Staff Summary for May 5-6, 2026

17. General Public Comment for Items Not on the Agenda

Today's Item **Information ☒** **Action ☐**

Receive public comment regarding topics within the Commission's authority that are not included on the agenda.

Summary of Previous/Future Actions (N/A)

Background

This item is to provide members of the public an opportunity to address the Commission on topics not on the agenda. Staff may include written materials and comments received prior to the meeting as exhibits in the meeting binder (if received by the written comment deadline), or as supplemental materials and comments at the meeting (if received by the supplemental comment deadline).

General public comments are categorized as either: (1) requests for non-regulatory action or (2) informational-only. Under the Bagley-Keene Open Meeting Act, the Commission cannot discuss or take action on any matter not included on the agenda, other than to schedule issues raised by the public for consideration at future meetings. Thus, non-regulatory requests (any request of the Commission that does not require a regulation change) generally follow a two-meeting cycle (receipt and direction).

Any non-regulatory request submitted during today's meeting, and unrelated to marine protected areas, will be received by the Commission at its next regularly scheduled meeting (currently June 17-18, 2026) under "Non-regulatory requests from previous meetings."

Significant Public Comments (N/A)

Recommendation

Commission staff: Consider whether to add any future agenda items to address issues that are raised during public comment.

Exhibits

1. Santa Barbara Harbor Commission opposes proposed marine protected area expansions, citing conflicts with the Commission's Coastal Fishing Communities Policy and significant economic risks to local fishing-dependent businesses, and requests that decisions on the petitions be deferred pending a full socioeconomic impact review and consideration of stakeholder-driven alternatives, received March 5, 2026
2. Chris Arechaederra, Executive Director, Coastal Conservation Association California (CCA California), states that comments made by an individual during the April 14, 2026 Tribal Committee meeting were inappropriate and do not reflect the views of CCA California. As a result, the organization plans to revoke the individual's membership for failing to meet CCA California's standards of conduct. Received April 16, 2026.

3. A longtime commercial fisherman and two members of the public collectively share their support of science-based decision making in the MPA review process, calling for stronger public engagement — particularly for the Channel Islands — and continued improvement of regional fisheries management, expanding the MPA network to enhance biodiversity and climate resilience through larger, connected reserves, and strong enforcement, received between April 16 and April 22, 2026
4. Kaspar Kazazian, California Surf Fishing, supports allowing shore fishing in the expanded Duxbury State Marine Conservation Area (SMCA), expresses concern that other shore fishing petitions are being assessed by the Department using outdated 2009 criteria, requests the petitions be reevaluated using more current criteria, and requests that shore fishing remain an accessible, equitable, and economically important activity, received April 17, 2026
5. The San Diego Fishermen's Working Group, Alliance of Communities for Sustainable Fisheries, and California Fisherman's Resiliency Association raise concerns regarding the California Ocean Protection Council's approach to the MPA petition process, asserting that adaptive management is being applied inconsistently and that existing regulatory measures, pending federal closures, and scientific findings showing limited biodiversity or resilience gains from expanded MPAs are not being fully considered. They caution that additional closures may displace fishing effort without addressing broader stressors and affirm support for tribal co-management within existing MPAs while opposing further MPA expansions. Received April 18, 2026.
6. Darren Gertler disputes the need for MPA expansion proposals, noting California's fisheries are already effectively managed and additional closures could limit future fishing access and reduce opportunities for youth to develop stewardship connections, received April 20, 2026
7. Monica Martinez, Chair, Santa Cruz County Board of Supervisors, opposes Petition 2023-33MPA and supports the Departments recommendation to deny it due to limited scientific justification, the presence of existing healthy kelp forests in the proposed areas, insufficient community outreach, and potential impacts on local fishing access, received April 21, 2026
8. Tom Hafer, Secretary, Morro Bay Commercial Fishermen's Organization, contests the addition of more MPA designations, asserting that current scientific evidence does not show increases in biodiversity, biomass, or climate-resilience benefits. They state that expanding MPAs would negatively affect the commercial fishing sector, and recommend restoring fishing access, reinstating seasonal spawning closures, and consider adding slot limits as alternative measures. Received April 21, 2026.
9. Patrick Spalding urges the Commission to deny Petition 2023-23MPA noting that the region is already highly regulated, the petition provides no scientific evidence linking fishing restrictions to kelp restoration, and the proposed changes would harm local communities by removing long standing access for over 100,000 residents, received April 22, 2026

Motion (N/A)

City of Santa Barbara
Waterfront Department
SantaBarbaraCA.gov

Administration
Tel: (805) 564-5531
Fax: (805) 560-7580

Parking
Tel: (805) 897-1965
Fax: (805) 560-7580

Stearns Wharf
Tel: (805) 564-5518
Fax: (805) 963-1970

Harbor Patrol
Tel: (805) 564-5530
Fax: (805) 897-2588

Harbor Maintenance
Tel: (805) 564-5522
Fax: (805) 966-1431

132-A Harbor Way
Santa Barbara, CA
93109

March 5, 2026

California Fish and Game Commission
P.O. Box 944209
Sacramento, CA 94244-2090

RE: MPA Amendment Petitions Affecting Santa Barbara Channel

Dear Commissioners:

The Santa Barbara Harbor Commission writes to express concern about pending Marine Protected Area (MPA) petitions that would establish significant new fishing closures in the Santa Barbara Channel. We urge the Commission to evaluate these petitions carefully against their economic costs and consistency with the Commission's Coastal Fishing Communities Policy before taking action.

Santa Barbara Harbor is home to one of California's most active commercial fishing fleets and serves as a hub for recreational fishing, marine tourism, and ocean-based employment. The vitality of our working waterfront depends on maintaining viable access to productive fishing grounds for both commercial and recreational users.

Consistency with the Coastal Fishing Communities Policy

The Commission's Coastal Fishing Communities Policy commits to meaningful engagement with fishing communities, factoring community interests into decision-making, and increasing adaptive capacity and resilience. We are concerned that the petitions before the Commission do not meet these standards.

Meaningful consultation with harbor businesses, fishing crews, processors, and recreational operators whose livelihoods depend on the affected areas are critical before moving forward with decisions. The petitions also lack adequate socioeconomic impact analysis — there is no assessment of lost income, operational displacement, or cumulative effects on port viability. And because MPA designations are difficult to reverse, approving closures before adaptive management alternatives have been seriously evaluated would reduce, rather than increase, the fishing community's resilience and adaptive capacity.

Economic Concerns

The Santa Barbara port area ranked first in California for commercial fishing vessel count and second for poundage in 2023, with 296 vessels landing 23.4 million pounds valued at $35.1 million (CDFW). Our fleet of 185–200 owner-operated small boats supports over 500 jobs in Santa Barbara County. These livelihoods depend directly on continued access to productive fishing grounds.

Moreover, proposed expansions at Point Conception, South Point at Santa Rosa Island, and Gull Island would affect the majority of our fleet and our top fisheries, including Spiny Lobster and Red Sea Urchin. Cumulative closures of this magnitude risk pushing our port below the threshold needed to sustain the infrastructure, supply chains, and workforce that a functioning fishing community requires.

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The City of Santa Barbara has invested in partnerships like the Ocean Collective workforce development program at Santa Barbara City College to build career pathways in our maritime economy and expand ocean access for tribal communities. Closures that reduce fishing and tourism opportunity work against those investments.

Management Context

California's commercial and recreational fisheries operate under rigorous state and federal management. We share the concerns expressed by the Santa Barbara County Fish and Wildlife Commission that the proposed closures lack sufficient justification given their economic costs. When protection of particular species is the goal, adaptive fishery management tools — seasonal restrictions, depth limits, area closures subject to monitoring — are available and have a proven track record. These approaches should be seriously evaluated before the Commission acts on permanent closures.

Request

We respectfully urge the Commission to defer consideration of the pending petitions and direct the Department to examine socioeconomic impacts alongside ecological objectives and pursue management solutions developed through genuine stakeholder engagement, grounded in best available science, and consistent with the Marine Life Management Act and the California Fish and Game Commission's Coastal Fishing Communities Policy.

We appreciate your time and attention.

Respectfully,

Santa Barbara Harbor Commission

[redacted]

Adam Stanowick
Harbor Commission Chair, City of Santa Barbara

COASTAL
CONSERVATION
ASSOCIATION
CALIFORNIA

4065 Oceanside Blvd.
Suite Q
Oceanside, CA 92056

CCACalifornia.org

Commissioner Jacque Hostler-Carmesin
Chair, Tribal Committee
California Fish and Game Commission
P.O. Box 944209
Sacramento, CA 94244-2090

04/16/26

Dear Commissioner Hostler-Carmesin:

During the April 14, 2026, California Fish and Game Commission Tribal Committee meeting, an individual by the name of Eric Kramer provided public comments via Zoom regarding the Tribal MPA Petitions.

We want all to know that Mr. Kramer's comments do not represent the views of Coastal Conservation Association of California (CCA Cal). Like many others, we found his comments and language disruptive, insensitive, and hurtful. We sincerely regret the disruption and hurt that his actions caused.

CCA Cal strives to hold members to a high standard. Given Mr. Kramer's comments and language, he does not meet that standard. Consequently, CCA Cal is in the process of revoking his membership in our organization. Concurrently, we continue to communicate and emphasize to all CCA Cal members the importance of abiding by public comment procedures and expressing points of view in a respectful manner.

As you know, CCA Cal leadership works hard to build strong working relationships with the Commission and Department of Fish and Wildlife based on science and trust. We look forward to continuing to build on that foundation to work productively with the Commissioners and CDFW staff now and into the future.

Sincerely,

Chris Arechaederra
Executive Director

cc.

California Fish and Game Commissioners
Meghan Hertal, CDFW Director
Melissa Miller-Henson, CDFW Executive Director

From: [redacted]
Sent: Thursday, April 16, 2026 11:03 AM
To: FGC <FGC@fgc.ca.gov>
Subject: May 5th Regional Marine Protected Area Petitions Meeting

To whom it may concern,

I am writing to express my strong support for the continued expansion and strengthening of Marine Protected Areas (MPAs) along California’s coastline.

MPAs are one of the most effective, evidence-based tools available for preserving marine biodiversity, rebuilding depleted fish populations, and increasing ecosystem resilience in the face of climate change. Decades of research have consistently shown that well-managed MPAs lead to increased biomass, greater species diversity, and spillover benefits that enhance adjacent fisheries.

California has been a national and global leader in marine conservation through the implementation of the Marine Life Protection Act (MLPA). Expanding and reinforcing this network is a logical and necessary next step to ensure that these gains are not only maintained, but strengthened over time.

In particular, I support efforts to:

- Increase the size and connectivity of MPAs to support ecosystem-scale resilience
- Protect critical habitats such as kelp forests, estuaries, and spawning grounds
- Ensure strong enforcement and monitoring to maintain ecological integrity
- Incorporate adaptive management strategies to respond to climate-driven changes in ocean conditions

Healthy marine ecosystems are foundational not only to biodiversity, but also to California’s fishing economy, tourism industry, and coastal communities. By investing in long-term conservation through MPAs, the state is safeguarding both environmental and economic sustainability.

I encourage the Department and Commission to continue prioritizing science-based decision-making and to move forward with policies that expand and strengthen California’s MPA network.

Thank you for the opportunity to provide public comment.

Sincerely,

Sawyer Sacket

Paso Robles, CA

From: Robert Groeber <[redacted]>
Sent: Tuesday, April 21, 2026 02:39 PM
To: FGC <FGC@fgc.ca.gov>
Subject: Fish and Game Commission Meeting May 5, 6, 2026

April 21, 2026

California Fish and Game Commission

P.O. Box 944209

Sacramento, CA 94244-2090

Submitted electronically to fgc@fgc.ca.gov

Re: May 5,6,2026 Fish and Game Commission Meeting Agenda Item 2: Bin 2 MPA Petitions

Dear President Sklar and honorable Commissioners and Staff,

I am writing to express my strong support and gratitude to the Department of Fish &

Wildlife (Department) for their thoughtful and thorough analysis of the Marine Protected Area (MPA) petitions and my full agreement with their recommendations.

I strongly encourage the Commission to adopt the thoughtful, empirical recommendations of the Department's career staff scientists and to judiciously consider the diverse communities

who would be critically impacted by additional closures to coastal fisheries.

The Department's consistent application of the guidance provided by the Master Plan for MPAs, historical documentation of the original MLPA decision making process, and evaluation of best available science and policy was robust and transparent. While there were petitions that pro-fishing advocacy groups advocated for alternative outcomes, I recognize and

respect the determinations of Department staff and stand behind the established process for informed decision-making regarding petitions.

The Department's approach was not developed in a vacuum. Rather, it was the direct result of over two and a half years of Commission and MRC meetings, countless hours of testimony and thousands of pages of stakeholder input.

In addition, regular citizens, tribes,

other government agencies, and a myriad of NGOs shared their perspectives to ensure a clear and transparent process for petition evaluation and prioritization. From the initial referral of the petitions to the analysis and adoption of Bin 1, the creation of the decision-making matrix, creating a committee of the whole to hear the arguments, and a myriad of

other milestones, this process was the culmination of a diverse set of stakeholder voices and grounded in longstanding law and procedure. The Department's science-based recommendations are thus bolstered by the voices of a large and diverse constituency who helped to formulate the transparent process.

I strongly encourage the Commission to

honor the outcome of years of diligent work and to recognize the Department's

recommendations as the authority on these matters. The Commission can be confident that this decision will set the standard for our MPA network to be adaptively managed by science, stakeholder input and law, rather than

ideology or emotion, exactly as the MLPA dictated.

Furthermore, I look forward to reviewing the Department's recommendations on the

remaining petitions now classified as tribally led or co-led. I respect tribal sovereignty, the principles of tribal co-management and tribal authority to

conduct government to government consultations regarding tribal interests and access to natural resources. At the same time, I respectfully request that any decisions to expand the MPA network and to close recreational access to fishing for the general public follow the guidance provided by the Master Plan for MPAs and the science-based decision-making

framework that has guided the MPA petition evaluation process over the past several years.

Stay safe and healthy!

Carpe Diem!

Robert Gröeber

[redacted]

Port Hueneme CA [redacted]

[redacted]

[redacted]

iSent from my wonderfully iDdictive fujiPhone! Please forgive spelling and typographical errors...

Harry Liquornik
[redacted]
Santa Barbara, CA [redacted]
Fishing Vessel Abreojos

April 21, 2026

California Fish and Game Commission
California Department of Fish and Wildlife
Via email to fgc@fgc.gov.ca

Public Comment- Regional MPA meeting Goleta, California May 5-6

Dear Commissioners, Commission and Department Staff:
I have been a commercial diver and fishermen for 41years based out of Santa Barbara. My primary fishing experience is with abalone, sea urchins, sea cucumbers, and more recently, kelp harvesting. I have engaged extensively with fisheries management policies and plans beginning in the early 90s. I have sat on numerous advisory committees, panels and boards of fishing organizations, I was the president of Commercial Fishermen of Santa Barbara starting in 1997 for about 12 years. During that period The Marine Life Management Act and Marine Life Protection Act were legislated and enacted. Other Organizations and committees I have sat on include the following:

Fishing Associations:
California Abalone Association
California Sea Urchin Commission
Commercial Fishermen of Santa Barbara Inc.

Committees and Advisory Panels:
Fish and Game Directors Abalone Advisory Committee (Commercial fishery)
Fish and Game Directors Sea Urchin Advisory Committee
Channel Islands National Marine Sanctuary Advisory Council
Channel Islands Marine Reserve Working Group

My interest and support for marine reserves began in the early 90s with the closure of the Black abalone fishery. At that time, there was only one small marine reserve at Anacapa Island. The data showed the decline in Black abalone population in the Anacapa reserve was very similar to the decline in the fished areas. However, without a larger network of marine reserves there was not enough data to determine how much of the population decline could be attributed to fishing. This scenario played out again over the next handful of years with the closure of the Pink, Green and Red abalone fisheries with no reserve networks in place there was no way to determine the effects of fishing vs environmental changes.

My comments here are to address the current process, with the hope that the current process and future processes for managing marine reserves can be improved.

Being directly involved with the Channel Islands process and limited involvement with the MLPA process I cannot stress enough the importance of a robust regional public process prior to any regulatory/petition process.

I would recommend implementing regional working groups and leaving them in place, overtime managing marine reserves and fisheries management would benefit immensely.

Sincerely
Harry Liquornik
[redacted]

From: California Surf Fishing <calisurffishing@gmail.com>
Sent: Friday, April 17, 2026 09:46 PM
To: FGC <FGC@fgc.ca.gov>
Subject: Shore Fishing in Highly Protected SMCAs - Written Comment

Dear Commissioners,

This is Kaspar Kazazian with www.CaliforniaSurfFishing.net and www.instagram.com/CaliforniaSurfFishing.

It was a pleasure speaking with each of you on this topic and also commenting during the April 15 meeting.

We applaud CDFW's recommendation to continue permitting shore fishing in the expanded Duxbury SMCA. However, we have serious concerns that other shore fishing opportunities will be limited due to CDFW's use of an outdated 2009 SAT framework, which classified shore fishing as a low level of protection. Several petitions allowing shore fishing (such as Point Dume) were denied in the CDFW recommendations, citing this outdated low level of protection.

As I stated during the April 15 FGC meeting, the latest MPA science attributes a high level of protection to SMCA's that allow shore-only fishing, not low. Since 2009, the original SAT rationale has been shown to be flawed, overstating the cascading effects of shore fishing on deeper SMCA fish populations.

Please see our page below for a thorough justification of shore fishing in highly protected SMCAs, with data and references: https://www.change.org/p/allow-shore-fishing-in-smca-s

The page also shows signatures and written comments from 1,300+ surf fishermen in support of SMCA shore fishing.

After reading our page, we hope you more accurately and favorably evaluate petitions that allow SMCA shore fishing (Mishopshno, Point Dume, etc).

Alternatively, catch and release shore fishing is a very conservative option with scientific consensus; even the 2009 SAT attributed a high level of protection to SMCAs with catch and release shore fishing. While the data and references in the link above are for catch and keep shore fishing, catch and release shore fishing is an alternative that is already culturally engrained in shore fishing.

Shore fishing represents one of the most accessible and equitable forms of outdoor recreation, in alignment with several DMR recommendations and the MLPA. It is also one of the most popular forms of fishing in California, accounting for 34% of fishing trips according to recent CRFS data. Many local businesses are dependent on a thriving shore fishery.

Thank you.

SAN DIEGO FISHERMEN'S WORKING GROUP
CALIFORNIA
FISHERMEN'S
RESILIENCY
ASSOCIATION
ALLIANCE OF COMMUNITIES FOR SUSTAINABLE FISHERIES

Jenn Eckerle
April 18, 2026

Executive Director

California Ocean Protection Council (OPC)

Sent electronically to: jenn.eckerle@resources.ca.gov

RE: Comments on OPC's March 20, 2025, letter to the California Fish and Game Commission (CFGC) RE Marine Protected Area petitions

Dear Ms Eckerle,

Please accept the following comments from the San Diego Fishermen's Working Group (SDFWG), the Alliance of Communities for Sustainable Fisheries (ACSF), and the California Fishermen's Resiliency Association (CFRA), regarding OPC's letter to the CFGC. Thank you for providing an opportunity to comment on this important topic.

Who we are

The San Diego Fishermen's Working Group (SDFWG) was formed in 2011 to provide a unified voice to commercial fishermen of all gear types in the greater San Diego region. We are a 501(c)(3) non-profit organization, purposed to bring the collective views of commercial fishermen to fisheries science and management, and to any public process that may impact the success of our fisheries. The SDFWG is guided by a nine person Board of Directors (Board), representing the various important gear types and fisheries in the region.

The Alliance of Communities for Sustainable Fisheries (ACSF) is a 25-year-old 501(c)(3) not-for-profit organization, founded for the purposes of educating the public on fisheries issues, connecting fishing men and women ("fishermen") with their communities, and representing fishing interests in state and federal processes. The

ACSF is a regional organization, with commercial fishing leaders, representing Monterey, Moss Landing, Santa Cruz, Morro Bay, Pillar Point, Port San Luis, and Santa Barbara, on our Board of Directors. Thus, the ACSF represents a large cross-section of fishing and community interests for the Central Coast of California.

In January 2022, California port commercial fishermen's associations formed the California Fishermen's Resiliency Association (CFRA), a California Nonprofit Mutual Benefit Corporation. CFRA's Board of Directors is composed of port-level fishing organizations from Crescent City to San Francisco. In addition, CFRA includes consulting members from ports throughout the state, from San Diego to Crescent City, and currently represents seventeen separate fishermen's organizations (as of July 2025). CFRA represents its members' interests and provides support at the local, state, and federal levels on issues of spatial challenges, including access to fishing grounds, marine protected areas, non-fishing ocean industrialization, ecological and environmental concerns, zoning, port infrastructure, and impact mitigation. CFRA represents all fisheries and gear types through its member associations.

The term *fishermen* is inclusive of both our fishing men and women for all associations.

Policy Comments

The opening paragraph of the OPC's March 20, 2026 states:

"OPC is statutorily responsible for the direction of MPA policy (SB 96, 2013) and in this role, we set strategic priorities for the Network, lead coordinated implementation of the State's MPA Management Program, and convene the MPA Statewide Leadership Team, an advisory body of state and federal agencies, tribal representatives, and implementation partners, to coordinate MPA management activities across the state."

This section appears to assert an OPC role for MPA considerations superior to the DFW and FGC. Can you clarify if that is the OPC's contention? If so, what is the role of the CDFW's scientific assessment of the MPA petitions and of the CFGC?

OPC's Strategic Plan includes the explicit objectives of strengthening the performance and durability of California's MPA network. We wonder, what will the standard be for determining if MPA's must be "strengthened"? We suggest objectives need to be clearly defined and measurable, that major biodiversity benefits from no-take MPAs should only be expected where fishing pressure is very high, that the threats to biodiversity be identified and should determine the appropriate actions, and recognize that no-take areas are not effective against many of the threats.

The OPC asserts that it must use the principles of adaptive management in assessing the merits of MPA petitions, yet it dismisses out-of-hand several that would open certain MPA's to limited harvest. It appears that adaptive management is viewed as a one-way street: always aimed at increasing restrictions. A case in point: The petitions that propose opening two SMR's (Stewards Point and Bodega Head) to salmon trolling are not considered. This appears to be evaluated as a policy issue rather than a science issue. The ACSF and SDFWG find this deeply alarming. We dispute that fishing for salmon and other highly pelagic species contains any problem for which an MPA is the answer.

It is also exasperating that the OPC's role in meeting the "30X30" goal of protection does not include acknowledgement of many other state and federal regulations and closures. It would seem that ecosystem-based management by the state would include these, as well as large, pending closures such as will come from federal Aquaculture Opportunity Areas and Offshore Wind development. The state water boundary does not define an ecosystem.

OPC makes it clear that it will evaluate petitions modified after CDFW's cut-off of March, 2025. That is fair, but we presume that CDFW's science team will have an opportunity to provide additional review of the changes as well, before the petitions go to the OPC. Is that a fair assumption?

Last, the ACSF and SDFWG are pleased to see in the OPC letter the goal of "supporting thriving fishing communities". We note that some fishing communities are faring better than others but none are "thriving". This is one factor that saw the FGC recently adopt a policy for protecting fishing communities.

Science Comments

Members of the ACSF and SDFWG are not scientists. This said, many of our members pay close attention to the evolving science, including reading the literature, that supports fisheries management, ecosystem health, and understanding the problems that MPA's address or can not address. In many cases our decades of on-the-water observations can and have been used to support scientific research. This the background that we offer our opinions on some of the science claims in the OPC letter.

The OPC letter observes that even if all of the petition requests are met, "fishermen will still have 83% of state waters to fish in". We find this to be maddingly simplistic. Even a basic understanding of fisheries will teach that fisheries are habitat-based. Different species require different habitats. If a large percentage of a particular habitat is removed from fishing opportunity, that fishery will wither. During the first MLPA initiative, as much as 45% of quality hard-bottom habitat was placed into MPA's, thereby concentrating the displaced fishermen into the remaining open area for their particular fishery. Highly mobile species, such as salmon, swordfish, and sardines, range coastwide depending sea surface temperatures and other natural factors. Fishermen are also subject to limited entry management—meaning it takes a special permit to fish for specific seafood. Often limited entry permits are quite expensive, if available at all. Thus, fishermen can't often switch from one fishery to another, to fish different habitats..

The OPC letter claims that the Decadal Management Review...showed that the state's MPA network is improving ocean health. The decadal review states: "Although biodiversity of select marine species was higher inside MPAs in some habitats and bioregions (Appendix B.2-B.4), statewide and regional trends across habitats showed no difference in biodiversity inside compared to outside MPAs." While global analysis shows the diversity of species inside MPAs was higher than outside (Lester et al., 2009) this was not found in California's MPA network.

The Decadal Review also concluded: "Some ecological communities demonstrated greater resiliency inside MPAs compared to those outside of MPAs and recovered more quickly after the heatwave, though analysis across habitats in the central coast revealed that MPAs did not provide strong resilience against the marine heatwave." In papers we found in the scientific literature, Smith et al. (2023) examined climate resilience from the MLPA and concluded, "Collectively, our findings suggest that MPAs have limited ability to mitigate the impacts of marine heatwaves on community structure." Another paper, Freedman et al., (2020), looked at a range of species in kelp ecosystems and concluded the MPAs had not provided any resilience to the community.

We note that other ocean stressors, such as ocean acidification, fish migration, ocean pollution, and wasting diseases, do not benefit from MPA designations.

Much of the science that make claims of increased abundance inside MPA's, compared to "control" areas neighboring these MPA's. Since MPA's displace fishing effort outside of the MPA, there is little to no net increase in abundance. Further, as a control area, since fishermen are displaced to that area, it can never be a real control area.

Additionally, almost all of the published papers on MPAs equate evidence of spillover to areas outside MPAs to net increases in total abundance and catch (da Silva et al., 2015; Harmelin-Vivien et al., 2008; Di Lorenzo et al., 2020; Medoff et al., 2022). This assumption is not supported by either theory or empirical evidence. Because fish and/or larvae move, there will always be gradients in abundance near the edge of an MPA. However, it does not mean there are regional increases in abundance if the area outside has higher fishing pressure (Hilborn et al., 2025), nor that there is more catch simply because fish move from inside to outside. Net movement of eggs, larvae, or large fish from inside to outside is a necessary condition for regional abundance increases and benefits to catch, but numerous models (Botsford et al., 2003; Hilborn et al., 2006; White et al., 2011; White et al., 2013; Ovando et al., 2021) have found that to increase catch, overfishing must be taking place and the size of the MPAs must be matched to the movement of the fish. Overfishing is not occurring in California waters.

There is convincing evidence that fish inside MPA's are larger, and more fecund. However, fishery management regulations already set size limits on most species to address sustainability of populations. And, if larger fish are to be protected, regulations could increase species size, statewide, and not just in MPA's.

Tribal Petitions

While the idea of Tribal co-management of state MPA's merits consideration, such management should occur within the existing MPA's. Since the MLPAI process took much of the very best habitat for MPA designation, it is appropriate that tribal co-management occur in these areas for ceremonial and subsistence purposes.

Thank you for considering the views of the San Diego Fishermen's Working Group and the Alliance of Communities for Sustainable Fisheries.

[redacted]	[redacted]	[redacted]
Pete Halmay	Ken Bates & Linda Hildebrand	Alan Alward
President, SDFWG	Executive Directors CFRA	Co-Chair, ACSF

cc

California Fish and Game Commission

Department of Fish and Wildlife

Staci Lewis/OPC

From: Darren Gertler <[redacted]>
Sent: Monday, April 20, 2026 10:37 AM
To: FGC <FGC@fgc.ca.gov>
Cc: Christopher Killen <chris@allwaters.org>
Subject: Expanding MPA's is not the correct answer

Dear California Department of Fish and Wildlife,

My name is Darren Gertler I live and fish in and around Soquel CA, and I am a teacher, a father, and a lifelong fisherman. I am writing to express my support for the science-based denials of the proposed Marine Protected Area (MPA) expansion plans. Please listen to your educated and objective staff who have recommended denying the petitions that are trying to expand MPAS up and down our shared coastline.

California’s fisheries—both recreational and commercial—are widely recognized as some of the best managed in the world. This success is rooted in sound science, adaptive management, and a strong culture of stewardship among those who depend on these resources. Expanding MPAs beyond what science supports risks undermining that balance.

I am especially concerned about the long-term impact on future generations. If my 11-year-old daughter is not allowed to fish and meaningfully interact with her local waters, she risks growing up disconnected from the very environment we hope she will protect. She caught and cooked her first lingcod this weekend which will be an event she will remember for the rest of her life. It will guide her to protect and restore her environment. Direct experience with our nearshore ecosystems nurtures not only her ability to provide for herself, but also her sense of responsibility, respect, and advocacy for conservation and access.

Access to these waters helps cultivate the next generation of environmental stewards. Without that connection, we risk losing both the cultural and conservation-minded legacy that has made California a leader in fisheries management.

Thank you for considering my perspective.

Sincerely,
Darren Gertler

CALIFORNIA FISH AND GAME COMMISSION
RECEIVED 4/21/2026

1850

County of Santa Cruz

BOARD OF SUPERVISORS

701 OCEAN STREET, SUITE 500, SANTA CRUZ, CA 95060-4069
(831) 454-2200 FAX: (831) 454-3262 TDD/TTY - Call 711

MANU KOENIG FIRST DISTRICT
KIMBERLY DE SERPA SECOND DISTRICT
JUSTIN CUMMINGS THIRD DISTRICT
FELIPE HERNANDEZ FOURTH DISTRICT
MONICA MARTINEZ FIFTH DISTRICT

April 20, 2026

California Fish and Game Commission
1416 Ninth Street, Suite 1320
Sacramento, CA 95814

RE: Reaffirmation of Santa Cruz County Board of Supervisors' Opposition to Marine Protected Area Petition 2023-33MPA

Dear President Sklar, Vice President Anderson, and Members of the California Fish and Game Commission,

On behalf of the Santa Cruz County Board of Supervisors, I write in strong support of the California Department of Fish and Wildlife's Evaluation of the 2023 Decadal Management Review Marine Protected Area Petition's recommendation to **deny** Marine Protected Area Petition 2023-33MPA, which proposes to expand the State Marine Reserve (SMR) at Natural Bridges by 14.5 square miles and establish a new State Marine Conservation Area (SMCA) of approximately 3.2 square miles at Pleasure Point. The California Fish and Game Commission (CFGC) is scheduled to consider this petition on April 21, 2026, and we urge the Commission to reject it in its current form.

The Board first acted on this matter on March 12, 2024, voting unanimously to oppose the petition absent significant revisions. At that time, the Board identified four specific conditions that would need to be satisfied before further consideration was warranted:

1. Conduct studies to evaluate the specific factors influencing kelp forest expansion and contraction on the Central California Coast, including the role, if any, of recreational fishing activities.

2. Hold community outreach forums to inform the public about the purpose and scientific rationale for the proposed MPA changes.

3. Convene a regional stakeholder group, including scientists, environmentalists, fishers, indigenous tribes, and elected officials, to help determine appropriate designations and regulatory frameworks.

4. Identify specific areas where current management is failing to sustain kelp forests and prioritize MPA protections accordingly.

Unfortunately, the amended petition does not address the scientific and procedural deficiencies the Board identified. Since our 2024 action, the petitioners have met with the Third District office only once and to our knowledge have engaged minimal outreach with the broader community of stakeholders, including local fishers, Santa Cruz and Capitola City Councils, indigenous tribes, scientists, and residents directly affected by the proposed restrictions. This is not an acceptable foundation for regulations of this magnitude. For these reasons, on March 24, 2026, the Santa Cruz County Board of Supervisors unanimously voted to reaffirm their opposition to the creation of these two MPA's.

Our concerns fall into five principal areas:

1. Insufficient Scientific Evidence

The petition's central premise — that restricting recreational fishing will advance kelp forest health and expansion — is not supported by the available science. A December 2021 technical report on Monitoring and Evaluation of Kelp Forest Ecosystems in the MLPA Marine Protected Area Network found no substantial negative effect from current uses on average kelp canopy area in existing MPAs. Critically, the report found no effect of MPA status on kelp forest resilience during the 2014–2016 Marine Heat Wave, and found that existing Central Coast MPAs were evenly split between higher and lower resilience than nearby non-MPA reference sites. These findings do not support the conclusion that expanding MPAs in the proposed areas will reliably produce the outcomes the petitioners seek.

2. Proposed Areas Already Support Healthy Kelp Forests

The areas targeted by this petition contain persistent, stable kelp beds that recovered effectively from the 2014–2016 Marine Heat Wave. By focusing on sites where kelp is already thriving under current management, including existing recreational fishing activity, the petition undermines its own rationale. There is no data indicating that recreational fishing intensity in these areas is inhibiting kelp forest growth. Regulatory restrictions should be directed where management is demonstrably failing.

3. Significant Impacts on Recreational and Subsistence Fishing

A State Marine Reserve designation prohibits any taking or possession of living, geological, or cultural marine resources except under specific permits. Expansion of the

Natural Bridges SMR would curtail recreational and subsistence fishing opportunities for residents who depend on coastal access for recreation, cultural practice, and livelihood. While the amended petition proposes to create a State Marine Conservation Area that allows for shore-based recreational hook-and-line fishing and spearfishing (as opposed to the previously proposed SMR) we remain concerned that the designation will limit recreational and subsistence fishing opportunities in this area, where small vessels, kayaks, and paddle boards are also utilized for these purposes, and will provide no benefits that will improve kelp forest health through the new regulation.

The Santa Cruz region already carries significant protective designations through the Monterey Bay National Marine Sanctuary and multiple existing MPAs. Further restrictions, absent compelling and site-specific scientific justification, would impose disproportionate burdens on our community by further reducing access to marine ecosystems.

4. Inadequate Stakeholder Engagement and Public Outreach

Many residents first became aware of these proposals only when the item appeared on the Fish and Game Commission's agenda. A significant portion of the affected community remains uninformed of the proposed changes to this day. Sound environmental policy requires meaningful community engagement from the outset. That has not occurred here.

Santa Cruz County has a proud tradition of environmental stewardship grounded in balanced, evidence-based decision-making. We remain deeply committed to the health and resilience of our marine ecosystems. It is precisely because of that commitment that we cannot support a regulatory approach that lacks rigorous scientific justification, bypasses meaningful community participation, and imposes burdens on residents without a demonstrated need to do so.

5. Concurrence with Recommendations Proposed by Fish and Wildlife Staff

After reading the recommendations that were provided by Fish and Wildlife staff, we agree with their recommendations that overall the expansion of the Natural Bridges MPA would be unnecessary to achieve the goals of protecting kelp, which occurs mostly near shore, and the original intent of this particular MPA, which was designed to protect intertidal and nearshore habitats while minimizing socio-economic impacts. We also agree that the creation of the Pleasure Point MPA would be too small in nature to provide meaningful ecological impacts and instead impose socioeconomic impacts on residents and visitors to the region.

We respectfully urge the California Fish and Game Commission to deny Petition 2023-33MPA. If there are future efforts to expand MPA's in the Santa Cruz region, we hope to be notified of such changes and would encourage that any changes be driven by the scientific community, and include extensive community outreach and regional stakeholder engagement that the seriousness of these kinds of proposals demand. As a community that is a leader in environmental protection, we are committed to protecting our environment while balancing that with public access and we are always open and available to work with all parties to strike a healthy balance for both activities.

Thank you for your consideration of the Board's position.

Sincerely,

[redacted]

MONICA MARTINEZ, Chair
Santa Cruz County Board of Supervisors

Cc:
Senator Laird
Assemblymember Pellerin
Assemblymember Addis
Speaker Rivas
Mayor and City Council, City of Capitola
Mayor and City Council, City of Santa Cruz

From: mbcfo member <[redacted]>
Sent: Tuesday, April 21, 2026 02:57 PM
To: Miller-Henson, Melissa@FGC <Melissa.Miller-Henson@fgc.ca.gov>; FGC <FGC@fgc.ca.gov>
Subject: Peer reviewed studies show minimal if any benefit of MPAs.

Dear California Fish and Game Commission,

Before adding more MPA's, you should realize the science shows they are not increasing biodiversity, biomass and/or increasing resiliency against climate change- contrary to what you have been told.

1. MPA's do not add residency from heat waves.

2. MPA's do not increase biodiversity.

3. MPA's do not increase the total biomass densities or population levels.

If you want to help the sustainability of the commercial fishing community, give the fishermen back more valuable habitat to fish, put back the 2 month seasonal closure of the nearshore fishery during spawning, and perhaps try a slot size limit. Adding MPAs will only make things worse.

Tom Hafer

Secretary MBCFO

[redacted]

[redacted]

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Conservation Biology

CONTRIBUTED PAPERS

Assessing the population-level conservation effects of marine protected areas

Daniel Ovando[1] | **Jennifer E. Caselle**[2] | **Christopher Costello**[3,5] | **Olivier Deschenes**[3,4] | **Steven D. Gaines**[3,5] | **Ray Hilborn**[1] | **Owen Liu**[5]

[1] School of Aquatic and Fishery Sciences, University of Washington, Seattle, Washington, USA

[2] Marine Science Institute, University of California, Santa Barbara, Santa Barbara, California, USA

[3] Environmental Market Solutions Lab, University of California, Santa Barbara, Santa Barbara, California, USA

[4] Department of Economics, University of California, Santa Barbara, Santa Barbara, California, USA

[5] Bren School of Environmental Science and Management, University of California, Santa Barbara, Santa Barbara, California, USA

Correspondence
Daniel Ovando, School of Aquatic and Fishery Sciences, University of Washington, 1122 NE Boat Street, Seattle, WA 98195, USA.
Email: danovan@uw.edu

Article impact statement: Population-level conservation effects of marine protected areas are likely to be extremely challenging to measure and detect.

