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Enhancing climate change planning and adaptive management in marine protected areas through targets, thresholds, and social-ecological objectives

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Marine Protected Areas (MPAs) are being deployed globally to protect the Earth's biodiversity in rapidly changing oceans. Nesting climate change considerations within adaptive MPA management and monitoring is becoming a more common approach, and while climate change is increasingly addressed in MPA planning, implementation gaps remain. This study applied the climate robustness index (CRI) to MPA monitoring plans to assess how climate change is outlined within site- and regional-level plans. Previously developed to assess MPA management plans, the CRI scores plans based on their degree of incorporation of climate change adaptation principles, including core elements of adaptive management. We supplemented our CRI findings for monitoring plans by associating index scores of MPAs in the United States with selected MPA traits, as well as by examining specific physical, ecological, and sociological climate change impacts that were being considered within the monitoring scope of a subset of monitoring plans. We found considerable gaps in actionable targets and thresholds in MPA monitoring plans, consistent with a previous study evaluating MPA management plans, demonstrating that the adaptive management cycle is incomplete in many cases. We consider the importance of completing the adaptive management cycle as a core climate adaptation strategy, and explore the roles of social-ecological objectives and local partnerships as avenues to continue to improve MPA outcomes in a changing world.

KEYWORDS

benchmarks, triggers, monitoring, decision criteria, performance measures, adaptation

1 Introduction

Marine protected areas (MPAs) comprise a spectrum of conservation and management strategies for protecting ecological and cultural resources. Their aims vary, and include: protecting special seascape features; promoting sustainable harvest practices or other economic opportunities (e.g. tourism); protecting cultural features; or combinations of these goals (Day et al., 2019). When supported by ocean users and/or enforced (Johannes, 2002; Cinner et al., 2006), MPAs can provide boundaries to reduce pressures such as those from fishing (Lotze et al., 2011), vessel strikes (Schoeman et al., 2020), and industrial pollution (Brown et al., 2019). In some cases, they can also provide opportunities to examine local effects of global environmental changes in relative isolation from specific anthropogenic stressors (Dunham et al., 2020).

Enormous efforts are underway to expand marine areas under protection globally, which is an impetus for increasing the resilience of MPAs to climate pressures (Wilson et al., 2020; Peterson St-Laurent et al., 2021; Schuurman et al., 2022; Lopazanski et al., 2023). As observations of ecological and social-cultural responses attributed to changing ocean conditions continue to accumulate (Pecl et al., 2017; Frölicher and Laufkötter, 2018; Thompson et al., 2023), so do novel means of incorporating changing ocean conditions within MPAs' operational management to proactively establish a structure that can accommodate change while maximizing performance (Wilson et al., 2020; O'Regan et al., 2021).

To navigate management requirements and foster resilience, MPAs have broadly adopted an adaptive management approach (Geyer et al., 2017; Tony, 2020; O'Regan et al., 2021; Lopazanski et al., 2023). Adaptive management is an iterative decision-making framework, in which management objectives and processes are responsive to changing conditions and/or information gaps (Walters and Hilborn, 1978). Management interventions are viewed through an experimental lens, and monitoring of consequences guides the implementation of further actions as needed to achieve designated management objectives. Rigorous monitoring of carefully selected indicators that serve as proxies for ecological, physical, and/or social conditions is integral to adaptive management. Tracked over time, indicators reveal trends on the conditions of phenomena, providing a means of assessing the performance of MPA management interventions (Vandermeulen, 1998).

Directional trends of indicator condition alone, however, are limited in their utility and require targets and thresholds that serve as critical decision criteria (or performance measures) to trigger implementation of management interventions if an indicator's trajectory is not desirable (Samhouri et al., 2010, 2011). Such decision criteria are recommended to be concise, unambiguous, understandable, direct, and operational to guide the delivery of established management objectives (Gregory et al., 2012). Without full implementation of an operationally feasible management framework with clear targets and thresholds, performance on Target 3 of the Global Biodiversity Framework to protect 30% of marine areas from "dangerous loss of biodiversity" by 2030 (Convention on Biological Diversity [CBD], 2022a; 2022b), may be difficult to demonstrate.

Adaptive management has gained momentum as a framework through which static spatial conservation measures can remain functional and support ecological resilience specifically in the face of climate-driven ecological transformation (Lawler, 2009; McCook et al., 2010; International Union for Conservation of Nature [IUCN], 2016; Schuurman et al., 2022). The uptake of adaptive management is foundational to the uptake of climate-adaptive management (Lopazanski et al., 2023). A key strength of this management principle is its utility within data-poor management contexts (Marzin et al., 2016; Tony, 2020). It is also lauded for its ability to integrate social and ecological objectives of biodiversity conservation (McCook et al., 2010; Ban et al., 2011; Weeks and Jupiter, 2013; Zentner et al., 2023). Yet MPA managers may be limited in their ability to regulate impacts of local and global stressors within an adaptive management structure if it does not employ sound performance measures in support of conservation objectives (Gregory et al., 2012; Zentner et al., 2023).

The presence of a monitoring plan supports MPA management effectiveness and climate robustness (Geyer et al., 2017; IUCN and WCPA, 2017; O'Regan et al., 2021). In 2017, an evaluation of MPA management processes found that only 13% of MPAs globally used the results of scientific monitoring to guide management (Gill et al., 2017). In 2021, O'Regan et al. identified several key steps to better incorporate climate-change adaptation in MPA management plans, including developing objectives and strategies that specifically address climate change impacts, and monitoring specifically for climate change impacts. In this study, we expand on previous work evaluating MPA climate change robustness through the adaptive management lens (Geyer et al., 2017; O'Regan et al., 2021) by applying the climate robustness index (CRI) to MPA monitoring plans. In doing so, we gain insight on elements of climate-adaptive management that are well-integrated in MPA planning, and elements that are consistently lacking, and discuss the implications for MPA management in an era of ecological transformation.

2 Methods

2.1 Collecting MPA monitoring plans

We searched for English-language monitoring plans for 998 MPAs listed within an existing database of 647 corresponding MPA management plans. This database (hereafter referred to as the MPA Plan Database) was based on MPAs identified in the World Database on Protected Areas (UNEP-WCMC and IUCN, 2020). It was compiled by Dunham et al. (in press) and expanded and applied in a climate change context by O'Regan et al. (2021). OECMS were not included in this database. Within the MPA Plan Database, and following the previously mentioned studies, we searched for monitoring plans in two ways: 1) by searching within each management plan for reference to a monitoring plan; and 2) by conducting an internet search when monitoring plans were not referenced within a management plan. We used the built-in PDF viewer word-search function to search for the word "monitor" within the management plan to jump to sections that were likely to contain information regarding a monitoring plan. If a monitoring plan was referenced in the management plan, a Google search was initiated using either the search terms: ("Monitoring Plan Name"), or ("Name of MPA" "Monitoring Plan Name"). If the management plan did not reference a monitoring plan, a search using the following terms was used: ("Name of MPA" AND "Monitoring" "plan" OR "program" OR "strategy").

Any document found through the internet search that described a monitoring effort, goals, processes or results were recorded. The documents were then filtered by the same criteria used to assess management plans by O'Regan et al. (2021): written in English; produced by a legally mandated organization or government agency; focused on the area-based conservation of marine waters, which included estuaries and tidal wetlands; and for a designated MPA (i.e., no longer in the planning stage).

If no monitoring document was found in the first 10 pages of the Google search, it was concluded that we could not locate any monitoring plan for the MPA. In two cases (the United Kingdom (UK) and Australia), the search effort did not return monitoring plans for jurisdictions that seemed likely to have monitoring provisions. For these regions, we conducted a manual search at a regional level (instead of MPA-level) within the jurisdictions' main websites to locate monitoring plans.

The absence of a monitoring plan does not indicate a lack of monitoring effort. In many cases, monitoring is conducted by citizen science groups, universities, NGOs, private industry, etc. The absence of an overarching plan, however, contributes to data coordination and sharing issues, thus challenges for translating observations to management practices, compromising accountability with respect to local and global commitments towards conservation.

2.2 Climate robustness index

MPA monitoring plans were evaluated with the climate robustness index (CRI) (O'Regan et al., 2021). The CRI uses 12 questions to quantify the degree to which the monitoring plan incorporates climate change impact analysis, planning, and monitoring. See definitions of terms used in the questions in Figure 1.

