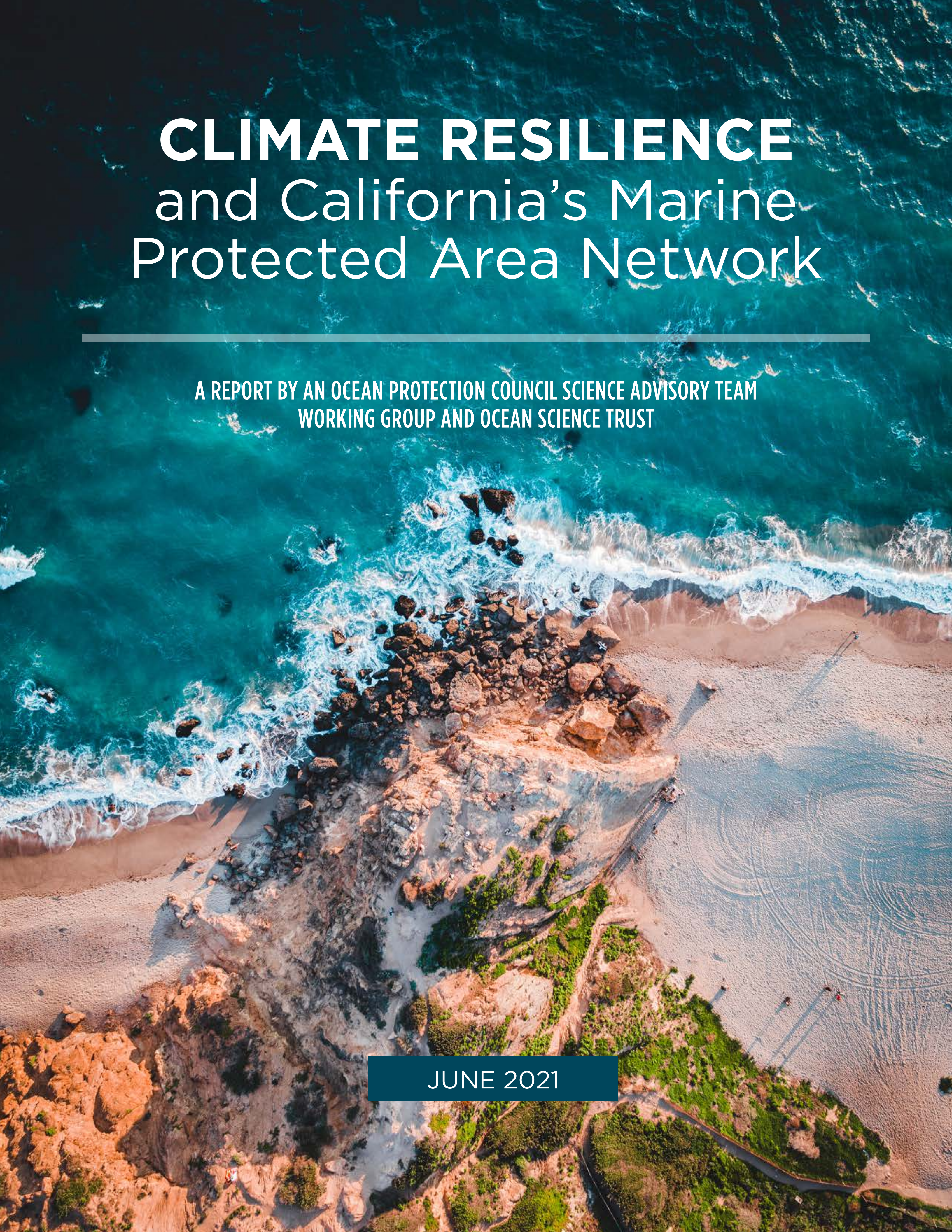
CLIMATE RESILIENCE and California's Marine Protected Area Network

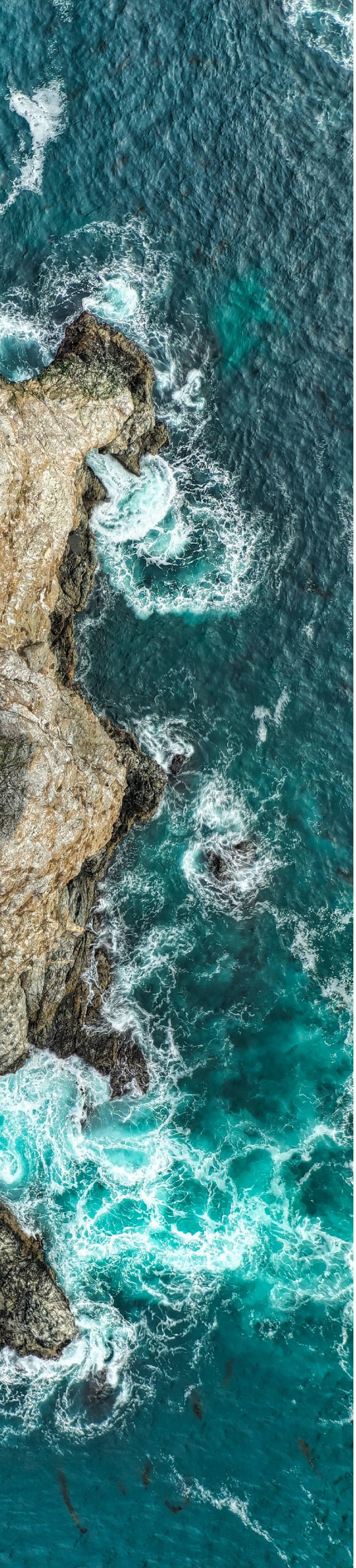
A REPORT BY AN OCEAN PROTECTION COUNCIL SCIENCE ADVISORY TEAM
WORKING GROUP AND OCEAN SCIENCE TRUST



JUNE 2021

In Memorium

This report is dedicated to the memory of Dr. Adrian Dahood-Fritz, Senior Scientist and Policy Advisor of the marine protected areas program at the California Ocean Protection Council.



About the Report

This report was produced by a working group of the Ocean Protection Council's Science Advisory Team (OPC SAT) and Ocean Science Trust on behalf of the Ocean Protection Council (OPC), California Department of Fish and Wildlife (CDFW), and Fish and Game Commission (FCG). In preparation for the first adaptive management review of California's MPA network, to be undertaken by CDFW in 2022, Ocean Science Trust convened an expert working group to explore the role of California's MPAs and MPA Network in imparting climate resilience. This working group was convened in parallel to the MPA Decadal Evaluation Working Group, tasked with developing scientific guidance that will be integral in supporting the decadal management review of the MPA network in 2022.

The development of this report took place during a time of uncertainty and turmoil with the effects of climate change becoming ever more present in the form of destructive wildfires, and the advent of the COVID-19 pandemic, which included major disruptions to almost all aspects of ocean and coastal research, natural resource management and university operations, as well as economic hardships for many Californians, including fishing communities and fleets. Even during a time of extreme uncertainty and turmoil, the working group acknowledged that climate change remains one of the most significant threats California faces, and should continue to be a major priority for state action now and into the future.

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The OPC SAT is a team of interdisciplinary scientists appointed by OPC to provide scientific advice on ocean and coastal issues. Working groups of the OPC SAT are composed of both SAT members and external experts and are formed to access, analyze, and synthesize scientific information on a particular topic or issue to inform policy, management, or investment decisions.

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The working group was convened from November 2019 - June 2021 and conducted their work via a series of remote meetings as well as an in-person workshop hosted by Ocean Science Trust in February 2020. Ocean Protection Council grantees who served as principal or co-principal investigators of MPA long-term monitoring projects were not considered for working group membership beyond one member, the Long-Term Monitoring Principal Investigator Liaison, to avoid conflict of interest.

California Ocean Science Trust

California Ocean Science Trust (OST) is a non-profit organization dedicated to accelerating progress towards a healthy and productive ocean future for California. Created by state legislation, OST bridges the gap between cutting-edge scientific research and sound ocean management. To learn more, visit http://www.oceansciencetrust.org.

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The Ocean Protection Council (OPC) is a cabinet-level state policy body nested within the California Natural Resources Agency. Created by the California Ocean Protection Act of 2004 (COPA), OPC advances the Governor's priorities for coastal and ocean policy and works broadly to ensure healthy coastal and ocean ecosystems for current and future generations by advancing innovative, science-based policy and management, making strategic investments, and catalyzing action through partnerships and collaboration. To learn more, visit http://www.opc.ca.gov.

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The California Department of Fish and Wildlife (CDFW) is the Department within the California Natural Resources Agency with designated authority to manage California's vast array of habitats and species. The Mission of the Department of Fish and Wildlife is to manage California's diverse fish, wildlife, and plant resources, and the habitats upon which they depend, for their ecological values and for their use and enjoyment by the public. To learn more, visit https://wildlife.ca.gov/

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Acknowledgements

Funding was provided by the California Ocean Protection Council. A Policy Advisory Committee, composed of leadership from the OPC (Mark Gold and Jenn Eckerle), CDFW (Becky Ota and Craig Shuman), and FGC (Susan Ashcraft and Melissa Miller-Henson) provided guidance to the working group throughout to ensure that the work product informs state policy and management needs and goals. Marissa Baskett and Kristy Kroeker provided review of this report at various points throughout the project as members of the OPC SAT to support sound scientific guidance for the State. Adrian Dahood-Fritz informed the working group charge and process. Report design by Hayley Carter.

Suggested citation: Hofmann, G.E.*, Hazen, E.L.*, Ambrose, R.F., Aseltine-Neilson, D., Carter H., Caselle, J.E., Chan, F., Kone, D., Levine, A., Micheli, F., Panos, D., Sunday, J., White, J.W. *Climate Resilience and California's Marine Protected Area Network: A Report by the Ocean Protection Council Science Advisory Team Working Group and California Ocean Science Trust*, June 2021. (*Working Group co-chairs, other co-authors in alphabetical order)

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Images: Melville McKee (cover image); Cameron Venti (About the Report)

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BCS – Baja California Sur
CCA – Central California
CDFW – California Department of Fish and Wildlife
Chl-a – chlorophyll a
ENSO – El Niño Southern Oscillation
FGC – California Fish and Game Commission
IPCC – Intergovernmental Panel on Climate Change
IUCN - International Union for Conservation of Nature
MHW – marine heatwave
MLPA – Marine Life Protection Act
MLPP – Marine Life Protection Plan
MPA – marine protected area
NCA – Northern California
NOAA – National Oceanic and Atmospheric Administration
NPGO - North Pacific Gyre Oscillation
OA – ocean acidification
OPC – California Ocean Protection Council
OPC SAT – Ocean Protection Council Science Advisory Team
OST – California Ocean Science Trust
PDO – Pacifi Decadal Oscillation
SCB – Southern California Bight
SMCAs – State Marine Conservation Areas
SST – sea surface temperature
UK – United Kingdom
UN – United Nations

McWay Falls, Big Sur, CA

Image: Ethan Dow

Executive Summary

- **Some of the most severe climate events on record are happening with increased frequency and intensity across the California Current Ecosystem, including marine heatwaves, low oxygen and pH conditions, and rising seas.** Marine populations, communities and ecosystems, including those within marine protected areas (MPAs), are facing widespread transformation, putting at risk all marine ecosystem services, including commercial and recreational fishing industries, public health, tourism, and coastal protection.
- **Ecosystems within MPAs are threatened by climate change, but MPAs also represent a promising but under-assessed place-based management tool to support climate resilience – allowing systems to absorb stress and recover from disturbance events.** MPAs have been shown to enhance biological attributes such as genetic and demographic diversity, intact food webs, and larger population sizes that are important for resisting or recovering from disturbances. Emerging evidence in several locations off the Pacific West Coast, including California, indicate that MPAs can provide resilience to marine heatwaves and hypoxia. However, the full potential of, and limits of MPAs as climate change mitigation and adaptation tools are not yet clear. Expanding this knowledge base for California can help direct MPA management strategies and network design decisions that may enhance the ability of ecosystems and communities to resist, recover from, or adapt to the impacts of climate change. The largest information gap is related to social and economic service provision of MPAs, highlighting a crucial need for more baseline social systems research in California to enable researchers, stakeholders and decision makers to better understand the human dimensions of MPA effects within a climate context, and support the continued flow of key services (Action 1.3).

- **Herein, this working group recommends a series of strategies, actions, and activities for decision-makers to ensure that a robust body of science is available to guide the implementation and evaluation of existing and new MPA management strategies aimed at supporting resilience to climate change, as a part of the state's climate resilience toolbox.** Recommendations consider both ecological and social systems, and are linked to MPA management opportunities as well as broader climate change action planning. Full consideration of how actions may impact or benefit multiple stakeholders, and mechanisms for promoting inclusion in science and management are crucial.
- **Continued long-term monitoring of key species, habitats, and oceanographic variables – including metrics predicted to respond to climate change – is essential to support climate-ready management (Action 1.1),** particularly as large-scale environmental changes increase in the future. Access to and investment in collaborative studies within MPAs are required for continued detection and tracking of climate impacts in California, and to assess the role the statewide MPA network can play in protecting or rehabilitating species or ecosystems.
- **Sustained efforts will be needed to fully integrate climate change resilience into MPA monitoring and management, but the state has a good head-start.** California's investments in the implementation of the Marine Life Protection Act (MLPA), including capacity for monitoring, management, and enforcement of a statewide, ecologically connected network of 124 MPAs provides an invaluable foundation for adaptive management to support ecosystem resilience in the face of climate change. Efforts to develop and incorporate climate-resilient MPA priorities into existing MPA management activities and state climate action plans (Action 2.3), and expanding governmental partnerships within and across state boundaries to advance and align MPA climate priorities across the region (Action 2.4) can move the state towards meeting the goals of the MLPA while supporting regional and international biodiversity and climate agreements. MPAs are one tool in a larger toolbox; continuing to reduce greenhouse gas emissions and advance statewide no-regrets climate actions are essential (Action 2.1).

In this report, the working group provides an overview of climate change impacts and scenarios for the California Current, catalogs potential mechanisms by which MPAs could provide resilience to climate change (and weighs the evidence for and against each), and suggests research questions and methods that could guide our detection and understanding of climate resilience in California's MPAs going forward. Lastly, we share a set of recommended actions, summarized in Table 4, that are intended to inform investments in a climate research and monitoring plan for the MPA network, help guide new policy, expand agency collaborations, position MPAs as a tool within the state's larger climate action toolbox, and ensure an inclusive, science-informed process for adaptive MPA management in a changing climate.

Channel Islands, CA

Image: Danielle Guyder

I. Overview

In recent years, the effects of climate change on marine ecosystems have come more sharply into focus. From marine heat waves, harmful algal blooms, sea-level rise, and changing ocean chemistry, coastal systems face new and ongoing challenges resulting in large-scale ecological impacts globally. There is growing scientific, management, and policy interest in understanding the role that marine protected areas (MPAs) – place-based marine managed regions with reduced or restricted harvest, disturbance and other human activity – may play in supporting ecosystem resilience and providing societal benefits in the face of climate change (hereafter, "climate resilience"; Box 1). The number of MPAs and MPA networks (hereafter, "MPAs" – referring to both individual sites and networks, unless specified) has been growing globally in an effort to meet international and national marine protection, conservation, fishery management, and biodiversity targets (IUCN 1948, United Nations 2015a, Newsom 2020). Increasingly, MPAs are being explored as tools for managing ecosystems in response to global change and meeting national and international climate agreements (e.g., United Nations 2015b, Ocasio-Cortez 2019, Newsom 2020, Wilson et al. 2020, Blue New Deal).

CLIMATE RESILIENCE

The ability of a coupled social-ecological-economic system and its components to absorb stressors and disturbance through resistance and/or recovery of core function, structure, and provision of services. For additional detail, see Box 1.

Evidence from the California Current Ecosystem and beyond suggests that protections provided by MPAs, including enhancing biological attributes such as genetic and demographic diversity, maintaining intact food webs, and supporting large population sizes (see Table A-2 for supporting evidence), are important in buffering against the impacts of climate change. MPAs may also serve a climate mitigation role, protecting habitats and ecosystems that sequester and store carbon. MPAs represent one of the few management interventions available to bolster the resilience of multiple trophic levels of an ecosystem and fisheries that rely on them to global change. However, the science to evaluate and plan for MPAs as a resilience management tool is not yet robust, and MPAs, even when ideally designed, are unlikely to support resilience against the full range of multiple stressors or extreme events facing coastal ecosystems. Determining the mechanisms by which MPAs may support resilience is an important first step toward developing comprehensive strategies for ocean protection as ecosystems face growing climate-related threats.

BOX 1. WHAT IS CLIMATE CHANGE RESILIENCE?

Socio-ecological 'resilience' is a term with a rich history in the ecological literature with a panoply of different definitions (O'Leary et al. 2017, Allen et al. 2019), focusing solely on biophysical resilience (Elton 1958, Holling 1973) to more holistic definitions that include biophysical and socio-ecological systems (Folke et al. 2002, Desjardins et al. 2015). For the purposes of this report, we adopted a definition of resilience that is based on that historical foundation but also including a coupled social-ecological-economic system framing (Elton 1958, Holling 1973, Folke et al. 2002, Desjardins et al. 2015) ***- the ability of a coupled social-ecological-economic system and its components to absorb stressors and disturbance through resistance and/or recovery of core function, structure, and provision of services.***

This can include ensuring resilience of foundational species such as kelp forests that provide important and irreplaceable function to the ecosystem. It also allows culturally important ecosystem services to be prioritized, which would be missed if prioritizing bio-physical functioning alone. Resilience may apply not only within an MPA, but healthy individuals may serve to provide resilience to the broader populations outside or among the network of MPAs. The group recognizes that systems of higher stability and therefore higher resilience may not be prioritized equally among stakeholders. For example, urchin barrens may be very stable yet the loss of ecosystem services may make them less desirable than the less stable state of a functioning kelp ecosystem.

It is recognized that under this definition, the concepts of structure, function, and provision of services need specific definitions and baselines to be useful in monitoring resilience and implementing climate-resilient strategies. This definition also requires specific operational goals and measurable variables to both identify the current ecosystem state, and to monitor changes in resilience under stress or perturbation. In this report we focus on the resilience to climate change but recognize that external forces including natural variability and other anthropogenic stressors also play a role.

California's network of 124 MPAs offers a unique opportunity to evaluate the capacity for MPAs and MPA networks to promote resistance and recovery from climate-related impacts. The network encompasses multiple ecosystems, with individual MPAs ranging in size, establishment date, location and level of protection, including those that are no-take reserves. The network was initially established with the goals of conserving the diversity and abundance of marine life along the entire coast, using ecological principles that considered larval connectivity, habitat replication and other metrics (CDFW 2016). While climate change was not explicitly considered during the design of the California MPA network, many of these same ecological principles are key aspects of environmental resilience. In addition, the state's MPA monitoring program is providing a valuable ecological baseline and time series to track and interpret the mosaic of large-scale oceanographic and ecological shifts along the California Current Ecosystem. As part of an adaptive management cycle, the state is undertaking the first decadal management review of the network, led by the California Department of Fish and Wildlife. This review provides an opportunity to update the scientific understanding of the potential ecological, social, economic benefits of MPAs beyond those considered at the time of designation of the MPA network.

In this report, we provide an overview of MPAs and climate change in the California Current. We then discuss potential mechanisms by which MPAs could provide resilience (and weigh the evidence for and against each). There are also many outstanding research questions, outlined in detail in this report, that if addressed, may offer insights on opportunities to adaptively manage MPAs in a way that can maximize the resilience of marine life populations and ecological systems to climate change. In closing, we share a set of recommendations and opportunities for state action, ranging from expert convenings and stakeholder consultation to suggested analyses that could be completed using existing data and models. It is our intent that insights from California's network can help inform efforts in other regions, states, or nations seeking to establish or manage MPAs as a climate resilience tool.

IA. Marine Protected Areas of California

Over a decade ago, the state of California implemented a network of MPAs between 2004 and 2012 that now consists of 124 MPAs over 852 square miles and protects approximately 16% of state waters (Figure 1B). The effort focused on the development of a functional network of ecologically connected MPAs, as opposed to a collection of MPAs designed independently of one another. There were two primary efforts that led to the existing network of MPAs (Davis 2005, Gleason et al. 2010, Saarman and Carr 2013, Botsford et al. 2014). The first effort led to the MPAs in the Northern Channel Islands in 2003; the second applied to the whole state and was driven by passage of the Marine Life Protection Act (MLPA) by the California Legislature in 1999 (California Fish and Game Code [FGC], §2850-2863). The MLPA mandated the redesign of California's existing MPAs in state waters (prior to the MLPA, these small, disconnected MPAs covered 2.7% of state waters, Fig. 1A) into an ecologically representative network under the guidance of the MLPA Master Plan (CDFW 2016). Regional MPA networks for the MLPA planning process were co-designed by stakeholders and scientists and implemented in four sequential regional planning efforts (Botsford et al. 2014). The design process has been well documented in Gleason, Kirlin and Fox (2013) and references therein.

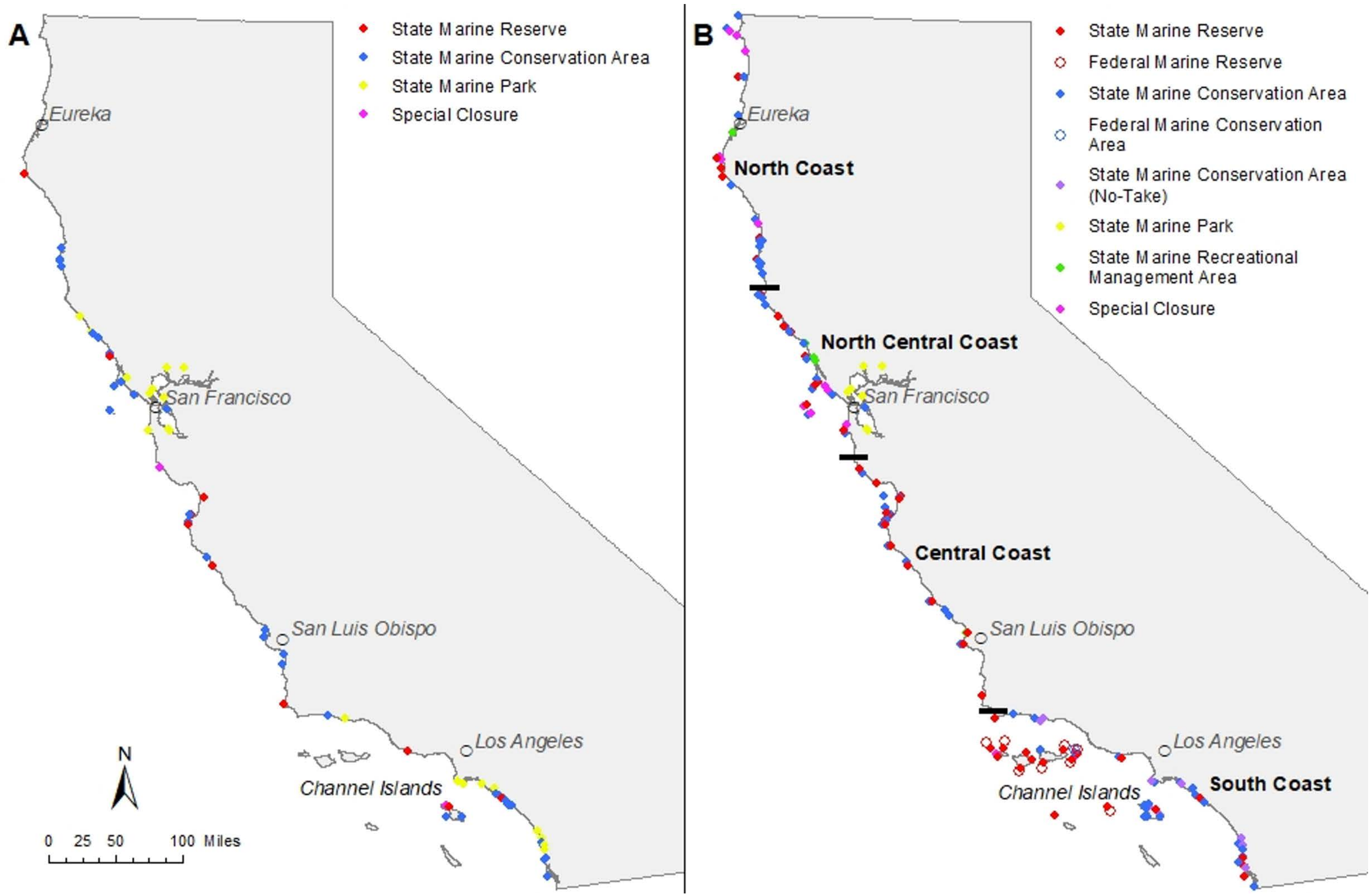


Figure 1. MPAs in California prior to 1999 (A) and after 2012 (B).

A) Prior to passage of the MLPA in 1999, only 2.7% of California's state waters were protected in 63 disconnected MPAs, with less than 1% in no-take MPAs. B) The ecologically connected network of 124 MPAs and 14 special closures designated under the MLPA became effective through a sequential regional planning process in 2007 (Central Coast), 2010 (North Central Coast), and 2012 (South and North Coasts), leading to the protection of 16.1% of state waters, with 9% in no-take MPAs. The Channel Islands MPAs in state waters were designated through a separate process in 2003 and expanded into federal waters in 2006–2007. (Figure: CDFW)

BOX 2. SIX GOALS OF CALIFORNIA'S MARINE LIFE PROTECTION ACT (1999).

California's Marine Life Protection Act was passed in 1999, directing the state to redesign California's system of MPAs to function as a statewide network to increase its coherence and effectiveness at protecting the state's marine life, habitats, and ecosystems (CDFW, OPC 2018). Six goals guided the development of MPAs in California's MLPA planning process:

1. To protect the natural diversity and abundance of marine life, and the structure, function, and integrity of marine ecosystems.
2. To help sustain, conserve, and protect marine life populations, including those of economic value, and rebuild those that are depleted.
3. To improve recreational, educational, and study opportunities provided by marine ecosystems that are subject to minimal human disturbance, and to manage these uses in a manner consistent with protecting biodiversity.
4. To protect marine natural heritage, including protection of representative and unique marine life habitats in California waters for their intrinsic value.
5. To ensure that California's MPAs have clearly defined objectives, effective management measures, and adequate enforcement, and are based on sound scientific guidelines.
6. To ensure that the MPAs are designed and managed, to the extent possible, as a component of a statewide network.

