SCIENCE POLICY

Integrating climate adaptation and biodiversity conservation in the global ocean

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The impacts of climate change and the socioecological challenges they present are ubiquitous and increasingly severe. Practical efforts to operationalize climate-responsive design and management in the global network of marine protected areas (MPAs) are required to ensure long-term effectiveness for safeguarding marine biodiversity and ecosystem services. Here, we review progress in integrating climate change adaptation into MPA design and management and provide eight recommendations to expedite this process. Climate-smart management objectives should become the default for all protected areas, and made into an explicit international policy target. Furthermore, incentives to use more dynamic management tools would increase the climate change responsiveness of the MPA network as a whole. Given ongoing negotiations on international conservation targets, now is the ideal time to proactively reform management of the global seascape for the dynamic climate-biodiversity reality.

INTRODUCTION

Climate change and biodiversity loss present two increasingly important challenges for modern civilization (*1*, *2*). They are also interlinked, with bidirectional feedback mechanisms and the potential for tipping points that may destabilize the Earth system, leading to unprecedented consequences for human societies (*3*). This connection has led to recognition that the climate- and biodiversity-focused policy agendas must become intertwined to better reflect the critical role the natural world plays in climate regulation, mitigation, and adaptation. Protected areas (PAs), crucial components of the biodiversity conservation toolbox, were originally conceived before awareness of the global, rapid, and enduring impacts of anthropogenic climate change. As a result, the global network of PAs does not consistently account for climate change in design and management (*2*), despite recognition of its importance (*4*) and notable conceptual advances in underlying design principles (*5*, *6*). Although its impacts are not geographically uniform, climate change will likely reduce PA effectiveness (*4*, *7*, *8*), here defined as the ability to meet stated biodiversity and conservation goals now and into the future.

Ocean ecosystems are particularly vulnerable to climate change (*9*–*11*). While marine PAs (MPAs) cannot halt the effects of climate change and are not a panacea, they are part of a larger portfolio of tools that can help with managing ecosystems and biodiversity in response. There is a clear and urgent need to move toward actively integrating climate change as a core consideration of MPA planning and implementation. Conceptual approaches and decision support tools for integrating climate change into MPA site and network design have existed for over a decade (*6*, *12*). However, the uptake of these measures into management and policy appears limited and globally uncoordinated. Climate change adaptation is also important in non-MPA spatial conservation and management tools, such as "other effective area-based conservation measures" (OECMs), which are not part of the legally designated PA network but conserve biodiversity regardless of their primary objective. OECMs are newer in definition and climate change is mentioned in their guiding principles, although acknowledgement of climate change in their design and management is not required (*13*).

Here, we explore the integration of climate change considerations into the global protected seascape. First, we review the evidence for integration in current MPA design and operation. We then examine the global distribution of past and future climate trajectories for MPAs and discuss explicitly embedding climate adaptation objectives into MPA networks. Last, we assess how a protected seascape that integrates dynamic management tools may look in practice, and then recommend policy options to help to advance this process. Policy incentives have helped spur international action and national frameworks on PA coverage (*14*) and may fulfill the same role for climate-smart network design. For each section, we finish with a practical recommendation, with the overall goal of accelerating the uptake of climate resilience as a fundamental component of the global protected seascape.

THE THEORY-PRACTICE GAP IN INTEGRATING CLIMATE CHANGE INTO MPA DESIGN AND OPERATION

Numerous organizations and governance bodies including nongovernmental organizations (NGOs) and government authorities are working to integrate climate change considerations into MPAs. Yet,

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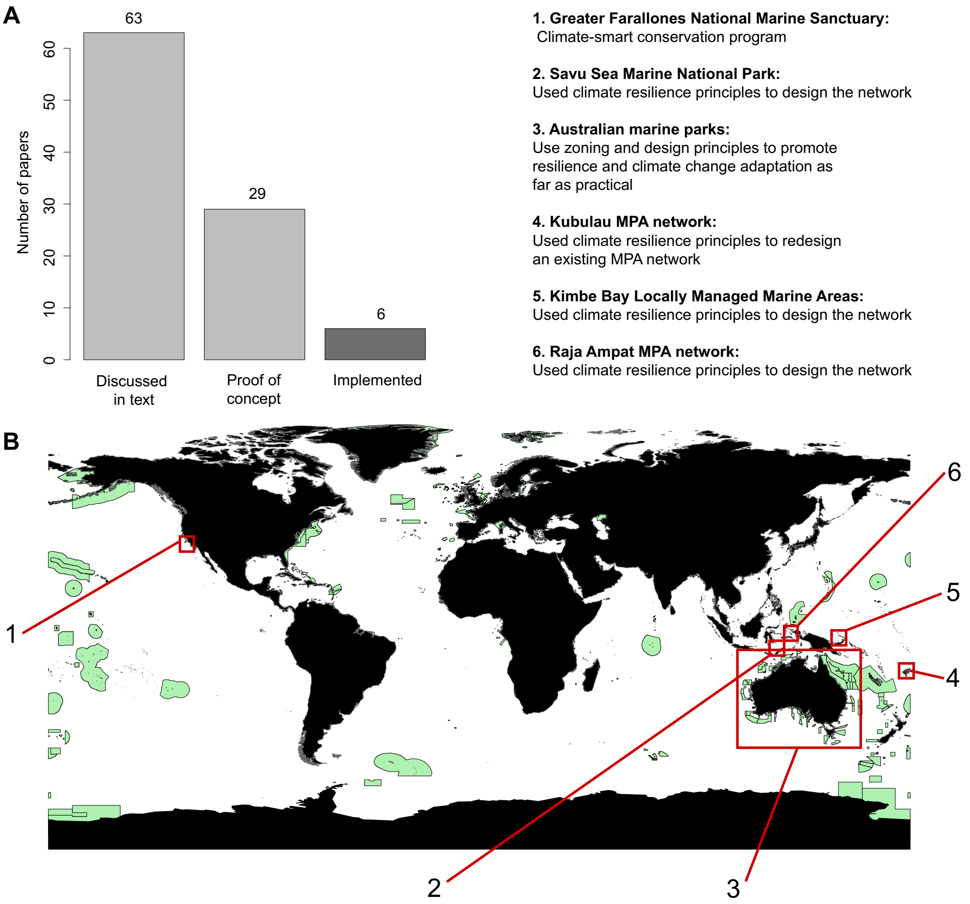
it is difficult to develop a comprehensive global overview of the extent to which climate change is integrated into the objectives and design of existing MPA networks, as a result of the lack of a coherent centralized repository that amalgamates this information. The recently released Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) Global Assessment indicates that there are "few protected areas whose objectives and management take climate change into account" but suggests that only limited studies exist with no comprehensive synthesis (*2*).