1. Did the plan discuss any past, present, or future effects of climate change on ecological, physical, or sociological components of the MPA (Yes/No for each of the three component types)? We did not discriminate on the level of detail (6 points).
2. Did the plan contain one or more objectives that explicitly mentioned climate change or one of its effects, such as sea level rise (Yes/No)? (2 points).
3. Did the plan contain one or more strategies that explicitly mentioned climate change or one of its effects, such as sea level rise (Yes/No)? (2 points).
4. Did the plan explicitly commit to monitoring or adapting to climate change (Yes/Planned/No; Planned was entered if the plan stated an intent to consider monitoring climate change effects)? (2 points).
5. Did the plan discuss baseline conditions in the MPA or state that they would be surveyed in the future (Yes/Ongoing/Planned/No; Ongoing was entered if the plan stated that some type of baseline monitoring had already begun; Planned was entered if the plan stated that the MPA intends to complete baseline monitoring in the future)? (2 points).
6. Did the plan list monitoring indicators of ecological, physical, or sociological components or state that they would be established in the future (Yes/Planned/No)? (2 points).
7. Did the plan list monitoring metrics for the indicators or state that they would be established in the future (Yes/Planned/No)? It was assumed that plans with a stated intent to establish indicators would also decide on metrics (2 points).
8. Were the indicators explicitly linked to climate change? That is, did they directly track climate changes OR were "climate change" or "sea level" mentioned in the same sentence as the indicator (Yes/Some/No/NA; NA was

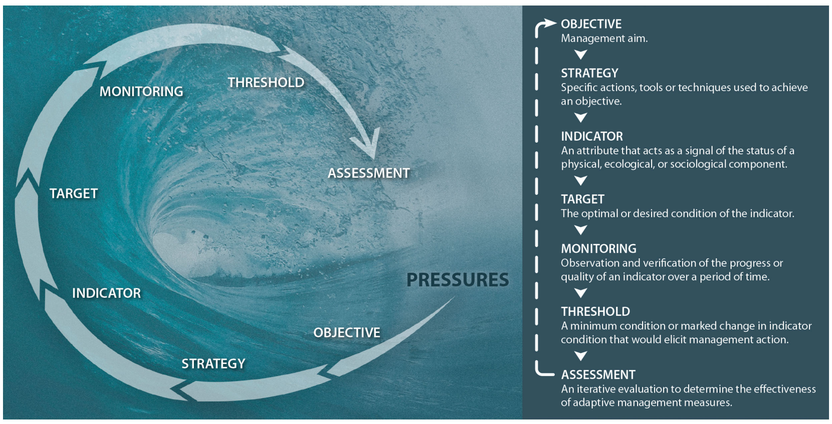

FIGURE 1
Adaptive management cycle and definitions of its components.

entered if there were no indicators listed or planned)? (2 points).

9. Did the plan contain detailed survey/monitoring methods (Yes/Some/No)? (2 points).
10. Did the plan list targets for the condition of the indicators or state that targets would be established in the future (Yes/Some/Planned/No; Some was entered if there were targets for some indicators but not all)? (2 points).
11. Did the plan list thresholds for the condition of the indicators or state that thresholds would be established in the future (Yes/Some/Planned/No)? (2 points).
12. Did the plan mention other climate change monitoring or mitigation efforts being completed by agencies other than park staff (Yes/No)? (2 points).

The sum of the question scores for each monitoring plan was its climate robustness score; a perfect score was 28. A plan received a score if it discussed an implemented element (Yes; 2 points) or planned/partial element (Planned/Some; 1 point). Plans with no information received a zero score (No; 0 points). Examples of 'Yes' and 'Planned/Some' scores are given in Table 1. In addition to the 12 questions included in the CRI, we asked two additional questions which were not included in the final CRI score: Does the plan contain a data management plan? Is there an explicit commitment to adaptive management?

In scoring each plan, the plans were not read in their entirety but scanned using the built-in PDF viewer word-search function to locate the following terms and jump to the relevant sections of text: "climate change," "warm," "sea level," "objective," "strategies," "monitor," "indicator," "target," "threshold," "metric," "parameter," "baseline", "data management", and "adapt". We also searched for "favorable condition," "limit," "desired condition," "trigger," "benchmark", "reference level", "performance measure," which were used in plans from some jurisdictions in lieu of "target" or "threshold". These terms are the same as those used in O'Regan et al., 2021, with the addition of "data management", "adapt", "benchmark", and "reference level".

2.3 MPA traits analysis

We gathered information on traits of United States (US) MPAs (the region for which most English-language monitoring plans were found) to investigate relationships between MPA traits and CRI. The traits were adopted from the US National Oceanic and Atmospheric Administration's (NOAA) Definitions and Classification System for US MPAs, and the NOAA MPA Inventory (NOAA, 2020; National Ocean Service, 2023), which represented an authoritative and comprehensive directory of US MPAs and their attributes. We filtered this directory for MPAs that were included in our analysis. We then plotted the total CRI scores (the sum of management and monitoring plan scores for each MPA) against the following traits: conservation focus (natural heritage, cultural heritage, sustainable production, and combinations); level of protection (uniform multiple-use, zoned multiple-use, zoned multiple-use with no-take area(s), no-take, no impact, and no access); area (km^2); level of governance (federal, state/province, partnership - i.e., MPA is designated and managed by multiple agencies across levels of government); and IUCN category (Ia - VI). Total CRI score was used to ensure any gaps in climate-robustness in either the monitoring or management plans (scored by O'Regan et al., 2021) had an opportunity to be filled by the other document. Adding the scores together also allowed for analysis at the MPA-level because many monitoring plans applied to multiple MPAs. In cases where monitoring plans were integrated with the management plan, only the management plan score was used.

Additionally, to better understand what aspects of climate change were being considered in the monitoring plans, we manually investigated the contents of 17 plans (from our total of 41) that scored 'Yes' to three CRI components pertaining to climate change planning: climate change objectives (question 2), strategies (question 3), and indicators (question 8); (Table 1). While the definitions and applications of these terms were highly variable by plan, our subset of plans were characterized by language indicating an intent to consider climate change as part of their overarching management or monitoring objectives. We read and manually searched these plans by using the built-in PDF viewer word-search function to search for "climate", and using the table of contents to jump to relevant sections of the text to determine the specific climate change effects under consideration within the management and monitoring framework. Finally, we manually extracted any management and monitoring objectives, monitoring indicators, and any targets and thresholds that were described from all of the monitoring plans. We did not conduct any quantitative analysis on this database, but we used the data to identify key examples where all components of adaptive management are being applied.

3 Results

Our study builds on what was previously learned from O'Regan et al. (2021) about the ways MPAs are considering climate change in their operations. Rather than comparing management and monitoring plans, we take this opportunity to expand our understanding of the management and monitoring provisions of MPAs in the context of climate change. We found few MPA monitoring plans compared to the number of available management plans, and observed striking variability in scope and content of the plans we evaluated. While a large number of monitoring-related resources were found, only 41 documents (covering 649 MPAs) met the criteria for further consideration in this analysis (Supplementary Table 1). These plans were collected from nine regions or countries (Antarctica, Australia, Belize, Canada, Saint Helena, St. Vincent and the Grenadines, Tanzania, UK, US). Three regional-level monitoring plans were found for MPAs in Australia and the UK only as a result of an additional manual search effort. Canada and the USA were the only countries for which more than two English-language monitoring plans could be found, greatly limiting the potential for regional comparisons of climate robustness.

TABLE 1 Climate robustness index components with examples of content in monitoring plans used to determine scores.

Climate Robustness Index Component	'Yes' example	'Planned/Some' example
1. a) Ecological climate change effects	Increase in air temperature will affect the sex ratio of sea turtles. *Port Honduras Marine Reserve, Belize*	NA
1. b) Physical climate change effects	Climate impacts that lead to sea ice loss may cause bottom-up impacts (change in productivity/energy flow) or top-down impacts (habitat loss, fragmentation). *Tarium Niryutait Marine Protected Area, Canada*	NA
1. c) Sociological climate change effects	Many islands have historic heritage sites and are of Indigenous heritage significance. They are threatened by sea-level rise, coastal erosion, severe weather (including cyclones and wildfires), marine debris and invasive species. *Great Barrier Reef, Australia*	NA
2. Objectives related to climate change	Better understand [...] the relative contributions of natural and anthropogenic influences (including climate change impacts) on estuarine ecosystems. *Oregon Marine Reserves, USA*	NA
3. Strategies related to climate change	A diverse suite of ocean observations can be synthesized to characterize historical conditions and spatial context to inform adaptive management strategies for the MPA Network that account for changing ocean conditions due to climate change. *California Marine Protected Areas, USA*	NA
4. Monitoring or adapting to climate change	The science goals described in the national [National Park Service Climate Change Response Strategy] include developing and applying climate science, collaborating with scientific agencies and institutions, and identifying and conducting scientific studies and resource monitoring activities. *North Atlantic Coastal Parks, USA*	Regime shifts due to large global processes such as the Pacific decadal oscillation (PDO), El Niño, and climate change may have unanticipated results on the MPA ecosystem. These large scale stressors or ecosystem drivers are not within the scope of management, but will need to be taken into consideration and may require indicators and monitoring. *Endeavour Hydrothermal Vents Marine Protected Area, Canada*
5. Baseline conditions	Current status of climate change impacts […]: Increased storms from 1999 onwards, with annual fluctuations. More storms during El Nina, fewer during El Nino. Stronger storms >Cat 4/5. *Port Honduras Marine Reserve, Belize*	[M]inimal baseline data exist for the lagoons [...] Determine seasonal and long-term trends in dissolved oxygen, salinity, conductivity, and pH on a semiannual basis in the coastal lagoons *National Park Service Arctic Network, USA*
6. Indicators of ecological, physical or social components	Number of transits through the MPA by vessels other than pleasure craft, such as mercantile vessels, surface naval vessels, and fishing vessels not fishing in the area. *Gully Marine Protected Area, Canada*	To support the identification of indicators, collection of baseline data to complete an Ecological Risk Assessment of the stressors identified for the [Endeavour Hydrothermal Vents] MPA and a comprehensive reporting system for existing and proposed activities is recommended. *Endeavour Hydrothermal Vents Marine Protected Area, Canada*
7. Metrics linked to ecological, physical or social indicators	Temperature, DO, pH, conductivity. *National Park Service South Florida/Caribbean Network, USA*	The key biodiversity components that require appropriate parameters, indicators, and monitoring include: Status and trends of habitats; Status and trends of native species (genetic, taxa, and populations); Specially protected species (genetic, taxa, and populations). *Papahänaumokuäkea Marine National Monument, USA*
8. Indicators linked to climate change	Geological, physical, chemical, and biological environmental and stressor ecosystem components- metrics are primary and secondary productivity, temperature, current, pH, oxygen (list primarily driven by climate change impacts). *Sgaan Kinghlas Bowie Seamount Marine Protected Area, Canada*	Collect baseline information on populations of giant kelp Macrocystis pyrifera, bull kelp Durvillaea antarctica and Desmarestia ligulata (brown seaweed) as potential future indicators of warming marine conditions). [This was the only climate change indicator listed in the plan.] *Gough and Inaccessible Islands, Saint Helena*
9. Monitoring methods	Each reserve deploys at least four Yellow Springs Instrument Co. (YSITM) Model 6600 and/or 6600 Extended Deployment System (EDS), and/or V2 water quality sondes ("datasondes") for continuous monitoring of water quality parameters. Data are collected for four seconds at fifteen minute intervals, where possible. *National Estuarine Research Reserve System, USA*	It is recommended that coral surveys to monitor Indicators 13-16 be conducted following the methodology of the 2007 coral study in the Gully […] Protocols for reporting and analysis of these observations would need to be developed. *Gully Marine Protected Area, Canada*
10. Targets for condition of indicators	Increase lingcod populations to greater than 25% of unfished spawning biomass by 2027 and increase rockfish populations to	Consistent with a precautionary approach, existing indicator data may be used to establish reference points. Reference levels for the population should be explored to provide a benchmark against