To see the full text of the MLPA, visit www.wildlife.ca.gov/Conservation/Marine/MPAs/MLPA

Prior to the MLPA, discussion of MPAs largely focused on fisheries impacts (Murray et al. 1999). The MLPA mandated a broader view of the benefits accruing from an MPA, with a focus on marine ecosystems rather than just species of economic value. The MLPA was also forward-thinking by requiring monitoring to facilitate adaptive management to ensure the MPA network meets the goals of the MLPA, including protecting diverse and abundant marine life and ecosystems, sustaining marine populations, improving recreational and educational opportunities, and protecting natural heritage (Box 2).

Climate considerations in California's Marine Life Protection Act

The MLPA does not explicitly mention "climate" or "climate change." In the MLPA Master Plan (CDFW 2016), 'climate' or 'climate change' is almost always referenced on a list with 'other' considerations that MPAs and MPA monitoring could provide information for, including fisheries, water quality, marine debris, and invasive species. There is no indication that climate change was explicitly considered as a stressor for which MPAs might provide resilience. For example, in the 2008 MLPA Master Plan, which was developed during the implementation process, climate change is not mentioned in the section on Factors Affecting California's Marine Ecosystems. In the 2016 Master Plan, climate is more prominent, being mentioned 23 times compared to only five times in the 2008 Master Plan. In the one-paragraph discussion of climate change, the 2016 Master Plan states: “Although the MLPA does not require consideration of climate change in MPA management, the Marine Life Protection Plan (MLPP) recognizes that climate change will likely have an effect on MPAs. At the same time, California’s MPAs could potentially help buffer California’s marine resources against the negative impacts of climate change by providing areas of reduced pressures exerted on the resources (Micheli et al. 2012).”

It was recognized that MPAs and especially MPA monitoring had the potential to provide additional information to managers concerned with climate change. The state’s MPA Monitoring Plan (CDFW and OPC 2018), which prioritizes key monitoring metrics to target for long-term monitoring, does highlight the need to consider species that may act as good indicators for studying the effects of climate change. A 2012 report prepared by EcoAdapt for OST provided recommendations for a three-tier design that could be incorporated into MPA monitoring efforts to document climate change effects and increase the effectiveness of adaptive MPA management in light of climate change. The first tier of this design identified species currently included in the monitoring plans that might also prove useful in understanding climate change effects (OST and EcoAdapt 2012). Recommendations for augmenting the monitoring with new metrics and/or species were included in the second tier while the third tier identified new areas of research. While the recommendations in the second and third tiers were not incorporated into the monitoring efforts, some of these ideas have subsequently been addressed through specific research activities (Gaylord et al. 2018).

While California’s MPA design process may not have explicitly accounted for climate change resilience, many fundamental science guidelines that were used during the design of the MPA network are key aspects of environmental resilience (Box 3; Bernhardt and Leslie, 2013). The MLPA Initiative established Science Advisory Teams to develop science-based design guidelines for establishing MPA networks in each region. Using the best available science, the SATs developed guidelines regarding aspects of the MPA network such as habitat representation, habitat replication, MPA size, and spacing. Climate change, specifically resilience to climate change, was not considered when these guidelines were developed. However, specific design considerations for the North Coast, North Central Coast and South Coast (Appendix C, D and F in the 2016 Master Plan) did list “Consider the potential impacts of climate change, community alteration, and distributional shifts in marine species when designing MPAs.”

While California’s MPA network was not originally established with the goal of providing resilience to climate change, it provides an excellent place to research and evaluate the climate resilience benefits of area-based management tools. The state of California has well-resourced MPA management and monitoring programs, including capacity for enforcement, factors which have been found to play a strong role in the ability of MPAs to meet their ecological and conservation goals (Gill et al. 2017, Sala et al. 2018).

BOX 3. ECOLOGICAL RESILIENCE PRINCIPLES THAT GUIDED THE DESIGN OF CALIFORNIA'S MPA NETWORK.

During the design of California's MPA network, guidelines were developed that included recommendations for habitat representation, replication and minimum area, and MPA size and spacing, among other factors that are grounded in general ecological resilience principles (Botsford et al. 2014).

1. **Simply by designing a connected 'network' of protected areas as mandated by the MLPA legislation, the California MPA network may provide several resilience attributes.** This includes genetic and demographic diversity, which is strongly related to recovery following a disturbance; a 'portfolio' effect (i.e., modularity among functional roles); and increasing adaptive capacity (through both higher plasticity and/or greater genetic variation) especially if the network spans an environmental gradient such as the California MPA network.
2. **Habitat representation and replication were fundamental design criteria.** Protecting multiple different types of habitats within an MPA and across MPAs in the network can allow for greater ecosystem connectivity, as well as higher genetic diversity, species diversity, functional redundancy, and response diversity. Protecting replicate habitats of the same type across the network allows for population connectivity, potentially protecting climate refugia. All of these diversity attributes can increase system resilience.
3. **The California MPAs include habitat from the shoreline to the outer edge of state waters and thus include a gradient of depths.** Deeper, colder waters might provide potential refugia for mobile species to warming of shallower waters.

BOX 3 CON'T.

4. **The California MPA network includes a variety of levels of protection, including no-take state marine reserves (which encompass 56% of the network), the highest level of state MPA protection.** There is evidence that fully protected reserves are more likely to build up large population sizes, larger individuals and greater biodiversity than partially protected MPAs (Lester and Halpern, 2008; Sciberras et al., 2013; Zupan et al., 2018), each of which can positively impact resilience. Many of the partial-take state marine conservation areas (SMCAs) also have regulations that support a relatively high level of protection (e.g., no take of groundfish or kelp forest species).
5. **Size and spacing guidelines were developed to ensure larval connectivity.** Connections at multiple scales of biological organization can enhance recovery from disturbance. Movement of larval or adult stages among populations can reduce the risk of local extinction and movement of nutrients or energy is essential to community and ecosystem persistence.
6. **The California MPA network spans the entire coast.** If species distributions shift in response to climate change, the geographically dispersed MPAs might provide potential refuges up to the northern edge.

A network design that is grounded in general resilience principles is considered a common climate change adaptation strategy and is also observed in Papau New Guinea and Fiji (McLeod et al. 2009, Wilson et al. 2020).

IB. Summary of Climate Change in the California Current

Human impacts on the global climate system are irrefutable, resulting primarily from anthropogenic greenhouse gas emissions and land-use changes (IPCC 2013, 2019). Changing conditions within the California Current include a suite of direct and indirect physical changes associated with ocean warming and marine heatwaves, alterations in ocean chemistry (ocean acidifi ation and deoxygenation), sea-level rise and extreme storms, increases in the variability of ocean conditions as a result of fluctuations in atmospheric patterns, alterations to large-scale ocean patterns (including El Niño-Southern Oscillation and Pacific Decadal Oscillation), and changes in rainfall (Figure 2; Table 1) (Hales et al. 2015, Chan et al. 2017, Sievanen et al. 2018). Marine life populations and communities in the California Current Ecosystem, including those within MPAs, are under threat and face ocean conditions that have already diverged from when the MPA network was completed in 2012.

DEEP DIVE: CLIMATE CHANGE IN THE CALIFORNIA CURRENT

For additional climate change observations and impacts, see *Appendix A: Primary Climate Drivers, Trends and Projections for California.*

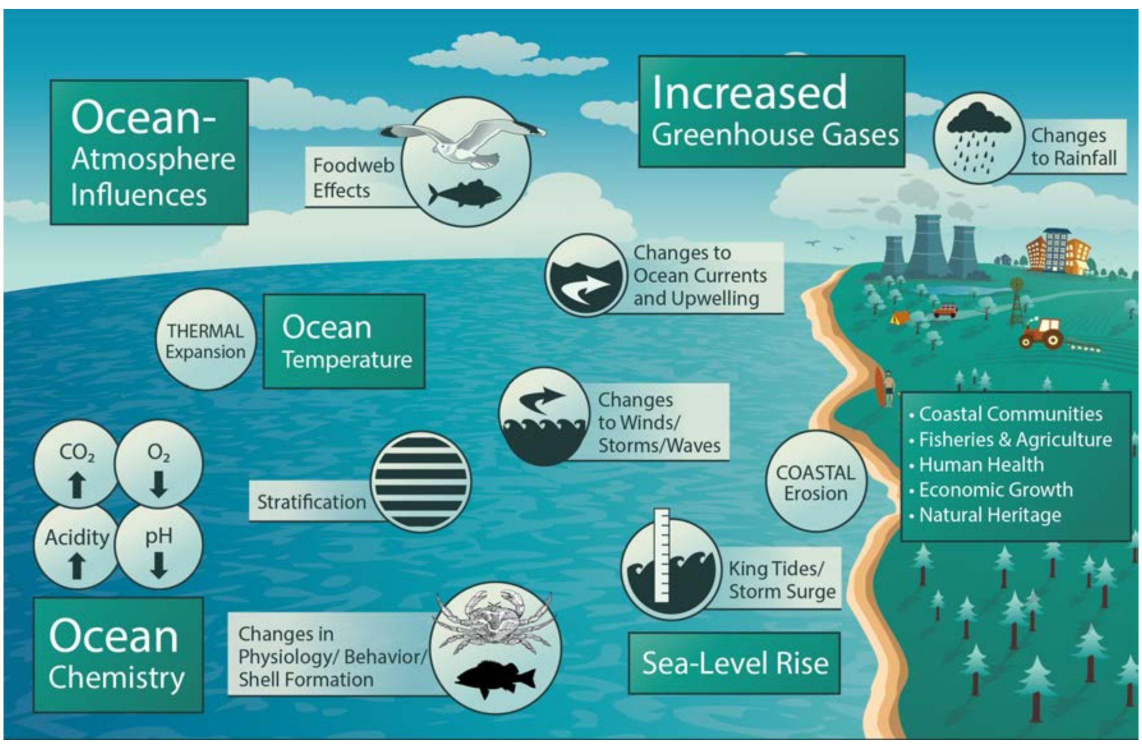


Figure 2. Overview of climate change in Cailfornia.

Greenhouse gases in the atmosphere are the primary driver of climate change. This affects sea-level rise, increases ocean temperature, alters ocean-atmosphere influ nces, and affects ocean chemistry with consequences for California's coastal communities, fisheries and aquaculture, human health, economic growth, and natural heritage. For additional information on climate stressors affecting marine systems at global, national, and regional levels, see IPCC 2013, 2019; Jewett & Romanou, 2017; and Sievanen, Phillips, et al. 2018. Figure source: Della Gilleran from Sievanen, Phillips, et al. 2018, adapted from QSR 2010 https://qsr2010.ospar.org/en/ch03_01.html.

Table 1. Primary physical and chemical environmental variables for California's ocean and coasts that will change with changing global climate change, and the predicted social-ecological-economic consequences.

(Table adapted for California from Carr et al. 2017)

Environmental variable	Predicted / observed change in California	Predicted consequences for California
Ocean temperature	Historically increasing at about a rate of 0.7° C per century; Projected to warm by an additional 2–4°C by the end of this century (Sievanen et al. 2018); Increasing frequency and intensity of prolonged periods of anomalously high temperatures (marine heatwaves) (Oliver et al. 2018)	Shifts in specific species distributions and population sizes; mass mortalities; changes in organism phenology, growth, and mortality rates; increase in disease; and loss of ecosystem services
Ocean acidity (pH / *p*CO_2)	Decrease in pH of 0.21 since 1895 (Osborne et al. 2020); Coastal systems highly variable (daily, tidal, and seasonal cycles), but greater pH reductions are projected with increasing CO_2 emissions (Gattuso et al, 2015)	Projected decreases in shell size and/or thickness in mollusks, increased mortality in larval stages of Dungeness crab and other shellfish, and shell dissolution in small plankton (pteropods and foraminifera) that form the base of the food web
Dissolved oxygen	Declining subsurface oxygen in some regions (deoxygenation) and shoaling of the oxygen minimum zone (Bograd et al. 2008); Greater frequency and magnitude of low oxygen events in the last two decades (Booth et al. 2014); low oxygen events (hypoxia) often paired with low pH waters (Chan et al. 2019).	Reduction of benthic shelf and pelagic habitat; reduced habitat quality for nearshore species like rockfish and Dungeness crab; die-offs in less-mobile animals when habitat is lost rapidly
Ocean currents / stratification	Currents can shift as atmospheric circulation patterns change (Castelao and Luo 2018; Yang et al. 2020); Changes in the currents are less clear. Increased stratification is predicted (Cheng et al. 2020).	Changes in the positioning of currents will affect the downstream ecosystem productivity (Sydeman et al. 2011); Increased stratification would result in a reduction in mixing and in turn productivity in the photic zone.
Sea level / storm frequency	Sea level rise is currently at a relatively low rate but is accelerating; By 2050 at least 12 inches (30 centimeters) of sea level rise is projected (Sievanen et al. 2018); The frequency and intensity of extreme atmospheric river storm events are expected to increase (OPC 2018, Gershunov et al. 2019)	Coastal flooding and shoreline erosion
Coastal upwelling / winds	Upwelling-favorable winds have intensified in the California Current System (CCS) over the past six decades, with an increased likelihood of intensification within the poleward portion of the CCS, and some relaxation equatorward (Rykaczewski et al 2015)	Stronger upwelling events and longer upwelling season in the northern CCS, but shorter events and shorter duration in the southern CCS. Upwelled waters are often cold, acidic, and low-oxygen.
Changes in rainfall	Increasing frequency of extreme rain events (Yoon et al. 2015), including atmospheric rivers, are expected to produce commensurate changes in runoff nd sudden freshwater intrusions into brackish bays and estuaries. Increasingly frequent and severe droughts will reduce river flows, potentially to the point of closing river mouths (Yoon et al. 2015, Behrens et al 2016).	Sudden intense freshwater events can trigger mass mortality of estuarine benthic organisms (Cheng et al. 2016). Reduced river flow can impede salmon smoltification (Marine et al. 2004), allows salinization of estuaries, and limits river outflow into the coastal ocean, changing coastal productivity.
Ocean-basin scale climate indices	Long-term variability in the CCS circulation and environment is linked to several ocean-scale patterns of atmospheric and oceanic circulation. The best know is the El Niño-Southern Oscillation (ENSO) but the Pacific Decadal Oscillation (PDO) and North Pacific Gyre Oscillation (NPGO) have similar influence. Studies indicate that a variant of the eastern Pacific El Niño became more common during the late twentieth century with maximum SST anomalies located in the central Pacific and flanked on both the east and west by cooler SSTs (Yeh et al. 2009); Models predict an increase in frequency of this variant of ENSO events (Yeh et al. 2009) and in extreme ENSO events (Cai et al. 2014). However the PDO and NPGO may be growing less coupled with CCS ecosystem dynamics (Litzow et al. 2020).	Variability in recruitment, fish production, and fish distributions; Warmer phases can favor subtropical, more diverse and less productive food-webs; cooler phases associated with more productive ecological state. Historically the PDO and NPGO have been highly predictive for the productivity and health of many fishery stocks, particularly Chinook salmon (Peterson et al. 2003). If those climate indices become decoupled from CCS processes, we will lose predictability for management.

Understanding the capacity for MPAs and MPA networks to enhance the ability of systems to absorb climate stressors and disturbances requires knowledge of the oceanographic conditions within individual MPAs and across the network as a whole, and of how climate change will interact with local disturbances to affect these conditions. For example, as California's coastal marine waters experience greater frequency of marine heatwaves, how will this impact social-ecological-economic systems within each MPA and the MPA network as a whole? And further, in what ways will the network of MPAs improve the resilience of communities under these conditions (e.g., provide refuges for poleward-migrating species)?

We are already seeing striking examples of how natural and anthropogenic environmental stressors interact to influence marine ecosystems (Hoegh-Guldberg and Bruno 2010, Harley 2014, Poloczanska et al. 2016, Pecl et al. 2017, Bruno et al. 2018, Frölicher et al. 2018). In California, climate change poses risks to commercial and recreational fishing industries, public health, tourism, coastal protection, as well as ecosystem structure and function. The 2014-16 marine heatwave was transformational for the California Current Ecosystem (CCE) and was intensified by a coincident positive ('warm') phase of the El Niño-Southern Oscillation and climate change-driven temperature increases (Bond et al. 2015, Cavole et al. 2016, Jacox et al. 2018, 2019). The anomalous warm waters are correlated with widespread ecological changes, including a northward shift of southern, warm-water species (Morgan et al. 2019, Sanford et al. 2019), a coast-wide outbreak of toxic algae led to west coast Dungeness crab fishery delays and record entanglements with large whales (Santora et al. 2020), urchin outbreaks and loss in kelp cover in northern California causing closure of the red abalone fishery (Rogers-Bennett et al. 2019, McPherson et al. 2021), kelp decline throughout the region (Arafeh-Dalmau et al. 2020, Beas-Luna et al. 2020b), shifts in sea urchin diversity and recruitment, and abalone recruitment in southern California (Kawana et al. 2019, Okamoto et al. 2020), outbreaks of sea star wasting disease (Menge et al. 2016, Miner et al. 2018, Aalto et al. 2020, Aquino et al. 2021), and seabird and marine mammal unusual mortality events (Laake et al. 2018, NOAA Fisheries 2020).

This event was a climate stress-test, potentially indicative of future conditions under climate change, yet we do not know the extent or duration of the ecosystem perturbations. These large-scale changes and novel interactions (e.g., Dungeness crab fishery operations and whale migrations) may offer a glimpse into future ecosystem responses to climate changes predicted for the California Current (Marshall et al. 2017, Xiu et al. 2018). Climate change scenarios for the California Current that reflect potential future ecosystem responses are included in a report Readying California Fisheries for Climate Change (Chavez et al. 2017, Box 4).

These changes and impacts are likely to increase in the future (Oliver et al. 2018), with impacts to ecosystems and communities varying geographically in the California Current (Beas-Luna et al. 2020a; Box 5), which will lead to unanticipated effects and novel management challenges. In addition, climate stressors will not act in isolation, and California decision-makers should also consider cumulative impacts and interactions with non-climate stressors (Mach et al. 2017; see also Appendix A "Additional influencing factors and cumulative impacts that should be considered when assessing the resilience capacity of the MPA network"). California's MPA network is far from immune from these risks and ecological interactions. Climate change observations and impacts in California are summarized in Table 1 and discussed in greater detail in Appendix A.

BOX 4. POTENTIAL CLIMATE CHANGE SCENARIOS FOR THE CALIFORNIA CURRENT

Climate change predictions for the California Current have been grouped into four potential ecological change scenarios that will have indirect or direct impacts to species and ecosystems (Chavez et al. 2017):

1. **Historic variability.** Variability equivalent to that observed in the past.
2. **Increased variability.** Increases in the amplitude and changes to the period (or duration) of natural variations
3. **Range shifts.** Poleward displacements as tropical waters expand over time.
4. **Crossing thresholds.** Abrupt changes in the ecosystem as thresholds are crossed due to slow and steady or rapid changes in the biophysical and geochemical environment.

These scenarios are not mutually exclusive (nor are they forecasts) but provide a way to understand the range of possibilities that could occur under climate change.

BOX 5: REGIONAL OBSERVATIONS AND PROJECTIONS OF CALIFORNIA KELP FOREST COMMUNITIES IN RESPONSE TO MARINE HEATWAVES

Results from a recent study in North American kelp forest communities reveal major region-wide changes in response to the 2014–2016 marine heatwave (Beas-Luna et al. 2020). Long-term monitoring surveys from five regions from Alaska to Baja California showed that kelp forest ecosystem structure and distribution exhibited regional variation in response to long-term (2006-2016) and short-term (i.e., 2014-2016; encompassing a marine heatwave) climate variability (Figure 3). Canopy-forming kelps were most sensitive to warming across all regions with notable declines in abundance over the past decade, while other macroalgal groups tended to show no significant changes. Kelp associated functional groups exhibited more variable responses across regions; only detritivores mirrored kelp responses (except for Northern California). Kelp forest ecosystems were observed (through 2016) to be most resilient in the Central California and Southern California Bight regions, but relatively less resilient in Northern California and Baja California Sur. Overall, Baja California Sur experienced the greatest change in overall ecosystem structure with loss of canopy-forming kelp and changes in abundance for several functional groups. Examination of distribution centroids indicated that canopy-forming kelp and detritivores shifted northward and exhibited range

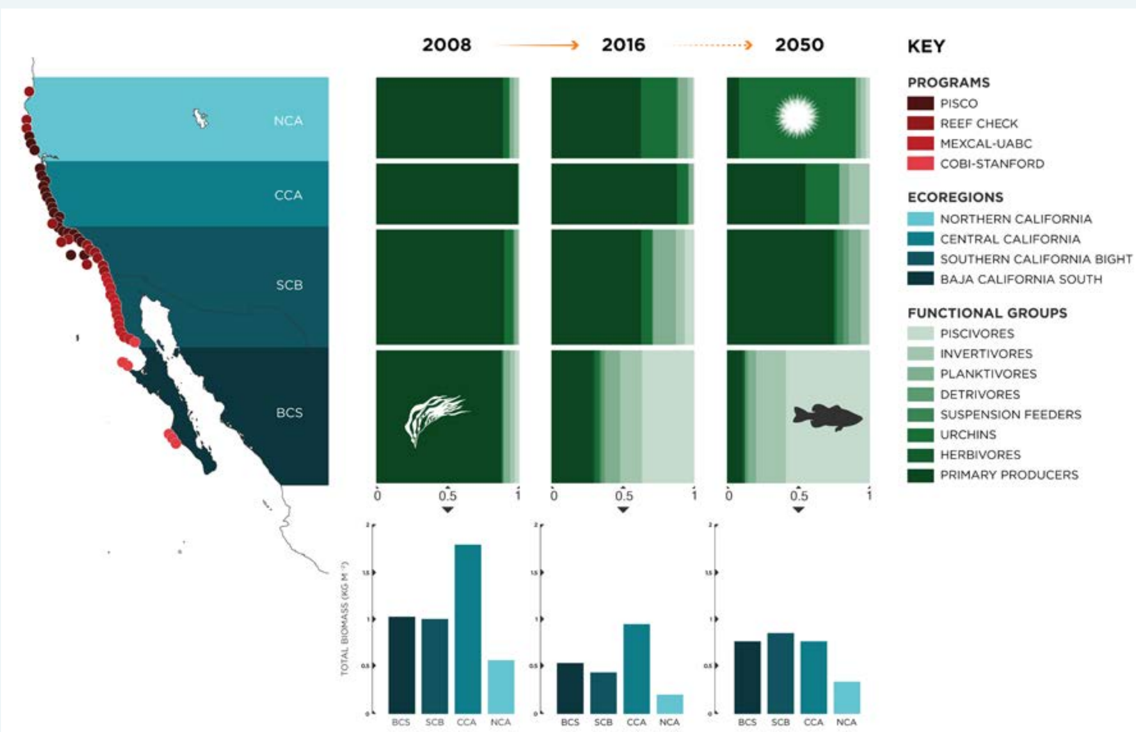
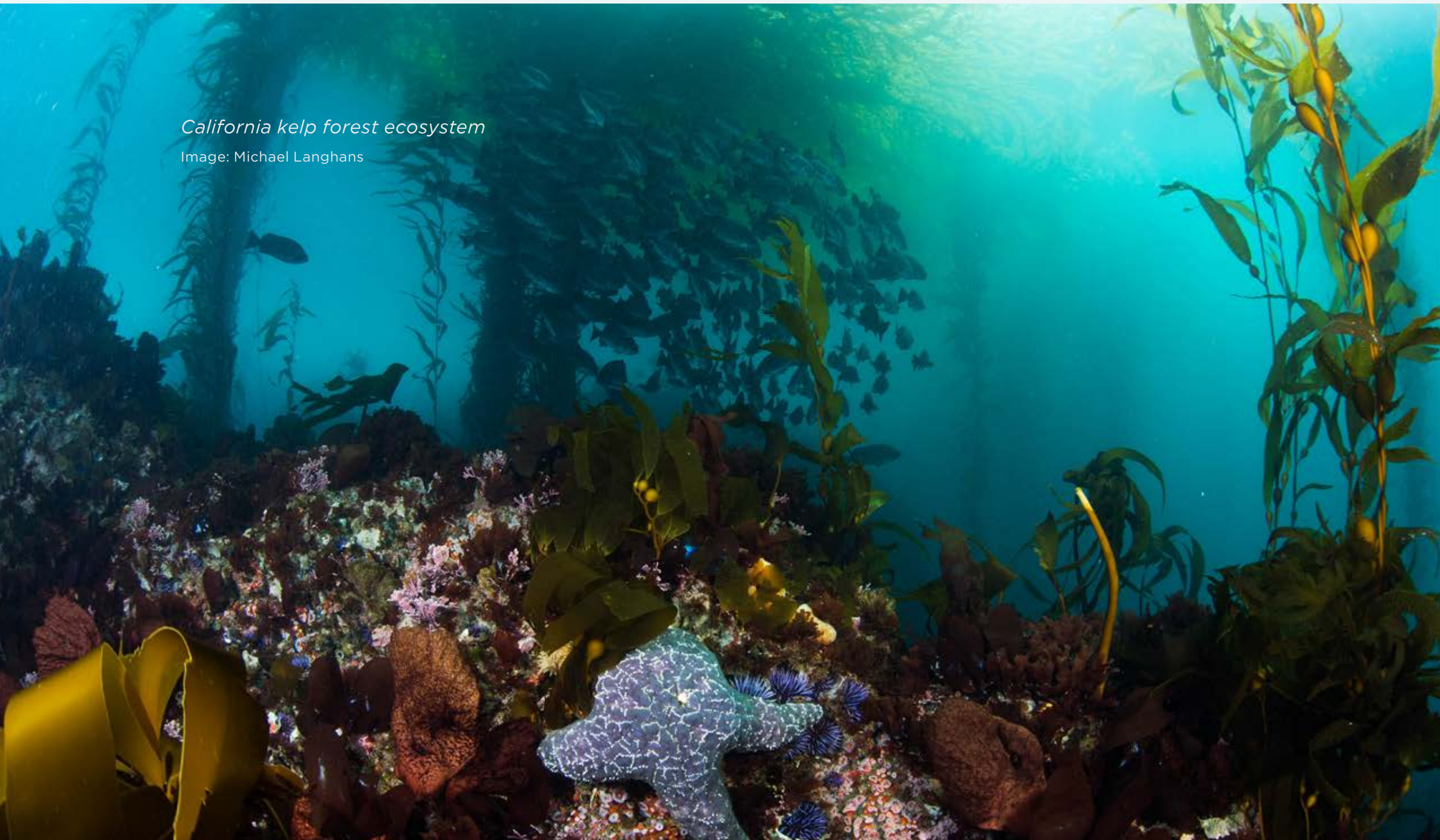


Figure 3. Biomass and ecosystem structure before and during warming period from 2014 to 2016 along the U.S. West Coast.