To assess this, we reviewed the scientific literature on climate change adaptation in the design and operation of MPAs and MPA networks (see the Supplementary Materials). Of the 98 relevant papers identified, only 6 reported concrete on-the-ground implementation (Fig. 1). Of the remaining 92 papers, 29 were unimplemented examples of how to incorporate climate change considerations into specific existing or new MPA and/or network designs, and 63 consisted of theoretical reviews or planning frameworks not tied to specific MPAs or networks (Fig. 1, table S1, and refer to the text in the Supplementary Materials). Of the six examples with on-the-ground implementation, only one (the Greater Farallones National Marine Sanctuary in California) explicitly considered climate change in its management plan (table S3) (*15*). The "Climate Adaptation Plan" includes a vulnerability assessment of the sanctuary, climate change recommendations, and an implementation plan (https://farallones.noaa.gov/manage/climate/adaptation.html).

The other five examples are of MPA networks rather than single MPAs. Australian Marine Parks (MPAs designated and managed by the federal government) include design principles that identify the need to incorporate increased resilience and adaptation to climate change as far as practicable (*16*, *17*). For the remaining four examples, all concentrated in and around the Coral Triangle (table S3), MPA network design and management were informed by explicit climate resilience principles (*6*, *18*). The Kubulau MPA network in Fiji, for example, was redesigned by selecting critical coral reef areas that have shown resilience to bleaching events, maintenance of connectivity between individual MPAs, and protection of larger MPAs that include the full range of marine habitats. Resilience principles were also incorporated into management, for example with recommendations for fishing restrictions to maintain ecosystem function.

A literature review only captures part of ongoing efforts at climate change adaptation because initiatives implemented by governments or NGOs may not be captured in the scientific literature and are also difficult to synthesize (*19*); for example, the MPA-ADAPT project in the Mediterranean (https://mpa-adapt.interreg-med.eu/), the Californian Channel Islands National Marine Sanctuary, Primeiras



1. Greater Farallones National Marine Sanctuary:
Climate-smart conservation program

2. Savu Sea Marine National Park:
Used climate resilience principles to design the network

3. Australian marine parks:
Use zoning and design principles to promote resilience and climate change adaptation as far as practical

4. Kubulau MPA network:
Used climate resilience principles to redesign an existing MPA network

5. Kimbe Bay Locally Managed Marine Areas:
Used climate resilience principles to design the network

6. Raja Ampat MPA network:
Used climate resilience principles to design the network

Fig. 1. Literature review of climate change consideration in MPA design. (**A**) Number of studies from the review where MPA climate change adaptation strategies were broadly discussed, presented as a proof of concept, or implemented in practice, respectively. (**B**) Location and brief description of the six implemented examples. Green areas represent MPA locations from the World Database on Protected Areas (*79*). See main text for further discussion, including search limitations, and text and tables in the Supplementary Materials for full methodological details and results.

and Segundas Environmental Protected Area in Mozambique, and the Bahamian, Palau's, and the Federated States of Micronesia's MPA networks.

Efforts to integrate climate change adaptation and biodiversity conservation may be more advanced for coral reef MPAs, perhaps as a result of the disruptive nature of bleaching impacts (*20*), although this is challenging to quantify. Furthermore, managers working in reefs and other coastal systems will face additional impacts (e.g., nutrient runoff) and specific constraints from land-based activities in comparison to offshore management regimes. Given this, design, management, and monitoring of coastal MPA networks should explicitly consider terrestrial impacts through integrated terrestrial-marine planning and modeling (*21*) and through assessment of how climate change impacts in proximal terrestrial environments may influence adjacent marine systems (*22*, *23*).

A further challenge is that the evidence base for MPAs conferring resilience to climate change is limited, largely based on coral reef ecosystems, and the effectiveness of MPAs as tools for climate-change resilience remains a matter of ongoing debate (*24*, *25*). The managed-resilience paradigm posits that MPAs, by reducing other stressors, will improve reef recovery after bleaching, but the limited data available are not sufficient to confirm this hypothesis. A solid empirical basis demonstrating the benefits of MPAs for climate resilience is required. This limited evidence base remains difficult to resolve, given the fact that most MPAs are currently not explicitly sited, designed, and/or managed for climate resilience. Controlled studies of the potential benefits of climate-smart MPAs across multiple ecosystem types are required to resolve this issue.

Our results (Fig. 1) highlight a crucial gap between theory and practice, which limits mobilization of research on the benefits of climate-smart implementation for MPAs and MPA networks (*26*, *27*). Several factors may explain this gap. First, the limited availability of spatially explicit climate and ecosystem forecasts at the MPA site scale may hamper efforts to operationalize climate change strategies. The uncertainty associated with climate models and their outputs is a challenge for managers, and a limited integration between ecology and climate science may inhibit understanding of how climate projections can be used at appropriate ecological scales (*28*–*30*).

Second, access to effective, readily implementable management strategies is predicated on information about tested practices and management interventions. Much of the literature has focused on integrating climate change considerations into MPA design through general design principles (*6*, *18*). However, more specific and scale-appropriate guidance is needed to account for local climate patterns and impacts, to help managers readily translate design principles into management strategy (*31*).

Last, in most cases, MPAs have been sited and networks have been developed to maximize conservation (and other) values while minimizing conflict with users (*32*). Including climate change in this complex negotiation may be difficult, particularly where climate adaptation pays no immediate benefit and may impose an additional burden on managers. Managers may also not have the resources to consider climate change, and hence respond instead to more immediate challenges and goals. If the benefits of accounting for climate change are not realized for decades to come, then the incentive structure is stacked against including climate change in planning.

A community of practice could help build awareness of the importance of MPA climate adaptation and mitigation benefits, helping to shift the incentive structure to be more favorable. As an example of benefits, mangroves not only are characterized by long-term carbon burial rates averaging >45 times those found in terrestrial forest ecosystems (*33*, *34*) but also provide major fisheries and coastal protection benefits as the climate changes, and can help to sustain high biodiversity elsewhere through larval and juvenile export. An important concrete first step toward a community of practice would be a means of documenting climate-smart MPA implementation experiences (see Recommendation 1).