Abstract

Marine protected areas (MPAs) cover 3–7% of the world's ocean, and international organizations call for 30% coverage by 2030. Although numerous studies show that MPAs produce conservation benefits inside their borders, many MPAs are also justified on the grounds that they confer conservation benefits to the connected populations that span beyond their borders. A network of MPAs covering roughly 20% of the Channel Islands National Marine Sanctuary was established in 2003, with a goal of providing regional conservation and fishery benefits. We used a spatially explicit bioeconomic simulation model and a Bayesian difference-in-difference regression to examine the conditions under which MPAs can provide population-level conservation benefits inside and outside their borders and to assess evidence of those benefits in the Channel Islands. As of 2017, we estimated that biomass densities of targeted fin-fish had a median value 81% higher (90% credible interval: 23–148) inside the Channel Island MPAs than outside. However, we found no clear effect of these MPAs on mean total biomass densities at the population level: estimated median effect was –7% (90% credible interval: –31 to 23) from 2015 to 2017. Our simulation model showed that effect sizes of MPAs of <30% were likely to be difficult to detect (even when they were present); smaller effect sizes (which are likely to be common) were even harder to detect. Clearly, communicating expectations and uncertainties around MPAs is critical to ensuring that MPAs are effective. We provide a novel assessment of the population-level effects of a large MPA network across many different species of targeted fin-fish, and our results offer guidance for communities charged with monitoring and adapting MPAs.

KEYWORDS

bioeconomic modeling, causal inference, Channel Islands National Marine Sanctuary, marine conservation, marine protected area networks, program evaluation

Resumen

Las áreas marinas protegidas (AMPs) cubren entre 3–7% de los océanos del planeta y las organizaciones internacionales piden una cobertura del 30% para el 2030. Aunque numerosos estudios muestran que las AMPs producen beneficios de conservación dentro de sus límites, muchas de estas áreas también están justificadas por otorgarles beneficios de conservación a las poblaciones conectadas que abarcan más allá de sus fronteras. Una red de AMPs que cubre aproximadamente el 20% del Santuario Marino Nacional de las Islas del Canal fue establecida en 2003 con el objetivo de proporcionar beneficios para la conservación y las pesquerías regionales. Usamos un modelo de simulación bioeconómica

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espacialmente explícito y una regresión bayesiana de diferencia-en-diferencia para examinar las condiciones bajo las que las AMPs pueden proporcionar beneficios de conservación a nivel poblacional dentro y fuera de sus límites y para evaluar las evidencias de esos beneficios en las Islas del Canal. Hasta el 2017, estimamos que la densidad de la biomasa de los peces focalizados tuvo un valor medio de 81% (90% intervalo creíble 23–148) dentro de las AMPs de las Islas del Canal que fuera de ellas. Sin embargo, no encontramos un efecto claro de estas AMPs sobre la densidad de biomasa total promedio a nivel poblacional; el efecto medio estimado fue de -7% (90% intervalo creíble -31 - 23) entre 2015 y 2017. Nuestro modelo de simulación mostró que los tamaños del efecto de las AMPs menores al 30% tenían mayor probabilidad de ser difíciles de detectar (incluso cuando estaban presentes); los tamaños de efecto más pequeños (que es probable que sean comunes) fueron incluso más difíciles de detectar. Claramente, es muy importante comunicar las expectativas e incertidumbres en torno a las AMPs para asegurar que éstas sean efectivas. Proporcionamos una evaluación novedosa de los efectos a nivel poblacional de una red extensa de AMPs para muchas especies de peces focalizados y nuestros resultados ofrecen una guía para las comunidades encargadas de monitorear y adaptar las AMPs.

PALABRAS CLAVE
conservación marina, inferencia causal, modelo bioeconómico, programa de evaluación, redes de áreas marinas protegidas, Santuario Marino Nacional de las Islas del Canal

INTRODUCTION

No-take marine protected areas (MPAs), spatial regions of the ocean in which fishing is prohibited, have a long history in the management of marine resources (Johannes, 1978). Modern MPAs were first established largely as marine analogs to the terrestrial protection of iconic landscapes (IUCN, 1976). Recent international efforts to expand MPAs, such as The International Union for Conservation of Nature's 30% by 2030 MPA targets, are based in part on the assumption that well-designed MPAs will not only provide conservation benefits inside their borders, but also have broader conservation effects on unprotected areas surrounding the MPAs, whether MPAs are designed explicitly for conservation, fishery benefits, or both (Gaines et al., 2010).

The empirical MPA literature has focused on assessing the ability of MPAs to provide conservation gains within their borders (Lester et al., 2009; Edgar et al., 2014). However, as conservation benefits accrue inside MPAs, MPAs also affect the waters beyond their borders through the spillover of adult and larval fish from the protected to the fished areas, as well as through displacement of fishing effort. Therefore, MPAs contribute to local and regional population-level effects. Numerous factors influence the population-level effects of MPAs. These include the scale of adult and larval dispersal relative to the size of the MPAs (Gaines et al., 2003); strength, timing, and location of density dependence (Burgess et al., 2014); design of the network (Gaines et al., 2010; Rassweiler et al., 2014); degree of enforcement (Edgar et al., 2014); level of fishing pressure; time span under evaluation; and how fishing and management responds to the implementation of the MPAs (Walters et al., 2000; Botsford et al., 2003; Gerber et al., 2003; Smith & Wilen, 2003; Hilborn et al., 2004; Gaines et al., 2010; White et al., 2011; Moffitt et al., 2013; Ovando et al., 2016; Jaco & Steele, 2020).

This largely theoretical literature is generally based on modeling of closed populations with some fraction protected inside MPAs. In contrast to this population paradigm used in MPA simulations, MPAs are often evaluated empirically at local scales with spatial response ratios, commonly measured as the ratio of biomass densities (weight of organisms per unit area) of species inside relative to selected control sites outside MPAs (Halpern, 2003; Lester et al., 2009; Edgar et al., 2014; Caselle et al., 2015). These studies show clear evidence that well-enforced and sufficiently sized MPAs are associated with high response ratios. Several studies document empirical evidence for the existence of adult or larval fish spillover affecting fish abundance (Russ & Alcala, 1996; McClanahan & Mangi, 2000; Halpern et al., 2009; Kay et al., 2012). Where response ratios are available before and after MPA implementation, spatial before-after-control-impact (BACI) style studies show similarly clear and positive results (Thiault et al., 2019). These studies demonstrate the ability of MPAs to create differences between local fished and unfished areas.

What is lacking is clear evidence for the population-level effects of MPAs. Spatial inside-versus-outside studies rely on an assumption that selected control sites serve as a measure of what would have happened in the absence of MPAs. Habitat characteristics are often used to justify the selection of particular fished sites as counterfactuals (controls) in response ratios (Ferraro et al., 2019). However, beyond habitat differences, the very spillover effects it is hoped MPAs produce can negate the ability of spatial response ratio or BACI designs to accurately estimate the effects of MPAs because these methods require that control sites be conditionally unaffected by the treatment (Moffitt et al., 2013; Ferraro et al., 2019). Spillover of adults or larvae from MPAs to control sites can mask conservation benefits, whereas displacement of fishing effort from MPAs to control sites (which is rarely addressed directly

[Ferraro et al., 2019]) can lead to overestimates of conservation gains caused by MPAs measured by spatial response ratios. Control sites sufficiently far from MPAs to negate both spillover of fish or larvae and concentration of the fishing fleet could be selected, but finding suitably distant sites that are also appropriate proxies for the ecological and economic context of the MPAs is challenging. Because variations of spatial response ratios and BACI studies have been a primary source of evidence for the conservation effects of MPAs, this means empirical understanding of the population-level impacts of MPAs is surprisingly limited.

We conducted a paired theoretical and empirical assessment to examine the challenges of assessing population-level impacts of MPAs. In 2003, a network of MPAs was established in the Channel Islands National Marine Sanctuary, California (USA) (hereafter Channel Islands). This MPA network covers approximately 20% of the Channel Islands' waters (which span over 800 km^2). The network has been used as a model in protected area design around the world (Botsford et al., 2014). We used data from the first 14 years of protection in a difference-in-difference (DiD) model (Angrist & Pischke, 2009) to assess the population-level effect of a large MPA network on a wide array of fin-fish species. Rather than relying on spatial controls, we used groups of species targeted and not targeted by fishing pressure as our treatment and control groups. We built on existing MPA theory to interpret our results and devised guidance for scientists and managers as to when and how they might expect to detect population-level conservation effects of MPAs.

METHODS

We built a spatially explicit bioeconomic simulation model and conducted a Bayesian DiD regression. The DiD is akin to a BACI in that it is used to assess changes in control and treatment groups before and after treatment (Larsen et al., 2019). We used our bioeconomic simulation model to provide theoretical expectations of population-level effects of MPAs, which we then compared with the empirical results from our DiD regression.

All analyses were conducted in R (R Core Team, 2019). Our DiD regression was fit with Stan (Carpenter et al., 2017) through the rstanarm package (Goodrich et al., 2020). All data and code needed to fully replicate our study are publicly available from github.com/DanOvando/population-effects-of-mpas. Detailed descriptions of the simulation model structure and sensitivity analyses of our estimation model are in Appendix S2.

Simulation model

Our bioeconomic model simulated the effect of MPAs on a spatially explicit age-structured representation of a fish population. Readers can explore the functionality of the model with the online tool available from danovando.shinyapps.io/simmpa/. The purpose of the simulation model was to set expectations for our empirical results and demonstrate the ways in which ecological and economic dynamics can interact to produce a wide range of population-level MPA effects. The full range of factors explored and the equations of the simulation model are in Appendix S2. We used this model to generate 10,168 simulated MPA outcomes across 7618 species.

Many authors have presented simulation analyses of MPA outcomes (Fulton et al., 2015). Our model incorporates core ecological and economic drivers of MPA performance assessed by these individual authors into a cohesive model, similar in spirit to Krueck et al. (2017). The simulation model consisted of 50 patches with wrapped edges. For each simulation, we first randomly pulled a species and its associated life-history traits from the FishLife (Thorson et al., 2017) package. We paired these data with randomly selected values governing the characteristics of the simulation (Appendix S2). Key choices available to the model include parameters governing fishing pressure and MPA design. For a given simulation, the model randomly selected a fleet model and fishing effort allocation strategy. The fleet model could be either constant catch (fleet exerts as much effort as needed to maintain a fixed amount of catch), constant effort (fleet maintains a constant amount of effort over time), or open access (fishing effort of fleet expands and contracts in response to available profits). The total fishing effort exerted by the fleet was then distributed in space uniformly, in proportion to spatial catch per unit effort or in proportion to spatial profit per unit effort.

The simulation then applied the fleet model to the population, and in a randomly selected year implemented an MPA network. The model sampled a percentage of the population's range to place in MPAs, and randomly assigned patches to MPAs either across a uniform system or preferentially on higher quality habitat. The model then randomly selected whether fishing effort that used to operate inside the MPAs was redistributed to areas outside the MPAs or left the fishery entirely. We then continued the simulations with the MPAs in place. Each simulation was paired with a simulation identical in every way except that MPAs were not implemented (i.e., a simulated control). Using these paired simulations, we calculated the effect of the MPAs on the population as the difference between biomass densities in the simulation with MPAs and biomass densities in the simulation without MPAs.

These simulation results provided a library of plausible MPA effects for a range of biological and economic assumptions. One set of simulations was specifically designed to reflect the dynamics of the subset of species available in the Partnership for Interdisciplinary Studies of Coastal Oceans (PISCO), which provided the data from the Channel Islands that we used in this study. For this set, we only included species of the same genus as those targeted by fishing in the PISCO data. We also restricted fishing pressure such that the simulated populations were moderately to lightly exploited (because the PISCO data we used exclude deeper water species, such as boccacio [*Sebastes paucispinis*], which were overexploited at the inception of the MPAs, and threatened invertebrates, such as red abalone [*Haliotis rufescens*]), and capped the MPA size at 20% of the population's range (Rassweiler et al., 2012). For each of these Channel Islands

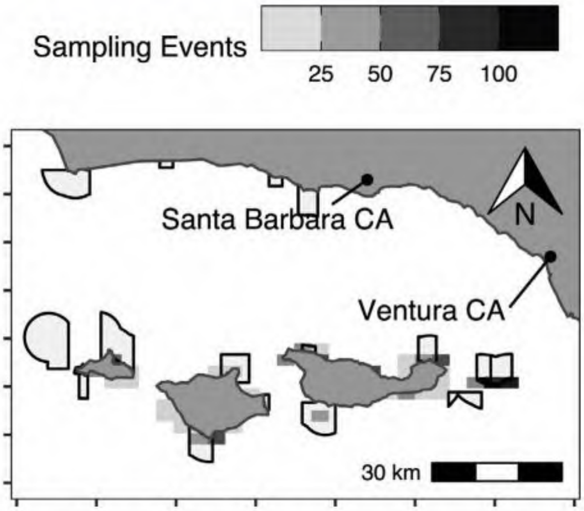

FIGURE 1 Map of the study region in the Northern Channel Islands, California (USA) (shading, binned number of Partnership for Interdisciplinary Studies of Coastal Oceans [PISCO] sampling events over the study period)

simulations, we calculated the true population-wide difference in biomass between the simulations with and without the MPAs and the response ratio of biomass densities inside and outside the simulated MPAs. We then calculated the response ratios observed in the PISCO survey data from the Channel Islands and matched these empirical results with simulations that produced similar response ratios after the same number of years of MPA protection. Because each simulation included measures of both response ratios and population-level effects, this process provided a library of simulations (and their associated attributes) that could have produced the types of empirical response ratios measured in the Channel Islands.

Difference-in-difference regression

We used kelp forest survey data from the PISCO surveys in the Channel Islands in the DiD analyses. Divers from PISCO conducted visual scuba surveys at a large number of rocky reef and kelp forest sites inside and outside MPAs throughout the Channel Islands to produce estimates of densities of fishes that are both targeted and nontargeted by fishers (Figures 1 and 2). The details of the monitoring program are described in Caselle et al. (2015). We defined the population-level conservation effects of MPAs as the change in mean total biomass densities of targeted fin-fish inside and outside MPAs relative to the mean total biomass densities of targeted fin-fish inside and outside MPAs that would have occurred without the MPAs.

Building on Caselle et al. (2015), we used an identification strategy in which 11 species not directly targeted by fishing comprised the control group (nontargeted) and 12 species targeted by fishing comprised the treatment group (Figure 2). We then measured differences between the trends of biomass densities of the treated group relative to the trends we would have expected based on the biomass densities of the control group. Data on targeted fin-fish species in the Channel Islands available to this study included California sheephead (*Semicossyphus pulcher*) and copper (*Sebastes caurinus*) and blue rockfish (*Sebastes mystinus*). Nontargeted species included garibaldi (*Hypsypops rubicundus*), halfmoons (*Medialuna californiensis*), and blacksmith (*Chromis punctipinnis*). Our regression estimated any difference in mean total biomass densities of fin-fish species targeted by fishing effort (i.e., those potentially affected by an MPA) and those species not targeted by fishing before and after MPA implementation. To account for the fact that sampling locations were not uniformly distributed across the islands, we weighted the samples in our regression in proportion to the total area inside and outside the MPAs.

This identification strategy attempted to control for unobserved environmental shocks to the system that are independent of the MPAs. Conditional on the assumptions of the model, this regression produced an estimate of the effect of the MPAs on the mean total biomass densities of targeted species throughout the Channel Islands. For example, consider an evenly distributed population that has 50% of its range protected by an MPA. If the MPA increased biomass densities by 20% insides its boundaries, but had a 0% effect on the connected population outside its boundaries, the population effect of the MPA estimated by our DiD would be 10%.

The DiD regression amounts to estimating the pre- and post-MPA difference in the biomass densities of targeted species, minus the same difference for nontargeted species in the Channel Islands:

$$\begin{aligned}&\left[\log\left(D_{\mathrm{MPA}=1,T=1}\right)-\log\left(D_{\mathrm{MPA}=0,T=1}\right)\right]\\&-\left[\log\left(D_{\mathrm{MPA}=1,T=0}\right)-\log\left(D_{\mathrm{MPA}=0,T=0}\right]\right)\end{aligned}\qquad(1)$$

where T is targeted ($T = 1$) or nontargeted ($T = 0$) by fishing, MPA indicates whether the data are pre-MPA (0) or post-MPA (1), and D is the observed mean total biomass density across all observations of the appropriate group.

The expanded DiD regression is

$$\begin{aligned}&d_i \sim \mathit{Gamma}\left(e^{\beta_0+\beta_1 T_i+\beta_2 \mathrm{MPA}_i+\beta_3 T_i \mathrm{MPA}_i+\mathbf{B}^c\mathbf{X}_i+\mathbf{B}^s S_i}, \mathrm{shape}\right)\\&\mathbf{B}^s \sim \mathit{Normal}(\beta_r, \sigma_r)\end{aligned}\qquad(2)$$

where d_i is the biomass density at observation i. To account for the fact that MPA effects evolve over time, we estimated a vector of MPA effects in 3-year blocks for all years after the MPAs were implemented in 2003. The $\mathbf{B}^c$ is a vector of coefficients for additional control variables in matrix $\mathbf{X}$, such as water temperature and observer experience, and $\mathbf{B}^s$ is a vector of hierarchical coefficients for each sampling location S, clustered by island β_r with variance σ_r^2. Under the assumptions of this model, β_3 is the causal effect of the treatment (MPA = 1) on the treated targeted group ($T = 1$) (Appendix S4). We used a Bayesian hierarchical generalized linear model because it allowed us to interpret our estimated effects probabilistically. Being a Bayesian regression, our DiD analysis produced posterior probability distributions (the probability distribution of our coefficients conditional on the data, priors, and model assumptions) of our

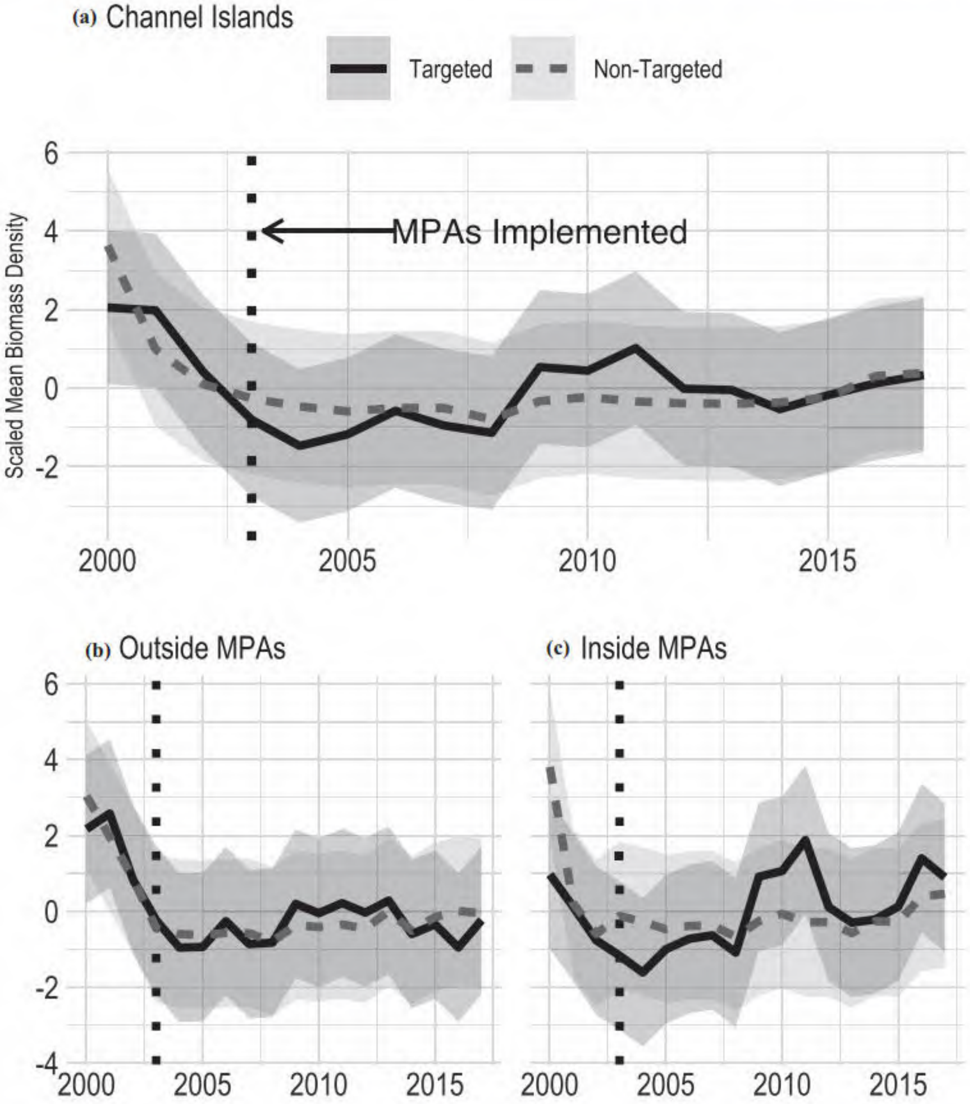

FIGURE 2 Centered and scaled trends in biomass densities of targeted (solid lines) and nontargeted (dashed lines) fin-fish included in our study of the Channel Islands Marine Protected Area (MPA) network: (a) mean trends across all sites and the same trends for sites only (b) outside and (c) inside MPAs (shaded areas, 95% confidence intervals; vertical dotted line, MPA implementation in 2003)

coefficients, from which we constructed Bayesian credible intervals (also termed *uncertainty* or *compatibility* intervals) (Gelman, 2014; McElreath, 2020).

Simulating difference-in-difference performance

Our library of simulation results allowed us to explore how accurate estimates of population-level MPA effects generated by a DiD regression in the style used here are likely to be under a plausible set of scenarios. We fitted a simplified DiD regression to data generated from simulation results that spanned a range of observation error and degrees of autocorrelated recruitment variation and allowed for potentially negatively correlated recruitment shocks between targeted and nontargeted species. We then estimated the percent error between the posterior probability distribution of the estimated MPA effect from the regression and the true simulated MPA effect and examined how the error in the DiD estimate changed as a function of the true simulated MPA effect.

RESULTS

Updating the results of Caselle et al. (2015) with data collected through 2017, we found an increasing but fluctuating trend in the empirical response ratios of targeted species (Figure 3). We then compared these empirical response ratios to the population-level effects generated by simulated MPAs that had simulated response ratios similar to those observed in the data.

Simulations of the Channel Island MPAs that produced response ratios over 50% had a median simulated population-level effect on total biomass of 2.5% (90% of which fell between 0% and 24%). This means that in the majority of simulations, response ratios >50% were produced by population-level

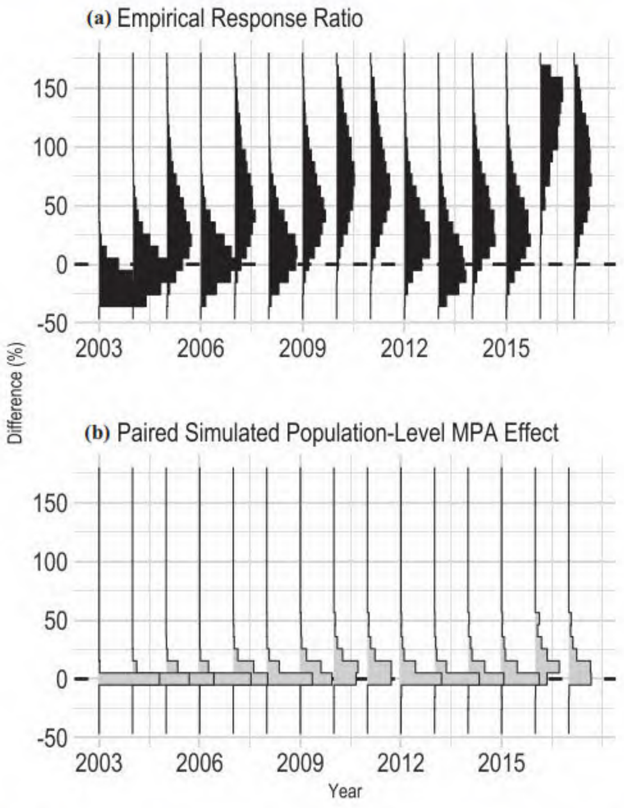

FIGURE 3 For the Channel Islands Marine Protected Area (MPA), (a) empirically observed 90% posterior probability distributions of response ratios of biomass densities inside MPAs relative to biomass densities outside MPAs (0%, biomass densities of targeted species identical inside and outside MPAs; 100%, biomass densities 100% greater inside MPAs than outside) and (b) simulated population-level effects on biomass densities of fin-fish matched to empirical response ratios that could have produced observed response ratios in (a) (0% difference, biomass densities are identical in the with- and without-MPA scenarios; 100% difference, biomass densities are 100% greater in the scenario with MPAs than the scenario without)

effects of <10%, measured as a percent gain in total population biomass inside and outside MPAs.

Over the first 3 years of implementation (2003–2006), the effects of the MPAs were unclear. The median estimated population-level effect over this period was 31%. There was statistical support for a small (3%, bottom 5th percentile of the posterior probability distribution) to large (>69%, top 95th percentile of the posterior probability distribution) effect.

From 2006 to 2012, the model estimated greater probabilities of an increasingly positive MPA effect that peaked in 2009–2011. The median estimate of the population-level MPA effect in this period was a 79% increase in mean total biomass density of targeted species (90% credible interval, 40–133) (Figure 4). These estimates were in line with outcomes our simulation model suggested were plausible. However, in the subsequent years the trend reversed, and in 2015–2017 there was once again no clear effect of the MPAs (median estimated effect, −7%; 90% credible interval, −31 to 23) (Figure 4).

Turning to our assessment of the ability of the kind of DiD model employed here to detect the true population-level effect of an MPA network, the percent error in the DiD regression's estimate of the population-level MPA effect was extremely high when MPA effect sizes were <25%, and the model had both observation and process errors in the simulated data (Figure 5). Even models fitted to data generated from large effect sizes commonly mis-estimated the true MPA effect by 50% or more. Obtaining a mean absolute percent error (MAPE) of 25% or less across our simulated data sets required a true population-level MPA effect of at least 30%.

Two of the most critical drivers of MPA effect size were the size of the MPA network and the degree of fishing pressure (Figure 6). Based on our simulations, the MPA network had to be large (25% or more of a species' range) and the target species overfished (pre-MPA depletion >60%) to achieve an effect size with a likely MAPE of 25% or less (Figures 5 and 6).

DISCUSSION

Containing a carefully designed, well-enforced, and well-studied MPA network, the Channel Islands seems to be an ideal location to study the population-level effects of protected areas. But, in contrast to clear differences in biomass densities observed inside and outside well-protected MPAs, both globally (Lester et al., 2009) and in the Channel Islands (Caselle et al., 2015) we were unable to detect a clear population effect from the Channel Islands MPAs.

Caselle et al. (2015) found a statistically significant increase in the response ratios of targeted species over time and evidence that this increase is smaller for nontargeted species. We found a similar increasing trend in the response ratios of targeted species (Figure 3). This provides evidence that the Channel Islands MPAs are large enough and sufficiently well-enforced as to provide meaningful protection within their borders (White et al., 2020). These response ratios cannot, however, be used as a definitive indicator of population-level effects of these MPAs. In the case of the Channel Islands MPAs, control sites were often located within a few kilometers of an MPA, making them susceptible to both biological spillover and concentration of fishing effort excluded from the MPAs. According to our simulations, the response ratio trends we observe in the data could plausibly be produced by a wide range of population-level MPA effects, the majority of which were <10% (Figure 3). This can occur if, for example, fishing pressure is moderate, adult movement is low, larval dispersal is high, and displaced fishing effort concentrates around the border of the MPAs.

Our targeted versus nontargeted DiD regression provides an alternative approach to spatial controls for estimating population-level MPA effects that does not rely on the assumption that MPAs do not affect control sites, a required assumption of spatial response ratios. Although we estimated an uncertain but overall positive effect of the MPA network in its first few years of existence, we were unable to detect a robust signal from 2012 to 2017. We found that given the dynamics of the Channel Islands, particularly given the lack of heavily exploited species (e.g., abalone and deep-water rockfish), that helped motivate the Channel Island MPAs in the available data, this result was to be expected. After 14 years of MPA

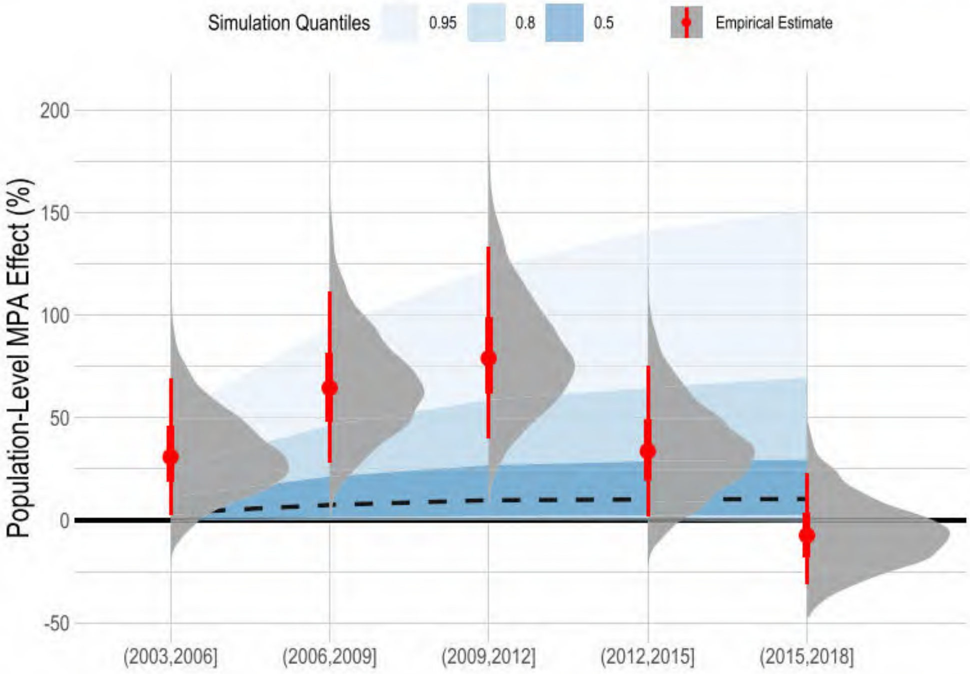

FIGURE 4 Results of difference-in-difference regression estimating the population-level effect of the Channel Island Marine Protect Area (MPA) on mean total biomass densities of targeted species. Gray distributions show posterior probability distribution of estimated MPA effect; red point is median estimated effect, thicker red line 50% credible interval, and thinner red line 90% credible interval. Blue distributions in background show range of MPA effects produced by simulation model tuned to reflect the dynamics of the Channel Island MPAs (black dashed line is median simulated value). Results are estimated in blocks of 3 years, with notation of (2003,2006] indicating that that block includes years ≥2003 and <2006. MPAs were implemented in 2003

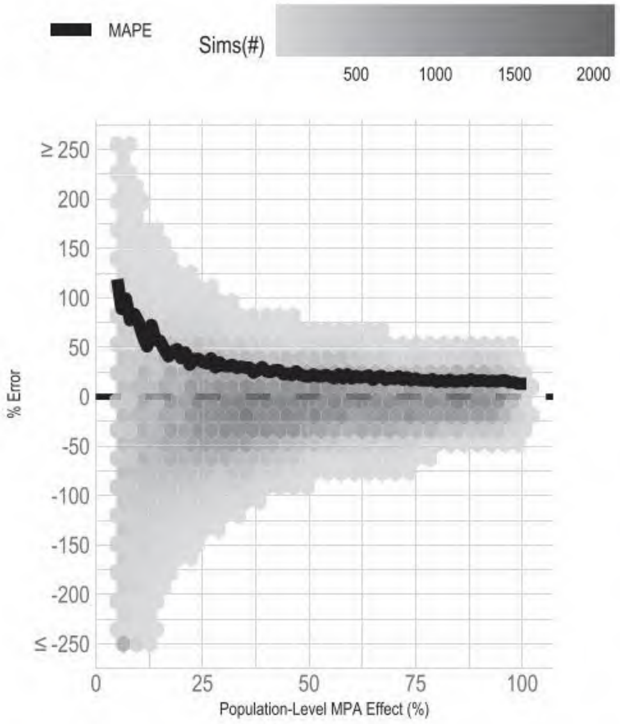

FIGURE 5 Distribution of percent error (y-axis) in posterior estimates of population-level marine protected area effect relative to true simulated MPA effect (x-axis). Shading shows concentration of simulations. Black line shows mean absolute percent error (MAPE) as a function of simulated population-level MPA effect

protection, there is no clear picture of the population-level effect of the Channel Island MPA network on biomass densities of targeted fin-fish.

Fishing dynamics may be one factor contributing to a lack of strong MPA network effects. Much of the theoretical literature on MPAs is based on the assumption that larger reserves produce larger conservation gains (White et al., 2011). However, these models generally simulate fleet dynamics through fishing mortality rates; that is, the proportion of total mortality experienced by a population attributable to fishing pressure (e.g., Halpern et al. 2004). Alternatively, under a constant-catch strategy, fishers have a catch objective and exert as much (or little) effort as needed to achieve that objective. Subsistence fishers may use a constant-catch style policy over the short term if they seek to ensure that food needs are met. Constant-catch dynamics might also occur in fisheries with constraining quotas that are not updated after the implementation of MPAs. Fishers pursuing a constant-catch strategy in areas outside an MPA may have to fish harder to achieve the same catch from a smaller part of the population, causing a population loss under 70% of our constant-catch simulations. This potential negative interaction between constant catch and MPAs is an important risk to consider (as done in Little et al. [2011]), especially because MPAs are increasingly implemented in quota-managed fisheries (Liu et al., 2018). We did not have access to fine-scale fishing data from the Channel Islands alone, but reported catches for the species of interest in the Santa Barbara region exhibited a mix of stable, downward, and upward trajectories (Appendix S3), which

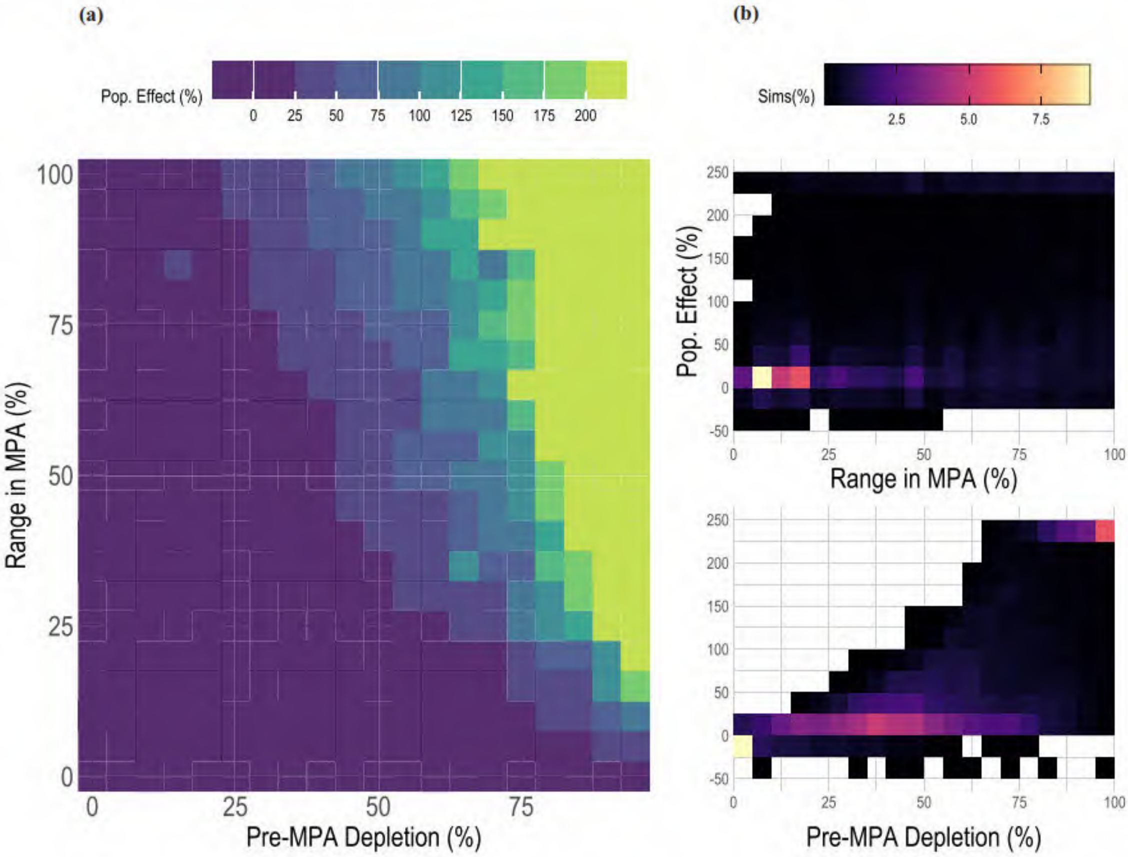

FIGURE 6 Simulated population-level effects of marine protected areas (MPAs). (a) Median simulated fin-fish population-level (pop.) MPA effect sizes (percent change in total biomass) as a function of percentage of species' range inside MPA (*y*-axis) and pre-MPA depletion (*x*-axis). Pre-MPA depletion is a measure of fishing pressure, where 0% means the population is unfished and 100% means the population is extinct in the period immediately prior to MPA implementation. (b) Distribution of simulations across range of MPA sizes and pre-MPA depletions, shown separately

indicates that a negative MPA effect caused by a constant-catch fishing strategy is unlikely.

Environmental disturbance is another possible explanation for the decline in the population-level effects of Channel Islands MPA estimated by our model. The Channel Islands region experienced a dramatic marine heatwave beginning in 2014 and persisting through 2016, resulting in part in extremely elevated water temperatures throughout the region (Gentemann et al., 2017). Many of the nontargeted species in the Channel Islands have warm thermal affinities and have increased in numbers since the heatwave (Freedman et al., 2020). The targeted group is made up mostly of fishes with cold-water affinities. In the presence of this marine heatwave, the nontargeted species may no longer serve as an effective control for the evolution of biomass densities of targeted fin-fish in the absence of the MPAs, given the magnitude of the environmental shock relative to the size of the population-level MPA effect.

