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## Measurement, mechanisms, and management recommendations for how MPAs can provide climate resilience

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1 **Measurements, mechanisms, and management recommendations for how**  
2 **marine protected areas can provide climate resilience**

3  
4 Type of contribution: Short Communication

6 **Abstract**

7 The number of marine protected areas (MPAs) implemented globally is rising, with calls to  
8 protect 30% of the ocean by 2030. One potential benefit of MPAs is increased resilience to  
9 anthropogenic climate change impacts. However, realistic ecological expectations are needed  
10 to identify the conditions that may yield resilience benefits and determine effective evaluation  
11 methods. To date, global meta-analyses have consistently shown positive ecological effects of  
12 protection, yet assessing resilience effects has been more complex. 'Resilience' is challenging to  
13 define and measure and may manifest at various spatiotemporal scales. Additionally,  
14 identifying an appropriate reference point to quantify resilience is challenging. Robust  
15 assessments require long time series to estimate variability or opportunistic observation of  
16 disturbance and recovery. Such data are not always available. We suggest an alternative,  
17 complementary approach. First, it is crucial to define the ecological and socioeconomic  
18 mechanisms by which an MPA could provide any resilience benefit to the human-natural  
19 system; these mechanisms are both limited and context-dependent. Then, we can measure  
20 indicators of resilience to assess the contribution of such mechanisms inside MPAs. This  
21 provides a pathway to assess how conservation influences adaptive capacity, overcoming the  
22 challenge of directly measuring resilience itself. Finally, it is critical to recognize that MPAs are  
23 only one tool in a portfolio of management actions that could improve resilience. They should  
24 not be misconstrued as standalone solutions, but rather as integral parts of a comprehensive  
25 approach to ecosystem-based sustainability management.

26  
27 **Keywords:** Marine Protected Areas, marine reserves, climate resilience, adaptive management,  
28 age structure, functional diversity, climate smart

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31 **Introduction**

32 The post-2020 Global Biodiversity Framework, agreed upon at the Conference of the  
33 Parties 15 (COP15) in December 2022, calls for protecting 30% of the global ocean by 2030  
34 through marine protected areas (MPAs) and other effective area-based conservation measures,  
35 while adapting to climate change [1]. Consistent with that agreement and and previous  
36 international commitments, the number of MPAs implemented globally continues to rise [2].  
37 Indeed, at the time of this writing, the global coverage of MPAs was approximately 8% of the  
38 ocean, and growing [3]; but only a fourth is effectively implemented and protected [4] limiting  
39 our ability to measure the role of MPAs for providing climate resilience.

40 Historically, MPAs have been designed and established to protect ecological populations  
41 from human activities and promote biodiversity and habitat conservation [5–7]. That role has  
42 largely been effective, and MPAs (particularly no-take MPAs that prohibit all fishing activities)  
43 are most often effective in rebuilding overexploited fish populations within their boundaries  
44 (e.g., [8–10]). MPAs are also embedded in social-ecological systems and can provide benefits in  
45 that context [11,12]. However, as anthropogenic climate change increasingly threatens species,  
46 populations, and ecosystems [13–16], there is an emerging science aiming to evaluate the role  
47 of MPAs as potential management tools to mitigate climate impacts [17].

48 Marine protected areas are fundamentally local management tools and are unlikely to  
49 affect the overall global trajectory of the atmospheric carbon cycle (notwithstanding some  
50 recent hope for 'blue carbon' sequestration solutions; [18]). Therefore the climate mitigation  
51 role of MPAs has centered on their ability to augment the *resilience* of social-ecological systems  
52 (with resilience broadly interpreted as the ability of a system to retain, or rapidly return to, its  
53 structure and function when perturbed; we discuss this further in the next section [19,20]). This  
54 includes resilience to both long-term changes (e.g., geographical range shifts; [21–23]) and the  
55 short-term climate extremes that are increasing in frequency and magnitude (e.g., marine  
56 heatwaves; [24–27]). However, resilience as a management objective could be challenging to  
57 implement if not defined precisely, so that actions can be linked to an adaptive management  
58 framework [28–31].

