Marine Policy 171 (2025) 106419

Contents lists available at ScienceDirect

Marine Policy

journal homepage: www.elsevier.com/locate/marpol

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

J. Wilson White [a,*], Jess K. Hopf [a], Nur Arafeh-Dalmau [b,c], Natalie C. Ban [d], Amanda E. Bates [e], Joachim Claudet [f], Cori Lopazanski [g], Jennifer M. Sunday [h], Jennifer E. Caselle [i]

[a] Department of Fisheries, Wildlife, and Conservation Sciences, Coastal Oregon Marine Experiment Station, Oregon State University, Newport, OR, USA
[b] Oceans Department, Hopkins Marine Station and Center for Ocean Solutions, Stanford University, Pacific Grove, CA 93950, USA
[c] Department of Geography, University of California Los Angeles, Los Angeles, CA, USA
[d] School of Environmental Studies, University of Victoria, Victoria, BC, Canada
[e] Department of Biology, University of Victoria, Victoria, BC, Canada
[f] National Center for Scientific Research, PSL Université Paris, CRIOBE, CNRS-EPHE-UPVD, Paris, France
[g] Bren School of Science and Management, University of California, Santa Barbara, CA, USA
[h] Department of Biology, McGill University, Montreal, Quebec, Canada
[i] Marine Science Institute, University of California Santa Barbara, Santa Barbara, CA USA

ARTICLE INFO

Keywords:
Marine Protected Areas
Marine reserves
Climate resilience
Adaptive management
Age structure
Functional diversity
Climate smart

ABSTRACT

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

1. Introduction

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

Historically, MPAs have been designed and established to protect ecological populations from human activities and promote biodiversity and habitat conservation [5–7]. That role has largely been effective, and MPAs (particularly no-take MPAs that prohibit all fishing activities) are most often effective in rebuilding overexploited fish populations within their boundaries (e.g., [8–10]). MPAs are also embedded in social-ecological systems and can provide benefits in that context [11,

* Corresponding author.
E-mail address: will.white@oregonstate.edu (J.W. White).

https://doi.org/10.1016/j.marpol.2024.106419
Received 16 November 2023; Received in revised form 23 August 2024; Accepted 27 August 2024
Available online 7 October 2024

12]. However, as anthropogenic climate change increasingly threatens species, populations, and ecosystems [13–16], there is an emerging science aiming to evaluate the role of MPAs as potential management tools to mitigate climate impacts [17].

Marine protected areas are fundamentally local management tools and are unlikely to affect the overall global trajectory of the atmospheric carbon cycle (notwithstanding some recent hope for 'blue carbon' sequestration solutions; [18]). Therefore the climate mitigation role of MPAs has centered on their ability to augment the *resilience* of social-ecological systems (with resilience broadly interpreted as the ability of a system to retain, or rapidly return to, its structure and function when perturbed; we discuss this further in the next section [19, 20]). This includes resilience to both long-term changes (e.g., geographical range shifts; [21–23]) and the short-term climate extremes