***Recommendation 1*: Create a centralized resource to catalog whether climate change adaptation has been accounted for in the design and management of individual MPAs, OECMs, and protected seascape networks.**

- It is, at present, impossible to precisely quantify how often climate adaptation is integrated into MPA and network design/operation.
- A centralized database would enable evaluation of the uptake of climate considerations in the protected seascape and help to inform policy targets (see Recommendation 5).
- In addition to such a resource, the evidence base for MPAs conferring resilience under climate change needs to be extended through controlled studies that span multiple ecosystem types.
- The theory-practice gap for integrating climate adaptation into MPAs also needs further evaluation, and the specific local reasons for such a gap could be included with each record in the centralized resource.

ENSURING REPRESENTATION OF ALL CLIMATE TRAJECTORIES IN THE PROTECTED SEASCAPE

MPAs around the globe are already and will continue to be affected by climate change to varying degrees (*7*). Nevertheless, while it is recognized that network design needs to incorporate climate resilience (*24*), ideas differ on how to best prioritize areas to account for climate change. For example, it has been suggested that temporary climate refugia (here defined as locations with slower projected increases in future climate stress) be prioritized as part of the PA network [e.g., (*35*, *36*)]. These areas are important but are relatively rare, cannot be solely relied upon to achieve global conservation goals (*37*), and do not eliminate the need to manage for change. If we prioritize the protection of climate refugia, then we downweight vulnerable ecosystems that may require the most assistance against synergistic but abatable threats. Instead, a range of areas representing the spectrum of vulnerability, impact, and climate futures need to be included in the protected seascape to ensure that ecosystems with differing trajectories can be adequately represented and managed (Table 1) (*38*, *39*). Assessing climate futures and vulnerability for different ecosystems and MPAs (*7*) remains extremely challenging as a result of the large variation in biological responses, uncertainty around climate signals, and the difficulties in linking protection to resilience (*24*, *25*). However, one way to approach this is by analyzing the distribution of MPAs against future (*7*) and historical thermal conditions (Fig. 2). Globally, and within each MPA, we calculated the historical thermal variability (1900–2018) and the projected thermal exposure to 2100 (*7*). Almost half of the MPA area assessed (46%) is characterized by low historical environmental variability, but with novel and unprecedented thermal conditions already occurring or projected within several decades. An even larger proportion (49%) also has had low historical thermal variability, but novel thermal conditions are not projected until the mid- to late century. A very small area of MPAs (<5%) has experienced high historical variability (Fig. 2)

Table 1. Examples of climate change adaption objectives and possible actions.

Objective with climate change	Example actions to operationalize
Early detection of climate change impacts	Enhanced multisensor monitoring
	Citizen science observer networks
	Use of sentinel species as indicators
Protecting species or habitats that move	Support migration of climate-displaced species or habitats with flexible design features or other management measures and protect from other stressors
Enabling reorganization of ecosystems to retain functions and services under climate change	Manage for resilience under a changing climate rather than assuming static features and outcomes
	Reassess and revise zoning and management plans to account for ecosystem and species shifts
	Specify climate mitigation into MPA network design and management objectives
Maintaining representative MPA networks in a changing climate	Include areas of high and low predicted climate resilience, future change, and adaptation potential in representative network design
Use both static and dynamic features to better conserve ecosystems	Better integrate conservation and fisheries management measures to augment one another
	Focus network around anchor-point static areas but integrate multiple tools including more dynamic and responsive approaches (see Table 2)
Adapting to unforeseen conservation challenges and opportunities as climate change reconfigures ecosystems	Move toward dynamic conservation objectives
	Update management plans and objectives a based on observed changes
	Collect stakeholder observations and feedback

While the distribution across novel climate futures is relatively balanced, the current global MPA network is heavily skewed toward areas that have experienced relatively low historical variability in temperature (Fig. 2). However, this distribution closely reflects the proportion of these areas in the global ocean (clockwise from top left: <1, <2, 47, and 50%). Deviations from the background distribution may reflect prioritization with respect to climate variability and change, and conversely, a network distribution that closely matches that of the global ocean may represent climate-agnostic planning. It may be prudent to place more MPAs in locations with high historical variability, although the hypothesis that this may translate to greater climate resilience requires more explicit and context-dependent testing (*40*, *41*).

The idea of true representation of ocean futures means accepting the dynamic reality of climate change. While permanent refugia do not exist, sites with a longer time until novel climatic conditions emerge (i.e., temporary refugia) may prove important. However, all types of climatic trajectories should be integrated into the protected seascape, because they will all need management assistance to navigate the novel climate of the future. The resilience, adaptability, and evolutionary potential of organisms may also be influenced by their historical experience (*41*), so accounting for this in the protected seascape may add further robustness.

***Recommendation 2*: Create networks of MPAs and OECMs that span the range of past and future climate space along multiple axes of change (e.g., temperature, oxygen, and acidification) to ensure inclusion of all climate trajectories.**

- While recognizing that refugia are important, all types of climate futures should be represented, as ecosystems experiencing more rapid change may require more active management and protection from synergistic human stressors.
- Accounting for differing historical trajectories may add further robustness.

SETTING EXPLICIT CLIMATE ADAPTATION OBJECTIVES FOR MPAs

Climate change is reconfiguring marine ecosystems globally (*42*). Yet, in contrast to other potentially abatable human impacts such as fishing, it is impossible to immediately limit the in situ effects of climate change, some of which are already inescapable. Therefore, as society works to reduce greenhouse gas emissions (*24*, *25*), we also need to accept the present reality of ecosystem change and transition. Ensuring that the protected seascape achieves its conservation objectives requires much tighter integration between biodiversity conservation and climate change agendas.

This integration will require concrete MPA objectives relating to the direct and indirect impacts of climate change (see examples in Table 1). The fundamental notion of conserving habitats and ecosystems "as is," or restoring them to a previous baseline, has been replaced by the realization that climate change will cause rearrangements of marine systems on scales much larger than those of individual MPAs. Thus, objectives need to shift toward a more dynamic set of goals and actions at both the network and individual MPA level to explicitly acknowledge ongoing climate change. This shift may require embracing difficult realities of limited capacity. Dynamic responses to climate change must be spatially prioritized with clear adaptation objectives, which should result in more efficient global and regional networks. Indirectly dealing with climate change through previously established MPA network design principles (such as replication, representation, and connectivity) is important yet does not take ongoing dynamic impacts into account. Climate change needs to be explicitly incorporated into both the design phase (by optimizing siting choices) and management (operationalizing objectives that acknowledge climate change) (*24*, *43*).

