org/10.3390/earth5010004>

Bunting, P., Rosenqvist, A., Hilarides, L., Lucas, R. M., & Thomas, N. (2022). Global Mangrove Watch: Updated 2010 Mangrove Forest Extent (v2.5). *Remote Sensing*, 14(4), 1034. <https://doi.org/10.3390/rs14041034>

Carruthers, L., Ersek, V., Maher, D., Sanders, C., Tait, D., Soares, J., Floyd, M., Hashim, A. S., Helber, S., Garnett, M., East, H., Johnson, J. A., Ponta, G., & Sippo, J. Z. (2024). Sea-level rise and extreme Indian Ocean Dipole explain mangrove dieback in the Maldives. *Scientific Reports*, 14(1), 27012. <https://doi.org/10.1038/s41598-024-73776-z>

Cinco-Castro, S., & Herrera-Silveira, J. (2020). Vulnerability of mangrove ecosystems to climate change effects: The case of the Yucatan Peninsula. *Ocean and Coastal Management*, 192. <https://doi.org/10.1016/j.ocecoaman.2020.105196>

- Cohen, M. C. L., Yao, Q., de Souza, A. V., Liu, K.-B., Nunes, S., Rodrigues, E., Pessenda, L. C. R., & Culligan, N. (2024). Do hurricanes or freezing events regulate the sustainability of subtropical mangroves on the Gulf of Mexico coast? *Regional Environmental Change*, 24(2). <https://doi.org/10.1007/s10113-024-02225-4>
- Cramer, N. J., & Ellison, J. C. (2022). Atoll inland and coastal mangrove climate change vulnerability assessment. *Wetlands Ecology and Management*, 30(3), 527–546. <https://doi.org/10.1007/s11273-022-09878-0>
- Dahdouh-Guebas, F., Jayatissa, L. P., Di Nitto, D., Bosire, J. O., Lo Seen, D., & Koedam, N. (2005). How effective were mangroves as a defence against the recent tsunami? *Current Biology*, 15(12), R443–R447. <https://doi.org/10.1016/j.cub.2005.06.008>
- Ding, R., Cai, R., Yan, X., Li, C., Wang, C., & Nie, X. (2024). Comprehensive Risk Assessment of Sea Level Rise and Tropical Cyclones in Dongzhaigang Mangroves, China. *Chinese Geographical Science*, 34(4), 631–646. <https://doi.org/10.1007/s11769-024-1442-9>
- Dong, X., Martin, J. B., Cohen, M. J., & Tu, T. (2023). Bedrock mediates responses of ecosystem productivity to climate variability. *Communications Earth & Environment*, 4(1), 114. <https://doi.org/10.1038/s43247-023-00773-x>
- Duke, N. C., Kovacs, J. M., Griffiths, A. D., Preece, L., Hill, D. J. E., van Oosterzee, P., Mackenzie, J., Morning, H. S., & Burrows, D. (2017). Large-scale dieback of mangroves in Australia. *Marine and Freshwater Research*, 68(10), 1816. <https://doi.org/10.1071/MF16322>
- Duncan, C., Owen, H. J. F., Thompson, J. R., Koldewey, H. J., Primavera, J. H., & Pettorelli, N. (2018). Satellite remote sensing to monitor mangrove forest resilience and resistance to sea level rise. *Methods in Ecology and Evolution*, 9(8), 1837–1852. <https://doi.org/10.1111/2041-210X.12923>
- Dutta Roy, A., Karpowicz, D. A., Hendy, I., Rog, S. M., Watt, M. S., Reef, R., Broadbent, E. N., Asbridge, E. F., Gebrie, A., Ali, T., & Mohan, M. (2024). Current Status of Remote Sensing for Studying the Impacts of Hurricanes on Mangrove Forests in the Coastal United States. *Remote Sensing*, 16(19). <https://doi.org/10.3390/rs16193596>
- Ellison, J., & Strickland, P. (2015). Establishing relative sea level trends where a coast lacks a long term tide gauge. *Mitigation and Adaptation Strategies for Global Change*, 20(7), 1211–1227. <https://doi.org/10.1007/s11027-013-9534-3>
- Feehan, C. J., Filbee-Dexter, K., Thomsen, M. S., Wernberg, T., & Miles, T. (2024). Ecosystem damage by increasing tropical cyclones. *Communications Earth and Environment*, 5(1). <https://doi.org/10.1038/s43247-024-01853-2>
- Feit, B., Blüthgen, N., Daouti, E., Straub, C., Traugott, M., & Jonsson, M. (2021). Landscape complexity promotes resilience of biological pest control to climate change. *Proceedings of the Royal Society B: Biological Sciences*, 288(1951), 20210547. <https://doi.org/10.1098/rspb.2021.0547>