(Continued)

TABLE 1 Continued

Climate Robustness Index Component	'Yes' example	'Planned/Some' example
	greater than 25% of unfished spawning biomass by 2037. *San Juan County Marine Stewardship Area, USA*	which to determine population status. *Gilbert Bay Marine Protected Area, Canada*
11. Threshold for condition of indicators	Grey seal pup production during the preceding 6 year period has not declined by more than an average of 1% per year, and/or b) grey seal pup production has not decreased by more than 25% since the baseline year (1992 or start of time series, if later). *UK Marine Strategy*	Do observed values exceed a regulatory standard, a known or hypothesized ecological threshold, or a management-driven target? What is the level of confidence that the observed values exceeded the standard, target, or threshold? *National Park Service Southeast Coast Network, USA*
12. Monitoring or mitigation by external agencies	The Refuge System will also seek collaboration with established programs, such as the North American Amphibian Monitoring Program or the Terrestrial Wetland Global Change Research Network, which brings focus to amphibians, a taxonomic group that is highly vulnerable to climate change. *National Wildlife Refuges, USA*	NA

Of the 41 monitoring documents meeting our criteria, 22 were multi-MPA plans applying to a suite of MPAs within a broad jurisdiction, and 19 were single-site MPA monitoring plans. More than half (63%) of the MPAs in the MPA Plan Database were affiliated with a monitoring plan, and 13 out of 41 monitoring plans found were located within the management plan. Additionally, within our list of multi-MPA monitoring plans, we noted 23 additional MPAs not previously included in the 998 MPAs in the MPA Plan Database, which led us to expand the original list to 1021 MPAs.

3.1 Climate robustness index results

The mean CRI score for the 41 monitoring plans used in this study was 16.7 points out of a total possible score of 28 (60%), with a range of 6 to 27 (21 to 96%). The percentage of plans that fell within each score category for each CRI component are presented in Table 2. Here, we present our 'Yes' results by grouping CRI components based on whether they were included in over half, or less than half of the monitoring plans. CRI components included in over half of the monitoring plans were: monitoring indicators (80%), commitment to monitor or adapt to climate change (78%), any mention of external agencies involved in climate monitoring or mitigation (71%), indicators specifically linked to climate change (68%) discussion of physical climate effects (66%), management or monitoring strategies that explicitly mentioned climate change (66%), discussion of ecological climate change effects (63%), a discussion of baseline conditions or an intent to survey for them (56%), detailed survey/monitoring methods (56%), and metrics for indicators (51%). While not included in the CRI score, the majority of monitoring plans contained a data management plan (68%), and aligned with the adaptive management approach (81%). CRI components included in less than half of monitoring plans were: management or monitoring objectives that explicitly mention climate change or its effects (46%), discussion of sociological climate change effects (39%), targets for indicator condition (17%), and thresholds for indicator condition (7%). These results did not capture the plans that indicated 'Some' or 'Planned' with regard to the CRI components, which can be found in Table 2.

We also assessed the distribution of CRI scores to rank CRI components that have been achieved ('Yes') or are in progress ('Planned', 'Some'), in MPA monitoring plans (Figure 2A) and repeated our analysis with the CRI scores of management plans as evaluated by O'Regan et al. (2021), to compare the distribution of CRI scores between monitoring and management plans (Figure 2B). The three highest scoring components of the CRI (indicators, baseline conditions, and commitment to climate monitoring) were the same in monitoring and management plans. Most of the lowest scoring components were also the same between management and monitoring plans: thresholds, targets, discussion of sociological climate impacts, and climate change objectives.

3.2 MPA traits analysis

We visualized a series of MPA traits associated with US MPAs assessed in this study against their total (the sum of management and monitoring plan scores) CRI score. We did not observe patterns between CRI score and MPA conservation focus, level of protection, area (km^2), or IUCN category. MPA governance type, including full federal jurisdiction, full state jurisdiction, and MPAs designed and managed in partnership with multiple agencies across levels of government showed that for the US, the partnership category clustered around a higher mean score (66%) than other federally (59%) and state-governed (45%) MPAs (Figure 3).

In our subset of 17 monitoring plans that indicated a clear commitment to climate planning, we found that certain aspects of climate change were more widely represented than others in the objectives, strategies, and indicators. Physical aspects of climate change (including sea temperature, sea level, acidification, dissolved oxygen levels, extreme weather events, permafrost, sediments) were referenced in all plans in our subset. Fifteen out of 17 referenced ecosystem integrity (community structure, productivity, ecosystem function, ecosystem processes), species assemblage (diversity, distribution, abundance, occurrence). The majority of plans also discussed exotic/invasive species (12/17), recruitment and reproduction (11/17), and recreation (9/17). Less than half mentioned aspects of climate change pertaining to ecosystem services (4/17), governance/management (6/

TABLE 2 Percentage of 41 MPA monitoring plans that included each climate robustness index component.

Climate Robustness Index Component	Percentage of monitoring plans that scored 'Yes'	Percentage of monitoring plans that scored 'Planned/Some'	Percentage of monitoring plans that scored 'No'
a) Ecological climate effects b) Physical climate effects c) Sociological climate effects	a) Ecological: 63 b) Physical: 66 c) Sociological: 41	NA	a) Ecological: 37 b) Physical: 34 c) Sociological: 59
2. Objectives related to climate change	46	NA	53
3. Strategies related to climate change	66	NA	34
4. Commitment to monitoring or adapting to climate change	78	5	17
5. Baseline conditions	56	42	2
6. Indicators	80	20	0
7. Metrics	51	39	10
8. Indicators linked to climate change	68	7	24
9. Monitoring methods	56	10	34
10. Targets	17	32	51
11. Thresholds	7	34	59
12. Monitoring or mitigation by external agencies	71	NA	29
Data management plan	37	34	29
Commitment to adaptive management	71 (explicit commitment to adaptive management)	10 (integration of adaptive management principles)	19

The last two questions regarding data management and commitment to adaptive management were not included in the CRI score.

17), research (5/17), harvest (6/17), and education/community engagement (6/17). Aspects of climate change that were mentioned rarely in climate change planning were mitigation (i.e., carbon capture) (2/17), phenology (3/17), genetic diversity (2/17), disease and pathogens (3/17), MPA operational climate footprint (i.e., MPA infrastructure energy use, sustainable businesses) (3/17), and indigenous cultural heritage (2/17). On the whole, sociological aspects of climate change were less prominent than physical and ecological aspects in the strategies, objectives, and indicators, though certain biological aspects (e.g. phenology, genetic diversity) were also poorly represented.

3.3 Climate robustness index identifies advanced adaptive planning

We present two examples of MPA plans that achieved high CRI scores and were successful in incorporating full-cycle adaptive management into their planning: the UK Marine Strategy, and Glover's Reef Marine Reserve in Belize (Department of Food Environment and Rural Affairs [DEFRA], 2019; Wildtracks, 2019). These plans demonstrate the value of the adaptive approach in structuring marine management in the climate change context where there is uncertainty both regarding the scope of pressures, and the effects of management action. For each example, we extracted information relating to the key elements of climate robustness and presented these within the context of the adaptive management cycle (Figure 1).