The uncertainty inherent in climate change projections, scenarios, and ecological responses does not justify inaction. Climate change is unfolding, biological systems are responding, and the effectiveness of MPAs designed for today will be reduced in the future (*7*). Explicitly integrating climate adaptation objectives into MPA design and management provides a concrete step toward adaptation to climate

Table 2. Climate design principles for the protected seascape. Different tools perform complementary functions within a climate-resilient conserved seascape.

Management tool		Objectives/characteristics	Examples
Static tools	Static MPAs (anchor points)	Conservation of assemblages associated with static geomorphological features and other sites of present and future conservation importance	Great Barrier Reef Marine Park (Australia)
		Maintaining long-term monitoring (control/baseline) sites where climate impacts can be assessed in the absence of other stressors	Galapagos Marine Reserve (Ecuador)
		Creating networks for meta-populations and fixed migration corridors	Marianas Trench National Monument (USA)
	Static OECMs	Effective conservation of key ecological features and biodiversity from a single or several threats (regardless of primary objective of OECM)	Rockall Haddock Box High Seas Trawl Closure (North East Atlantic Fisheries Commission)
		Act as long-term monitoring sites for climate impacts with single or multiple additional uses and/or stressors superimposed	
		Creating networks for meta-populations and fixed migration corridors	
Dynamic tools	Dynamic ocean management areas*	Respond to rapid shifts in species distribution and threats	Dynamic fisheries closures to protect North Atlantic right whales (Canada)
		Provide short-term/seasonal corridors or stepping stones	
		Provide quicker deployment (and removal) than MPAs	
		Not fully multisectoral; often single-sectoral	
		Unlikely to be considered OECMs under the present definition, unless they remain in place for an extended period (see Table 3)	
	Climate-responsive biodiversity closures (CRBCs)	A hybrid of MPAs (multisectoral) with shorter-term closures (ability to relocate and react to climate-driven changes)	Currently conceptual—see main text
		Respond to climate-driven biological responses by moving boundaries to track shifting habitats or ecosystems	
		Focus on shifts due to climate signal rather than other fluctuations	
		Unlikely to be considered OECMs under the present definition, unless they remain in place for an extended period (see Table 3)	

*Also known as dynamic conservation features and/or short-term closures.

change. Rather than waiting and letting the effectiveness of the global protected seascape deteriorate, we need to embrace uncertainty and move forward with an ambitious coupled climate-biodiversity response, actualized through explicit climate adaptation objectives for every MPA and network.

***Recommendation 3*: Ensure that climate adaptation objectives are explicitly included in all MPA (and network) management plans.**

- This can be evaluated by setting a target for the proportion of MPAs that do so (see Recommendation 5), which can be facilitated by creating a database of this climate change integration (see Recommendation 1).

DEVELOPING CLIMATE-RESPONSIVE CONSERVATION NETWORKS IN THE OCEAN

A crucial contradiction of climate-smart MPA network design is that climate impacts and ecological responses are dynamic, yet PAs and OECMs are, by definition, spatially static (*44*–*46*). Designing the global protected seascape by combining multiple static and dynamic tools may help overcome this contradiction. Yet, while conceptual approaches have been developed to integrate static and dynamic tools in PA networks (*44*, *46*, *47*), it remains unclear how a climate-responsive seascape conservation network would look in practice.

It could be argued that climate change will erode the value of static protection. However, while changes will occur throughout the

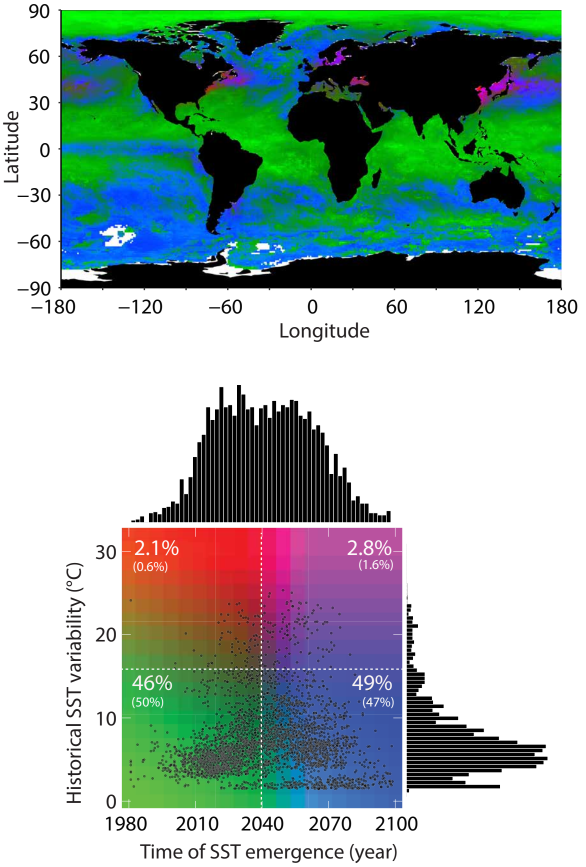


Fig. 2. Vulnerability of the existing global MPA network to climate change. (**A**) Bivariate map of the time of emergence and historical variability for the global ocean [see (B) for color axes] under a business-as-usual emissions scenario [Representative Concentration Pathway (RCP) 8.5]. Time of emergence refers to the year when projected mean sea surface temperature (SST) at a given location exceeds the bounds of preindustrial conditions. Historical variability is the total thermal range calculated from a detrended 1900 to 2018 SST time series. (**B**) Quadrant plot of MPA position in climate emergence and historical variability space. Black points represent 1° × 1° grid cells within MPAs, with larger MPAs having more points based on overlap with SST data (see text in the Supplementary Materials for full methodological details). Histograms provide the distribution of MPAs along each axis. Percentage values indicate the proportion of MPA area (grid cells) in each quadrant; percentages in brackets indicate the proportion of the global ocean in each quadrant. Color scale is based on background distribution in global ocean.

ocean, considerable evidence points to the ecological benefits of well-managed and enforced static conservation areas (*48*). Fixed MPAs, covering both the seabed and overlying water column (*49*), play a vital role in building ecological resilience to anthropogenic pressures, through long-term ecosystem-focused protection that addresses human activities across multiple sectors, and facilitating cumulative benefits (*49*–*51*). Given the strength of the evidence, fixed "anchor-point" MPAs should help to offer long-term support for marine life to adapt to changing conditions. Furthermore, a static protected seascape can conserve geographical features that are structurally complex (e.g., coral reefs, submarine canyons, and seamounts) and likely to remain important to marine life even in a changing world.