- Flower, H., Rains, M., & Fitz, C. (2017). Visioning the Future: Scenarios Modeling of the Florida Coastal Everglades. *Environmental Management*, 60(5), 989–1009. <https://doi.org/10.1007/s00267-017-0916-2>
- Friess, D. A., Rogers, K., Lovelock, C. E., Krauss, K. W., Hamilton, S. E., Lee, S. Y., Lucas, R., Primavera, J., Rajkaran, A., & Shi, S. (2019). The State of the World's Mangrove Forests: Past, Present, and Future. *Annual Review of Environment and Resources*, 44(1), 89–115. <https://doi.org/10.1146/annurev-environ-101718-033302>
- Galeano, A., Urrego, L. E., Botero, V., & Bernal, G. (2017). Mangrove resilience to climate extreme events in a Colombian Caribbean Island. *Wetlands Ecology and Management*, 25(6), 743–760. <https://doi.org/10.1007/s11273-017-9548-9>
- Gijsman, R., Horstman, E. M., van der Wal, D., Friess, D. A., Swales, A., & Wijnberg, K. M. (2021). Nature-Based Engineering: A Review on Reducing Coastal Flood Risk With Mangroves. *Frontiers in Marine Science*, 8. <https://doi.org/10.3389/fmars.2021.702412>
- Goldberg, L., Lagomasino, D., Thomas, N., & Fatoyinbo, T. (2020). Global declines in human-driven mangrove loss. *Global Change Biology*, 26(10), 5844–5855. <https://doi.org/10.1111/gcb.15275>
- Guo, Z., Li, X., He, Z., Yang, Y., Wang, W., Zhong, C., Greenberg, A. J., Wu, C.-I., Duke, N. C., & Shi, S. (2018). Extremely low genetic diversity across mangrove taxa reflects past sea level changes and hints at poor future responses. *Global Change Biology*, 24(4), 1741–1748. <https://doi.org/10.1111/gcb.13968>
- Haby, M. M., Barreto, J. O. M., Kim, J. Y. H., Peiris, S., Mansilla, C., Torres, M., Guerrero-Magaña, D. E., & Reveiz, L. (2024). What are the best methods for rapid reviews of the research evidence? A systematic review of reviews and primary studies. *Research Synthesis Methods*, 15(1), 2–20. <https://doi.org/10.1002/jrsm.1664>

- Harrison, H., Griffin, S. J., Kuhn, I., & Usher-Smith, J. A. (2020). Software tools to support title and abstract screening for systematic reviews in healthcare: an evaluation. *BMC Medical Research Methodology*, 20(1), 7. <https://doi.org/10.1186/s12874-020-0897-3>
- Hasan, M., Priatna, D., & Istiadi, Y. (2022). The role of the parties in mangrove ecosystem recovery in Juntinyuat Coast, West Java, Indonesia. *Indonesian Journal of Applied Environmental Studies*, 3(2), 111–119. <https://doi.org/10.33751/injast.v3i2.5120>
- Hens, L., Thinh, N. A., Hanh, T. H., Cuong, N. S., Lan, T. D., Van Thanh, N., & Le, D. T. (2018). Sea-level rise and resilience in Vietnam and the AsiaPacific: A synthesis. *Vietnam Journal of Earth Sciences*, 40(2), 126–152. <https://doi.org/10.15625/0866-7187/40/2/11107>
- Hill, J. W., Bennion, V., & Lovelock, C. E. (2024). Mangrove tree strength estimated with field experiments. *Ecological Engineering*, 203. <https://doi.org/10.1016/j.ecoleng.2024.107259>
- Huang, H., Anderegg, L. D. L., Dawson, T. E., Mote, S., & D'Odorico, P. (2020). Critical transition to woody plant dominance through microclimate feedbacks in North American coastal ecosystems. *Ecology*, 101(9). <https://doi.org/10.1002/ecy.3107>
- Imbert, D. (2018). Hurricane disturbance and forest dynamics in east Caribbean mangroves. *Ecosphere*, 9(7). <https://doi.org/10.1002/ecs2.2231>
- Kathirvelpandian, A., Rasheeq, A., Kantharajan, G., Kumawat, T., Kumar, T. T. A., & Sarkar, U. K. (2024). Evaluating the climate change-induced vulnerability of the Pichavaram mangrove ecosystem through a stakeholder-centric multiscale approach. *Journal of Water and Climate Change*, 15(8), 4177–4195. <https://doi.org/10.2166/wcc.2024.373>