Shown with estimated structure based on instantaneous rates of change for the year 2050 in Northern California (NCA), Central California (CCA), Southern California (SCB), and Baja Norte, Baja California Sur (BCS). (Figure: Rodrigo Beas-Luna based on Beas-Luna et al. 2020)

BOX 5 con't.

expansion. In contrast, higher-trophic level species (e.g., invertivores and piscivores) shifted southward with slight range reduction. These shifts in species abundances across regions could portend a dramatic shift in ecosystem structure and function if the rates of change observed in this study continue over the next 20-30 years (Figure 3). The ecosystem changes observed in Baja California may provide a 'crystal ball' view of future change in the currently more resilient central and southern California regions under continued warming, deoxygenation and acidification. While a range of scenarios may be possible (Box 4), projected ecosystem changes call for additional protection of the most vulnerable ecosystem components (such as canopy-forming kelp and lower trophic level functional groups, particularly kelp-dependent detritivores) through careful management of additional stressors from, e.g., fishing and pollution, and identification and protection of climate refugia for these functional groups.



California kelp forest ecosystem
Image: Michael Langhans

IC. Summary of Climate Resilience and MPAs

For decades, evidence has been growing that well-designed and well enforced[1] MPAs and MPA networks can support larger populations of larger individual organisms than those found in fished areas, and that those populations contribute to more stable ecosystems that can provide a host of ecosystem services and socioeconomic benefits (e.g., Shears and Babcock 2003, Lester et al. 2009, Edgar et al. 2014, Leenhardt et al. 2015, Arkema et al. 2017, Caselle et al. 2018). It is now hypothesized that those consequences of protection in MPAs may also contribute to climate resilience. Below, we provide an overview of the potential mechanisms by which MPAs provide climate resilience benefits, across a range of scales from individual organisms to biogeochemical cycling and coastal economies (Figure 4). In Section II we catalog these potential benefits from the scientific literature, and weigh the evidence for and against each.

[1] enforced enough to limit poaching to very low or non-existent levels.

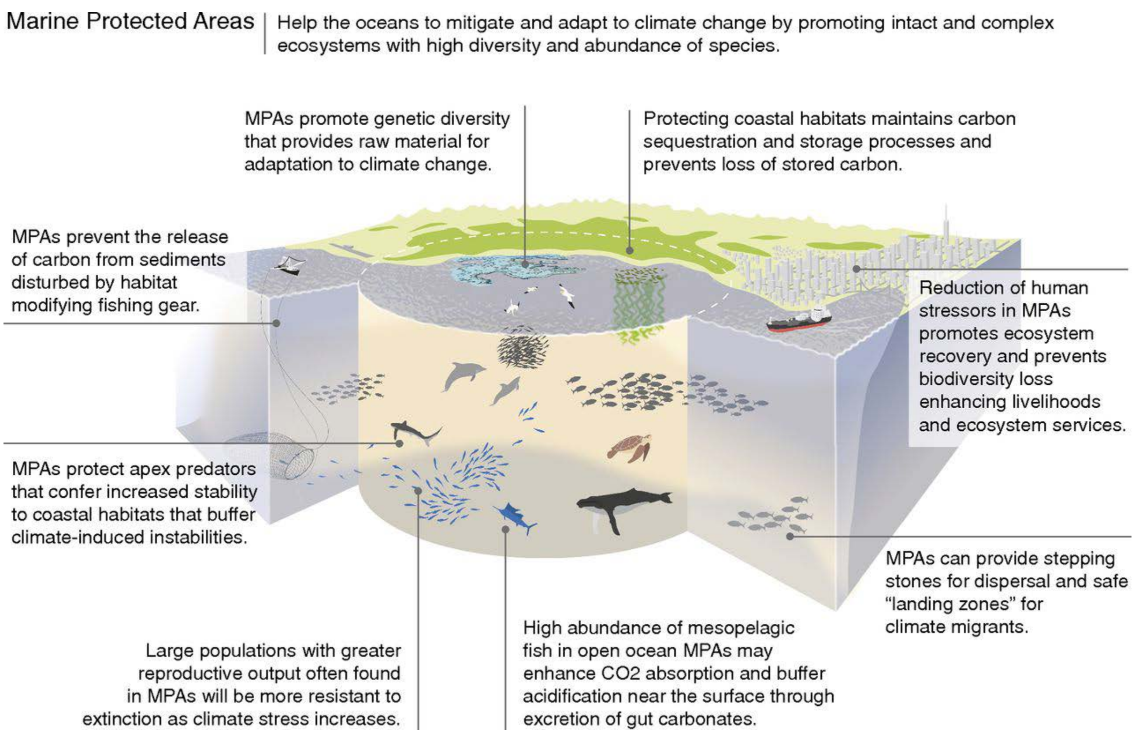


Figure 4. Potential mechanisms by which MPAs may promote resilience to climate change.
(Figure from Roberts et al. 2017)

Expected Benefits Provided by MPAs

Most of the potential sources of climate resilience arise as a consequence of having larger populations comprised of larger individuals inside MPA boundaries, making those populations less likely to collapse from a disturbance (Baskett and Barnett 2015). Larger populations can lead to greater reproductive rates, greater genetic diversity, and potentially greater individual physiological resilience. All of these contribute to an improved ability to resist or recover from climate disturbances and ultimately adapt to changing climate conditions. Having more large individuals may also provide stronger and more diverse food web linkages, leading to more stable ecosystems. In some cases, this may also lead to greater, more stable biomass of biogenic habitats such as kelp and seagrasses; those in turn could buffer changes in water chemistry and provide other ecosystem services.

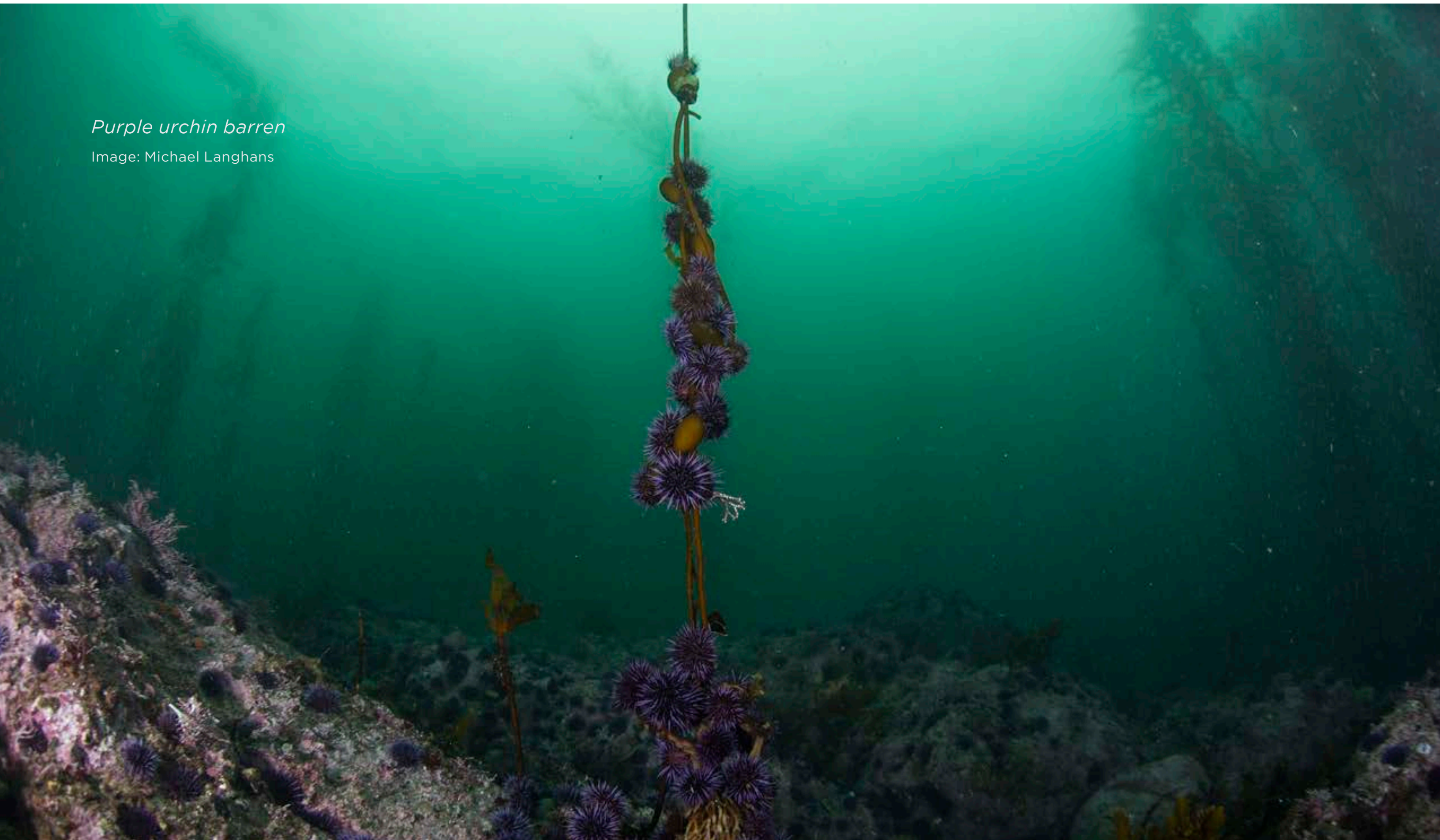
It is important to recognize that many of these resilience benefits of MPAs are hypothesized based on our understanding of ecology, physics, and socioeconomics, but not yet fully documented by empirical studies. For example, it is well established that California MPAs contain greater abundances of larger individuals of fished species (e.g., Caselle et al. 2015, White et al. 2021), and that larger marine animals have greater reproductive biomass per unit mass (Marshall et al. 2010, Hixon et al. 2014, Barneche et al. 2018), but it has not yet been demonstrated that this leads to California MPAs contributing to faster recoveries from climate-related disturbances. Other resilience benefits have been demonstrated, such as an MPA preserving functional redundancy in sea urchin predation: when one major urchin predator (sunflower sea stars) was locally extirpated in the Northern Channel Islands by a sea star wasting disease (a climate-exacerbated epizootic; Harvell et al. 2019), other predatory fishes kept urchins at low abundance, preserving kelp habitat inside the MPAs (see Box 7; Eisaguirre et al. 2020).

Challenges for Documenting Climate Resilience Effects of MPAs

The lack of existing evidence for some of the other potential resilience mechanisms stems from several factors. First, one must note that conceptually it is not possible to document responses to disturbances until they occur, so we have not yet witnessed responses to some types of disturbances predicted under future climate scenarios. Disturbances are also unpredictable, which makes it difficult to plan studies and collect sufficient and timely pre- and post-disturbance data to observe system responses. A second reason for the absence of evidence for some mechanisms at this time is that they depend on the accumulation of old, large individuals in MPAs, a process that can take decades (White et al. 2013, Kaplan et al. 2019, Nickols et al. 2019). Succession (the cascading series of biomass build-ups) from population-level resilience to community-level resilience can further cause time lags to realize ecosystem-level resilience, thus effects will vary depending on when an MPA was established and will require long-term monitoring of these systems (Babcock et al. 2010). Finally, some of the proposed mechanisms and benefits are diffuse and difficult to quantify with existing methods. For example, it is difficult to detect export of larvae from a particular MPA to a disturbed site because one would need laborious genetic studies to link individual fishes to their place of birth (e.g., Baetscher et al. 2019). In Section III we propose and prioritize the types of research (and importantly, monitoring) that could guide our detection and understanding of these mechanisms in California MPAs going forward.

It is important to realize that there are limits to the resilience afforded by MPAs, and they are one tool in a larger toolbox for adapting to and mitigating climate change impacts; continuing to reduce greenhouse gas emissions and advance statewide no-regrets climate actions are essential (see Action 2.1 in Table 4). Because ecosystems in MPAs are fundamentally connected to and embedded in larger meta-ecosystems and the coastal ocean, it is unreasonable to expect them to buffer against large-scale, large-magnitude climate impacts (Bruno et al. 2019, Kroeker et al. 2019). Nonetheless, better study of the mechanisms behind potential climate resilience conferred by MPAs should improve our ability to adaptively manage MPAs and the socioeconomic networks to which they are linked (Kroeker et al. 2019).

In the following section, we summarize potential resilience mechanisms and available evidence that span different social-ecological levels of organization, including evidence from MPA research and monitoring in California.



Purple urchin barren

Image: Michael Langhans

Morro Rock, Morro Bay, CA

Image: Cameron Venti

II. In What Ways Could MPAs and MPA Networks Provide Resilience to Climate Change?

SUMMARY

- Assessing the climate resilience capacity of MPAs and MPA networks is a new area of research globally, and empirical evidence from California and other comparative temperate systems is limited to a few ecological studies at the level of an individual MPA, highlighted in case studies below.
- There is moderate to strong empirical evidence from California and beyond suggesting that MPAs support larger populations with more old, larger individuals than surrounding fished waters, and that can lead to populations that are less likely to collapse from a disturbance.
- There is far less evidence of MPAs leading to resilience from climate change impacts. In the California Current, MPAs have been shown to promote abalone fishery recovery from hypoxia-driven mass mortality events, and resilience from disturbance-induced changes in kelp forest communities by protecting key predators. Other climate resilience mechanisms are more speculative or have conflicting evidence, but are being studied (e.g., the role MPA networks could play for range-shifting populations).

- Of these limited studies that showcase climate resilience effects linked to MPAs, more research is needed to understand how broadly applicable these phenomena are for California systems and species.
- Notably, the largest information gap is related to understanding of human dimensions-specific MPA effects and resilience mechanisms, both globally and particularly within California. This highlights a crucial gap and need for more baseline social systems research for California MPAs before researchers can begin to understand and attribute any MPA resilience effects within a climate context.
- California's MPA network provides an excellent place to research and evaluate the climate resilience benefits of area-based management tools. Expanding this knowledge base is timely because MPAs in this region, particularly those that were established prior to the MLPA, are now old enough for researchers to begin understanding trends and ecological changes attributable to MPAs.

Potential Mechanisms for Climate Resilience

There are several mechanisms by which California MPAs could provide resilience to climate change. These are supported with varying degrees of evidence, from studies that demonstrate climate resilience of MPAs in California, to studies conducted elsewhere, that together demonstrate potential expected effects of California MPAs. We organize proposed mechanisms into five categories of effects of MPAs: on the environment itself, on individual species, on populations of species, on community resilience, and finally on resilience in the human dimension. We also organize evidence into two components: the biophysical effect of the MPA, and the mechanism by which this might confer resilience (evidence summarized in Table 2 and in greater detail in Appendix B). This organization provides a structure for identifying specific research needs to help fill knowledge gaps on the role of California MPAs in climate resilience, and might also be used to direct future design decisions or for setting climate-resilient MPA objectives.

Table 2. A summary of evidence for proposed mechanisms by which MPAs and MPA networks could provide climate resilience.

Level of support (strong, modest, mixed, sought but not found, little evidence) is indicated for (A.) MPA/MPA network effects and (B.) hypothesized resilience mechanisms based on evidence from studies in California MPAs, in California generally (non-MPA specific research), and in geographic locations outside of California. This offers insight on knowledge gaps in California, and was used by the working group to inform priority research questions presented in Section III. This table was generated based on a review of over 80 publication in the literature and expert consultation, but may not be exhaustive. For details on the scoring process, parameters, and the full list of references used in this table, see Appendix B.

✓+ Strong evidence in direction expected | ✓ Modest evidence in direction expected | — Evidence not found | ~ Mixed evidence | ? Little evidence

A. EFFECT OF MPA / MPA NETWORK	SUPPORT FOR MPA EFFECT		B. HYPOTHESIZED RESILIENCE MECHANISM OF MPA EFFECT	SUPPORT FOR RESILIENCE MECHANISM		
	IN CA	AT LARGE		IN CA MPA	IN CA	AT LARGE
REDUCTION OF ENVIRONMENTAL STRESS						
Increased biogenic habitats such as kelp, seagrasses, and salt marshes; increased biomass of macrophytes	✓	✓	Buffering physical stressors such as storms and surge	?	✓	✓
			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	?	?	✓
Increased body sizes	✓+	✓+	Increased organismal tolerance to climate stress among larger individuals	?	✓	~
POPULATION RESILIENCE						
Larger population sizes	✓+	✓+	Increased recovery after disturbance via higher 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	✓+	✓+	Faster recovery by maintaining greater reproductive output from larger individuals	?	?	✓
Complete (full) age structure	✓	✓	Make populations less vulnerable to a series of poor reproductive years (storage effect)	?	?	✓
Maintenance of genetic diversity	?	✓	Greater likelihood of resistant genotypes and increased potential for recovery via evolutionary rescue	?	✓	✓+
Networks encompass sites that are climate refugia	✓	✓	Increased resistance and recovery of meta-population via spatial refugia of some populations from environmental stress	?	?	✓
Increased biogenic habitat	✓	✓	Increased population vital rates due to intact nursery habitats	✓	✓	✓+

Table 2 con't.

A. EFFECT OF MPA / MPA NETWORK	SUPPORT FOR MPA EFFECT		B. HYPOTHESIZED RESILIENCE MECHANISM OF MPA EFFECT	SUPPORT FOR RESILIENCE MECHANISM		
	IN CA	AT LARGE		IN CA MPA	IN CA	AT LARGE
ECOSYSTEM RESILIENCE						
Maintenance of taxonomic and functional diversity	✓+	✓+	Increased resistance to climate change via higher functional redundancy	?	?	?
			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	✓	✓	✓
			Increased resistance to disease epidemics via suppression of population outbreaks	✓	✓	✓
Increased connectivity (MPA networks)	?	?	Increased resistance of communities undergoing range shifts via stepping stones of protection from harvest or disturbance	?	?	?
HUMAN DIMENSIONS AND COMMUNITY RESILIENCE						
Reduction of fishing pressures	✓+	✓+	Spill-over for fisheries	✓	✓	✓
			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	?	?	?
Increased biogenic habitat buffers strong waves and storm surges	✓	✓	Protection against damage from extreme storm events	?	✓	✓
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	?	?	?

Assessing the climate resilience capacity of MPAs and MPA networks is a new area of research globally, and empirical evidence from California and other comparative temperate systems is limited to a handful of studies, discussed in case studies within this section. Expanding this knowledge base for California's network is timely because MPAs in this region, particularly those that were established prior to the MLPA, may now be old enough for researchers to begin understanding trends and ecological changes attributable to MPAs.

IIA. Reduction of environmental stress

MPAs can protect living (biogenic) habitats such as kelps, seagrass, and salt marshes which can alter the physical conditions experienced by organisms and coastlines within and around the MPA. For example, seagrass and macroalgal (kelp) habitats can be indirectly supported or augmented when MPAs protect species that contribute to their persistence, as demonstrated in kelp forests in California (Eisaguirre et al. 2020), and temperate MPAs in Australia (Ling et al. 2009, Ling and Johnson, 2012) and New Zealand (Shears and Babcock, 2003). In these examples, MPAs protect fish and crustaceans that feed on herbivorous urchins, indirectly benefiting kelp. These habitats can dampen or attenuate waves and reduce the velocity of breaking waves, providing a buffer against storm surges, reducing turbidity and sediment suspension, reducing coastal erosion, and protecting coastlines from sea-level rise (Lovas and Torum 2001, Kirwan and Megonigal 2013, Krumhansl et al. 2016, Thorne et al. 2018).

In California, water flow attenuation is positively correlated with the extent, density, and morphology of the canopy-forming *Macrocystis pyrifera* (Gaylord et al. 2007). On average, macrophyte density increases in temperate MPAs, although the effect is inconsistent across studies (Lester et al. 2009). A key gap in our current knowledge of California MPAs is the extent to which they increase the density of kelp, and if this effect could offset predicted losses in kelp with warming (e.g., Rogers-Bennett et al. 2019, Beas-Luna et al. 2020, McPherson et al. 2021).

In addition to storm buffering, increased abundance of macrophytes may also reduce oxygen limitation and carbon dioxide (CO_2) stress to organisms living in and around macrophytes. Local (within-site) drawdown of CO_2 and pH amelioration has been shown in seagrass beds (Hendriks et al. 2014, reviewed by Nielsen et al. 2018, Ricart et al. 2021) and kelp forests (canopy) in California (Koweek et al. 2017, Hirsch et al. 2020). In kelp forests, carbon drawdown has been documented in the canopy, locally increasing surface pH, with little to no effect at the benthos, where many organisms are found. The spatial extent of these effects is unknown; hence any positive effects of oxygen enrichment or CO_2 drawdown on habitat-associated species may not occur at scales relevant to climate resilience in MPAs, but warrants further study (Kroeker et al. 2019).

Protection of salt marsh and seagrass habitats may also play a broader role in carbon sequestration and storage by removing CO_2 from the atmosphere through photosynthesis and storing organic carbon in their biomass and sediments (Duarte 2017, Ward et al. 2021 in review). New research in California documents carbon stocks and sources in salt marshes and seagrass meadows, indicating that both are an important storage mechanism for burying carbon in coastal systems (Ward et al. 2021 in review). This is an active area of study, and more work is needed to understand the role that protections offered by the MPA network may contribute to greenhouse gas reduction efforts statewide.

Box 6. Evidence that reserves promote more rapid recovery of abalone after a hypoxic event in Baja California

Several studies in Baja California have shown that a network of small, no-take marine reserves can improve resilience to mass mortality events (Micheli et al. 2012), promote population and fishery recovery following hypoxia-driven mass mortality events (Smith et al., in prep.), and reduce sensitivity to impacts from extreme events (e.g., hypoxia) and management errors (Rossetto et al. 2015, Aalto et al. 2019).

Voluntary no-take marine reserves established and enforced by the fishing cooperative of Isla Natividad, in Baja California Sur, Mexico, maintained higher post-mass mortality density of pink abalone (due to the removal of all fishing associated mortality in the reserves) following prolonged hypoxia (Figure 5; Micheli et al. 2012). Reserves also maintained significantly larger abalone sizes compared with the fished regions, with correspondingly higher recruitment and larval spillover across the reserve boundaries (Figure 5b), indicating that reserves can support the resilience of impacted populations to mass mortality caused by environmental extremes (Micheli et al. 2012). Population models projected greater population and fisheries resilience based on the observed recruitment and spillover (Rossetto et al. 2015).

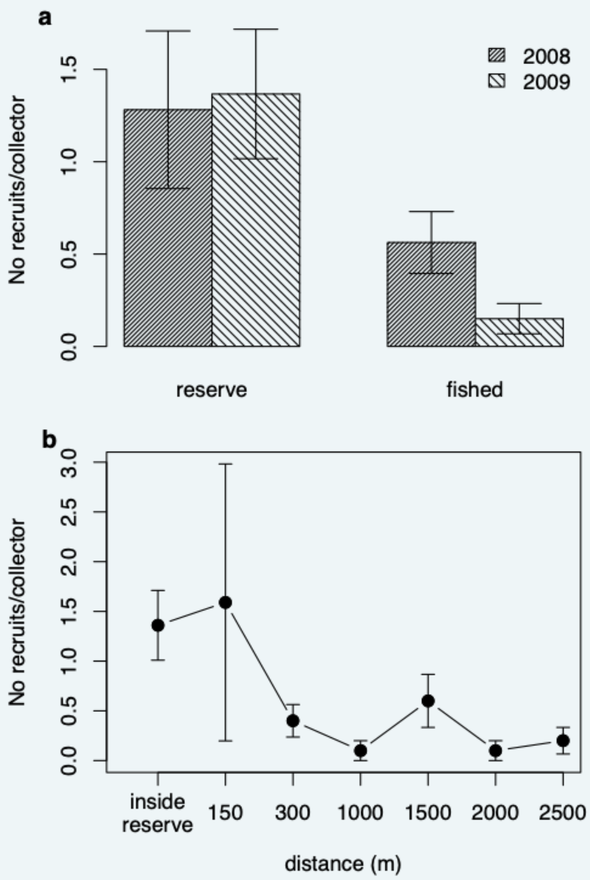


Figure 5. Comparison of abalone recruitment in reserve and fished sites following hypoxia-driven mass mortality event in Isla Natividad, in Baja California Sur, Mexico (a); and recruit abundance (averaged across the recruitment season) within the reserve and at varying distances from the reserve edge (b).

Box 6 con't.

In species like abalone, sea cucumbers and sea urchin that experience lower breeding success at low densities (known as the Allee effect), extreme events can lead to a period of heightened mortality that can reduce abundance to a threshold level that threatens recovery - a risk exacerbated by additional fishing mortality in harvested species. A study using the green abalone (*Haliotis fulgens*) fishery in Baja California Sur, Mexico, modeled population recovery in response to catastrophes (of varying number and frequency) and predicted that a network of protected areas that reduce or eliminate fishing harvest can minimize the risk of population collapse caused by large scale extreme climatic events for species characterized by an Allee effect (Aalto et al. 2019). Consistent with modeling projections, abalone abundances have recovered to pre-mortality levels rapidly and the abalone fishery reopened 8 years after mass mortalities (Smith et al., in review). Finally, genetic analyses have shown that genetic diversity of pink abalone has remained high within these reserves (Munguia-Vega et al. 2015), providing and additional mechanism for potential long-term population resilience in the face of climate variability and extremes.