Nonetheless, it is clear that the ability of static features to meet conservation objectives may be undermined under climate change (*7*). Furthermore, implementing new MPAs based on projections of changing species distributions under specific scenarios at specific dates in the future risks ignores projection uncertainty and resulting in placements that wax and wane in effectiveness under climate change—it is again planning for a static future at some fixed date. This may not be a strategy that is robust over a long-term dynamic future (*52*).

This potential for climate change to undermine the effectiveness of static MPAs might be partly countered by setting objectives at a network level that evolve as the climate continues to restructure ecosystems (Table 1), although this is unlikely to fully suffice. A new paradigm would be to focus on accrued benefits to ecosystems, which may shift in geographic location, rather than on benefits to specific sites, in which the ecological composition may become altered and affect the delivery of location-specific benefits. If ecosystems, habitats, or communities move with climate change, then accruing benefits to or from an ecosystem necessitates moving or extending management measures as that ecosystem moves; otherwise, accrued benefits may begin to deteriorate as the objectives move beyond the boundaries of protection (*47*). This shift in focus can help to guide a conservation approach that includes dynamic management tools, here explicitly referring to dynamic management measures rather than dynamic zoning within existing static measures.

Safeguarding marine life under future change will require an MPA network that is based around existing (and new) static anchor-point MPAs, supplemented with dynamic (in time and space) management elements to accommodate rapid ecological changes (Table 2). These combined dynamic-static networks have been conceptually proposed (*44*, *46*), though not explicitly operationalized for the oceans. Here, we envisage how such a combined network might appear in practice.

Of existing area-based management tools, dynamic ocean management (temporary management measures in response to changes in and forecasts of shifts in the biophysical marine environment) is generally applied with a relatively short time horizon (days to months) (*53*) that may not appear to intuitively align with the longer-term implications of climate change. However, the ability of dynamic ocean management (and similar tools) to respond to threats to species and shifts in their distributions in near real time (*54*) makes it suitable to help to "fill the gaps" between other management measures and respond to rapid changes (Table 2).

One such example is the recent (2018 and 2019) management measures in reaction to the North Atlantic right whale (*Eubalaena glacialis*) shifting its distribution in response to climate-driven changes in environmental conditions and redistribution of prey (*55*). As a result of a habitat shift into the Gulf of St. Lawrence in Canada, these whales have experienced increased mortality from vessel strikes and entanglements in fishing gear. In response, the federal government created near real-time and spatially dynamic fishery closures and gear and vessel speed restrictions, designed specifically to limit seasonal mortality risks, and updated daily based on visual and acoustic tracking of the species (*56*).

These dynamic fishery closures can be rapidly implemented, potentially offer long-term protection, and, in some instances, could even develop into static OECMs. However, they may not be specifically designed to address long-term biodiversity objectives. Therefore, these closures do not provide all of the benefits of MPAs, as they typically address single or only several sectors, gears, or target species and permit other activities that might be harmful. This limitation could hypothetically be ameliorated by layering multiple dynamic single-sector management tools (e.g., for fishing, shipping, and seabed exploitation) in concert. However, this would require coordinated action across multiple agencies, communities, and legislative frameworks and may still fail to manage all stressors. A full conservation network should not be built solely around limited sectoral measures (*51*). It may be more effective to deploy rapid-response, multisectoral conservation management tools designed specifically to deal with climate-driven impacts on marine ecosystems.

These toolkits have been explored in hypothetical scenarios (*45*, *46*) but do not yet exist in practice. For dynamic spatially explicit and conservation-focused management, the ideal measure would hybridize the benefits of MPAs (multisectoral protection with a long-term biodiversity conservation objective) with those of dynamic sectoral closures (ability to be rapidly deployed and to be relocated to respond to climate impacts, based on changes in the effectiveness or efficiency of the network). They would not move frequently but could be triggered for relocation under specific conditions mapped to climate change response time scales, thus recognizing that climate change is an ongoing and continual problem. We term these measures "climate-responsive biodiversity closures" (CRBCs) (Table 2), given that they would be implemented primarily to deal with the effects of climate change on biodiversity.

CRBCs require, as above, viewing permanency of protection (and accrued benefits) from the perspective of tracking a particular ecosystem, habitat, or species, rather than protection of a fixed location in space. CRBCs could be used to protect habitats or ecosystems expected to gradually redistribute as a consequence of climate change; they may, therefore, be particularly suited to biogenic habitats (e.g., corals, kelp forests, and seagrass meadows), oceanographically complex regions, or aggregation points that will shift but continue to provide a key habitat for species assemblagees. For example, if a network design objective was to represent at least half of the range of a specific biogenic habitat, such as seagrass, which subsequently shifted as the climate changed, then CRBCs could be relocated to maintain representation (Fig. 3).

However, the implementation of these measures would need to be informed by robust science and ongoing monitoring, require intensive stakeholder engagement and potentially cross-jurisdictional partnerships, and necessitate high volumes of data. Alternatives to CRBCs could include implementing additional static MPAs (e.g., by increasing spatial targets) and then supplementing them using dynamic ocean management; the relative benefits and costs of these alternatives require further investigation. Nonetheless, multisectoral, long-term biodiversity-focused tools specifically designed to dynamically respond to climate change remain absent from the conventional conservation portfolio.

In summary, a paradigm is emerging of a climate change reality that cannot be fully addressed by purely static closures. By combining static and dynamic conservation measures, gaps in target coverage may be filled (Fig. 3), although international objectives may require greater consideration of how these measures fit within the policy landscape (Recommendation 6). There is an important trade-off in

Table 3. Assessment of whether dynamic management tools meet the CBD criteria (*13*) for being OECMs.