- Kindeberg, T., Almström, B., Skoog, M., Olsson, P. A., & Hollander, J. (2023). Toward a multifunctional nature-based coastal defense: a review of the interaction between beach nourishment and ecological restoration. *Nordic Journal of Botany*, 2023(1). <https://doi.org/10.1111/njb.03751>
- Knight, J. (2024). The Green Infrastructure of Sandy Coastlines: A Nature-Based Solution for Mitigation of Climate Change Risks. *Sustainability*, 16(3), 1056. <https://doi.org/10.3390/su16031056>
- Krauss, K. W., Mckee, K. L., Lovelock, C. E., Cahoon, D. R., Saintilan, N., Reef, R., & Chen, L. (2014). How mangrove forests adjust to rising sea level. *New Phytologist*, 202(1), 19–34. <https://doi.org/10.1111/nph.12605>
- Lee, S. Y., Primavera, J. H., Dahdouh-Guebas, F., McKee, K., Bosire, J. O., Cannicci, S., Diele, K., Fromard, F., Koedam, N., Marchand, C., Mendelssohn, I., Mukherjee, N., & Record, S. (2014). Ecological role and services of tropical mangrove ecosystems: a reassessment. *Global Ecology and Biogeography*, 23(7), 726–743. <https://doi.org/10.1111/geb.12155>
- Li, X., Liu, Z., Wang, S., Li, F., Li, H., Zhu, T., Qian, Z., Tu, Y., Liu, Y., Wang, X., Wang, Q., Shi, W., & Li, D. (2022). Spatial characteristics of the stability of mangrove ecosystems in freshwater and seawater floods in Southeast Asia. *Journal of Geographical Sciences*, 32(9), 1831–1846. <https://doi.org/10.1007/s11442-022-2025-2>
- Liang, S., Hu, W., Liu, J., Su, S., Chen, G., Chen, S., Xie, B., Du, J., Liu, W., & Chen, B. (2023). Mapping mangrove sustainability in the face of sea level rise and land use: A case study on Leizhou Peninsula, China. *Journal of Environmental Management*, 325. <https://doi.org/10.1016/j.jenvman.2022.116554>
- Lovelock, C. E., Cahoon, D. R., Friess, D. A., Guntenspergen, G. R., Krauss, K. W., Reef, R., Rogers, K., Saunders, M. L., Sidik, F., Swales, A., Saintilan, N., Thuyen, L. X., & Triet, T. (2015). The vulnerability of Indo-Pacific mangrove forests to sea-level rise. *Nature*, 526(7574), 559–563. <https://doi.org/10.1038/nature15538>
- Macamo, C. C. F., Massuanganhe, E., Nicolau, D. K., Bandeira, S. O., & Adams, J. B. (2016). Mangrove's response to cyclone Eline (2000): What is happening 14 years later. *Aquatic Botany*, 134, 10–17. <https://doi.org/10.1016/j.aquabot.2016.05.004>
- Maina, J. M., Bosire, J. O., Kairo, J. G., Bandeira, S. O., Mangora, M. M., Macamo, C., Ralison, H., & Majambo, G. (2021). Identifying global and local drivers of change in mangrove cover and the implications for management. *Global Ecology and Biogeography*, 30(10), 2057–2069. <https://doi.org/10.1111/geb.13368>
- Martínez, M. L., Silva, R., Chávez, V., López-Portillo, J., Salgado, K., Marín-Coria, E., Pérez-Maqueo, O., Maximiliano-Cordova, C., Landgrave, R., & de la Cruz, V. (2025). The challenges of climate change and human impacts faced by Mexican coasts: A comprehensive evaluation. *PLOS ONE*, 20(4), e0320087. <https://doi.org/10.1371/journal.pone.0320087>
- McKee, K. L., Mendelssohn, I. A., & Hester, M. W. (2020). Hurricane sedimentation in a subtropical salt marsh-mangrove community is unaffected by vegetation type. *Estuarine, Coastal and Shelf Science*, 239. <https://doi.org/10.1016/j.ecss.2020.106733>

- Menéndez, P., Losada, I. J., Torres-Ortega, S., Narayan, S., & Beck, M. W. (2020). The Global Flood Protection Benefits of Mangroves. *Scientific Reports*, 10(1), 4404. <https://doi.org/10.1038/s41598-020-61136-6>
- Mo, Y., Simard, M., & Hall, J. W. (2023). Tropical cyclone risk to global mangrove ecosystems: potential future regional shifts. *Frontiers in Ecology and the Environment*, 21(6), 269–274. <https://doi.org/10.1002/fee.2650>