Crashing waves
Image: Melanie Morales

IIB. Increased organismal resilience

MPAs can support individual features of organisms, such as increased body size due to release in fishing pressure and nutritive state, which can confer stronger individual resilience against climate change. Body size of both fishes and invertebrates increases inside temperate MPAs (by an average by 27%; Lester et al. 2009), and a return to broader age structure is the most commonly observed effect in California MPAs (Paddack and Estes 2000, Parnell et al. 2005, Tetreault and Ambrose 2007, Kay et al. 2012, Hamilton and Caselle 2014, Caselle et al. 2015, Starr et al. 2015, Selden et al 2017, Jaco and Steele 2020). These effects have been greater when there was higher fishing pressure pre-closure (White et al. 2013, Jaco and Steele 2019, Kaplan et al. 2019). For an individual organism, a larger body size could lead to increased resistance to environmental stress. A notable example of this was that the greater abundance of larger abalone in marine reserves compared to fished sites in Baja California after hypoxic events (Box 6; Micheli et al. 2012). However, the generality of that phenomenon is unknown. Larger organisms within a species typically have lower mass-specific metabolic rates and greater energy storage, and so may be more resilient to acute oxygen or heat stress events, which potentially improved resistance in the Baja California abalone case study. However, larger organisms have greater metabolic rates at the whole-organism scale; if oxygen supply is limited, larger individuals are expected to suffer heat and oxygen stress disproportionately because of their greater basal metabolic demand. In fish, there is considerable variability among species in the relationship between body size and metabolic rate, with a greater rate of increase in metabolic rate with body size for more sedentary benthic fishes (Killen et al. 2010). More research is needed to directly investigate how the mechanisms that lead to greater body size in MPAs may affect individual resilience to climate-related disturbances (Kroeker et al. 2019).

It is also possible that individuals within MPAs are in improved nutritional states, having greater or more constant access to food supply, and that this provides individuals with greater resistance or tolerance to climate-related stress. Energetic modelling and empirical evidence suggest that increased food intake increases optimal temperatures for growth and the highest temperatures sustaining growth (i.e. upper thermal limits; Huey and Kingsolver, 2018). Increased food supply can also mitigate the negative effects of ocean acidification on calcification (Ramajo et al. 2016, Brown et al. 2018). There is some evidence that documents healthier corals in reserves, though this was less evident in corals within MPAs impacted by terrestrial runoff Lamb et al 2016). However, the extent and variation to which individuals within and around MPAs might enjoy greater nutritional states, through either more resources or greater fat stores within organisms inside MPAs, and the possible effects on climate resistance, is currently unknown (Davies 2020). Diet composition analysis of kelp bass (Davis et al. 2019) and gopher rockfish (Loury et al. 2015) indicated no difference in trophic position or niche inside and outside of California MPAs, but the effects of protection on nutritional state per se are not known.

IIC. Increased Population Resilience

There are several mechanisms by which MPAs can increase climate resilience at the population level. First, larger body sizes inside MPAs can increase recovery from disturbance via higher fecundity of larger individuals. Larger fish produce disproportionally more and higher quality offspring (Hixon et al. 2014, Bernache et al. 2018), adding to the capacity of populations in MPAs to replenish themselves (Marshall et al. 2019). Indeed, larger abalone in MPAs in Baja California produced more offspring compared to smaller abalone in fished areas, improving recovery after a regional hypoxic event (Micheli et al. 2012). Similarly, MPAs can provide a fuller age structure of populations, i.e., one that is not truncated due to fishing (White et al. 2013, Baskett and Barnett 2015). In organisms with sporadic recruitment success, protection of older age classes can produce a "storage effect" in which elders can out-live a series of poor reproductive years, and then take disproportionately greater advantage of favorable conditions when they return, fostering population persistence (Hjort 1914, Warner and Chesson 1985, White et al. 2019). A broader age structure also reduces the sensitivity of populations to environmental fluctuations at particular frequencies. In the phenomenon known as 'cohort resonance', populations with truncated age structure (as by fishing) tend to amplify environmental fluctuations that have frequencies near the generation time of the species (Bjørnstad et al. 2004, Botsford et al. 2014, 2019). For example, the El Niño-Southern Oscillation (ENSO) has a periodicity of 4-6 years, which coincides with the age of maturity of many California Current species. To the extent that MPAs create a broader age structure of populations, this should help buffer against ENSO variability because reproduction of a cohort is spread out in time (Botsford et al. 2019).

Next, MPAs typically support larger population sizes (reviewed by Lester et al. 2009), and increased density and biomass is commonly observed in California MPAs (Paddack and Estes 2000, Parnell et al. 2005, Froeshke et al. 2006, Tetreault and Ambrose 2007, Caselle et al. 2010, Karpov et al. 2012, Kay et al. 2012, Hamilton and Caselle 2014, Caselle et al 2015, Starr et al. 2015, Keller et al. 2019, Eisaguirre et al. 2020, Esgro et al. 2020). Larger population sizes can increase resilience in three key ways. It can (i) reduce the chance that a random disturbance drives the population below some critical threshold or tipping point beyond which recovery is not possible (Botsford et al. 2019), (ii) improve the chances that evolutionary adaptations to changed environmental conditions arise, because there is a smaller chance that favorable alleles are lost from the population due to genetic drift (Masel 2011), and (iii) increased recovery rates after disturbance because higher population densities lead to higher probability of fertilization success and greater reproductive output in species that are broadcast spawners or aggregating spawners (Gascoigne and Lipcius, 2004).

MPAs are also expected to act as refuges for genetic diversity, increasing the likelihood of resistant genotypes and the potential for recovery via evolutionary rescue. Despite this expectation, there are surprisingly few studies of genetic diversity in MPAs. Genetic diversity of a harvested fish was found to be greater in Mediterranean MPAs (Pérez-Ruzafa, 2006), and allelic diversity and effective population size of pink abalone was greater in an MPA than in fished areas in Baja California, Mexico (Munguia-Vega et al. 2015). In comparisons of

Box 7. Evidence of resilience through species interactions in the Santa Barbara Channel Islands in response to climate-induced disease outbreak

Modeling and experiments have demonstrated that diverse ecosystems with high levels of functional redundancy – where multiple species share similar roles in an ecosystem - can enhance ecosystem stability and resilience in the face of disturbance. Researchers explored trophic redundancy and predator diversity in MPAs of the Northern Channel Islands, California, in response to the outbreak of sea star wasting disease, an epidemic affecting more than 20 sea star species from Alaska to Mexico which corresponded with strong temperature increases associated with El Niño (Eisaguirre et al. 2020). By 2014, sunflower sea stars (*Pycnopodia helianthoides*) were completely extirpated from their historic range, removing a major keystone predator in kelp forest ecosystems that have kept populations of kelp-grazing urchins under control.

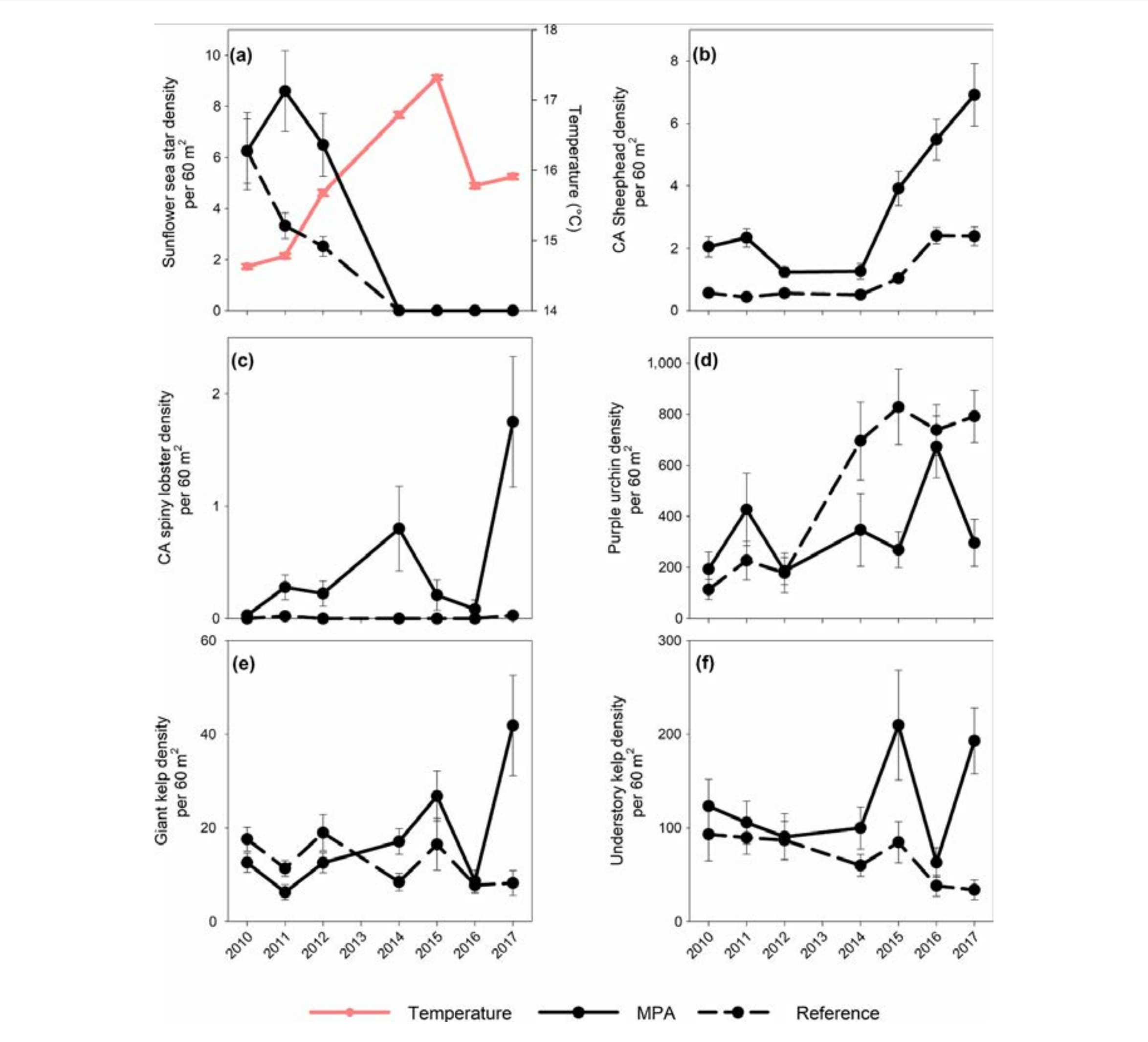


Figure 6. Temporal patterns of key members of the kelp forest community and sea surface temperature from 2010 to 2017.

Solid lines are marine protected areas (MPA) sites, dashed lines are reference sites. All species data are mean density (per 60 m2) ± 1 standard error. (a) Sunflower sea star and temperature (°C), (b) California (CA) sheephead, (c) California spiny lobster, (d) purple urchin, (e) giant kelp, and (f) understory kelp. (Figure from Eisaguirre et al. 2020)

Box 7 con't.

However, in the Northern Channel Islands, unlike areas further to the north in California, there are two additional urchin predators besides the sunflower stars - California Sheephead (*Semicossyphus pulcher*) and California spiny lobsters (*Panulirus interruptus*). Both of these species are fished and have been previously shown to be more abundant and larger in MPAs (Hamilton et al. 2010, Kay et al. 2012, Caselle et al. 2015, Hamilton and Caselle, 2015). Following the sea star wasting event, the large numbers and sizes of these remaining urchin predators inside unfished Channel Island MPAs kept purple urchin densities low, and there was greater persistence of Giant and understory kelp (Figure 6). Outside of MPAs where California Sheephead and spiny lobsters were smaller in number and size, purple urchin densities increased dramatically following the loss of sunflower stars. The increase in urchin density coincided with a steady reduction in algae and an increase in urchin barrens.

These results demonstrate that the MPAs provided resilience from disturbance-induced changes to the communities by protecting important functions such as predation. In locations where predators have key functions and are fished, MPAs might provide this form of resilience.

Sunflower star
Image: iStock

California sheephead
Image: Ana Sofía Guerra

fisheries stocks over a range of fishing intensities, it has also been shown that overfishing has led to 12% reduced allelic richness among fisheries stocks (Pinsky and Palumbi, 2014). If genetic variation is greater inside MPAs, as expected, this would confer greater resilience to climate impacts. For example, purple sea urchin larvae exhibited allelic changes consistent with natural selection and adaptation in response to ocean acidification treatments in the laboratory (Pespeni et al. 2013). Sunday et al. (2011) found that an urchin species had more than 100 times the genetic variability in larval traits than a mussel in an acidification experiment, and thus much faster rates of adaptation to high-CO_2 conditions in a simulated population model. That result compared two species, but the same principle would apply to comparisons among populations of a single species.

MPAs may also improve population resilience through preservation of habitats critical to population vital rates, such as spawning or nursery habitats (e.g., the biotic habitats of estuaries used by many California species, Beck et al. 2001, or kelp canopies, White and Caselle 2008). An important aspect of this protection is that if species are fished in both nursery and adult habitats, then MPAs must span adjacent nursery and adult habitats to effectively support population persistence (White 2015). The degree to which protected nursery habitats are altered in this function due to climate change could change their effectiveness.

Finally, a network of MPAs can protect populations or species distributed across a range of environmental conditions or exposure to stress. In the extreme, a network of MPAs can represent replication across many patches of similar habitat types, providing insurance against catastrophic disturbance of any one patch during an extreme event, such as a storm, heat wave, or direct human disturbance such as an oil spill (Allison et al. 2003). In a less extreme context, a spatially distributed MPA network spanning metapopulations could allow individual local populations to fluctuate in response to local disturbances independently, such that the overall metapopulation experiences the buffering benefits of a portfolio effect (Anderson et al. 2015, Hammond et al. 2020). However, there is a tradeoff, in that greater connectivity among MPAs would tend to synchronize population responses to localized disturbances, such as potential population collapse (Goldwyn and Hastings 2008, Wagner et al. 2018) but also would tend to enhance the replenishment of individual disturbed MPAs by neighboring MPAs. Whether these populations are resilient to disturbances (e.g., replenishment of individual neighboring MPAs) will likely depend on the frequency and magnitude of the disturbance, the species' dispersal capability which influences level of connectivity, and distance and spacing of the individual MPAs within the network. For example, if the goal is to maximize population persistence and viability within MPAs following a large disturbance, it is best to have MPAs spread further apart to avoid population collapse across all MPAs. Furthermore, optimal MPA spacing also increases when disturbance frequency is high, but decreases when frequency is low (White et al. 2020).

It has also been suggested that an MPA network can enhance protection of species undergoing climate-induced range shifts, i.e., in which occupancy declines at the warm end of the range, and increases beyond the cold end of the range. The concept of corridors of protection to enhance climate change resilience is well-developed in terrestrial systems (Hilty et al. 2020), but not in marine systems. This is possibly because on land, protection tends to have a direct effect on habitats (as opposed to harvest rates), and dispersal potential is thought to be more habitat-limited. Less is known about the effect of protection in marine systems and MPA networks in particular on persistence during range shifts. Theoretical work supports a positive role of MPA networks for harvested species; as long as MPAs regionally reduce harvest rates (and don't simply displace fishing effort to non-MPA sites), an MPA network can increase persistence of a range-shifting species (Fuller et al. 2015). However, if fishing intensity is simply displaced outside of MPAs without a change in total harvest rate, an MPA network could reduce the probability of persistence of a harvested species given a fixed fishing intensity and pace of climate change (Fuller et al. 2015), essentially by making the poleward range edge more inhospitable through greater displaced fishing. Assessing the effect of MPAs on fishing behavior and intensity could help to disentangle these predictions for individual species in the California MPA network. However, this model was sufficiently general to suggest that any increase in population growth rate conferred by MPAs could increase the resilience of individual species connected through dispersal across MPAs; hence any other aspect of population resilience conferred by MPAs (e.g., through trophic linkages, larger sizes, and improved habitats) could increase species persistence during range shifts, although more work is needed to develop and test these predictions.

IID. Increased Ecosystem Resilience

MPAs can increase ecosystem-level resilience through various mechanisms. First, they can support greater species or functional diversity. Globally, temperate MPAs increase species richness by 14% on average (Lester et al. 2009), and increased fish diversity in MPAs is associated with increased functional diversity of fish communities (Micheli and Halpern 2005). Although there is little evidence to date in support of California MPAs increasing in species diversity or richness (Paddack and Estes 2000, Froeschke et al. 2006, Starr et al. 2015, but see Caselle et al. 2018, Esgro et al. 2020), these effects may increase with time (Claudet et al. 2008). One mechanism by which species diversity can improve resilience is through functional redundancy, whereby the ecosystem-level effect of one species that may be declining under climate change is maintained by the persistence of one or more functionally similar species. This will be especially relevant when the functionally redundant species exhibit response diversity to climate change impacts (Elmquist et al 2003, Baskett et al. 2014).

Higher levels of functional diversity and redundancy were documented for fish communities in MPAs spanning a suite of geographies, including California (Micheli and Halpern, 2005). Although the results of Micheli and Halpern (2005) predicted low functional redundancy in marine assemblages protected by MPAs, a recent study in the Northern Channel Islands MPA found a strong case for functional redundancy: following the loss of a predatory sea star, two other species compensated for the loss of that function through their own predation (Box 7; Eisaguirre et al. 2020). Because both remaining species are fished (California sheephead and California spiny lobster) their compensatory effects were greater in MPAs. More work is needed to resolve how functional redundancy and diversity are affected by MPAs and how this could provide climate resilience to ecosystem function.

Another impact of MPAs on ecosystem resilience appears to occur through the maintenance of larger body sizes which can lead to a more resilient network of trophic interactions. Although larger body sizes in MPAs have already been cited for their potential impacts on individual and population-level resilience (above, and Table 2), through trophic interactions this can also impact ecosystems. For example, outside of MPAs in temperate Tasmania, climate-induced range expansion of large, long-spined sea urchins (*Centrostephanus rodgersii*) has decimated kelp forests rapidly upon arrival. Yet, inside MPAs, kelp forests remained intact because predatory lobsters were allowed to grow large enough (due to lack of fishing pressure) to prey on these large sea urchins by overturning and extracting urchins from the substratum. Other predators in this system were unable to exploit these urchins using this technique due to their large size (Ling et al. 2009, Ling and Johnson, 2012). By protecting the size structure of fished populations (i.e., the distribution of large and small sizes), MPAs also could prevent predator-prey systems from shifting into alternate stable states. For example, if large predators facilitate the survival of juvenile conspecifics (i.e., a younger cohort of the same species) by consuming smaller-bodied predators from another species (a 'cultivation effect'), harvest could remove that benefit and collapse the larger species' population (as is hypothesized to have happened in Atlantic cod), whereas MPAs could preserve the original state (Barnett and Baskett, 2015).

MPA networks could theoretically improve ecosystem resilience to climate change through similar mechanisms as their population-level effects. MPAs located across sites that encounter asynchronous climate impacts can confer resiliency at larger scales via the portfolio effect (Anderson et al. 2015, Hammond et al. 2020). Also, networks of interacting species each shifting their ranges under climate change may remain more intact if MPAs promote population growth of each at their leading edge. Empirical work to test these predictions is lacking.

IIE. Human Dimensions and Coastal Community Resilience

The increased resilience that MPAs provide to broader ecosystems also has potential to support resilience in linked socioeconomic systems. Resilient social systems are characterized by diversity and flexibility (assessed through indicators such as livelihood and income diversity, economic opportunities, place attachment, etc.), access to assets (physical, economic, and social), learning and knowledge, and responsive social institutions and governance systems (Whitney et. al. 2017). To date, research on understanding human dimensions of MPAs focuses primarily on outcomes for fisheries and governance system (Ban et al. 2019, Rasheed 2020), with little attention to other indicators of social resilience. Thus, the relationship between MPAs and social resilience to climate change is characterized by limited information and is largely inferential. Here, we discuss what is currently understood from the available literature, focusing on MPA outcomes for healthy fisheries and food production, local economic support through tourism, coastal resilience, protection of culturally significant habitat and species, and broader outcomes relating to human wellbeing.

Healthy fisheries and food production

Resilient fisheries can support healthy coastal economies through the commercial sale of seafood, supporting local food supplies and businesses, and contributing economic and subsistence benefits to local communities and economies. California is mandated through the MLMA to sustainably manage it fisheries (Weber et al. 2018) and MPAs (and the MPA network) are one of many tools being used by marine managers to achieve the goals of the MLMA. Sustainable fisheries necessitates that these fisheries be resilient in the face of climate change and MPAs play an important role in the effort to ready these fisheries for climate change (Chavez et al. 2017).

Fisheries have been documented to benefit from spillover effects of target species from MPAs, which may support fisheries resilience under a changing climate. For instance, Goni et. al. (2010) found that harvested spill-over of lobster from an MPA in Spain offset potential losses from the reduction in available fishing grounds, resulting in a 10% increase of total catch in weight. The study also documented increased spill-over during an extreme storm; lobsters likely moved as a result of high energy levels at the bottom indicating that extreme climate events may cause movement of species that results in increased spill-over. MPAs may also support increased larval transport of target species, with evidence of larval dispersal of kelp rockfish (*Sebastes atrovirens*) in several Central Coast MPAs in California, as well as evidence of connectivity between populations in protected MPA areas and in fished populations (Baetscher et. al. 2019). Protected habitat within MPAs can also increase fishery yields by serving as a nursery or feeding ground for commercially targeted fish species; for instance, Aburto-Oropeza et al. (2008) documented increased fishery yields from intact mangrove habitat in the Gulf of California.

Lucas Wharf fish house, Bodega Bay, CA

Image: Meritt Thomas

MPAs may also have the potential to provide food security in the case of disaster or disruption in supply chains by maintaining localized fish biomass, but evidence to support this hypothesized use of MPAs is scant. Some modeling studies indicate that rotational MPA schemes that periodically allow harvest can support healthy fisheries (Game et al. 2008, Plaganyi et al. 2015). Valderrama and Anderson (2007) have documented significant economic and ecological benefits to the sea scallop fishery in the Northeast U.S. from a rotational closure system, but Williams et al. (2006) found increases in fish biomass during periods of closure were insufficient to compensate for the effects of fishing during open periods for rotational closures in Hawaii. MPAs in California do not operate on a rotational basis, and instituting periodic openings of protected areas to fishing in response to extreme events or supply shortages runs the risk of quickly eliminating many of the other resilience mechanisms described in this report, particularly those related to having larger, longer-lived individuals (Russ and Alcala 1999, Russ and Alcala 2003).

A recent effort to model a globally optimized MPA network for food production suggests that global MPA network expansion of just 5% could improve fisheries productivity by at least 20% (Cabral et al. 2020). It is important to note that this work includes analysis and consideration of productivity of many international fisheries stocks, including those that are poorly managed at present, so the same type of marginal benefit would not be expected at the scale of California MPAs alone. Additional model downscaling is needed to better understand the role of California MPA network in maximizing ocean food production in light of a growing population and the projected changes ahead. Additional questions remain regarding how MPAs will enhance productivity of target species under a changing climate, as well as how changes in ocean systems will affect larval transport mechanisms, and whether the existing MPA network can protect targeted species and support associated fisheries as ranges shift under a changing climate. Answers to such questions are important developing ocean plans that take shifting fisheries into account (Pinsky et al. 2020).

Supporting local economies through tourism

MPAs also maintain species abundance, diversity and biogenic habitat that can serve as a draw for ocean-based tourism. This, in turn, has the potential to support local economies through direct and indirect revenue derived from diving, snorkeling, and recreational fishing. For instance, Arkema et al. (2017) found that higher tourism expenditures were attributable to two MPAs in the Bahamas, citing how the protection of marine species fostered the area's reputation as a world-renowned location for tourism. Hargreaves-Allen et al. (2011), in a global survey of 78 coral reef-based MPAs, found that over half of reported jobs supported by MPAs were in the tourism industry. However, increased tourism to a region can also increase the demand for local seafood, which in some instances may conflict with MPA goals (Lopes et. al. 2017).

California has a thriving coastal tourism economy. Tourism and recreation is the largest of California's ocean-dependent economic sectors, accounting for 39 percent of the ocean economy's gross domestic product, or $17.6 billion, as well as 75 percent of the ocean economy's employment in 2012. However, studies documenting how the MPA network supports tourism, recreation, and related revenue in California are limited. Increased opportunities for livelihood diversity from tourism and increased potential for tourist-derived revenue to communities adjacent to MPAs has the potential to support resilience to climate-induced and other economic stressors, but this has not yet been documented.

Coastal resilience

Intact coastal habitats can increase coastal resilience, both by protecting man-made coastal infrastructure, as well as through carbon sequestration. Coastal habitats shield people and property from the effects of sea-level rise and storm surges, saving money that might otherwise be spent on disaster aid (Arkema et al. 2013). Biogenic habitat provides advantages over man-made coastal infrastructure (such as sea walls) in that it adapts naturally with sea-level rise (Rodriguez et al. 2014, Roberts et al. 2017). In a review of the literature, Geden et al. (2011) found evidence of protection from erosion and storm surge with salt marsh habitat; however, the benefits of coastal habitat protection are in many places context dependent. Kelp forests dampen and attenuate waves and reduce the velocity of breaking waves, providing a buffer against storm surges and reducing coastal erosion (Lovas and Torum 2001), and water flow attenuation by kelp forests is correlated with the extent, density, and morphology of canopy-forming giant kelp in California (Gaylord et al. 2007). Coastal habitats, like mangroves, tidal wetlands, kelp forests, and seagrasses also currently store up to 25.1 billion metric tons of carbon (Howard et al. 2017), and protection and restoration of these habitats can provide important contributions toward meeting global climate goals (Dundas et al. 2020).