3.3.1 United Kingdom marine strategy

Developed under the umbrella of the Marine Strategy Framework Directive (MSFD), the UK Marine Strategy (the Strategy) is part of a coordinated effort with European Union member states to achieve Good Environmental Status (GES) in their marine areas: "The environmental status of marine waters where these provide ecologically diverse and dynamic oceans and seas which are clean, healthy and productive" (MSFD, 2008/56/EC). The MSFD mandates each nation to develop measures to describe GES (i.e. set targets), monitor the conditions relative to GES, and take management actions to reach or maintain GES if a certain threshold is exceeded. Each nation interprets and defines GES within a list of 11 broad descriptors (i.e. goals) from the MSFD (e.g. "Descriptor 1: Biodiversity is maintained"; "Descriptor 7: Permanent alteration of hydrographical conditions does not adversely affect the ecosystem"). The Strategy covers the entirety of the UK's marine waters including but not limited to MPAs. Here we exemplify the component processes of the adaptive management cycle (Figure 1) by focusing on some of the elements of the Strategy that aim to address declining breeding success of black-legged kittiwakes (*Rissa tridactyla*), which are considered an indicator of the productivity of other breeding seabirds as well as an indicator of broader biodiversity and food web descriptors.

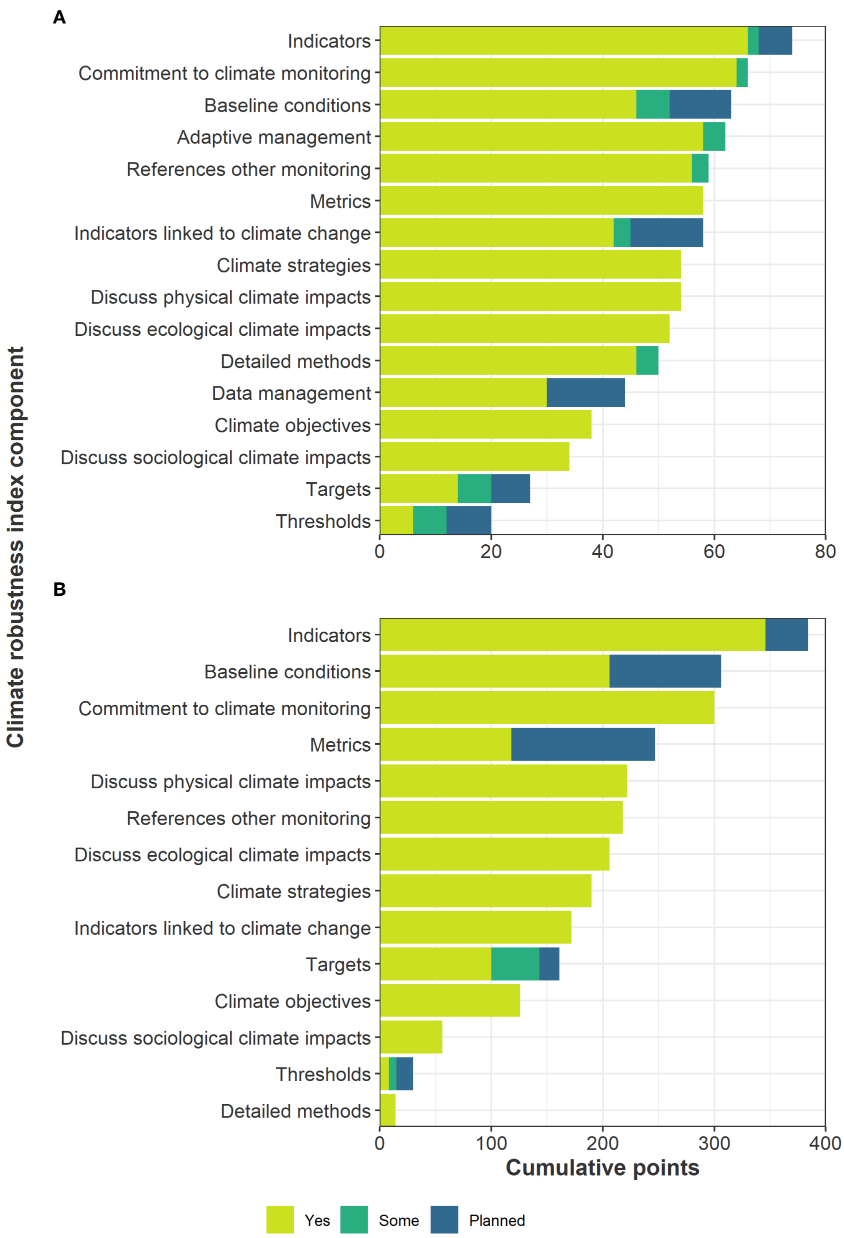

FIGURE 2
Distribution of cumulative climate robustness index scores by index question for **(A)** MPA monitoring plans (n = 41), and **(B)** MPA management plans (n = 223). Panel **(A)** includes two additional questions posed in the current study: whether the plan included a data management plan, and whether the plan explicitly adhered to adaptive management, but these did not contribute to plan scores. The x-axes differ based on the number of plans included in each assessment.

The Strategy outlines the vulnerabilities of kittiwake populations both to climate change and fishery pressures. Pressures on kittiwake breeding include reduced availability of key prey due to climate-induced changes in forage fish distribution, and competing fishery impacts (bans on the sandeel (*Ammodytes marinus)* fishery have been correlated with improved breeding success of kittiwakes and other species (Daunt et al., 2008)). The guiding GES objective states that the abundance and demography of marine bird species should indicate healthy populations that are not significantly affected by human activities. The target states that "annual breeding success of kittiwakes should not be significantly different, statistically, from levels expected under prevailing climatic conditions," independent of fishing pressure, in at least five years out of six (DEFRA, 2019). To assess the performance of management measures in meeting this target, the British Trust for Ornithology Seabird Monitoring Programme surveys kittiwake colonies to measure breeding success, and models breeding rates expected in the absence of fishing pressure, based on sea surface temperature. Quantitative threshold values are defined to assess the status of seabirds relative to the target. 'Lack of breeding success', for example, is defined as <0.1 chicks per pair at a seabird colony in a year, and 'widespread breeding failure' is

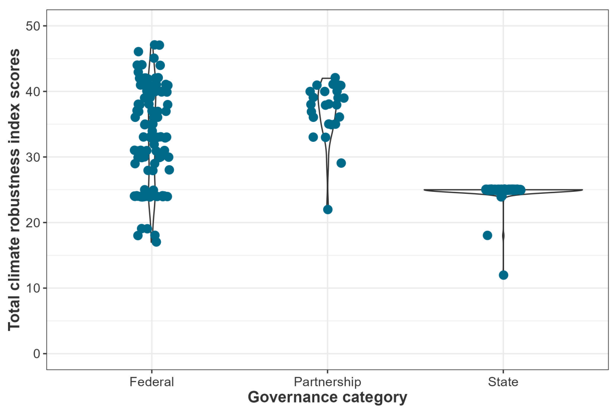

FIGURE 3
Violin plot of total climate robustness index scores (sum of management and monitoring plans) plotted against level of governance for 282 MPAs in the United States.

considered to occur 'frequently' if it occurred in more than three years out of six. In the current (2018-2024) management cycle, GES has not been achieved for breeding seabirds. The suggested next steps include further research to determine impacts of human pressures on marine birds, completion of the UK MPA network, and further protection measures for the kittiwake and other marine birds. This example takes a broad goal (achieve 'good' environmental status) and translates it into research directives and suggested policy measures that reflect an effort to align the indicators observed through the monitoring program with the established target. Built into this process is the capacity to adapt the management responses as information accumulates.

The UK Marine Strategy achieved a CRI score of 26, or 90%. It contained all climate robustness components except for specific climate change related objectives (question 8).

3.3.2 Glover's Reef Marine Reserve, Belize

Glover's Reef Marine Reserve (GRMR) is located within an important fishing area for lobster, conch, and finfish, and is an attractive destination in a nation that received over 500,000 overnight tourists in 2019 (Statistical Institute of Belize, 2023). GRMR operates via four central objectives that guide ecological and social outcomes for the MPA: protecting physical and biological resources, enabling economic opportunities for local communities and society, using education and research to further awareness and understanding of GRMR's natural resources, and providing resources for recreation and tourism. The monitoring plan is integrated with the 2019-2023 site-specific management plan.

Social objectives are at the forefront of this zoned multiple-use MPA, and it is managed through a partnership Belize's Fisheries Department and the Wildlife Conservation Society (a research-based conservation NGO), with input "of equal importance" from fishing and tourism stakeholders "whose lives are linked to the health of the marine resources at Glover's Reef Atoll" (Wildtracks, 2019). Critically, this plan discusses the linkages between the ecological, physical, and sociological impacts of climate change, and strives to address them in tandem. Here we trace a specific application of the adaptive management cycle to improving conch fishing practices, as it was demonstrated in the GRMR management plan.

The Queen conch *(Lobatus (Strombus) gigas)* is an important export species in Belize. Rising sea surface temperatures are expected to affect conch reproduction and depth range, and these expected climate impacts on conch stocks will be compounded by poor fishing practices. To address the limited enforcement and engagement of fishers, GRMR participates in Belize's Managed Access program, which preserves "the rights of fishers in their traditional fishing areas whilst stopping the unsustainable growth in the number of fishers […] through developing, encouraging and incentivizing good stewardship, towards better catches and improved incomes" (Wildtracks, 2019). To increase conch stocks – and support the livelihoods of the fishers who depend upon this species, one of the GRMR management strategies is to strengthen the Managed Access program. Their target for 2020 was for 75% of fishermen to consider themselves stewards of GRMR and integrated into the decision-making processes.