- Mugilan, S., Manivasakan, S., Baranidharan, K., Jayabalakrishnan, R. M., Ragunath, K. P., Hemalatha, P., Ravi, R., & Krishnamoorthi, S. (2024). Mangroves as Natural Shields: A Comprehensive Review of Their Role in Mitigating Natural Disasters and Conservation Strategies. *Asian Journal of Environment & Ecology*, 23(7), 1–10. <https://doi.org/10.9734/ajee/2024/v23i7559>
- Odériz, I., Gómez, I., Ventura, Y., Díaz, V., Escalante, A., Gómez, D. T., Bouma, T. J., & Silva, R. (2020). Understanding Drivers of Connectivity and Resilience under Tropical Cyclones in Coastal Ecosystems at Puerto Morelos, Mexico. *Journal of Coastal Research*, 95(sp1), 128–132. <https://doi.org/10.2112/SI95-025.1>
- Osland, M. J., Day, R. H., From, A. S., McCoy, M. L., McLeod, J. L., & Kelleway, J. J. (2015). Life stage influences the resistance and resilience of black mangrove forests to winter climate extremes. *Ecosphere*, 6(9). <https://doi.org/10.1890/ES15-00042.1>
- Osland, M. J., Day, R. H., Hall, C. T., Brumfield, M. D., Dugas, J. L., & Jones, W. R. (2017). Mangrove expansion and contraction at a poleward range limit: Climate extremes and land-ocean temperature gradients. *Ecology*, 98(1), 125–137. <https://doi.org/10.1002/ecy.1625>
- Parkinson, R. W., & Wdowinski, S. (2022). Accelerating sea-level rise and the fate of mangrove plant communities in South Florida, U.S.A. *Geomorphology*, 412. <https://doi.org/10.1016/j.geomorph.2022.108329>
- Peereman, J., Hogan, J. A., & Lin, T.-C. (2022). Disturbance frequency, intensity and forest structure modulate cyclone-induced changes in mangrove forest canopy cover. *Global Ecology and Biogeography*, 31(1), 37–50. <https://doi.org/10.1111/geb.13407>
- Portela, A. P. (2025). Freshwater ecosystem services resilience in a changing world. *Limnetica*, 45(1), 1. <https://doi.org/10.23818/limn.45.13>
- Rethlefsen, M. L., Kirtley, S., Waffenschmidt, S., Ayala, A. P., Moher, D., Page, M. J., Koffel, J. B., Blunt, H., Brigham, T., Chang, S., Clark, J., Conway, A., Couban, R., de Kock, S., Farrah, K., Fehrmann, P., Foster, M., Fowler, S. A., Glanville, J., ... Young, S. (2021). PRISMA-S: an extension to the PRISMA Statement for Reporting Literature Searches in Systematic Reviews. *Systematic Reviews*, 10(1), 39. <https://doi.org/10.1186/s13643-020-01542-z>
- Rivers-Moore, N. A., & Dallas, H. F. (2022). A spatial freshwater thermal resilience landscape for informing conservation planning and climate change adaptation strategies. *Aquatic Conservation: Marine and Freshwater Ecosystems*, 32(5), 832–842. <https://doi.org/10.1002/aqc.3812>
- Rumondang, R., Feliatra, F., Warningsih, T., & Yoswati, D. (2024). Sustainable management model and ecosystem services of mangroves based on socio-ecological system on the coast of Batu Bara Regency, Indonesia. *Environmental Research Communications*, 6(3), 035008. <https://doi.org/10.1088/2515-7620/ad2d01>
- Sardar, P., & Samadder, S. R. (2023). Long-term ecological vulnerability assessment of Indian Sundarban region under present and future climatic conditions under CMIP6 model. *Ecological Informatics*, 76. <https://doi.org/10.1016/j.ecoinf.2023.102140>
- Sasmito, S. D., Kuzyakov, Y., Lubis, A. A., Murdiyarso, D., Hutley, L. B., Bachri, S., Friess, D. A., Martius, C., & Borchard, N. (2020). Organic carbon burial and sources in soils of coastal mudflat and mangrove ecosystems. *CATENA*, 187, 104414. <https://doi.org/10.1016/j.catena.2019.104414>
- Sewilam, H., Hassan, B. T., & Khalil, B. S. (2024). Spatiotemporal distribution of mangrove along the Egyptian Red Sea coast and analysis of hydrological impact on growth patterns. *International Journal of Environmental Science and Technology*. <https://doi.org/10.1007/s13762-024-05670-0>