CBD criterion		Do dynamic management tools as envisaged meet criterion?
A: Area is not currently recognized as a PA		
	Not currently recognized as a PA	Yes
B: Area is governed and managed		
	Geographically defined space	Yes in size and area described
		No for geographically delineated boundaries
	Legitimate governance authorities	Yes
	Managed	Yes
C: Achieves sustained and effective contribution to in situ conservation of biodiversity		
	Effective	Yes (assuming biodiversity and conservation benefits, regardless of objectives)
	Sustained over the long term	Depends on definition of "long term." Some features may shift year to year but be in place for many years. Ultimately, it may be the intent; is the proposed length of management expected to be long-term, regardless of shorter-term dynamics?
	In situ conservation of biological diversity	Yes
	Information and monitoring	Yes
D: Associated ecosystem functions and services and cultural, spiritual, socioeconomic, and other locally relevant values		
	Ecosystem functions and services	Yes
	Cultural, spiritual, socioeconomic, and other locally relevant values	Yes (assuming explicitly accounted for)

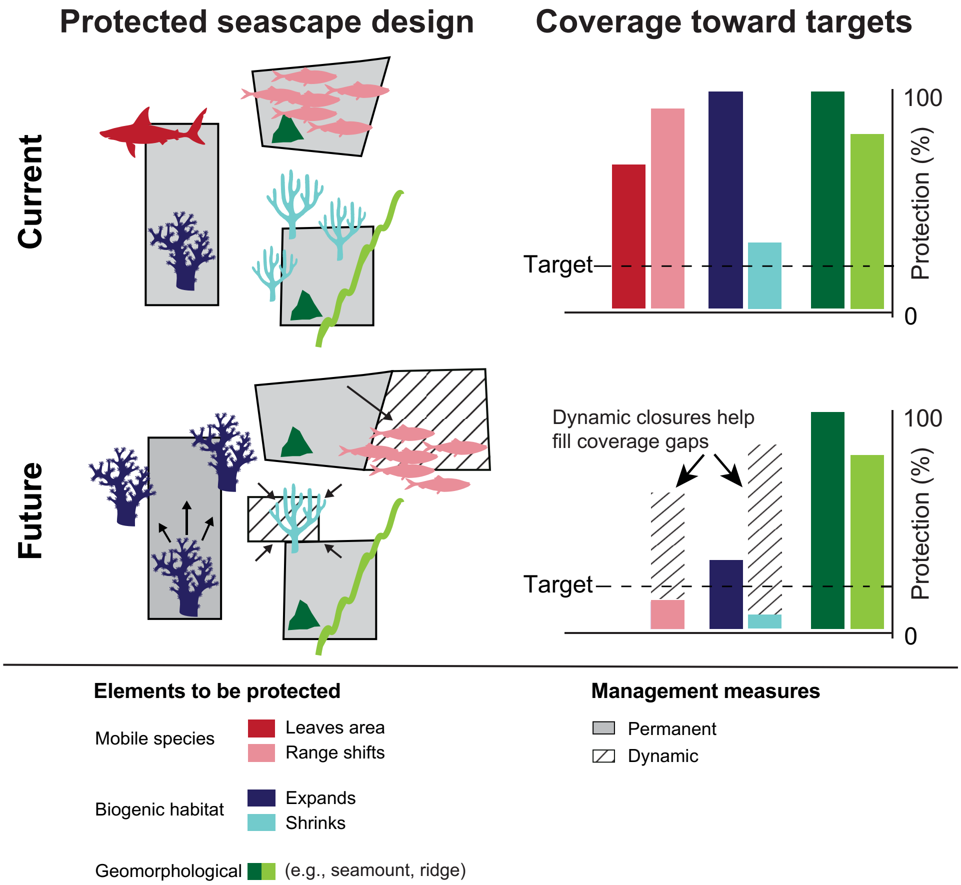


Fig. 3. The need for climate-responsive management features. Climate-driven changes in mobile species, biogenic habitat features, and static geomorphological features (e.g., seamounts and ridges), with management measures (permanent and dynamic) superimposed (left column). In this example, under the current distribution percent coverage targets (e.g., Aichi Target 11 of 10% by 2020) will be met for many species, habitats, and features (right column). However, climate-driven shifts will affect future distributions such that these targets would no longer be met, as a result of species and biogenic habitats expanding, shrinking, disappearing, or moving in relation to static protected features (although some features may get increased protection if they move into MPAs). Dynamic closures (hashed boxes, Table 2) can help to fill the protection gap in a more rapid manner than simply extending or adding new MPAs; however, these dynamic areas will not count toward international targets unless they meet OECM criteria (see Table 3).

the selection of dynamic versus static features, specifically between the cumulative ecological benefits acquired by sustained spatial protection and the declining efficiency associated with not adapting the network to changing conditions. Mobilizing new and existing tools to build dynamic climate adaption into the MPA network is feasible, if deemed of collective importance.

***Recommendation 4*: Design the global MPA network around fully protected static management measures supplemented by dynamic, climate-responsive tools.**

- A multisectoral, rapid-response spatial management tool with a long-term biodiversity conservation focus (here termed climate responsive biodiversity closures, or CRBCs), dynamically deployed to protect biodiversity under climate change, is missing from the conservation portfolio.
- Evaluating the legislative, technical, and practical feasibility of these tools, as well as their benefits and trade-offs versus other options (e.g., overlaying single-sector measures), remains an operational gap.
- Case studies of these measures could be developed and disseminated, as well as funding and capacity transfer for their implementation, if they are demonstrated to be effective.

POLICY INCENTIVES TO ENABLE A CLIMATE-BIODIVERSITY SYNTHESIS IN GLOBAL SEASCAPE MANAGEMENT

Setting explicit climate change objectives for conserved seascape management measures (Recommendation 3) and integrating static anchor points, dynamic conservation features, and other management tools (Recommendation 4) will contribute toward building a climate-resilient network. However, to enable this ambition in practice and build flexibility into management instruments, appropriate policy incentives are needed. The lack of these incentives may help explain why the uptake and adoption of climate principles into MPA design and operation have been relatively slow (Fig. 1). New international biodiversity or conservation targets could provide one such incentive.

The implementation of the global network of MPAs has been accelerating, which may, in part, be explained by Parties to the Convention on Biological Diversity (CBD) attempting to meet Aichi Target 11 that requires 10% areal protection for coastal and marine areas (*57*). Percentage targets, however, are not a panacea; they can promote perverse outcomes and cause PAs to be established at sites with relatively low biodiversity value (*58*). PAs can also vary considerably in their effectiveness, depending on capacity, management, and enforcement (*59*). Nonetheless, the steady progress toward

Aichi Target 11 in terms of percentage area covered suggests that having such specific and measurable targets may result in improvements (*60*). Certainly, specific proposals for the post-2020 biodiversity agenda have provision for increased percentage targets for global PA coverage (*61*). Ideally, these targets should be combined with others on biodiversity state or ecosystem services rather than management responses (*58*). However, in practical terms, percentage area targets for PA coverage are very likely to be a component of any post-2020 biodiversity agreement. Given this, and their effectiveness at driving global action, additional and specific measurable targets for climate-related conservation would accelerate tackling climate change impacts in the world's oceans.