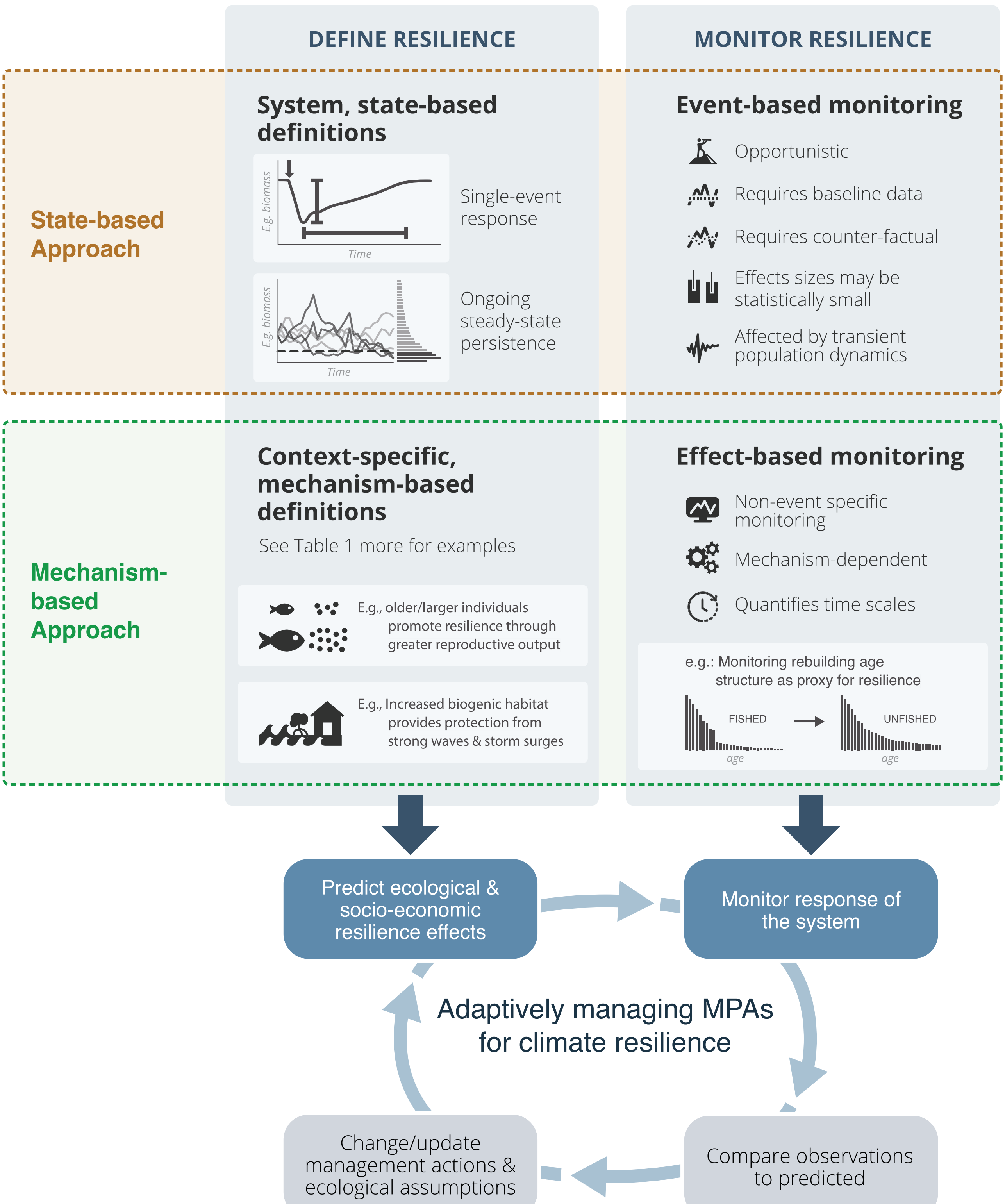

Fig. 1. Current state-based, and proposed alternative mechanism-based, approaches to defining and monitoring for resilience in marine protected areas (MPAs).

that are increasing in frequency and magnitude (e.g., marine heatwaves; [24–27]). However, resilience as a management objective could be challenging to implement if not defined precisely, so that actions can be linked to an adaptive management framework [28–31].

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

2. What is resilience?

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

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

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

3. An alternative approach to thinking about resilience

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

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

A focus on mechanisms provides a constructive avenue for adaptive management. Specifically, monitoring the factors associated with specific mechanisms (e.g., the size structure of a protected fish population, which can indicate reproductive capacity and potential trophic effect), will be more effective than waiting for climate-related disturbances to occur, or waiting to accrue a long enough time series to estimate the variability of a system [42,47]. Thus, this new approach provides a proactive rather than reactive approach to quantifying resilience.

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

Finally, it is critical to recognize that MPAs are only one tool in a portfolio of management actions that could improve resilience and cannot be expected to work alone outside of broader ecosystem-based

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.

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_2 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 probability of reproductive success	?	Monitor for increases in abundance of populations of interest
		Increased resistance from stochastic demographic loss below some critical threshold of recovery	?	
		Greater response to selection (greater resistance to genetic drift)	?	