The GRMR management plan includes a detailed stakeholder analysis, describing the influence and impacts of the reserve on stakeholders, and vice-versa. This information guides a planning and implementation approach that considers the MPA ecosystem and its users as an integrated whole. Monitoring indicators for conch management include conch population density as well as fisher attitudes, and Managed Access logbooks contribute to the monitoring/data collection effort. Performance is measured through a generic Viability Assessment tool developed by nonprofit nature conservation organizations, which ranks the condition of focal ecosystem components based on qualitative thresholds. In the current (2019-2023) management cycle, conch condition was deemed 'Fair': catches have declined from historic levels, but stocks are showing some signs of improvement at GRMR. Stocks are still considered to be outside of the acceptable range of variation (which was not defined in the management plan), and intervention is needed to maintain stock viability. Results of research and monitoring are presented to stakeholders and the public, who engage with the development of further management measures.

GRMR returned the highest CRI score of 27, or 96%. It met all climate robustness criteria but had only partial thresholds (question 11).

4 Discussion

The CRI was developed to identify opportunities and examples from around the world where MPA management and monitoring are at the forefront of integrating the twin crises of biodiversity loss and climate change. While not always explicitly linked to climate pressures, most of the MPA monitoring plans we evaluated in this study stated an intent to take an adaptive management approach. This approach positions them to respond to the urgency and uncertainty of climate change effects given its responsiveness to new information and changing conditions (Ban et al., 2011; IUCN, 2016; Rilov et al., 2019; O'Regan et al., 2021; Lopazanski et al., 2023). The adaptive management process requires that pressures be accounted for in an interactive cycle (Figure 1). As climate change adaptation is nested within the adaptive management process, this CRI analysis highlights two opportunities to improve climate adaptation and resilience planning in MPA monitoring (and management) plans specifically for climate change where CRI scores were low in both plan types (Figure 2; Table 2). First, by setting operational targets and thresholds for use as decision criteria and performance measures as per the adaptive management cycle (i.e. supporting practitioners to respond transparently when thresholds are met regardless of pressure). Second, by expanding social-ecological considerations of MPAs by explicitly recognizing the sociological vulnerabilities, assets, and objectives in MPA climate planning, as well as by leveraging the adaptive capacity of local partnership opportunities.

4.1 Bridging the adaptation link: targets and thresholds

The CRI results for monitoring plans were similar to that of the management plans evaluated in O'Regan et al. (2021), despite our expectation to find greater emphasis on measurable components in the monitoring plans (i.e., indicators, targets, thresholds; O'Regan et al., 2021; Figures 2A, B). While indicators were the highest scoring component of MPA monitoring and management plans alike (80% and 77% respectively scored 'Yes' on question 6), targets were defined in 17% and 42% percent of monitoring and management plans, and thresholds in 7% and 5%.

Targets should unambiguously define the desired condition or state of indicators. Management thresholds (or triggers) define the limits of the desired condition, beyond which management action would be required in order to mitigate potentially irreversible shifts to undesirable states or outcomes (Scholes and Kruger, 2011; IPCC, 2019; 2021). These components of adaptive management serve as decision criteria and as performance measures. The absence of these elements in MPA planning has implications not only for climate change robustness, but on the ability to fully engage in adaptive management, to which the majority (81%) of MPA plans evaluated here subscribe (Table 2).

Common MPA management objectives - such as, 'maintain biodiversity, ecological integrity and resilience' - are not specific or measurable (Game et al., 2013; Magris et al., 2014; Domínguez-Tejo and Metternicht, 2018). This heightens the importance of assigning targets and thresholds (Gregory et al., 2012). Targets and thresholds can distill objectives to comparable numbers (e.g. desired and minimum population size) or probabilities (e.g. probability of extinction in 50 years) to facilitate decision-making (Gregory et al., 2012; e.g. Hamilton et al., 2021). Both qualitative and quantitative data can be interpreted in this way through careful selection of indicators (Tam et al., 2024). In other resource management fields, ecological targets are defined as an optimal or desired level of an indicator. For example, some quantity (the target) of intact old-growth forest habitat (the indicator) needed to maintain biodiversity (the objective). In this case, the threshold defines the minimum condition or marked change in the forest habitat that triggers management action to support forest biodiversity. The adaptive management approach provides an impetus for clarifying management aims and for conducting long-term monitoring in MPAs to determine whether management measures are appropriate for evolving conditions (e.g. Hayes et al., 2021; ONMS, 2021). As core components of adaptive management, targets and thresholds are essential tools for translating monitoring observations into management actions, particularly when rapid transformation (resulting from manageable or unmanageable stressors) affects some of the MPA's objectives (e.g. Zentner et al., 2023). We focus this discussion on thresholds as the least represented, and potentially more challenging of the two adaptive management components.

The identification of thresholds that provide clear delineations of acceptable (and unacceptable) conditions were an exception rather than a norm in the monitoring plans we examined. This is consistent with another recent analysis of thresholds defined by protected areas on the IUCN Green List, which found that approximately half were insufficiently specific to be operational (Hilton and Cook, 2022).

Here we give examples of biophysical and sociological thresholds as used by MPA managers in two different jurisdictions. One of the ecologically-oriented conservation objectives of a federally managed Eastern-Canadian MPA, Basin Head, is: "Maintain health (biomass and coverage) of Basin Head *Chondrus crispus*" (Department of Fisheries and Oceans [DFO], 2016). While this objective provides guidance for the kind of indicators to monitor to track the MPA's performance in meeting this objective, it is unclear in the document what quantity of biomass and coverage are considered acceptable to achieve the objective. To this end, the threshold (defined in the text as a "trigger") reads: "Take management action if there are declining trends in Chondrus biomass and bed size from baseline data" (DFO, 2016, p. 35). To be operational and fully transparent, this threshold could identify a specific value that defines the lower limit of acceptable Chundrus biomass and bed size. Another primary objective of Basin Head MPA is: "Maintain the quality of the marine environment supporting the Basin Head *Chondrus crispus*" (DFO, 2016, p. 33). The bio-physical thresholds linked to this objective are: "Water quality indicators show[ing] persistent increases in either nitrogen or phosphorus (i.e., over three consecutive summers) and persistent hypoxic or anoxic conditions and expansion toward the Chondrus bed. Dissolved oxygen levels below 3 mg/L is considered hypoxic and is stressful to most aquatic organisms" (DFO, 2016, p. 33). These thresholds present a clear launch point for action, though possible management interventions were not discussed in the plan.

Qualitative data pertaining to human dimensions of MPAs are no less valuable in benchmarking objectives. In several of Belize's MPAs, an integrated approach to management has been implemented with a strong focus on engaging traditional fishermen in managing fishing pressures within the MPAs (Wildtracks, 2018, 2019; McDonald et al., 2017). As a result, there are a number of distinctive mechanisms and indicators included in the management planning process. One exemplary indicator in the Community Outreach and Development theme is to track the 'percent of fishers who consider the Managed Access Committee is functioning well' (Wildtracks, 2019). As part of the Community Engagement Strategy, the condition of this indicator is determined by surveying participant satisfaction and reported as a numeric value (Wildtracks, 2018). The associated performance measure for this indicator is: "by 2022, at least 20% of SWCMR fisher households in the communities have benefited from income diversification strategies, and have demonstrated reduced impacts on the marine protected area over the 2018 baseline" (Wildtracks, 2018; 2019). This clearly delineates the lower limit of the desired condition of this sociological indicator, and relates it to positive ecological outcomes.

There is a growing basis of literature to guide the development of sound thresholds and performance measures for environmental management (Samhouri et al., 2010; Gregory et al., 2012; Hilton and Cook, 2022), as well as momentum toward integrating social-ecological parameters through values-based decisions and human dimensions indicators (Salomon et al., 2018; Hamilton et al., 2021; Atmore et al., 2021; Tam et al., 2024). Novel frameworks have been structured specifically to consider uncertainty and risks posed by climate change to physical, ecological, and sociological MPA values. New tools, approaches and frameworks remain challenged by the necessity to make decisions across a variety of global and local objectives (ecological, economic, cultural) and still require clear decision criteria to be operational.