All of the species in this empirical analysis may affect each other through mechanisms such as predation, competition, and habitat modification. We used convergent cross mapping (CCM), in the manner of Clark et al. (2015), to test for significant dynamic interactions between species and therefore the possibility of the trophic cascades biasing our results. We found no significant cross-mappings between targeted and nontargeted species, indicating that although clearly there were interactions between these groups on some level, the effects within the time span of the data were not pronounced enough to affect our results (Appendix S7). However, the longer MPAs are in place, the greater the possibility that substantial species interactions that can affect use of nontargeted species as a control may arise.

As the number and size of global MPA networks increase, we must set appropriate expectations for their outcomes on both local and regional scales. Simulation modeling can help inform the range of effect sizes that may be expected, and monitoring programs can be tuned to focus on the species groups that have the highest chance of a detectable effect size over the early years of the reserve (Nickols et al., 2019). Expanding data collection to include robust monitoring of spatiotemporal fleet dynamics may help assess the validity of control sites used in response ratios, support the direct inclusion of these fleet dynamics into statistical models, and allow managers to take into account potential negative interactions between MPAs and fleet dynamics, such as those that may occur under constant-catch dynamics. Whenever possible monitoring programs should be implemented prior to MPA implementation to provide a pretreatment benchmark.

There are many potential alternatives to spatial response ratios for estimating the population effects of MPAs that better account for the challenges of causal inference (though that may be more data intensive) (Larsen et al., 2019). We applied one such approach here, yet we were still unable to reach robust conclusions as to the effect of MPAs on the total biomass density of targeted fin-fish in the Channel Islands, due to the likely small size of the true effect relative to the influence of environmental variability. In the context of the moderately exploited species in the Channel Islands PISCO data, our simulation testing suggests that we should not have been surprised at our difficulty in precisely estimating the population-level effect of the MPAs. There are other promising statistical approaches to setting expectations for MPA effects, including using models fitted to local data to set population-level expectations and create synthetic counterfactuals (White et al., 2011; Nickols et al., 2019).

The scientific community must effectively communicate the challenges of estimating the population-level effects of MPAs. Lack of a clear population-level MPA effect should not necessarily be viewed as a failure of a conservation program, and, likewise, large response ratios should not be automatically taken as evidence of a population-level conservation success. Rather, results and subsequent management actions must be considered in the context of reasonable expectations given the size, age, and degree of enforcement of the MPAs in question, together with the ecological and economic dynamics of a given system. Although recently some extremely large MPAs have been enacted that may indeed reach into the higher levels of MPA coverage, most MPA networks for near-shore commercial finfish are likely to cover areas more in line with the Channel Islands (20%) or smaller. As such, many MPA networks are expected to have population-level effect sizes that are difficult to detect unless the target species would have been extremely overfished without the protection of MPAs (Figure 6a).

As advocacy for large networks of MPAs grows around the world, MPA scientists must directly tackle the challenge of evaluating the performance of MPAs at the population scale. Commonly employed metrics, such as spatial response ratios, may be applicable in some circumstances, but are vulnerable to inaccuracy or misuse as metrics of population-level effects. Bioeconomic modeling can help frame community expectations, reducing the potential for a reduction in support if unrealistic conservation or fishery expectations are not realized. Statistical approaches that explicitly address complications, such as the spatial spillover effects of MPAs, may give users an improved understanding of the performance of their MPAs, but even they may struggle when expected effect sizes are small. Clearly communicating what to expect from and what can be detected from MPAs is critical to ensuring that MPAs play effective roles in fisheries management and marine conservation.

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ORCID

Daniel Ovando https://orcid.org/0000-0003-2120-7345

LITERATURE CITED

Angrist, J. D., & Pischke, J.-S. (2009). *Mostly harmless econometrics: An empiricist's companion*. Princeton University Press.

Botsford L. W., Micheli F., & Hastings A. (2003). Principles for the design of marine reserves. *Ecological Applications*, *13*, 25–31.

Botsford, L. W., White, J. W., Carr, M. H., & Caselle, J. E. (2014). Marine protected area networks in California, USA. In M. L. Johnson & J. Sandell (Eds.), *Advances in marine biology* (pp. 205–251). Academic Press.

Burgess S. C., Nickols K. J., Griesemer C. D., Barnett L. A. K., Dedrick A. G., Satterthwaite E. V., Yamane L., Morgan S. G., White J. W., & Botsford L. W. (2014). Beyond connectivity: How empirical methods can quantify population persistence to improve marine protected-area design. *Ecological Applications*, *24*, :257–270.

Carpenter B., Gelman A., Hoffman M. D., Lee D., Goodrich B., Betancourt M., Brubaker M., Guo J., Li P., & Riddell A. (2017). *Stan*: a probabilistic programming language. *Journal of Statistical Software*, *76*, 1–32.

Caselle J. E., Rassweiler A., Hamilton S. L., & Warner R. R. (2015). Recovery trajectories of kelp forest animals are rapid yet spatially variable across a network of temperate marine protected areas. *Scientific Reports*, *5*:14102.

Clark A. T., Ye H., Isbell F., Deyle E. R., Cowles J., Tilman G. D., & Sugihara G. (2015). Spatial convergent cross mapping to detect causal relationships from short time series. *Ecology*, *96*, :1174–1181.

Edgar G. J., Stuart-Smith R. D., Willis T. J., Kininmonth S., Baker S. C., Banks S., Barrett N. S., Becerro M. A., Bernard A. T. F., Berkhout J., Buxton C. D., Campbell S. J., Cooper A. T., Davey M., Edgar S. C., Försterra G., Galván D. E., Irigoyen A. J., Kushner D. J., … Thomson R. J. (2014). Global conservation outcomes depend on marine protected areas with five key features. *Nature*, *506*, :216–220.

Ferraro, P. J., Sanchirico, J. N., & Smith, M. D. (2019). Causal inference in coupled human and natural systems. *Proceedings of the National Academy of Sciences of the United States of America*, *116*(12), 5311–5318.

Freedman R. M., Brown J. A., Caldow C., & Caselle J. E. (2020). Marine protected areas do not prevent marine heatwave-induced fish community structure changes in a temperate transition zone. *Scientific Reports*, *10*:21081.

Fulton E. A., Bax N. J., Bustamante R. H., Dambacher J. M., Dichmont C., Dunstan P. K., Hayes K. R., Hobday A. J., Pitcher R., Plagányi Év. E., Punt A. E., Savina-Rolland M., Smith A. D. M., & Smith D. C. (2015). Modelling marine protected areas: insights and hurdles. *Philosophical Transactions of the Royal Society B: Biological Sciences*, *370*:20140278.

Gaines S. D., Gaylord B., & Largier J. L. (2003). Avoiding current oversights in marine reserve design. *Ecological Applications*, *13*, :32–46.

Gaines S. D., White C., Carr M. H., & Palumbi S. R. (2010). Designing marine reserve networks for both conservation and fisheries management. *Proceedings of the National Academy of Sciences*, *107*, :18286–18293.

Gelman, A. (2014). *Bayesian data analysis* (3rd ed.). CRC Press.

Gentemann C. L., Fewings M. R., & García-Reyes M. (2017). Satellite sea surface temperatures along the West Coast of the United States during the 2014–2016 northeast Pacific marine heat wave. *Geophysical Research Letters*, *44*, :312–319.

Gerber L. R., Botsford L. W., Hastings A., Possingham H. P., Gaines S. D., Palumbi S. R., & Andelman S. (2003). Population models for marine reserve design: A retrospective and prospective synthesis. *Ecological Applications*, *13*, :47–64.

Goodrich, B., Ali, I., & Brilleman, S. (2020). rstanarm: Bayesian applied regression modeling via Stan. http://mc-stan.org/.

Halpern B. S. (2003). The impact of marine reserves: do reserves work and does reserve size matter? *Ecological Applications*, *13*, :117–137.

Halpern B. S., Gaines S. D., & Warner R. R. (2004). Confounding effects of the export of production and the displacement of fishing effort from marine reserves. *Ecological Applications*, *14*, :1248–1256.

Halpern B. S., Lester S. E., & Kellner J. B. (2009). Spillover from marine reserves and the replenishment of fished stocks. *Environmental Conservation*, *36*, :268–276.

Hilborn, R., Stokes, K., Maguire, J. J., Smith, T., Botsford, L. W., Mangel, M., Orensanz, J., Parma, A., Rice, J., Bell, J., Cochrane, K. L., Garcia, S., Hall, S. J., Kirkwood, G. P., Sainsbury, K., Stefansson, G., & Walters, C. (2004). When can marine reserves improve fisheries management? *Ocean & Coastal Management*, *47*:197–205.

International Union for Conservation of Nature (IUCN). (1976). IUCN yearbook, 1975–76: annual report of the International Union for Conservation of Nature and Natural Resources for 1975 and for *January-May 1976*. https://portals.iucn.org/library/node/5984

Jaco E. M., & Steele M. A. (2020). Pre-closure fishing pressure predicts effects of marine protected areas. *Journal of Applied Ecology*, *57*:229–240.

Johannes R. E. (1978). Traditional marine conservation methods in Oceania and their demise. *Annual Review of Ecology and Systematics*, *9*:349–364.

Kay M. C., Lenihan H. S., Kotchen M. J., & Miller C. J. (2012). Effects of marine reserves on California spiny lobster are robust and modified by fine-scale habitat features and distance from reserve borders. *Marine Ecology Progress Series*, *451*:137–150.

Krueck N. C., Ahmadia G. N., Possingham H. P., Riginos C., Treml E. A., & Mumby P. J. (2017). Marine reserve targets to sustain and rebuild unregulated fisheries. *PLOS Biology*, *15*:e2000537.

Larsen A. E., Meng K., & Kendall B. E. (2019). Causal analysis in control–impact ecological studies with observational data. *Methods in Ecology and Evolution*, *10*:924–934.

Lester S. E., Halpern B. S., Grorud-Colvert K., Lubchenco J., Ruttenberg B. I., Gaines S. D., Airamé S., & Warner R. R. (2009). Biological effects within no-take marine reserves: A global synthesis. *Marine Ecology Progress Series*, *384*:33–46.

Little, L. R., Grafton, R. Q., Kompas, T., Smith, A. D. M., Punt, A. E., & Mapstone, B. D. (2011). Complementarity of no-take marine reserves and individual transferable catch quotas for managing the line fishery of the great barrier reef. *Conservation Biology*, *25*:333–340.

Liu O. R., Kleisner K. M., Smith S. L., & Kritzer J. P. (2018). The use of spatial management tools in rights-based groundfish fisheries. *Fish and Fisheries*, *19*:821–838.

Mcclanahan T. R., & Mangi S. (2000). Spillover of exploitable fishes from a marine park and its effect on the adjacent fishery. *Ecological Applications*, *10*:1792–1805.

McElreath, R. (2020). *Statistical rethinking: A Bayesian course with examples in R and Stan* (2nd ed.). CRC Press.

Moffitt E. A., White J. W., & Botsford L. W. (2013). Accurate assessment of marine protected area success depends on metric and spatiotemporal scale of monitoring. *Marine Ecology Progress Series*, *489*:17–28.

Nickols K. J., White J. W., Malone D., Carr M. H., Starr R. M., Baskett M. L., Hastings A., & Botsford L. W. (2019). Setting ecological expectations for adaptive management of marine protected areas. *Journal of Applied Ecology*, *56*:2376–2385.

Ovando D., Dougherty D., & Wilson J. R. (2016). Market and design solutions to the short-term economic impacts of marine reserves. *Fish and Fisheries*, *17*:939–954.

R Core Team. (2019). *R: a language and environment for statistical computing*. R Foundation for Statistical Computing. http://www.R-project.org/

Rassweiler A., Costello C., Hilborn R., & Siegel D. A. (2014). Integrating scientific guidance into marine spatial planning. *Proceedings of the Royal Society B: Biological Sciences*, *281*:20132252.

Rassweiler A., Costello C., & Siegel D. A. (2012). Marine protected areas and the value of spatially optimized fishery management. *Proceedings of the National Academy of Sciences*, *109*:11884–11889.

Russ G. R., & Alcala A. C. (1996). Do marine reserves export adult fish biomass? Evidence from Apo Island, central Philippines. *Marine Ecology Progress Series*, *132*:1–9.

Smith M. D., & Wilen J. E. (2003). Economic impacts of marine reserves: the importance of spatial behavior. *Journal of Environmental Economics and Management*, *46*:183–206.

Thiault L., Kernaléguen L., Osenberg C. W., Lison De Loma T., Chancerelle Y., Siu G., & Claudet J. (2019). Ecological evaluation of a marine protected area network: a progressive-change BACIPS approach. *Ecosphere*, *10*:e02576.

Thorson J. T., Munch S. B., Cope J. M., & Gao J. (2017). Predicting life history parameters for all fishes worldwide. *Ecological Applications*, *27*:2262–2276.

Walters C., Pauly D., Christensen V., & Kitchell J. F. (2000). Representing density dependent consequences of life history strategies in aquatic ecosystems: EcoSim II. *Ecosystems*, *3*:70–83.

White J. W., Botsford L. W., Baskett M. L., Barnett L. A. K., Barr R. J., & Hastings A. (2011). Linking models with monitoring data for assessing performance of no-take marine reserves. *Frontiers in Ecology and the Environment*, *9*:390–399.

White J. W., Yamane M. T., Nickols K. J., & Caselle J. E. (2020). Analysis of fish population size distributions confirms cessation of fishing in marine protected areas. *Conservation Letters*, *14*(2), e12775.

SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section at the end of the article.

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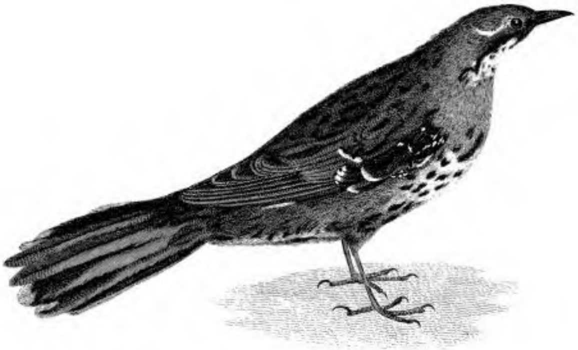

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RESEARCH ARTICLE

A marine protected area network does not confer community structure resilience to a marine heatwave across coastal ecosystems

Joshua G. Smith[1,2] | Christopher M. Free[3,4] | Cori Lopazanski[1,3] | Julien Brun[1] | Clarissa R. Anderson[5] | Mark H. Carr[6] | Joachim Claudet[7] | Jenifer E. Dugan[4] | Jacob G. Eurich[1,8] | Tessa B. Francis[9] | Scott L. Hamilton[10] | David Mouillot[11,12] | Peter T. Raimondi[6] | Richard M. Starr[10] | Shelby L. Ziegler[13] | Kerry J. Nickols[14] | Jennifer E. Caselle[4]

[1]National Center for Ecological Analysis and Synthesis, University of California, Santa Barbara, Santa Barbara, California, USA
[2]Conservation and Science Division, Monterey Bay Aquarium, Monterey, California, USA
[3]Bren School of Environmental Science and Management, University of California, Santa Barbara, Santa Barbara, California, USA
[4]Marine Science Institute, University of California, Santa Barbara, Santa Barbara, California, USA
[5]Scripps Institution of Oceanography/Southern California Coastal Ocean Observing System, University of California, San Diego, La Jolla, California, USA
[6]Department of Ecology and Evolutionary Biology, University of California, Santa Cruz, Santa Cruz, California, USA
[7]National Center for Scientific Research, PSL Université Paris, CRIOBE, CNRS-EPHE-UPVD, Paris, France
[8]Environmental Defense Fund, Santa Barbara, California, USA
[9]Puget Sound Institute, University of Washington, Tacoma, Washington, USA
[10]Moss Landing Marine Laboratories, San Jose State University, Moss Landing, California, USA
[11]MARBEC, University of Montpellier, CNRS, IFREMER, IRD, Montpellier, France
[12]Institut Universitaire de France (IUF), Paris, France
[13]Odum School of Ecology, University of Georgia, Athens, Georgia, USA
[14]Department of Biology, California State University Northridge, Northridge, California, USA

Correspondence
Joshua G. Smith, National Center for Ecological Analysis and Synthesis, University of California, Santa Barbara, Santa Barbara, CA, USA.
Email: joshsmith@nceas.ucsb.edu

Present address
Kerry J. Nickols, Ocean Visions, Leesburg, Virginia, USA

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Abstract

Marine protected areas (MPAs) have gained attention as a conservation tool for enhancing ecosystem resilience to climate change. However, empirical evidence explicitly linking MPAs to enhanced ecological resilience is limited and mixed. To better understand whether MPAs can buffer climate impacts, we tested the resistance and recovery of marine communities to the 2014–2016 Northeast Pacific heatwave in the largest scientifically designed MPA network in the world off the coast of California, United States. The network consists of 124 MPAs (48 no-take state marine reserves, and 76 partial-take or special regulation conservation areas) implemented at different times, with full implementation completed in 2012. We compared fish, benthic invertebrate, and macroalgal community structure inside and outside of 13 no-take MPAs across rocky intertidal, kelp forest, shallow reef, and deep reef nearshore habitats in

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California's Central Coast region from 2007 to 2020. We also explored whether MPA features, including age, size, depth, proportion rock, historic fishing pressure, habitat diversity and richness, connectivity, and fish biomass response ratios (proxy for ecological performance), conferred climate resilience for kelp forest and rocky intertidal habitats spanning 28 MPAs across the full network. Ecological communities dramatically shifted due to the marine heatwave across all four nearshore habitats, and MPAs did not facilitate habitat-wide resistance or recovery. Only in protected rocky intertidal habitats did community structure significantly resist marine heatwave impacts. Community shifts were associated with a pronounced decline in the relative proportion of cold water species and an increase in warm water species. MPA features did not explain resistance or recovery to the marine heatwave. Collectively, our findings suggest that MPAs have limited ability to mitigate the impacts of marine heatwaves on community structure. Given that mechanisms of resilience to climate perturbations are complex, there is a clear need to expand assessments of ecosystem-wide consequences resulting from acute climate-driven perturbations, and the potential role of regulatory protection in mitigating community structure changes.

KEYWORDS

California, climate change, community composition, community structure, marine heatwaves, marine protected area networks, resilience

1 | INTRODUCTION

Climate change can rapidly reshape the distribution of species and the composition of ecological communities (Pörtner et al., 2023; Smale et al., 2019), imperiling nature's contributions to people. In particular, episodic periods of anomalous ocean warming, hereafter "marine heatwaves," are driving pronounced shifts in species distributions across marine ecosystems (Azzurro & D'Amen, 2022; Olsen et al., 2022), with direct implications for ecological processes and associated human benefits (Cheung et al., 2021; Cinner et al., 2022; Payne et al., 2021; Smale et al., 2019; Smith et al., 2023). While the urgency to plan for adaptation to climate change is clear, as marine heatwaves increase in frequency and severity (Holbrook et al., 2019), pathways to enhance ecosystem resilience are mixed. Therefore, understanding how ecological communities resist, recover from or are transformed by climate perturbations, such as marine heatwaves, represents one of the most pressing challenges for building ecosystem resilience capacity (Mason et al., 2022).

Marine protected areas (MPAs) are an important conservation strategy for preserving biodiversity and nature's contributions to people (Grorud-Colvert et al., 2021; Nowakowski et al., 2023). MPAs may provide network-scale population connectivity that can enhance spillover of individuals and the replenishment of populations in both protected and fished areas (Baetscher et al., 2019; Di Lorenzo et al., 2020; Goetze et al., 2021; Harrison et al., 2012; Williamson et al., 2016). Although most MPAs were initially designed to reduce the effects of overfishing and habitat loss, they are frequently hypothesized to provide long-term protection against climate impacts (Hofmann et al., 2021; Roberts et al., 2017). For example, networks of MPAs may provide refugia as species redistribute in response to climate change, owing to lower anthropogenic stressors and higher population sizes resulting from reduced harvest (Carr et al., 2017; McLeod et al., 2009). MPA features such as habitat diversity, historic fishing pressure, age, and size may also influence the capacity for MPAs to provide ecological resilience (Jacquemont et al., 2022). As such, MPAs and MPA networks are being increasingly highlighted as a key tool for enhancing climate resilience (IUCN-WCPA, 2008; Jacquemont et al., 2022).

Despite the growing number of studies examining MPAs as a tool for mitigating climate impacts, the effectiveness of MPAs (both individually and as networks) for enhancing the resilience (i.e., resistance to and recovery from disturbance, Bates et al., 2019) of marine communities to climate change remains contested (Johnson et al., 2022, but see Jacquemont et al., 2022). Climate change stressors (e.g., ocean acidification, sea level rise, hypoxia, warming) may have effects on populations and communities that occur regardless of regulatory protection (Bates et al., 2019; Bruno et al., 2019). Marine heatwaves can also reduce connectivity by changing prevailing current patterns—a key design attribute for many MPA networks (Lima et al., 2021). Mixed evidence surrounding the efficacy of MPAs in providing climate resilience may be explained in part by the single-habitat (e.g., coral reef, seagrass, kelp forest, etc.) focus of many studies, and also in part by the ways in which assemblages of species are partitioned.

Our understanding of whether and how MPAs confer ecological resilience to climate change can be improved by synthesizing the effects of regulatory protection across multiple taxa, habitats, ecosystems, and protection levels. Potential mechanisms producing ecological shifts in response to climate change may include altered mortality due to physiological environmental tolerances, changes in species interactions (e.g., competition, predation, disease, facilitation), adult movement across habitats and along the coast, ontogenetic shifts, and changes in recruitment success (Harley et al., 2006). Moreover, the ways in which species responses are evaluated (e.g., trait-based, functional groups, feeding guilds, evolutionary lineages, etc.) can influence detection of climate-driven outcomes. Therefore, long-term monitoring across multiple habitats subjected to similar (or the same) perturbations is needed to thoroughly examine the impacts of climate change on marine ecosystems, to test whether (and which) MPAs confer climate resilience, and to assess the relative resilience among ecosystems and taxa. Such cross-ecosystem studies are rare, especially those that include monitoring across networks of MPAs before, during, and after extreme climate change-driven perturbations.

In 1999, California passed the Marine Life Protection Act (MLPA), which expanded its system of MPAs to function as a coherent ecological network and to address six goals aimed at conservation, fisheries, and other human benefits (Gleason et al., 2013; Marine Life Protection Act, 1999). Guided by these goals, California established a network of 124 MPAs (48 no-take state marine reserves, 76 partial-take or special regulation conservation areas) distributed along the state's entire 1300-km coastline that protects 16% of state waters. The network protects hard- and soft-bottom habitats ranging in depth from the intertidal to depths of 1000 m. However, with few exceptions, ecological monitoring studies focused on hard-bottom habitats. Leading up to and following MPA implementation, an extensive ecological monitoring effort of these habitats began to support adaptive management of the network (Botsford et al., 2014). During the course of California's MPA monitoring, a major marine heatwave occurred that was the consequence of two environmental anomalies: a 2014–2015 warming event known as "the Blob," and a major El Niño event in 2015–2016 (Bond et al., 2015; Di Lorenzo & Mantua, 2016; Gentemann et al., 2017). This pronounced climate perturbation was the largest marine heatwave on record in California (Laufkötter et al., 2020).

This study leveraged over a decade of monitoring across the rocky intertidal, kelp forest, shallow reef, and deep reef habitats to evaluate whether a network of MPAs confers community structure resilience to climate disturbances. Specifically, we tested the following hypotheses: (1) the 2014–2016 marine heatwave event resulted in the reorganization of community structure across multiple nearshore habitats and taxa, (2) MPAs enhanced the ability for ecological communities to resist and recover from the impacts of climate perturbations, and (3) species traits (thermal affinities) explained differential responses to the marine heatwave in relation to regulatory protection (MPAs). After testing these hypotheses, we explored whether MPA features (size, age, historic fishing pressure, habitat diversity, and connectivity) enhanced ecological community resilience across habitats to inform the design of MPA networks that are resilient to climate change.

2 | METHODS

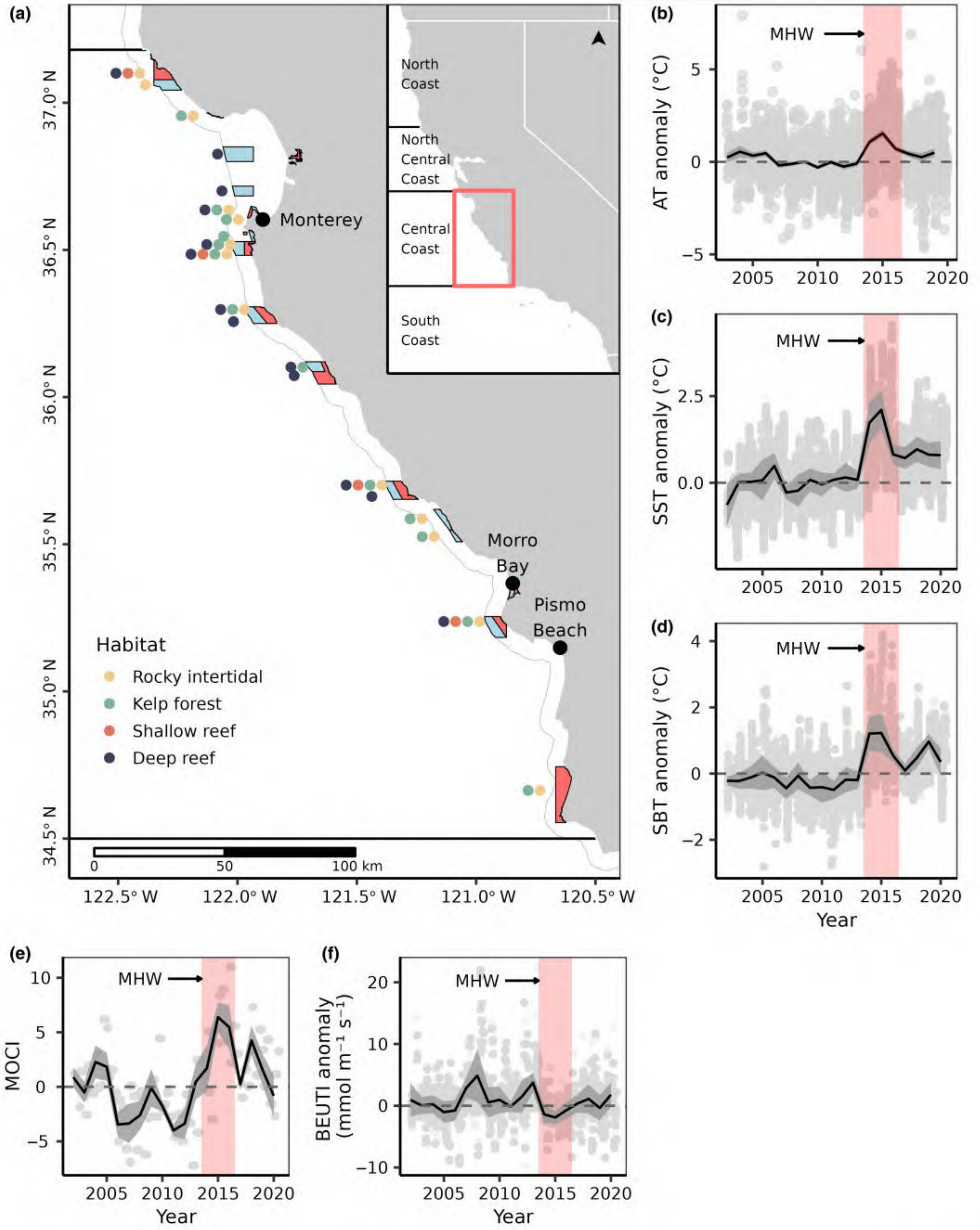
2.1 | MPA sampling and data collection

As part of the State of California's long-term MPA evaluation and monitoring program, several habitat-specific research groups conduct annual surveys designed to monitor ecological changes over time inside MPAs and at areas of comparable habitat outside MPAs (Figure 1a; Figure S1). Conceptually, while MPAs could be considered the "treatment" or "control" in our analyses (i.e., fishing is considered either the experiment or the control), we take a social–ecological system perspective and consider human activities, including fishing, to be integral system components (Kandel et al., 2022). Thus, in our analytical framework, MPAs are considered the experimental treatment where fishing is removed (e.g., Pacoureau et al., 2023).

Our analyses focused on four habitats that have extensive long-term monitoring data: rocky intertidal, kelp forest, shallow reef, and deep reef (Figure 1a; Figure S1). Across the four habitats included in our analyses, three organismal groups were sampled: macroalgae (rocky intertidal and kelp forest), conspicuous mobile and sessile invertebrates (rocky intertidal and kelp forest), and fishes (kelp forest, shallow reef, and deep reef). We focused our community structure analyses on 13 MPAs located along the temperate Central Coast of California (Figure 1a) because this area was the most comprehensively sampled region of the MPA network and had sufficient pre-marine heatwave data to evaluate baseline community structure (Table S1; Figure S1). To evaluate MPA features as potential drivers of ecological resilience, we included 28 MPAs across all of California for two of the habitats (rocky intertidal and kelp forest), where more extensive spatial and temporal coverage exists (see Section 2.6).

Two general types of data were used in our analyses: species counts (kelp forest, shallow reef, deep reef) and the proportional cover of invertebrates and macroalgae (rocky intertidal and kelp

FIGURE 1 The (a) coverage of ecological monitoring in marine protected areas (MPAs) in California's Central Coast region and (b–f) exposure of these MPAs to five indicators of environmental conditions. In (a), points indicate which habitats were monitored both inside and outside of MPAs (i.e., points indicate data availability, not the location of sampling sites). Red polygons indicate no-take MPAs ($n=12$, called State Marine Reserves), and blue polygons indicate partial-take MPAs ($n=10$, called State Marine Conservation Areas; see Table S1 for list of partial-take MPAs that are de facto no-take MPAs by habitat). The dark horizontal lines delineate the Central Coast region, and the thin gray line indicates state waters (three nautical miles offshore and all of Monterey Bay). Environmental indicators include (b) air temperature (AT); (c) sea surface temperature (SST); (d) sea bottom temperature (SBT); (e) the multivariate oceanographic climate index (MOCI); and (f) the biologically effective upwelling index (BEUTI). Lines indicate the median and shading indicates the 95% confidence interval. The 2014–2016 marine heatwave (MHW) is indicated by the vertical red rectangle.



forest invertebrates and algae). While biomass is often used as a common measurable response across taxa (Duffy et al., 2017), it is not suitable for our analyses because of the large number of taxa for which it is difficult to accurately measure biomass (e.g., macroalgae and invertebrates). Therefore, we elected to use a taxonomic abundance-based approach to compare changes in community structure. All analyses were conducted using published data for each habitat (Brooks et al., 2022; Cieri et al., 2022; Malone et al., 2022; MARINe et al., 2022).

2.2 | Changes in community structure associated with the marine heatwave

We used non-metric multidimensional scaling (nMDS) to visualize community structure before (2007–2013), during (2014–2016), and after (2017–2020) the 2014–2016 marine heatwave. Prior to ordination, a base similarity matrix was constructed for each habitat type using Bray–Curtis dissimilarity on Hellinger-transformed counts or on percent cover of species. The Hellinger transformation converts absolute counts to the square root of proportional counts, which reduces the disproportionate contribution of highly abundant species (Legendre & Gallagher, 2001). We elected to use the transformation to relative species abundance to improve the robustness, comparability, and ecological interpretation of our community structure analyses. Each site sampled inside or outside of a MPA surveyed in a single year represents a single unit of replication. To visualize the state of each ecological community, we plotted centroids and 95% confidence ellipses that represent the generalized position of the community in ordinated two-dimensional nMDS space before, during, and after the marine heatwave event.

We used a pairwise permutational analysis of variance (PERMANOVA) to test three hypotheses surrounding community structure changes (Figure 2a). First, if MPAs do not mitigate marine heatwave impacts on community structure, then communities inside MPAs should respond similarly (i.e., comparable change in multivariate distance) to those outside. Second, if MPAs confer resistance, then communities inside MPAs should remain unchanged while those outside shift. Finally, if MPAs enhance recovery, then communities inside MPAs should shift during the marine heatwave, but return to or move back in the direction of their previous state following the disturbance. To test these hypotheses, a single PERMANOVA was performed for each habitat and site type (inside or outside a MPA) using pairwise comparisons between marine heatwave periods (before vs. during, before vs. after) using the *pairwiseAdonis* wrapper function (Martinez Arbizu, 2020) in the *vegan* package (Oksanen et al., 2022) in R (R Core Team, 2021).

2.3 | Effect of MPAs on community structure resistance and recovery

We used a multivariate distance-based approach to test whether MPAs conferred ecological community resistance to or recovery from the marine heatwave. We refer to this measurement as "multivariate distance" to distinguish it from "geographic distance," which is often a measure of climate change impacts on marine species distributions. We define resistance as community structure (i.e., relative abundance of species) that remained unchanged during the marine heatwave (low change in multivariate distance-based centroids), and recovery as a community that returned to a similar structure post-heatwave. Resistance was evaluated by calculating the multivariate vector distance (in high-dimensional space using the Bray–Curtis dissimilarity matrix) of the centroid of the ecological community between the periods before (2007–2013) and during (2014–2016) the marine heatwave (e.g., high resistance is indicated by a smaller change in multivariate distance-based centroids).

Recovery was evaluated by calculating the multivariate distance between the before (2007–2013) and after period (2017–2020) centroids. We calculated the change in multivariate distance between centroids using the *betadisper* function in the *vegan* package (Oksanen et al., 2022). The *betadisper* function returns the principal coordinates of centroids, which we used to calculate multivariate distance after ensuring positive-definite eigenvalues. Finally, statistical significance was evaluated using a PERMANOVA on community structure resistance (before vs. during) and recovery (before vs. after).

To explore whether the timing of community shifts coincided with temporal changes in oceanographic variables, we used a Granger causality test on Bray–Curtis dissimilarity. For this analysis, annual dissimilarity was calculated for each site (inside or outside an MPA) and habitat relative to 2007. Dissimilarity was then offset (lagged) against oceanographic variables (see Section 2.5) in 1-year increments for a maximum of 3 years (maximum lag based on length of the time series). We used 2007 as the baseline year because it preceded the marine heatwave and because we were interested in lag effects specifically related to the marine heatwave, rather than gradual environmental changes over time. However, 2008 was used as the baseline year for the deep reef habitat because surveys were not extensively conducted in 2007. It is important to note that the Granger test only examines lagged effects between the time series of community change and the environmental variables, it does not examine correlations, which are explored using other diagnostics described in Section 2.5.

2.4 | Species associated with community changes

To evaluate which species were associated with community change, we used two approaches. First, we used a similarity percentage analysis (SIMPER) to decompose community structure using Bray–Curtis dissimilarity and to examine the percent contribution of each species to the before versus after marine heatwave communities. However, because SIMPER is known to confound the mean between group variation and dispersion (Warton et al., 2012), we cross-validated the SIMPER output using the *mvabund* package (Wang et al., 2022) in R. The *mvabund* package uses fitted generalized linear models to account for nonlinear mean-to-variance relationships of each species. Both of these analyses were conducted on the absolute abundance of species (rather than relative abundance) because they are not sensitive to common or rare taxa. This combination of approaches allowed us to determine the contribution of individual

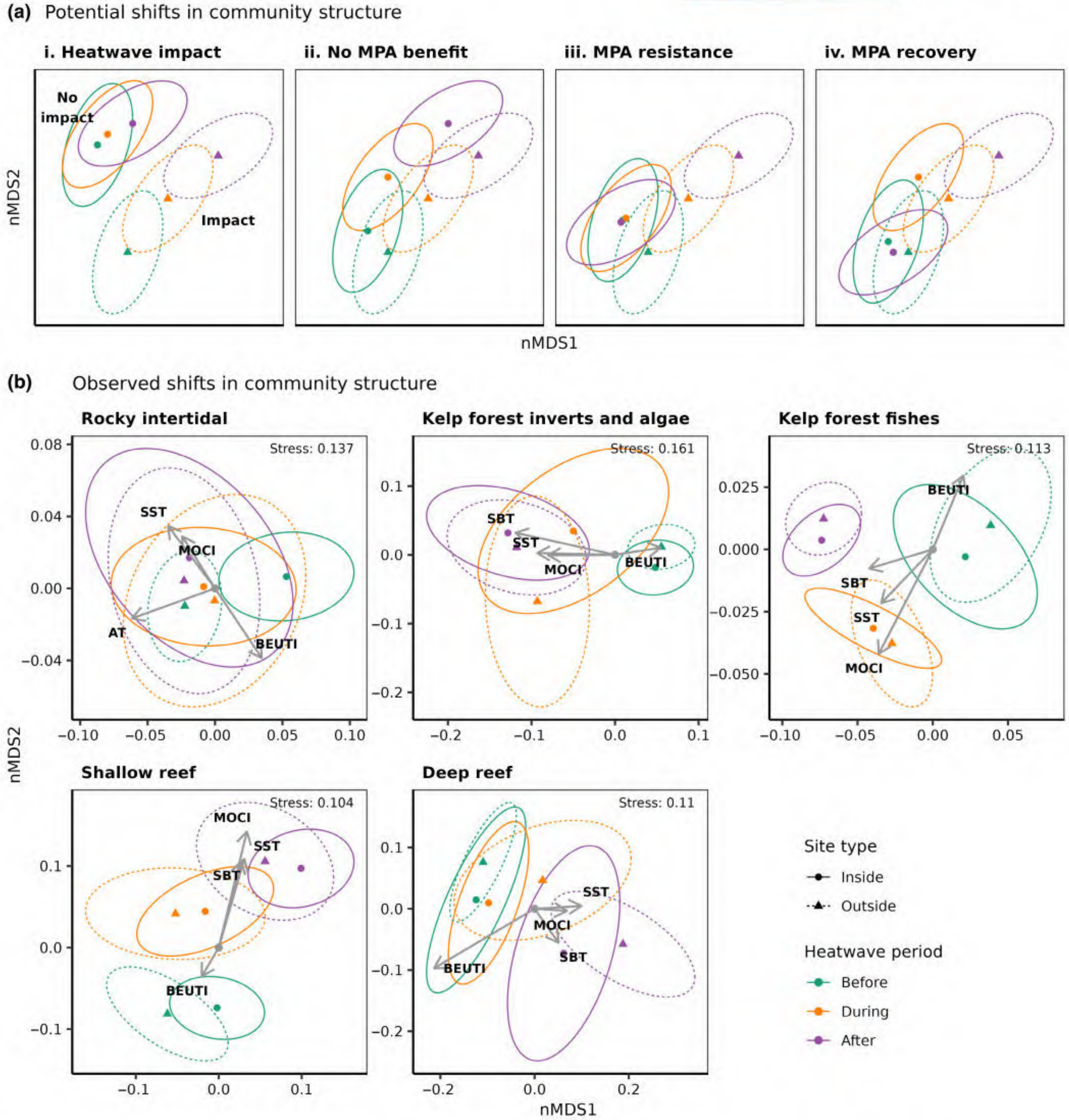


FIGURE 2 (a) Potential and (b) observed shifts in community structure from 2007 to 2020. (a) Illustrates a typology of potential community structure shifts: (i) "No impact," where community structure does not shift, and "impact", where community structure significantly shifts. Non-overlapping ellipses indicate significant differences in community structure. In this example, pre-heatwave community structure was significantly different inside (solid lines ellipses around points) versus outside (dashed lines around triangles) MPAs; (ii) "No MPA benefit," where communities inside MPAs respond similar to those outside; (iii) "MPA Resistance," where communities inside MPAs remain stable while those outside shift; and (iv) "Recovery," where communities inside MPAs shift during the heatwave, but return to their previous state following the disturbance while communities outside of MPAs do not return. (b) Shows observed shifts in community structure before (2007–2013), during (2014–2016), and after (2017–2020) the marine heatwave inside (circles) and outside (triangles) MPAs in the Central Coast region of California. Each subpanel represents a habitat and each point depicts the centroid position with 95% confidence ellipses. Also included are vectors for each environmental anomaly: air temperature (AT, rocky intertidal only), sea surface temperature (SST), sea bottom temperature (SBT), the multivariate ocean climate index (MOCI), and the biologically effective upwelling transport index (BEUTI). The trajectory of each vector reflects its correlation with community structure (Table 2). Therefore, indicators that are highly correlated with changes in community structure are aligned with the centroids (points). MPA, marine protected area; nMDS, non-metric multidimensional scaling.

taxa to observed community structure differences. Additionally, because the PERMANOVA analyses revealed that community change was similar inside and outside of MPAs, we analyzed compositional changes overall rather than within each site by protection status. Finally, we constructed an analysis of deviance table using the multivariate generalized linear model fits to test whether species structure changed as a result of the marine heatwave (before vs. after). Test statistics and *p*-values for each species were generated using the PIT-trap (probability integral transform) resampling method.