59 By adaptive management, we mean the process of predicting the likely effects of a  
60 management action, monitoring the response of the system following that management action,  
61 and then comparing outcomes to predictions to evaluate success and inform the next set of  
62 actions (Fig. 1). The concept of resilience can be broad and nebulous, making it challenging to  
63 set standardized approaches to its measurement [32]. While it is relatively straightforward to  
64 identify signs of population declines, fishery collapses, or other types of management failures,  
65 detecting resilience *per se* (i.e., the absence of those failures) is more complex without  
66 measurable criteria. Here, we propose a new approach to address this challenge to ground  
67 conversations about climate resilience and MPAs within the framework of adaptive  
68 management (Fig. 1).

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70 **What is resilience?**

71 A first step must be to define 'resilience' (e.g., in what measure? to what disturbance?)  
72 and specify the expected mechanism through which protection in MPAs could improve  
73 resilience to changing climate impacts [19,33]. There are dozens of possible definitions within  
74 the context of social-ecological systems [34–37]. One useful framework for defining resilience in  
75 ecology is to distinguish the response of a system (e.g., a population or ecosystem) to a single  
76 discrete disturbance – which involves both the magnitude of initial loss and the subsequent  
77 recovery time [38] – from the longer-term ability of a system to remain close to a steady state  
78 in the face of ongoing disturbances (Holling [39] termed these 'engineering' and 'ecological'  
79 resilience, respectively) (Fig. 1). A broader social-ecological view of resilience is conceptually the  
80 same, but would include the response of people to disturbances and associated effects on  
81 ecosystems, and the role of people in governing and managing these ecosystems [37,40].

82 We note that resilience may not be defined identically in different regions, ecosystems or  
83 countries, and may also differ under different planning objectives. Definitions might thus be  
84 specific to contexts. Having established those definitions, one can see the challenges that will  
85 be inherent in quantifying or detecting resilience (outlined in Fig. 1). To assess the response to a  
86 discrete disturbance, one must wait for an event and be ready to measure the response and  
87 recovery. Additionally, evaluating either recovery times, stability, or variability over time  
88 requires a pre-disturbance reference point or basis of comparison, just as historical climatology  
89 can be used to evaluate changes in physical variability in the ocean [41]. Finding appropriate  
90 reference points is challenging because long-term ecological data are rarely collected prior to  
91 MPA implementation, and because populations in protected areas undergo transient  
92 fluctuations in abundance as they transition from a fished to an unfished state. These transient  
93 dynamics mean populations would not be expected to be at a steady state for many years after  
94 implementation [42], even in the absence of climate-related perturbations. Thus, the time scale  
95 over which resilience benefits could accrue is uncertain. Moreover, given the limited portion of  
96 the ocean that is effectively protected [4], it is challenging to select suitable candidate MPAs for  
97 evaluating the resilience mechanism of interest.

98 Additionally, it is challenging to find suitable spatial 'control' reference points for  
99 evaluating change because MPAs are connected to the meta-ecosystems outside their  
100 boundaries, providing spill-over (and spill-in) of larvae and biomass [43]. The magnitude and  
101 effect size of any resilience benefit will also be context-dependent; for example, Hopf et al. [44]  
102 found that MPAs would provide little benefit in terms of buffering temporal variability in fishery  
103 yields if fishery management outside MPA boundaries is conservative. Perhaps it is not  
104 surprising, then, that a meta-analysis of the potential climate-change benefits of MPAs found  
105 only four studies suitable to quantify a temporal stability benefit [18]. Finally, evaluating a

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4 106 resilience target could require an unobserved counterfactual: how would the system have  
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6 107 responded to the disturbance in the absence of an MPA?  
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9 109 ***An alternative approach to thinking about resilience***

