TITLE: FROM CLIMATE AWARENESS TO CLIMATE-INFORMED PLANNING IN EXISTING MARINE PROTECTED AREAS

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ABSTRACT

Marine protected areas underpin global biodiversity commitments, but climate change challenges management systems built around historical conditions. Existing guidance defines climate-adaptive practice, yet many plans contain resilience-supporting provisions without linking them explicitly to climate decisions. We present CliMPA, a human-centred framework that connects management needs, actor roles, social-ecological pathways and climate evidence within management-plan review. Plan diagnosis, stakeholder and agency analysis, participatory systems mapping and climate-information translation form a linked sequence in which each step informs the next. At Mafia Island Marine Park, existing provisions supported resilience but were not explicitly connected to climate-informed decisions. Managers, communities and experts represented vulnerability differently; integrating their knowledge retained livelihood, market and governance pathways less visible in a predominantly biophysical representation. These pathways guided selection of decision-relevant climate information and development of a management-facing factsheet, providing traceable inputs for subsequent risk assessment, adaptation planning and management-plan revision.

Keywords: adaptive management; climate information; CliMPA; human-centred design; marine protected areas; social-ecological systems; Climate Information

1. INTRODUCTION

Marine protected areas (MPAs) are central to the Kunming-Montreal Global Biodiversity Framework commitment to conserve and equitably govern 30% of coastal and marine areas by 2030, within a broader 2050 vision of living in harmony with nature (Convention on Biological Diversity 2022). Yet, most were designed around relatively stable environmental baselines and fixed spatial boundaries (Maxwell et al. 2015; Whitney et al. 2023). Warming, ocean acidification, marine heatwaves, sea-level rise and species redistribution now cross those boundaries, altering the ecosystems and benefits that MPAs were established to protect (Bruno et al. 2018; Wilson et al. 2020). Climate change therefore challenges not only ecological conditions but the continued relevance of objectives, zones, monitoring programmes and management responses that were developed from historical conditions (Craig 2012; Dunham et al. 2024; Fuchs et al. 2026).

A key implementation challenge is translating climate-ready MPA guidance into the decisions, roles and planning processes of existing MPAs. Wilson et al. (2020) synthesised established approaches into a general process of defining and adapting conservation goals, assessing vulnerability, identifying strategies and monitoring for adjustment. IUCN-WCPA guidance subsequently organised climate-ready practice around understanding change, strengthening adaptation and resilience, ensuring equity and inclusivity, and generating holistic co-benefits (Wenzel et al. 2025). Many management plans already contain relevant components that would enable climate change adaptation: among 172 plans covering 555 MPAs, long-term objectives, threat reduction, monitoring and adaptive management were widespread, yet only 9.3% contained a specific climate-vulnerability assessment (Lopazanski et al. 2023). Similarly, O'Regan et al. (2021) found that 57% of 362 post-2010 plans mentioned climate change, while the 223 climate-considering plans reviewed in detail incorporated, on average, only 39% of the climate-adaptation principles assessed.

The implementation gap also has social and institutional dimensions. Climate impacts change also have an impact on livelihood dependence, market access, local pressures, governance performance and organisational capacity to act (Cinner et al. 2012, 2013; Bennett & Dearden 2014; Gurney et al. 2014; Gill et al. 2017). Generic participation or a technical climate appendix is not sufficient to address questions about whose knowledge informs the plan, who has authority to respond, or how monitoring results should trigger management action (Cvitanovic et al. 2015; Flannery et al. 2018; Di Franco et al. 2020; Norström et al. 2020). Published applications of climate-informed MPA planning remain concentrated in tropical coral-reef systems and a limited number of jurisdictions, while climate information at management-relevant spatial and temporal scales remains unevenly available (Hopkins et al. 2016; Wilson et al. 2020).

Assessment tools can evaluate climate integration, management effectiveness and equitable governance, while downstream decision frameworks can help compare adaptation options (Anthony et al. 2015; Wilson et al. 2020; O'Regan et al. 2021; Wells et al. 2026). Neither necessarily addresses the intervening problem: how an existing MPA can identify relevant actors and authority, co-produce a shared understanding of social–ecological vulnerability, and translate climate information into usable inputs for management-plan review (Cvitanovic et al. 2015; McDonald et al. 2019; Norström et al. 2020). The missing connection is therefore not simply between science and policy, but among climate evidence, institutional authority, locally experienced impact pathways and the recurring planning process through which management objectives, rules and responses are revised (Craig 2012; Morrison et al. 2017; McDonald et al. 2019).

Here we present CliMPA, a human-centred implementation framework for integrating climate change knowledge into existing MPAs. Human-centred means that managers, communities and other relevant actors help shape the process and its outputs through their knowledge, responsibilities and capacity to act (Di Franco et al. 2020; Norström et al. 2020). Stakeholders helped frame management questions, construct the social-ecological system representation, identify and interpret climate information, and refine the content, format and intended use of management-facing products. CliMPA provides a linked pathway through four steps in management-plan review: diagnosing the plan, identifying who can act, building a shared understanding of the system, and translating climate information into planning inputs. By connecting these steps, the framework preserves traceability from management needs through relevant actors and system pathways to supporting climate evidence and intended planning use. We ask: (1) How can existing MPAs integrate climate information into management-plan reviews? and (2) What did applying CliMPA at MIMP in Tanzania reveal about what is required in practice?