Table 1 (*continued*)

Effect of MPA/ MPA network	Support for MPA effect	Hypothesized Resilience Mechanism	Support for resilience effect	Mechanism-based Monitoring Options
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 ofsome 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				
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	✓	Monitor changes community

(*continued on next page*)

Table 1 (*continued*)

Effect of MPA/ MPA network	Support for MPA effect	Hypothesized Resilience Mechanism	Support for resilience effect	Mechanism-based Monitoring Options
		epidemics via suppression of population outbreaks		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
HUMAN DIMENSIONS AND COMMUNITY RESILIENCE				
Regulations and enforcement that ensure reduction of fishing pressures	✓+	Spill-over for fisheries	✓	Monitor the spatial distribution of fishing effort and landings
		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

management. Because MPAs are nearly always embedded within meta-ecosystems, activities beyond their boundaries affect populations and communities of marine organisms within the MPAs, and the benefits of MPAs beyond their boundaries are limited by those activities [55–57].

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

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

While our approach and related resilience literature is focused mostly on ecological mechanisms, there are future opportunities to include the human and governance factors that affect resilience, moving towards a more integrated social-ecological systems view of resilience [40](Table 1). In particular, how people respond to changes in ecosystems (e.g., increasing fishing pressure in response to decreased biomass due to a heatwave) has direct implications for ecological resilience. This presents an excellent opportunity for the co-creation of knowledge surrounding resilience with people and institutions embedded in these social-ecological systems [66].

As resource managers and stewards grapple with the changing climate, effective adaptive management is essential to ensure that conservation efforts are effective and efficient. This will require being realistic about what MPAs can and cannot achieve for climate resilience, what mechanisms are at play, and the time scales over which those mechanisms can develop to produce the desired effect.

CRediT authorship contribution statement

Amanda Bates: Conceptualization, Writing – review & editing. **Joachim Claudet:** Conceptualization, Writing – review & editing. **Cori Lopazanski:** Conceptualization, Writing – review & editing. **Jennifer Sunday:** Conceptualization, Writing – review & editing. **J. Wilson White:** Conceptualization, Funding acquisition, Writing – original draft. **Jess Hopf:** Conceptualization, Writing – review & editing. **Nur Arafeh-Dalmau:** Conceptualization, Writing – review & editing. **Natalie Ban:** Conceptualization, Writing – review & editing. **Jennifer Caselle:** Conceptualization, Funding acquisition, Writing – review & editing.

Data availability

No data was used for the research described in the article.

Acknowledgements

The ideas in this manuscript were developed during panel discussions at a symposium during the 5th International Marine Protected Area Congress in Vancouver, British Columbia, in February 2023. The ideas presented here also benefited from discussions with other members of the California Ocean Protection Council Science Advisory Team Working Group on climate resilience and MPAs. The symposium and the writing of this manuscript were supported by the David and Lucile Packard Foundation (award 2021–73144). This is contribution 539 of the Partnership for Interdisciplinary Study of Coastal Oceans, funded primarily by the David and Lucile Packard Foundation.

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.marpol.2024.106419.