10 110 We propose here a new, alternative approach to thinking about MPA management for  
11 111 resilience (Fig. 1). Unlike prior efforts in this area, our proposed approach promotes setting  
12 112 realistic goals and timelines regarding resilience, as well as concrete targets for monitoring and  
13 113 evaluation within an adaptive management context. First, it is crucial to identify the ecological  
14 114 (and socioeconomic) mechanisms by which an MPA could provide any resilience benefit to the  
15 115 human-natural system; these mechanisms are both limited and vary from place to place  
16 116 [19,33]. In Table 1 we summarize a recent literature review of those potential mechanisms at  
17 117 different levels of biological organization, and published evidence of their existence [33]. To  
18 118 examine one of the mechanisms operating at a population level, a first-order consequence of  
19 119 ceasing fishing will be increased longevity and thus body size of fished species. Larger  
20 120 individuals could improve resilience in different ways, in different contexts [45]. For example, in  
21 121 abalone populations (*Haliotis corrugata* and *H. fulgens*), larger individuals inside two MPAs  
22 122 were less affected than non-protected abalone when exposed to a hypoxic event in 2010 in Isla  
23 123 Natividad, Baja California Sur, Mexico. Those MPAs also provided population-level resilience in  
24 124 the form of lower impact and faster recovery due to the greater fecundity of the surviving large  
25 125 abalone [46]. In another example, larger sea urchin predators (which are more abundant in  
26 126 MPAs) can feed on larger sea urchins and limit the potential of urchins to overgraze habitat-  
27 127 forming macroalgae on temperate reefs during marine heatwaves: In the California Channel  
28 128 Islands, larger California Sheephead (*Bodianus pulcher*) in MPAs prevented urchins from  
29 129 decimating kelp forests there during an extensive marine heatwave [47], and in Tasmania  
30 130 lobsters have played a similar role [48]. Similarly, protection of herbivorous parrotfishes in a  
31 131 Bahamian MPA led to suppression of macroalgal growth and faster recovery of coral cover  
32 132 following a bleaching event [49].

33 133 Thinking mechanistically also helps identify contexts in which protection should not be  
34 134 expected to produce a resilience benefit. For example, some temperate reef communities lack  
35 135 urchin predators that are fished, so urchin grazing would not be expected to be lower in MPAs  
36 136 [50]. On coral reefs, macroalgal overgrowth may not be the primary threat to coral populations,  
37 137 so protecting macroalgal grazers should not be expected to benefit corals [51]. Tempering  
38 138 expectations for what MPAs can accomplish, and how soon, is an important aspect of adaptive  
39 139 management.

40 140 A focus on mechanisms provides a constructive avenue for adaptive management.  
41 141 Specifically, monitoring the factors associated with specific mechanisms (e.g., the size structure  
42 142 of a protected fish population, which can indicate reproductive capacity and potential trophic  
43 143 effect), will be more effective than waiting for climate-related disturbances to occur, or waiting

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144 to accrue a long enough time series to estimate the variability of a system [42,47]. Thus, this  
145 new approach provides a proactive rather than reactive approach to quantifying resilience.

146 In Table 1 we identify some mechanisms that could be monitored under this framework,  
147 and note other mechanisms that appear to defy monitoring with existing technology. In Figure  
148 1 we summarize the contrast between measuring resilience and monitoring for resilience  
149 mechanisms. Centering adaptive management on mechanisms allows for quantitative  
150 projections of the time scale over which resilience benefits should accrue, and how soon they  
151 should be detectable [52,53]. For example, population dynamics theory suggests that MPAs  
152 should have an initial negative effect on fishery yields, even if they will later increase yields via  
153 spillover [54], an important prediction for the socio-economic consequences of MPA  
154 protection.

155 Finally, it is critical to recognize that MPAs are only one tool in a portfolio of management  
156 actions that could improve resilience and cannot be expected to work alone outside of broader  
157 ecosystem-based management. Because MPAs are nearly always embedded within meta-  
158 ecosystems, activities beyond their boundaries affect populations and communities of marine  
159 organisms within the MPAs, and the benefits of MPAs beyond their boundaries are limited by  
160 those activities [55–57].

161 Achieving international aspirations of protecting 30% of the oceans by 2030 while  
162 adapting to climate change requires integrating climate resilience and socio-economic  
163 adaptation into the MPA planning process [58–62]. For example, researchers and practitioners  
164 are developing new frameworks, tools, and approaches for designing climate-smart MPAs  
165 [22,63] to provide managers with guidelines and design principles to support the resilience of  
166 biodiversity to climate change impacts. These frameworks and recommendations can benefit  
167 from a more refined definition of resilience objectives, and a better understanding of the  
168 system-specific mechanisms supporting resilience. Failing to do so may result in unrealistic  
169 resilience goals for MPAs and potentially undermine any real capacity MPAs have to support  
170 marine ecosystems.