2. METHODS

2.1 Framework design and development

CliMPA operationalises the four IUCN-WCPA principles for integrating climate change into MPA planning and management (Wenzel et al. 2025) through a transferable Monitor-Learn-Plan-Do cycle adapted from (Webb et al. 2018). Outputs are linked sequentially: management-plan diagnosis identifies climate and engagement gaps; stakeholder agency identifies who should participate and how; participatory systems mapping clarifies the social-ecological pathways through which climate change is experienced; and these outputs guide the selection and interpretation of climate information. The resulting variables, indicators and management implications are assembled into a climate factsheet and local monitoring priorities that support subsequent risk assessment and adaptation planning (Figure 1).

Across the linked components of the workflow, outputs from earlier activities (i.e. dependencies) were carried forward where they were needed to inform or justify subsequent analysis and planning inputs. For each proposed monitoring priority, management implication or adaptation recommendation, we recorded the management need addressed, the knowledge contributors, the relevant social-ecological pathway, the supporting climate variable or indicator, and its intended use in plan review. This allowed us to trace each recommendation back to its evidence and identify relationships requiring local validation.

We translated the four IUCN-WCPA principles for establishing MPAs in a changing climate into practical questions for management-plan review and refined the framework at Mafia Island Marine Park, Tanzania, with managers, communities and technical specialists. Management-plan review is the primary entry point, although repeated threshold exceedance or a major climate event may prompt re-entry before the next scheduled review (Figure 1). Individual tools may be adapted or replaced where alternative tools produce locally relevant and strong evidence and fulfil the same function within the framework (Table S11).

2.2 Management-plan gap analysis

Mafia Island Marine Park (MIMP), Tanzania, protects coral reefs, seagrass meadows and mangroves that support fisheries, seaweed farming and tourism in a highly resource-dependent setting. The gap analysis assessed the General Management Plan (GMP) enacted in 2011 (Marine Parks and Reserves Unit 2011); the 2023-2033 draft GMP and MPRU Strategic Plan 2023/24-2027/28 were consulted for current context but were not included in the formal assessment (Table S3). Guiding questions derived from the four IUCN-WCPA principles (i.e. understand change, adaptation and resilience, equity and inclusivity, holistic co-benefits) (Wenzel et al. 2025), were coded deductively in NVivo 15 (Allsop et al. 2022), with inductive subthemes developed within each principle (Table S2). Managers reviewed the findings in a virtual workshop, added legal and financial context, and proposed integration routes and interventions that informed the recommendations. In interpreting the plan, we distinguished formal provisions from evidence that participation, equity or intended outcomes had been achieved in practice.

2.3 Participatory systems mapping

Causal loop diagramming represented variables and directed, signed relationships (Voinov et al. 2016; Gray et al. 2018). Park-manager and community diagrams were co-created in separate sessions: participants identified variables, discussed causal relationships and explained the resulting pathways, which facilitators converted into source-specific diagrams and narratives (Table S6). These were integrated with an expert-derived diagram. Conceptually similar variables were harmonised across seven social-ecological domains (i.e. climate and ocean drivers, coastal hazards and water quality, coastal habitat condition, biodiversity and ecological benefits, livelihoods and well-being, local human pressures, and governance, responses and resilience), while provenance was retained for each node and signed link to preserve differences among expert, manager and community framings (Figure 2; Tables S7-S8). The integrated register was analysed for reinforcing and balancing feedbacks, cross-source convergence and distinctive contributions (Sterman 2002). Feedback loops supported across the source diagrams were distinguished from source-specific pathways represented by a single source and interpreted according to their provenance (Tables S9-S10; Supplementary Methods S6).

2.4 Climate-information selection and translation

The climate pathway and factsheet were co-developed through a decision-first, human-centred approach (Di Franco et al. 2020; Norström et al. 2020). Management questions guided the selection of variables, indicators, candidate thresholds and framing. Selection drew on systems mapping, scientific literature and stakeholder priorities for zoning, fisheries regulation, infrastructure siting and bleaching response (Figure 2; Tables S7-S10). Stakeholders reviewed clarity, relevance and applicability, while technical specialists reviewed data sources, interpretation, uncertainty and candidate thresholds.

Five themes linked system drivers to management applications: Ocean warming, ocean acidification, sea-level rise, storms and extreme events, and rainfall and freshwater runoff (Table 3). Marine heatwaves and degree-heating weeks were temperature-derived indicators, while salinity and surface-air temperature were supporting variables. Observations and projections under SSP2-4.5 and SSP5-8.5 were organised in a past-present–future narrative linked to monitoring and management. Figure 3 illustrates the translation process using the rainfall-Rufiji runoff pathway, tracing a management question through the social–ecological pathway, information needs, evidence and uncertainty to proposed planning inputs. Tables S11 report the full data inventory of essential climate variables considered for MIMP together with data source, spatial and temporal resolution and justification for each.

2.5 Scope of the demonstration

The demonstration completed the Monitor and Learn stages and extended into Plan through development of a management-facing climate factsheet and associated planning inputs (Figure 1; Table 1). These outputs establish the evidence base and institutional pathway for subsequent risk and community-vulnerability assessment, adaptation-option appraisal and selection, plan revision and adoption, implementation, and outcome evaluation.