Protection of Cultural, Spiritual, and Aesthetic Benefits

MPAs can also play a role in protecting culturally significant habitats and species whose existence and use value may be important to society. Potts et al. 2014 found that MPAs in the United Kingdom (UK) protect species that are considered culturally important to residents of the UK, such as marine mammals and other charismatic species. In California, evidence that MPAs can provide climate resilience to culturally significant species and habitats is limited, in part due to a lack of research documenting what species or habitat types are considered significant to different stakeholder groups. A report led by the Tolowa Dee-ni' Nation (2017) identified five keystone species, including abalone, clams, mussels, seaweed, and smelt (surf fish and night fish) that were considered to be a cultural indicator or cultural keystone for many North Coast Tribes in California (primarily for food or ceremony) that were likely to benefit from MPAs. Abalone, in particular, is a critically threatened species of cultural significance to many residents born and raised in California (Vileisis 2020), which may show potential for recovery within MPAs, due in part to protection of kelp habitat and other associated species. For instance, Rogers-Bennett et. al. (2002) found higher densities of juvenile abalone under red sea urchins' spine canopies in protected areas, than in non-protected areas. A theoretical model by Aalto et al. (2019) also found that MPA networks dramatically reduced the risk of collapse of abalone populations following catastrophic events (75%–90% mortality), showing the theoretical potential of MPAs to enhance the resilience of this culturally significant species to climate change.

MPAs have also been documented to have broader effects on human wellbeing, though these impacts remain largely understudied to date. Ban et al. (2019) conducted a review of 118 peer-reviewed articles documenting wellbeing outcomes of MPAs globally, finding that about half of wellbeing outcomes were positive, and about one-third were negative. However, the majority of these studies focused on economic aspects of wellbeing (primarily fish catch and income), or on resource governance, with few studies documenting outcomes relating to social, health, or cultural outcomes from MPAs, or documenting conference of resilience to climate impacts. Another review by Rasheed (2020) found that most studies focused on wellbeing outcomes of MPAs emphasized employment, income, and food security, but other aspects of wellbeing remain under-studied. Both reviews documented that studies of wellbeing tend to focus on objective measures derived from previous studies that can be easily quantified (thus the focus on fish catch and income), but that there are few studies documenting other quantifiable social measures such as equity (Hicks et al. 2016), and that more effort is required to capture the broader range of multi-dimensional outcomes relating to human well-being, particularly social and cultural values and broader societal outcomes. Bennett et al. (2020) documented differing perceptions of social equity amongst different demographic groups in Mediterranean MPAs, with older fishers perceiving lower levels of recognitional equity, while wealthier fishers and those with more diversified livelihoods perceived higher levels of distributional equity. Their study highlights a need for tailored management actions to improve equity outcomes in different MPA sites and amongst different groups, and these challenges may be altered or exacerbated under changing climate scenarios.

In terms of wellbeing outcomes specific to California MPAs, studies are also limited. One monitoring study, currently underway, will explore wellbeing outcomes of MPAs on fishing communities (defined by port), with a focus on commercial fisheries (Ecotrust 2020). Hackett et al. (2007) found that MPAs in the North Coast did not result in a clear increase or decrease in catch or income for fishermen after the implementation of MPAs. Fishermen in the rockfish/lingcod fishery reported the greatest livelihood disruptions, as many could no longer fish in traditional grounds and had to travel longer distances to fish, though overall incomes for fishermen did not change as a result of the implementation of MPAs. A study by Guenther et al. (2015) also documented challenges for commercial lobster fishermen who could no longer fish in their traditional grounds after the implementation of MPAs in the Channel Islands, as well as logistical difficulties due to the requirement that they stow all fishing gear while transiting through MPAs to and from their fishing grounds. While MPAs have resulted in displacement of fishing effort in California fisheries, it is not yet known how MPAs will interact with potential future shifts in fishing areas under a changing climate.

Trust in California management agencies was documented to be low amongst fishermen in Northern California after the implementation of MPAs (Ordonez-Gauger et. al. 2018), which may pose challenges to the implementation of future management actions to address climate impacts. Ordonez-Gauger et al. surveyed 178 fishermen in Northern California, finding overall low levels of trust in management, dissatisfaction with the MPA designation process, and lack of belief that MPAs would result in improved ocean health or economic benefits. Fishermen who had higher levels of trust in relevant management agencies tended to have higher satisfaction with MPA locations and outcomes, but most fishermen stated that they did not believe the socioeconomic outcomes of MPAs would be substantial.

Rocky intertidal surveys
Image: Rich Ambrose

III. Prioritized Research Needs to Assess the Climate Resilience Capacity of California's MPA Network

The working group developed a list of 15 priority research questions and suggested methods that could be used to assess the performance of California's MPA network in the context of climate change (Table 3). These questions were identified based on an understanding of the historical and projected climate changes in California, the potential resilience mechanisms described above, an analysis of gaps in supporting evidence for those mechanisms identified from a review of the literature (summarized in Table 2), and with the current configuration of the MPA network in mind. Questions are organized around five themes: (1.) cross-cutting and integrative research, (2.) increased organismal resilience, (3.) population resilience, (4.) ecosystem resilience, and (5.) human dimensions. Addressing these questions can further our scientific understanding of how MPAs contribute to climate change resilience, and also help direct preferred management strategies and design decisions (e.g., whether to protect refugia, diversity, habitat heterogeneity (including depth zones), or connectivity). For the detailed process used to identify the research priorities within this report, see Appendix C.

Table 3. Prioritized Climate Resilience Research Questions and Associated Methods for California's MPA network.

The Working Group identifi d 15 research questions to address knowledge gaps associated with distinct MPA benefits and mechanism themes (Table 2). The Working Group prioritized these research questions based on anticipated level of impact and the associated effort required to address it (for a more detailed summary of the process to prioritize these questions, see Appendix C). Only relatively high-impact questions were selected as top priority. The Working Group determined whether each question could be feasibly addressed by the 2022 MPA decadal management review and suggested methods one could enlist to answer these questions. Italicized text represents the MPA benefit and effect mechanism themes identified in Table 2. Asterisk (*) denotes questions that are similar in nature (i.e. based on topic or could be answered using existing long-term monitoring indicators) to those articulated in Appendix B from the California MPA Monitoring Action Plan.

PRIORITY RESEARCH QUESTION	SUGGESTED METHODS
THEME 1: CROSS-CUTTING / INTEGRATIVE RESEARCH	
1. What role does the current MPA network play in meeting societal needs (e.g., economics, human dimensions, cultural values) and which needs are most likely to be impacted under climate change in the future?	• Key informant interviews to gain a better understanding of societal needs for different stakeholder groups in California • Focus groups and/or surveys with multiple stakeholder groups to assess the outcomes of MPAs for societal needs • Economic analysis of catch data, tourist revenue, and other monetary needs identified during interviews • Census analyses to understand key demographic trends in communities affected by MPAs
2. What is the spatial distribution of MPAs relative to historic and current stressor exposures, and how are those stressors likely to evolve in the future?	• Regional data syntheses – query long-term climate datasets to assess historic variability and projected stressor distribution relative to MPAs • Short-term in situ observation networks • Coupled circulation-biogeochemistry models • Climate models with downscaled coastal circulation-biogeochemistry models • Climate models with projected shoreline evolution with sea level rise (CoSMoS 3 USGS)
3. Does MPA-induced ecological resilience spill over to areas outside MPAs? What mechanisms increase the likelihood of resilience spillover and are they quantifiable?	• Analyses to characterize the relationship between biological and ecological attributes and the potential resilience they confer against various stressors, independently and in concert • Using foundational knowledge on MPA performance, analyses of existing data to evaluate how MPAs affect biological and ecological attributes outside of protected areas (i.e., spillover) • New measurements of biological and ecological attributes of greatest utility for resilience, if such parameters have not been the subject of traditional MPA monitoring efforts
4. How will knowledge on the patterns of community resilience, and their underlying mechanisms, inform the appropriate role for MPAs in policy, management, and conservation to address future climate impacts?	• Policy and/or value-of-information analysis of existing management and policy tools, and opportunities to integrate findings from MPA monitoring and climate research
THEME 2: ORGANISMAL RESILIENCE / ADAPTIVE CAPACITY OF ORGANISMS	
5. Will California's MPA network continue to protect key species, and a significant portion of their habitat, as species migrate (i.e., range, depth) due to climate variability, marine heatwaves, and climate change?	• Continued MPA monitoring and analysis of that existing data • Species distribution modeling coupled with downscaled climate modeling to predict species redistributions • Habitat assessments • Assess range shifts inside and outside of MPAs in CA • Analyses of shoreline change and sea level rise
6. Do MPAs facilitate species' adaptive responses to climate change via increased genetic diversity due to increases in population size?	• Sampling genetic diversity of model species in the field • Lab experiments to test for differential responses of different genotypes (or epigenomes, etc.) to stressors • Eco-evolutionary modeling to assess potential for adaptation given the observed schedule of disturbances

Table 3 con't.

PRIORITY RESEARCH QUESTION	SUGGESTED METHODS
THEME 3: POPULATION RESILIENCE	
7. What are physical, ecological, and biological characteristics of climate refugia? Do MPAs include or promote these conditions? Will climate refugia persist into the future?	• Synthesis of current literature on refugia; expert workshop to determine refugia criteria in a California MPA context • Analysis of historic and future climate scenarios, species responses, and MPA exposure for multiple stressors • Biophysical monitoring, habitat evaluations, and field studies
8. Does the California MPA network provide adequate levels of disconnection between MPAs (e.g., modularity) to ensure some populations persist in the face of climate change?	• Map existing MPAs onto climate stressor maps (e.g., prediction maps and projections) • Use existing data to understand biogeographic variation across the MPA network • Connectivity modeling • Conduct ecosystem vulnerability analyses, particularly for shorelines and estuaries
THEME 4: ECOSYSTEM RESILIENCE (AND NETWORK FUNCTION)	
9. Do California MPAs provide ecological resilience (e.g., via increased functional diversity & redundancy) in response to marine heatwaves and anomalous oceanographic changes?	• Classify species in terms of functions (trophic levels, adult mobility, larval mobility, other traits), that affect ecosystem function (effect traits) or respond to climate change (response traits) • Analyze overlap of functions in and out of MPAs • Track patterns of functions (via diversity, abundance) over time (e.g. to detect response time lags) • Predict or estimate changes in biodiversity across and within trophic levels using ecological models (e.g., size models) and in situ community and biodiversity assessments (e.g., eDNA)
10. How will climate change affect ecosystem connectivity across the MPA network? How do current and future connectivity patterns and species interactions affect resilience of MPAs?	• Couple individual-based larval mechanistic models of larval transport forced with regional climate change scenarios • Explore the combined effects of changes in hydrodynamics, adult reproductive timing, and larval dispersal on the connectivity among MPAs and their ability to seed fished areas with larvae • Explore other types of connectivity (e.g., via drift kelp, surf grass, eelgrass) that provide cross ecosystem subsidies
THEME 5: HUMAN DIMENSIONS	
11. As fishermen alter fishing behavior (e.g., spatial or temporal patterns, targets) in response to migrating species due to climate change, will California's MPA network continue to protect and provide habitat to commercially and recreationally targeted, and culturally significant, species?	• Assess changes in fishing behavior using interviews/surveys or catch data under different oceanic conditions to extrapolate to future potential conditions, while considering species distribution and spillover potential. (Draw upon outcomes of Q. 13 below to inform what species are considered culturally significant.) • Assess changes in non-consumptive/non material use of MPAs such as whale and/or bird watching • Evaluate ecosystem vulnerability for shorelines and estuaries in MPAs
12. What ecosystem services do MPAs provide and how might those ecosystem services change under climate stressors?	• Drawing upon outcomes of Q1, conduct a workshop, with MPA managers and experts, to cross-list Ecosystem Service categories with observed or expected services provided by MPAs, followed up with service-specific studies (including provisioning, regulating, cultural services, storm buffering, flood protection etc.)
13. What do people consider culturally, spiritually, and aesthetically beneficial about coastal and ocean regions protected by MPAs, and will MPAs continue to support the provision of these values under a changing climate?	• Focus groups with different stakeholder groups to identify cultural, spiritual, and aesthetic benefits • Determine if there are key species, habitats, etc. associated with these benefits, and to what extent these are protected by the MPA network (overlay MPA population and habitat distribution maps with MPA coverage) • Cross check with biophysical predictions about species, habitat, etc. under changing climate to see if key species, habitat, etc. are likely to be affected by climate change

Table 3 con't.

PRIORITY RESEARCH QUESTION	SUGGESTED METHODS
14. What are the equity issues around MPAs in a changing climate?	• Review of available literature on equity concerns relating to MPAs and climate change; survey of key stakeholders; review of secondary indicators as relevant • Analyze the results of the assessments of changes in both consumptive and non-consumptive uses of MPAs to determine if the changes negatively impact certain groups of stakeholders (as categorized, for example, by race, class, and ethnicity).
15. Do MPAs support and facilitate climate adaptation in coastal communities (e.g., provide alternative livelihoods or coastal protection)?	• Use historical case studies to assess whether MPAs facilitated protection or adaptation following previous extreme climate events

Anacapa Island, CA
Image: Ana Sofia Guerra

IV. Science, Policy and Management Recommendations to Support a Climate-resilient Marine Protected Area Network

Based on an evaluation of existing evidence and in consultation with staff from the California Ocean Protection Council and California Department of Fish and Wildlife, the working group recommends a series of suggested actions (summarized in Table 4) grouped under two overarching strategies: (1.) develop and implement a climate change research and monitoring plan for California's MPA network, and (2.) employ new and existing tools and partnerships to maximize the benefits of a climate-resilient MPA network.

These recommendations are intended to deepen understanding of the capacity for California's MPA network to provide ecological and societal resistance and resilience to climate change (Strategy 1) and ensure that a robust body of science is available to guide the development, implementation, and evaluation of existing and new MPA resilience management strategies as a part of the state's climate resilience toolbox (Strategy 2). Recommendations consider both ecological and social systems, and are linked to MPA management opportunities as well as broader climate change action planning. They are intended to guide research and monitoring that will fill key knowledge gaps in California, position MPAs as a tool within the state's larger climate action toolbox, encourage alignment of regional, national, and international climate priorities for MPAs, and ensure an inclusive, science-informed process for adaptive MPA management in a changing climate. The working group acknowledges that any proposed or operationalized actions should balance multiple economic, social and biological objectives, and include stakeholder participation. Full consideration of how actions may impact or benefit diverse stakeholders, and mechanisms for promoting inclusion in science and management are crucial.

To inform the first steps in the development of a research and monitoring plan (Strategy 1), the working group provides additional detail for Actions 1.1 through 1.3, including suggestions for several near-term projects that can be completed within the next four years. These range from expert convenings and stakeholder consultation to suggested analyses that could be completed using existing data and models. Investments in near-term research and monitoring should be paired with development of longer-term climate focused management priorities for the MPAs (e.g., defining specific operational climate change resilience objectives and measurable variables that build on the goals of the MLPA) (Activity 2.3.2) in order to assess and track the climate resilience capacity of the network going forward.

Table 4. Science, Policy and Management Recommendations to Support a Climate-resilient Marine Protected Area Network.

The working group developed two overarching strategies with a series of suggested actions and activities that can (1.) deepen understanding of the capacity for California's MPA network to provide ecological and societal resistance and resilience to climate change (Strategy 1) and (2.) ensure that a robust body of science is available to guide the development, implementation, and evaluation of existing and new MPA resilience management strategies as a part of the state's climate resilience toolbox (Strategy 2). Action and activities within strategy 1 are supported by more detailed project descriptions and timelines in Section IV of this report. Actions are not presented in order of priority and can be approached in sequence or in parallel. It is noted when actions or activities are dependent on the science presented in a previous action or activity.

STRATEGY 1: DEVELOP AND IMPLEMENT A CLIMATE CHANGE RESEARCH AND MONITORING PLAN FOR CALIFORNIA'S MPA NETWORK		
SUGGESTED ACTIONS	**RATIONALE**	**SUGGESTED ACTIVITIES**
1.1 Prioritize investment in integrated long-term MPA monitoring of key species, habitats, and oceanographic variables. Advancement of all subsequent actions dependent on Action 1.1.	Maintain the state's current MPA monitoring program and enhance it to include variables predicted to respond to climate change. This can support a more robust, integrated long-term monitoring program that can detect, track, and quantify the impacts of climate change on California's MPA network.	**1.1.1 Add new climate resilience monitoring metrics to the State's existing long-term monitoring plan.** This includes incorporating variables (sentinel sites or climate change indicators) where oceanographic and social-ecological-economic observations are tracked.
1.2 Advance scientific understanding of MPA exposure across the network, including potential areas of refuge, vulnerability, and resilience.	Determining areas of refuge and vulnerability is a first step to understanding the resilience capacity of the network, informing network design considerations, and supporting living marine resource management decisions.	**1.2.1 Define refugia for California's MPA network** via literature synthesis and expert workshop. **1.2.2 Characterize the local oceanography of MPAs across multiple stressors** using existing data. **1.2.3 Model habitat and species distributions in current and future conditions.** **1.2.4 Perform tiered risk assessment of species, ecosystems, and habitats** within MPA.
1.3 Expand capacity to assess and address social science climate resilience research needs.	Engaging stakeholders to better understand regional and local impacts, interests and needs under a changing climate - and integrating those considerations into decisions about climate-resilient MPA management priorities and science investments - will be vital to ensuring success of the network. Baseline studies are needed on social and economic service provision, and cultural and spiritual values of MPAs, and how those might change under climate stressors.	**1.3.1 Assess state of the knowledge of social values and outcomes** relating to MPAs and climate resilience in California. **1.3.2 Engage stakeholders to: (a) ensure cultural and spiritual values and benefits associated with MPAs** are fully identified, and **(b) better understand regional and local impacts or benefi s,** as well as social priorities and needs under a changing climate. **1.3.3 Conduct baseline studies on social and economic service provision of MPAs.** **1.3.4 Assess equity issues around MPAs in a changing climate.**

Table 4 con't.

STRATEGY 2: EMPLOY NEW AND EXISTING TOOLS AND PARTNERSHIPS TO MAXIMIZE THE BENEFITS OF A CLIMATE-RESILIENT MPA NETWORK		
SUGGESTED ACTIONS	**RATIONALE**	**SUGGESTED ACTIVITIES**
2.1 Continue to advance statewide no-regrets climate actions*, particularly as they intersect with or advance MPA management goals.	Expanding agency partnerships to advance no-regrets, multi-benefit climate and resilience management actions can move us towards meeting the goals of the MLPA while simultaneously making progress towards broader climate change and coastal management priorities.	**2.1.1 Continue actions to climate-ready fisheries** (e.g., new or more flexible fishery management tools and fishing practices) and better integration of fisheries management approaches with MPAs. **2.1.2 Support comprehensive watershed management and reduction of land-based sources of pollution** (including nutrients, microplastics, and other contaminants), particularly in locations that feed into MPAs. **2.1.3. Protect, restore, and expand sensitive coastal habitats to enhance climate resilience,** including coastal wetlands, rocky intertidal and kelp forest ecosystems as nature-based climate resilience management strategies. Continue to investigate the role of MPAs in protecting habitats that sequester and store carbon. **2.1.4 Continue aquatic invasive species (AIS) prevention, detection, or removal efforts statewide** in alignment with the best available science. Explore opportunities to align AIS management with MPA management goals.
2.2 Adopt policies that allow for evaluation of the efficacy and feasibility of climate resilience management strategies and interventions within and outside of MPAs.	Evaluating the effectiveness and potential outcomes of existing and new climate resilience MPA management actions will be essential to inform which strategies can best support the goals of the MLPA in light of climate change. Continued access to collaborative study opportunities within MPAs are necessary to support adaptive MPA management (per goal 4 of the MLPA), particularly as large-scale environmental changes increase in the future.	**2.2.1 Review which active management interventions have been effective in or around MPAs** in support of resistance to and/or recovery from climate disturbance. Interventions might include habitat restoration including artificial reefs, species enhancements/removals, and assisted migration. Re-evaluate as new information becomes available. **2.2.2 Consider the use of "experimentation MPAs"** (i.e., MPAs that allow collaborative scientific studies to explore the efficacy of various resilience management strategies) using existing MPAs or by designating additional experimentation MPAs. Re-evaluate permitting guidance for collaborative research activities permissible within select existing or newly proposed MPAs. **2.2.3 Evaluate the intersection of MPA management with dynamic ocean management tools** (i.e., other spatial/temporal management measures, such as temporary closures). Dynamic approaches offer the ability to encode dynamism directly in the management process so that new conditions trigger automatic management actions but also can be used to test the efficacy of existing closures. **2.2.4 Assess existing MPA design and network connectivity for their role in enhancing climate resilience** and explore whether changes may enhance protections for climate-sensitive habitat, species, or coastal communities. Assess social, economic, and ecological tradeoffs for alternative MPA network designs. **2.2.5 Explore the role of evaluation science** (e.g., management strategy evaluation and other structured decision-making frameworks) as a means to identify and evaluate trade-offs resulting from different climate resilience MPA management scenarios.

*actions that are likely to generate net social benefits under all future scenarios of climate change and impacts (Heltberg et al. 2009)

Table 4 con't.

STRATEGY 2 CON'T.		
SUGGESTED ACTIONS	**RATIONALE**	**SUGGESTED ACTIVITIES**
2.3 Develop and incorporate climate-resilient MPA priorities into existing MPA management activities and state climate action plans. Advancement of Action 2.3 is dependent on the science suggested in 2.2.	As we learn more about climate change exposure and vulnerability of the state's social-ecological-economic systems, managing the network in a way that enhances resilience to these impacts is essential. The MPA network may also be leveraged as a tool for advancing progress towards the state's climate change goals.	**2.3.1 Invest in the climate research above (Strategy 1 and research in table 3)** and continue to track and integrate findings into adaptive management of the network. **2.3.2 Develop climate focused management priorities for the MPAs, building on the original goals of the MLPA.** Update state MPA Action Plans as needed to include new climate priorities. **2.3.3 Incorporate the MPA network into state climate action plans based on an evaluation of effective management strategies (per action 2.2)** (e.g., Safeguarding California, California Climate Assessments, Natural and Working Lands).
2.4 Expand partnerships within and across state boundaries to align regional, national, and international climate priorities for MPAs.	Expanding partnerships to advance collective climate change targets can move us towards meeting the goals of the MLPA while continuing California's role as a leader in climate-ready management approaches.	**2.4.1 Enhance existing or develop new MOU(s) across 3 west coast States, the federal government, British Columbia, Mexico, and including tribes, to advance and align MPA climate priorities across the region**, exchange best available science, best practices, and develop opportunities to maximize impacts. **2.4.2 Elevate California's leadership in climate readying the MPA network in international venues and discussions** (e.g., United Nations Conference of Parties). Continue to assess the role of California's MPA network in supporting UN Sustainable Development Goal 14 and in the design of a post-2020 global biodiversity framework (Conference of the Parties to the Convention on Biological Diversity 2050 Vision for Biodiversity).

Strategy 1: Develop and implement a climate research and monitoring plan for California's MPA network

Filling priority science gaps may inform additional opportunities to manage MPAs in a way that can enhance the ability of California's ecosystem and communities to resist, recover from, or adapt to the impacts of climate change. Below, the working group articulates a set of near-term projects that can be completed within the next four years, ranging from expert convenings and stakeholder consultation to suggested analyses that could be completed using existing data and models.

Action 1.1: Prioritize investment in integrated long-term MPA monitoring of key species, habitats, and oceanographic variables.

Relevant research questions: all

Sustained investment in long-term monitoring of the MPAs is critical to continuing to track climate change impacts in California. Continued data collection on key species and habitats under climate extremes will give us insight into future conditions and is required to address many of the research questions in this report. The MPA Monitoring Action Plan (CDFW and OPC 2018) provides an important first step towards ongoing monitoring for better-informed management.

Add new climate resilience monitoring metrics to the State's existing long-term monitoring plan.

Projected duration: 6 months – 1 year

Identifying sentinel species and resilience metrics offer the ability to track ecosystem tipping points before it would be detected using traditional survey methods (Dai et al. 2012, Hazen et al. 2019, Tittensor et al. 2019). Candidate MPA monitoring metrics that could be used to detect climate change effects – including metrics for species that are currently identified in MPA monitoring plans, as well as new species and metrics - have been previously identified and may be a good starting point for the state to consider (OST and EcoAdapt 2012).

Action 1.2: Advance scientific understanding of MPA exposure across the network, including potential areas of refuge, vulnerability, and resilience.

Relevant research questions: 2, 5, 7, 9

One of the first steps to understanding the resilience capacity of California's MPA network includes assessing the spatial distribution of MPAs relative to historic and current stressor exposures, and determining areas of potential refuge and vulnerability for important taxa and habitats. Depending on the disturbance frequency and intensity, it has been suggested that climate-resilient MPA networks should prioritize protection of both climate refugia as well as vulnerable regions that may require the most assistance against future climate threats (Game et al. 2008, Tittensor et al. 2019), with caveats regarding that results vary with disturbance strength (Game et al. 2008). While more work is needed to map disturbance frequency and intensity on the California coast, ensuring that a network of MPAs span the range of past and future climate space along multiple axes of change (e.g., temperature, oxygen, and acidification) may ensure resilience to multiple potential climate trajectories. This survey should also consider shoreline features and habitat-types, e.g., dune or bluff acked beaches, or open coasts and estuaries. This information is also vital to understanding whether MPAs may play a role in supporting species-specific range shifts under climate change. Some proposed next steps are identified below that could be approached individually, sequentially or in parallel.

1.2.1. Define refugia for California's MPA network via literature synthesis and expert workshop.

Projected duration: 6 months – 1 year

One climate resilience tool is the protection of areas of potential refuge to unfavorable conditions. Refugia have been defined and explored in many contexts globally (e.g., low climate velocity in regions as determined by future climate projections, or using paleological records to identification locations of stasis), but it is important to note that climate change refugia could look quite different depending on an individual stressor, species or ecosystem of interest. As a first step to addressing research within this recommendation and to inform approaches to 2.2 and 2.3 below, the working group recommends defining the physical, ecological, and biological characteristics of climate refugia for California's MPA network (Q7). This could be approached via a synthesis of the current literature on refugia and/or convening an expert workshop.