171 In addition to developing new conceptual tools, we call for research to test the framework  
172 we have proposed here, and specifically to fill in some of the gaps in Table 1 (e.g., a better  
173 understanding of the expected relationship between organisms body size and stress tolerance  
174 is needed, because conflicting evidence across taxa makes it difficult to make general  
175 predictions [46,64]). We acknowledge that there will also be challenges in applying our  
176 framework to MPA management. In some cases, the challenge may be data availability – for  
177 example, measuring fish population size structure with visual surveys is relatively  
178 straightforward on coral reefs but more challenging in high-latitude or deepwater MPAs. In  
179 other contexts, socio-political mechanisms have more influence on MPA success [65].

180 While our approach and related resilience literature is focused mostly on ecological  
181 mechanisms, there are future opportunities to include the human and governance factors that

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4 182 affect resilience, moving towards a more integrated social-ecological systems view of resilience  
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6 183 [40](Table 1). In particular, how people respond to changes in ecosystems (e.g., increasing  
7 184 fishing pressure in response to decreased biomass due to a heatwave) has direct implications  
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9 185 for ecological resilience. This presents an excellent opportunity for the co-creation of  
10 186 knowledge surrounding resilience with people and institutions embedded in these social-  
11  
12 187 ecological systems [66].

13 188 As resource managers and stewards grapple with the changing climate, effective adaptive  
14 189 management is essential to ensure that conservation efforts are effective and efficient. This will  
15 190 require being realistic about what MPAs can and cannot achieve for climate resilience, what  
16 191 mechanisms are at play, and the time scales over which those mechanisms can develop to  
17 192 produce the desired effect.  
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Table 1. Summary of evidence for proposed mechanisms by which MPAs could provide climate resilience. The table organizes proposed ecological and socio-economic effects of MPAs and MPA networks by level of ecological organization (from physical factors to ecosystems and then human communities), and for each effect lists proposed mechanisms by which climate resilience could be promoted. Where possible, a potential measurable response variable that could be used as an indicator for that resilience mechanism is proposed. For each effect and mechanism, we indicate whether there is strong evidence in the expected direction (✓+), modest evidence (✓), mixed evidence (~), or no assessment found (?), based on a non-exhaustive review of the global MPA literature. References supporting each assessment of evidence is provided in Table S1. Modified from Hofmann et al. (2021).

Effect of MPA/MPA network	Support for MPA effect	Hypothesized Resilience Mechanism	Support for resilience effect	Mechanism-based Monitoring Options
REDUCTION OF ENVIRONMENTAL STRESS				
Increased biogenic habitat such as kelp and sea grasses; Increased biomass of macrophytes	✓	Buffering physical stressors such as storms and surge	✓	Monitor for increases in amount or quality of biogenic habitat
		Increased resistance to ocean acidification and hypoxia via intact plant communities that drawdown CO <sub>2</sub> and produce dissolved oxygen	✓	
ORGANISMAL RESILIENCE				
Increased physical and nutritive condition of organisms	✓	Increased organismal tolerance to climate stress among healthier individuals	✓	Difficult to monitor non-destructively
Increased body sizes	✓+	Increased resistance/tolerance to environmental stress among larger individuals	~	Monitor population size structure, identify whether it resembles the unfished state
POPULATION RESILIENCE				
Larger population sizes	✓+	Increased recovery after disturbance via higher	?	Monitor for increases in abundance of populations of interest