3. RESULTS

3.1 A practical pathway for management-plan review

Operationalizing the four principles produced a co-created pathway linking plan diagnosis, differentiated stakeholder roles, shared system understanding, decision-relevant climate evidence and planning inputs. Diagnosis identified climate and institutional gaps; stakeholder and agency analysis clarified authority, knowledge, community reach; resources and communication roles; systems mapping identified vulnerability pathways and climate information needs; and stakeholder review refined the management-facing product. Together, these steps preserved traceability from a management need through relevant actors and social–ecological pathways to supporting climate evidence and intended planning use.

3.2 Existing provisions were not explicit climate management

The 2011 GMP contained useful foundations but not explicit climate management. Biodiversity objectives, zoning, monitoring, participatory structures and livelihood support were not linked to climate objectives, scenarios, indicators, thresholds, responsibilities or predefined responses (Table 2; Table S2). Monitoring focused mainly on human pressures, with little attention to climate variable observations or attributing climate impacts. Village Liaison Committees and support for women's seaweed-farming groups provided entry points for participation and livelihood adaptation, but equitable outcomes were not demonstrated. A mismatch between national and park fishing-net rules revealed regulatory incoherence (Table S2).

3.3 Stakeholders shaped tools through differentiated roles

Authority, technical capability, social or political power, community reach, implementation resources and communication capacity were distributed among organisations, requiring differentiated roles and products (Tables S4-S5). Managers contributed operational knowledge of park assets, enforcement, tourism and conservation performance, whereas communities contributed livelihood, market and governance pathways that were less visible in the predominantly biophysical expert representation (Figure 2; Tables S7–S10). Across the process, stakeholders helped in shaping management questions, system representation and climate framing, and reviewed the factsheet's clarity, relevance and management applicability (Figure 3; Tables 2 and 3).

3.4 Co-created knowledge changed the management problem

The three knowledge sources aligned on the broad climate – ecosystem - livelihood relationships but represented vulnerability differently. In the retained register, 18 of 32 harmonised nodes and 20 of 52 signed links were shared by all three sources, indicating agreement on the underlying system structure despite differences among the source-specific diagrams (Figure 2; Figure S1; Tables S7-S10;). Experts emphasised climate forcing, ecological mechanisms and resilience; managers emphasised protected-area assets, tourism and conservation performance; and communities emphasized seaweed production and markets, fish catch, household income and governance constraints, including ineffective monitoring and bribery. An expert-only representation would therefore have underrepresented livelihood, market and institutional pathways.

Five feedback structures were identified: three reinforcing pathways involving ecological degradation and livelihood pressure, seaweed and livelihood decline, and loss of coastal protection and increasing erosion; and two balancing pathways involving governance and enforcement, and restoration and adaptation (Figure 2; Figure S2; Table S9). Reinforcing structures showed how ecological decline interacted with livelihoods and local pressures, while balancing structures identified candidate responses. Across these pathways, vulnerability emerged through linked effects of climate and local pressures on habitat condition, ecosystem benefits and livelihoods, with governance and livelihood conditions shaping how impacts propagated through the system (Tables S9-S10; Supplementary Methods S6). Together, they showed that adaptation also depends on fisheries governance, market access and catchment management beyond direct control of the park management.

3.5 Co-creation converted climate evidence into planning inputs

Decision-relevant co-creation shifted the focus from available data to the management decisions that climate information needed to support (Figure 3; Table 3). Sea-surface temperature and thermal stress informed bleaching preparedness; rainfall and runoff from Rufiji River, a major source of land-based pollution, informed turbidity management; sea-level rise informed infrastructure siting and shoreline planning; storms informed early warning and preparedness; and acidification informed long-term monitoring and protection of potentially favourable conditions.

The Rufiji runoff-turbidity pathway illustrates how this traceability operates in practice (Figure 3). Stakeholders linked rainfall and freshwater discharge to turbidity, ecological condition and management concerns, directing attention to runoff indicators for monitoring and catchment coordination. This showed how a locally recognised system pathway guided both climate-information selection and its proposed planning use. Stakeholders reviewed these links for relevance, interpretation, format and applicability. The factsheet combined trends, scenarios, ecological and livelihood consequences, monitoring priorities and proposed responses, while distinguishing observed baselines, projected ranges, derived indicators and locally unmeasured variables (Figure 3; Tables 2, 3 and S11). This clarified where existing evidence could inform decisions and where additional local monitoring was needed. The factsheet recommended a climate section in the next GMP, quantified review triggers and alignment with the adaptive-management timetable (Table S12). Risk ratings and thresholds remained provisional pending local validation and formal adoption (Figure 3; Tables 3 and S12).

3.6 Integration inputs were prepared, but implementation was not tested

The application identified management-plan gaps, clarified differentiated stakeholder roles, integrated multiple perspectives on vulnerability, identified potential management entry points, and produced a stakeholder-refined climate product (Figure 1; Figure S3; Tables 1-2). These outputs establish the evidence base and institutional pathway for climate-informed plan review, with formal adoption, implementation and outcome evaluation occurring in subsequent stages. The application did not complete formal risk or community-vulnerability assessment, assign responsibilities or budgets, select or implement actions, or evaluate outcomes (Figure 1; Table 1). Formal uptake would require plan review or amendment, although severe bleaching, mass mortality or cyclone impacts could prompt earlier review.