4.2 Partnerships and social-ecological objectives

The CRI takes into account social vulnerabilities to climate change with the understanding that many MPAs include social objectives, be they explicit (e.g. with an objective of protecting cultural heritage sites), or implicit (e.g. by sanctioning certain human activities within their boundaries). Our results suggest that sociological climate change impacts are the least likely to be considered in the discussion of climate vulnerability in both management and monitoring plans of MPAs, ranking far behind discussions of physical and ecological climate impacts (Table 2; Figures 2A, B). This suggests that the sociological elements of MPAs are often not fully articulated, even though protected areas are socially constructed tools that aim to conserve nature for the benefit of human communities, be they tangible ecosystem services (Leenhardt et al., 2015; Ban et al., 2019), or less tangible effects such as spiritual or emotional fulfillment (Wilson, 1984; Chang et al., 2020). MPA monitoring plans generally focused on physical (e.g. temperature, sea level, acidification) and ecological (e.g. community structure, species assemblage) aspects of climate change in their objectives, strategies, indicators, and discussions of climate impacts. The linkages between climate change and its sociological implications and responses were not as well established in the monitoring and management planning (Figures 2A, B). This observation in our analysis reflects an underlying worldview in Western conservation and environmental management that is primarily informed by natural scientific insights rather than approaches that integrate human dimensions and nature (Salomon et al., 2018; Whitney and Ban, 2019; Tam et al., 2024; Löfqvist et al., 2023). Two themes with regard to the human dimensions of MPA management and monitoring emerged through our analysis: 1) integration of social-ecological MPA objectives to support improved climate robustness and social outcomes, and 2) the role of partnerships in supporting climate-adaptive MPA management and monitoring.

Carefully conceived and managed protected areas can be a means to many ends, particularly when the ecosystem under protection is viewed as a social-ecological system (Pollnac et al., 2010; Chazdon and Brancalion, 2019; Löfqvist et al., 2023). Enshrining these ends in the management and monitoring plans as objectives with associated monitoring indicators could clarify the potential benefits of well-managed protection, increase buy-in and expand adaptation options. When social parameters are not fully or explicitly stated in management and monitoring planning, the ability to measure, mitigate and monitor the impacts of human activity in MPAs can be limited - as is the ability to measure the value of the MPA to humans. Local human impacts (e.g. wear and tear from poor diving practices) and climate change impacts (e.g. deoxygenation) are often compounding (Zentner et al., 2023). These impacts threaten social objectives (e.g. tourism appeal compromised by degraded dive sites) and ecological objectives (e.g. loss of biogenic habitat and key species) alike. Paying attention to the intersections of social and ecological objectives and vulnerabilities presents opportunities to consider challenges through multiple lenses to improve MPA robustness and persistence. Expanding the list of explicitly defined objectives to reflect an appropriate range of social and ecological goals may 'maximize' the perceived or realized purpose of conservation sites. Additionally, in an era of ecological transformation, diversification of an MPA's objectives may be an approach to maintain its relevance in the event that strictly ecological objectives are under threat. For example, if an MPA's only stated objective is to protect a breeding seabird population and climate-driven changes in food web dynamics forces a range shift of the seabirds beyond the MPA's boundaries, the MPA may be subject to forces misaligned with longer term biodiversity conservation (Mascia and Pailler, 2011; Albrecht et al., 2021). It must be acknowledged, however, that factoring objectives from various dimensions of the social-ecological system into conservation planning requires very different kinds of information for monitoring and assessment and a corresponding breadth of staff capacity (Gill et al., 2017).

Adaptive management and its component processes support the development of management actions that are grounded in global goals and local culture (Ban et al., 2011). We examined the role of partnerships in MPA monitoring plans through a specific question in the CRI to gauge involvement of external organizations in climate change monitoring or mitigation efforts (question 12), and through an examination of MPA traits (limited to US MPAs due to sample size). The vast majority of monitoring plans referenced involvement of external groups, and MPAs designed and managed as partnerships clustered around a higher mean CRI score than MPAs managed at a single level of government. A partnership approach to conservation management – management coordinated across multiple agencies at various levels of governance – can leverage existing adaptive management and monitoring capacity of local stakeholders (Cinner et al., 2006; Ban et al., 2011; NERRS, 2011; Pringle, 2017; CDFW and COPC, 2018). Blending local opportunities with high-level planning has potential to strengthen and democratize conservation measures both in developing and developed nations – particularly where local social contexts exert a large influence on ecosystem use and ownership (Johannes, 2002; Cinner et al., 2006; Ban et al., 2011; Salomon et al., 2018; Hamilton et al., 2021). For example, in the Glovers Reef Marine Reserve management plan, we observe that social-economic interests of local stakeholders are regarded in tandem with national-level fisheries and conservation planning. This reveals linkages between local (e.g. unsustainable fishing practices) and global (e.g. climate change) ecosystem pressures, and strategies to improve social and ecological conditions are designed to achieve mutual benefits (see Section 3.3). This MPA takes the strategy of cultivating a stewardship role amongst fishers through educational infrastructure, coordinated policy, and financial incentives. Reframing the role of humans in and around protected areas in this way presents an opportunity for 'biocultural restoration': strengthening the social-ecological dynamic for improved mutual outcomes (Janzen, 1988).

The value in integrating local stakeholders in designating and managing effective MPAs is widely accepted for functional and moral reasons (Johannes, 2002; Pressey and Bottrill, 2009; Ban et al., 2011; Löfqvist et al., 2023). Inviting, fostering or restoring a stewardship ethic among communities within or adjacent to protected areas can in effect create live-in managers who can directly benefit from the services provided by a functional ecosystem (Janzen, 1988; Pringle, 2017). Furthermore, many long-standing systems of community-based resource stewardship are adaptive by design and highly socially integrated. Strategies such as periodic closures of harvest zones, cultural taboos on harvest, and gear restrictions have been implemented at the community level long prior to the academic uptake of adaptive management (Johannes, 1978; Fa'asili and Kelokolo, 1999; Cinner et al., 2006). The success of this type of flexible management in meeting both ecological and social outcomes has been particularly well documented in small tropical island nations with subsistence fisheries (Johannes, 1978; Cinner et al., 2006; Pollnac et al., 2010; Ban et al., 2011). These systems rely more on the influence of local cultural authorities than on externally imposed static boundaries for both compliance, and for defining targets and thresholds. Combining the accountability and responsiveness of community-based management with high-level data management and regional coordination may lead to more climate-robust adaptive management as areas under spatial protection expand.

4.3 Study limitations

Our study was limited by its focus on English-language plans, leading to the analysis of monitoring plans primarily from temperate regions. Additionally, the presence of a high-quality monitoring plan does not prove that high-quality monitoring is occurring, as we did not confirm execution of the plan in our study. Conversely, we note that a large body of ongoing monitoring is not captured by official monitoring plans. Monitoring efforts of external groups such as NGOs, citizen science initiatives, private industry, and local land stewards were not included in this study unless explicitly included in the MPA monitoring plan. Thus, our study does not represent the entirety of monitoring efforts within MPAs. Last, several designations of MPAs alluded to ongoing monitoring programs for which monitoring plans could not be located. We did not conduct direct outreach to MPA managers to inquire after the availability of monitoring plans, which may have yielded more plans for analysis.

5 Conclusion

Acknowledgement of climate change effects, and a commitment to an adaptive management approach within MPA planning documents establishes the premise that the ecosystem under protection is on a trajectory of transformation (Schuurman et al., 2022). Although progress on addressing the climate threat by MPAs is being demonstrated by comprehensive analyses of key management components (Lopazanski et al., 2023), the CRI identified two core areas for improvement in climate-robust adaptive management: targets and thresholds in support of adaptive decision-making, and uptake of sociological aspects of climate change planning. We support clearly defined performance measures within an adaptive framework that demonstrate a strong cyclical relationship between pressures, objectives, strategies, targets, thresholds, and assessments of MPA performance. MPA climate robustness may also be facilitated through partnership governance arrangements, but more investigations are needed to determine relevant structures, frameworks and tools. We acknowledge that MPAs are always, to varying degrees, embedded within a social-ecological system, and echo calls to explicitly link climate change projections and vulnerabilities with social-cological objectives and performance measures (Ban et al., 2011; Magris et al., 2014; Atmore et al., 2021; O'Regan et al., 2021; Bryndum-Buchholz et al., 2022). Further, objectives, targets and thresholds set today may need to adjust to emerging impacts to remain relevant and operational. As coastal nations move to meet the CBD's 30% spatial target, we see the climate adaptive management approach as a means for MPAs to take a proactive, transparent, climate-robust, locally engaged, and scientific approach to marine conservation management.

Data availability statement

The datasets presented in this study can be found in the online repository listed below: https://drive.google.com/drive/folders/1d5QdZnlhtguhlCKLQA1rv_i7-O0-ZUgI?usp=sharing.