References

[1] Convention on Biological Diversity, First draft of the post-2020 global biodiversity framework, (2021). ⟨https://www.cbd.int/article/draft-1-global-biodiversity-framework⟩ (accessed May 10, 2023).
[2] M. Maestro, M.L. Pérez-Cayeiro, J.A. Chica-Ruiz, H. Reyes, Marine protected areas in the 21st century: current situation and trends, Ocean Coast. Manag. 171 (2019) 28–36, https://doi.org/10.1016/j.ocecoaman.2019.01.008.
[3] Marine Conservation Institute, MPA Atlas, (2023). ⟨https://mpatlas.org/⟩ (accessed May 10, 2023).
[4] E.P. Pike, J.M.C. MacCarthy, S.O. Hameed, N. Harasta, K. Grorud-Colvert, J. Sullivan-Stack, J. Claudet, B. Horta E Costa, E.J. Gonçalves, A. Villagomez, L. Morgan, Ocean protection quality is lagging behind quantity: applying a scientific framework to assess real marine protected area progress against the 30 by 30 target, Conserv. Lett. 17 (2024) e13020, https://doi.org/10.1111/conl.13020.
[5] J. Lubchenco, S.R. Palumbi, S.D. Gaines, S. Andelman, Plugging a hole in the ocean: the emerging science of marine reserves, Ecol. Appl. 13 (2003) S3–S7.
[6] E. Pikitch, E.A. Santora, A. Babcock, A. Bakun, R. Bonfil, D.O. Conover, P. Dayton, others, P. Doukakis, D. Fluharty, B. Heheman, Ecosystem-based fishery management, Science 305 (2004) 346–347.
[7] C.R. Margules, R.L. Pressey, Systematic conservation planning, Nature 405 (2000) 243–253.
[8] S.E. Lester, B.S. Halpern, K. Grorud-Colvert, J. Lubchenco, B.I. Ruttenberg, S. D. Gaines, S. Airame, R.R. Warner, Biological effects within no-take marine reserves: a global synthesis, Mar. Ecol. Prog. Ser. 384 (2009) 33–46, https://doi.org/10.3354/meps08029.
[9] J. Claudet, P. Guidetti, D. Mouillot, N.T. Shears, F. Micheli, Ecological effects of marine protected areas: conservation, restoration, and functioning, in: J. Claudet (Ed.), Marine Protected Areas: A Multidisciplinary Approach (Ecology, Biodiversity and Conservation), Cambridge University Press, Cambridge, UK, 2011.
[10] G.J. Edgar, R.D. Stuart-Smith, T.J. Willis, S. Kininmonth, S.C. Baker, S. Banks, N. S. Barrett, M.A. Becerro, A.T.F. Bernard, J. Berkhout, C.D. Buxton, S.J. Campbell, A.T. Cooper, M. Davey, S.C. Edgar, G. Försterra, D.E. Galván, A.J. Irigoyen, D. J. Kushner, R. Moura, P.E. Parnell, N.T. Shears, G. Soler, E.M.A. Strain, R. J. Thomson, Global conservation outcomes depend on marine protected areas with five key features, Nature 506 (2014) 216–220, https://doi.org/10.1038/nature13022.
[11] G.C. Barreto, M. Di Domenico, R.P. Medeiros, Human dimensions of marine protected areas and small-scale fisheries management: a review of the interpretations, Mar. Policy 199 (2020) 104040.
[12] A. Charles, L. Wilson, Human dimensions of marine protected areas, ICES J. Mar. Sci. 66 (2009) 6–15, https://doi.org/10.1093/icesjms/fsn182.
[13] G.T. Pecl, M.B. Araújo, J.D. Bell, J. Blanchard, T.C. Bonebrake, I.-C. Chen, T. D. Clark, R.K. Colwell, F. Danielsen, B. Evengård, L. Falconi, S. Ferrier, S. Frusher, R.A. Garcia, R.B. Griffis, A.J. Hobday, C. Janion-Scheepers, M.A. Jarzyna, S. Jennings, J. Lenoir, H.I. Linnetved, V.Y. Martin, P.C. McCormack, J. McDonald, N.J. Mitchell, T. Mustonen, J.M. Pandolfi, N. Pettorelli, E. Popova, S.A. Robinson, B.R. Scheffers, J.D. Shaw, C.J.B. Sorte, J.M. Strugnell, J.M. Sunday, M.-N. Tuanmu, A. Vergés, C. Villanueva, T. Wernberg, E. Wapstra, S.E. Williams, Biodiversity redistribution under climate change: impacts on ecosystems and human well-being, Science 355 (2017) eaai9214, https://doi.org/10.1126/science.aai9214.
[14] J.M. Sunday, The pace of biodiversity change in a warming climate, Nature 580 (2020) 460–461.