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Effect of MPA/MPA network	Support for MPA effect	Hypothesized Resilience Mechanism	Support for resilience effect	Mechanism-based Monitoring Options
		probability of reproductive success		
		Increased resistance from stochastic demographic loss below some critical threshold of recovery	?	
		Greater response to selection (greater resistance to genetic drift)	?	
Older/Larger individuals in MPAs	✓+	Faster recovery by maintaining greater reproductive output from larger individuals	✓	Monitor population size structure, identify whether it resembles the unfished state
Complete (full) age structure	✓	Make a population less vulnerable to a series of poor reproductive years (storage effect)	✓	Monitor population size structure, identify whether it resembles the unfished state
Maintenance of genetic diversity	✓	Greater likelihood of resistant genotypes and increased potential for recovery via evolutionary rescue	✓+	Monitor genetic diversity of species of interest
Networks encompass sites that are climate refugia	✓	Increased resistance and recovery of meta-population via spatial refugia of some populations from environmental stress	✓	Compare network map to results of downscaled climate projections, identify whether the MPA in a refugia region
Increased biogenic habitat	✓	Increased population vital rates due to intact nursery habitats	✓+	Monitor for increases in populations of habitat-forming species
ECOSYSTEM RESILIENCE				

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Effect of MPA/MPA network	Support for MPA effect	Hypothesized Resilience Mechanism	Support for resilience effect	Mechanism-based Monitoring Options
Maintenance of taxonomic and functional diversity	✓+	Increased resistance to climate change via higher functional redundancy	?	Monitor changes community composition, compare to trophic interaction network to identify whether redundancies have been formed
		Increased potential for resistance and recovery via differential responses (portfolio effect)	✓+	
Maintenance of trophic linkages via large body sizes	✓+	Increased resistance to invading/range shifting species that cause community shifts through predation	✓	Monitor population size structure of higher trophic level species, identify whether it resembles the unfished state
		Increased resistance to disease epidemics via suppression of population outbreaks	✓	Monitor changes community composition, compare to trophic interaction network to identify whether redundancies have been formed
Increased connectivity (MPA networks)	?	Increased resistance of communities undergoing range shifts via stepping stones of protection from harvest or disturbance	?	Difficult to estimate using current technologies
<b>HUMAN DIMENSIONS AND COMMUNITY RESILIENCE</b>				
Regulations and enforcement that ensure reduction	✓+	Spill-over for fisheries	✓	Monitor the spatial distribution of fishing effort and landings

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Effect of MPA/MPA network	Support for MPA effect	Hypothesized Resilience Mechanism	Support for resilience effect	Mechanism-based Monitoring Options
of fishing pressures				
		Post-disaster food security via increase in productivity of harvestable species	✓	
Serve as a draw for tourism	✓+	Increased economic resilience in the face of climate stressors	?	Survey tourism operators to determine if business has increased.
Increased biogenic habitat buffers strong waves and storm surges	✓	Protection against damage from extreme storm events	✓	Monitor for increases in populations of habitat-forming species
Cultural, spiritual, and aesthetic benefits	~	Protect culturally significant species and habitats, existence value of certain species or habitats, cultural/spiritual benefits of healthy ocean habitat	?	Survey community members, stakeholders, and rightsholders

**Figure Legends**

Figure 1. Current state-based, and proposed alternative mechanism-based, approaches to defining and monitoring for resilience in marine protected areas (MPAs).