Author contributions

KB: Data curation, Formal analysis, Methodology, Visualization, Writing – original draft, Writing – review & editing. KH: Conceptualization, Funding acquisition, Investigation, Methodology, Project administration, Resources, Supervision, Visualization, Writing – original draft, Writing – review & editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fmars.2024.1339871/full#supplementary-material

References

Albrecht, R., Cook, C. N., Andrews, O., Roberts, K. E., Taylor, M. F. J., Mascia, M. B., et al. (2021). Protected area downgrading, downsizing, and degazettement (PADDD) in marine protected areas. *Mar. Policy* 129, 104437. doi: 10.1016/j.marpol.2021.104437

Atmore, L. M., Aiken, M., and Furni, F. (2021). Shifting baselines to thresholds: reframing exploitation in the marine environment. *Front. Mar. Sci.* 8. doi: 10.3389/fmars.2021.742188

Ban, N. C., Adams, V. M., Almany, G. R., Ban, S., Cinner, J. E., McCook, L. J., et al. (2011). Designing, implementing and managing marine protected areas: emerging trends and opportunities for coral reef nations. *J. Exp. Mar. Biol. Ecol.* 408, 21–31. doi: 10.1016/j.jembe.2011.07.023

Ban, N. C., Gurney, G. G., Marshall, N. A., Whitney, C. K., Mills, M., Gelcich, S., et al. (2019). Well-being outcomes of marine protected areas. *Nat. Sustain.* 2, 524–532. doi: 10.1038/s41893-019-0306-2

Brown, C. J., Jupiter, S. D., Albert, S., Anthony, K. R. N., Hamilton, R. J., Fredston-Hermann, A., et al. (2019). A guide to modelling priorities for managing land-based impacts on coastal ecosystems. *J. Appl. Ecol.* 56 (5), 1106–1116. doi: 10.1111/1365-2664.13331

Bryndum-Buchholz, A., Boerder, K., Stanley, R. R. E., Hurley, I., Boyce, D. G., Dunmall, K. M., et al. (2022). A climate-resilient marine conservation network for Canada. *Facets* 7, 571–590. doi: 10.1139/facets-2021-0122

CBD (2022a) Decision adopted by the conference of the parties to the convention on biological diversity 15/4. Kunming-montreal global biodiversity framework. Available online at: https://www.cbd.int/doc/decisions/cop-15/cop-15-dec-04-en.pdf.

CBD (2022b). *Decision adopted by the conference of the parties to the convention on biological diversity 15/5. Monitoring Framework for the Kunming-Montreal Global Biodiversity Framework*.

CDFW and COPC. (2018). *Marine Protected Area Monitoring Action Plan*. California, USA. Available at: https://wildlife.ca.gov/Conservation/Marine/MPAs/Management/monitoring/action-plan.

Chang, C. C., Cheng, G. J. Y., Nghiem, T. P. L., Song, X. P., Oh, R. R. Y., Richards, D. R., et al. (2020). Social media, nature, and life satisfaction: global evidence of the biophilia hypothesis. *Sci. Rep.* 10, 1–8. doi: 10.1038/s41598-020-60902-w

Chazdon, R., and Brancalion, P. (2019). Restoring forests as a means to many ends. *Science* 364, 24–25. doi: 10.1126/science.aax9539

Cinner, J., Marnane, M. J., and McClanahan, T. R. (2006). Periodic closures as adaptive coral reef management in the Indo-Pacific. *Ecol. Soc* 11, 1. doi: 10.5751/ES-01618-110131

Daunt, F., Wanless, S., Greenstreet, S. P. R., Jensen, H., Hamer, K. C., and Harris, M. P. (2008). The impact of the sandeel fishery closure on seabird food consumption, distribution, and productivity in the northwestern North Sea. *Can. J. Fish. Aquat. Sci.* 65, 362–381. doi: 10.1139/f07-164

Day, J., Dudley, N., Hockings, M., Glen, H., Laffoley, D., Stolton, S., et al. (2019). *Guidelines for applying the IUCN protected area management categories to marine protected areas* (Gland, Switzerland: IUCN).

Department for Environment Food and Rural Affairs [DEFRA] (2019). *Marine strategy part one: UK updated assessment and good environmental status* (London, UK: DEFRA). Available at: https://www.gov.uk/government/publications/marine-strategy-part-one-uk-updated-assessment-and-good-environmental-status.

Department of Fisheries and Oceans [DFO] (2016). *Basin Head Marine Protected Area: 2014 Operational Management Plan. Basin Head Management Series* (Ottawa, ON: Department of Fisheries and Oceans Canada).

Domínguez-Tejo, E., and Metternicht, G. (2018). Poorly-designed goals and objectives in resource management plans: assessing their impact for an ecosystem-based approach to marine spatial planning. *Mar. Pol.* 88, 122–131, doi: 10.1016/j.marpol.2017.11.013

Dunham, A., Dunham, J. S., Rubidge, E., Iacarella, J. C., and Metaxas, A. (2020). Contextualizing ecological performance: rethinking monitoring in marine protected areas. *Aquat. Conserv. Mar. Freshw. Ecosyst.* 30, 2004–2011. doi: 10.1002/aqc.3381

Dunham, A., Iacarella, J. C., Hunter, K. L., Davies, S. C., Dudas, S., Gale, K. S. P., et al. (In press). Conserving ecosystem integrity: ecological theory as a guide for marine protected area monitoring. *Ecol. Appl.*

Fa'asili, U., and Kelokolo, I. (1999). The use of village bylaws in marine conservation and fisheries management. *SPC Traditional Mar. Resource Manage. Knowledge Inf. Bull.* 11, 7–10.

Frölicher, T. L., and Laufkötter, C. (2018). Emerging risks from marine heat waves. *Nat. Commun.* 9, 1–4. doi: 10.1038/s41467-018-03163-6

Game, E. T., Kareiva, P., and Possingham, H. P. (2013). Six common mistakes in conservation priority setting. *Cons. Biol.* 27, 480–485. doi: 10.1111/cobi.12051

Geyer, J., Kreft, S., Jeltsch, F., and Ibisch, P. L. (2017). Assessing climate change-robustness of protected area management plans—The case of Germany. *PloS One* 12, e0185972. doi: 10.1371/journal.pone.0185972

Gill, D. A., Mascia, M. B., Ahmadia, G. N., Glew, L., Lester, S. E., Barnes, M., et al. (2017). Capacity shortfalls hinder the performance of marine protected areas globally. *Nature* 543, 665–669. doi: 10.1038/nature21708

Gregory, R., Failing, L., Harstone, M., Long, G., McDaniels, T., and Ohlson, D. (2012). *Structured decision making: a practical guide to environmental management choices* (Hoboken, NJ: Wiley-Blackwell). doi: 10.1002/9781444398557

Hamilton, T. M., Canessa, S., Clark, K., Gleeson, P., Mackenzie, F., Makan, T., et al. (2021). Applying a values-based decision process to facilitate comanagement of threatened species in Aotearoa New Zealand. *Cons. Biol.* 35, 1162–1173. doi: 10.1111/cobi.13651

Hayes, K. R., Dunstan, P., Woolley, S., Barrett, N., Howe, S. A., Samson, C. R., et al. (2021). Designing a Targeted Monitoring Program to Support Evidence Based Management of Australian Marine Parks: A Pilot on the South-East Marine Parks Network. *Report to Parks Australia and the National Environmental Science Program, Marine Biodiversity Hub* (Hobart, Australia: Parks Australia, University of Tasmanian and CSIRO).

Hilton, M., and Cook, C. N. (2022). Defining performance thresholds for effective management of biodiversity within protected areas. *Cons. Biol.* 36, 6. doi: 10.1111/cobi.13963

Intergovernmental Panel on Climate Change [IPCC] (2019). *IPCC Special Report on the Ocean and Cryosphere in a Changing Climate*. Eds. H. O. Portner, D. C. Roberts, V. Masson-Delmotte, P. Zhai, M. Tignor, E. Poloczanska, E. Mintenbeck, A. Alegría, M. Nicolai, A. Okem, J. Petzold, B. Rama and N. M. Weyer (Cambridge, UK and New York, NY, USA: Cambridge University Press).

International Union for the Conservation of Nature [IUCN] (2016). *Marine Protected Areas and Climate Change: Adaptation and Mitigation Synergies, Opportunities and Challenges*. Eds. F. Simard, D. Laffoley and J. M. Baxter (Gland, Switzerland: IUCN).

International Union for the Conservation of Nature [IUCN] and World Commission on Protected Areas (WCPA) (2017) *IUCN Green List of Protected and Conserved Areas: Standard, Version 1.1. 1st ed.* Gland, Switzerland: IUCN).

IPCC. (2021). "Summary for policymakers," in *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. Eds. V. Masson-Delmotte, P. Zhai, A. Pirani, S. L. Connors, C. Péan, S. Berger, et al In Press.

Janzen, D. H. (1988). *Tropical Ecological and Biocultural Restoration* (243–44: Science. 239:4837). doi: 10.1126/SCIENCE.239.4837.243

Johannes, R. E. (1978). Traditional marine conservation methods in Oceania and their demise. *Annu. Rev. Ecol. Syst.* 9, 349–364. doi: 10.1146/annurev.es.09.110178.002025

Johannes, R. E. (2002). The renaissance of community-based marine resource Management in Oceania. *Annu Rev. Ecol. Syst.* 33, 317–340. doi: 10.1146/annurev.ecolsys.33.010802.150524

Lawler, J. J. (2009). Climate change adaptation strategies for resource management and conservation planning. *Ann. N.Y. Acad. Sci.* 1162, 79–98. doi: 10.1111/j.1749-6632.2009.04147.x

Leenhardt, P., Low, N., Pascal, N., Micheli, F., and Claudet, J. (2015). "The role of marine protected areas in providing ecosystem services," in *Aquatic Functional Biodiversity: An Ecological and Evolutionary Perspective*. Eds. A. Belgrano, G. Woodward and U. Jacob (Cambridge, MA: Academic Press), 211–239.