[15] Intergovernmental Panel on Climate Change (IPCC), A report of the Intergovernmental Panel on Climate Change. Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change, (2023).
[16] A.E. Bates, G.T. Pecl, S. Frusher, A.J. Hobday, T. Wernberg, D.A. Smale, J. M. Sunday, N.A. Hill, N.K. Dulvy, R.K. Colwell, N.J. Holbrook, E.A. Fulton, D. Slawinski, M. Feng, G.J. Edgar, B.T. Radford, P.A. Thompson, R.A. Watson, Defining and observing stages of climate-mediated range shifts in marine systems, Glob. Environ. Change 26 (2014) 27–38, https://doi.org/10.1016/j.gloenvcha.2014.03.009.
[17] C. Lopazanski, B. Foshay, J.L. Couture, D. Wagner, L. Hannah, E. Pidgeon, D. Bradley, Principles for climate resilience are prevalent in marine protected area management plans, Conserv. Lett. 16 (2023) e12972, https://doi.org/10.1111/conl.12972.
[18] J. Jacquemont, R. Blasiak, C. Le Cam, M. Le Gouellec, J. Claudet, Ocean conservation boosts climate change mitigation and adaptation, One Earth 5 (2022) 1126–1138, https://doi.org/10.1016/j.oneear.2022.09.002.
[19] K.J. Kroeker, M.H. Carr, P.T. Raimondi, J.E. Caselle, L. Washburn, S.R. Palumbi, J. A. Barth, F. Chan, B.A. Menge, K. Milligan, M. Novak, J.W. White, Planning for change: assessing the potential role of marine protected areas and fisheries management approaches for resilience management in a changing ocean, Oceanography 32 (2019) 116–125.
[20] S.A. Levin, J. Lubchenco, Resilience, robustness, and marine ecosystem-based management, BioScience 58 (2008) 27–32, https://doi.org/10.1641/B580107.
[21] E. Fuller, E. Brush, M.L. Pinsky, The persistence of populations facing climate shifts and harvest, Ecosphere 6 (2015) art153, https://doi.org/10.1890/ES14-00533.1.
[22] N. Arafeh-Dalmau, A. Munguia-Vega, F. Micheli, A. Vilalta-Navas, J.C. Villaseñor-Derbez, M. Précoma-de La Mora, D.S. Schoeman, A. Medellín-Ortíz, K. C. Cavanaugh, O. Sosa-Nishizaki, T.L.U. Burnham, C.J. Knight, C.B. Woodson, M. Abas, A. Abadía-Cardoso, O. Aburto-Oropeza, M.W. Esgro, N. Espinosa-Andrade, R. Beas-Luna, N. Cardenas, M.H. Carr, K.E. Dale, F. Cisneros-Soberanis, A. L. Flores-Morales, S. Fulton, E. García-Rodríguez, A. Giron-Nava, M.G. Gleason, A. L. Green, A. Hernández-Velasco, B. Ibarra-Macías, A.F. Johnson, J. Lorda, L. Malpica-Cruz, G. Montaño-Moctezuma, C. Olguín-Jacobson, A. Parés-Sierra, P. T. Raimondi, G. Ramírez-Ortiz, A. Ramírez-Valdez, H. Reyes-Bonilla, E. Saarman, L.E. Saldaña-Ruiz, A. Smith, C. Soldatini, A. Suárez, G. Torres-Moye, M. Walther, E. B. Watson, S. Worden, H.P. Possingham, Integrating climate adaptation and transboundary management: guidelines for designing climate-smart marine protected areas, S2590332223004529, One Earth (2023), https://doi.org/10.1016/j.oneear.2023.10.002.
[23] N. Arafeh-Dalmau, I. Brito-Morales, D.S. Schoeman, H.P. Possingham, C.J. Klein, A. J. Richardson, Incorporating climate velocity into the design of climate-smart networks of marine protected areas, Methods Ecol. Evol. 12 (2021) 1969–1983, https://doi.org/10.1111/2041-210X.13675.
[24] N. Arafeh-Dalmau, D.S. Schoeman, G. Montaño-Moctezuma, F. Micheli, L. Rogers-Bennett, C. Olguin-Jacobson, H.P. Possingham, Marine heat waves threaten kelp forests, 635–635, Science 367 (2020), https://doi.org/10.1126/science.aba5244.
[25] K.E. Smith, M.T. Burrows, A.J. Hobday, N.G. King, P.J. Moore, A. Sen Gupta, M. S. Thomsen, T. Wernberg, D.A. Smale, Biological Impacts of Marine Heatwaves, Annu. Rev. Mar. Sci. 15 (2023) 119–145, https://doi.org/10.1146/annurev-marine-032122-121437.