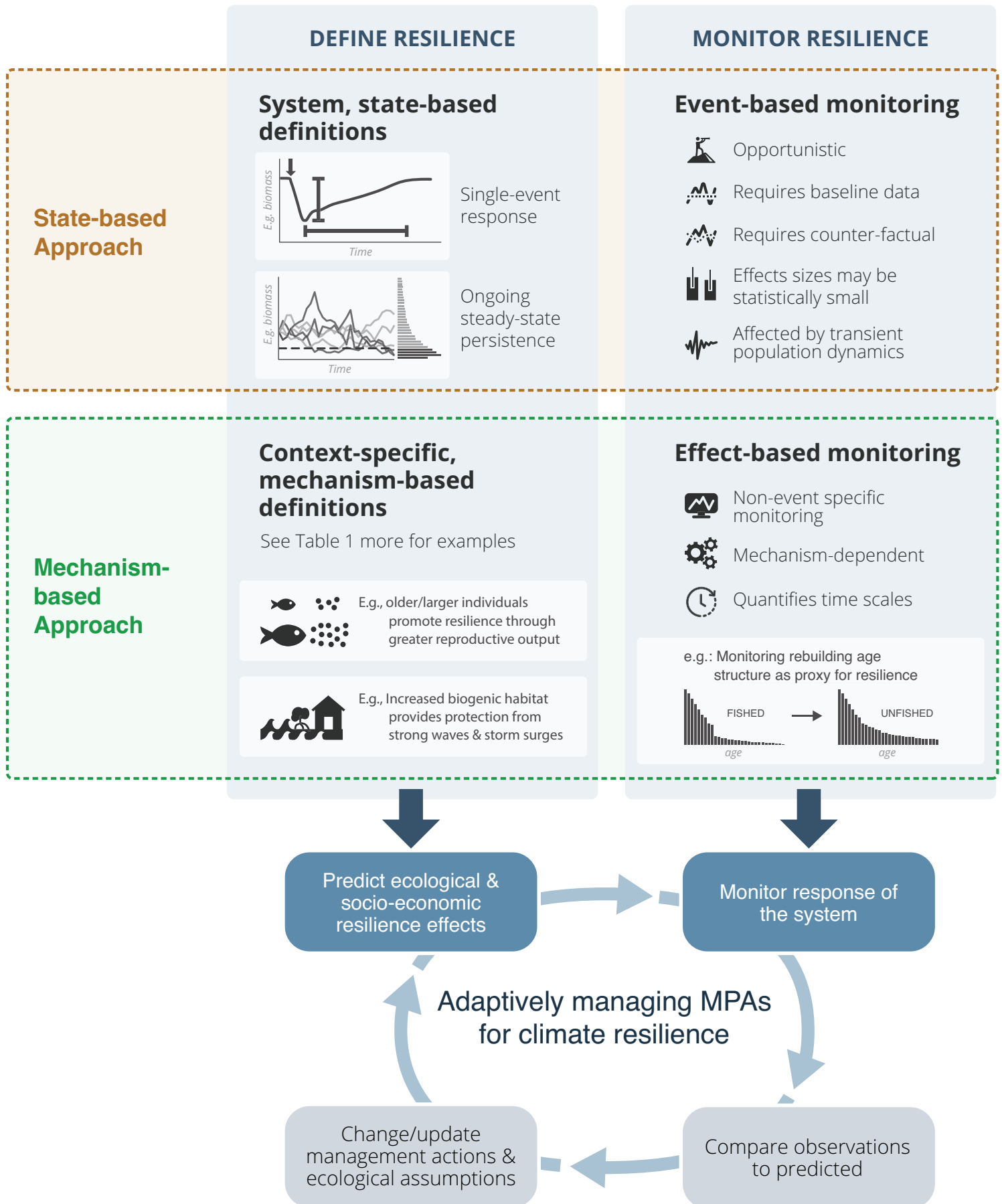


Table 1. Summary of evidence for proposed mechanisms by which MPAs could provide climate resilience. The table organizes proposed ecological and socio-economic effects of MPAs and MPA networks by level of ecological organization (from physical factors to ecosystems and then human communities), and for each effect lists proposed mechanisms by which climate resilience could be promoted. Where possible, a potential measurable response variable that could be used as an indicator for that resilience mechanism is proposed. For each effect and mechanism, we indicate whether there is strong evidence in the expected direction ( $\uparrow+$ ), modest evidence ( $\uparrow$ ), mixed evidence ( $\sim$ ), or no assessment found (?), based on a non-exhaustive review of the global MPA literature. References supporting each assessment of evidence is provided in Table S1. Modified from Hofmann et al. (2021).

Effect of MPA/MPA network	Support for MPA effect	Hypothesized Resilience Mechanism	Support for resilience effect	Mechanism-based Monitoring Options
REDUCTION OF ENVIRONMENTAL STRESS				
Increased biogenic habitat such as kelp and sea grasses; Increased biomass of macrophytes	$\uparrow$	Buffering physical stressors such as storms and surge		Monitor for increases in amount or quality of biogenic habitat
		Increased resistance to ocean acidification and hypoxia via intact plant communities that drawdown CO <sub>2</sub> and produce dissolved oxygen	$\uparrow$	
ORGANISMAL RESILIENCE				
Increased physical and nutritive condition of organisms	$\uparrow$	Increased organismal tolerance to climate stress among healthier individuals	$\uparrow$	Difficult to monitor non-destructively
Increased body sizes	$\uparrow+$	Increased resistance/tolerance to environmental stress among larger individuals	$\sim$	Monitor population size structure, identify whether it resembles the unfished state
POPULATION RESILIENCE				
Larger population sizes	$\uparrow+$	Increased recovery after disturbance via higher probability of	?	Monitor for increases in abundance of populations of interest