CREATING TARGETS FOR THE PROPORTION OF MPAs AND OECMs THAT EXPLICITLY SET CLIMATE OBJECTIVES

To fully embrace the links between climate and biodiversity, every MPA should explicitly and proactively integrate climate change considerations into their management plans and operation, and all new areas should be designed with climate change in mind (Recommendation 3). Developing a new measurable target (or target component) that these climate-focused objectives could count toward would be an incentive that helps to raise the level of climate integration in the wider network. One promising starting point would be to promote a quantifiable target for the proportion of MPAs that explicitly incorporate climate change into their management plans and/or design.

For example, such a target could read "All marine protected areas integrate climate change into their management plans," with the associated indicator simply being the percentage of these sites that actually do so. This target has the advantage of being explicitly tied to a measurable indicator, a feature that many of the Aichi Targets lack (*57*) and that has been shown to be important for driving international action (*62*). As an additional benefit, this process may help to further explicitly integrate recognition of ecosystem-based approaches to climate mitigation, as per the CBD decision on climate and biodiversity change (*63*). Additional targets or target components could also apply to other conservation measures (e.g., "all OECMs integrate climate change into their management plans") or apply at the network level.

***Recommendation 5*: Develop a specific target for the post-2020 global biodiversity framework that measures the proportion of MPAs and marine OECMs that explicitly integrate climate change adaptation in their management plans.**

- The target should be that 100% of MPAs and OECMs include climate change adaptation into their management plans.
- A climate adaptation catalog (Recommendation 1) could provide the data to develop an indicator to measure this.
- Climate-smart management at the network level should also be incentivized.

RECOGNIZING DYNAMIC CONSERVATION FEATURES AS CONTRIBUTORS TOWARD COVERAGE TARGETS

Given that the increase in PA coverage has, in part, been driven by international targets, it seems likely that to promote the integration of dynamic conservation measures into the protected seascape, measurable post-2020 international targets will be important. The most straightforward way of enabling this would be to recognize, where appropriate, such features as OECMs and hence contributors to percentage targets for areal protection under the CBD post-2020 framework or, alternatively, and perhaps more appositely, to establish a new category for dynamic features. For example, if a 30% target for area protected by 2030 is agreed, then enabling some dynamic measures, depending on their intent, to contribute toward this would likely enhance their uptake, as would the alternative of having a separate 5% (for example) dynamic measures target on top. While the core component of any network should still be anchored around fixed multisectoral protection (*51*), dynamic features, as described above, can help to build climate responsiveness.

By their very nature, these tools (Table 2) include aspects of impermanence, which challenges whether they constitute OECMs. As with more traditional static OECMs, these assessments will vary on a case-to-case basis and may continue to do so even over time as individual features evolve. Short-term or temporary dynamic ocean management is unlikely to count, for example, while longer-term dynamic closures (for instance, shorter-term regulatory instruments renewed annually or seasonal measures as part of a long-term overall management regime) and CRBCs may be closer to OECM intentions. The most direct way of evaluating this is to compare individual dynamic elements against the CBD OECM definition (Table 3). From this definition (*13*), some dynamic features as currently conceived match the intended goals of OECMs because, regardless of objectives, they are likely to achieve ancillary positive outcomes for biodiversity conservation by reducing one or more stressors. However, we note that dynamic management may not always entail broader conservation benefits and may be narrowly focused on single species or stocks.

The primary uncertainties revolve around two requirements: that areas are "geographically defined space" (specifically "boundaries are geographically delineated") and "sustained over the long term" (Table 3). For the former, while dynamic features always have a specific geographic delineation, the location, instantiation, and size of this boundary vary over time.

With regard to being sustained over the long term, it is important to separate the permanency of intent versus the permanency of specific instantiation. The underlying intent of a dynamic feature may be to contribute to the preservation of a species, habitat, or biodiversity over a long period—in fact, it may track that biological feature to ensure its continued preservation—regardless of the fact that it can be designated, reevaluated, and redesignated at shorter time scales. Truly ephemeral or seasonal features should not qualify toward coverage targets. However, when a management feature, despite being temporally dynamic, is sustained over the long term with a defined spatial intent and application, and with a strong probability of the conservation outcome being achieved, then it may adhere more closely to the spirit of the OECM definitions.

These issues could greatly benefit from further debate and from clarification and guidelines from the Subsidiary Body on Scientific, Technical, and Technological Advice of the CBD. The challenging task of developing precise definitions and agreement on intent is needed to ensure that dynamic features fulfill their potential of improving the ability of the MPA network to respond to climate change. We recommend that serious consideration be given to further clarification of the specific role and formulation of dynamic features under the OECM definition or through the formulation of a new OECM-like definition, perhaps through an expert workshop on integrating climate considerations into network design.

Crucially, the implementation of dynamic features should not detract from the importance of a growing static anchor network of protection. Dynamic features are a supplement that can be added to ensure continued efficiency and may be particularly useful under resource limitations, especially given their rapidity of deployment. Naturally, the need for dynamic climate-conservation elements will vary depending on the local context, rate of change, and climate vulnerability (Fig. 2). There is a gain-loss proposition that must always be balanced and carefully articulated, of cumulative benefits versus sustained protection in a dynamic environment.

***Recommendation 6*: Provide explicit policy incentives, such as counting toward national fulfillment of international targets, to accelerate the uptake of dynamic features as a supplement to the global protected seascape.**

- Specifically, evaluate whether dynamic features (where appropriate in intent and execution) should either (i) count under the OECM definition or (ii) comprise a new climate-responsive category that can contribute toward existing or new global coverage targets.
- Any such contributions should not undermine but instead supplement the total coverage of fully PAs (i.e., static MPAs).

DEVELOPING LEGISLATIVE TOOLS

Legislative hurdles may also help explain why CRBCs have not yet moved from theory (*45*, *46*) to practice. It is not clear that legislation exists within national jurisdictions to allow the operationalization of these features. There may be ways of approximating this with existing tools. For example, fisheries closures and vessel speed restrictions can be made dynamic to help respond to climate-driven challenges (*56*). The protection of biodiversity across multiple sectors can only be implemented through MPAs, but the regulatory process is often time consuming and can require coordination and cooperation between multiple jurisdictions. OECMs or dynamic measures are highly variable in scope and purpose but have the potential to be quicker to implement with fewer sectoral regulatory considerations (*53*, *64*). While there is considerable variability among countries, we know of no legislative or policy framework that combines the comprehensive protection through multisectoral activity restrictions in MPAs with the potential for speed and flexibility in OECM implementation and the dynamic ability to be relocated to enable a rapid response to climate-driven ecosystem impacts. Working within the existing legal framework, the layering of protection measures through existing single-sectoral management (in a process such as marine spatial planning) remains the only approach to approximate rapid and dynamic multisectoral climate protection for ecosystems.