[26] J.G. Smith, C.M. Free, C. Lopazanski, J. Brun, C.R. Anderson, M.H. Carr, J. Claudet, J.E. Dugan, J.G. Eurich, T.B. Francis, S.L. Hamilton, D. Mouillot, P.T. Raimondi, R. M. Starr, S.L. Ziegler, K.J. Nickols, J.E. Caselle, A marine protected area network does not confer community structure resilience to a marine heatwave across coastal ecosystems, Glob. Change Biol. 29 (2023) 5634–5651, https://doi.org/10.1111/gcb.16862.
[27] S.L. Ziegler, R.O. Brooks, S.L. Hamilton, B.I. Ruttenberg, J.A. Chiu, R.T. Fields, G. T. Waltz, C. Shen, D.E. Wendt, R.M. Starr, External fishing effort regulates positive effects of no-take marine protected areas, Biol. Conserv. 269 (2022) 109546, https://doi.org/10.1016/j.biocon.2022.109546.
[28] C. Walters, Adaptive management of renewable resources, 1986.
[29] J.W. White, L.W. Botsford, M.L. Baskett, L.A. Barnett, R.J. Barr, A. Hastings, Linking models with monitoring data for assessing performance of no-take marine reserves, Front. Ecol. Environ. 9 (2011) 390–399, https://doi.org/10.1890/100138.
[30] R.Q. Grafton, T. Kompas, Uncertainty and the active adaptive management of marine reserves, Mar. Policy 29 (2005) 471–479, https://doi.org/10.1016/j.marpol.2004.07.006.
[31] M.C. Runge, An Introduction to Adaptive Management for Threatened and Endangered Species, J. Fish. Wildl. Manag. 2 (2011) 220–233, https://doi.org/10.3996/082011-JFWM-045.
[32] E. McLeod, R. Salm, A. Green, J. Almany, Designing marine protected area networks to address the impacts of climate change, Front. Ecol. Environ. 7 (2009) 362–370, https://doi.org/10.1890/070211.
[33] G.E. Hofmann, E.L. Hazen, R.F. Ambrose, D. Aseltine-Neilson, H. Carter, J.E. Caselle, F. Chan, D. Kone, A. Levine, F. Micheli, D. Panos, J. Sunday, J.W. White, Climate resilience and California's Marine Protected Area Network: A report by the Ocean Protection Council Science Advisory Team Working Group and Ocean Science Trust, (2021).
[34] C.R. Allen, D.G. Angeler, B.C. Chaffin, D. Twidwell, A. Garmestani, Resilience reconciled, Nat. Sustain 2 (2019) 898–900, https://doi.org/10.1038/s41893-019-0401-4.
[35] S.L. Pimm, I. Donohue, J.M. Montoya, M. Loreau, Measuring resilience is essential to understand it, Nat. Sustain 2 (2019) 895–897, https://doi.org/10.1038/s41893-019-0399-7.
[36] P. Capdevila, I. Stott, M. Beger, R. Salguero-Gómez, Towards a Comparative Framework of Demographic Resilience, Trends Ecol. Evol. 35 (2020) 776–786, https://doi.org/10.1016/j.tree.2020.05.001.
[37] G.S. Cumming, C.R. Allen, N.C. Ban, D. Biggs, H.C. Biggs, D.H.M. Cumming, A. De Vos, G. Epstein, M. Etienne, K. Maciejewski, R. Mathevet, C. Moore, M. Nenadovic, M. Schoon, Understanding protected area resilience: a multi-scale, social-ecological approach, Ecol. Appl. 25 (2015) 299–319, https://doi.org/10.1890/13-2113.1.
[38] J. Ingrisch, M. Bahn, Towards a Comparable Quantification of Resilience, Trends Ecol. Evol. 33 (2018) 251–259, https://doi.org/10.1016/j.tree.2018.01.013.
[39] C.S. Holling, Engineering resilience versus ecological resilience, in: P. Schulze (Ed.), Engineering within Ecological Constraints, National Academy of Sciences, 1996, pp. 31–44.
[40] P.J.S. Jones, Governing marine protected areas: resilience through diversity, Routledge/Taylor & Francis Group, 2014.
[41] D.J. Amaya, M.G. Jacox, M.R. Fewings, V.S. Saba, M.F. Stuecker, R. R. Rykaczewski, A.C. Ross, C.A. Stock, A. Capotondi, C.M. Petrik, S.J. Bograd, M. A. Alexander, W. Cheng, A.J. Hermann, K.A. Kearney, B.S. Powell, Marine heatwaves need clear definitions so coastal communities can adapt, Nature 616 (2023) 29–32, https://doi.org/10.1038/d41586-023-00924-2.
[42] J.W. White, L.W. Botsford, A. Hastings, M.L. Baskett, D.M. Kaplan, L.A.K. Barnett, Transient responses of fished populations to marine reserve establishment, Conserv. Lett. 6 (2013) 180–191, https://doi.org/10.1111/j.1755-263x.2012.00295.x.