1.2.2. Characterize the local oceanography of MPAs across multiple stressors using existing data.

Projected duration: 1 year

Identifying climate refugia (i.e., areas that are "climate safe") that, for example, support reproduction for species, as well as vulnerable systems could be done by examining historical temperature, oxygen, $p\mathrm{CO}_2$, sea-level rise and ENSO data (and other available climate datasets) to query historic variability and exposure. This analysis could be done with existing data in hand, and can help identify the distribution of MPAs relative to historic exposure. However, here, shoreline evolution under sea-level rise predictions should also be taken into account.

1.2.3. Model habitat and species distributions in current and future conditions.

Projected duration: 2 - 4 years

Building off of fforts towards examining historical data and collecting additional baseline data, studies that identify or model physiological tolerances, tipping-point thresholds, or species range shifts for important taxa could be used to project future species and habitat distributions. Existing global climate models (GCMs) are coarse resolution, at 110 km x 110 km grid cells but numerous efforts are underway to downscale these models to scales more relevant to regional management (10 km x 10 km) – (Fagundes et al. 2020, Pozo Buil et al. in review). These downscaled climate models could be used to assess which MPA habitats are experiencing changing environmental regimes based on the physical-chemical variables (SST, Chl-a, pCO_2), but also could be used to predict future species distributions relative to existing MPAs.

1.2.4. Perform tiered risk assessment of species, ecosystems, and habitats within MPA.
Projected duration: 1 – 2 years
Risk assessments offer the ability to triage which managed species are most at risk from climate change and to adjust resources and effort towards them. The state could take an expert elicitation-based climate vulnerability assessment approach similar to efforts underway nationally for federally managed fish species, where experts rank sensitivity and exposure of each MPA and key species within each to climate variability and change. This is likely the least expensive but also the least quantitative approach towards estimating the effects of climate on the MPA network.

Action 1.3: Expand capacity to assess and address social science climate resilience research needs.

Relevant research questions: 10 – 15

As part of this working group effort, it became clear that additional capacity and coordination of human dimensions researchers and experts are needed to address social science resilience questions within this report. As a near-term step, the working group recommends convening social science researchers, including long-term monitoring principal investigators actively involved in MPA monitoring, to assess and inventory existing, ongoing, or planned data collection and projects that could be leveraged in support of the human dimensions research questions in this report. In parallel, more clearly defining and identifying baselines for "provision of services" is needed to be useful in monitoring resilience and implementing climate-resilient strategies. This is also an opportunity to develop and, going forward, implement participatory science models around climate resilient MPAs that harness and engage the expertise, experiences and capacity of stakeholders and communities, and to expand research focused on social as well as ecological outcomes of MPAs. Below are some next steps that can help fill gaps in our knowledge of socioeconomic aspects of MPAs in a changing climate.

1.3.1. Assess state of the knowledge of social values and outcomes relating to MPAs and climate resilience in California.
Projected duration: 6 months – 1 year
While research exists on the social and economic outcomes of MPAs internationally, most studies are site specific and/or focused on specific stakeholder groups, with limited understanding of the broader outcomes of MPA networks for society or the role that MPA networks play in supporting societal adaptive capacity and resilience to climate change. Very few studies have been conducted specific to the MPA network in California. As a first step to understanding social resilience outcomes of MPAs, the working group proposes to convene a workshop of social scientists currently engaged in research relating to human dimensions of coastal and ocean systems in California

to collate available information, assess the state of the knowledge, and identify important gaps in our understanding of the interactions between MPAs and social resilience under a changing climate.

1.3.2. Engage stakeholders to: (a) ensure cultural and spiritual values and benefits associated with MPAs are fully identified, and (b) better understand regional and local impacts or benefits, as well as social priorities and needs under a changing climate.

Projected duration: 1 – 2 years

Ongoing support for MPAs amongst the broader public is contingent on MPAs providing perceived benefits to society. For individuals who do not directly benefit from enhanced fisheries production or other economic opportunities, MPAs may still provide important cultural, spiritual, or aesthetic benefits. Very little is known about broader public values relating to MPAs, the role that MPAs play in protecting or rehabilitating species or ecosystems that are considered culturally important to different societal groups, or what species or ecosystems are considered important to society (beyond economic or consumptive uses). In order to better understand what role MPAs play in protecting culturally significant species and habitats, it is important to determine what species and habitats are considered culturally relevant by different stakeholder groups in California. This could be done through focus group studies with relevant stakeholders (e.g., fishermen, coastal advocates, recreational ocean users, tribal groups, etc.) to determine if there are certain species, habitats, or aspects of coastal systems that are of particular significance to these groups. This would allow for prioritized monitoring of the role that MPAs play in supporting climate resilience of species, habitats, or other aspects of coastal systems that are of critical cultural importance.

1.3.3. Conduct baseline studies on social and economic service provision of MPAs (to follow outcomes of 3.2 above).

Projected duration: 1 – 2 years

Our ability to assess or monitor socioeconomic resilience conferred by MPAs is hindered by a dearth of baseline knowledge regarding the extent to which MPAs provide hypothesized ecosystem services to society. A preliminary workshop with MPA managers and experts could assist in determining key ecosystem services relevant to MPAs in California and in need of assessment, with a focus on provisioning, regulating, and cultural services. Examples of potential assessment topics include: analysis of fishing behavior and catch for fisheries affected by MPAs, determination of whether and how MPAs contribute to local and regional economies through increased tourism or other benefits, and studies to understand cultural and existence values of protected ecosystems and species (see 1.3.2).

1.3.4. Assess equity issues around MPAs in a changing climate.

Projected duration: 2 – 4 years

MPAs have unequal effects on different social groups, and costs and benefits of MPAs may accrue to different stakeholders. Likewise, climate change effects have differential impacts on different societal groups, with the greatest impacts often accruing groups that are already socially marginalized and vulnerable. While there is a rich literature documenting equity concerns and differential costs and benefits of MPAs in the global South and internationally, there is limited research defining or documenting equity concerns specific to California's MPA network, or how climate change will affect these equity concerns. A first step in addressing this knowledge gap would be to conduct a review of the literature to determine common equity concerns that may be relevant to the social and economic context in California, followed by a survey of key stakeholders to determine equity outcomes, and potentially a review of secondary socioeconomic indicators relevant to equity in areas adjacent to, or affected by, MPAs. Assessments documenting changes in both consumptive and non-consumptive uses of MPA could also be used to determine if costs and benefits of MPA implementation accrue differently amongst different groups (categorized, for example, by race, class, ethnicity, occupation, target fishery, etc.). Once equity concerns are identified, the role of climate change in either exacerbating or mitigating the concerns can be assessed by monitoring predicted changes to ecosystem services relevant to vulnerable groups.

Point Reyes, CA
Image: Lex Zhao

V. Looking Forward: Advancing Climate Resilience from Concept to Implementation

A number of climate resilience planning resources and decision frameworks are available that can be used to support integration of climate change into MPA monitoring, design and management (see Figure 7 for a simplified general planning framework; Climate Adaptation Knowledge Exchange 2021, CEC 2017, National Academies 2019a, National Academies 2019b, Wilson et al. 2020). The first step often requires establishing explicit climate change resilience goals for the MPAs, including defining clear management priorities, objectives and metrics to monitor changes in resilience. Several examples of potential climate change adaptation objectives and possible actions are shared in Table 5. See Tittensor et al. 2019 and Wilson et al. 2020 for additional recommendations for integrating climate change into management plans for MPAs and MPA networks. The process to develop and implement climate resilience-focused goals and objectives would benefit from continued, iterative communication and engagement among scientists, decision-makers, conservation practitioners, stakeholders and others. Further efforts to integrate social and ecological data and goals in MPA monitoring and management are paramount to optimize the functioning of the broader socio-ecological system.

Of the few global MPAs that have explicitly incorporated climate change into their operation, the Greater Farallones National Marine Sanctuary (GFNMS) off alifornia is an example of a region moving from triage to implementing solutions that enhance resource resilience to climate impacts. The GFNMS developed a Climate Action Plan (GFNMS 2016) which includes a vulnerability assessment, climate change recommendations and management strategies to respond to and decrease those vulnerabilities, and an implementation plan for the sanctuary. While this plan applies to a single protected area, not a network, the approach and process undertaken to transition the sanctuary toward advancing climate change science, developing climate-smart adaptation strategies, and taking actions to manage for the impacts of climate change could be a valuable model for the state of California to consider.

Lastly, it is important to highlight that climate impacts and responses are dynamic, while MPAs are static area-based management tools that are unlikely to address the full range of emerging threats despite being adaptively managed. Continuing to advance no-regrets, multi-benefit climate and resilience management actions are crucial to fulfilling the goals of the MLPA. Reduction of greenhouse gas emissions, sustainable management of fisheries approaches (as required by California's Marine Life Management Act), comprehensive watershed management, nature-based actions including restoration and other coastal resilience management efforts all play an important role in adapting to and mitigating climate change effects. Fundamentally, the design of California's MPA network (including habitat representation and replication, network connectivity, variety of levels of protection, etc.) may ensure that some portion of the network is available to maintain critical habitat for various species or ecosystem components. As the rate of climate change and extreme events continues to increase, there may be a need to evaluate the efficacy of existing MPAs under novel environmental conditions or explore additional dynamic ocean management tools that can respond to rapid changes and forecasts.

Table 5. Examples of climate change adaptation objectives and possible actions.

(Table from Tittensor et al 2019)

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

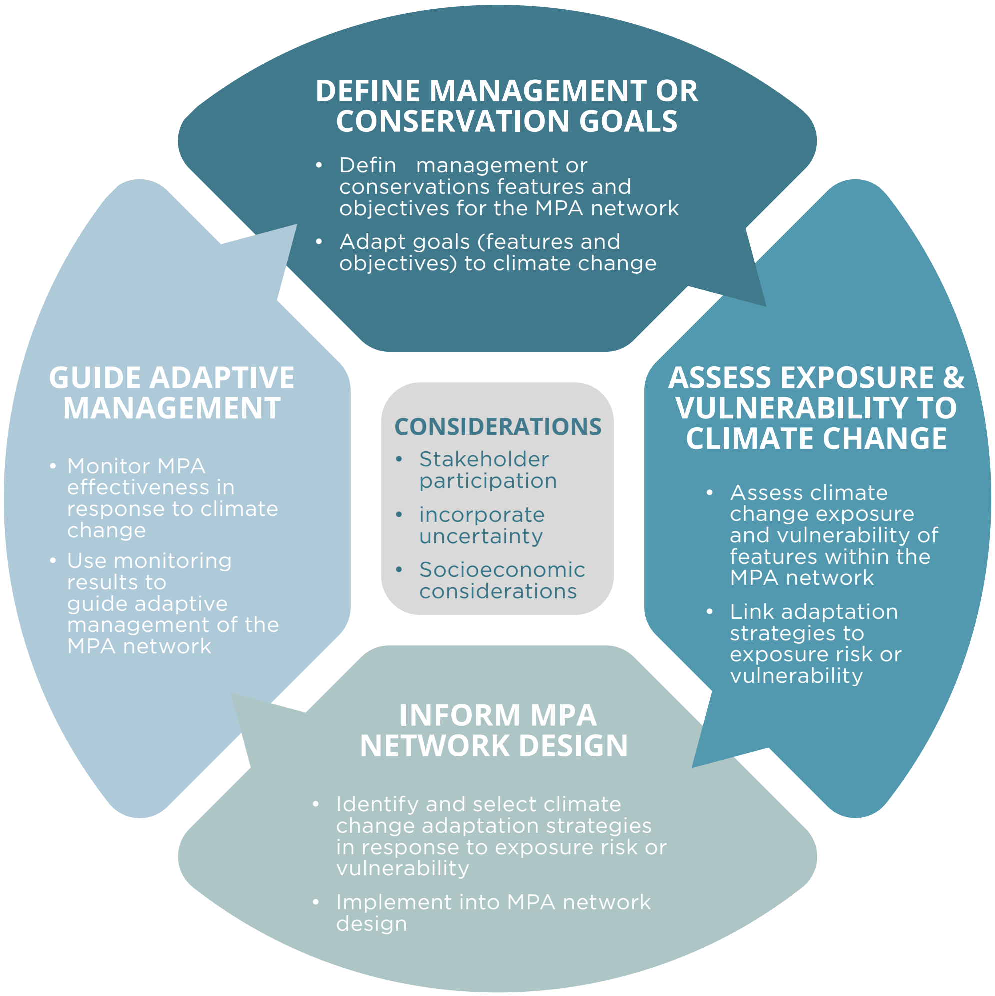


Figure 7. Integrating climate change adaptation in all stages of marine protected area planning, design and management.

Shown is a simplified planning framework based on the general features of five common existing frameworks for biodiversity conservation. (Figure modified from Wilson et al. 2020)

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Giant kelp
Image: Caleb Kastein

Appendices

Appendix A: Primary Climate Drivers, Trends, and Projections for California

In the California Current System (CCS), climate change is expected to lead to warming sea surface temperatures (including more frequent and intense marine heatwaves), changing ocean chemistry (declining oxygen and pH), and rising seas, with implications for ecosystem productivity, structure and function (Deutsch et al. 2015; Howard et al. 2020; Koslow et al. 2013). Below, the working group provides a summary of the primary climate drivers in the CCS which extends from Baja California, Mexico (20°N) to British Columbia, Canada (50°N) (Figure A-1). An understanding of historic patterns, current conditions, natural variability, and future changes in physical conditions for California are discussed here. We include information generated from California MPA monitoring, where available.

Figure A-1. Map of the California Current System, including major regions and currents

Source: Checkley & Barth 2009.

Episodic Upwelling and Winds

Off alifornia, alongshore winds transport nearshore waters away from the coast in accordance with Ekman dynamics and are replaced by deeper and colder upwelled waters that are nutrient rich, oxygen poor, and lower in pH (Huyer 1983, García-Reyes & Largier 2012, Sievanen et al. 2018). Eastern boundary upwelling systems such as the CCS are some of the most productive regions in the global ocean (Pauly & Christensen 1995). Upwelled waters serve as the lifeblood for primary producers and the associated food webs from zooplankton to larger forage species to top predators (Cushing 1990, Sydeman & Allen 1999, Croll et al. 2005, Dorman et al. 2005, Kudela et al. 2008, Thompson et al. 2012).

The timing and strength of upwelling varies along the California coast (Checkley & Barth 2009; García-Reyes & Largier 2012). These seasonal phases (phenology) of upwelling play a critical role in the functioning of the CCS ecosystem (Bograd et al. 2009). Many CCS species have life histories that show some degree of dependence on this upwelling phenology and the resulting primary production. Changes in the upwelling phenology, such as a delay in the onset of coastal upwelling or a reduced upwelling season, can disrupt trophic dependencies and result in reduced CCS ecosystem productivity, structure, and function (Abraham & Sydeman 2004; Edwards & Richardson 2004, Schwing et al. 2006, Barth et al. 2007, Durant et al. 2007). These changes may vary along the coast, resulting in differences regionally in the magnitude of impacts. For example, ecological effects resulting from anomalous oceanographic conditions in 2005 occurred mainly in waters north of Point Conception (Brodeur et al. 2006,Mackas et al. 2006, Sydeman et al. 2006).

A review of upwelling literature from the past six decades indicates that upwelling-favorable winds have intensified in the California Current System (CCS) with an increased likelihood of intensification within the poleward portion of the CCS (Sydeman et al. 2014). Several mechanisms for this intensification have been suggested including increased land-sea temperature contrasts and shifts in the Hadley Cell (Bakun 1990, Hu et al. 2011, Bakun et al. 2015). Model projections generally support the intensification of coastal upwelling-favorable winds with some models associating this intensification with changes in the positioning oceanic high-pressure systems (García-Reyes et al. 2015, Rykaczewski et al. 2015, Xiu et al. 2018). Rykaczewski et al. 2015 also suggests that upwelling-favorable winds will intensify near the poleward boundaries of the CCS upwelling zone while weakening near the equatorward boundaries. Additional modeling studies indicate that the intensification of upwelling occurs inshore, but that offshore waters experience less upwelling and enhanced upper-ocean stratification (Jacox et al. 2014, Xiu et al. 2018).

This projected alteration in upwelling patterns has some “bad news/good news” perspectives for coastal MPAs (Sydeman et al. 2014, Bakun et al. 2015). In northern and central California, increased pulses of cold water could act to offset the stress from marine heatwaves and the nutrient rich waters could potentially increase primary productivity. Alternatively, increased upwelling could bring more frequent events of low oxygen, possibly creating stressful hypoxic conditions for organisms. In addition, upwelled water tends to be more acidic and thus, the waters of MPAs might spend more time at low pH as compared to decades ago. Responses to these interacting processes (temperature, pH, oxygen levels, and nutrient levels) will very much depend on the plasticity and adaptability of resident organisms. In southern California, MPAs may experience fewer events of low oxygen and higher acidity but will potentially face decreased productivity.

Large-Scale Patterns of Variability: El Niño Southern Oscillation (ENSO), the Pacific Decadal Oscillation (PDO), and the North Pacific Gyre Oscillation (NPGO)

Climate scientists and oceanographers have identified several large-scale atmospheric-oceanic phenomena that affect the CCS occurring over seasonal, interannual, and multidecadal timescales: the El Niño Southern Oscillation (ENSO), the Pacific Decadal Oscillation (PDO), and the North Pacific Gyre Oscillation (NPGO). These forcings, described in more detail below, can be considered as "warm-less productive" or "cool-more productive" regimes, which drive substantial variability in recruitment, production, and distributions, summarized for key California fished species in Table A-1 (Chavez et al. 2017).

Table A-1. Selected fish and invertebrate stocks in California grouped by favored climate phase (warm-less productive vs. cool-more productive) for production in California waters, based on best available data.

(Table from Chavez et al. 2017)

Favored phase	Selected CA fish and invertebrate stocks
warm	• basses (kelp bass, barred sand bass, spotted sand bass) (Jarvis et al. 2014) • California halibut (Allen 1990) • California sheephead (Lenarz et al. 1995) • California spiny lobster (Koslow et al. 2015) • kellet's whelk (Zacherl et al. 2003) • Pacific (chub) mackerel (Parrish 1978) • Pacific bonito (Radovich 1961) • Pacific sardine (Jacobson and MacCall 1995) Lindegren and Checkley 2013) • white seabass (Williams et al. 2007)
cool	• California market squid (Koslow and Allen 2011) • Chinook salmon (Mantua et al. 1997, Lindley et al. 2009, Wells et al. 2016) • dungeness crab (Shanks 2013) • geoduck clam (Zhang and Hand 2006) • most groundfish (flatfish, rockfish, roundfish) (Ralston et al. 2013, Stachura et al. 2014) • Northern anchovy (Lindegren et al. 2013) • Pacific ocean (pink) shrimp (Hannah 2010) • Pacific halibut (Clark et al. 1999) • red abalone (Vilchis et al. 2005)
unknown, limited data, or large group where not all members favor the same regime	barred surfperch, bay shrimp, California corbina, some groundfish (flatfish, rockfish, roundfish), hagfish, Pacific herring (roe), highly migratory species (tuna, shark, swordfish), jacksmelt, night smelt, ocean whitefish, pismo clam, red sea urchin, redtail surfperch, ridgeback and spot prawn, rock and spider crab, sea cucumber (giant red, warty), shark (brown smoothhound, Pacific angel), shiner seaperch, spot prawn, white sturgeon

El Niño Southern Oscillation (ENSO)

ENSO is an ocean-atmosphere phenomenon that historically occurs every 3 to 8 years, lasting from 12-18 months, and affects climate over the globe. The different phases of ENSO are related to changes in the Southern Oscillation, a pressure gradient between high pressure over the eastern Pacific and low pressure in the western Pacific over Indonesia, and ocean conditions along the equatorial ocean (Jin et al. 1996). El Niño is the warm phase of the El Niño Southern Oscillation, and is associated with weakened trade winds, reduced upwelling, and warming ocean temperatures in the eastern and equatorial tropical Pacific (Jacox et al. 2015). During a La Niña, the opposite happens; the trade winds strengthen, waters in the eastern equatorial Pacific cool (temperature anomalies become strongly negative), and the mixed layer becomes shallower.

The CCS experienced La Niña from 2010-2012, a return to normal conditions in 2013, and a transition to a strong El Niño in 2014 that peaked in the summer of 2015 and persisted into 2016 (Figure A-2). Studies indicate that a variant of the eastern Pacific El Niño became more common during the late twentieth century (Yeh et al. 2009). This El Niño differs in that its maximum SST anomalies are located in the central Pacific and are flanked on both the east and west by cooler SSTs. Model results from Yeh et al., 2009 predict that this central Pacific El Niño will increase in frequency with anthropogenic climate change. In addition, model results from Cai et al., 2014 predict an increase in the frequency of extreme El Niños.

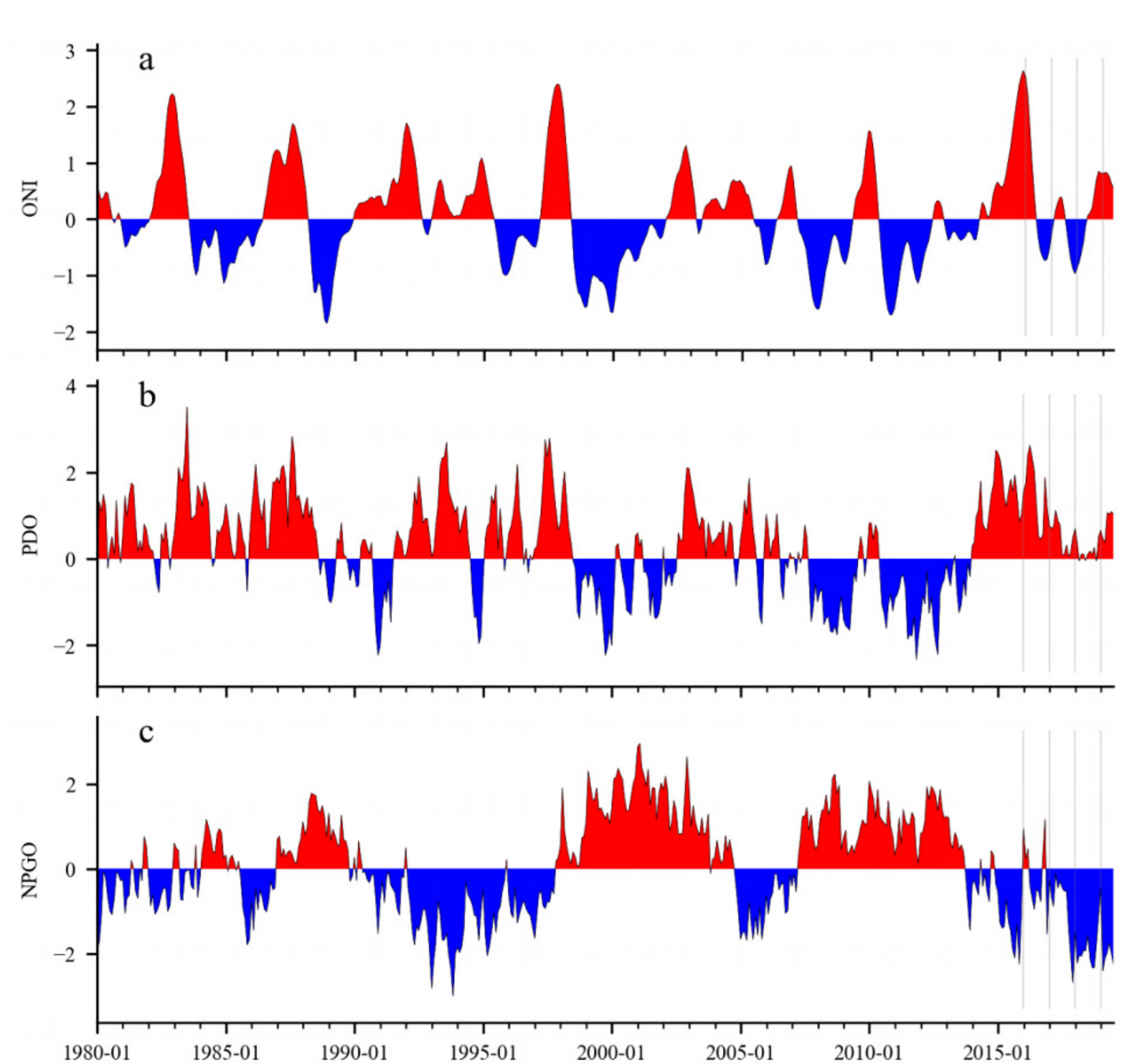

Figure A-2. Time series of monthly values for three ocean indices especially relevant to the California Current.

a) Oceanic Niño Index (ONI), b) Pacific Decadal Oscillation (PDO), and c) North Pacific Gyre Oscillation (NPGO). Vertical lines mark January 2016–19. (Figure from CalCOFI 2019)

Pacific Decadal Oscillation (PDO), and the North Pacific Gyre Oscillation (NPGO)

The PDO and NPGO phenomena reflect large-scale ocean responses to atmospheric variability in the North Pacific mid-latitudes. The Pacific Decadal Oscillation (PDO) is an ocean-atmosphere pattern centered over the North Pacific that has warm and cool phases (Mantua et al. 1997) (Figure 9B). In contrast to ENSO, the PDO has much of its variability occurring on decadal time scales. During the positive phase of PDO, the CCS is warm and the central North Pacific is cool. Monthly SST anomalies are used to track trends in the PDO which shifts between warm and cold phases that can persist over multiple decades. Over short time scales, the influence of the PDO on the CCS is generally weaker than ENSO, but since it persists over a longer time scale, it can over time strongly affect productivity within the CCS.

The North Pacific Gyre Oscillation (NPGO) is a signal of sea surface height variations across the North Pacific, indicating variations in the circulation of the North Pacific Subtropical Gyre and Alaskan Gyre, with positive values linked with increased equatorward flow in the California Current, and increased surface salinities, nutrients, chlorophyll, and productivity in the southern-central CCE (CalCOFI 2019, Di Lorenzo et al. 2008, Di Lorenzo et al. 2009). It is typically shorter in duration than the PDO and is associated with the strength of the NPG. From October 2017 to June 2019, the NPGO reached some of the strongest negative values observed over the entire time-series (since 1950) (Figure 9C) (CalCOFI 2019).