4. DISCUSSION

CliMPA provides an operational pathway for integrating climate information into management-plan review in existing MPAs. Previous studies defined climate-adaptive planning, documented its limited incorporation into management plans, and showed that resilience-supporting provisions may exist without explicit climate framing (Wilson et al. 2020; O'Regan et al. 2021; Lopazanski et al. 2023). Subsequent work articulated principles for climate-ready MPA practice, described the shift toward explicit adaptation, and synthesised approaches for assessing management effectiveness and equitable governance (Cannizzo et al. 2025; Wenzel et al. 2025; Wells et al. 2026) (Table S13). Strategic guidance further emphasises monitoring, inclusive governance, institutional alignment and financing (Fuchs et al. 2026). CliMPA builds on this foundation by linking management needs, differentiated actor roles, shared social-ecological understanding and decision-relevant climate evidence into traceable planning inputs for management-plan review.

The contribution is a linked framework that brings established methods together within management-plan review. CliMPA links management-plan diagnosis, stakeholder and agency analysis, participatory systems mapping and climate-information translation so that evidence remains connected to the actors, pathways and management decisions it is intended to inform. These components create a traceable sequence from management question to actor, social–ecological pathway, climate evidence and planning use, consistent with evidence that usable knowledge emerges through iterative framing and shared interpretation (Cvitanovic et al. 2015; Norström et al. 2020). At MIMP, the 2011 plan contained monitoring, zoning, participation and livelihood provisions that could support adaptation, but these were not linked to climate-sensitive objectives, indicators, thresholds, responsibilities or response rules. Connecting these elements makes existing resilience capacity more explicit and actionable within climate-informed planning (Anthony et al. 2015; Cvitanovic et al. 2015; Wilson et al. 2020; Bryce & Hunter 2024; Dunham et al. 2024).

Stakeholder involvement reshaped both the analysis and its outputs. Managers, communities and technical actors helped frame questions, construct the system representation, interpret climate information and refine factsheet applications, reflecting substantive co-production (Di Franco et al. 2020; Norström et al. 2020). Their perspectives retained livelihood, market and governance pathways with ecological processes, broadening the diagnosis of vulnerability and the range of responses considered. Stakeholder review also shaped how trends, uncertainty and management implications were communicated. Climate integration therefore depends not only on the evidence available, but also on how it is interpreted, made relevant to users and connected to management practice.

CliMPA provides a foundation for subsequent action selection. Its outputs, a diagnosed management problem, differentiated roles, a shared vulnerability representation, decision-relevant evidence and candidate management entry points, can feed into participatory scenario planning, structured decision-making or Resist-Accept-Direct deliberation to compare options, clarify trade-offs and assign responsibilities (Gregory et al. 2012; Miller et al. 2022; Schuurman et al. 2022). Targets, thresholds and social-ecological objectives can then connect diagnosis to adaptive choices (Bryce & Hunter 2024). The transferable core elements are management plan review, linked steps, differentiated roles, evidence provenance and translation of climate information for management decisions. Local application requires actors, indicators, thresholds and responses to be defined in relation to site-specific authority, resource dependence, knowledge systems and management capacity (Bennett & Dearden 2014; Gurney et al. 2014; Gill et al. 2017).

At MIMP, the application demonstrates how these core elements can be operationalised within an existing MPA and provides a foundation for subsequent climate-risk assessment, community-vulnerability assessment, adaptation-option appraisal, plan revision, implementation and evaluation. Future applications should document iterative feedback, assess the consistency of stakeholder scoring and validate candidate thresholds locally before adoption. Comparative application across MPAs in tropical oceans globally could test the framework under different governance, livelihood and organisational-capacity conditions. Evaluation should follow the traceability chain from evidence and planning inputs through plan uptake, decision quality and implementation to ecological and social outcomes, including the distribution of costs, benefits and authority.

5. CONCLUSION

Existing MPAs need a practical route from climate awareness to climate-informed planning. CliMPA links plan diagnosis, differentiated stakeholder roles, shared social-ecological understanding and decision-first climate-information translation within management-plan review. At Mafia Island, co-creation made existing resilience-supporting provisions more explicit, retained livelihood and governance pathways while incorporating biophysical evidence, and produced management-facing planning inputs. These outputs provide a foundation for subsequent risk assessment, plan revision, implementation and evaluation. Management-plan review offers the institutional opportunity to translate them into climate-sensitive objectives, indicators, thresholds, responsibilities and adaptive actions.

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Table 1. CliMPA structure for integrating climate information into MPA management-plan review.

Adaptive management stage and tool	Practical question	Output and dependency	Status at MIMP
Monitor: management-plan gap analysis	What is already present, and what is missing for explicit climate management?	Diagnosis of climate objectives, indicators, thresholds, participation and institutional entry points; defines the gaps subsequent tools must address	Completed
Learn: stakeholder mapping and agency analysis	Who must be involved, and what can each actor contribute or authorise?	Differentiated roles for formal adoption, evidence, implementation, facilitation and local legitimacy; identifies who should co-create subsequent tools and informs engagement and systems mapping	Completed
Learn: participatory systems mapping	How do climate, ecosystems, livelihoods, pressures and governance interact?	Co-created pathways, distinctive knowledge contributions, validation needs and candidate management entry points; informs climate-variable selection and risk assessment	Completed
Learn/Plan: decision-first climate-information selection	Which climate information would improve priority decisions, and how should intended users interpret it?	Co-selected climate themes, derived indicators, data gaps and candidate thresholds linked to zoning, fisheries, infrastructure and preparedness	Completed
Plan: management-facing climate factsheet	How should evidence be communicated so that intended users find it relevant and usable?	A stakeholder-reviewed past-present-future product with scenarios, provisional risks and management applications; provides an input to plan review and further risk deliberation	Core output completed
Plan: risk-and-vulnerability/community-risk assessment	Which risks and trade-offs should be prioritised with affected groups?	Locally validated risk priorities and distributional consequences; should constrain action selection	Not completed
Do: action selection and plan integration	Which actions, responsibilities, budgets and timelines should be adopted?	Formally approved objectives, rules, responsibilities, finance and implementation arrangements.	Not completed
Monitor: implementation and outcome evaluation	Did the adopted actions improve ecological and social outcomes?	Monitoring, evaluation and learning that trigger adjustment or the next review cycle.	Not completed