[43] E.A. Moffitt, W.J. W, L.W. Botsford, Accurate assessment of marine protected area success depends on metric and spatiotemporal scale of monitoring, Mar. Ecol. Prog. Ser. 489 (2013) 17–28, https://doi.org/10.3354/meps10425.

[44] J.K. Hopf, G.P. Jones, D.H. Williamson, S.R. Connolly, Marine reserves stabilize fish populations and fisheries yields in disturbed coral reef systems, Ecol. Appl. 29 (2019), https://doi.org/10.1002/eap.1905.

[45] J.W. White, C. Barceló, A. Hastings, L.W. Botsford, Pulse disturbances in age-structured populations: Life history predicts initial impact and recovery time, J. Anim. Ecol. 91 (2022) 2370–2383, https://doi.org/10.1111/1365-2656.13828.

[46] F. Micheli, A. Saenz-Arroyo, A. Greenley, L. Vazquez, J.A. Espinoza Montes, M. Rossetto, G.A. De Leo, Evidence That Marine Reserves Enhance Resilience to Climatic Impacts, PLoS ONE 7 (2012) e40832, https://doi.org/10.1371/journal.pone.0040832.

[47] J.H. Eisaguirre, J.M. Eisaguirre, K. Davis, P.M. Carlson, S.D. Gaines, J.E. Caselle, Trophic redundancy and predator size class structure drive differences in kelp forest ecosystem dynamics, Ecology 101 (2020), https://doi.org/10.1002/ecy.2993.

[48] S.D. Ling, C.R. Johnson, S.D. Frusher, K.R. Ridgway, Overfishing reduces resilience of kelp beds to climate-driven catastrophic phase shift, Proc. Natl. Acad. Sci. 106 (2009) 22341–22345.

[49] P.J. Mumby, A.R. Harborne, Marine reserves enhance the recovery of corals on Caribbean reefs, PLoS ONE 5 (2010) e8657, https://doi.org/10.1371/journal.pone.0008657.g001.

[50] J.K. Hopf, J.E. Caselle, J.W. White, No-take marine protected areas enhance the benefits of kelp-forest restoration for fish but not fisheries, Ecol. Lett. 25 (2022) 1665–1675, https://doi.org/10.1111/ele.14023.

[51] J.F. Bruno, I.M. Côté, L.T. Toth, Climate Change, Coral Loss, and the Curious Case of the Parrotfish Paradigm: Why Don't Marine Protected Areas Improve Reef Resilience?, (2018) 30.

[52] J.K. Hopf, J.E. Caselle, J.W. White, Recruitment variability and sampling design interact to influence the detectability of protected area effects, Ecol. Appl. 32 (2022), https://doi.org/10.1002/eap.2511.

[53] J.K. Hopf, J.W. White, Extreme events delay the detection of marine protected area effects: Implications for monitoring and management, Biol. Conserv. 285 (2023) 110250, https://doi.org/10.1016/j.biocon.2023.110250.