Recent investigations into the mechanisms behind large-scale ocean responses like ENSO, PDO, NPGO, and the warm water event of 2014-2016 suggest that atmospheric teleconnections between the mid-latitudes and the tropics play an important role in the changes observed in the North Pacific and consequently within the CCS. These teleconnections will likely be affected by the warming climate as will the associated atmospheric-ocean responses. For instance, models suggest that the PDO may shift more frequently.

Ocean temperature

Ocean Warming

The world's oceans have absorbed about 93% of the excess heat from global warming since the mid-20th century, with heat content increasing at all ocean depths since the 1960s (Jewett & Romanou 2017). Analyses of a recently-constructed ocean heat content data set for the upper 2000 m show that the ranks for the last five years in the data set (2015-2019) are all in the top 5 for highest heat content, with 2019 being the warmest year on record (Cheng et al., 2020). Overall, it is a certainty that the global ocean has warmed over the last 3 decades, with a doubling of the rate of warming since 1993, and now a likely doubling of the frequency of marine heatwaves (IPCC SROCC 2019).

Transfer of heat from surface waters to deeper waters is a slow process; consequently, warming in deep ocean waters occurs at a slower pace than surface waters, but will continue to warm for centuries even if greenhouse gas emissions are significantly reduced (Jewett & Romanou 2017). This has long-term implications in regard to upwelled waters and sea level rise.

Off of alifornia, coastal surface waters warmed at about a rate of 0.7°C per century over a period from 1900 to 2016, which is comparable to the overall rate of warming observed for global surface waters (Jewett & Romanou 2017, Sievanen et al. 2018). Results from model simulations using a high-end greenhouse gas emissions scenario indicate that CCS waters will warm an additional 2-4°C above the 1920-2016 average by 2100 (Alexander et al. 2018, Sievanen et al. 2018). These models also predict that the range in sea surface temperature (SST) anomalies (differences between the observed SSTs and the mean) will change very little, but that the frequency of warm extremes will increase (more about warm water events below).

As average temperatures along the coast increase, shifts in specific species distributions and population sizes are expected (Pinsky et al. 2020, Sanford et al. 2019). Species with high capacity to disperse can more easily respond to warming temperatures, but establishment of populations in new areas (for both mobile and less-/non-mobile species alike) requires ocean processes and available habitat that facilitate distribution and support production for all life stages (Pinsky et al. 2020). Warming waters also can promote other stressors such as sea level rise, ocean stratification, decreased nutrients and dissolved oxygen, harmful algal blooms (HABs), and disease, all of which can impact California's coastal ecosystems (Sievanen et al. 2018; see below for more information on combined effects of stressors).

Marine Heatwaves

Marine heatwaves (MHWs) – defined as prolonged periods of anomalously high seawater temperatures (Hobday et al., 2016) – have emerged as major climate-change driven disturbances in coastal oceans, threatening marine biodiversity worldwide (Smale et al. 2019). Although warming anomalies have previously been linked to their impacts on marine ecosystems, the phrasing of MHWs was first noted and underscored in Australia by investigators reporting on ecosystems ranging from coral reefs to seagrass beds (Wernberg et al. 2011, Smale & Wernberg 2013, Wernberg et al. 2013, Wernberg et al. 2016, Arias-Ortiz et al. 2018, Smale 2020), with studies now emerging in Northern Hemisphere coastal ecosystems (Reed et al. 2016, Cavanaugh et al. 2019, Rogers-Bennett & Catton 2019, Sanford et al. 2019, Seuront et al. 2019, Shanks et al. 2019).

In Northern California, a 2014–2016 MHW in the California Current Ecosystem (CCE) (aka "The Blob") (Figure A-3, Kintisch 2015) triggered a series of events that resulted in a >90% decline in kelp canopy (Rogers-Bennett & Catton 2019), induced 80% abalone mortality (Rogers-Bennett & Catton 2019), and altered the biogeographic ranges of intertidal marine invertebrates (Sanford et al. 2019). What has emerged is a picture of extreme heat events that have been increasing in intensity and frequency over the last decades (Oliver et al., 2018), and further, that will have significant effects on marine organisms and communities in the future (IPCC SROCC 2019, Laufkotter et al. 2020). If atmospheric warming continues as projected under the "business-as-usual" scenario, it will increasingly continue to interact with the surface oceans, increasing the intensity and frequency of MHWs (Oliver et al. 2019).

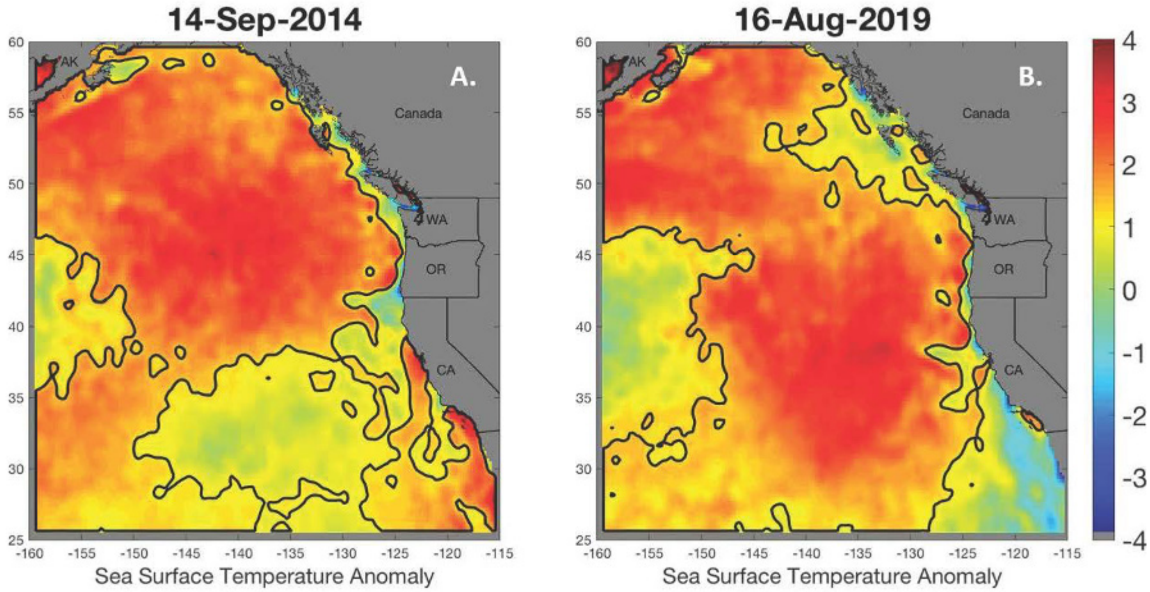

Figure A-3. The MHW known as "the blob" at its near maximum areal extent in September 2014 (left); The 2019 MHW (NEP19) at its near maximum areal extent in August 2019 (right). SST data from NOAA's Coral Reef Watch program (https://coralreefwatch.noaa.gov/satellite/index.php), with the SST anomaly calculated using climatology from NOAA's OISST dataset. (Source: The California Current Marine Heatwave Tracker – An experimental tool for tracking marine heatwaves https://www.integratedecosystemassessment.noaa.gov/regions/california-current/cc-projects-blobtracker)

At present, temperature data are available for California MPA locations via various long- term studies on the coast of California (Figure A-4). In addition, analyses that employ methods to express temperature data as MHW events can be developed (e.g. heatwaveR, Schiegel & Smit 2018). Using this tool to identify MHWs in long term temperature data, MHWs are evident within Naples State Marine Conservation Area (Figure A-5), with MHW events detected during the extreme events of 2014-2016, but also more recently in 2019 and 2020 (Figure A-3; 2020 data not shown). The 2019 and 2020 MHWs were the third and second largest events, respectively, recorded in the northern Pacific Ocean since 1982 (when consistent remote SST recording began) (CCIEA 2020).

In the face of this advancing pressure on California coastal marine ecosystems and thus MPAs, the understanding of the ecological consequences of MHWs is vital, but is constrained due to major knowledge gaps on the capacity of organisms to tolerate these short-term extreme heat events (Oliver et al. 2019), and whether plasticity can buffer these influences across space and time (Donelson et al. 2019). There are excellent reports of impacts on community structure, but fewer studies that can help assess the vulnerability of marine communities to these extreme climatic events by studying the thermal tolerance and sensitivity of marine organisms. The oceanography community has also focused on efforts to develop a forecasting platform for MHWs (Holbrook et al. 2020).

As a result of recent reports, analysis and publications on MHWs over last several years (Wernberg et al. 2013, Hobday et al. 2016, Wernberg et al. 2016, Hobday et al. 2018, Smale et al. 2019, Smale 2020), it is clear that (1) MWHs represent extreme climatic events that can alter ecosystem structure and function (as has been noted for terrestrial ecosystems), (2) their frequency and intensity are expected to accelerate in the coming decades (Oliver et al. 2018, Oliver et al. 2019), (3) for many coastal marine ecosystems we have little insight into the tolerance of the community to extreme heat events (save perhaps coral reefs), and (4) there are significant knowledge gaps about the thermal tolerance of important species to MHWs (Oliver et al. 2019, Smale et al. 2019).

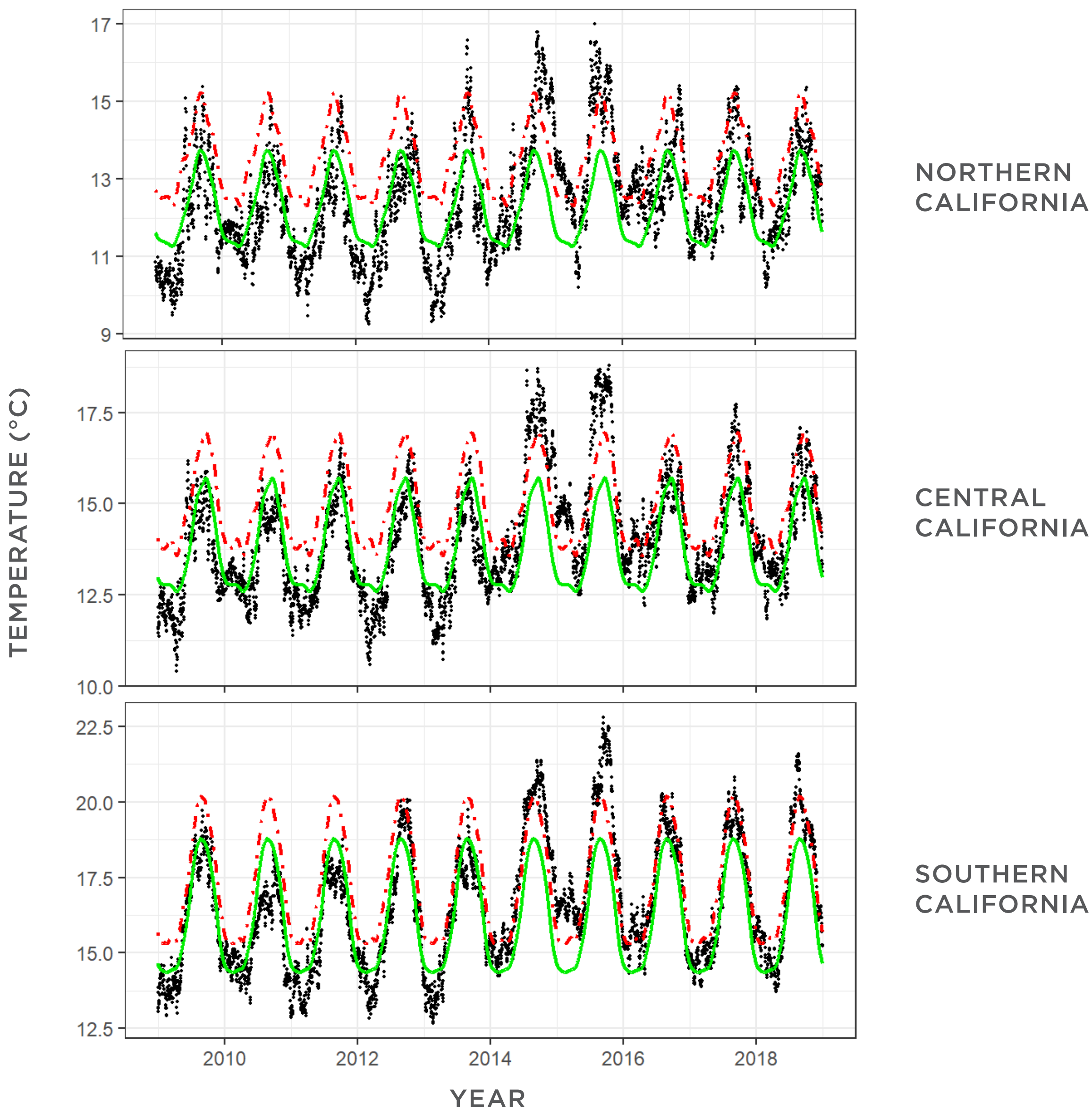

Figure A-4. California-specific temperature patterns in MPA regions.

Green lines indicate 30 year mean temperature, while dots indicate observed daily temperature. The red dotted line is the 90 percentile above 30 year mean for each day of year. Whenever the black dots are above the red line, that indicates a positive thermal anomaly, or heatwave.

(Figure: J. Caselle and P. Carlson)

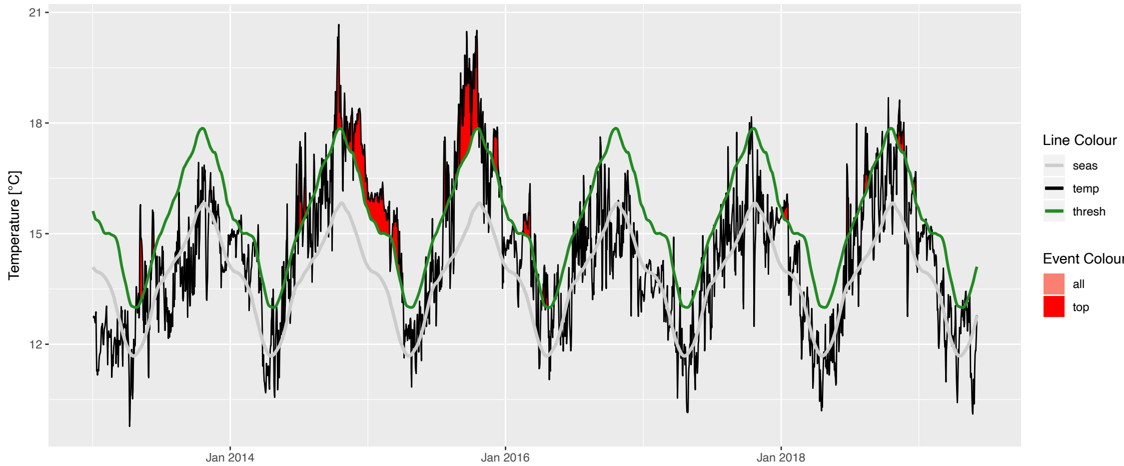

Figure A-5. Marine heatwave events recorded at Naples Reef, a California Marine Conservation area.

Marine heatwave events were calculated for a Santa Barbara Coastal Long Term Ecological Research Program (UC Santa Barbara; PI: Robert Miller) core site, Arroyo Quemado (ARQ) from Jan 2014 to Jan 2020. Data were collected using ONSET Tidbit loggers deployed at the benthos and on the ARQ core site mooring. MHW events were calculated using the formula and criteria presented in Hodbay et al (2016) using heatwaveR (Schlegel and Smit, 2018). MHW events were calculated using the formula and criteria presented in Hobday et al (2016). Specifically, average daily temperature data from 2003-03 to 2012-12 at the site were used to calculate the long-term climatology seasonal cycle (grey line), seasonally-varying threshold at 90th percentile (green line), and the heatwave events were by definition required to occur for at least 5 consecutive days (areas shaded in red).

Ocean chemistry

Ocean Acidification

Ocean acidification (OA) is a global change stressor that is driven by the absorption of anthropogenic CO_2 into surface waters. Estimates are that the ocean has absorbed 20-30% of CO_2 emissions since the 1980's and the pH of surface open ocean waters has declined by 0.017-0.027 pH units per decade since the 1980's (IPCC SROCC 2019). Based on multi-year NOAA cruises, corrosive CO_2-rich waters (insitu pH_T < 7.75) have been upwelled to depths as shallow as 20–200 m in the region between northern California near Cape Mendocino to Heceta Head, Oregon (Figure A-6; Feely et al., 2016). In contrast to the open ocean, coastal oceans are characterized by a much more complex and dynamic pH seascape (Hofmann et al. 2011) where physical (e.g., upwelling of cold, low pH waters) and biological (e.g., photosynthesis and respiration) conditions impose strong spatial and temporal variability in carbonate chemistry.

Research from lab, field, and modeling experiments have demonstrated that OA conditions impact (or are projected to impact) important organisms and industries of the California coast. Zooplankton such as pteropods which are food for salmon, commercially important fish such as some species of rockfish, and economically important shell-forming organisms, including crabs, lobsters, mussels, oysters are all particularly negatively affected by lower pH and lower aragonite saturation state (e.g., Kroeker et al. 2010, Waldbusser et al. 2013, Gazeau et al. 2007, Ries et al. 2009, Bednarsek et al. 2020, Hamilton et al. 2017). Modeling efforts project declines in employment, revenue, and income for wild caught fisheries by the 2060s for the majority of the U.S. West Coast due to OA effects (Hodgson et al. 2018).

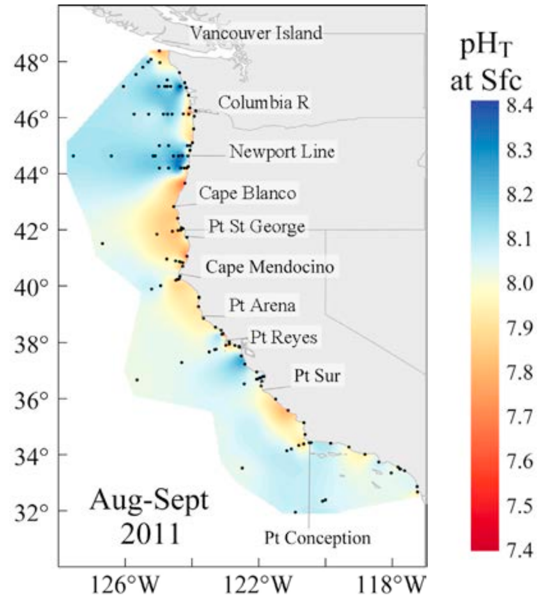

Figure A-6. Map of surface ocean pH_T values for August through September 2011 NOAA cruises.

The 2011 map includes the shore-based intertidal data. (Figure from Feely et al. 2016)

With regard to the dynamics of low pH exposure, regions on the CA coast where MPAs are located are very much experiencing multi-day pulses of low pH waters during episodic upwelling. Research performed on cruises along the west coast have demonstrated that this low pH water reaches the shore (Feely et al. 2008) and extends into MPAs along the CA coast. In terms of spatial variability, there is variation at scale as well. Oceanographers have demonstrated that there is a mosaic of pH along the west coast (Chan et al. 2017), with some regions experiencing more low pH exposure than others. Modeling efforts indicate that upwelling intensity will increase in the future (Gruber et al. 2012), a projection that suggests MPAs of the California coast will experience ever lower pH extremes in the future.

In addition, pH variation can occur on smaller scales with variation occurring relative to kelp forests and proximity to beds of macrophytes (Koweek et al. 2017, Hoshijima & Hofmann 2019). Research has demonstrated that beds of macrophytes such as kelp or seagrass are capable of drawing down CO_2 from the water column via photosynthesis (Koweek et al. 2017, Nielsen et al. 2018, Silbiger & Sorte 2018) in such a manner that pH variation occurs on a daily basis. The biological processes that alter pCO_2 of seawater also interact with local oceanography such that pH and upwelling interact significantly (Figure A-7), and thus, the dynamics of pH exposure for residents of MPAs is a feature of the local oceanography and how it interacts with habitat at a local scale.

The significance of small-scale, local variation could interact strongly with the role that MPAs play in driving resilience to climate change. Specifically, there is significant interest as to whether kelp forests and other macrophyte habitat create refuges from OA. Should such refuges exist within the boundaries of MPAs this would enhance the role of MPAs in supporting climate resilience of marine communities. This concept of refuges has been raised in a marine conservation context (Woodson et al. 2018). Here, small-scale, local micro-climates created by various oceanographic features and/or habitat such as kelp beds or seagrass are hypothesized to create possible 'safe sites' that are more physiologically "friendly" and less abiotically stressful for resident organisms (Woodson et al 2018). Again, MPAs along the CA coast would therefore have the potential to hold such safe sites from climate stressors as they develop now and into the future.

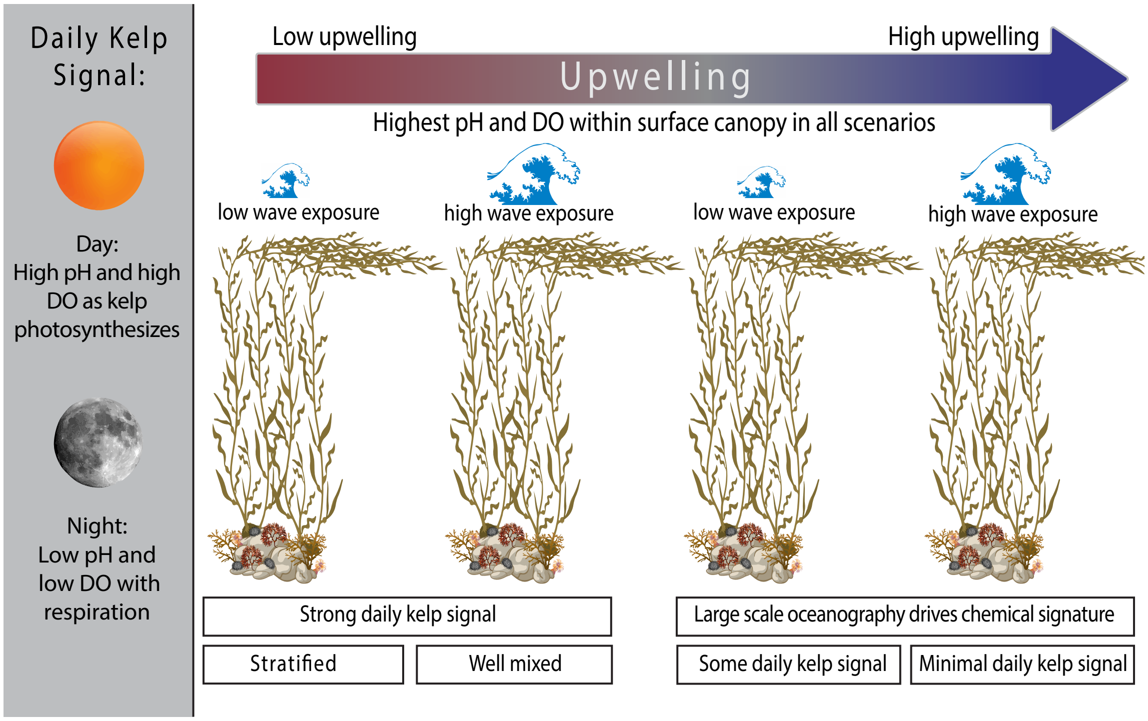

Figure A-7. The influence of kelp on the chemistry of temperate rocky reefs is affected by the magnitude of upwelling and wave exposure.

Low wave exposure accompanied with low upwelling results in strong daily kelp signal in a stratified water column where the kelp signal might not reach the bottom. The strong daily kelp signal persists in high exposure systems with low upwelling but have a well-mixed water column where the kelp signal extends to the bottom. In high upwelling environments, large scale oceanography strongly influences the chemical signature of the water column with some daily kelp signal and higher dissolved oxygen (DO) and pH in low wave exposed environments compared to high wave exposed environments. Courtesy of Dr. Kerry Nickols (California State Northridge).

Deoxygenation

Over the last decades oxygen depletion, the formation of hypoxic zones, (dissolved oxygen ≤1.4 ml l–1) and shoaling of the oxygen minimum zone (OMZ) have emerged as major changes in the physical state of coastal waters globally (Vaquer-Sunyer & Duarte 2008, Levin et al. 2009). Our understanding of the issue gradually increased in scale through time toward our current understanding of global deoxygenation and the coupled nature of OAH in upwelling systems. Hypoxia has emerged locally in the northern portion of the CCE, including bouts of anoxic waters along the Oregon shelf that have resulted in massive benthic die-offs (Chan et al. 2008). Decadal trends in oxygen have been observed in regions of the Southern California Bight (see Figure A-8; McClatchie et al. 2010). In California, low oxygen events have been less severe than their Oregon and Washington counterparts (Levin et al. 2009), however the shoaling of the OMZ can reduce pelagic habitat of marine ecosystems, increasing hypoxia exposure and reducing habitat quality for nearshore species like rockfish (Bograd et al. 2009, McClathchie et al. 2010).

Hypoxia is a major threat to the health to marine ecosystems, particularly for benthic organisms that may be unable to avoid such low-oxygen events. Upwelled waters are often acidic and low in dissolved oxygen which when extreme can result in calcium carbonate dissolution from bivalves to crustaceans (Bednarsek 2020) and benthic or demersal die-offs as events can be both rapid and severe (Chan et al. 2017, 2019). Highly migratory species have been shown to concentrate above the hypoxic boundary layer which puts them at greater risk from fishing pressure and may lead to greater mismatch from their prey (Zhang et al. 2009). These effects are not only seen in the pelagic environment, as low oxygen from canyon-directed upwelling events resulted in measurable hypoxia in nearshore habitats and fish kills in aquaria (Booth et al. 2012). Estuarine and strong riverine input can result in eutrophication (Rabalais et al. 2009) but the Columbia river plume is the main source on the west coast affecting largely Oregon and Washington. Similar to temperature, we have to be aware of acute events combined with long term changes in low oxygen and ocean acidification as together they will have a greater effect than either stressor alone.