Table 2. Key findings from the Mafia Island application and their implications for climate-informed management-plan review. Detailed results and supporting registers are provided in the Supplementary Information.

Consequential finding	**What the MIMP application showed**	**Implication for management-plan review**
Existing (implicit) planning foundations could support climate action	The 2011 plan contained zoning, monitoring, participation and livelihood provisions but lacked climate objectives, scenarios, indicators, thresholds and response rules	Build on existing institutions and provisions by linking them to climate evidence, triggers, responsibilities and review procedures
Stakeholders contributed through different roles	Authority, technical capacity, community reach, resources and legitimacy were distributed among organisations. Stakeholders also helped shape management questions, system representations, climate-information framing and the factsheet	Build co-creation into each stage and assign distinct roles for evidence generation, operational translation, formal adoption, implementation, facilitation and local deliberation
Different knowledge sources changed the understanding of vulnerability	Expert, manager and community maps emphasised different mechanisms. Their integration retained livelihood, market and governance pathways together with biophysical processes	Assess vulnerability across ecological, livelihood and governance dimensions while retaining the source of knowledge and areas requiring further validation
Management entry points extended across several domains	The integrated system model identified potential responses involving habitat management, enforcement and awareness, livelihoods and markets, and catchment-to-coast and shoreline management	Use these entry points to structure stakeholder deliberation, risk assessment and prioritisation of management options
Climate evidence became usable planning information through co-creation	Climate themes and indicators were selected around management questions, while stakeholder feedback refined how trends, risks and applications were ommunicated in the factsheet.	Develop climate products backwards from management questions and test their relevance, clarity and applicability with intended users during development
The application established inputs for subsequent planning stages	The factsheet, candidate thresholds and management entry points created an evidence base for further risk assessment, option appraisal, plan revision and implementation	Carry these inputs into formal assessment, adoption, resourcing, implementation and evaluation, and track their uptake through subsequent stages

Table 3. Decision-relevant climate-information themes in the MIMP factsheet. The hierarchy reconciles five core themes with derived indicators and supporting variables.

Core climate theme	Derived indicators or supporting variables	Management question and application	Status and uncertainty
Ocran warming and Sea-surface temperature	Marine heatwaves; degree-heating weeks; local temperature logger observations	When should bleaching preparedness and response intensify? Use thermal-stress alerts, field verification and predefined review or response procedures.	Observed and projected warming is decision-relevant; proposed 4 °C weeks watch and 8 °C weeks warning thresholds require local validation and governance approval
Ocean acidification	Surface pH; carbonate saturation where available	Where should long-term monitoring and protection of potentially favorable conditions or refugia be prioritized?	Regional/global evidence is available, but the factsheet identifies the need for in-situ MIMP measurements and local interpretation with caution
Sea-level rise	Satellite-altimetry trend; tide-gauge anomalies; storm-surge interaction	Where should infrastructure setbacks, shoreline planning and landward habitat-migration space be protected?	Scenario ranges support anticipatory planning; local elevation, exposure and infrastructure data are needed for site level rules
Storms and extreme events	Cyclone category and frequency; surge alerts; damage observations	When should preparedness, emergency coordination and pre-storm alerts be activated?	The projected category-dependent signal is uncertain; early-warning actions can use observed forecasts without claiming precise long-term local frequency
Rainfall and freshwater runoff	Seasonal rainfall; salinity; Rufiji River discharge; turbidity and sedimentation indicators	When and where should turbidity, runoff and catchment-to-coast pressures alter monitoring or management?	Seasonal projections indicate potential intensification, but local discharge, salinity and water-quality monitoring are required to resolve nearshore impacts