[54] J.K. Hopf, G.P. Jones, D.H. Willamson, S.R. Connolly, Fishery consequences of marine reserves: short-term pain for longer-term gain, 150825143423007, Ecol. Appl. (2015), https://doi.org/10.1890/15-0348.1.

[55] D.S. Holland, R.J. Brazee, Marine reserves for fisheries management, Mar. Resour. Econ. 11 (1996) 157–172.

[56] J.W. White, L.W. Botsford, E.A. Moffitt, D.T. Fischer, Decision analysis for designing marine protected areas for multiple species with uncertain fishery status, Ecol. Appl. 20 (2010) 1523–1541.

[57] J.F. Bruno, A. Valdivia, Coral reef degradation is not correlated with local human population density, Sci. Rep. 6 (2016) 29778, https://doi.org/10.1038/srep29778.

[58] M.L. Pinsky, N.J. Mantua, Emerging adaptation approaches for climate-ready fisheries management, Oceanography 27 (2014) 146–159.

[59] S.D. Gaines, C. Costello, B. Owashi, T. Mangin, J. Bone, J.G. Molinos, M. Burden, H. Dennis, B.S. Halpern, C.V. Kappel, K.M. Kleisner, D. Ovando, Improved fisheries management could offset many negative effects of climate change, Sci. Adv. 4 (2018) eaao1378, https://doi.org/10.1126/sciadv.aao1378.

[60] M.L. Pinsky, E. Fenichel, M. Fogarty, S. Levin, B. McCay, K. St. Martin, R.L. Selden, T. Young, Fish and fisheries in hot water: What is happening and how do we adapt? Popul. Ecol. 63 (2021) 17–26, https://doi.org/10.1002/1438-390X.12050.

[61] N.C. Ban, M. Mills, J. Tam, C.C. Hicks, S. Klain, N. Stoeckl, M.C. Bottrill, J. Levine, R.L. Pressey, T. Satterfield, K.M. Chan, A social–ecological approach to conservation planning: embedding social considerations, Front. Ecol. Environ. 11 (2013) 194–202, https://doi.org/10.1890/110205.

[62] N.J. Bennett, J. Blythe, S. Tyler, N.C. Ban, Communities and change in the anthropocene: understanding social-ecological vulnerability and planning adaptations to multiple interacting exposures, Reg. Environ. Change 16 (2016) 907–926, https://doi.org/10.1007/s10113-015-0839-5.

[63] A.M. Queirós, E. Talbot, N.J. Beaumont, P.J. Somerfield, S. Kay, C. Pascoe, S. Dedman, J.A. Fernandes, A. Jueterbock, P.I. Miller, S.F. Sailley, G. Sará, L. M. Carr, M.C. Austen, S. Widdicombe, G. Rilov, L.A. Levin, S.C. Hull, S. F. Walmsley, C. Nic Aonghusa, Bright spots as climate-smart marine spatial planning tools for conservation and blue growth, Glob. Change Biol. 27 (2021) 5514–5531, https://doi.org/10.1111/gcb.15827.

[64] V. Messmer, M.S. Pratchett, A.S. Hoey, A.J. Tobin, D.J. Coker, S.J. Cooke, T. D. Clark, Global warming may disproportionately affect larger adults in a predatory coral reef fish, Glob. Change Biol. 23 (2017) 2230–2240, https://doi.org/10.1111/gcb.13552.

[65] P.J.S. Jones, S.D. Long, Analysis and discussion of 28 recent marine protected area governance (MPAG) case studies: Challenges of decentralisation in the shadow of hierarchy, Mar. Policy 127 (2021) 104362, https://doi.org/10.1016/j.marpol.2020.104362.

[66] E. Lähde, M. Pohja-Mykrä, J. Schreck, Co-creation of socio-ecological systems knowledge to adopt an Ecosystem-based Approach and Land-Sea Interactions in maritime spatial planning, Mar. Policy 163 (2024) 106079, https://doi.org/10.1016/j.marpol.2024.106079.