2.5 | Environmental correlates and species traits

We explored temperature and oceanographic conditions before, during, and after the marine heatwave to evaluate whether community structure shifts were explained by environmental changes (Figure 1b–f; Figure S2). For these environmental analyses, we used air temperature (AT, °C) measured in situ at rocky intertidal long-term monitoring sites (as an environmental correlate for rocky intertidal communities only, Supplementary Methods, Appendix S1); sea surface temperature (SST, °C) at 1 km daily resolution from MURSST (Chin et al., 2017); sea bottom temperature (SBT, °C) at 8 km daily resolution from GLORYS (Jean-Michel et al., 2021); the Biologically Effective Upwelling Transport Index (BEUTI, $\text{mmol}\,\text{m}^{-1}\text{s}^{-1}$; Jacox et al., 2018) calculated at 1° latitude bins; and the Multivariate Oceanographic Climate Index (MOCI), which is a long-term (30 year) indicator of several oceanographic and atmospheric conditions (García-Reyes & Sydeman, 2017) calculated at the regional level (Central California). We selected these environmental indicators and associated products because they provide biologically meaningful climatology at the best available spatial resolution for our study area.

To process the environmental data, we first calculated the monthly mean AT, SST, SBT, BEUTI, and quarterly MOCI values at each site. We then calculated monthly anomalies for AT, SST, SBT, and BEUTI as the difference between the observed monthly mean and the baseline average (long-term average for each month, 2000–2012 for AT, 1988–2012 for BEUTI, 1993–2012 for SBT, and 2002–2012 for SST; start year of the historical climatology reflects the first year with data). Baseline averages were calculated through the end of 2012 to accommodate a buffer before the onset of the marine heatwave in 2014. For MOCI, we calculated the annual mean (2000–2020) at each site as a standard index. To visualize and pair the environmental data with the long-term biological monitoring data, we calculated the mean anomalies across all calendar months for each year (Figure 1b–f). Finally, to determine whether observed shifts in community structure were associated with changes in oceanographic conditions, we used the *envfit* function in the *vegan* package (Oksanen et al., 2022) to overlay the four environmental variables as vectors on the ordinated community data. The *envfit* function computes the rank-based correlation coefficient and significance is evaluated through permutation-based resampling.

We used a trait-based fourth-corner model to evaluate effects of environmental variables and species thermal affinities on the relative abundance of all recorded taxa. Species thermal affinities were obtained from literature reported classifications and expert judgment (Supplementary Methods, Appendix S1). The fourth-corner model relates the interaction between the environment and species traits (thermal affinities) on variation in the abundance of taxa (Brown et al., 2014). Briefly, we used the *mvabund* package to fit simultaneous generalized linear models for counts of all species at each site as a function of the environmental and oceanographic conditions (AT, SST, SBT, BEUTI, MOCI), the relative representation of thermal affinities, and their interaction.

2.6 | Drivers of resistance and recovery

The ecological and design context of California's MPA network is well documented, allowing us to explore whether certain MPA features conferred community structure resilience to the marine heatwave. These analyses were spatially expanded to include a subset of MPAs covering the entire network from northern to southern California, thereby providing a greater scope of MPA feature diversity (Figure S3). However, only the kelp forest and rocky intertidal habitats contained sufficient pre-heatwave monitoring data with consistent annual surveys in all bioregions of the state to appropriately examine drivers of ecological resilience among MPAs at the network level (Figure 1a; Figure S1). MPA features included habitat richness and habitat diversity (calculated using Shannon–Wiener on depth-stratified hard and soft bottom, proportion of rock, and the extent of kelp forest canopy, rocky intertidal, sandy beach, coastal marsh, tidal flats, and armored shore), historic fishing pressure, MPA age and size, connectivity, and kelp forest fish biomass response ratios (as a proxy for MPA ecological performance, see Supplementary Methods, Appendix S1).

We developed a two-stage multivariate model to examine the effect of MPA features on community resistance and recovery. First, we used a PERMANOVA to identify MPAs that significantly resisted or recovered from the marine heatwave (building on the methods outlined in Section 2.3). We then used logistic regression to evaluate the probability that specific MPA features enhanced resistance or resilience. For the logistic regression, any MPA community that significantly resisted or recovered from the marine heatwave was assigned a target level of "1," and any MPA community that did not resist or recover from the marine heatwave a "0."

3 | RESULTS

3.1 | Community structure resistance and recovery

Ecological community change was widespread across all habitats, and three habitats (kelp forest, shallow reef, deep reef) showed no clear differences inside and outside of MPAs in the magnitude of community change (Figure 2b). Prior to the marine heatwave, community structure was similar inside and outside of MPAs in all habitats except the rocky intertidal (indicated by the non-overlapping ellipses in Figure 2b). However, ecological community structure dramatically shifted as a result of the marine heatwave event across all measured nearshore habitats ($n=4$), regardless of whether the communities ($n=5$) were inside or outside of MPAs (Figure 2b; Figure S8; Table 1).

Community structure changes coincided with oceanographic conditions associated with the marine heatwave (Figure 1; Tables 1 and 2). At the onset of the marine heatwave in 2014, SST was anomalously warm by as much as 2°C, and sea bottom temperature was also 1°C above the baseline average. MOCI and BEUTI experienced precipitous changes during the marine heatwave, reflecting reduced upwelling and productivity, and these anomalies persisted until at least mid-2016 (Figure 1e,f). Although each oceanographic anomaly aligned well with community shifts in nMDS space (Figure 2b), significant correlations were habitat-specific (Table 2). In the rocky intertidal, warmer AT was the strongest environmental correlate with community structure changes, although warmer SST and declines in upwelling (BEUTI) were also correlated with community change. For shallow reef, kelp forest fishes, and kelp forest invertebrates and algae, SST, SBT, and MOCI were significantly associated with community change, such that communities shifted with increases in surface and bottom water temperature and positive values of the MOCI index. In the deep reef habitat (fishes only), the only significant oceanographic correlate was BEUTI (Table 2), where the community shifted in response to reduced upwelling. Finally, there were no significant temporal lags determined except for one interaction between the shallow reef and BEUTI (*lag*=3 years for sites inside and outside of MPAs, Table S4).

For all habitats except the rocky intertidal, MPAs did not impart increased resistance to or recovery from marine heatwave-driven community changes compared to sites outside of MPAs (Figure 3). The rocky intertidal and deep reef were the only two habitats that resisted the marine heatwave (based on nonsignificant PERMANOVA result, Figure 3a). The rocky intertidal was the only habitat where community structure inside MPAs was not significantly different either during or post-marine heatwave (Figure 3b). Kelp forest invertebrates, algae, and fishes all substantially shifted during the marine heatwave, and these changes persisted for several years later with no apparent recovery. The shallow reef habitat responded similarly with pronounced shifts in community structure during the marine heatwave, although the trajectory of the shallow reef habitat started to move toward the pre-heatwave state beginning in the year 2018, with the biggest shifts toward recovery occurring inside MPAs (Figures S5 and S6). In the deep reef habitat, year-to-year changes

TABLE 1 Results from a series of pairwise permutational analysis of variance (PERMANOVA) tests on community resistance (before–during) and recovery (before–after). PERMANOVAs were performed separately for each habitat and calculated on Bray–Curtis dissimilarity matrices.

Habitat	MPA type	Transition	B–C distance	Sum of squares	R^2	Psuedo *F*	*p* (Perm)
Rocky intertidal	Outside	Resistance	0.059	0.155	.02	1.883	.071
		Recovery	0.053	0.219	.025	2.635	.006*
	Inside	Resistance	0.064	0.154	.026	1.824	.114
		Recovery	0.063	0.174	.026	1.946	.091
Kelp forest inverts and algae	Outside	Resistance	0.085	0.49	.061	4.381	.001*
		Recovery	0.125	0.921	.099	8.211	.001*
	Inside	Resistance	0.08	0.333	.047	2.823	.003*
		Recovery	0.142	0.849	.102	7.189	.001*
Kelp forest fishes	Outside	Resistance	0.081	0.249	.047	3.22	.007*
		Recovery	0.1	0.64	.109	9.098	.001*
	Inside	Resistance	0.066	0.21	.05	2.944	.015*
		Recovery	0.124	0.505	.109	7.569	.001*
Shallow reef	Outside	Resistance	0.073	0.146	.061	2.349	.064
		Recovery	0.071	0.586	.188	9.515	.001*
	Inside	Resistance	0.066	0.159	.093	3.676	.002*
		Recovery	0.112	0.486	.225	11.882	.001*
Deep reef	Outside	Resistance	0.136	0.198	.124	1.839	.064
		Recovery	0.167	0.681	.308	6.687	.001*
	Inside	Resistance	0.104	0.121	.082	1.163	.296
		Recovery	0.107	0.337	.163	2.53	.015*

Note: Pseudo *p*-values were generated using 999 permutations of residuals.

* Denote that community structure was significantly different ($p < .05$) for pairwise comparisons (Resistance=before vs. during, Recovery=before vs. after).

TABLE 2 EnvFit scores indicating the significance level of correlations between environmental conditions and community change in non-metric multidimensional scaling space.

Habitat	Environmental variable	Type	R^2	*p*-Value
Rocky intertidal	AT	Anomaly	.07	.043*
		Absolute	.33	.001*
	SST	Anomaly	.04	.149
		Absolute	.09	.012*
	BEUTI	Anomaly	.04	.121
		Absolute	.09	.011*
	MOCI	Absolute	.02	.324
Kelp forest inverts and algae	SST	Anomaly	.10	.004*
		Absolute	.04	.077
	BEUTI	Anomaly	.03	.128
		Absolute	.02	.323
	MOCI	Absolute	.07	.009*
	SBT	Anomaly	.17	.001*
		Absolute	.14	.001*
Kelp forest fishes	SST	Anomaly	.06	.016*
		Absolute	.04	.066
	BEUTI	Anomaly	.05	.029*
		Absolute	.03	.17
	MOCI	Absolute	.12	.002*
	SBT	Anomaly	.07	.012*
		Absolute	.01	.635
Rocky reef fishes	SST	Anomaly	.17	.002*
		Absolute	.18	.002*
	BEUTI	Anomaly	.02	.401
		Absolute	.03	.257
	MOCI	Absolute	.29	.001*
	SBT	Anomaly	.16	.002*
		Absolute	.12	.009*
Deep reef fishes	SST	Anomaly	.05	.524
		Absolute	.08	.292
	BEUTI	Anomaly	.25	.014*
		Absolute	.27	.016*
	MOCI	Absolute	.02	.726
	SBT	Anomaly	.03	.699
		Absolute	.15	.099

Abbreviations: AT, air temperature (°C); BEUTI, biologically effective upwelling transport index (mmol $m^{-1} s^{-1}$); MOCI, multivariate oceanographic climate index; SBT, sea bottom temperature (°C); SST, sea surface temperature (°C).

*Denote significant ($p < .05$) correlations.

were more variable, resulting in a larger multivariate distance relative to the other habitats, but this community change was not significantly different from the baseline year (Figure 3a; Figure S9). However, recovery was more variable than resistance. The shallow reef habitat exhibited relatively greater recovery (i.e., less shift in multivariate distance compared to the pre-heatwave community state) than the kelp forest and deep reef habitats.

3.2 | Species responses

The multivariate analyses revealed several species that explained differences between the pre- and post-heatwave periods. Among the three habitat types with monitoring of fish species (kelp forest, shallow reef, deep reef), the blue and deacon rockfish complex (*Sebastes mystinus* and *S. diaconus*) was positively correlated with the post-heatwave period (Table S5). Fish species that declined and were found within the top 80% contribution of pre- versus post-heatwave community structure included: *Sebastes serranoides* (kelp forest), *S. chrysomelas* and *carnatus* (kelp forest), *S. miniatus* (kelp forest, shallow reef), *Brachyistius frenatus* (kelp forest), *S. semicinctus* (deep reef), and *S. hopkinsi* (deep reef). For invertebrates and algae, the multivariate analyses revealed an increase in the abundance of purple sea urchins (*Strongylocentrotus purpuratus*) and a decline in macroalgae in both the rocky intertidal and kelp forest habitats.

3.3 | Community structure and thermal traits

The relative proportional representation of thermal affinities significantly changed during the marine heatwave for kelp forest invertebrates and algae, kelp forest fishes, and shallow reef fishes ($p < 0.001$, $F_{6,708} = 62.24$; $p < .05$, $F_{6,700} = 2.18$; $p < .001$, $F_{4,315} = 37.41$, respectively). Cold-temperate species significantly declined during the marine heatwave for these habitats (Figure 4a). During the marine heatwave, there was a slight increase in cosmopolitan species for the rocky intertidal and kelp forest (invertebrates and algae), and an even more pronounced increase in warm-temperate and subtropical fish species in the kelp forest, shallow reef, and deep reef habitats. Importantly, these changes in community composition that occurred during the marine heatwave (2014–2016) persisted into the following years (2017 and beyond), which partially explains the lack of observed recovery to the pre-heatwave community structure.

Variation in species abundance was explained by significant interactions between thermal affinities and oceanographic variables for all habitats from the fourth-corner model (Figure 4b; Figure S7). In general, species thermal affinities responded similarly across habitats. The abundance of cold-temperate species declined with increased SST anomalies and reduced upwelling (BEUTI), while the abundance of warm-temperate, subtropical, and tropical species increased with the oceanographic conditions that were associated with the onset of the marine heatwave, such as MOCI and warming water temperature. Sea bottom temperature had the most variable interactive effect across habitats and thermal affinities. Interestingly, thermal associations for the deep reef habitat had an opposite sign for cold-temperate and warm-temperate interactions, relative to the other habitats.

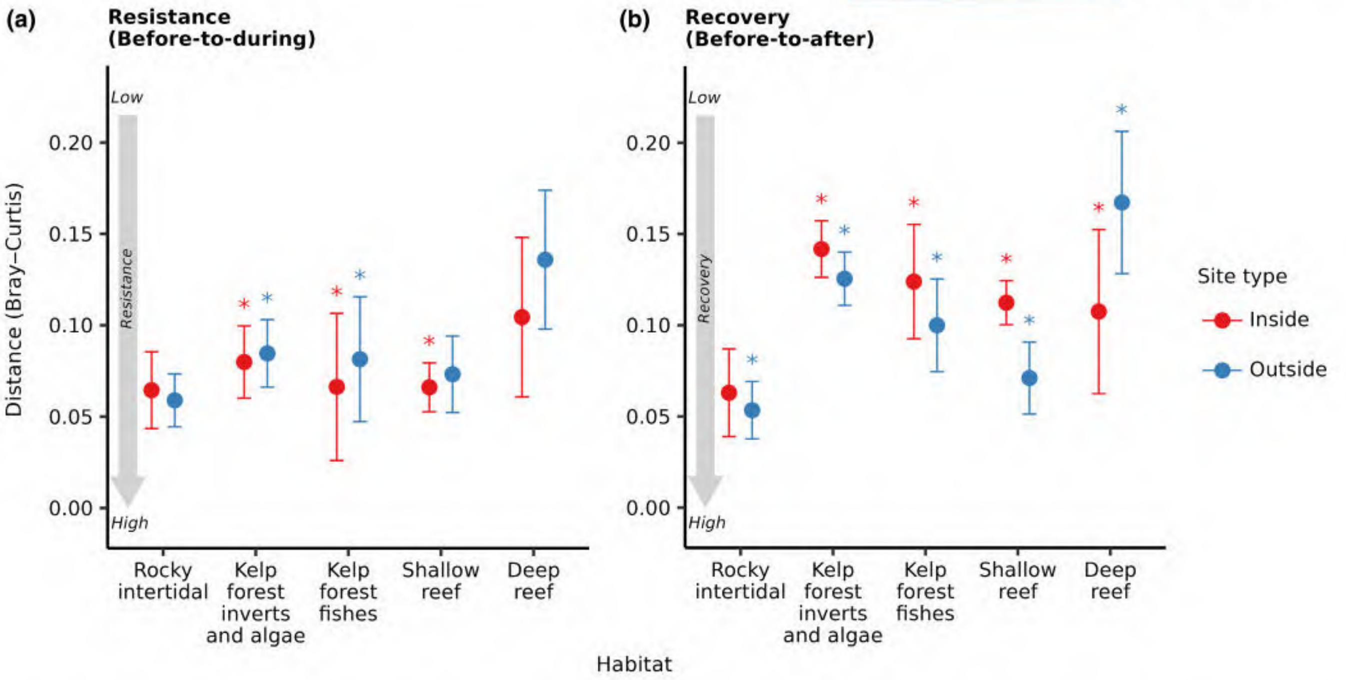


FIGURE 3 Community resistance [(a) before to during marine heatwave comparison] and recovery [(b) before to after marine heatwave comparison] as measured by multivariate distance between centroids. Each point depicts the multivariate distance between the pre-heatwave centroid (before) and the during-heatwave or the post-heatwave centroid inside (red) and outside (blue) marine protected areas. Therefore, higher values indicate less resistance or recovery. Error bars depict the pooled standard error between centroids and the asterisks denote significant differences in community structure between marine heatwave periods, as derived from a pairwise permutational analysis of variance (PERMANOVA). Points without asterisks indicate resistance or recovery (as measured by nonsignificant PERMANOVA, Table 1). Note that some communities have inherently greater interannual variability, potentially resulting from variation in sampling methodology, which can lead to larger mean multivariate distances that are not significantly different (Figure S9).

3.4 | MPA features and ecological stability

Community structure responses were highly variable across the state-level network for MPAs. In general, rocky intertidal communities showed higher resistance than kelp forest communities, as indicated by smaller shifts in multivariate distance (Figure 5c; smaller points). While shifts in community structure were generally larger in the kelp forest (Figure 5c; larger points), in some cases, the magnitude of shifts inside MPAs was less relative to shifts outside of MPAs (Figure 5a). In general, MPA protection fostered more resistance than recovery (Figure 5c; i.e., more blue points in the resistance column and more red points in the recovery column), although these results were not statistically significant. For example, kelp forest communities in the Point Buchon, South Point, and Harris Point MPAs resisted and moved toward recovery from the heatwave more than communities outside these MPAs (Figure 5; blue points). However, kelp forest communities in the Scorpion, Anacapa Island, and Campus Point MPAs were less successful at resisting shifts than communities outside these MPAs (Figure 5c, left; red points). Similarly, kelp forest communities in the Point Lobos, Santa Barbara, Farnsworth, and Blue Cavern MPAs were less successful at recovering from shifts than communities outside these MPAs (Figure 5c, right; red points). None of the evaluated MPA features (age, size, historic fishing pressure, habitat diversity, connectivity, biomass response ratios) were statistically significant drivers of this variability (Figure S11).

4 | DISCUSSION

Our findings suggest that the 2014–2016 Northeast Pacific marine heatwave impacted ecological community structure across four nearshore habitats, and that MPAs did not confer widespread resistance or recovery. MPAs have gained increased attention as a conservation strategy for mitigating the effects of climate change (Duncan et al., 2019; Wilson et al., 2018), but evidence of their efficacy in providing ecosystem-wide resilience to climate disturbances remains mixed (Bates et al., 2019; Jacquemont et al., 2022; Roberts et al., 2017). Critically, international efforts to conserve 30% of marine habitats via MPA implementation by the year 2030 (Day et al., 2012) highlight the need for planning that considers the effect of large climate-driven perturbations on local ecological processes. Therefore, while MPAs may be implemented with specific conservation targets, our study suggests that extreme climate perturbations, such as marine heatwaves, can overwhelm intended climate benefits of MPAs over the short-term (<5 years following a marine heatwave). These results highlight the ecosystem-wide consequences of acute climate-driven perturbations despite regulatory protection.

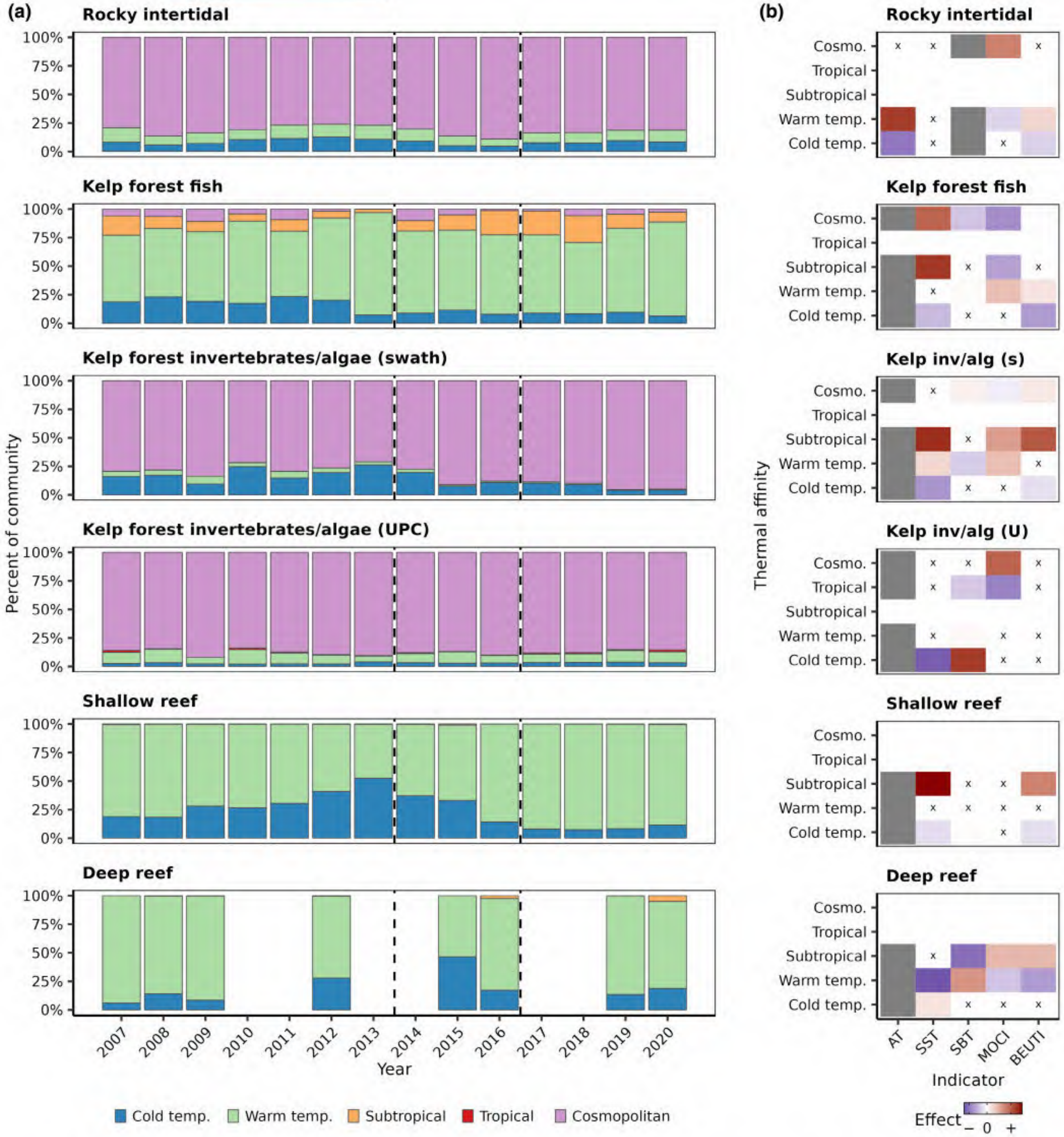


FIGURE 4 The (a) proportional community composition by thermal affinity groups from 2007 to 2020 and the (b) interactive effect of environmental anomalies (AT, air temperature, rocky intertidal only; BEUTI, biologically effective upwelling transport index; MOCI, multivariate oceanographic climate index; SBT, sea bottom temperature; SST, sea surface temperature) and species traits on variance in the abundance of species over the same time period. In (a), vertical lines bound the 2014–2016 marine heatwave years. In (b), colors indicate the standardized coefficients for all trait–oceanographic indicator interaction terms, based on multiple generalized linear-LASSO models. Coefficients were scaled to unit variance to make them visually comparable. Darker squares indicate stronger associations; positive associations are red; and negative associations are blue. Black x's mark interaction terms dropped in model selection. White squares without x's indicate traits that were never observed. Dark grey squares indicate non-applicable indicators.

Several ecological processes may explain the pronounced shifts observed across habitats, such as altered adult movement, changes to recruitment regimes, tropicalization, deborealization, and shifts in species interactions such as herbivory, competition, predation, and disease (Free et al., 2019; García Molinos et al., 2016; Mignot et al., 2022; Vergés et al., 2014; Wernberg et al., 2016). First, our

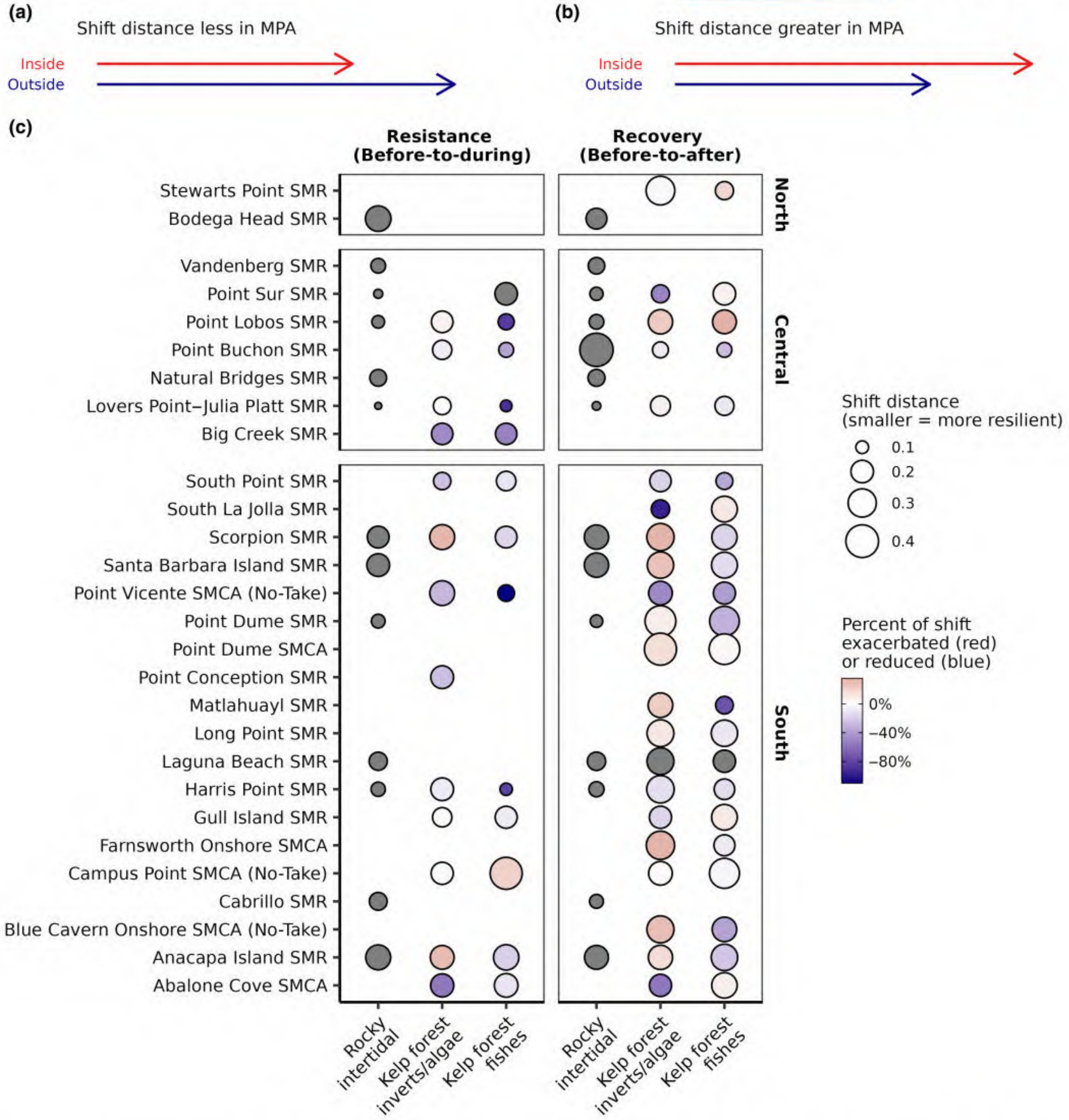


FIGURE 5 Conceptual schematics illustrating scenarios where (a) community structure shifts less inside an MPA than outside, thereby reducing community structure shifts, and (b) community structure shifts more inside an MPA than outside, thereby exacerbating community structure shifts relative to the outside sites. (c) Shows resistance (before-to-during marine heatwave comparison) and recovery (before-to-after marine heatwave comparison) of community structure to the 2014–2016 marine heatwave by MPA and habitat type along a latitudinal gradient. Point size indicates the Bray–Curtis multivariate distance for resistance or recovery. Therefore, smaller points indicate MPAs that exhibited greater resistance or recovery (i.e., communities inside the MPA shifted smaller multivariate distances). Point color indicates the magnitude of the shift of community structure inside a given MPA relative to its paired outside site. Red shades indicate MPAs where the change in multivariate distance was greater than the paired outside site (i.e., shift exacerbated inside MPAs relative to outside). Blue shades indicate MPAs where the change in multivariate distance was greater in the paired outside site than inside the MPA (i.e., community structure changes were less in the MPA). Note that the rocky intertidal does not use a paired inside–outside sampling design (outside site selection is described in Supplementary Methods, Appendix S1), and therefore, the grey points indicate MPAs without the necessary data from adjacent outside sites. Missing points indicate insufficient data to evaluate changes. MPA, marine protected area; SMCA, State Marine Conservation; SMR, State Marine Reserve (no-take MPA).

study found that the relative proportion of warm-temperate and subtropical species increased during and after the marine heatwave. The increased proportional representation of species with warm water thermal affinities may be explained by adult movement into the study area, changes in recruitment patterns, or by a decline in the relative abundance of cold-temperate species (Fredston et al., 2021; Sanford et al., 2019; Walker et al., 2020). For example, the large increase in blue rockfish in kelp forest, shallow reef, and deep reef habitats was associated with strong recruitment and pelagic young-of-the-year abundance of rockfishes in midwater trawl surveys at the start of the marine heatwave period (Field et al., 2021). Large increases in the subtropical wrasse, senorita (*Oxyjulis californica*), were also observed in multiple habitats, contributing to community change. Second, during the marine heatwave, a large-scale outbreak of herbivorous sea urchins occurred throughout the study region that coincided with precipitous declines in kelp (and other macroalgae) and the loss of an important benthic mesopredator, the sunflower sea star (*Pycnopodia helianthoides*), due to a large-scale marine disease outbreak (Harvell et al., 2019; Smith et al., 2021).

Species life-history traits in relation to the marine heatwave event may explain why the rocky intertidal was the only habitat where community structure exhibited resilience. Variation in stress tolerance to AT is a fundamental driver of rocky intertidal community structure. Although 2014 was the warmest year on record in California, the sustained sea surface temperature anomalies associated with ocean warming during the marine heatwave may have impacted the rocky intertidal less than the subtidal habitats. Resilience in rocky intertidal MPAs may be explained by increased propagule delivery to MPAs, particularly by long-lived foundation species that stabilize the community (Raimondi & Smith, 2022), or through regulatory protection that prohibits the harvest of habitat-forming mussels (*Mytilus* spp.) in MPAs. Additionally, the rocky intertidal is the only habitat that used a fixed-plot design (Supplementary Methods, Appendix S1) and this methodological form of sampling could have resulted in smaller propagated spatial variance, which could be more biased toward conclusions of enhanced resilience relative to the sampling used in the other habitats. More research is needed to distill the mechanistic processes associated with MPA resilience in the rocky intertidal.

The primary regulation associated with MPAs in California involves a restriction of fishing activities; thus, we were interested in understanding whether ecological communities inside no-take MPAs are more resilient to marine heatwaves than our control social–ecological system. We consider human activities, such as fishing, as integral parts of the social–ecological system, since fishing occurred decades before MPA establishment and the marine heatwave, with the restriction of harvest through regulatory protection as the primary conservation mechanism. However, there are multiple viewpoints pertaining to interactions between humans and the oceans, and similarly, there are many approaches to evaluating the effects of fishing and regulatory protection. Alternative frameworks might consider areas inside MPAs as "reference" locations for places where harvest occurs (Costello, 2014). While we believe human and natural systems are now so integrated in coastal areas that there are virtually no pristine ecosystems, the framing of considering MPAs as controls and fished systems as experimental treatments would not impact our results.

It is not surprising that community shifts occurred inside and outside MPAs simultaneously for most habitats, since many of the species exhibiting the biggest changes are not directly targeted by fishing activities (e.g., invertebrates and algae). In cases where MPAs do not confer ecological resilience to marine heatwaves, it is important to note that the capacity of MPAs to harbor higher biomass than unprotected sites can still be maintained (Frid et al., 2023). Other studies have documented increases in targeted species biomass inside of MPAs within this system, which is a focal MPA conservation objective (Caselle et al., 2015; Hamilton et al., 2010; Ziegler et al., 2022). Similar responses to the marine heatwave in southern California fish communities were reported by Freedman et al. (2020), who found that non-targeted subtropical species were most responsible for community reorganization. Ziegler et al. (2023) also reported that fish species diversity recovered more quickly after the heatwave inside of MPAs.

Although the anomalously warm environmental conditions subsided after 2016, changes in community structure persisted, especially in the kelp forest, shallow reef, and deep reef habitats. These results are particularly interesting in the context of ecosystem stability and transition dynamics. Given the highly variable recruitment of the dominant fishes in the study region (Field et al., 2021; Schroeder et al., 2019), it is possible that sufficient time has not elapsed for the communities to return to a pre-perturbed state. Lagged effects due to ontogenetic shifts and methodological sampling that disproportionately select for adults may also contribute to the observed lack of recovery. For example, declines in vermilion rockfish (*S. miniatus*) in the shallow reef habitat coincided with increases in that species in the deep reef habitat, likely reflecting ontogenetic movements from shallow to deep habitats (Love, 2011; Love et al., 2002). In addition, the shallow reef habitat monitoring program used hook and line sampling, which disproportionately selects individuals that are older than 2–3 years, which is why lagged effects of oceanography were more likely to be detected in this habitat (Ziegler et al., 2023). Moreover, many species in the California Current are slow-growing, late to mature, long-lived, and relatively sedentary with small home ranges (Love, 2011; Love et al., 2002). These life-history traits may create inertia to resistance or recovery from change. However, the persistence of novel community structure configurations observed in this study, despite the return of pre-heatwave environmental conditions, highlights the need for further assessments of community transition dynamics over ecologically meaningful timescales.

Our finding of no effect of MPA features on dampening marine heatwave-driven responses in the rocky intertidal and kelp forest habitats is particularly interesting given that habitat mosaics, historic fishing effort, and connectivity have been linked to MPA conservation capacity (Bastari et al., 2016). The widespread effects of marine heatwaves and other climate perturbations may overwhelm local stressors (e.g., fishing, marine pollution) that MPAs were initially successful at mitigating (Bruno et al., 2019). Indeed, even biodiversity-rich spots or deep water communities are susceptible to the impacts of climate change (Emblemsvåg et al., 2022; Kocsis et al., 2021). Our results highlight the need for management frameworks that include climate adaptation strategies, the protection of range-shift corridors, and consideration of the compounding effects of both fishing and marine heatwaves on resilience (Burrows et al., 2014). More investigation is needed to better understand the drivers that can help MPAs to maintain higher fish biomass than unprotected sites under climate change (Frid et al., 2023).