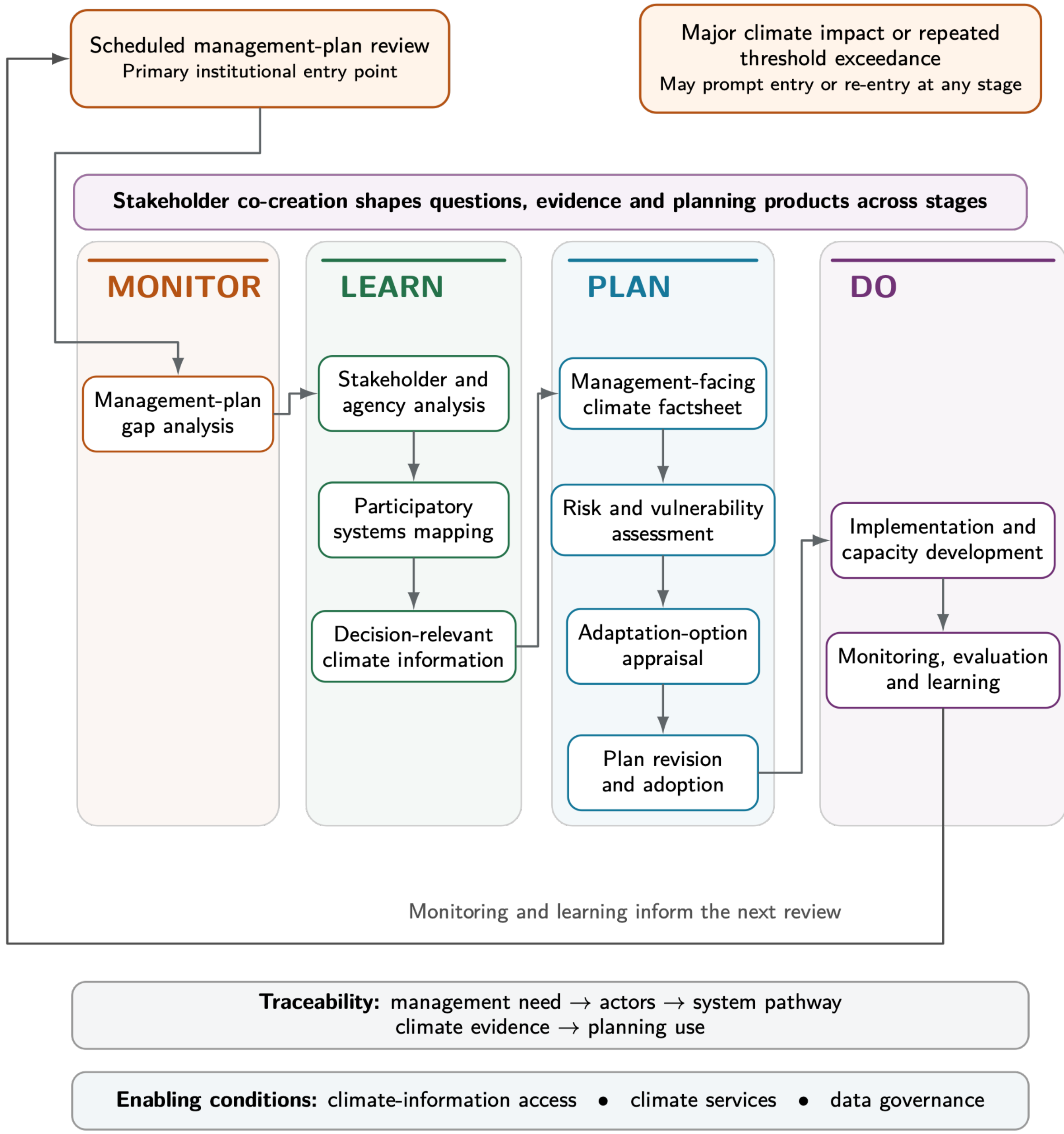
Figure captions

Figure 1. CliMPA implementation framework for integrating climate information into management-plan review in an existing marine protected area. The framework is nested within adaptive-management cycle (Webb et al. 2018) and is entered primarily through scheduled management-plan review, with major climate impacts or repeated threshold exceedance able to prompt earlier entry. The linked workflow comprises management-plan gap analysis (Monitor); stakeholder and agency analysis, participatory systems mapping and decision-relevant climate information (Learn); development of a management-facing climate factsheet, risk and vulnerability assessment, adaptation-option appraisal, and plan revision and adoption (Plan); and implementation, capacity development, monitoring, evaluation and learning (Do). Outputs from each component inform subsequent components, preserving traceability from management need through actors and system pathways to climate evidence and planning use. Co-creation shapes questions, evidence and planning products throughout the process.

Figure 2. Integrated causal loop diagram of climate change vulnerability and response pathways in the MIMP social-ecological system. **Panel A** shows the integrated model at module level, combining an expert-derived diagram with participatory diagrams developed with park managers and communities across seven system domains: climate and ocean drivers; coastal hazards and water quality; coastal habitat condition; biodiversity and ecological benefits; livelihoods and well-being; local human pressures; and governance, responses and resilience. **Panel B** summarises five key feedback loops: three reinforcing pathways involving ecological degradation and livelihood pressure, seaweed and livelihood decline, and loss of coastal protection and increasing erosion; and two balancing pathways involving governance and enforcement, and restoration and adaptation.