Effect of MPA/MPA network	Support for MPA effect	Hypothesized Resilience Mechanism	Support for resilience effect	Mechanism-based Monitoring Options
		reproductive success		
		Increased resistance from stochastic demographic loss below some critical threshold of recovery	?	
		Greater response to selection (greater resistance to genetic drift)	?	
Older/Larger individuals in MPAs	↑+	Faster recovery by maintaining greater reproductive output from larger individuals	↑	Monitor population size structure, identify whether it resembles the unfished state
Complete (full) age structure	↑	Make a population less vulnerable to a series of poor reproductive years (storage effect)	↑	Monitor population size structure, identify whether it resembles the unfished state
Maintenance of genetic diversity	↑	Greater likelihood of resistant genotypes and increased potential for recovery via evolutionary rescue	↑+	Monitor genetic diversity of species of interest
Networks encompass sites that are climate refugia	↑	Increased resistance and recovery of meta-population via spatial refugia of some populations from environmental stress	↑	Compare network map to results of downscaled climate projections, identify whether the MPA in a refugia region
Increased biogenic habitat	↑	Increased population vital rates due to intact nursery habitats	↑+	Monitor for increases in populations of habitat-forming species
<b>ECOSYSTEM RESILIENCE</b>				
Maintenance of taxonomic and	↑+	Increased resistance to climate change	?	Monitor changes community composition,

<b>Effect of MPA/MPA network</b>	<b>Support for MPA effect</b>	<b>Hypothesized Resilience Mechanism</b>	<b>Support for resilience effect</b>	<b>Mechanism-based Monitoring Options</b>
functional diversity		via higher functional redundancy		compare to trophic interaction network to identify whether redundancies have been formed
		Increased potential for resistance and recovery via differential responses (portfolio effect)	↑+	
Maintenance of trophic linkages via large body sizes	↑+	Increased resistance to invading/range shifting species that cause community shifts through predation	↑	Monitor population size structure of higher trophic level species, identify whether it resembles the unfished state
		Increased resistance to disease epidemics via suppression of population outbreaks	↑	Monitor changes community composition, compare to trophic interaction network to identify whether redundancies have been formed
Increased connectivity (MPA networks)	?	Increased resistance of communities undergoing range shifts via stepping stones of protection from harvest or disturbance	?	Difficult to estimate using current technologies
<b>HUMAN DIMENSIONS AND COMMUNITY RESILIENCE</b>				
Reduction of fishing pressures	↑+	Spill-over for fisheries	↑	Monitor the spatial distribution of fishing effort and landings
		Post-disaster food security via increase	↑	

Effect of MPA/MPA network	Support for MPA effect	Hypothesized Resilience Mechanism	Support for resilience effect	Mechanism-based Monitoring Options
		in productivity of harvestable species		
Serve as a draw for tourism	↑+	Increased economic resilience in the face of climate stressors	?	Survey tourism operators to determine if business has increased.
Increased biogenic habitat buffers strong waves and storm surges	↑	Protection against damage from extreme storm events	↑	Monitor for increases in populations of habitat-forming species
Cultural, spiritual, and aesthetic benefits	~	Protect culturally significant species and habitats, existence value of certain species or habitats, cultural/spiritual benefits of healthy ocean habitat	?	Survey community members, stakeholders, and rightsholders

## Author contributions

### *Author Contributions*

J. Wilson White: Conceptualization, Funding Acquisition, Writing – Original Draft. Jess K. Hopf, Nur Arafeh-Dalmau, Natalie C. Ban, Amanda Bates, Joachim Claudet, Cori Lopazanski, Jennifer M. Sunday: Conceptualization, Writing – Review & Editing. Jennifer E. Caselle: Conceptualization, Funding Acquisition, Writing – Review & Editing

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