Increasing our understanding of the pathways through which marine heatwaves restructure ecological communities is central to developing adaptive management solutions. In our study, we used a taxonomic (i.e., species) abundance-based approach to evaluate changes in community structure, but functional diversity may also be impacted by warming events and should be explored (McLean et al., 2019; Murgier et al., 2021). Prolonged warming events may differentially impact groups and guilds of species with similar traits, such as dispersal ability, thermal tolerance, metabolic rate, and mobility (Duncan et al., 2019; Harvey et al., 2021). Moreover, to understand the ability of MPA networks to resist and recover from future marine heatwaves, it is critical to have sufficient monitoring across multiple habitats, taxa, and regions. Because pre-perturbation data are essential for establishing baselines and comparatively evaluating ecological responses, consistent monitoring is fundamental to capture the effect of marine heatwave events. Although the timing of marine heatwaves is unpredictable, evidence suggests that the frequency and magnitude of abrupt warming events are expected to increase (Frölicher et al., 2018; Holbrook et al., 2020).

Evidence of MPAs as a tool for mitigating the effects of climate change remains controversial, especially since most MPAs were initially designed for other conservation priorities. Our analysis of ecological community change across a network of MPAs highlights that widespread effects of climate-driven stressors such as marine heatwaves can dramatically restructure ecological communities, regardless of regulatory protection. Ultimately, improved resilience capacity of MPA networks will require integrating adaptive management with careful consideration of how abrupt climate change-driven perturbations may inhibit intended conservation outcomes.

AUTHOR CONTRIBUTIONS

Joshua G. Smith, Christopher M. Free, Cori Lopazanski, Scott L. Hamilton, Richard M. Starr, David Mouillot, Kerry J. Nickols, and Jennifer E. Caselle conceived the ideas and designed methodology. Joshua G. Smith, Christopher M. Free, Cori Lopazanski, Julien Brun, Mark H. Carr, Scott L. Hamilton, Peter T. Raimondi, Shelby L. Ziegler, and Jennifer E. Caselle collected the data. Joshua G. Smith, Christopher M. Free, Cori Lopazanski, Julien Brun, and Clarissa R. Anderson analyzed the data. Joshua G. Smith led the writing of the manuscript. All authors contributed substantially to revisions. The authors have agreed to be listed and approved the manuscript for submission.

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CONFLICT OF INTEREST STATEMENT

The authors have no conflicts of interest to declare.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are openly available in DataONE from the following resources: Brooks et al. (2022), https://search.dataone.org/view/urn%3Auuid%3Af843f110-e691-4d26-bf12-3854a4b641cd; Cieri et al. (2022), https://opc.dataone.org/view/urn%3Auuid%3A7353f779-b722-4064-8074-3e9c651ed38e; Malone et al. (2022), https://doi.org/10.1002/ecy.3630; MARINe et al. (2022), https://doi.org/10.6085/AA/marine_cbs.5.5. All source code is available in GitHub at https://github.com/NCEAS/ca-mpa.

ORCID

Joshua G. Smith https://orcid.org/0000-0003-4633-4519
Christopher M. Free https://orcid.org/0000-0002-2557-8920
Cori Lopazanski https://orcid.org/0000-0002-4086-102X
Julien Brun https://orcid.org/0000-0002-7751-6238
Clarissa R. Anderson https://orcid.org/0000-0001-5970-0253
Mark H. Carr https://orcid.org/0000-0001-9644-7680
Joachim Claudet https://orcid.org/0000-0001-6295-1061
Jacob G. Eurich https://orcid.org/0000-0003-1764-7524
Tessa B. Francis https://orcid.org/0000-0002-3383-5392
Scott L. Hamilton https://orcid.org/0000-0001-5034-4213
David Mouillot https://orcid.org/0000-0003-0402-2605
Richard M. Starr https://orcid.org/0000-0002-4010-5152
Shelby L. Ziegler https://orcid.org/0000-0001-7218-0811
Kerry J. Nickols https://orcid.org/0000-0003-3476-4247
Jennifer E. Caselle https://orcid.org/0000-0002-1364-3123

REFERENCES

Azzurro, E., & D'Amen, M. (2022). Climate change paves the way for a new inter-ocean fish interchange. *Frontiers in Ecology and the Environment*, *20*(10), 558–563. https://doi.org/10.1002/fee.2459

Baetscher, D. S., Anderson, E. C., Gilbert-Horvath, E. A., Malone, D. P., Saarman, E. T., Carr, M. H., & Garza, J. C. (2019). Dispersal of a nearshore marine fish connects marine reserves and adjacent fished areas along an open coast. *Molecular Ecology*, *28*(7), 1611–1623. https://doi.org/10.1111/mec.15044

Bastari, A., Micheli, F., Ferretti, F., Pusceddu, A., & Cerrano, C. (2016). Large marine protected areas (LMPAs) in the Mediterranean Sea: The opportunity of the Adriatic Sea. *Marine Policy*, *68*, 165–177. https://doi.org/10.1016/j.marpol.2016.03.010

Bates, A. E., Cooke, R. S. C., Duncan, M. I., Edgar, G. J., Bruno, J. F., Benedetti-Cecchi, L., Côté, I. M., Lefcheck, J. S., Costello, M. J., Barrett, N., Bird, T. J., Fenberg, P. B., & Stuart-Smith, R. D. (2019). Climate resilience in marine protected areas and the 'Protection Paradox'. *Biological Conservation*, *236*, 305–314. https://doi.org/10.1016/j.biocon.2019.05.005

Bond, N. A., Cronin, M. F., Freeland, H., & Mantua, N. (2015). Causes and impacts of the 2014 warm anomaly in the NE Pacific. *Geophysical Research Letters*, *42*(9), 3414–3420. https://doi.org/10.1002/2015GL063306

Botsford, L. W., White, J. W., Carr, M. H., & Caselle, J. E. (2014). Chapter six—Marine protected area networks in California, USA. In M. L. Johnson & J. Sandell (Eds.), *Advances in marine biology* (Vol. *69*, pp. 205–251). Academic Press. https://doi.org/10.1016/B978-0-12-800214-8.00006-2

Brooks, R., Ziegler, S., Starr, R., Wendt, D., Ruttenberg, B., Bellquist, L., Caselle, J., Morgan, S., Mulligan, T., Semmens, B., Tyburczy, J., & Hamilton, S. (2022). *Nearshore fishes abundance and distribution data*. California Collaborative Fisheries Research Program (CCFRP). https://search.dataone.org/view/urn%3Auuid%3Af843f110-e691-4d26-bf12-3854a4b641cd

Brown, A. M., Warton, D. I., Andrew, N. R., Binns, M., Cassis, G., & Gibb, H. (2014). The fourth-corner solution – Using predictive models to understand how species traits interact with the environment. *Methods in Ecology and Evolution*, *5*(4), 344–352. https://doi.org/10.1111/2041-210X.12163

Bruno, J. F., Côté, I. M., & Toth, L. T. (2019). Climate change, coral loss, and the curious case of the parrotfish paradigm: Why don't marine protected areas improve reef resilience? *Annual Review of Marine Science*, *11*(1), 307–334. https://doi.org/10.1146/annurev-marine-010318-095300

Burrows, M. T., Schoeman, D. S., Richardson, A. J., Molinos, J. G., Hoffmann, A., Buckley, L. B., Moore, P. J., Brown, C. J., Bruno, J. F., Duarte, C. M., Halpern, B. S., Hoegh-Guldberg, O., Kappel, C. V., Kiessling, W., O'Connor, M. I., Pandolfi, J. M., Parmesan, C., Sydeman, W. J., Ferrier, S., … Poloczanska, E. S. (2014). Geographical limits to species-range shifts are suggested by climate velocity. *Nature*, *507*(7493), 492–495. https://doi.org/10.1038/nature12976

Carr, M. H., Robinson, S. P., Wahle, C., Davis, G., Kroll, S., Murray, S., Schumacker, E. J., & Williams, M. (2017). The central importance of ecological spatial connectivity to effective coastal marine protected areas and to meeting the challenges of climate change in the marine environment. *Aquatic Conservation: Marine and Freshwater Ecosystems*, *27*(S1), 6–29. https://doi.org/10.1002/aqc.2800

Caselle, J. E., Rassweiler, A., Hamilton, S. L., & Warner, R. R. (2015). Recovery trajectories of kelp forest animals are rapid yet spatially variable across a network of temperate marine protected areas. *Scientific Reports*, *5*(1), 14102. https://doi.org/10.1038/srep14102

Cheung, W. W. L., Frölicher, T. L., Lam, V. W. Y., Oyinlola, M. A., Reygondeau, G., Sumaila, U. R., Tai, T. C., Teh, L. C. L., & Wabnitz, C. C. C. (2021). Marine high temperature extremes amplify the impacts of climate change on fish and fisheries. *Science Advances*, *7*(40), eabh0895. https://doi.org/10.1126/sciadv.abh0895

Chin, T. M., Vazquez-Cuervo, J., & Armstrong, E. M. (2017). A multi-scale high-resolution analysis of global sea surface temperature. *Remote Sensing of Environment*, *200*, 154–169. https://doi.org/10.1016/j.rse.2017.07.029

Cieri, K., Starr, R., Caselle, J., Kahn, A., Lauermann, A., Lindholm, J., Tissot, B., Ziegler, S., Bretz, C., Carlson, P., Hoeke, J., Jainese, C., Martel, G., McDermott, S., Mohay, J., & Salinas-Ruiz, P. (2022). *Monitoring and evaluation of mid-depth rock ecosystems in the California MLPA marine protected area network: ROV dataset*. https://opc.dataone.org/view/urn%3Auuid%3A7353f779-b722-4064-8074-3e9c651ed38e

Cinner, J. E., Caldwell, I. R., Thiault, L., Ben, J., Blanchard, J. L., Coll, M., Diedrich, A., Eddy, T. D., Everett, J. D., Folberth, C., Gascuel, D., Guiet, J., Gurney, G. G., Heneghan, R. F., Jägermeyr, J., Jiddawi, N., Lahari, R., Kuange, J., Liu, W., … Pollnac, R. (2022). Potential impacts of climate change on agriculture and fisheries production in 72 tropical coastal communities. *Nature Communications*, *13*(1), 3530. https://doi.org/10.1038/s41467-022-30991-4

Costello, M. J. (2014). Long live Marine Reserves: A review of experiences and benefits. *Biological Conservation*, *176*, 289–296. https://doi.org/10.1016/j.biocon.2014.04.023

Day, J., Dudley, N., Hockings, M., Holmes, G., Laffoley, D. D. A., Stolton, S., & Wells, S. M. (2012). *Guidelines for applying the IUCN protected area management categories to marine protected areas*. IUCN.

Di Lorenzo, E., & Mantua, N. (2016). Multi-year persistence of the 2014/15 North Pacific marine heatwave. *Nature Climate Change*, *6*(11), 1042–1047. https://doi.org/10.1038/nclimate3082

Di Lorenzo, M., Guidetti, P., Di Franco, A., Calò, A., & Claudet, J. (2020). Assessing spillover from marine protected areas and its drivers: A meta-analytical approach. *Fish and Fisheries*, *21*(5), 906–915. https://doi.org/10.1111/faf.12469

Duffy, J. E., Godwin, C. M., & Cardinale, B. J. (2017). Biodiversity effects in the wild are common and as strong as key drivers of productivity. *Nature*, *549*(7671), 261–264. https://doi.org/10.1038/nature23886

Duncan, M. I., Bates, A. E., James, N. C., & Potts, W. M. (2019). Exploitation may influence the climate resilience of fish populations through removing high performance metabolic phenotypes. *Scientific Reports*, *9*(1), 11437. https://doi.org/10.1038/s41598-019-47395-y

Emblemsvåg, M., Werner, K. M., Núñez-Riboni, I., Frelat, R., Torp Christensen, H., Fock, H. O., & Primicerio, R. (2022). Deep demersal fish communities respond rapidly to warming in a frontal region between Arctic and Atlantic waters. *Global Change Biology*, *28*(9), 2979–2990. https://doi.org/10.1111/gcb.16113

Field, J. C., Miller, R. R., Santora, J. A., Tolimieri, N., Haltuch, M. A., Brodeur, R. D., Auth, T. D., Dick, E. J., Monk, M. H., Sakuma, K. M., & Wells, B. K. (2021). Spatiotemporal patterns of variability in the abundance and distribution of winter-spawned pelagic juvenile rockfish in the California Current. *PLoS One*, *16*(5), e0251638. https://doi.org/10.1371/journal.pone.0251638

Fredston, A., Pinsky, M., Selden, R. L., Szuwalski, C., Thorson, J. T., Gaines, S. D., & Halpern, B. S. (2021). Range edges of North American marine species are tracking temperature over decades. *Global Change Biology*, *27*(13), 3145–3156. https://doi.org/10.1111/gcb.15614

Free, C. M., Thorson, J. T., Pinsky, M. L., Oken, K. L., Wiedenmann, J., & Jensen, O. P. (2019). Impacts of historical warming on marine fisheries production. *Science*, *363*(6430), 979–983. https://doi.org/10.1126/science.aau1758

Freedman, R. M., Brown, J. A., Caldow, C., & Caselle, J. E. (2020). Marine protected areas do not prevent marine heatwave-induced fish community structure changes in a temperate transition zone. *Scientific Reports*, *10*(1). https://doi.org/10.1038/s41598-020-77885-3.

Frid, O., Malamud, S., Di Franco, A., Guidetti, P., Azzurro, E., Claudet, J., Micheli, F., Yahel, R., Sala, E., & Belmaker, J. (2023).

Marine protected areas' positive effect on fish biomass persists across the steep climatic gradient of the Mediterranean Sea. *Journal of Applied Ecology*, *60*(4), 638–649. https://doi.org/10.1111/1365-2664.14352

Frölicher, T. L., Fischer, E. M., & Gruber, N. (2018). Marine heatwaves under global warming. *Nature*, *560*, 360–364. https://doi.org/10.1038/s41586-018-0383-9

García Molinos, J., Halpern, B. S., Schoeman, D. S., Brown, C. J., Kiessling, W., Moore, P. J., Pandolfi, J. M., Poloczanska, E. S., Richardson, A. J., & Burrows, M. T. (2016). Climate velocity and the future global redistribution of marine biodiversity. *Nature Climate Change*, *6*(1), 83–88. https://doi.org/10.1038/nclimate2769

García-Reyes, M., & Sydeman, W. J. (2017). California Multivariate Ocean Climate Indicator (MOCI) and marine ecosystem dynamics. *Ecological Indicators*, *72*, 521–529. https://doi.org/10.1016/j.ecolind.2016.08.045

Gentemann, C. L., Fewings, M. R., & García-Reyes, M. (2017). Satellite sea surface temperatures along the West Coast of the United States during the 2014–2016 Northeast Pacific marine heat wave. *Geophysical Research Letters*, *44*(1), 312–319. https://doi.org/10.1002/2016GL071039

Gleason, M., Fox, E., Ashcraft, S., Vasques, J., Whiteman, E., Serpa, P., Saarman, E., Caldwell, M., Frimodig, A., Miller-Henson, M., Kirlin, J., Ota, B., Pope, E., Weber, M., & Wiseman, K. (2013). Designing a network of marine protected areas in California: Achievements, costs, lessons learned, and challenges ahead. *Ocean & Coastal Management*, *74*, 90–101. https://doi.org/10.1016/j.ocecoaman.2012.08.013

Goetze, J. S., Wilson, S., Radford, B., Fisher, R., Langlois, T. J., Monk, J., Knott, N. A., Malcolm, H., Currey-Randall, L. M., Ierodiaconou, D., Harasti, D., Barrett, N., Babcock, R. C., Bosch, N. E., Brock, D., Claudet, J., Clough, J., Fairclough, D. V., Heupel, M. R., … Harvey, E. S. (2021). Increased connectivity and depth improve the effectiveness of marine reserves. *Global Change Biology*, *27*(15), 3432–3447. https://doi.org/10.1111/gcb.15635

Grorud-Colvert, K., Sullivan-Stack, J., Roberts, C., Constant, V., Pike, E. P., Kingston, N., Laffoley, D., Sala, E., Claudet, J., Friedlander, A. M., Gill, D. A., Lester, S. E., Day, J. C., Gonçalves, E. J., Ahmadia, G. N., Rand, M., Villagomez, A., Ban, N. C., Gurney, G. G., … Lubchenco, J. (2021). The MPA Guide: A framework to achieve global goals for the ocean. *Science*, *373*, eabf0861.

Hamilton, S. L., Caselle, J. E., Malone, D. P., & Carr, M. H. (2010). Incorporating biogeography into evaluations of the Channel Islands marine reserve network. *Proceedings of the National Academy of Sciences of the United States of America*, *107*(43), 18272–18277. https://doi.org/10.1073/pnas.0908091107

Harley, C. D. G., Randall Hughes, A., Hultgren, K. M., Miner, B. G., Sorte, C. J. B., Thornber, C. S., Rodriguez, L. F., Tomanek, L., & Williams, S. L. (2006). The impacts of climate change in coastal marine systems. *Ecology Letters*, *9*(2), 228–241. https://doi.org/10.1111/j.1461-0248.2005.00871.x

Harrison, H. B., Williamson, D. H., Evans, R. D., Almany, G. R., Thorrold, S. R., Russ, G. R., Feldheim, K. A., van Herwerden, L., Planes, S., Srinivasan, M., Berumen, M. L., & Jones, G. P. (2012). Larval export from marine reserves and the recruitment benefit for fish and fisheries. *Current Biology*, *22*(11), 1023–1028. https://doi.org/10.1016/j.cub.2012.04.008

Harvell, C. D., Montecino-Latorre, D., Caldwell, J. M., Burt, J. M., Bosley, K., Keller, A., Heron, S. F., Salomon, A. K., Lee, L., Pontier, O., Pattengill-Semmens, C., & Gaydos, J. K. (2019). Disease epidemic and a marine heat wave are associated with the continental-scale collapse of a pivotal predator (*Pycnopodia helianthoides*). *Science Advances*, *5*(1), eaau7042. https://doi.org/10.1126/sciadv.aau7042

Harvey, B. P., Marshall, K. E., Harley, C. D. G., & Russell, B. D. (2021). Predicting responses to marine heatwaves using functional traits. *Trends in Ecology & Evolution.*, *37*, 20–29. https://doi.org/10.1016/j.tree.2021.09.003

Hofmann, G., Hazen, E., Ambrose, R., Aseltine-Beilson, D., Caselle, J., Chan, F., Levine, A., Micheli, F., Sunday, J., & White, W. (2021). *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.

Holbrook, N. J., Scannell, H. A., Sen Gupta, A., Benthuysen, J. A., Feng, M., Oliver, E. C. J., Alexander, L. V., Burrows, M. T., Donat, M. G., Hobday, A. J., Moore, P. J., Perkins-Kirkpatrick, S. E., Smale, D. A., Straub, S. C., & Wernberg, T. (2019). A global assessment of marine heatwaves and their drivers. *Nature Communications*, *10*(1), 2624. https://doi.org/10.1038/s41467-019-10206-z

Holbrook, N. J., Sen Gupta, A., Oliver, E. C. J., Hobday, A. J., Benthuysen, J. A., Scannell, H. A., Smale, D. A., & Wernberg, T. (2020). Keeping pace with marine heatwaves. *Nature Reviews Earth & Environment*, *1*, 482–493. https://doi.org/10.1038/s43017-020-0068-4

IUCN-WCPA. (2008). *Establishing resilient marine protected area networks - Making it happen: Full technical version, including ecological, social and governance considerations, as well as case studies*. IUCN World Commission on Protected Areas, National Oceanic and Atmospheric Administration, and The Nature Conservancy. https://portals.iucn.org/library/node/9284

Jacox, M. G., Edwards, C. A., Hazen, E. L., & Bograd, S. J. (2018). Coastal upwelling revisited: Ekman, Bakun, and improved upwelling indices for the U.S. West Coast. *Journal of Geophysical Research: Oceans*, *123*(10), 7332–7350. https://doi.org/10.1029/2018JC014187

Jacquemont, J., Blasiak, R., Le Cam, C., Le Gouellec, M., & Claudet, J. (2022). Ocean conservation boosts climate change mitigation and adaptation. *One Earth*, *5*(10), 1126–1138. https://doi.org/10.1016/j.oneear.2022.09.002

Jean-Michel, L., Eric, G., Romain, B.-B., Gilles, G., Angélique, M., Marie, D., Clément, B., Mathieu, H., Olivier, L. G., Charly, R., Tony, C., Charles-Emmanuel, T., Florent, G., Giovanni, R., Mounir, B., Yann, D., & Pierre-Yves, L. T. (2021). The copernicus global 1/12° oceanic and sea ice GLORYS12 reanalysis. *Frontiers in Earth Science*, *9*. https://doi.org/10.3389/feart.2021.698876.

Johnson, J. V., Dick, J. T. A., & Pincheira-Donoso, D. (2022). Marine protected areas do not buffer corals from bleaching under global warming. *BMC Ecology and Evolution*, *22*(1), 58. https://doi.org/10.1186/s12862-022-02011-y

Kandel, P., Pandit, R., White, B., & Polyakov, M. (2022). Do protected areas increase household income? Evidence from a meta-analysis. *World Development*, *159*, 106024. https://doi.org/10.1016/j.worlddev.2022.106024

Kocsis, Á. T., Zhao, Q., Costello, M. J., & Kiessling, W. (2021). Not all biodiversity rich spots are climate refugia. *Biogeosciences*, *18*(24), 6567–6578. https://doi.org/10.5194/bg-18-6567-2021

Laufkötter, C., Zscheischler, J., & Frölicher, T. L. (2020). High-impact marine heatwaves attributable to human-induced global warming. *Science*, *369*(6511), 1621–1625. https://doi.org/10.1126/science.aba0690

Legendre, P., & Gallagher, E. D. (2001). Ecologically meaningful transformations for ordination of species data. *Oecologia*, *129*(2), 271–280. https://doi.org/10.1007/s004420100716

Lima, L. S., Gherardi, D. F. M., Pezzi, L. P., dos Passos, L. G., Endo, C. A. K., & Quimbayo, J. P. (2021). Potential changes in the connectivity of marine protected areas driven by extreme ocean warming. *Scientific Reports*, *11*(1), 10339. https://doi.org/10.1038/s41598-021-89192-6

Love, M. S. (2011). *Certainly more than you want to known about the fishes of the Pacific Coast*. Really Big Press.

Love, M. S., Yoklavich, M., & Thorsteinson, L. K. (2002). *The rockfishes of the Northeast Pacific*. University of California Press.

Malone, D. P., Davis, K., Lonhart, S. I., Parsons-Field, A., Caselle, J. E., & Carr, M. H. (2022). Large-scale, multidecade monitoring data from kelp forest ecosystems in California and Oregon (USA). *Ecology*, *103*(5), e3630. https://doi.org/10.1002/ecy.3630

Marine Life Protection Act. (1999). *Chapter 10.5, California State Legislature, Fish and Game Code (FGC)*. https://leginfo.legislature.ca.gov/faces/codes_displayText.xhtml?lawCode=FGC&division=3.&title=&part=&chapter=10.5.&article=

Martinez Arbizu, P. (2020). *pairwiseAdonis: Pairwise multilevel comparison using adonis*. R package version 0.4.

Mason, J. G., Eurich, J. G., Lau, J. D., Battista, W., Free, C. M., Mills, K. E., Tokunaga, K., Zhao, L. Z., Dickey-Collas, M., Valle, M., Pecl, G. T., Cinner, J. E., McClanahan, T. R., Allison, E. H., Friedman, W. R., Silva, C., Yáñez, E., Barbieri, M. Á., & Kleisner, K. M. (2022). Attributes of climate resilience in fisheries: From theory to practice. *Fish and Fisheries*, *23*(3), 522–544. https://doi.org/10.1111/faf.12630

McLean, M., Mouillot, D., Lindegren, M., Villéger, S., Engelhard, G., Murgier, J., & Auber, A. (2019). Fish communities diverge in species but converge in traits over three decades of warming. *Global Change Biology*, *25*(11), 3972–3984. https://doi.org/10.1111/gcb.14785

McLeod, E., Salm, R., Green, A., & Almany, J. (2009). Designing marine protected area networks to address the impacts of climate change. *Frontiers in Ecology and the Environment*, *7*(7), 362–370. https://doi.org/10.1890/070211

Mignot, A., von Schuckmann, K., Landschützer, P., Gasparin, F., van Gennip, S., Perruche, C., Lamouroux, J., & Amm, T. (2022). Decrease in air-sea CO_2 fluxes caused by persistent marine heatwaves. *Nature Communications*, *13*(1), 4300. https://doi.org/10.1038/s41467-022-31983-0

Multi-Agency Rocky Intertidal Network (MARINe), Partnership for Interdisciplinary Studies of Coastal Oceans (PISCO), & Raimondi, P. (2022). *MARINe/PISCO: Intertidal: MARINe coastal biodiversity surveys: Point contact surveys summarized*. https://doi.org/10.6085/AA/marine_cbs.5.5

Murgier, J., McLean, M., Maire, A., Mouillot, D., Loiseau, N., Munoz, F., Violle, C., & Auber, A. (2021). Rebound in functional distinctiveness following warming and reduced fishing in the North Sea. *Proceedings of the Royal Society B: Biological Sciences*, *288*(1942), 20201600. https://doi.org/10.1098/rspb.2020.1600

Nowakowski, A. J., Canty, S. W., Bennett, N. J., Cox, C. E., Valdivia, A., Deichmann, J. L., Akre, T. S., Bonilla-Anariba, S. E., Costedoat, S., & McField, M. (2023). Co-benefits of marine protected areas for nature and people. *Nature Sustainability*, 1–9. https://doi.org/10.1038/s41893-023-01150-4

Oksanen, J., Simpson, G. L., Blanchet, F. G., Kindt, R., Legendre, P., Minchin, P. R., Friendly, M., McGlinn, D., O'Hara, R. B., Solymos, P., Stevens, M. H. H., Szoecs, E., & Wagner, H. (2022). *vegan: Community ecology package* (R package version 2.6-2). https://CRAN.R-project.org/package=vegan

Olsen, A. Y., Larson, S., Padilla-Gamiño, J. L., & Klinger, T. (2022). Changes in fish assemblages after marine heatwave events in West Hawai'i Island. *Marine Ecology Progress Series*, *698*, 95–109. https://doi.org/10.3354/meps14156

Pacoureau, N., Carlson, J. K., Kindsvater, H. K., Rigby, C. L., Winker, H., Simpfendorfer, C. A., Charvet, P., Pollom, R. A., Barreto, R., Sherman, C. S., Talwar, B. S., Skerritt, D. J., Sumaila, U. R., Matsushiba, J. H., VanderWright, W. J., Yan, H. F., & Dulvy, N. K. (2023). Conservation successes and challenges for wide-ranging sharks and rays. *Proceedings of the National Academy of Sciences of the United States of America*, *120*(5), e2216891120. https://doi.org/10.1073/pnas.2216891120

Payne, M. R., Kudahl, M., Engelhard, G. H., Peck, M. A., & Pinnegar, J. K. (2021). Climate risk to European fisheries and coastal communities. *Proceedings of the National Academy of Sciences of the United States of America*, *118*(40), e2018086118. https://doi.org/10.1073/pnas.2018086118

Pörtner, H.-O., Scholes, R. J., Arneth, A., Barnes, D. K. A., Burrows, M. T., Diamond, S. E., Duarte, C. M., Kiessling, W., Leadley, P., Managi, S., McElwee, P., Midgley, G., Ngo, H. T., Obura, D., Pascual, U., Sankaran, M., Shin, Y. J., & Val, A. L. (2023). Overcoming the coupled climate and biodiversity crises and their societal impacts. *Science*, *380*(6642), eabl4881. https://doi.org/10.1126/science.abl4881

R Core Team. (2021). *R: A language and environment for statistical computing*. R Foundation for Statistical Computing. http://www.R-project.org/

Raimondi, P., & Smith, J. (2022). *Assessment of rocky intertidal habitats for the California marine protected area decadal report*. A report to the Ocean Protection Council and UC Sea Grant. https://www.opc.ca.gov/webmaster/_media_library/2022/05/MPA_RO1.pdf

Roberts, C. M., O'Leary, B. C., McCauley, D. J., Cury, P. M., Duarte, C. M., Lubchenco, J., Pauly, D., Sáenz-Arroyo, A., Sumaila, U. R., Wilson, R. W., Worm, B., & Castilla, J. C. (2017). Marine reserves can mitigate and promote adaptation to climate change. *Proceedings of the National Academy of Sciences of the United States of America*, *114*(24), 6167–6175. https://doi.org/10.1073/pnas.1701262114

Sanford, E., Sones, J. L., García-Reyes, M., Goddard, J. H. R., & Largier, J. L. (2019). Widespread shifts in the coastal biota of northern California during the 2014–2016 marine heatwaves. *Scientific Reports*, *9*(1), 4216. https://doi.org/10.1038/s41598-019-40784-3

Schroeder, I. D., Santora, J. A., Bograd, S. J., Hazen, E. L., Sakuma, K. M., Moore, A. M., Edwards, C. A., Wells, B. K., & Field, J. C. (2019). Source water variability as a driver of rockfish recruitment in the California Current Ecosystem: Implications for climate change and fisheries management. *Canadian Journal of Fisheries and Aquatic Sciences*, *76*(6), 950–960. https://doi.org/10.1139/cjfas-2017-0480

Smale, D. A., Wernberg, T., Oliver, E. C. J., Thomsen, M., Harvey, B. P., Straub, S. C., Burrows, M. T., Alexander, L. V., Benthuysen, J. A., Donat, M. G., Feng, M., Hobday, A. J., Holbrook, N. J., Perkins-Kirkpatrick, S. E., Scannell, H. A., Sen Gupta, A., Payne, B. L., & Moore, P. J. (2019). Marine heatwaves threaten global biodiversity and the provision of ecosystem services. *Nature Climate Change*, *9*(4), 306–312. https://doi.org/10.1038/s41558-019-0412-1

Smith, J. G., Tomoleoni, J., Staedler, M., Lyon, S., Fujii, J., & Tinker, M. T. (2021). Behavioral responses across a mosaic of ecosystem states restructure a sea otter–urchin trophic cascade. *Proceedings of the National Academy of Sciences of the United States of America*, *118*(11), e2012493118. https://doi.org/10.1073/pnas.2012493118

Smith, K. E., Burrows, M. T., Hobday, A. J., King, N. G., Moore, P. J., Sen Gupta, A., Thomsen, M. S., Wernberg, T., & Smale, D. A. (2023). Biological impacts of marine heatwaves. *Annual Review of Marine Science*, *15*(1), 119–145. https://doi.org/10.1146/annurev-marine-032122-121437

Vergés, A., Steinberg, P. D., Hay, M. E., Poore, A. G. B., Campbell, A. H., Ballesteros, E., Heck, K. L., Booth, D. J., Coleman, M. A., Feary, D. A., Figueira, W., Langlois, T., Marzinelli, E. M., Mizerek, T., Mumby, P. J., Nakamura, Y., Roughan, M., van Sebille, E., Gupta, A. S., … Wilson, S. K. (2014). The tropicalization of temperate marine ecosystems: Climate-mediated changes in herbivory and community phase shifts. *Proceedings of the Royal Society B: Biological Sciences*, *281*(1789), 20140846. https://doi.org/10.1098/rspb.2014.0846

Walker, H. J., Hastings, P. A., Hyde, J. R., Lea, R. N., Snodgrass, O. E., & Bellquist, L. F. (2020). Unusual occurrences of fishes in the Southern California Current System during the warm water period of 2014–2018. *Estuarine, Coastal and Shelf Science*, *236*, 106634. https://doi.org/10.1016/j.ecss.2020.106634

Wang, Y., Naumann, U., Eddelbuettel, D., Wilshire, J., & Warton, D. (2022). *mvabund: Statistical methods for analysing multivariate abundance data* (R package version 4.2.1). https://CRAN.R-project.org/package=mvabund

Warton, D. I., Wright, S. T., & Wang, Y. (2012). Distance-based multivariate analyses confound location and dispersion effects. *Methods in Ecology and Evolution*, *3*(1), 89–101. https://doi.org/10.1111/j.2041-210X.2011.00127.x

Wernberg, T., Bennett, S., Babcock, R. C., de Bettignies, T., Cure, K., Depczynski, M., Dufois, F., Fromont, J., Fulton, C. J., Hovey, R. K., Harvey, E. S., Holmes, T. H., Kendrick, G. A., Radford, B., Santana-Garcon, J., Saunders, B. J., Smale, D. A., Thomsen, M. S., Tuckett, C. A., … Wilson, S. (2016). Climate-driven regime shift of a temperate marine ecosystem. *Science*, *353*(6295), 169–172. https://doi.org/10.1126/science.aad8745

Williamson, D. H., Harrison, H. B., Almany, G. R., Berumen, M. L., Bode, M., Bonin, M. C., Choukroun, S., Doherty, P. J., Frisch, A. J., Saenz-Agudelo, P., & Jones, G. P. (2016). Large-scale, multidirectional larval connectivity among coral reef fish populations in the Great Barrier Reef Marine Park. *Molecular Ecology*, *25*(24), 6039–6054. https://doi.org/10.1111/mec.13908

Wilson, J. R., Lomonico, S., Bradley, D., Sievanen, L., Dempsey, T., Bell, M., McAfee, S., Costello, C., Szuwalski, C., McGonigal, H., Fitzgerald, S., & Gleason, M. (2018). Adaptive comanagement to achieve climate-ready fisheries. *Conservation Letters*, *11*(6), e12452. https://doi.org/10.1111/conl.12452

Ziegler, S. L., Brooks, R. O., Hamilton, S. L., Ruttenberg, B. I., Chiu, J. A., Fields, R. T., Waltz, G. T., Shen, C., Wendt, D. E., & Starr, R. M. (2022). External fishing effort regulates positive effects of no-take marine protected areas. *Biological Conservation*, *269*, 109546. https://doi.org/10.1016/j.biocon.2022.109546

Ziegler, S. L., Johnson, J. M., Brooks, R. O., Johnston, E. M., Mohay, J. L., Ruttenberg, B. I., Starr, R. M., Waltz, G. T., Wendt, D. E., & Hamilton, S. L. (2023). Marine protected areas, marine heatwaves, and the resilience of nearshore fish communities. *Scientific Reports*, *13*(1), 1405. https://doi.org/10.1038/s41598-023-28507-1

SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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A Synthesis of Ecological and Social Outcomes from the California Marine Protected Area (MPA) Network

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Jennifer E Caselle
University of California, Santa Barbara
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University of California, Santa Barbara
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A Synthesis of Ecological and Social Outcomes from the California Marine Protected Area (MPA) Network

A report to the California Ocean Protection Council
and California Department of Fish and Wildlife

NCEAS
National Center for Ecological Analysis and Synthesis

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Report Authors

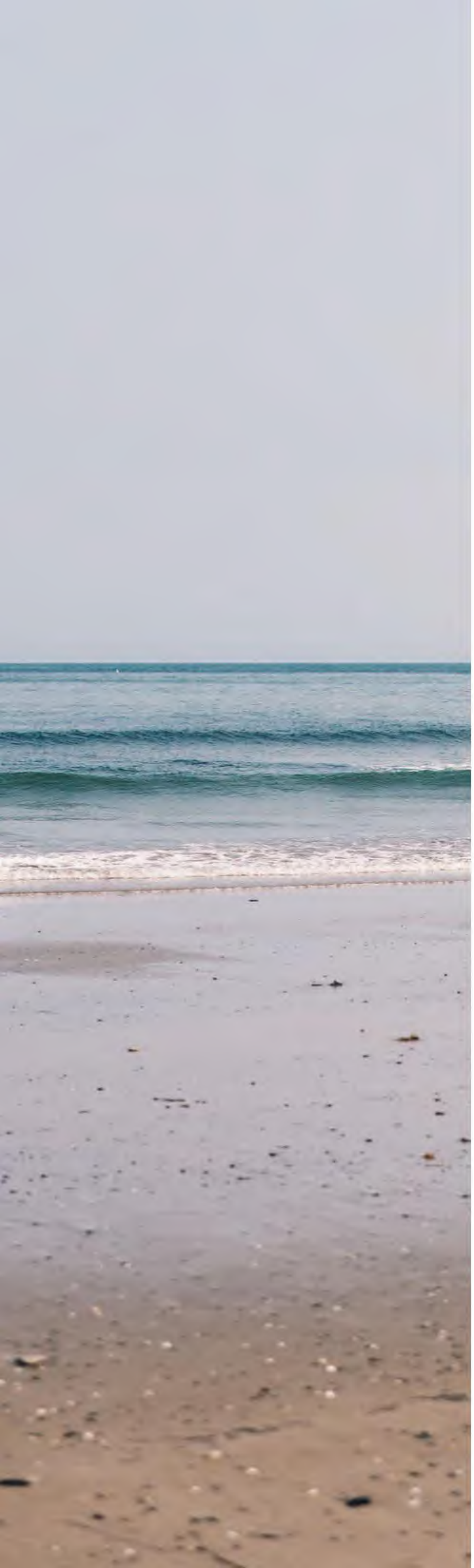
Jennifer E. Caselle
University of California Santa Barbara
Co-Principal Investigator

Kerry J. Nickols
California State University Northridge
Co-Principal Investigator

Joshua G. Smith
University of California Santa Barbara
Postdoctoral Researcher

Cori Lopazanski
University of California Santa Barbara
Graduate Student Researcher

Julien Brun
National Center for Ecological Analysis and Synthesis
Data Scientist



Working Group Members

Clarissa Anderson
Scripps Institution of Oceanography

Mark Carr
University of California Santa Cruz

Joachim Claudet
National Center for Scientific Research, PSL Université Paris

Jenny Dugan
University of California Santa Barbara

Jacob Eurich
Environmental Defense Fund

Tessa Francis
University of Washington Tacoma

Chris Free
University of California Santa Barbara

David Gill
Duke University

Scott Hamilton
Moss Landing Marine Laboratories

Kristin Kaschner
University of Freiburg

David Mouillot
Université de Montpellier

Pete Raimondi
University of California Santa Cruz

Rick Starr
Moss Landing Marine Laboratories

Shelby Ziegler
University of Georgia

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Executive Summary

As part of the Decadal Management Review, and with support from California's Ocean Protection Council, the National Center for Ecological Analysis and Synthesis (NCEAS) initiated a working group to develop an understanding of how the State of California's Network of marine protected areas (MPAs) has performed over the past decade, and the lessons those insights provide for future monitoring and management of the network. The project leveraged a working group of experts from within and outside California to synthesize existing MPA monitoring data and data related to additional factors likely to influence MPA performance.