Löfqvist, S., Kleinschroth, F., Bey, A., de Bremond, A., DeFries, R., Dong, J., et al. (2023). How social considerations improve the equity and effectiveness of ecosystem restoration. *BioScience* 73, 134–148. doi: 10.1093/biosci/biac099

Lopazanski, C., Foshay, B., Couture, J. L., Wagner, D., Hannah, L., Pidgeon, E., et al. (2023). Principles for climate resilience are prevalent in marine protected area management plans. *Cons. Lett.* 16, e12972. doi: 10.1111/conl.12972

Lotze, H. K., Coll, M., and Dunne, J. A. (2011). Historical changes in marine resources, food-web structure and ecosystem functioning in the Adriatic Sea, Mediterranean. *Ecosystems* 14, 198–222. doi: 10.1007/s10021-010-9404-8

Magris, R. A., Pressey, R. L., Weeks, R., and Ban, N. C. (2014). Integrating connectivity and climate change into marine conservation planning. *Biol. Cons.* 170, 207–221. doi: 10.1016/j.biocon.2013.12.032

Marzin, C., Benzaken, D., Otero, M. D. M., Quemmerais, F., Bates, A., Brown, M., et al. (2016). "Marine protected areas and adaptation to climate change: how can MPAs increase climate resilience?," in *Marine Protected Areas and Climate Change: Adaptation and Mitigation Synergies, Opportunities and Challenges*. Eds. F. Simard, D. Laffoley and J. M. Baxter (IUCN, Gland, Switzerland), 29–39.

Mascia, M. B., and Pailler, S. (2011). Protected area downgrading, downsizing, and degazettement (PADDD) and its conservation implications. *Cons. Lett.* 4, 9–20. doi: 10.1111/j.1755-263X.2010.00147.x

McCook, L. J., Ayling, T., Cappo, M., Choat, J. H., Evans, R. D., de Freitas, D. M., et al. (2010). Adaptive management of the Great Barrier Reef: A globally significant demonstration of the benefits of networks of marine reserves. *Proc. Natl. Acad. Sci. U.S.A.* 107, 18278–18285. doi: 10.1073/pnas.0909335107

McDonald, G., Harford, B., Arrivillaga, A., Babcock, E. A., Carcamo, R., Foley, J., et al. (2017). An indicator-based adaptive management framework and its development for data-limited fisheries in Belize. *Mar. Pol.* 76, 28–37. doi: 10.1016/j.marpol.2016.11.027

National Estuarine Research Reserve System [NERRS] (2011). *National Estuarine Research Reserve System: System-Wide Monitoring Program Plan* (Maryland: Silver Spring).

NOAA. (2020). *Definitions and Classification System for U.S* (Marine Protected Areas). https://nmsmarineprotectedareas.blob.core.windows.net/marineprotectedareas-prod/media/docs/20200715-mpa-classification.pd

National Ocean Service (2023) *The MPA Inventory*. Available online at: https://marineprotectedareas.noaa.gov/dataanalysis/mpainventory/.

Office of National Marine Sanctuaries [ONMS] (2021) *Climate Change Impacts: Monitor National Marine Sanctuary*. Available online at: https://nmssanctuaries.blob.core.windows.net/sanctuaries-prod/media/docs/202104-mnms-climate-impacts-profile.pdf.

O'Regan, S. M., Archer, S. K., Friesen, S. K., and Hunter, K. L. (2021). A global assessment of climate change adaptation in marine protected area management plans. *Front. Mar. Sci.* 8. doi: 10.3389/fmars.2021.711085

Pecl, G. T., Araújo, M. B., Bell, J. D., Blanchard, J., Bonebrake, T. C., Chen, I.-C., et al. (2017). Biodiversity redistribution under climate change: impacts on ecosystems and human well-being. *Science* 355, eaai9214. doi: 10.1126/science.aai9214

Peterson St-Laurent, G., Oakes, L. E., Cross, M., and Hagerman, S. (2021). R–R–T (resistance–resilience–transformation) typology reveals differential conservation approaches across ecosystems and time. *Commun. Biol.* 4 (1), 39. doi: 10.1038/S42003-020-01556-2

Pollnac, R., Christie, P., Cinner, J. E., Dalton, T., Daw, T. M., Forrester, G. E., et al. (2010). Marine reserves as linked social-ecological systems. *Proc. Natl. Acad. Sci. U.S.A.* 107, 18262–18265. doi: 10.1073/pnas.0908266107

Pressey, R. L., and Bottrill, M. C. (2009). Approaches to landscape- and seascape-scale conservation planning: convergence, contrasts and challenges. *Oryx* 43, 464–475. doi: 10.1017/S0030605309990500

Pringle, R. M. (2017). Upgrading protected areas to conserve wild biodiversity. *Nature* 546, 91–99. doi: 10.1038/nature22902

Rilov, G., Mazaris, A. D., Stelzenmüller, V., Helmuth, B., Wahl, M., Guy-Haim, T., et al. (2019). Adaptive marine conservation planning in the face of climate change: What can we learn from physiological, ecological and genetic studies? *Glob. Ecol. Conserv.* 17, e00566. doi: 10.1016/j.gecco.2019.e00566

Salomon, A. K., Lertzman, K., Brown, K., Wilson, K. B., Secord, D., and McKechnie, I. (2018). Democratizing conservation science and practice. *Ecol. Soc* 23, 44. doi: 10.5751/ES-09980-230144

Samhouri, J. F., Levin, P. S., and Ainsworth, C. H. (2010). Identifying thresholds for ecosystem-based management. *PloS One* 5 (1), e8907. doi: 10.1371/journal.pone.0008907

Samhouri, J. F., Levin, P. S., Andrew James, C., Kershner, J., and Williams, G. (2011). Using existing scientific capacity to set targets for ecosystem-based management: A Puget Sound case study. *Mar. Pol.* 35, 508–518. doi: 10.1016/j.marpol.2010.12.002

Schoeman, R. P., Patterson-Abrolat, C., and Plön, S. (2020). A global review of vessel collisions with marine animals. *Front. Mar. Sci.* 7. doi: 10.3389/fmars.2020.00292

Scholes, R. J., and Kruger, J. M. (2011). A framework for deriving and triggering thresholds for management intervention in uncertain, varying and time-lagged systems. *Koedoe* 53, 2. doi: 10.4102/koedoe.v53i2.987

Schuurman, G. W., Cole, D. N., Cravens, A. E., Covington, S., Crausbay, S. D., Hoffman, C. H., et al. (2022). Navigating ecological transformation: resist–accept–direct as a path to a new resource management paradigm. *BioScience* 72, 16–29. doi: 10.1093/biosci/biab067

Statistical Institute of Belize (2023). Available online at: https://sib.org.bz/ (Accessed June 28, 2023).

Tam, J. C., Parlee, C. E., Campbell-Miller, J., Bellanger, M., Bentley, J., Pourfaraj, V., et al. (2024). Expanding the scope and roles of social sciences and humanities to support integrated ecosystem assessments and ecosystem-based management. *IJMS*, 81 (1), 22–42. doi: 10.1093/icesjms/fsad172

Thompson, P. L., Rooper, C. N., Nephin, J., Park, A. E., Christian, J. R., Davies, S. C., et al. (2023). Response of Pacific halibut (Hippoglossus stenolepis) to future climate scenarios in the Northeast Pacific Ocean. *Fish. Res.* 258, 106540. doi: 10.1016/j.fishres.2022.106540

Tony, A. B. R. (2020). Adaptive management in context of MPAs: challenges and opportunities for implementation. *J. Nat. Conserv.* 56, 125864. doi: 10.1016/J.JNC.2020.125864

UNEP-WCMC and IUCN (2020). *Protected Planet: The World Database on Protected Areas (WDPA). September 2020* (Cambridge: UNEP-WCMC and IUCN).

Vandermeulen, H. (1998). The development of marine indicators for coastal zone management. *Ocean Coast. Manage.* 39, 63–71. doi: 10.1016/S0964-5691(98)00014-3

Walters, C. J., and Hilborn, R. (1978). Ecological optimization and adaptive management. *Ann. Rev. Ecol. Syst.* 9, 157–188. doi: 10.1146/annurev.es.09.110178.001105

Weeks, R., and Jupiter, S. D. (2013). Adaptive co-management of a marine protected area network in Fiji. *Cons. Biol.* 27, 1234–1244. doi: 10.1111/cobi.12153

Whitney, C. K., and Ban, N. C. (2019). Barriers and opportunities for social-ecological adaptation to climate change in coastal British Columbia. *Ocean Coast. Manage.* 179, 104808. doi: 10.1016/j.ocecoaman.2019.05.010

Wildtracks (2018). *Community Engagement Strategy, South Water Caye Marine Reserve* (Belize City: Belize Fisheries Department).

Wildtracks (2019). *Management Plan: Glover's Reef Marine Reserve* (Belize City: Belize Fisheries Department).

Wilson, E. O. (1984). *Biophilia* (Cambridge, Massachussets: Harvard University Press). doi: 10.4159/9780674045231

Wilson, K. L., Tittensor, D. P., Worm, B., and Lotze, H. K. (2020). Incorporating climate change adaptation into marine protected area planning. *Glob. Change Biol.* 26, 3251–3267. doi: 10.1111/gcb.15094

Zentner, Y., Rovira, G., Margarit, N., Ortega, J., Casals, D., Medrano, A., et al. (2023). Marine protected areas in a changing ocean: Adaptive management can mitigate the synergistic effects of local and climate change impacts. *Biol. Cons.* 282, 110048. doi: 10.1016/j.biocon.2023.110048