***Recommendation 7*: Develop legislative tools to enable rapid-response, multisectoral dynamic ocean management features with a biodiversity conservation objective to be deployed specifically in response to climate change.**

- This legislation will need to consider the relative trade-offs involved, which need to be specifically and carefully evaluated (see Recommendation 4).

SOCIAL AND EQUITY CHALLENGES

Complementing the inherent uncertainty around anticipated climate impacts on a regional and global scale, and the policy context, is the inherent social and equity challenge of implementation. Trade-offs between human well-being and the health of the ecosystems upon which we depend have been a long-term consideration in conservation science (*65*, *66*). Although biodiversity loss and climate change present global problems, they affect states to varying degrees. Low-income nations, indigenous peoples, and small island states are frequently most affected by both of these challenges (*67*, *68*). Individual states have varying financial and social capacities to mitigate and respond. To this end, ensuring that the burden of any climate-responsive marine conservation initiatives does not disproportionately fall on low-income countries is of vital importance (*69*).

Ultimately, creating an MPA system robust to climate change will incur short-term costs and yield long-term intergenerational benefit. Unless resources are available to balance these, and overcome resource iniquities (*70*), conservation efforts will not be as successful, and benefits will go unrealized. The long-term advantage of maintaining the development and conservation benefits of MPAs in the face of rapid climate change will likely be sacrificed for short-term economic gain as discussed in the broader climate change context (*71*, *72*). Providing resources to offset at least the added costs not only of establishment of systems robust to climate change but also of ongoing monitoring and addressing short-term opportunity costs (for instance, reduced fisheries catches) will help. These requirements can also be enshrined in international targets, such as Aichi Target 20, on the mobilization of financial resources. Furthermore, funding bodies and foundations may also make explicit consideration of climate change objectives a requirement when funding MPA network design or operation.

Mirroring the biodiversity observed in their underwater counterparts, there is high socioeconomic and cultural heterogeneity in coastal human communities around the world—conditions that often play a decisive role in the outcome of conservation planning (*73*). Strong local leadership and social capital play a critical role in realizing fisheries local co-management objectives at a global scale (*74*). Improved compliance with regulations (e.g., adhering to defined fishing areas and limits) occurs—even when monitoring and enforcement are lacking—if there is sufficient understanding of local norms and beliefs, and management approaches designed with these in mind (*75*). Thus, in addition to ensuring that sufficient resources are available, consultation and direct involvement in planning with affected sectors are vital for building trust between stakeholders and, ultimately, for ensuring that conservation objectives are implemented and retained (*76*, *77*).

***Recommendation 8*: Center climate-smart conservation and management around principles of stakeholder inclusiveness and capacity transfer.**

- This can be realized by funding choices and integrating principles in specific policy targets.
- The need is especially acute as new tools are developed and deployed to address ongoing change and potential loss in effectiveness of the existing MPA network.

CONCLUSIONS

Climate and biodiversity are inextricably linked and, in combination, have formed the conditions for human civilization to flourish, as evidenced by their prominence in the United Nations Sustainable Development Goals. Climate change adaptation and biodiversity conservation should form the combined basis of marine management and seascape protection. While this has long been recognized, implementation has lagged.

To drive implementation, we need to measure the uptake of climate adaptation principles into MPA (and OECM) design and management (Recommendation 1). This uptake should come through the explicit integration of these principles into MPA distribution (Recommendation 2) and objectives (Recommendation 3) to maintain network effectiveness as the ocean changes. Building climate change objectives into post-2020 targets and indicators (Recommendation 5) would expedite this process. In addition to static anchor MPAs, dynamic conservation tools need to be deployed (Recommendation 4), recognizing their strengths in terms of responding to climate change while acknowledging potential drawbacks, so as to augment ongoing efforts to increase coverage of highly PAs. The post-2020 biodiversity agenda should consider whether dynamic measures, where appropriate in terms of intent, longevity, and execution, should contribute toward global protection targets; ensuring that parties to any international biodiversity agreement are appropriately recognized for implementing new tools will help to promote their use (Recommendation 6). Furthermore, individual states may want to consider developing new multisectoral legislation to help bring new and dynamic climate-smart conservation planning tools into existence (Recommendation 7). Considerations of equity in the conservation burden, stakeholder involvement, and societal impacts need to be at the forefront when implementing a climate-resilient protected seascape (Recommendation 8).

At a high level, many of these recommendations may equally apply to terrestrial systems, although the challenges and specifics may differ. However, implementing climate-resilient biodiversity protection measures across all ecosystems is a critical and global need.

Climate change can overwhelm even strong management measures (*20*), and we should not imagine that this management is a substitute for the reduction of greenhouse gas emissions (*24*, *25*, *50*). Nonetheless, we must face the current climate change reality. Unless accounted for, it will erode the effectiveness of MPA networks through changes in the phenology, distribution, and composition of marine ecosystems. Climate change impacts on human communities can also result in adverse ecological effects, and recognizing the variation in adaptive capacity of human communities remains a key part of climate-smart decision-making (*12*, *78*). We need to anticipate and prepare for these socioecological effects with new incentives and solutions. Our shared paradigm should recognize that climate change is ongoing and will continue to affect our marine ecosystems and that the future spatial management must embrace and operationalize such dynamism.

Expanding the global protected seascape with climate resilience in mind, to meet stated biodiversity and conservation objectives in a changing world, should be a key focus for the post-2020 biodiversity framework. Addressing the crucial challenges of climate change and biodiversity loss underpins efforts to improve human well-being. To meet societal objectives as articulated in the United Nations Sustainable Development Goals, and beyond, these agendas need to be twinned, operationalized, and effectively integrated into global seascape conservation and management.

SUPPLEMENTARY MATERIALS

Supplementary material for this article is available at http://advances.sciencemag.org/cgi/content/full/5/11/eaay9969/DC1

Section S1. Methods for review of climate change adaptation in MPAs

Section S2. Methods for derivation assessing MPA vulnerability (see Fig. 2)

Table S1. References for the marine specific papers that incorporated climate change adaptation in MPA design or management presented in Fig. 1.

Table S2. Google scholar search term results for April 2019.

Table S3. Examples where climate change adaptation has been implemented in the design or management of an MPA.

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