The primary goal of this MPA analysis and synthesis project is to perform social and ecological analyses using a diverse set of available monitoring data that address critical MPA performance evaluation questions, guided by the MPA Monitoring Action Plan and the recommendations of both the Decadal Evaluation and the Climate Resilience Working Groups, and working in close coordination with long-term MPA monitoring researchers, some of which are working group members.

The working group focused on four main aspects of MPA evaluation: Ecological Performance, Habitat, Climate Resilience, and Human Engagement. We first examined what synthetic analyses could be performed across the Network, different habitats, and across the North, Central, South, and Northern Channel Islands regions to evaluate whether MPA implementation resulted in increased metrics of performance. We then evaluated the proportional representation of coastal habitats across the MPA Network. We also examined how an unprecedented climate change driven marine heatwave impacted ecological communities within and outside of MPAs. Lastly, we assessed how human engagement was distributed across the MPA Network.

Ecological Performance

Key Findings:

- Fish biomass in 2019-2020 tended to be greater in MPAs relative to outside of MPAs for targeted species across different monitored habitats and for all regions except Northern California. However, only in the South Coast region was this MPA effect significant, with this region driving a significant positive 'statewide' effect of MPAs.
- The positive MPA responses in fish biomass within each region were related to MPA age (which is closely correlated with region) and not related to MPA size or distance to port (as a proxy for fishing effort).
- For three habitats (kelp forest, rocky reef, and deep reef) there is a sufficient time series with which to measure change over time. Biomass of fish species targeted by fishing increased over time for two habitats (kelp forest and rocky reef) in three out of four regions.
- There was no difference in fish diversity between MPA and reference sites within any of the habitats.

Recommendations:

- Continued comprehensive monitoring is required to measure MPA performance effectively and to identify changes over time.
- Incorporating additional influencing factors such as fishing pressure prior to implementation and connectivity is important to evaluating patterns of response to MPA implementation.
- Ecological performance of MPAs must be evaluated against science-based expectations of performance.

Habitat

Key Findings:

- Onshore habitat composition (i.e., proportion of shoreline that is sandy beach, rocky intertidal, coastal marsh, tidal flats, and hardened/armored shoreline) varies among MPAs and regions within the network. South Coast MPAs contained more sandy beach, while the Northern Channel Islands and Central coast MPAs contained more rocky intertidal. MPAs in the North Coast were highly variable, with some containing 100% sandy beach and others 100% rocky intertidal.
- Nearshore/offshore habitat composition (i.e., proportion of hard and soft substrate and kelp cover by depth stratum) varies among MPAs within the network. Interestingly, within each region, larger MPAs tend to contain greater relative amounts of soft bottom, deeper habitats
- MPAs can be classified by their situational context – whether they are estuary-only, coastal, or offshore – and there are significant differences in habitat composition among these three classifications.
- There are significant differences in coastal MPA habitat composition among each of the four regions (North, Central, N. Channel Islands, and South).

Recommendations:

- With the extensive habitat data available, future analyses can examine linkages between habitat diversity and species diversity.
- Further human dimensions data are required to assess whether culturally important habitats are adequately protected.

Climate Resilience

Key Findings:

- Community composition in Central California changed as a result of the marine heatwave in three out of five habitats (kelp forest, rocky reef, and deep reef).
- Community shifts in Central California were associated with changes in oceanographic conditions.
- In Central California, some ecological communities in SMRs experienced less change than in associated reference sites, but across all monitoring groups and MPAs, there was no overarching effect of MPAs in mitigating change. Continued monitoring will be able to address differential effects of MPAs on recovery.

Recommendations:

- In order to understand the ability of the MPA Network to resist and recover from future marine heatwave events, it is critical to have sufficient monitoring across regions. Therefore, continued comprehensive monitoring is required.
- California’s habitats are likely still recovering from the heatwave and it is possible that more time needs to pass before recovery and resilience can be adequately assessed.
- Climate change threatens to inhibit the intended performance outcomes of marine protected areas. Additional tools and strategies are needed in conjunction with regulatory protection to plan for and mitigate the consequences of marine heatwave events and other climate perturbations. As long as the world continues to emit carbon dioxide, both protected and unprotected areas in California’s waters will remain under threat. Hofmann et al. (2021) prioritized research questions and methods, and proposed recommendations for the State to follow. We recommend centering that report in future monitoring and research.

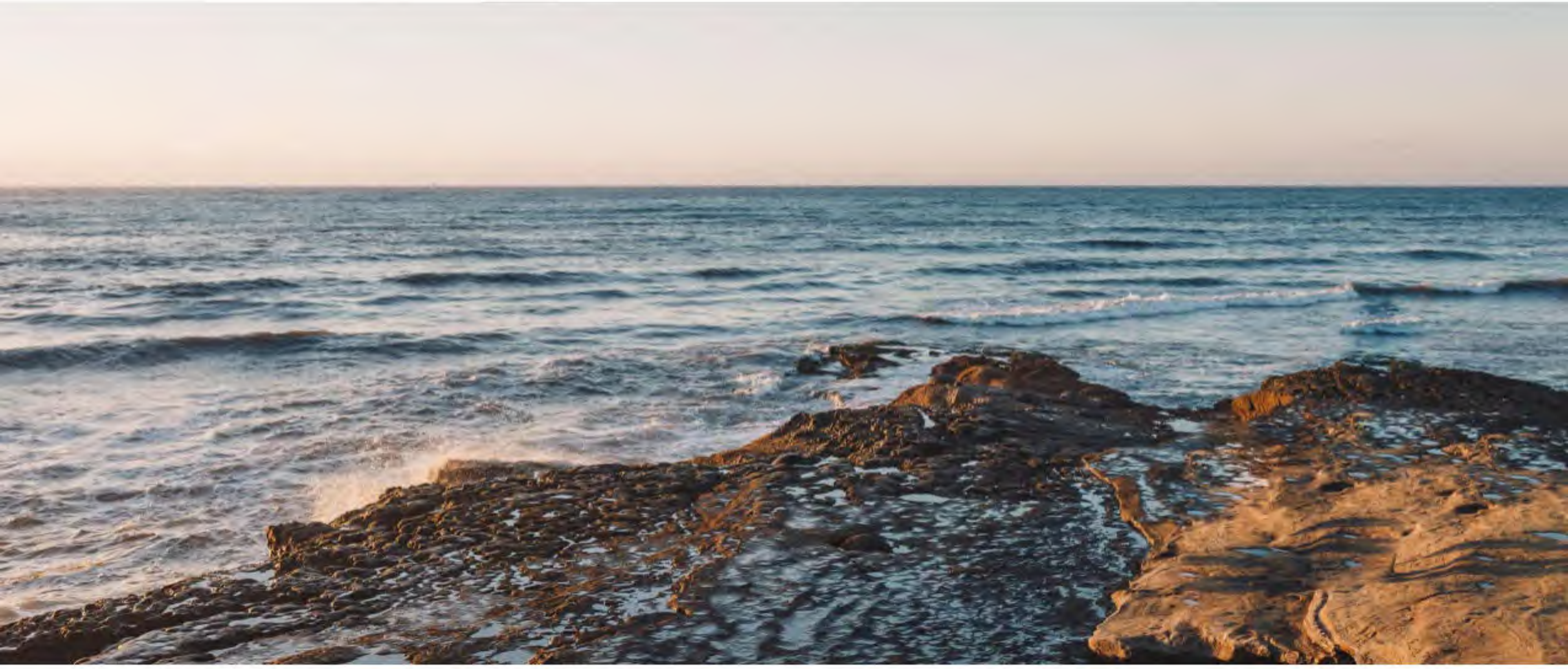
Human Engagement

Key Findings:

- Engagement in MPAs is largely proportional to population density (number of people within 50 km), but some 'charismatic' MPAs have shared traits that further expand human use.
- MPAs affiliated with state and county parks, extensive sandy beach shoreline, and that allow take show disproportionately high engagement relative to population density.

Recommendations:

- Engagement in MPAs could be promoted by developing land-based infrastructure that facilitates access to coastal MPAs or by co-locating new MPAs with existing infrastructure during the design phase.
- Knowledge of the representativeness of current users is necessary to design and implement programs that promote access and engagement among underrepresented groups.
- Further data on human dimensions is required to evaluate California's MPA Network in this regard. Hall-Arber et al. (2021) lay out specific recommendations for advancing the capacity to evaluate California's MPA Network within the human domain. We recommend using that report as a roadmap for the future.



Project Narrative

Background:

Acknowledging the importance of California’s marine resources to the state’s economy and ecological systems, the California Legislature passed the Marine Life Protection Act (MLPA, Chapter 10.5 of the California Fish and Game Code, §2850-2863) in 1999. This legislation required the state to design and implement a network of MPAs to meet the following six goals:

Protect the natural diversity and abundance of marine life, and the structure, function and integrity of marine ecosystems.

Help sustain, conserve and protect marine life populations, including those of economic value, and rebuild those that are depleted.

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.

Protect marine natural heritage, including protection of representative and unique marine life habitats in California waters for their intrinsic values.

Ensure California's MPAs have clearly defined objectives, effective management measures and adequate enforcement and are based on sound scientific guidelines.

Ensure the State's MPAs are designed and managed, to the extent possible, as a network.

Guided by these goals, California established a globally significant MPA network that consists of 124 individual MPAs and spans the state's entire 1,100-mile coastline, resulting in protection of 16% (850 square miles) of state waters. Management of the statewide MPA network is guided by the 2016 Master Plan for Marine Protected Areas (CDFW 2016), which establishes a decadal, network-wide management review cycle for MPAs:

"The formal 10-year management review will emphasize ecological, socioeconomic, and governance aspects of the network… [the review] may include, but not be limited to, a scientific evaluation, public scoping meetings, and panel discussions to determine the status, function, and possible changes to the network. The scientific evaluations that inform the formal 10-year management review will encompass multiple elements, including a scientific assessment of ecological and socioeconomic MPA monitoring results, together with other data streams such as MPA enforcement data."

The first Decadal Management Review (DMR) is currently underway. This review will evaluate MPA performance against the six goals of the MLPA and will be informed by a variety of data and information streams including both baseline and long-term MPA monitoring (**Figure 1**). The first phase of MPA monitoring was intended to establish an ecological and socioeconomic baseline at or near the time of MPA implementation in each region, against which future changes can be measured. Baseline MPA monitoring concluded in 2018. To guide long-term MPA monitoring into the future, the California Department of Fish and Wildlife (CDFW) has created an MPA Monitoring Action Plan (CDFW 2018) that lays out priority metrics, habitats, sites, and species to focus on for long-term monitoring. The Action Plan was approved by the California Fish and Game Commission (CFGC) and the California Ocean Protection Council (OPC) in the fall of 2018. In the spring of 2019, OPC funded several long-term, habitat-specific MPA monitoring projects that are grounded in the Action Plan. Habitat-specific technical reports have been submitted to CDFW as part of the DMR (**Box 1**).

Box 1 | *California MPA monitoring habitat-specific technical reports.*

Habitat and Species Type	Description
Rocky Intertidal o Invertebrates o Algae	Historical biological and environmental data collected in the rocky intertidal statewide, dating back to the 1980s.
Kelp Forests o Invertebrates o Algae o Benthic & midwater fishes	Historical biological surveys of kelp forests and shallow rocky reefs (less than 30 meters) statewide, dating back to 2000, at MPAs and reference sites.
Rocky Reef (CCFRP) o Demersal fishes	Hook-and-line surveys of fish composition, abundance, size, and biomass at MPAs and reference sites.
Deep Reef o Invertebrates o Demersal fishes	Surveys of invertebrates and fishes conducted at deep (greater than 30 meters) rocky reefs at MPAs and reference sites.
Sandy Beach and Surf Zone o Birds o Fishes	Surveys of birds, stranded kelp, and surf zone fishes at MPAs and reference sites.

From December 2019 - June 2021, OPC and CDFW supported a Decadal Evaluation Working Group (DEWG) of the OPC Science Advisory Team (SAT) that was tasked with translating the goals of the MLPA into scientifically tractable questions and associated analytical approaches, building on the Action Plan (in particular Appendix B) to guide evaluation of the MPAs during the DMR. Emphasis was placed in that report (Hall-Arber et al. 2021) on integrating data across habitats, regions, and domains in the DMR, especially to answer evaluation questions related to the performance of the overall network. In parallel, a second working group was convened by the OPC and Ocean Science Trust on behalf of CDFW to explore the role of California's MPAs and MPA Network in imparting climate resilience. The Climate Resilience report (Hofmann et al. 2021) provided a set of research questions and recommendations to support the DMR. These two reports, together with the Action Plan, provide the rationale and framing for this synthesis report.

With support from OPC, the National Center for Ecological Analysis and Synthesis (NCEAS) initiated this project to develop an understanding of how the State of California's network of MPAs has performed over the past decade, and the lessons those insights provide for future monitoring and management of the network. The project leveraged a working group of experts from within and outside CA to synthesize existing MPA monitoring data and data related to additional factors likely to influence MPA performance.

The primary goal of this MPA analysis and synthesis project is to perform social-ecological analyses using a diverse set of available monitoring data that address critical MPA performance evaluation questions, guided by the Action Plan and the recommendations of both the Decadal Evaluation and the Climate Resilience Working Groups, and working in close coordination with long-term MPA monitoring researchers, some of which are working group members.

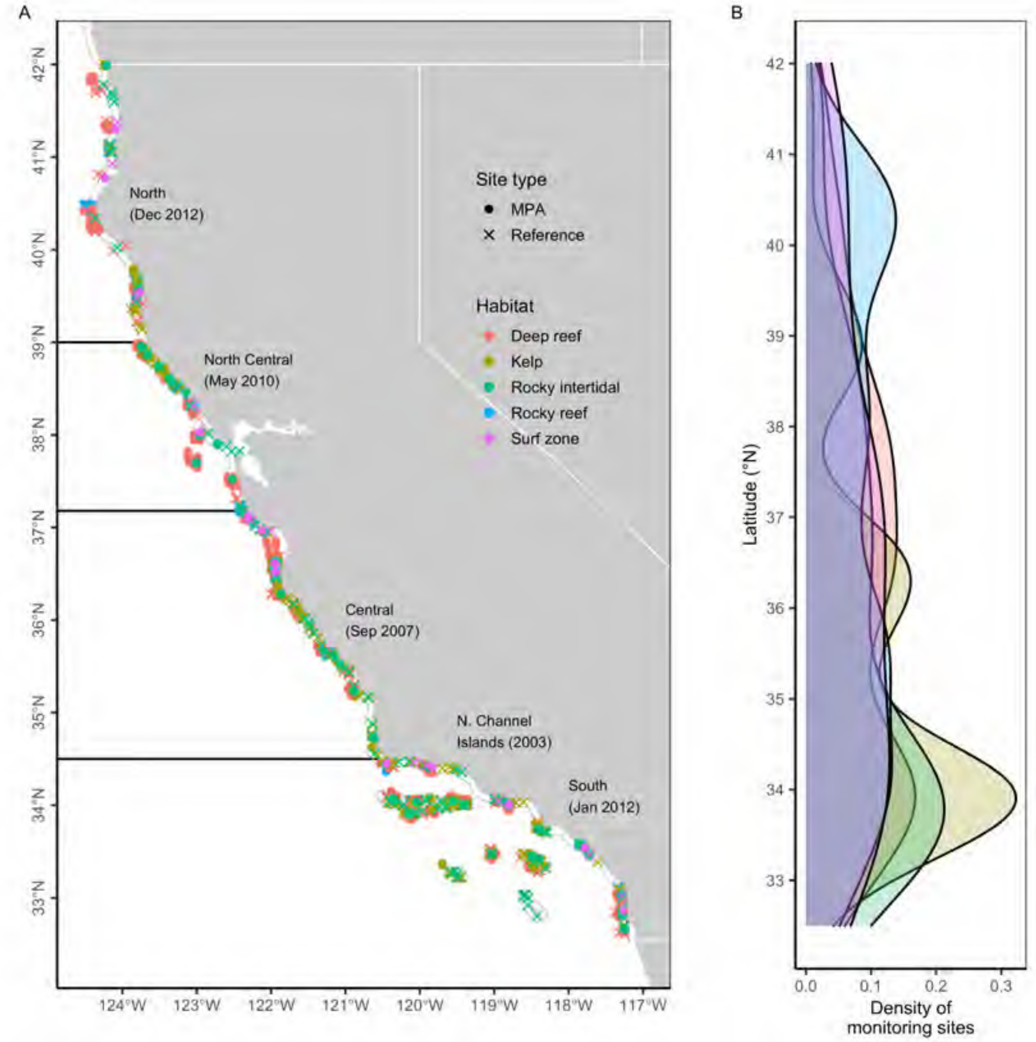


Figure 1 | *Ecological monitoring sites inside (circle) and outside (x) of marine protected areas (MPAs) along California's coast. In panel A, the dark horizontal lines delineate the four MLPA planning regions (labeled with year of implementation) and the thin gray line indicates state waters (3 nautical miles offshore). Panel B depicts the density of sites for each monitoring group and MLPA planning regions. The colors in each panel correspond to the six long term monitoring programs included in this synthesis report: deep reef, kelp forest, rocky intertidal, rocky reef (CCFRP), and surf zone.*

Objectives:

The group was tasked with building upon existing analyses stemming from the habitat-specific monitoring teams and providing new analyses as needed, to provide answers to MPA performance evaluation questions outlined in Appendix B of the Action Plan and refined by the DEWG. The broad objectives for this group were to:

Identify patterns and trends emerging from existing data streams and analytical products, including baseline and long-term MPA monitoring projects, by integrating across habitats and integrating across the statewide network.

Incorporate influencing factors (e.g., climate change, environmental conditions, historical fishing pressure) into analyses related to MPA performance evaluation, especially as they relate to performance of the network of MPAs.

Explore MPA performance evaluation questions that are not currently being addressed, but for which sufficient data exist to conduct analyses.

Evaluate MPA design criteria using best available science and cutting-edge analytical approaches.

To date, the working group focused on four main aspects of MPA evaluation: Ecological Performance, Habitat, Climate Resilience, and Human Engagement. We first examined what synthetic analyses could be performed across the network and different habitats to evaluate whether or not MPA implementation resulted in increased metrics of MPA performance. We then evaluated the proportional representation of coastal habitats across the MPA network. We also examined how an unprecedented climate change driven marine heatwave impacted ecological communities within and outside of MPAs. Lastly, we assessed how human engagement was distributed across the MPA network.

The analyses presented in this report included data collected by five habitat monitoring groups: rocky intertidal, surf zone, kelp forest (visually sampled by divers at 5-20 m depth), rocky reef (sampled by hook and line at <40 m depth; CCFRP), and deep reef (sampled at 30-130 m using a remotely operated vehicle). Across the habitat monitoring groups, two organismal groups were sampled: fishes (kelp forest, rocky reef, and deep reef), and benthic invertebrates and algae (rocky intertidal and kelp forest). The remainder of the report is organized into four chapters: Ecological Performance, Habitats, Climate Resilience, and Human Engagement. The overarching questions for each chapter were guided by the following MLPA goals and DEWG questions:

Chapter One: Ecological Performance

(1) Did regulatory implementation of a marine protected area network result in the increase of fish biomass and diversity inside of MPAs relative to outside (hereafter, 'reference') locations?

- MLPA Goal 1: To protect the natural diversity and abundance of marine life, and the structure, function, and integrity of marine ecosystems.
- MLPA Goal 2: To help sustain, conserve, and protect marine life populations, including those of economic value, and rebuild those that are depleted.
- MLPA Goal 6: To ensure that the MPAs are designed and managed, to the extent possible, as a component of a connected statewide network.
- DEWG question 1c: Does the difference between MPAs and reference sites in biomass of a focal and/or protected species increase over time?
- DEWG question 1g: Does the difference between MPAs and reference sites in overall biomass of focal and/or protected species increase over time?
- DEWG question 1h: Does the difference between MPAs and reference sites in overall biomass of fished species increase over time relative to species that are not fished?
- DEWG question 20a: Has the difference between MPAs and reference areas in the size/age structure of recreationally fished species increased over time?
- DEWG question 2a: Does the difference between MPAs and reference sites in species diversity within any given functional group increase over time?

Chapter Two: Habitat

(1) How are coastal and marine habitats distributed across the MPA network?

(2) Are there regional differences in habitat composition among the management regions?

- MLPA Goal 4: Protect marine natural heritage, including protection of representative and unique marine life habitats in CA waters for their intrinsic value.
- DEWG question 21: Have unique habitats been adequately represented and protected by the current distribution and designation of MPAs?

Chapter Three: Climate Resilience

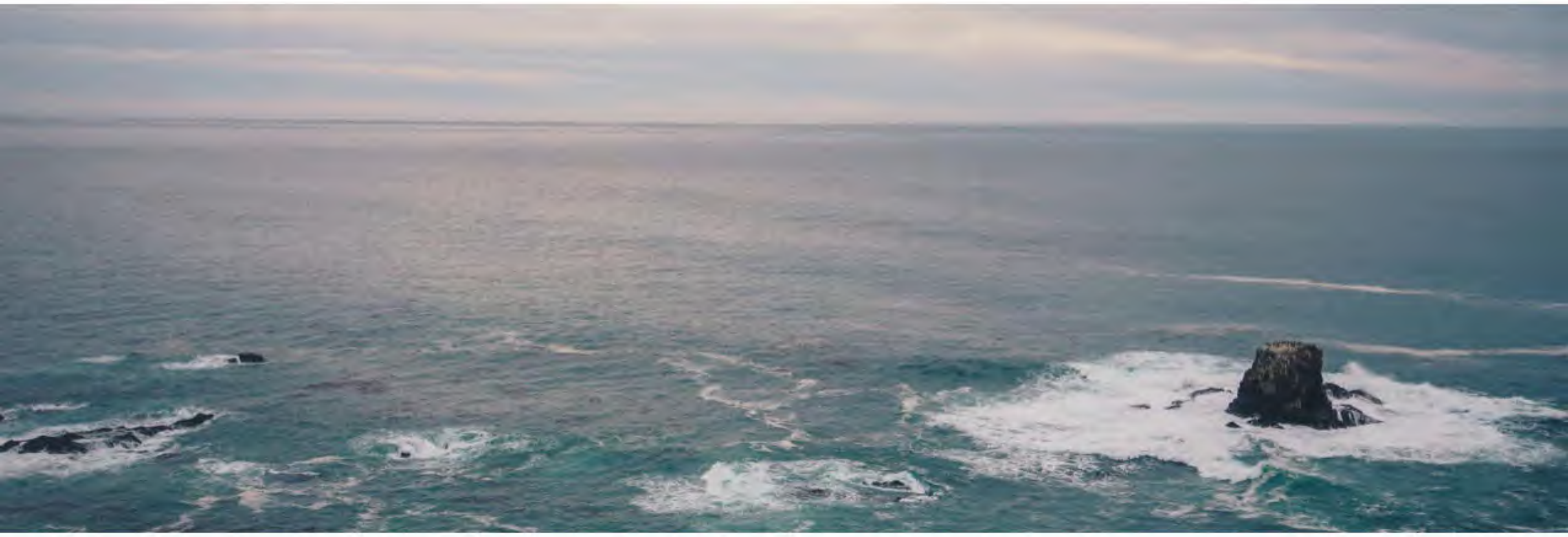
(1) How did ecological communities within and outside of MPAs respond to a marine heatwave?
(2) Were changes in ecological communities similar across ecosystems?
(3) Are communities in MPAs more resistant or resilient to disturbances like marine heatwaves?

- MLPA Goal 1: To protect the natural diversity and abundance of marine life, and the structure, function, and integrity of marine ecosystems.
- MLPA Goal 2: To help sustain, conserve, and protect marine life populations, including those of economic value, and rebuild those that are depleted.
- DEWG question 5a: Does the nature of recovery of natural communities from disturbance events differ in MPAs relative to outside reference sites?
- DEWG question 5b: Does the timing of recovery of natural communities from disturbance events differ in MPAs relative to outside reference sites?
- DEWG question 5e: Do MPAs contribute to the recovery of impacted ecosystems?

Chapter Four: Human Engagement

(1) How is human engagement distributed across the network?

- MLPA Goal 1: To protect the natural diversity and abundance of marine life, and the structure, function, and integrity of marine ecosystems.
- MLPA Goal 2: To help sustain, conserve, and protect marine life populations, including those of economic value, and rebuild those that are depleted.
- DEWG question 5a: Does the nature of recovery of natural communities from disturbance events differ in MPAs relative to outside reference sites?
- DEWG question 5b: Does the timing of recovery of natural communities from disturbance events differ in MPAs relative to outside reference sites?
- DEWG question 5e: Do MPAs contribute to the recovery of impacted ecosystems?



Chapter One: Ecological Performance

Introduction:

California's network of MPAs span multiple habitats and ecosystems, providing a unique opportunity to evaluate emergent social and ecological effects in relation to the design of the network (i.e., MPA 'performance'). As part of the Marine Life Protection Act (MLPA), the California MPA network was designed to conserve the diversity and abundance of marine life, and to protect the structure and function of marine ecosystems. Through the State's MPA Monitoring Program, there is now a wealth of monitoring data available to support the evaluation of the MPA network in relation to the goals of the MLPA.

The MLPA mandated that California re-design a system of small numbers of unconnected protected areas into a functional network of ecologically connected MPAs. A network generally includes a set of multiple MPAs, located in critical habitats, and designed to be connected by the dispersal of larvae and/or movement of juveniles and adults. In an effective network, organisms must be able to travel beyond the boundaries of a single protected area into other protected areas. By using different sizes and spacing of protected areas, a network can protect species with different life history and behavioral characteristics, and may offer a better compromise between human use and conservation than single large protected areas. California went through a lengthy and science-informed process for implementing the network (Gleason et. al 2013, Kirlin et al. 2013, Botsford et al. 2014).

For all the potential benefits of well-designed MPA networks, they pose many difficulties in assessing MPA performance. Often, and even by definition, a network is placed across a biogeographic region and designed to capture a variety of habitat types and environmental characteristics. While this may be useful for protecting a wide range of species, assessment is challenging because the effect of each MPA in the network may be different, depending on the traits and life-histories of the species it contains, the variety of environmental characteristics it experiences, and the spatial distribution of human usage around and within it. Further, each MPA also protects a diversity of habitats, each monitored independently using methods best suited to the particular habitat characteristics.

Both the baseline and long-term monitoring of California's MPAs have been organized around specific habitats (e.g., rocky intertidal, shallow and mid-depth rocky reefs, sandy beach, and estuaries) as called for in the MPA Monitoring Action Plan. Despite a well-resourced MPA Management and Monitoring Program and some coordination between the habitat-specific monitoring programs, we found that there were limitations in the comprehensiveness and comparability of the datasets across time and space (**Table S1**). For example, since MPAs in different regions of California were implemented at different times, baseline monitoring for each region occurred in different years. In addition, although some efforts were made to rank the importance of individual MPAs for monitoring prioritization, spatial overlap among different habitat monitoring groups was not consistent (**Table S2**). Despite these limitations, we present a suite of analyses designed to evaluate the performance of California's MPAs across habitats and regions. We focus on taxa (fishes) and years (2019-20) where we have the most complete datasets across habitats. The insights generated from these analyses will be of broad interest to other regions seeking to develop reserve systems and MPA networks.

We used a meta-analytical framework to test for emergent effects of MPA implementation. It should be noted that we did not do network analyses *per se* - that is we do not account for connectivity or between-habitat ecological relationships.

The MPA Ecological Performance chapter of this report aims to address the following MLPA goals:

- MLPA Goal 1: To protect the natural diversity and abundance of marine life, and the structure, function, and integrity of marine ecosystems.
- MLPA Goal 2: To help sustain, conserve, and protect marine life populations, including those of economic value, and rebuild those that are depleted.
- MLPA Goal 6: To ensure that the MPAs are designed and managed, to the extent possible, as a component of a statewide network.

Methods and Analytical Approaches:

We explored the ecological performance of the MPA network by evaluating regional trends in fish biomass and diversity inside and outside of SMRs and de facto SMRs (evaluated for each individual habitat based on regulations; hereafter 'SMRs', see below). We used a meta-analytic approach to evaluate these performance metrics, where we summarized results for each habitat within a region in a synthetic framework, to determine whether any effects of no-take regulations manifest across habitat monitoring groups. This particular analysis does not evaluate changes over time. Instead, it uses the means of biomass (for targeted and nontargeted fish species) or diversity (for all fish species) inside and outside of SMRs across the 2019-20 sampling period as a measure of effect size – that is, an MPA effect. For this analysis, we only used data from the 2019-20 sampling period for two fundamental reasons. First, the 2019-20 sampling period is the most spatially comprehensive time point across all of the habitat monitoring groups; and second, this sampling period is well after MPA establishment for all regions. The model using fish biomass distinguishes between targeted and nontargeted fish species. The null hypothesis is that biomass of targeted and nontargeted fish should be similar if there is no effect of no-take regulations (all else being equal). Therefore, we interpret significant differences between these two categories of harvest status (targeted and nontargeted) as being reflective of an effect of regulatory protection (Carr et al. 2021).

De facto SMRs

A SMCA was designated as a de facto SMR (no-take reserve) for a particular habitat if the allowed take in the SMCA was unlikely to affect that particular habitat. For example, if the only allowed take in a SMCA is salmon (found mostly offshore), this SMCA might be considered a de facto SMR for kelp forests, surf zone and rocky intertidal habitats. This decision was made using expert judgment of the Principal Investigators of the habitat monitoring groups. See **Table S3** for list of de facto SMRs by region and habitat group.

Model construction

The meta-analysis was constructed using the mean response ratio (fish biomass or diversity of SMRs / fish biomass or diversity of reference sites) for each region and for each habitat. For each habitat, we first calculated the mean biomass or diversity (Shannon-Wiener Index) for each protected area (SMRs only) and for each reference site (non-protected areas outside SMRs) within a region across the 2019-20 sampling period. After calculating the mean for each protected area and reference site, we then computed the log ratio using the grand mean of all protected areas and of all reference sites for a given habitat within a region. Therefore, the log response ratio (logRR) for a given region, habitat, and fished status is equivalent to:

$$\log{(RR)}_{\text{region, habitat, fished status}} = \log\frac{x_{\text{protected}}}{x_{\text{reference}}}$$

Importantly, the meta analysis also includes an overall pooled effect size, which is weighted by the spatial sampling effort of each habitat. Therefore, habitats that had greater sampling effort at SMRs and reference sites have greater ‘weight’ in the overall pooled effect.

We tested for significance of the within-region pooled effect using a random effect (RE) linear meta-regression. The RE model assumes that the effect of regulatory protection might vary by ecological community type (i.e., by habitat). It is a suitable model fitting type for this analysis because it also assumes that variability may be due to real (unexplained) differences inherent to each region or habitat.

Drivers of performance

We constructed a linear metaregression to evaluate the effect of MPA characteristics (MPA age, size, and distance to port) on fish biomass and diversity. Similar to the meta-analysis above, the meta-regression synthesizes across habitats to evaluate whether any observed differences in response ratio between regions are broadly explained by MPA age, size, and distance to the closest port. Port locations were identified from the CDFW MarineBIOS layer.

Temporal trends of fish biomass and diversity

We also examined the temporal trends (annual changes over time) of targeted and nontargeted fish biomass and total fish diversity for habitats that had sufficient data spanning multiple years. This included three habitats: kelp forest, rocky reef, and deep reef. For this analysis, we calculated the mean response ratio of SMR and reference site pairs for each habitat, region, and year using all years that were sampled for each group.

Data Summaries, Analyses, Figures, Tables, and Interpretation:

Although individual habitats showed significant and positive response ratios, the only significant pooled effect (across habitats within a region) was for targeted fish biomass in the South region (**Figure 1**; P < 0.001). However, there was a significant MPA effect on biomass overall (biomass of all fishes regardless of fished status) and targeted fish biomass at the state level (across all regions). This latter result is likely driven by the strong positive response ratio in the south, but also in-part by the positive (not significant) response ratios observed in other regions. These differences between SMR and reference sites were best explained by MPA age, although MPA age is closely correlated with bioregion, as many, but not all, MPAs were implemented at the same time within a region. MPA size and distance to port were not significantly related to regional differences in response ratios (**Table 1**). We did not find a significant effect size for fish diversity (**Figure 2**). Three out of four regions show increasing trends in biomass over time for targeted fish biomass within kelp forest and rocky reef habitats (**Figure 3**). No consistent changes in fish biodiversity were found over time across regions or habitats (**Figure 4**).