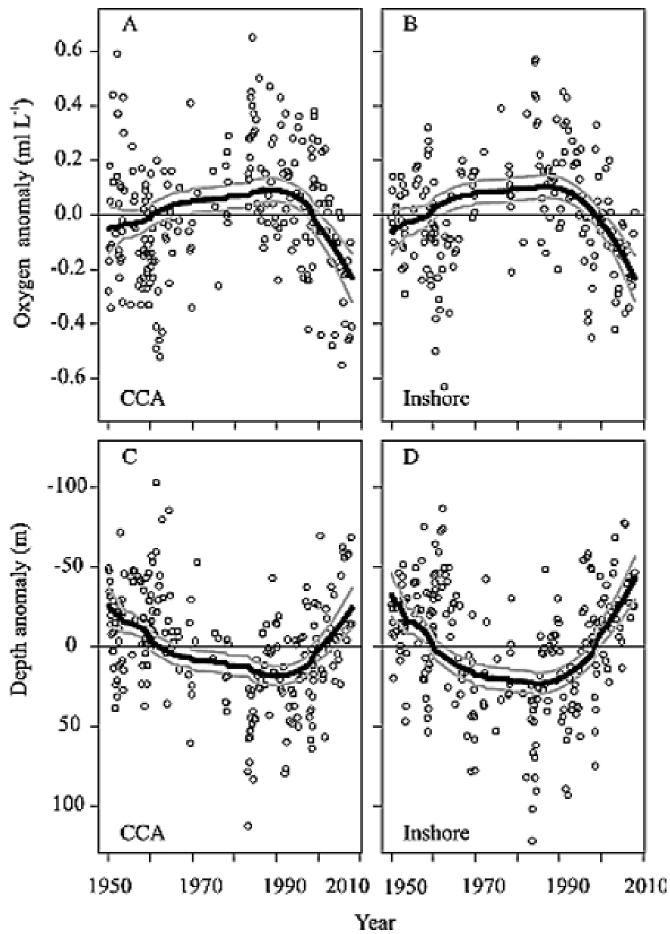

Figure A-8. Time series of oxygen concentration anomalies between 1950 and 2007 for (a) the Cowcod Conservation Area in the Southern California Bight and (b) the Inshore Area.

Time series of the depth anomaly for oxygen concentrations of 1.5 ml L−1 during the same time period for (c) the Cowcod Conservation Area and (d) the Inshore Area. The horizontal line represents the long-term average, which in the case of anomalies, is zero. (Figure from McClatchie et al. 2010)

Increased ocean acidification is often paired with low oxygen events (Gruber et al. 2012), presenting a combination of low dissolved oxygen, low pH and colder water temperatures. The occurrence of multiple stressors is definitely a scenario that MPAs on the CA coast will experience and as noted in the OA section above, the oceanography is complex and the impacts on local biota in MPAs will depend on local oceanography as it meets the adaptive capacity of the resident organisms.

Sea Level Rise, Peak Tides, and Extreme Storms

Over the 20th century, sea levels along the California coast south of Cape Mendocino have risen 10 to 20 centimeters (see A-9 and Sievanen et al., 2018). The thermal expansion of seawater is likely the primary contributor to this past rise in sea level; however, observations suggest that in recent years, contributions from the melting of continental glaciers and ice sheets have surpassed these contributions from thermal expansion. Satellite altimeter data also indicate that the rate of sea level rise is currently accelerating. Model projections generally agree that by 2050, sea levels will be at least 30 centimeters higher than a 1991-2009 baseline. Projections of sea level rise beyond 2050 depend on the choice of emission scenarios with additional sea level increases ranging from 0.7m to 2.4m (and potentially higher) by 2100.

High peak tides and surge and waves from storms cause flooding and erosion within coastal habitats (Griggs & Patsch 2004, Bromirski et al. 2016, Barnard et al. 2017, Sievanen et al. 2018, Goodman et al. 2018, Idier et al. 2019, Harvey et al. 2020). These impacts are particularly severe when they occur together during an El Niño when sea levels are elevated (Flick 1998, Storlazzi & Griggs 2000). Storm characteristics (e.g. landfall orientation, wave direction) and local topography also influence the severity of impacts (Storlazzi & Griggs 2000, Smith et al. 2010, Barnard et al. 2011, Dettinger 2011a, Guirguis et al. 2018).

California receives between 20 and 50% of its water-year precipitation from atmospheric rivers (ARs), long narrow filaments of water vapor (Dettinger et al. 2011a). Most of these ARs are weak; the amount of moisture being transported within the filament and the duration of the AR event are not sufficient to create hazardous conditions (Ralph et al. 2019). However, some ARs transport large amounts of moisture that can result in heavy precipitation, particularly if the landfall orientation and local topography are conducive for orographic precipitation. Severe impacts from these events include extreme storm runoff nd flooding in watersheds and along the coast (Ralph et al. 2006, Neiman et al. 2008, Dettinger 2011a,

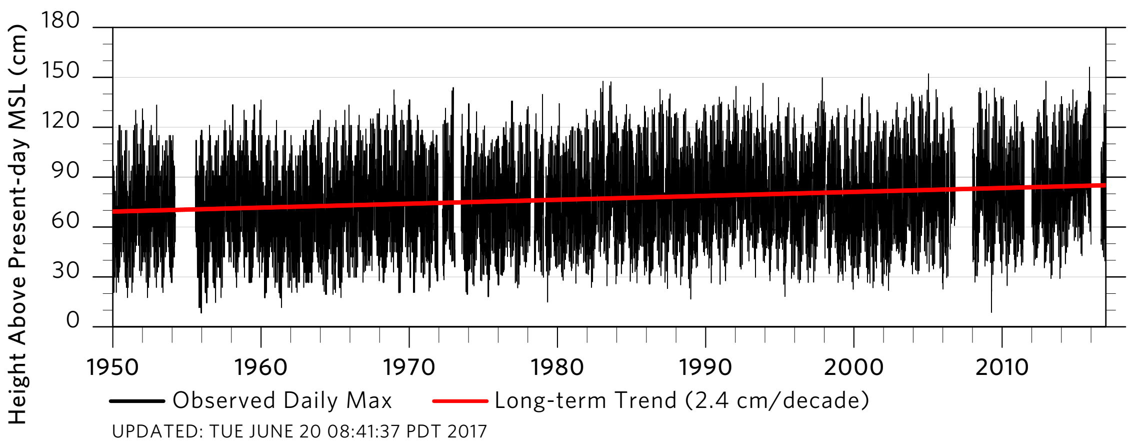

Figure A-9. Daily maximum sea level for the time period 1950 to 2016 at La Jolla Station (9410230).

Shown are daily values (black lines) and linear trend (red line). Source: CNAP.

Dettinger et al. 2011b) as well as strong winds (Waliser & Guan 2017) and storm surge (Khouakhi & Villarini 2016). Although ARs frequently occur during El Nino events, sub-seasonal regional climate modes appear to be more important in modulating precipitation variability in California (Guirguis et al. 2018). Recent studies also indicate that while the overall frequency of precipitation for California is expected to decrease due to fewer non-AR storms, the frequency and intensity of extreme ARs is expected to increase (Gershunov et al. 2019).

The impacts described above will only be exacerbated by the expected increases in sea level. Coastal habitats will experience more frequent flooding, increased erosion, and in some locations, inundation of low-lying terrain (Vitousek et al 2017). Predictions of shoreline change with limited human intervention indicate that 31% to 67% of Southern California beaches may become completely eroded by 2100 under sea level rise scenarios of 0.93 to 2.0 m (Vitousek et al 2017).

Additional influencing factors and cumulative impacts that should be considered when assessing the resilience capacity of the MPA network

Climate change will not act in isolation. When evaluating the climate resilience capacity of the MPA network, California decision-makers should also consider cumulative impacts and interactions. Work has been undertaken to identify cumulative impacts to habitats within MPAs in California using a California Current Cumulative Impacts Model to map climate, land-based, and ocean-based stressors, calculate the vulnerability of habitats within MPAs, and measure the cumulative impacts to these habitats (Mach et al. 2017, Halpern et al. 2009). These findings can help with prioritization of stressors and activities to manage at local to global scales, and help identify locations and MPAs to target that may be most vulnerable to cumulative impacts.

Appendix A References

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Appendix B: Supporting Evidence for MPA and Climate Resilience Effects and Process for Generating Table 2

As part of the analysis on the mechanisms by which MPAs and MPA networks could provide climate resilience (summarized in Table 2), the Working Group identified 5 major themes and their corresponding MPA effects and hypothesized climate resilience mechanisms. The group then reviewed the scientific literature on MPA and climate resilience effects and collectively compiled 86 relevant papers that address the identified MPA effects and resilience mechanisms. The literature review is outlined below in Table A-2 followed by a bibliography of full citations. Of these 86 papers, 14 reported concrete on-the-ground evidence for MPA effects and 11 reported concrete evidence for the hypothesized resilience mechanisms. Only 3 papers identified presented evidence contradicting expectation on effects or mechanisms. Working Group members were divided into subgroups of expertise to come to consensus on scoring for the level of evidence associated with the effects and mechanisms that aligned with their expertise.

During the scoring for level of evidence for each cell, the working group determined that strong evidence in the direction expected required that empirical evidence be found at high level of replication or along a broad spatial scope and/or that the effect was strong enough for resilience or ecological relevance. The modest evidence in the direction expected indicates that there is possibility of the evidence being idiosyncratic either due to lack of expansion geographically or taxonomically or that the effect may not scale up enough to provide strong resilience or ecological relevance. A question mark denotes that although there might be theoretical support for the effect or mechanism there is little evidence in the literature to date. A question mark could also indicate that although there is evidence in support of the mechanism, there is no evidence that the mechanism provides resilience. Support sought and not found indicates that there are studies in the literature that sought evidence to support the effect or mechanism but found null results. Mixed evidence indicates that there are studies in the literature that found evidence in the direction expected but there are also studies in the literature that found evidence opposing expectation. The literature is always expanding, and the references associated with this table may not be complete.

Table A-2. Supporting Evidence from the literature for MPA and Climate Resilience Effects.

MPA/NETWORK EFFECT	SUPPORTING LITERATURE	RESILIENCE MECHANISMS	SUPPORTING LITERATURE
REDUCTION OF ENVIRONMENTAL STRESS			
Increased biogenic habitats such as kelp, seagrasses, and salt marshes; increased biomass of macrophytes	(Shears and Babcock 2003, Ling et al. 2009, Ling and Johnson 2012, Sutton-Grier et al. 2015, Eisaguirre et al. 2020)	Buffering physical stressors such as storms and surge	(Eckman et al. 1989, Mork 1996, Løvås and Tørum 2001, Türker et al. 2006, Gaylord et al. 2007, Gedan et al. 2011, Arkema et al. 2013, Smale et al. 2013, Duarte et al. 2013, Spalding et al. 2014, Rodriguez et al. 2014, Roberts et al. 2017)
		Increased resistance to ocean acidification and hypoxia	(Hendriks et al. 2014, Koweek et al. 2017, Kroeker et al. 2019, Ricart et al. 2021)
INCREASED ORGANISMAL RESILIENCE / ADAPTIVE CAPACITY OF ORGANISMS			
Increased physical and nutritive condition of organisms	(Olds et al. 2012a, 2012b, Claisse et al. 2013, Loury et al. 2015, Mensinger et al. 2018, Davis et al. 2019)	Increased organismal tolerance to climate stress among healthier individuals	(Ramajo et al. 2016, Brown et al. 2018, Huey and Kingsolver 2019)
Increased body sizes	(Paddack and Estes 2000, Halpern and Warner 2002, Parnell et al. 2005, Tetreault and Ambrose 2007, Lester et al. 2009, Kay et al. 2012, Hamilton et al. 2014, Starr et al. 2015, Caselle et al. 2015, Selden et al. 2017, Marshall et al. 2019, Jaco and Steele 2020)	Increased organismal tolerance to climate stress among larger individuals	(Micheli et al. 2012, Messmer et al. 2017, Aalto et al. 2020, Dahlke et al. 2020)
POPULATION RESILIENCE			
Larger population sizes	(Parnell et al. 2005, Froeschke et al. 2006, Tetreault and Ambrose 2007, Lester et al. 2009, Kay et al. 2012, Karpov et al. 2012, Hamilton et al. 2014, Starr et al. 2015, Caselle et al. 2015, Keller et al. 2019, Eisaguirre et al. 2020, Esgro et al. 2020)	Increased recovery after disturbance via higher probability of reproductive success	(Gascoigne and Lipcius 2004)
		Increased resistance from stochastic demographic loss below some critical threshold of recovery	(Botsford et al. 2019)
		Greater response to selection	(Gascoigne and Lipcius 2004, Masel 2011)
Older/Larger individuals in MPAs	(Paddack and Estes 2000, Halpern and Warner 2002, Parnell et al. 2005, Tetreault and Ambrose 2007, Lester et al. 2009, Kay et al. 2012, Hamilton et al. 2014, Starr et al. 2015, Caselle et al. 2015, Selden et al. 2017, Marshall et al. 2019, Jaco and Steele 2020)	Faster recovery by maintaining greater reproductive output from larger individuals	(Micheli et al. 2012, Kindsvater et al. 2016, Barneche et al. 2018, Marshall et al. 2019, Aalto et al. 2020)
Complete (full) age structure	(White et al. 2013, Baskett and Barnett 2015)	Make populations less vulnerable to a series of poor reproductive years	(Hjort 1914, Warner and Chesson 1985, Botsford et al. 2014, 2019)
Maintenance of genetic diversity	(Pérez-Ruzafa et al. 2006, Pinsky and Palumbi 2014, Munguía-Vega et al. 2015, Kelly 2019)	Greater likelihood of resistance genotypes and increased potential for recovery via evolutionary rescue	(Pespeni et al. 2013)

MPA/NETWORK EFFECT	SUPPORTING LITERATURE	RESILIENCE MECHANISMS	SUPPORTING LITERATURE
Networks encompass sites that are climate refugia	(Game et al. 2008, Botsford et al. 2014)	Increased resistance and recovery of meta-population via spatial refugia of some populations from environmental stress	(Woodson et al. 2019)
Increased biogenic habitat	(Shears and Babcock 2003, Ling et al. 2009, Ling and Johnson 2012, Sutton-Grier et al. 2015, Eisaguirre et al. 2020)	Increased population vital rates due to intact nursery habitats	(Holbrook et al. 1990, Love et al. 1991, Beck et al. 2001, Fodrie and Levin 2008, White and Caselle 2008, Adam et al. 2011, White 2015)
ECOSYSTEM RESILIENCE (AND NETWORK FUNCTION)			
Maintenance of taxonomic and functional diversity	(Paddack and Estes 2000, Micheli and Halpern 2005, Froeschke et al. 2006, Lester et al. 2009, Starr et al. 2015, Caselle et al. 2018, Eisaguirre et al. 2020, Esgro et al. 2020)	Increased resistance to climate change via higher functional redundancy and differential responses	(Micheli and Halpern 2005, Schindler et al. 2010, Eisaguirre et al. 2020)
Maintenance of trophic linkages via larger body sizes	(Paddack and Estes 2000, Halpern and Warner 2002, Parnell et al. 2005, Tetreault and Ambrose 2007, Lester et al. 2009, Kay et al. 2012, Hamilton et al. 2014, Starr et al. 2015, Caselle et al. 2015, Selden et al. 2017, Marshall et al. 2019, Jaco and Steele 2020)	Increased resistance to invading/range shifting species that cause community shifts through predation	(Ling et al. 2009, Ling and Johnson 2012)
		Increased resistance to disease epidemics via suppression of population outbreaks	(Eisaguirre et al. 2020)
Increased connectivity (MPA networks)		Increased resistance to communities undergoing range shifts via stepping stones of protection from harvest or disturbance	
HUMAN DIMENSIONS			
Reduction of fishing pressures	(Tetreault and Ambrose 2007, Caselle et al. 2015)	Spill-over from fisheries	(Goñi et al. 2010, Kay et al. 2012, Baetscher et al. 2019)
		Post-disaster food security via increase in productivity of harvestable species	(Aswani and Furusawa 2007, Aburto-Oropeza et al. 2008)
Serve as a draw for tourism	(Hargreaves-Allen et al. 2011, Arkema et al. 2017, Lopes et al. 2017)	Increased economic resilience in the face of climate stressors	
Cultural, spiritual, and aesthetic benefits	(De Santo et al. 2011, De Santo 2013, Potts et al. 2014)	Protect culturally signifi ant species and habitats, existence value of certain species or habitats, cultural/spiritual benefits of healthier ocean habitat	

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Appendix C: MPA research prioritization process and full list of research questions

Given limited resources and the state's desire to maximize existing investments in MPA research and monitoring, OST together with the working group, undertook a semiquantitative approach to identify the priority MPA research questions listed in this report that could serve two objectives: (1.) fill key knowledge gaps and advance our scientific understanding of how MPAs could be used to infer ecosystem resilience to climate change, and (2.) provide OPC and CDFW with guidance on research that could lead to the most significant return on state investments (leverage existing data and resources, where appropriate), and that took into account the level of effort required (illuminating both near- and longer-term research priorities and needs).

This process, outlined here, comprised of (a.) a poll of individual working group members to generate an initial list of research questions and prioritization criteria, (b.) a Likert scale survey to rank and narrow the list of questions, followed by an analysis of the results, and (c.) group discussion of the results to generate the final prioritized list of MPA research questions.

Generating the Initial List of Research Questions and Prioritization Criteria

Via a series of polls and working group discussions, and with guidance from OPC and CDFW, the Working Group generated on an initial list of MPA research questions, a set of prioritization criteria (Box A-1), and a prioritization process to be guided by the Action Priority Matrix (impact-by-effort) (Figure A-10). The Action Priority Matrix allows for the categorization of potential projects that might achieve the greatest impact (i.e., advance the state of the science) while maximizing time, energy, and investments. Based on these categories, the Working Group agreed to prioritize research questions and potential projects that fell within the high impact quadrants (i.e., "quick wins" and "major projects")

Figure A-10. Action Priority Matrix used to guide the research prioritization process.

To generate the initial list of questions and the set of prioritization criteria, OST distributed a poll asking members to 1.) identify three main criteria that should be used to guide how the group should prioritize research and monitoring questions, and (2) list three pressing research questions and associated methods that could be used to assess the performance of California's MPA network in the context of climate change. In parallel, OST polled California's Long-term MPA Monitoring Principal Investigators to contribute near-term (1-2 year), medium-term (3-5 year) and longer-term (5+ years) research question that could advance our understanding of the climate resilience capacity of California's MPA network.

OST compiled all contributions into a list of prioritization criteria (Box A-1) and a full list of 34 research questions (Box A-3) covering theoretical and practical research questions that were then organized around the themes from Table 1 (e.g., cross cutting / integrative research; organismal resilience / adaptive capacity of organisms; population resilience; ecosystem resilience (and network function); human dimensions). The list was cross-referenced with Appendix B from the California MPA Monitoring Action Plan to identify overlap with existing state MPA monitoring priorities and projects, where available.

Likert Survey and Analysis of Results

In an effort to undertake a process for prioritizing specific research questions that was transparent, fair, and scientifically rigorous, OST generated a Likert scale prioritization survey and asked working group members to independently score each of the initial 34 research questions for both impact and effort, separately, on a scale of 1 to 4 (1 being low impact or effort, 4 being high impact or effort). Members were also allowed to score "unsure." In choosing their scores, members were asked to consider the prioritization criteria listed in Box A-1, as well as the strength of evidence (or lack of evidence) to demonstrate MPA effects and underlying mechanisms identified in a gap analysis from Table 1.

Following the completion of the survey, scores for each question were averaged across all member responses, and mapped onto one of the Action Priority Matrix quadrants (i.e., major projects, quick wins, thankless tasks, fill-ins). The cutoff hresholds for scores falling in the "high" impact or effort quadrants were determined based on the median for each scale, respectively. This process generated a shortlist of 17 questions.

Generating the Final List of Questions

Working group members were then given another opportunity to comment and provide feedback on the list (both via remote meetings and written comments). Co-chairs of the working group then took an editorial lens to the shortlist of 17 questions (editing language for consistency, combining duplicates, incorporating member feedback etc.) and narrowed the list to 15 questions. The Long-term Monitoring PIs and members of the Decadal Evaluation Working Group were also asked to review and provide feedback on the prioritized research questions and methods.

The final list of priority questions is provided in Table 2 within the report. All other research developed that may still be of interest to the State are included in Table A-3.

Box A-1. Working group criteria for generating the initial MPA research questions list

- Urgency for California to address
- Applicability to MPAs (i.e., have a moderate to strong linkage to MPAs)
- Realism (can address current configuration of MPAs, not propose a redesign)
- Importance to management decision-making
- Feasibility of research and monitoring
- Contribution to key gaps in understanding of climate resilience mechanisms
- Research that can efficiently and effectively observe climate resilience inside MPAs
- Research that can identify the mechanism of climate resilience
- Research in which the mechanism is plausibly large but evidence in California is low
- Resilience (e.g., does the research/monitoring question increase our understanding of and/or inform and support management aimed at promoting resilience?)
- Scale (questions that balance both regional and network effects)
- Consideration of diversity, equity, inclusion in MPA research and monitoring activities and practices
- Work that can be done with existing data from the MPA monitoring program (and beyond)
- Work that could inform development of MPA networks in other regions
- Breadth of questions answered
- Is there a link to population or ecosystem dynamics (scaling)
- Is the time scale relevant to management (effects relevant to annual/decadal scales)
- Appreciation of variability in the environment and across organism phenotypes

Table A-3. Full list of climate resilience MPA research questions generated by the working group.

Questions denoted with an asterisk (*) were determined to be high priority and are included in Table 3.

RESEARCH QUESTION
THEME 1: CROSS-CUTTING / INTEGRATIVE RESEARCH
• What role does the current MPA network play in meeting societal needs (e.g., economics, human dimensions, cultural values) and which needs are most likely to be impacted under climate change in the future?* • What is the spatial distribution of MPAs relative to historic and current stressor exposures, and how are those stressors likely to evolve in the future?* • Does MPA-induced ecological resilience spill over to areas outside MPAs? What mechanisms increase the likelihood of resilience spillover and are they quantifiable?* • How will knowledge on the patterns of community resilience, and their underlying mechanisms, inform the appropriate role for MPAs in policy, management, and conservation to address future climate impacts?* • How can we best attribute and monitor the benefits of MPA resilience and how those benefits change in time and space? Essentially, how do we know MPAs are inferring climate resilience? • How has habitat (biogenic, oceanographic) and biodiversity (biogenic, demersal, pelagic) changed since MPA network implementation? • What percent of MPAs in the network were affected (habitat, species diversity) by extreme events (e.g. marine heatwave)? • What percent of MPAs in the network are predicted to be affected (habitat, species diversity) by climate change under downscaled climate models?
THEME 2: ORGANISMAL RESILIENCE / ADAPTIVE CAPACITY OF ORGANISMS
• Will California's MPA network continue to protect key species, and a significant portion of their habitat, as species migrate (i.e., range, depth) due to climate variability, marine heatwaves, and climate change?* • Do MPAs facilitate species' adaptive responses to climate change via increased genetic diversity due to increases in population size?* • Do California MPAs harbor more or higher genetic intraspecific diversity than the surrounding non-MPA waters? • Does the MPA network capture intraspecific genetic variability across a gradient of conditions (e.g. temperature-latitudinal gradient) that might lead to local adaptation? • Is biogenic habitat increased by MPAs? • Can kelp or seagrass afford buffering capacity at the MPA scale?
THEME 3: POPULATION RESILIENCE
• What are physical, ecological, and biological characteristics of climate refugia? Do MPAs include or promote these conditions? Will climate refugia persist into the future?* • Does the California MPA network provide adequate levels of disconnection between MPAs (e.g., modularity) to ensure some populations persist in the face of climate change?* • Will the current configuration of MPAs provide habitat and protection for species that are shifting their ranges due to temperature? • What is the connectivity across MPAs in status quo? What is the role of disturbance?

THEME 4: ECOSYSTEM RESILIENCE (AND NETWORK FUNCTION)
• Do California MPAs provide ecological resilience (e.g., via increased functional diversity & redundancy) in response to marine heatwaves and anomalous oceanographic changes?*   • How will climate change affect ecosystem connectivity across the MPA network? How do current and future connectivity patterns and species interactions affect resilience of MPAs?*   • To what extent do MPAs provide more resilience to marine heatwaves and accompanying oceanographic changes than non-MPA waters?   • What is the relative importance of each of the resilience mechanisms in Table 2?   • What is the network-level responses of populations and communities in MPAs to climate variability and extremes? Is there evidence of such regional function?   • What is the regional variation in climate impacts or resilience and possible function of MPAs?
THEME 5: HUMAN DIMENSIONS
• As fishers alter fishing behavior (e.g., spatial or temporal patterns, targets) in response to migrating species due to climate change, will California's MPA network continue to protect and provide habitat to commercially and recreationally targeted, and culturally signifi ant, species?*   • What ecosystem services do MPAs provide and how might those ecosystem services change under climate stressors?*   • What do people consider culturally, spiritually, and aesthetically beneficial about coastal and ocean regions protected by MPAs, and will MPAs continue to support the provision of these values under a changing climate?*   • What are the equity issues around MPAs in a changing climate?*   • Do MPAs support and facilitate climate adaptation in coastal communities (e.g., provide alternative livelihoods, coastal protection)?*   • Can we quantify the net benefit of coastal habitat (and restoration) in protecting against storm surge and sea level rise? Can we model these for California to understand the economic benefits MPAs provide through coastal protec tion, as well as the potential of investing in restoration to provide jobs and protect coasts?   • How do people value species and ecosystems protected by MPAs, particularly those where it is clear that MPAs enhance climate resilience?   • Which researchers are doing diversity, equity, and inclusion (DEI) work in the MPA space?
ADDITIONAL CONTRIBUTIONS (BY CALIFORNIA MPA MONITORING RESEARCHERS)
• Do MPA protections result in more physically resilient sandy beaches?   • What are the links between physical (including beach and dune profiles) and ecological attributes of sandy beaches and patterns of resiliency to SLR, storm/wave erosion? Are more biodiverse beaches more resilient?