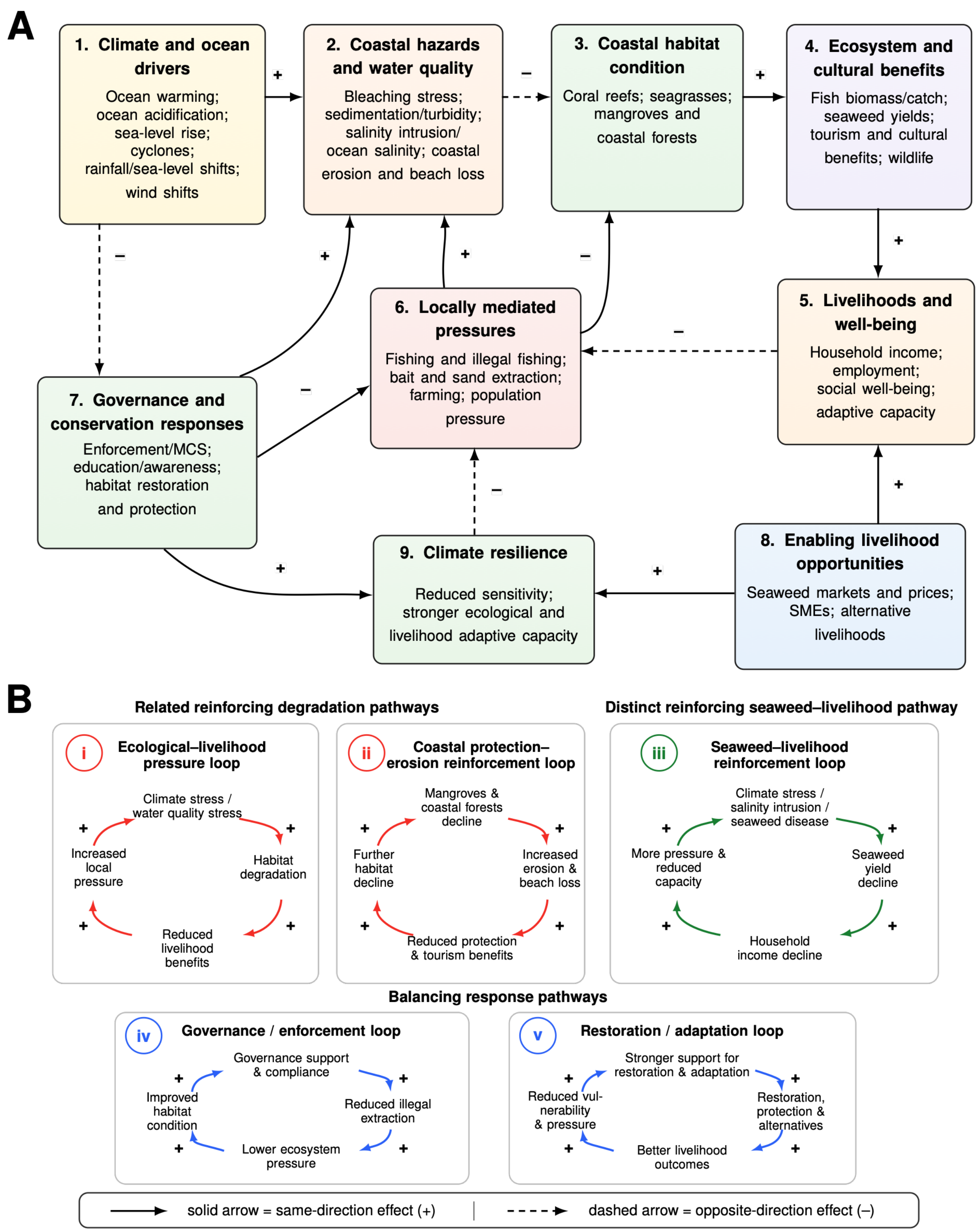
Figure 3. Worked traceability chain linking a management need to a climate-informed planning input. The Rufiji runoff example shows how a locally recognised management question is connected to a co-produced social-ecological pathway, information needs, available evidence and uncertainty, provisional interpretation and proposed planning inputs. The example illustrates how CliMPA translates climate evidence into management-relevant planning information while retaining provenance and uncertainty throughout.

FIGURE 1



Scheduled management-plan review
Primary institutional entry point
Major climate impact or repeated threshold exceedance
May prompt entry or re-entry at any stage
Stakeholder co-creation shapes questions, evidence and planning products across stages
MONITOR
LEARN
PLAN
DO
Management-plan gap analysis
Stakeholder and agency analysis
Participatory systems mapping
Decision-relevant climate information
Management-facing climate factsheet
Risk and vulnerability assessment
Adaptation-option appraisal
Plan revision and adoption
Implementation and capacity development
Monitoring, evaluation and learning
Monitoring and learning inform the next review
Traceability: management need → actors → system pathway
climate evidence → planning use
Enabling conditions: climate-information access • climate services • data governance

FIGURE 2



A
1. Climate and ocean drivers
Ocean warming; ocean acidification; sea-level rise; cyclones; rainfall/sea-level shifts; wind shifts
2. Coastal hazards and water quality
Bleaching stress; sedimentation/turbidity; salinity intrusion/ ocean salinity; coastal erosion and beach loss
3. Coastal habitat condition
Coral reefs; seagrasses; mangroves and coastal forests
4. Ecosystem and cultural benefits
Fish biomass/catch; seaweed yields; tourism and cultural benefits; wildlife
5. Livelihoods and well-being
Household income; employment; social well-being; adaptive capacity
6. Locally mediated pressures
Fishing and illegal fishing; bait and sand extraction; farming; population pressure
7. Governance and conservation responses
Enforcement/MCS; education/awareness; habitat restoration and protection
8. Enabling livelihood opportunities
Seaweed markets and prices; SMEs; alternative livelihoods
9. Climate resilience
Reduced sensitivity; stronger ecological and livelihood adaptive capacity
B
Related reinforcing degradation pathways
i Ecological–livelihood pressure loop
Climate stress / water quality stress
Habitat degradation
Reduced livelihood benefits
Increased local pressure
ii Coastal protection–erosion reinforcement loop
Mangroves & coastal forests decline
Increased erosion & beach loss
Reduced protection & tourism benefits
Further habitat decline
Distinct reinforcing seaweed–livelihood pathway
iii Seaweed–livelihood reinforcement loop
Climate stress / salinity intrusion / seaweed disease
Seaweed yield decline
Household income decline
More pressure & reduced capacity
Balancing response pathways
iv Governance / enforcement loop
Governance support & compliance
Reduced illegal extraction
Lower ecosystem pressure
Improved habitat condition
v Restoration / adaptation loop
Stronger support for restoration & adaptation
Restoration, protection & alternatives
Better livelihood outcomes
Reduced vul-nerability & pressure
solid arrow = same-direction effect (+)
dashed arrow = opposite-direction effect (–)

FIGURE 3

1 Management question

When and where should runoff and turbidity alter park monitoring or management?