Table 1 | *Results from a meta-regression on the between-region drivers of response ratios. Predictors are the input variables in the meta regression, Estimates are the model coefficients (the relative contribution of each variable to observed differences in response ratio), CI represents the 95% confidence interval surrounding each coefficient, and p is the significance level of each predictor variable.*

Predictors	Estimates	CI	*p*
Region [north]	3.57	0.48 – 6.65	**0.023**
Region [north islands]	-4.37	-0.89 – -0.64	**0.022**
Region [south]	5.20	1.11 – 9.29	**0.013**
MPA age	0.99	0.17 – 1.81	**0.018**
MPA size	0.01	-0.03 – 0.05	0.648
Distance to port (m)	0	0	0

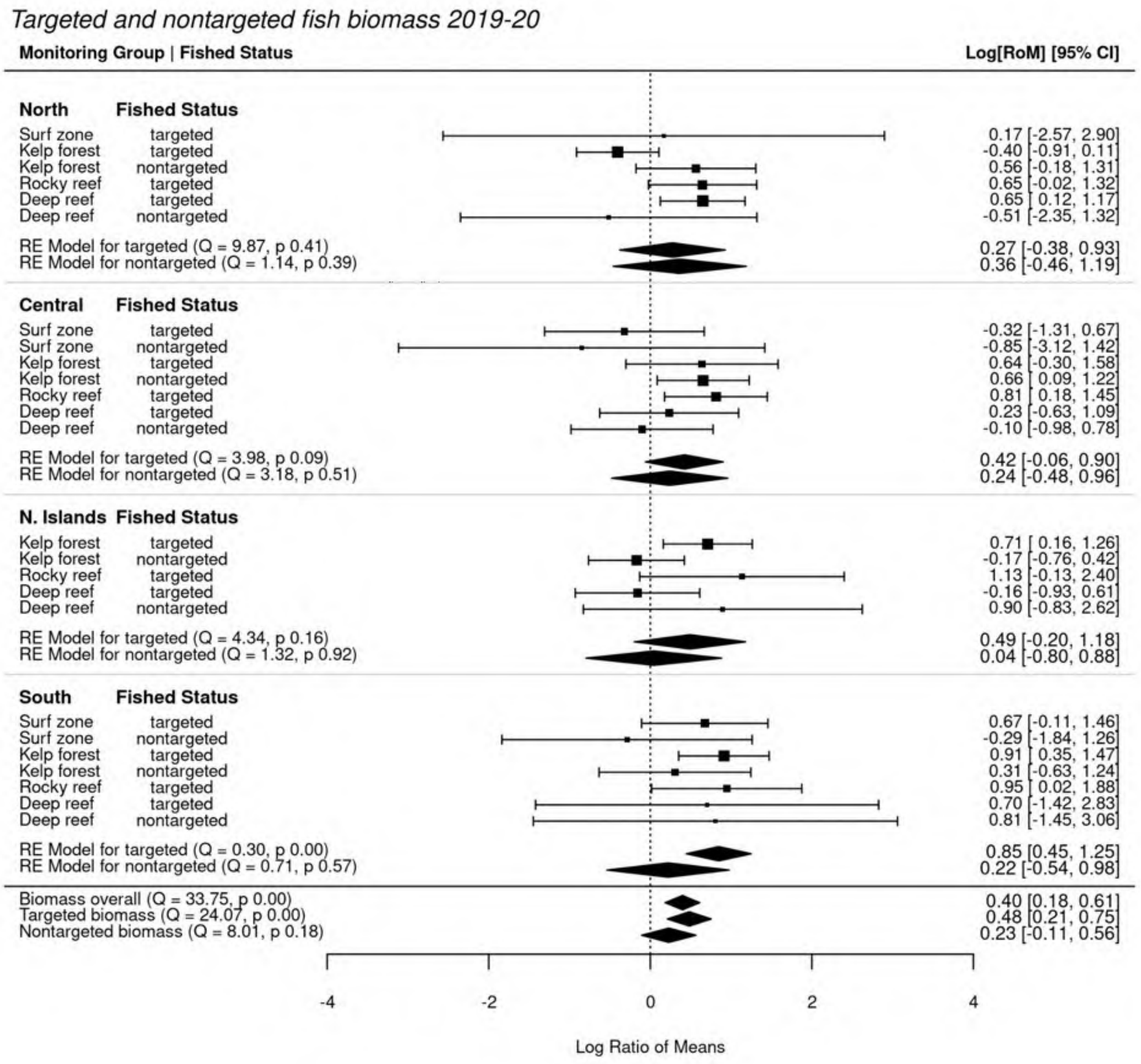


Figure 1 | *Targeted and nontargeted fish biomass response ratios across habitat monitoring groups. Each point depicts the log response ratio (SMR/reference) for a single habitat monitoring group across the 2019-20 sampling period and point sizes are scaled to their relative contribution to the regional pooled (across habitats; black diamond) effect. Positive values indicate greater fish biomass inside of MPAs relative to reference sites. Error bars represent 95% confidence intervals surrounding the response ratio. The vertical dashed line indicates a non-significant effect - where there is no difference in biomass between no-take MPAs and reference sites. Therefore, points with whiskers that do not overlap the line are statistically significant. Similarly, the edges of the pooled effect diamonds represent 95% confidence regions. Finally, each region includes results from a random effects model (RE Model) evaluating the significance of the pooled effect size.*

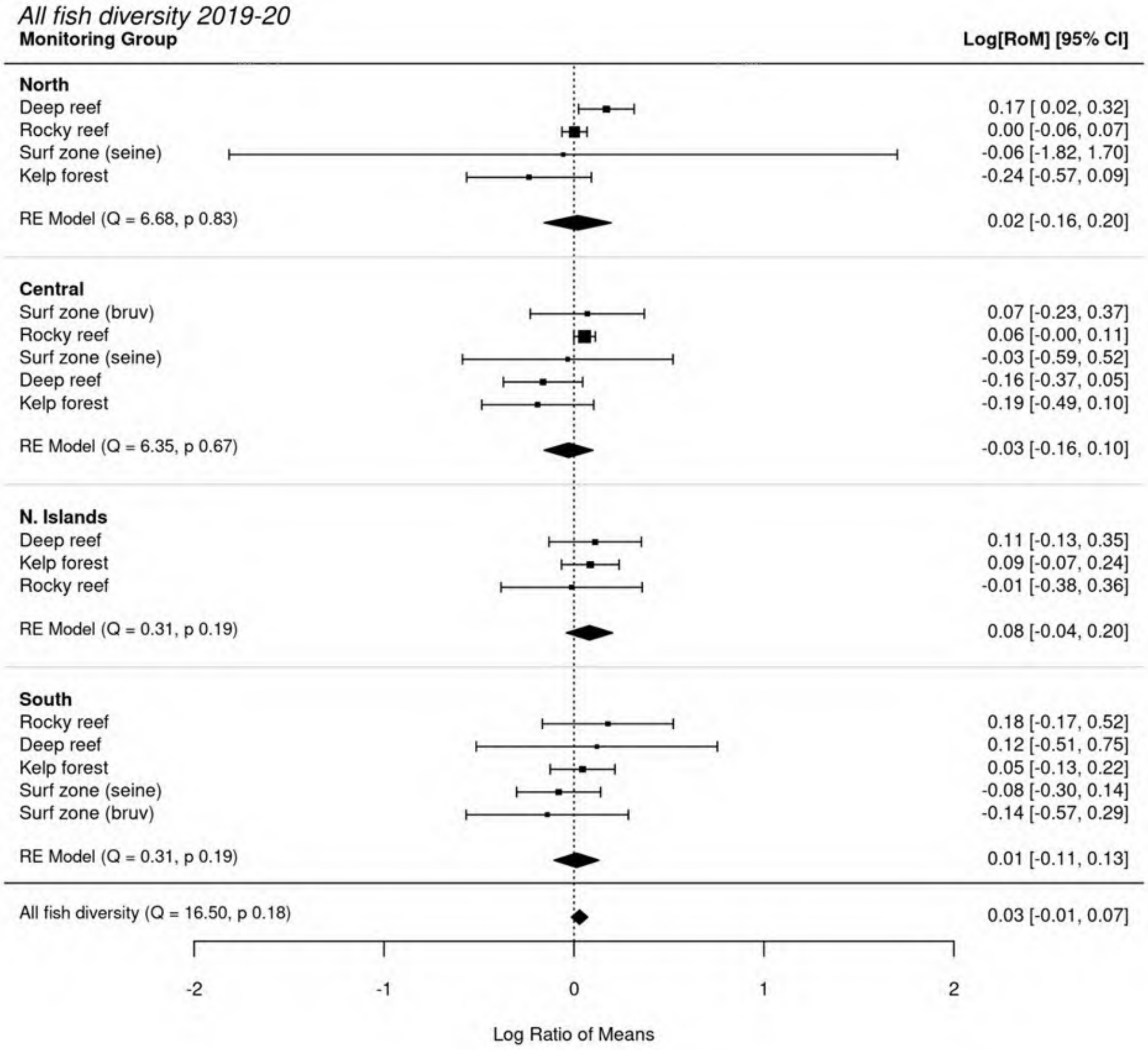


Figure 2 | *Fish diversity (Shannon-Wiener index) response ratios across habitat monitoring groups. Each point depicts the log response ratio (SMR/reference) for a single habitat monitoring group across the 2019-20 sampling period and point sizes are scaled to their relative contribution to the regional pooled (across habitats; black diamond) effect. Error bars represent 95% confidence intervals surrounding the response ratio. The vertical dashed line indicates a non-significant effect - where there is no difference in biomass between no-take MPAs and reference sites. Therefore, points with whiskers that do not overlap the line are statistically significant. Similarly, the edges of the pooled effect diamonds represent 95% confidence regions. Finally, each region includes results from a random effects model (RE Model) evaluating the significance of the pooled effect size.*

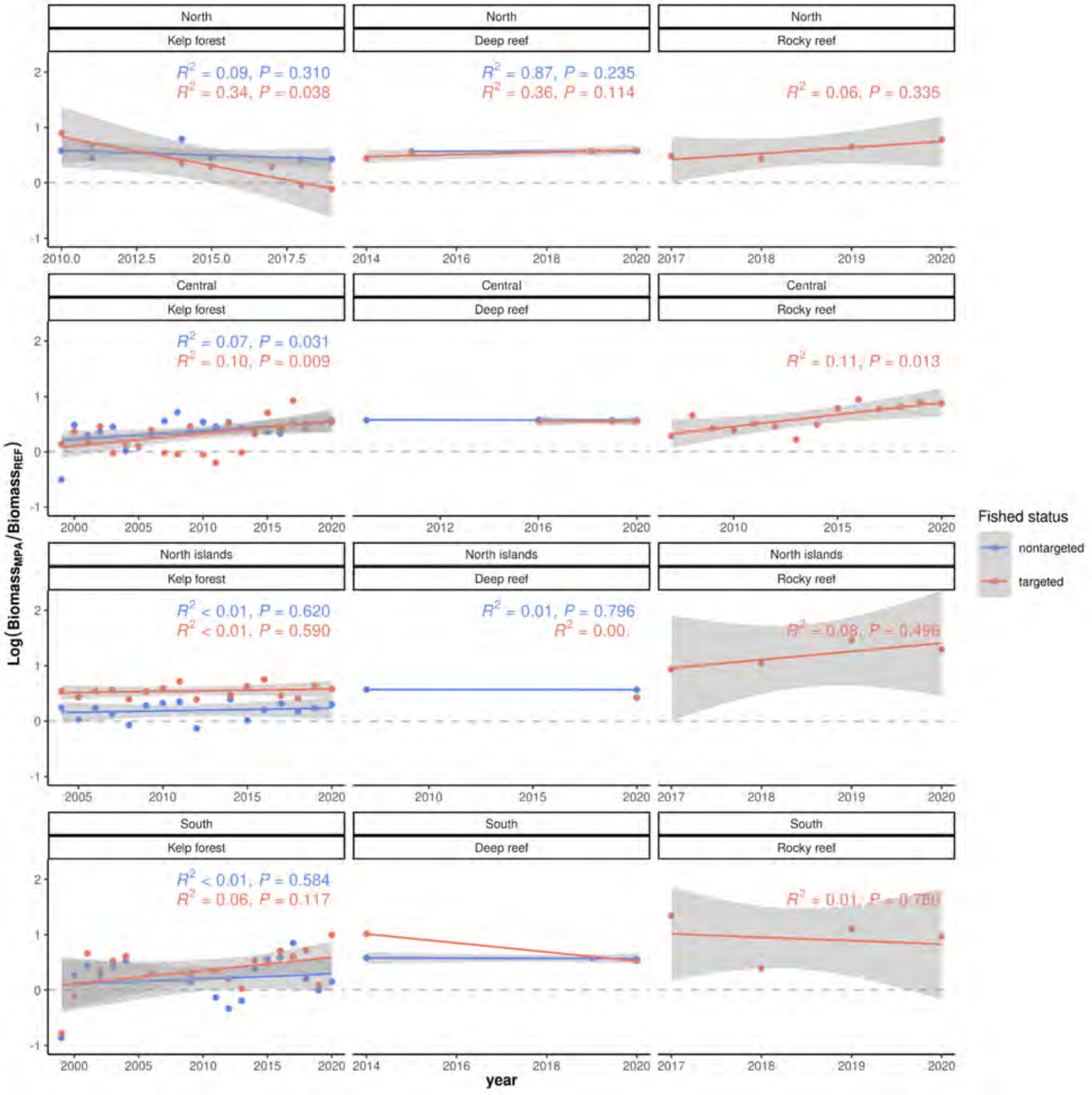


Figure 3 | *Temporal trends in response ratios for targeted and nontargeted fish biomass by monitoring group and region. Each point depicts the response ratio averaged over all MPAs sampled within a given year. Regression lines depict the trends over time for targeted (red) and nontargeted (blue) species with 95% confidence intervals shaded in grey.*

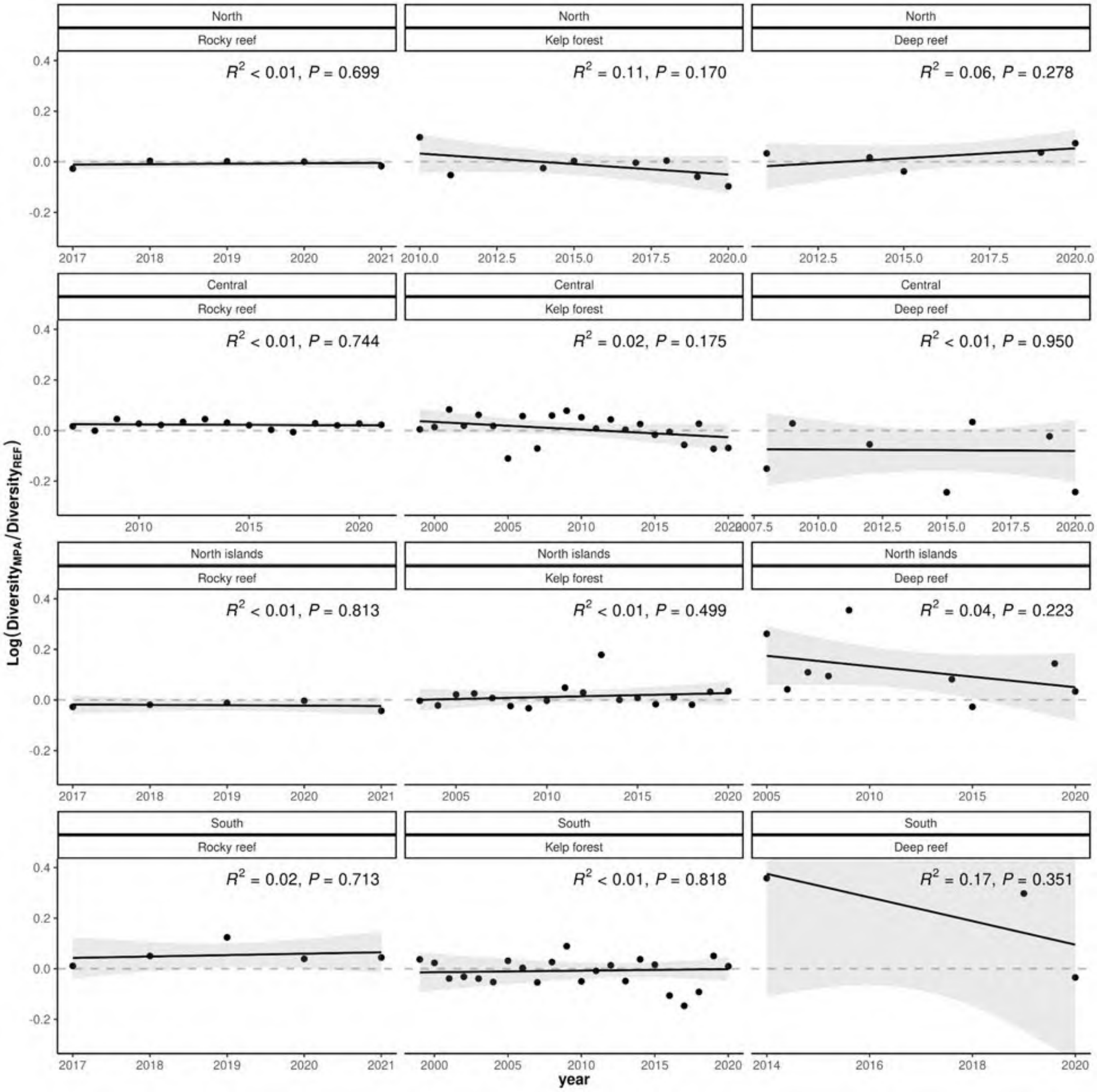


Figure 4 | *All fish diversity response ratios by monitoring group and region. Each point depicts the response ratio averaged over all MPAs sampled within a given year. Also included are regression lines that depict the trends over time with 95% confidence intervals shaded in gray.*

Response to DEWG questions:

DEWG question 1c: Does the difference between MPAs and reference sites in biomass of a focal and/or protected species increase over time?

While we could not look at individual species responses across the disparate habitats, we did find that the response of fish biomass of targeted species increased over time at three out of four regions within kelp forest and rocky reef habitats.

DEWG question 1g: Does the difference between MPAs and reference sites in overall biomass of focal and/or protected species increase over time?

While we could not look at individual species responses across the disparate habitats, we did find that the response of fish biomass of targeted species increased over time at three out of four regions within kelp forest and rocky reef habitats.

DEWG question 1h: Does the difference between MPAs and reference sites in overall biomass of fished species increase over time relative to species that are not fished?

Our findings suggest that MPAs generally have a positive impact on targeted fish biomass and this effect is most pronounced in the South Coast region. However, we did not detect a significant difference in overall fish diversity inside and outside of MPAs.

DEWG question 20a: Has the difference between MPAs and reference areas in the size/age structure of recreationally fished species increased over time?

While we did not look at this exact question, monitoring of fish in rocky reefs through CCFRP specifically looks at recreationally fished species, and we also examined trends for targeted species in the other habitat groups. While we did not look at the size and age structure of these fish, a positive response ratio in biomass, particularly in the South Coast, likely indicates a greater abundance of larger fish in MPAs as compared to reference areas.

DEWG question 2a: Does the difference between MPAs and reference sites in species diversity within any given functional group increase over time?

Results from the meta-analysis on fish diversity response ratios revealed that MPAs were not significantly different from reference sites in any of the regionally pooled results. However, two habitats showed slightly positive regionally-specific responses (deep reef in the north, rocky reef in the central coast). To examine changes in fish diversity over time, we examined the response ratios for three habitats (kelp forest, rocky reef, deep reef) that had sufficient data to examine trends over time. These time series did not reveal significant positive trends in fish diversity over time.

Discussion:

Marine protected areas are often implemented with the goal to protect biodiversity and increase the abundance of marine life (especially for harvested species; Halpern et al. 2010). As such, we evaluated the ecological performance of California's MPA network by examining trends in targeted and nontargeted fish biomass and diversity across multiple habitats, regions, and through time. Our results demonstrate that MPAs have positive effects on targeted species biomass and not on overall fish diversity, but these results are regionally and context-specific. These findings suggest that differences in MPA performance (as measured by fish biomass and diversity) between regions is likely explained by MPA age. However, other physical and biological drivers of performance such as oceanographic processes, connectivity, MPA size, historic fishing pressure, and other processes may not be captured using the regionally aggregated response ratios.

It is well established that regulatory implementation of marine reserves can positively impact the biomass of marine species, particularly those that are harvested (Stobart et al. 2009, Sala and Giakoumi, 2018). Our finding of greater targeted fish biomass across multiple habitats particularly in the South Coast region may be the result of several underlying mechanisms. First, historic pre-implementation fishing pressure is a known driver of MPA performance (Griffiths et al. 2022). Additionally, fishing pressure is often inversely related to MPA distance from port (Nickols et al. 2019). The strong positive response ratio of targeted fish biomass observed in the South Coast region may therefore be due to intense pre-implementation harvest, or because of the proximity of South Coast MPAs to large fishing ports. Second, our assessment of MPA performance as measured by fish biomass may be data limited in some regions. For example, the North Coast region was comparatively less sampled than the South Coast region by most of the long term monitoring groups. MPAs along the north coast are also the youngest in the network, and therefore more sampling through time is required to understand performance. Finally, during the course of long-term monitoring, a major environmental perturbation referred to as a marine heatwave occurred from 2014 through 2016. For many MPAs in the network, the marine heatwave occurred only two years after regulatory implementation. The impacts of the marine heatwave event on fish biomass remain unclear, but trends in biomass over time inside and outside of MPAs may have been impacted by this environmental perturbation.

Regulatory protection generally affects fish assemblages through pathways such as the total number of individuals, the relative abundance of species (proportional representation of each species), and size structure. In addition, as cessation of fishing is the primary management action, the fishes most impacted by fishing prior to MPA implementation are most likely to respond. These expectations are not likely to influence biodiversity. Our findings of higher response ratios for fish biomass and no differences in taxonomic diversity are consistent with other studies that explored these metrics of MPA performance (Ramirez-Ortiz et al. 2020, Blowes et al. 2020). Overall taxonomic diversity of fishes may not change as a result of regulatory implementation since diversity is estimated based on the number of species and the evenness of their abundance. Additionally, changes in diversity may be more localized or MPA-specific. Therefore, our regionally-aggregated response ratios may not capture individual MPA-level changes in fish diversity. Moreover, other taxonomic diversity indices and evaluations of changes in functional diversity or species richness could provide additional pathways for evaluating MPA performance.

A central challenge in synthesizing MPA performance outcomes across habitats and regions is the integration of performance metrics (biomass, diversity) into a single effect size that is representative of trends through time and space, and across several different habitats. Our meta-analytic framework used to synthesize across habitats and regions produced an integrative evaluation of fish biomass and diversity during the 2019-20 sampling period. However, meta-analyzing the response ratios of individual MPAs through time (rather than the regional average at a single time point) could provide more detailed insight into how performance varies across the entire network, and whether certain MPAs contain features that increase their performance over others. However, this approach requires the integration of individual MPAs consistently sampled by multiple monitoring groups through time, something that did not occur in California.

In order to evaluate MPAs, it is helpful to have clear expectations of how species in a given area will respond to protection. Such expectations include the time between regulatory implementation and an expected performance response (Nickols et al. 2019), and how performance metrics change over time. For example, response ratios are expected to increase until spillover ultimately replenishes adjacent non-MPA areas. If spillover is successful, then the adjacent areas will become more similar to the MPA and response ratios should approach zero. In addition, if fishing pressure inside and outside MPAs prior to implementation was low, one would not expect implementation of an MPA to lead to changes within the MPA site (Nickols et al. 2019). Our results showed an overall positive trend in targeted fish biomass response ratios, but the trajectory of these responses may change over time. Additionally, changes in fishing pressure adjacent to MPAs can affect performance outcomes and response ratio trends over time.

Overall, the results presented in this chapter reveal the holistic response of fish biomass and diversity to regulatory implementation. Importantly, these analyses are aggregated across all MPAs and reference sites and therefore they do not evaluate the performance of individual MPAs over time. As such, synthesizing MPA performance through time requires extensive monitoring, and monitoring should be synchronized to include multiple habitat monitoring groups at several of the same MPA locations and sampling years to ensure data compatibility in future integrative analyses.

Chapter Two: Habitat

Introduction:

Two overarching goals of the MPA Network are “To protect the natural diversity and abundance of marine life, and the structure, function, and integrity of marine ecosystems,” and “To protect marine natural heritage, including protection of representative and unique marine life habitats in California waters for their intrinsic value.” Achievement of these goals requires that the network of MPAs capture the diversity of California’s marine habitats. MPA selection during the MLPA planning process included science-based design criteria such as size, shape, spacing, and habitat representation (Saarman et al. 2013). Habitat is a fundamental factor for evaluating ecological performance in MPAs, and MPAs with diversity of habitat types and depths facilitate increased connectivity among habitats (Carr et al. 2017, Hopkins et al. 2020). As such, this chapter aims to evaluate the proportional representation of multiple habitat types across the MPA network.

We examined the habitat composition within marine protected areas across the Network using estimates of the amount of major habitats present within the boundaries of each MPA. Major habitats include both nearshore/offshore (0-3000 m depth) and onshore (shoreline) characteristics identified as important during the MLPA planning process (**Table 2**). We used non-metric multidimensional scaling (NMDS) to explore the variation in habitat characteristics among MPAs and found significant differences among regions.

The MPA Habitat chapter of this report aims to address the following MLPA goals:

- MLPA Goal 4: Protect marine natural heritage, including protection of representative and unique marine life habitats in CA waters for their intrinsic value.

Table 2 | *Metadata for habitats included in analyses.*

Categories	Habitat Type	Data Information
Nearshore and Offshore Estimated by area extent, km^2	Hard substrate (0-30m)	High resolution (2m to 10m) multibeam mapping, mostly from the California Seafloor Mapping Project. Area totals calculated from a vector file. Depth information from the high resolution bathymetry data where available. Small mapping gaps filled in through interpolation and added to the total.
	Hard substrate (30-100m)	
	Hard substrate (100-200m)	
	Hard substrate (200-3000m)	
	Soft substrate (0-30m)	
	Soft substrate (30-100m)	
	Soft substrate (100-200m)	
	Soft substrate (200-3000m)	
	Kelp canopy (0-30m)	Data from CDFW kelp overflights (14 years; '89, '99, '02-'06, '08-'10, '13-'16), composite of all available data for maximum canopy extent.(Saarman 2020, unpublished). Captures both giant and bull kelp and covers the whole coast of California.
Onshore Estimated by linear extent, km	Coastal marsh	Data from NOAA ESI shoreline file. Used 2010 update from southern California. Source data has up to 3 classifications for each coastal segment (landward, seaward1, seaward2), length totals reflect all of these classifications, but do not double-count (for example landward is gravel beach, seaward1 is fine-grained beach, this segment counted just once as beach).
	Tidal flats	
	Hardened/armored shoreline	
	Sandy beach	
	Rocky intertidal	

Methods and Analytical Approaches:

To compare habitat composition among MPAs of different sizes, we calculated the amount of each habitat relative to the total amount of habitat across the different habitat types within each MPA. We calculated habitat composition for onshore (e.g., sandy beach, rocky intertidal, estuary) and nearshore/offshore (e.g., soft bottom, hard substrate, kelp canopy) habitats separately because the data for shoreline habitats are reported in linear kilometers (measured along the shoreline) and nearshore/offshore habitats are reported in square kilometers (measured within the MPA area).

We also examined the variation in habitat characteristics among MPAs using non-metric multidimensional scaling (NMDS), using the vegan package in R. We standardized data to the maximum value to allow for comparison of habitats of different scales and unit measure (e.g. km vs. km^2). We conducted two separate NMDS ordinations. To examine the differences in habitat composition across the entire network, we first conducted an NMDS ordination for all MPAs. We used a permanova to test for differences in habitat composition of estuarine, coastal, and offshore MPAs. We define estuarine MPAs as those with any onshore habitats, but no nearshore/offshore habitats. Coastal MPAs contain some amount of both onshore and nearshore/offshore habitats. Offshore MPAs are those with no shoreline, and therefore only consist of nearshore/offshore habitats. To examine regional differences in habitat composition, we conducted a second ordination with only the coastal MPAs, as these MPAs had the potential to contain all of our focal onshore and offshore habitats. We then tested for differences among the four regions identified in many ecological studies as having different ecological communities and environmental conditions (North, Central, Northern Channel Islands, South) using a permanova and subsequent pairwise comparisons.

Data Summaries, Analyses, Figures, Tables, and Interpretation:

California’s MPAs vary greatly in their habitat composition for both onshore (**Figure 5**) and nearshore/offshore habitats (**Figure 6**). NMDS ordinations illustrate that these differences can be partly explained by the situational context of the MPA (**Figure 7**). Estuarine MPAs are characterized by substantial onshore habitat, particularly coastal marsh and tidal flats, but have no nearshore/offshore habitat and generally lower relative amounts of rocky intertidal and sandy beach habitats. Coastal MPAs contain both onshore and nearshore/offshore habitats, but relatively lower amounts of coastal marsh and tidal flats. Offshore MPAs, which do not have a shoreline, are composed entirely of nearshore/offshore habitats but no onshore habitats, and often have relatively higher amounts of deeper habitat compared to coastal and estuarine MPAs. These differences in habitat composition are significant across all pairwise comparisons ($p = 0.003$).

To further examine differences among regions apart from these differences in major habitat context, we compared the relative differences in habitat composition for only the coastal MPAs (**Figure 8**). Pairwise comparisons revealed that all regions are significantly different from each other (**Table 3**). Across the regions, Central Coast coastal MPAs have greater relative abundance of hard substrata and kelp habitat, whereas North Coast coastal MPAs have more comparable relative abundance of hard and soft substrates, and South Coast and Northern Channel Islands MPAs have a greater relative abundance of shallow and deeper soft substrates (**Figure 6** and **Figure 8**). The North, Central, and Northern Channel Islands coastal MPAs also have greater relative abundances of rocky intertidal habitat, whereas South coastal MPAs have greater relative amounts of sandy beaches (**Figure 5** and **Figure 8**). The Northern Channel Islands coastal MPAs have the highest amount of variation in their habitat composition compared to any of the other regions (**Figure 8**). We also note trends in relative habitat composition depending on the size of the MPA: within each region, larger MPAs tend to contain greater relative amounts of soft bottom, deeper habitats (**Figure 6**).

Table 3 | *Results from permanova pairwise comparisons for NMDS of all coastal MPAs.*

Pair	F	R^2	*p* value
North vs. Central	4.5833	0.0943	0.001
North vs. South	3.4230	0.0641	0.002
North vs. N. Channel Islands	3.2633	0.0876	0.003
Central vs. South	6.0245	0.1309	0.001
Central vs. N. Channel Islands	3.1866	0.1172	0.009
South vs. N. Channel Islands	3.5289	0.1052	0.005

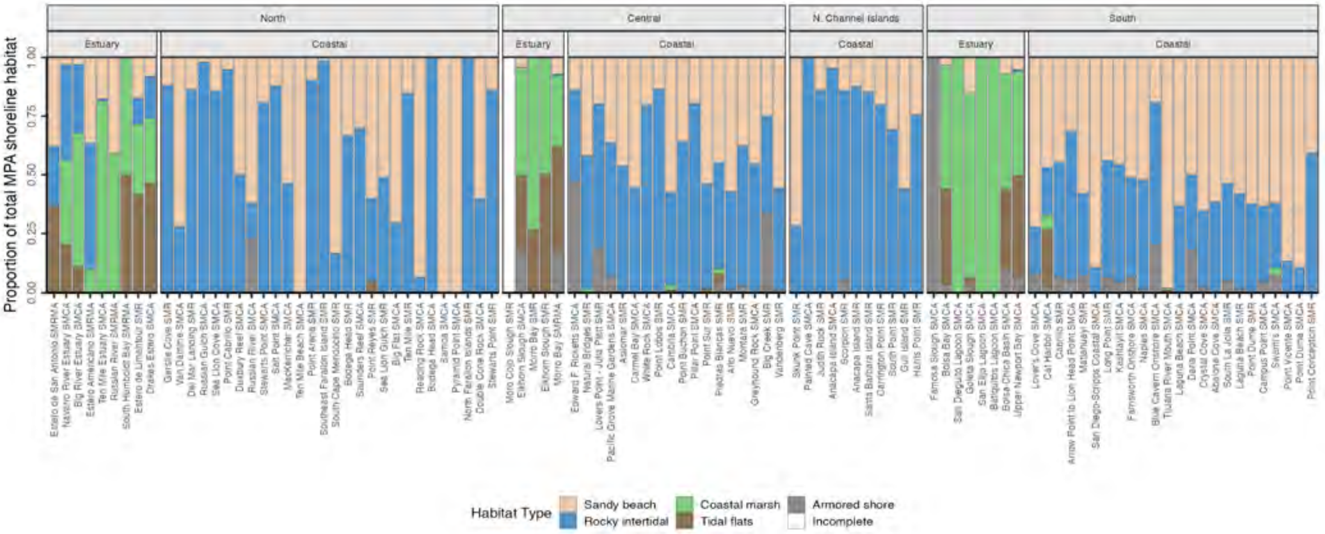


Figure 5 | *Shoreline habitat composition of estuary and coastal MPAs, calculated relative to the total amount of shoreline habitat (km). Estuary MPAs only contain shoreline habitat, by definition. Coastal MPAs are adjacent to a shoreline and also contain offshore habitats. Offshore MPAs are not shown as they do not have a shoreline, by definition. MPAs within each region and type are ordered by increasing size.*

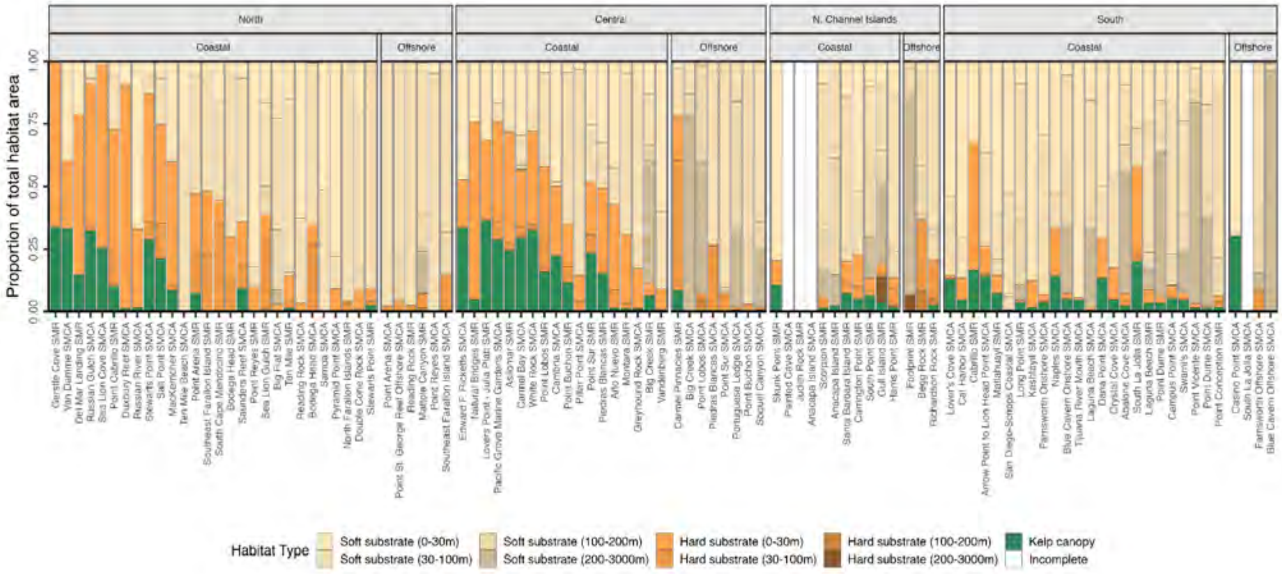


Figure 6 | *Nearshore/offshore habitat composition of coastal and offshore MPAs, calculated relative to the total amount of nearshore/offshore habitat within that MPA (km²). Coastal MPAs are adjacent to a shoreline and also contain offshore habitats, whereas offshore MPAs have no shoreline and therefore do not contain onshore habitats. Estuary MPAs are not shown because they do not contain any offshore habitat, by definition. MPAs within each region and type are ordered by increasing size.*

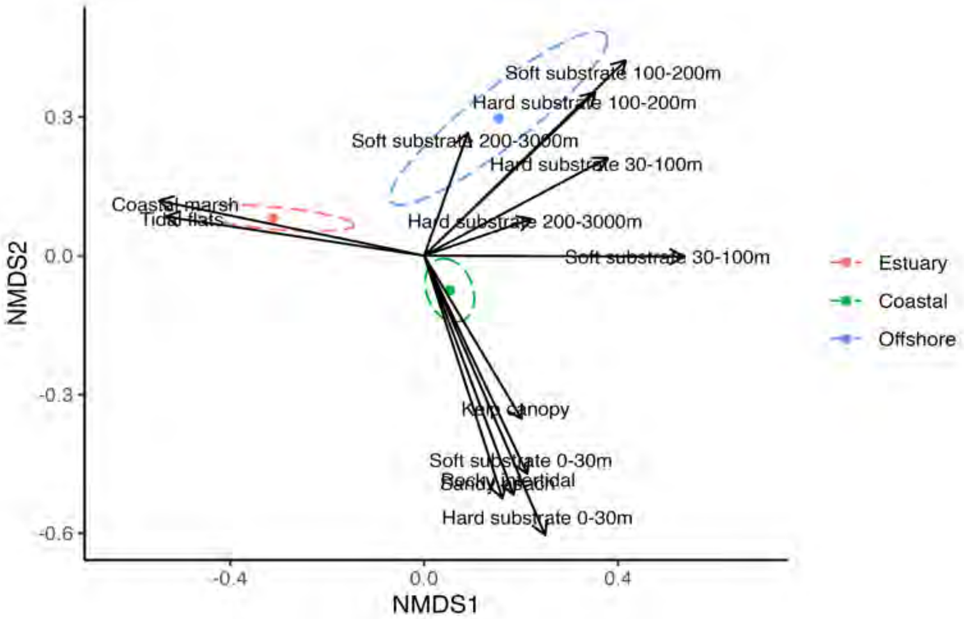


Figure 7 | *Relative differences in MPA habitat composition among estuarine, coastal, and offshore MPAs, from non-metric multidimensional scaling (NMDS) ordination of all MPAs. Dashed lines represent 95% confidence ellipses calculated around the mean position for each region. Vectors are displayed for each habitat type included in the ordination, and their length corresponds to their relative contribution in describing the variation among MPAs.*

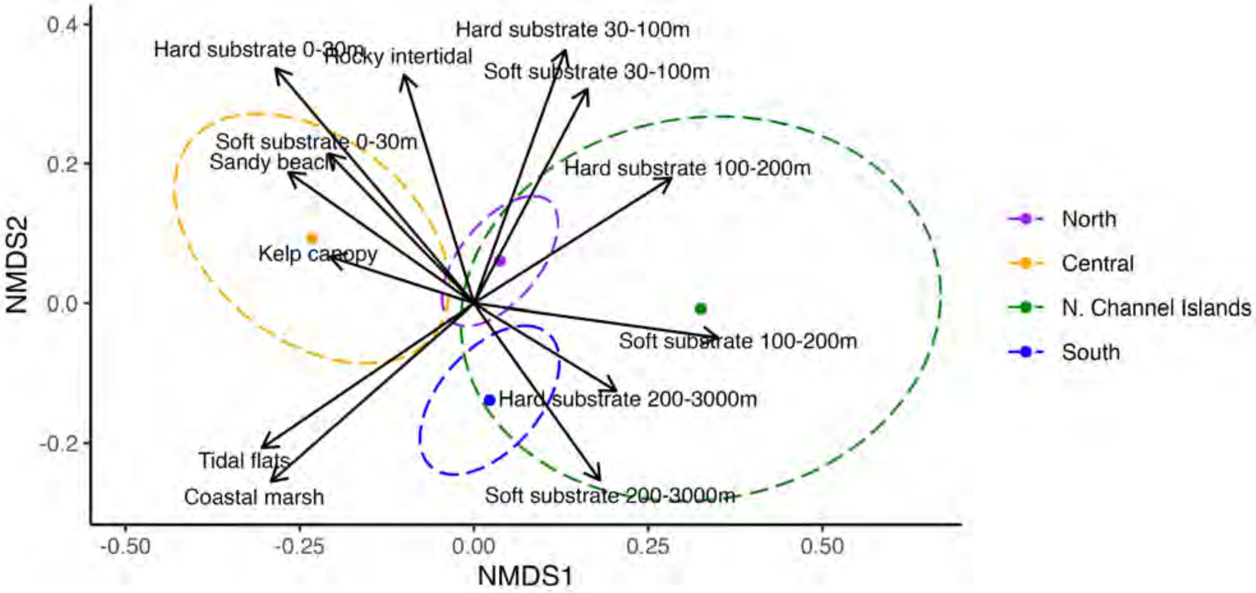


Figure 8 | *Relative differences in MPA habitat composition among planning regions from non-metric multidimensional scaling (NMDS) ordination of only coastal MPAs. Colors represent different MPA regions. Dashed lines represent 95% confidence ellipses calculated around the mean position for each region. Vectors are displayed for each habitat type included in the ordination, and their length corresponds to their relative contribution in describing the variation among MPAs.*

Response to DEWG questions:

DEWG question 21: Have unique habitats been adequately represented and protected by the current distribution and designation of MPAs?

The current distribution and designation of California's MPA network protects a variety of habitats distributed across California and represents regional differences in habitat composition.

Discussion:

California's marine protected area network protects a wide range of habitats and associated ecological communities (Young and Carr 2015). California's investment in statewide mapping of coastal ecosystems represents one of the most comprehensive and spatially extensive efforts to characterize nearshore habitats. Our results indicate that habitat composition varies across the MPA network, with significant differences among MPA locations (estuary, coastal, offshore) and regions.

One of the key network design considerations during the MLPA planning process was the representation and replication of multiple habitat types within regions and across the MPA network. Interestingly, the proportional representation of habitats (sandy beach, rocky intertidal, coastal marsh, tidal flats, hardened/armored shoreline) was different between regions, but this finding is consistent with the seascape and unique geographical features of each region. For example, our results showed that habitat representation varies regionally, with the South Coast containing proportionally more sandy beach and less rocky intertidal than other regions to the north. This finding is consistent with the natural gradient of habitats along the California coastline.

With this extensive habitat data in hand, and knowing that California's unique habitats are represented in the network, the State is poised to address further questions regarding linkages between habitat diversity and species diversity as well as to assess whether culturally important habitats are adequately protected.