- Silva, W. de, Perera, K. A. R. S., & Amarasinghe, M. D. (2022). Spatial distribution and dynamics of selected mangrove forests on the east and west coasts of Sri Lanka. *Sri Lanka Journal of Aquatic Sciences*, 27(2), 123–135. <https://doi.org/10.4038/sljias.v27i2.7601>
- Smith, T., Traxl, D., & Boers, N. (2022). Empirical evidence for recent global shifts in vegetation resilience. *Nature Climate Change*, 12(5), 477–484. <https://doi.org/10.1038/s41558-022-01352-2>
- Srivastava, P. K., Mehta, A., Gupta, M., Singh, S. K., & Islam, T. (2015). Assessing impact of climate change on Mundra mangrove forest ecosystem, Gulf of Kutch, western coast of

- India: a synergistic evaluation using remote sensing. *Theoretical and Applied Climatology*, 120(3-4), 685-700. <https://doi.org/10.1007/s00704-014-1206-z>
- Sunkur, R., Kantamaneni, K., Bokhoree, C., Rathnayake, U., & Fernando, M. (2024). Mangrove mapping and monitoring using remote sensing techniques towards climate change resilience. *Scientific Reports*, 14(1). <https://doi.org/10.1038/s41598-024-57563-4>
- Sutton, K., Tonge, C., Berglund, L., Kerr, G., & Sherren, K. (2023). Coastal resident perceptions of nature-based adaptation options in Nova Scotia. *Canadian Geographies / Géographies Canadiennes*, 67(3), 366-379. <https://doi.org/10.1111/cag.12818>
- Touza, J., Lacambra, C., Kiss, A., Amboage, R. M., Sierra, P., Solan, M., Godbold, J. A., Spencer, T., & White, P. C. L. (2021). Coping and Adaptation in Response to Environmental and Climatic Stressors in Caribbean Coastal Communities. *Environmental Management*, 68(4), 505-521. <https://doi.org/10.1007/s00267-021-01500-y>
- Urrego, L. E., Prado, M. A., Bernal, G., & Galeano, A. (2019). Mangrove responses to droughts since the little ice age in the Colombian Caribbean. *Estuarine, Coastal and Shelf Science*, 230. <https://doi.org/10.1016/j.ecss.2019.106432>
- van der Meulen, F., IJff, S., & van Zetten, R. (2023). Nature-based solutions for coastal adaptation management, concepts and scope, an overview. *Nordic Journal of Botany*, 2023(1). <https://doi.org/10.1111/njb.03290>
- Ward, R. D., Drude de Lacerda, L., da Silva Cerqueira, A., Miro C Silva, V. H., & Celis Hernandez, O. (2023). Vertical accretion rates of mangroves in northeast Brazil: Implications for future responses and management. *Estuarine, Coastal and Shelf Science*, 289. <https://doi.org/10.1016/j.ecss.2023.108382>
- Ward, R. D., Friess, D. A., Day, R. H., & Mackenzie, R. A. (2016). Impacts of climate change on mangrove ecosystems: a region by region overview. *Ecosystem Health and Sustainability*, 2(4). <https://doi.org/10.1002/ehs2.1211>
- Wu, T., & Barrett, J. (2022). Coastal Land Use Management Methodologies under Pressure from Climate Change and Population Growth. *Environmental Management*, 70(5), 827-839. <https://doi.org/10.1007/s00267-022-01705-9>
- Xavier, L. Y., Guilhon, M., Gonçalves, L. R., Corrêa, M. R., & Turra, A. (2022). Waves of Change: Towards Ecosystem-Based Management to Climate Change Adaptation. *Sustainability*, 14(3), 1317. <https://doi.org/10.3390/su14031317>
- Xu, Y., Shen, Z.-H., Ying, L.-X., Ciais, P., Liu, H.-Y., Piao, S.-L., Wen, C., & Jiang, Y.-X. (2016). The exposure, sensitivity and vulnerability of natural vegetation in China to climate thermal variability (1901-2013): An indicator-based approach. *Ecological Indicators*, 63, 258-272. <https://doi.org/10.1016/j.ecolind.2015.12.023>
- Yahia, A. K. M., Rahman, Dr. Md. M., Shahjalal, M., & Morshed, A. (2024). Implementing flood-resistant design strategies in coastal regions. *Non Human Journal*, 1(01), 1-20. <https://doi.org/10.70008/jeser.v1i01.37>
- Zhang, X., Lin, P., & Chen, X. (2022). Coastal Protection by Planted Mangrove Forest during Typhoon Mangkhut. *Journal of Marine Science and Engineering*, 10(9), 1288. <https://doi.org/10.3390/jmse10091288>