2 Co-produced system pathway

Rainfall change
↓
Rufiji discharge
↓
Plume extent, salinity and turbidity
↓
Coral and seagrass condition
↓
Fisheries and seaweed livelihoods

3 Information required

- Seasonal rainfall and Rufiji discharge
- Salinity and turbidity observations
- Plume extent and spatial pattern

4 Evidence & uncertainty

- Historical observations and projections
- Regional-to-nearshore scale mismatch
- Limited local water-quality observations

5 Provisional interpretation

- When monitoring should intensify
- Where impacts may be greatest
- Candidate trigger for local validation

6 Planning input

- Seasonal monitoring protocol
- Runoff/plume exposure mapping
- Catchment coordination
- Observation, reporting and review roles

Traceability: provenance and uncertainty retained throughout

Supporting Information: supplementary table captions

Figure S1. Map of the Mafia Island Marine Park, United Republic of Tanzania

Figure S2. Stakeholder-characteristic pathways in the integrated causal loop synthesis. The expert-derived pathway (EXP) emphasises biophysical mechanisms and resilience; the park-manager pathway (PM) emphasises park assets, benefits and management response; and the community pathway (COM) emphasises livelihoods, markets and governance constraints. Solid arrows indicate same-direction relationships and dashed arrows indicate opposite-direction relationships.

Figure S3. Management leverage points identified from the integrated CLD. The figure links major vulnerability pathways to potential management-plan entry points, including habitat restoration and protection, monitoring and enforcement, livelihood and market support, and catchment-to-coast or shoreline management. The leverage points are analytically identified from the CLD and should be interpreted as candidate management responses for further validation and prioritisation. Source labels indicate the knowledge sources supprting each pathway: EXP = expert-derived causal loop diagram; PM = park-manager causal loop diagram; COM = community causal loop diagram.

Table S1. Complete CliMPA implementation framework, including the Q1-Q10 guiding questions, adaptive-management stage, method, output, input-output dependency, intended user and status of application at MIMP.

Table S2. Detailed evaluation of the 2011 MIMP General Management Plan against the four IUCN-WCPA principles, including guiding questions, supporting plan text, implicit strengths, explicit climate gaps, validation comments and recommended plan-review response.

Table S3. Planning chronology and document roles at MIMP, distinguishing the 2011 General Management Plan assessed in the gap analysis from the 2023-2033 General Management Plan and MPRU Strategic Plan 2023/24-2027/28 used to characterise the current adaptive-management context.

Table S4. MIMP stakeholder inventory, institutional typologies, scale, power and resource scores, normalised agency dimensions, final reconciled cluster assignment and proposed role in climate-information integration.

Table S5. Stakeholder-agency scoring rubric and analysis workflow, including question wording, scoring ranges, excluded categorical variables, normalisation, aggregation, hierarchical-clustering settings and sensitivity checks.

Table S6. Participant, workshop and co-creation reporting information for the expert, park-manager and community processes, including participant numbers, selection criteria, dates, locations or virtual format, facilitation and translation arrangements, validation steps, consent and ethics approval or exemption, feedback rounds, and documented changes to diagrams, tools and products resulting from stakeholder input.

Table S7. Harmonised social-ecological system node register, including node identifier, harmonised label, definition, system domain and provenance from expert, park-manager and community diagrams. EXP = expert-derived generic CLD; PM = park-manager participatory CLD; COM = community participatory CLD. Multi-source attribution indicates provenance.

Table S8. Integrated signed causal-link register, including source node, target node, polarity, relationship interpretation, source provenance and evidence status. Positive polarity means variables move in the same direction; negative polarity means they move in opposite directions.

Table S9. Key feedback loops in the integrated system and source-specific pathways, showing causal sequence, net polarity, source support, loop-closure status and interpretation.

Table S10. Cross-source comparison of expert, park-manager and community diagrams by social-ecological domain, including descriptive register properties, shared and distinctive contributions.

Table S11. Essential Climate Variables considered for Marine Protected Area management, aligned with the Global Climate Observing System (GCOS) framework, with data provenance, resolution and ecological response.

Table S12. Risk pathways of the five Essential Climate Variables prioritised by stakeholders for Mafia Island Marine Park's ecological and socioeconomic systems. Thresholds are based on management rules identified through literature review.

Table S13. Positioning of CliMPA relative to selected MPA climate guidance, assessment tools and decision frameworks by purpose, MPA lifecycle stage, whether the approach diagnoses, produces or selects, treatment of social dimensions, and relationship to management-plan review. CC-RAPT and R-SAT descriptions follow the MPA management-effectiveness tool review.

RAD and scenario/structured decision approaches are positioned as downstream action-selection methods, whereas CliMPA produces upstream planning inputs.