Chapter Three: Climate Resilience

Introduction:

Along the California coastline, marine populations, communities, and ecosystems are experiencing pronounced changes resulting from increases in the frequency of marine heatwaves, rising sea levels, lowering pH conditions, and other climate-driven impacts (Jacox et al. 2019, Rogers-Bennet and Catton 2019). A fundamental goal for the 2022 decadal review of California's MPA network is to determine the extent to which the network provides resilience to climate change. Recently, the Ocean Science Trust convened an expert working group to explore how and whether California's MPAs provide climate resilience (Hofmann et al. 2021). Building on the report generated by this working group, we used a cross-ecosystem synthetic approach to understand the capacity for California's MPAs as a networked system to provide climate resilience.

During the course of California's MPA monitoring, a major climate event referred to as a "marine heatwave (MHW)" occurred along the California coastline. The MHW was the consequence of two environmental anomalies: a 2014-2016 warming event known as "the Blob," and a major El Niño event that occurred in 2015-2016 (Bond et al. 2015, Di Lorenzo and Mantua 2016, Gentemann et al. 2017). This pronounced environmental perturbation provided a timely opportunity to explore community responses and MPA performance across ecosystems, since these MHWs are predicted to become more persistent and frequent pressures to marine ecosystems in the future (Joh and Di Lorenzo 2017). Indeed, several of the MPA monitoring technical reports suggested community shifts inside and outside of MPAs following the MHW, and there was some evidence that for some habitats, more communities appeared on a trajectory to return to a pre-perturbed state in MPAs than in reference sites (Carr et al. 2021; Raimondi et al. 2021). However, other studies showed limited changes in response to the heatwave (Reed et al. 2016 for abundance of kelp), strong spatial variation in impact and recovery from heatwaves (Cavanaugh et al. 2019 for kelp) or dramatic changes in community structure but no mitigation of these changes inside MPAs relative to fished areas (Freedman et al. 2018 for fishes). Increasing understanding of how MPAs provide resilience in response to marine heatwaves and other anomalous oceanographic changes will support planning and adaptive management for MPAs given future climate scenarios. As such, the core questions and analytical approaches were centered around investigating whether California MPAs as a networked system provide resilience to environmental disturbances and climate change.

The MPA Climate Resilience chapter of this report aims to address the following MLPA goals:

- MLPA Goal 1: To protect the natural diversity and abundance of marine life, and the structure, function, and integrity of marine ecosystems.
- MLPA Goal 2: To help sustain, conserve, and protect marine life populations, including those of economic value, and rebuild those that are depleted.

Methods and Analytical Approaches:

Here we used a taxonomic-based approach to explore whether and how communities responded to the 2014-16 MHW event. We focused our analyses on MPAs located within the Central Coast region of California because this area is the most comprehensively sampled region across multiple habitats and time, particularly during the occurrence of the MHW event. Using the same approach as Chapter 1, we focused our analyses on sites inside and outside of SMRs and *de facto* SMRs (evaluated for each individual habitat based on regulations; hereafter 'SMRs'). A SMCA was designated as a *de facto* SMR (no-take reserve) for a particular habitat if the allowed take in the SMCA was unlikely to affect that particular habitat (see **Table S1** for list of *de facto* SMRs).

Model construction

We explored oceanographic conditions before, during, and after the marine heatwave at all Central Coast long-term monitoring sites to evaluate whether changes in the environment coincided with shifts in community structure. For these environmental analyses, we used multiscale ultra-high resolution sea surface temperature (SST) data calculated daily at a 1 km resolution (Chin et al. 2013) and two upwelling indices calculated at 1 degree latitude bins (Coastal Upwelling Transport Index, CUTI; Biologically Effective Upwelling Transport Index, BEUTI; Jacox et al. 2018). CUTI is an index describing the amount of vertical flux in the water column (i.e., upwelling and downwelling) while BEUTI indicates the amount of nitrate being vertically transported (Jacox et al. 2018). We also explored changes in the Multivariate Oceanographic Climate Index (MOCI), which is a long term (30 year) indicator of several oceanographic and atmospheric conditions (García-Reyes and Sydeman 2017) calculated at the regional level.

To process the environmental data, we first calculated the monthly mean SST, BEUTI, and CUTI, and quarterly MOCI values at each long term monitoring site. We then calculated monthly anomalies for SST, BEUTI, and CUTI as the difference between the observed monthly mean and the baseline average (long term average for each month, 1988-2012 for BEUTI and CUTI, and 2002-2012 for SST). For MOCI, we calculated the annual mean at each site as a standard index.

Finally, to visualize and pair the environmental data with the long-term biological monitoring data, we calculated the mean anomalies across all calendar months for each year (**Figure 9**).

We evaluated changes in community structure (**Table S2**) resulting from the marine heatwave event using a multidimensional approach. This analysis used two types of monitoring data: counts of species, and the proportional cover of invertebrates and algae. We used data from rocky reef (fish only), deep reef (fish only), rocky intertidal (invertebrates and algae combined) and three communities from the kelp forest monitoring (fish; sessile invertebrates and algae; and kelp and mobile invertebrates). First, we visualized changes in community structure before (2010-2013), during (2014-2016), and after (2017-2020) the heatwave using nonparametric multidimensional scaling (NMDS) plots. NMDS is a visual tool that displays the structure of ecological communities based on the abundance (counts or cover) of observed species. All NMDS plots were ultimately distilled using centroids to represent community structure. These centroids are representative of all MPAs or reference sites before, during, and after the marine heatwave. Finally, to determine whether observed shifts in community structure were associated with changes in oceanographic conditions, we overlaid the environmental variables (SST, BEUTI, CUTI, MOCI) as vectors on the NMDS plots.

To explore the magnitude of community change across monitoring groups, we examined the distance of shifts in community structure across all sampling sites, and with respect to regulatory protection status (inside and outside SMRs). For this analysis, we calculated the distance between the pre- and post-heatwave centroids (inside and outside of SMRs) using a Bray-Curtis dissimilarity matrix. This measure of distance is a way to examine the relative change of communities inside and outside of SMRs. The expectation is that if SMRs provide resilience to the marine heatwave event, then the change in distance in SMRs should be less than the change in distance in reference sites (suggesting that communities inside SMRs did not change as much as reference sites).

To examine the synthetic result of community change across monitoring groups, we measured the vector distance between the pre- and post-heatwave centroids of community structure. This distance vector is a relative measure of the degree of community change and is constrained between 0 and 1 (Bray-Curtis dissimilarity). Therefore, higher values indicate greater community change (greater distance between centroids). We also calculated the pooled standard deviation for each vector distance defined as:

$$S = \sqrt{\frac{(n^{pre} - 1)(sd^{pre})^2 + (n^{post} - 1)(sd^{post})^2}{n^{pre} + n^{post} - 2}}$$

Where n^{post} and n^{pre} are the sample sizes for each sampling period (number of MPAs and reference sites surveyed), and sd^{post} and sd^{pre} are the standard deviations.

Finally, to explore which species best explain community differences between the pre- and post-heatwave periods, we used a similarity percentages analysis (SIMPER). SIMPER breaks down the contribution of individual species to observed community structure differences between the pre- and post-heatwave periods. Importantly, SIMPER does not provide an estimate of changes in the absolute abundance of species. Instead, it provides an approximation of the proportional contribution of individual species to the observed community structure differences. We restricted the output of SIMPER to the species that best explain the top 80 percent contribution to dissimilarity. Beyond 80 percent, the individual contribution of species dramatically decreases (i.e., several species have low contribution).

Data Summaries, Analyses, Figures, Tables, and Interpretation:

Ecological community structure dramatically shifted across all habitats as a result of the marine heatwave and these shifts coincided with oceanographic changes associated with the marine heatwave event (**Figures 10 and 11**). The NMDS ordinations revealed that community structure was significantly different between the pre- and post-heatwave periods in four (rocky reef, kelp forest fish, kelp forest inverts and algae, deep reef fish) out five habitat monitoring groups (**Figure 10**). The pre-heatwave communities were strongly correlated with higher upwelling (measured by the BEUTI and CUTI indices) and lower SST, but the post-heatwave communities were defined by higher SST and MOCI.

Although all ecological communities shifted in response to the marine heatwave, the effect of regulatory protection on ecological resilience was more nuanced, and the magnitude of change varied by monitoring group (**Figure 11**). The community defined by kelp forest invertebrates and algae experienced the largest relative change in community structure. Fish community structure for kelp forest, deep reef, and rocky reef also substantially changed. Overall, all ecological communities responded similarly to the marine heatwave, regardless of regulatory protection status (inside or outside of MPAs).

The SIMPER analysis revealed several species that explained differences between the pre- and post-heatwave periods. Among the three habitat groups that record fish species (deep reef, rocky reef, kelp forest), blue rockfish (*Sebastes mystinus*) were positively correlated with the post-heatwave period (**Table 4**). Blue rockfish are the most abundant fish species of those that are found across the three habitat groups. The SIMPER analysis also revealed an uptick in the abundance of purple sea urchins and a decline in macroalgae (**Table 4**), which is consistent with coastwide sea urchin increases that coincided with the MHW event (McPherson et al. 2021, Smith and Tinker 2022).

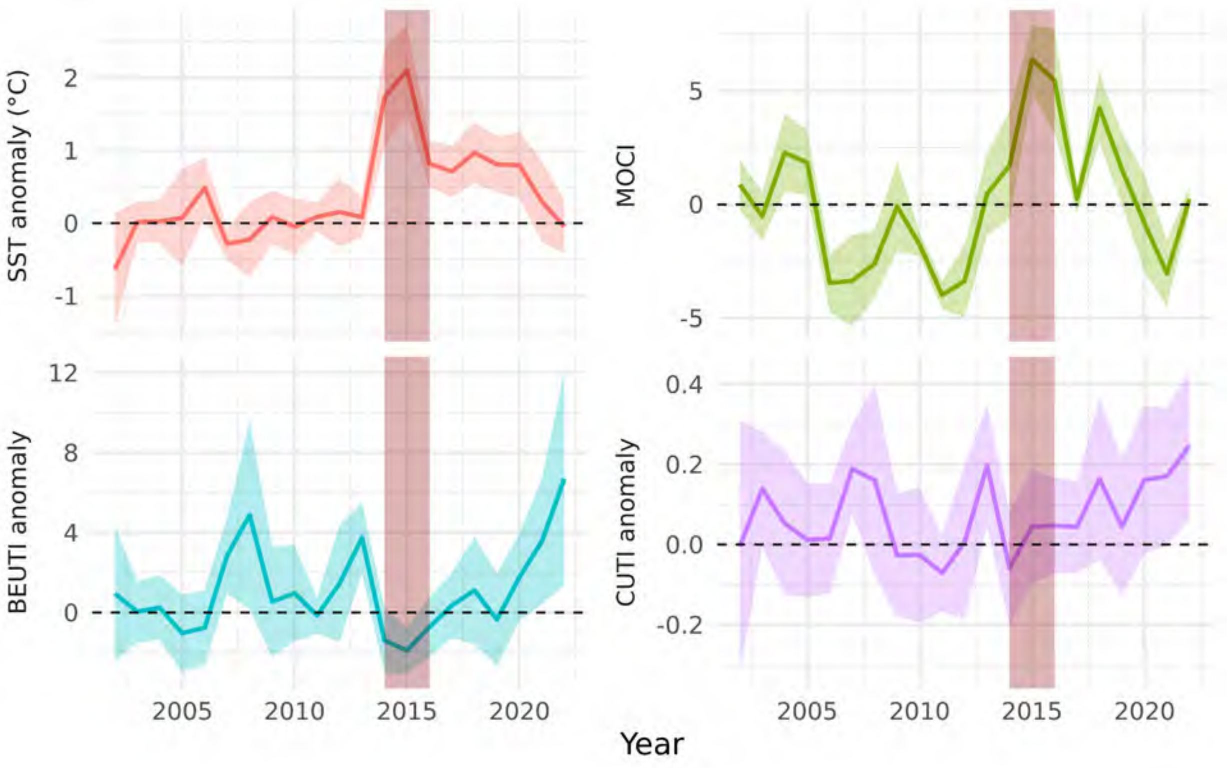


Figure 9 | *Oceanographic conditions from 2000-2022. Each panel depicts a single indicator (annual monthly mean Sea Surface Temperature, SST; Multivariate Oceanographic Climate Index, MOCI; Coastal Upwelling Transport Index, CUTI; Biologically Effective Upwelling Index, BEUTI) with annual trends (lines). Error bars depict 95% confidence intervals surrounding the annual means. Also depicted is the approximate duration of the marine heatwave event (2014-16) shaded in red. The before heatwave time period used in the community analysis was 2010-2013 and the after time period was 2017-2020.*

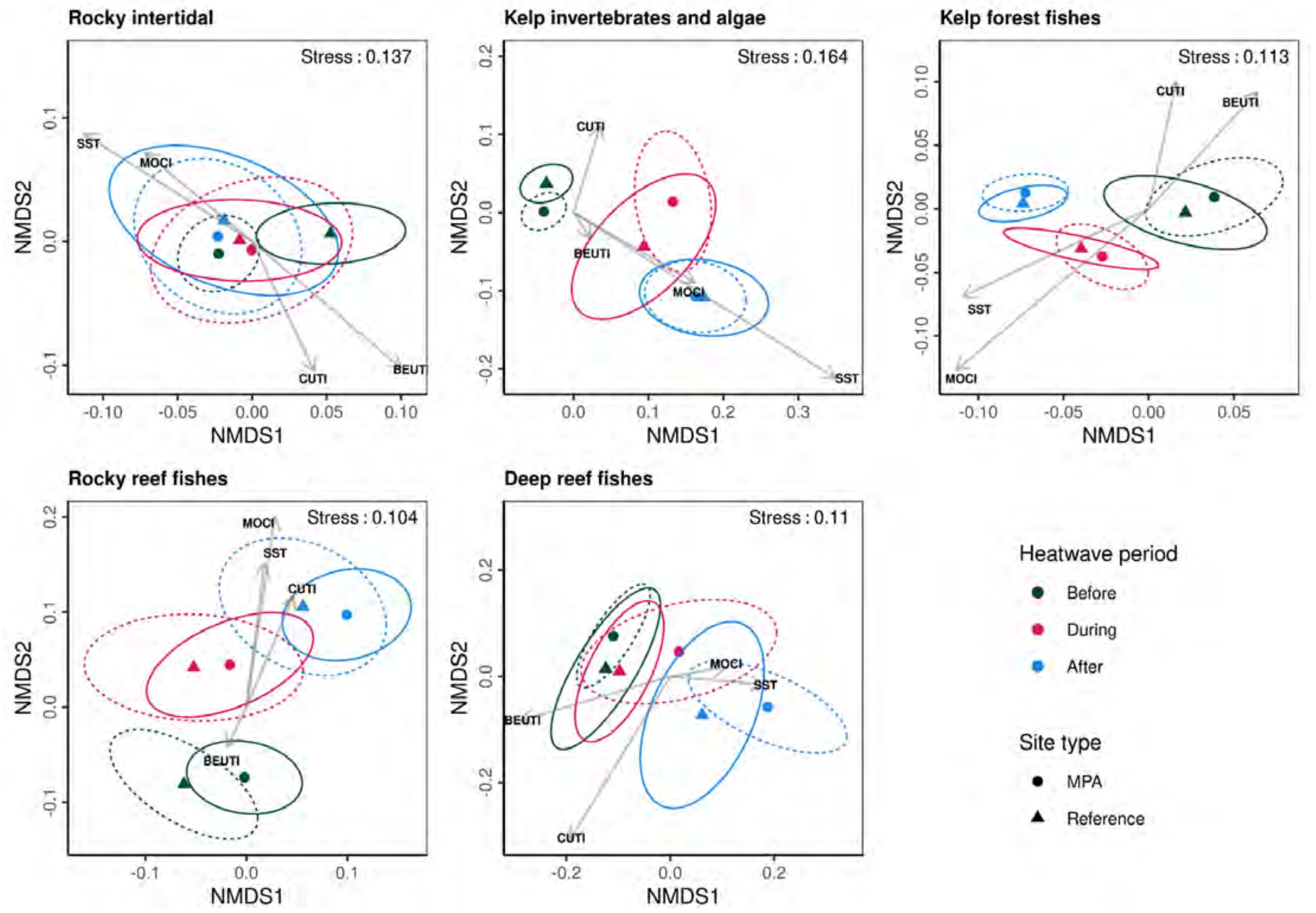


Figure 10 | *Community structure before (green), during (red), and after (blue) the marine heatwave event inside of SMRs (circles) and reference sites (triangles) in the Central Coast. Each panel represents a different monitoring program or subprogram. Each point depicts the centroid position, which is representative of all sites (SMRs or reference), with 95% confidence ellipses. Also included are vectors for each environmental indicator. The trajectory of each vector reflects its correlation with community structure. Therefore, indicators that are highly correlated with changes in community structure are aligned with the centroids (points).*

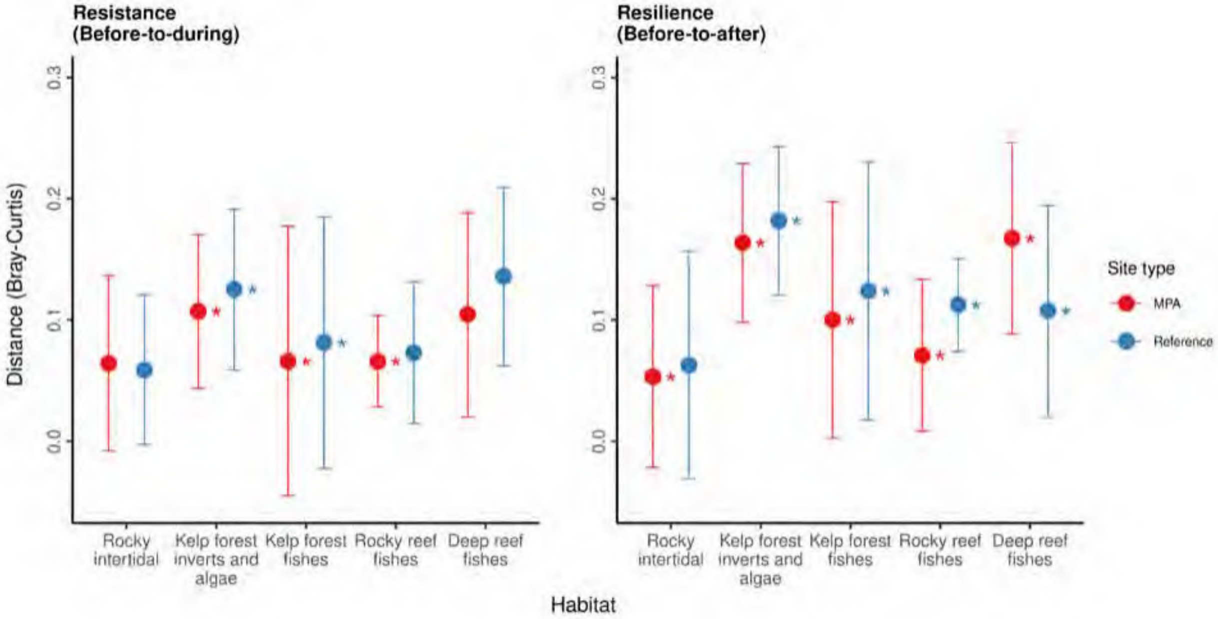


Figure 11 | *Community resistance (before-to-during) and resilience (before-to-after) as measured by distance between centroids for each habitat. Each point depicts the distance between the pre-heatwave centroid (before) and the during-heatwave or the post-heatwave centroid outside and inside of MPAs. Error bars depict the pooled standard deviation between centroids and the asterisks denote significant difference in community structure between heatwave periods, as derived from a pairwise permutational analysis of variance test.*

Table 4 | *Individual and cumulative contribution (top 80%) of species to before vs. after marine heatwave community structure. Individual contribution represents the proportional contribution of a given species to observed community structure differences between the pre- and post-heatwave periods for a single monitoring group. The cumulative contribution represents the total sum of each added species to observed community structure differences for the top 80% of species (species above the 80% margin have very little individual contribution). These values do not reflect changes in absolute abundance. Instead, they represent the proportional contribution of species to pre- vs. post-heatwave community structure.*

Monitoring Group	Community Type	Species	Individual Contribution	Cumulative Contribution
Rocky reef	Fish	Blue Rockfish	0.58	0.58
		Gopher Rockfish	0.12	0.70
		Black Rockfish	0.10	0.80
Deep Reef	Fish	Blue Rockfish	0.21	0.21
		Halfbanded Rockfish	0.13	0.34
		Rosy Rockfish	0.12	0.46
		Painted Greenling	0.07	0.53
		Pygmy Rockfish	0.07	0.59
		Vermilion Rockfish	0.04	0.64
		Pink Surfperch	0.04	0.67
		Gopher Rockfish	0.03	0.71
		Squarespot Rockfish	0.03	0.74
		Senorita	0.03	0.77
		Pile Surfperch	0.03	0.79

Kelp Forest	Fish	Blue Rockfish	0.49	0.49
		Senorita	0.13	0.62
		Olive/Yellowtail Rockfish	0.07	0.69
		Kelp Surfperch	0.04	0.74
		Kelp Rockfish	0.03	0.77
		Black Rockfish	0.03	0.80
	Sessile Invertebrates and Algae	Crustose Coralline Algae	0.09	0.09
		Branching Red Algae (Flat Blade)	0.07	0.16
		Erect Articulated Coralline Algae	0.05	0.21
		Diopatra/ Chaetopterus Spp	0.05	0.26
		Encrusting Red Algae	0.05	0.31
		Barnacle	0.04	0.35
		Red Algae (Leaf-like)	0.04	0.39
		Acidic Seaweed	0.04	0.43
		Colonial Sand Tube Worm	0.04	0.46
		Diatom Layer	0.03	0.49
		Red Algae (Cylindrical Branches)	0.03	0.52
		Red Filamentous Turf	0.03	0.55
		Surfgrass	0.03	0.58

		Strawberry Anemone	0.03	0.60
		Dictyoneurum	0.03	0.63
		Chain-Bladder Kelp Adult	0.03	0.65
		Dodecaceria	0.03	0.68
		Red Algae (Lacy Branching)	0.03	0.70
		Bryozoan	0.02	0.73
		Cup Coral	0.02	0.75
		Tube Snail, Scaled Worm Shell	0.02	0.77
		Tunicate Colonial Compound Social	0.02	0.80
	Kelp and Mobile Invertebrates	Purple Urchin Adult	0.62	0.62
		Pterygophora	0.08	0.70
		Bat Star	0.05	0.75
Rocky Intertidal	Invertebrates and Algae	Ulva Spp; Kornmannia Spp; Monostroma Spp	0.30	0.30
		Mytilus californianus	0.12	0.41
		Phyllospadix Spp	0.09	0.51
		Chthamalus dalli; Fissus; Balanus glandula	0.08	0.59
		Endocladia muricata	0.08	0.66
		Silvetia compressa	0.07	0.73
		Mastocarpus Spp	0.06	0.78

Response to DEWG questions:

DEWG question 5a: Does the nature of recovery of natural communities from disturbance events differ in MPAs relative to outside reference sites?

Our findings suggest that ecological communities in three (rocky reef, kelp forest fishes, kelp forest invertebrates and algae) out of five habitat monitoring groups in Central California were significantly impacted by the marine heatwave event. Community structure in these three habitats rapidly changed beginning in 2014 during the onset of the marine heatwave and persisted as a fundamentally different state through 2020 (the last year of data included in our analyses). Therefore, because these communities did not return to their pre-heatwave community structure, the degree of recovery in MPAs relative to outside reference sites cannot be assessed. However, the degree of change was similar inside and outside of MPAs, and changes in community structure were generally synchronous regardless of regulatory protection.

DEWG question 5b: Does the timing of recovery of natural communities from disturbance events differ in MPAs relative to outside reference sites?

To date, there was not a difference in community change between inside and outside MPAs. However, these areas are likely not 'recovered' from the MHW. Continued monitoring is needed to evaluate the timing of recovery inside and outside of MPAs.

DEWG question 5e: Do MPAs contribute to the recovery of impacted ecosystems?

As in the above question, to date there was not a difference in community change between inside and outside MPAs. However, these areas are likely not 'recovered' from the MHW. Continued monitoring is needed to evaluate the timing of recovery inside and outside of MPAs.

Discussion:

Climate change is increasingly impacting the structure and functioning of marine communities, including marine protected areas and networks. As such, adaptation strategies and adaptive management for MPA design are fundamental to conservation frameworks (Wilson et al. 2020). The 2014-16 marine heatwave event that occurred during MPA monitoring in California provided a unique opportunity to track ecological community responses inside and outside of marine protected areas, and to evaluate the degree to which MPAs confer resistance and resilience to climate perturbations. Our findings suggest that the marine heatwave had widespread impacts on community structure across ecosystems along the Central Coast of California, and that MPAs did not confer strong ecological resilience at either the habitat or synthetic level (i.e., across all ecosystems). However, climate resilience resulting from MPA implementation may be more habitat-specific. Therefore, management for climate change should be coordinated across the entire MPA network with habitat-specific indicators. These results highlight the ecosystem-wide consequences of acute environmental perturbations. It is also important to consider that habitats are likely still recovering from the heatwave and it is possible that more time needs to pass before recovery and resilience can be adequately assessed.

Increasing our understanding of the pathways through which marine heatwave events restructure ecological communities is central to developing adaptive management solutions. For example, our study used a taxonomic (i.e, species) based approach to evaluate changes in community structure, but functional diversity may also be impacted by warming events, and should also be explored. Prolonged warming events may differentially impact groups and guilds of species with similar functional traits (Harvey et al. 2021).

Although the MHW event was not limited to the Central Coast, it was the only region with adequate data across habitats to perform the synthetic analysis we present here. Therefore we cannot assess the differential impacts of warming events across the regions within the MPA network for multiple habitats, although individual habitat groups could make regional comparisons of MHW impacts. In order to understand the ability of the MPA network to resist and recover from future MHW events, it is critical to have sufficient monitoring across multiple habitats and regions. Because pre-perturbation data is necessary for comparatively evaluating ecological responses, consistent monitoring will be required to capture the effect of marine heatwave events. Although the timing of marine heatwaves is unpredictable, mounting evidence suggests that the frequency and magnitude of abrupt warming events are expected to increase (Frölicher et al. 2018; Holbrook et al 2020).

Finally, climate change threatens to inhibit the intended performance outcomes of marine protected areas. As such, additional tools and strategies are needed, in conjunction with regulatory protection to plan for and mitigate the consequences of marine heatwave events and other climate perturbations. Hofmann et al. (2021) previously proposed a suite of recommended research questions, approaches, and next steps for understanding the ability of MPAs to enhance resilience and we recommend implementing suggestions from that report. As long as the world continues to emit carbon dioxide both protected and unprotected areas in California’s waters will remain under threat.

Chapter Four: Human Engagement

Introduction:

Calls for using marine protected areas (MPAs) to achieve goals for nature and people are increasing globally. While the conservation and fisheries impacts of MPAs have been comparatively well studied (e.g., Claudet et al., 2008; Edgar et al., 2014; Giakoumi et al., 2017; Goñi et al., 2010; Lester & Halpern, 2008; Wilson et al., 2020), impacts on other dimensions of human use have received less attention (Ban et al., 2019; Erskine et al., 2021; Gerber et al., 2003; Naidoo et al., 2019; Turnbull et al., 2021). This is surprising given the frequency with which human use objectives, such as recreation, culture, education, and scientific research, are identified in international, national, and regional MPA planning documents. This is no different in California. For example, Goals 3 and 4 of California's MLPA include human use objectives such as improving recreational, educational, and study opportunities provided by marine ecosystems protected within MPAs, and protecting marine natural heritage, including protection of representative and unique marine life habitats in California waters for their intrinsic values.

Understanding how humans use MPAs and identifying the traits of MPAs that promote human engagement is critical to designing future networks and adaptively managing existing networks to ensure they achieve their goals effectively, equitably, and sustainably. Quantifying human engagement patterns can also provide needed context for evaluating the success or failure of MPAs to achieve conservation and fisheries goals.

In this chapter, we use available data from a variety of sources, including and in addition to habitat-specific monitoring programs, to characterize human engagement with California's MPA network. We provide a rare quantification of a suite of major ways in which people engage with MPAs and identify traits associated with high versus low human engagement. We assemble and evaluate indicators of human engagement that capture a diversity of recreational, educational, and scientific uses, and relate the level of human engagement to population density, accessibility, amenities, and other MPA traits likely to influence human engagement.

Methods and Analytical Approaches:

We characterized human engagement with California's marine protected areas throughout the Network and identified traits that contribute to human engagement in protected areas. We assembled and evaluated indicators of human engagement that capture a diversity of recreational, educational, and scientific uses across the MPA network (i.e., for MPAs only). Because these analyses are focused on non-consumptive engagement within MPAs, fishing effort is not included as an indicator. However, one indicator included in this analysis (MPA Watch) reports information on consumptive activities (broadly defined as multiple forms of take). We relate the level of human engagement to population density, accessibility, and other MPA traits.

We used several community-based data platforms as indicators for measuring engagement across the MPA network (**Table S5**), including MPA Watch (MPA Watch, 2022), iNaturalist (iNaturalist, 2022), eBird (eBird, 2022), and Reef Environmental Education Foundation (REEF, 2022). These indicators are community science programs where individuals can submit spatially referenced records of activities (e.g., fishing, watersport activities, etc.) or observations of wildlife. Therefore, these observations serve as useful indicators for evaluating human engagement across the MPA network. We also used data collected by California Department of Fish and Wildlife (CDFW) to quantify scientific research activity and regulatory compliance within California's MPA network. We focused on the 124 MPAs that the MLPA identifies as part of California's state-managed coastal Marine Protected Area Network. This excludes federally managed MPAs around the Channel Islands, and SMPs and one SMCA in San Francisco Bay, which were established before the MLPA planning process and are not coastal, and special closures, which are not identified as MPAs by the MLPA. We refer to the resulting network of 49 SMRs, 60 SMCAs, 10 no-take SMCAs, and 5 SMRMAs as California's state MPA network. For all indicators and data, we focused our analyses on data collected from 2012-2022, after full implementation of the network.

To compare human engagement across the MPA network, we standardized the various sources of human use data to allow comparison in an "engagement scorecard," scaling each indicator to ease comparison (**Figure 12**). After visually inspecting the results of the scorecard, it was clear that some MPAs have higher engagement beyond what might be explained by population density alone. Therefore, we used a regression approach to explicitly evaluate the degree to which engagement is explained by population density. For this regression model, we used the number of iNaturalist observers as our measure of engagement because the iNaturalist indicator was the most spatially comprehensive (included most of the MPAs within the network) and correlates well with other indicators. Any MPAs with residuals greater than 75% of the fitted values of the regression were classified as "charismatic", where engagement is higher than would be expected based on population density. Conversely, any MPAs with residuals less than 75% of the fitted values of the regression were classified as "underutilized".

We constructed a logistic regression to evaluate drivers of human use that may explain charismatic MPAs beyond population density alone. We defined the logistic target level based on the output from the linear regression of engagement, where “charismatic” MPAs were defined as “1” and “typical” MPAs (those predicted by population density) as “0.” Therefore, the logistic regression attempts to expand the explanatory drivers of charismatic MPAs beyond population density alone. These potential drivers included several infrastructure (such as number of parking lots, picnic areas, campgrounds, etc.) and biological (fish diversity, kelp cover, etc.) attributes (**Table S6**).

Lastly, we compared how selective each indicator was in terms of how engagement was distributed across the network looking at cumulative contributions of individual MPAs for each indicator. For this analysis, there are two null expectations. First, if all MPAs receive relatively equal engagement, then MPA rank should be directly proportional to engagement (i.e., the cumulative contribution of engagement increases by the same magnitude for each additional MPA added to the model). Second, if engagement is proportional to population density, then then MPA rank should be directly proportional to nearby population density. Therefore, if the cumulative contributions of engagement do not fit these expectations, then some MPAs receive disproportionately high engagement.

The MPA Human Engagement chapter of this report aims to address the following MLPA goals:

- MLPA Goal 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.
- MLPA Goal 5: To ensure that California's MPAs have clearly defined objectives, effective management measures, and adequate enforcement, and are based on sound scientific guidelines.

Data Summaries, Analyses, Figures, Tables, and Interpretation:

We found that human use inside protected areas is generally correlated to nearby population density across most indicators (**Figure 12**). Citation and research permit data were more aggregated (i.e., annual sums) than the other indicators of human use. In general, citation frequency was positively correlated with local human population density and MPA engagement (as measured using the spatially and temporally expansive iNaturalist indicator). Among all human uses, scientific research has been the most evenly spread activity across the MPA network, with every MPA receiving scientific attention. We also found that particular site characteristics can expand human use beyond what would be predicted by population density alone, resulting in "charismatic" sites. A linear regression on the number of iNaturalist observers within MPAs as predicted by nearby population density provided relatively strong fit after removing 18 ‘charismatic’ MPAs that were not explained by population density alone (**Figure 13**; $r^2=0.47$; $p<0.001$). Results from the logistic regression revealed that engagement in charismatic MPAs is best explained by locations that allow take (of any kind), have extensive sandy beaches, and have associated infrastructure such as parking lots (**Table 5**).

Interestingly, MPA engagement was less selective than predicted by human population density for iNaturalist (**Figure 14**). Despite the trend to submit eBird observations from estuary locations, the MPA engagement from this human use scaled positively with human population density in the region surrounding those MPAs (**Figure 14**). REEF divers have been more selective about their MPA use than any of the other evaluated user groups. Finally, citations were more highly concentrated in certain MPAs than would be predicted by human population density alone.

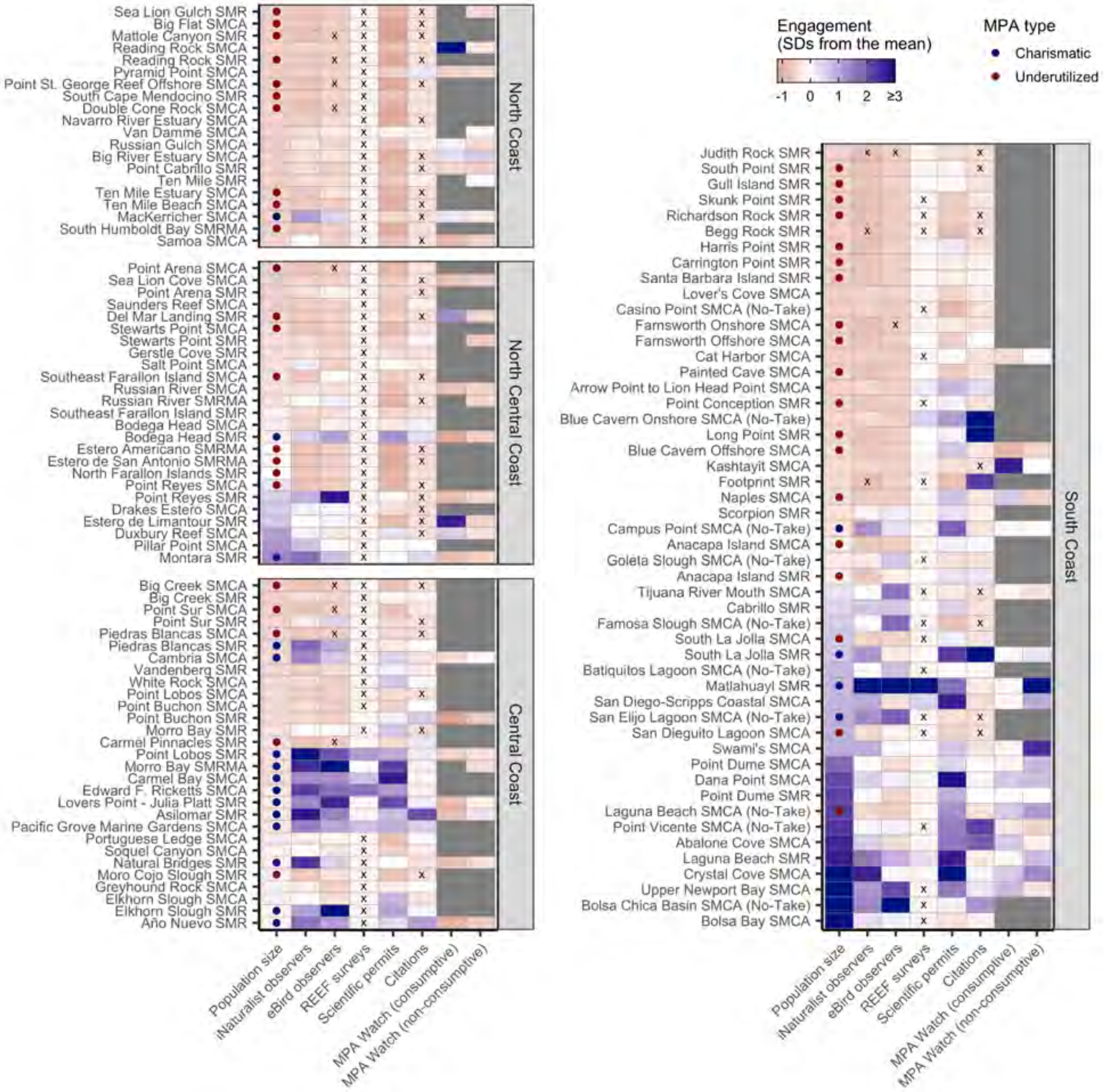


Figure 12 | *A synthesis of human use indicators within California's state marine protected areas (MPAs). MPAs are organized by region and are sorted by population density within 50 km (first column of each plot). Human use indicators are centered and scaled to ease comparison across indicators; thus, purple shades indicate MPAs with above average engagement and red shades indicate MPAs with below average engagement. Gray indicates MPAs without data and x's indicate MPAs with true zeros. MPAs with greater ("charismatic") and less ("underutilized") engagement than expected based on surrounding population density are marked in the population size column (purple circles for greater engagement and red circles for less engagement).*

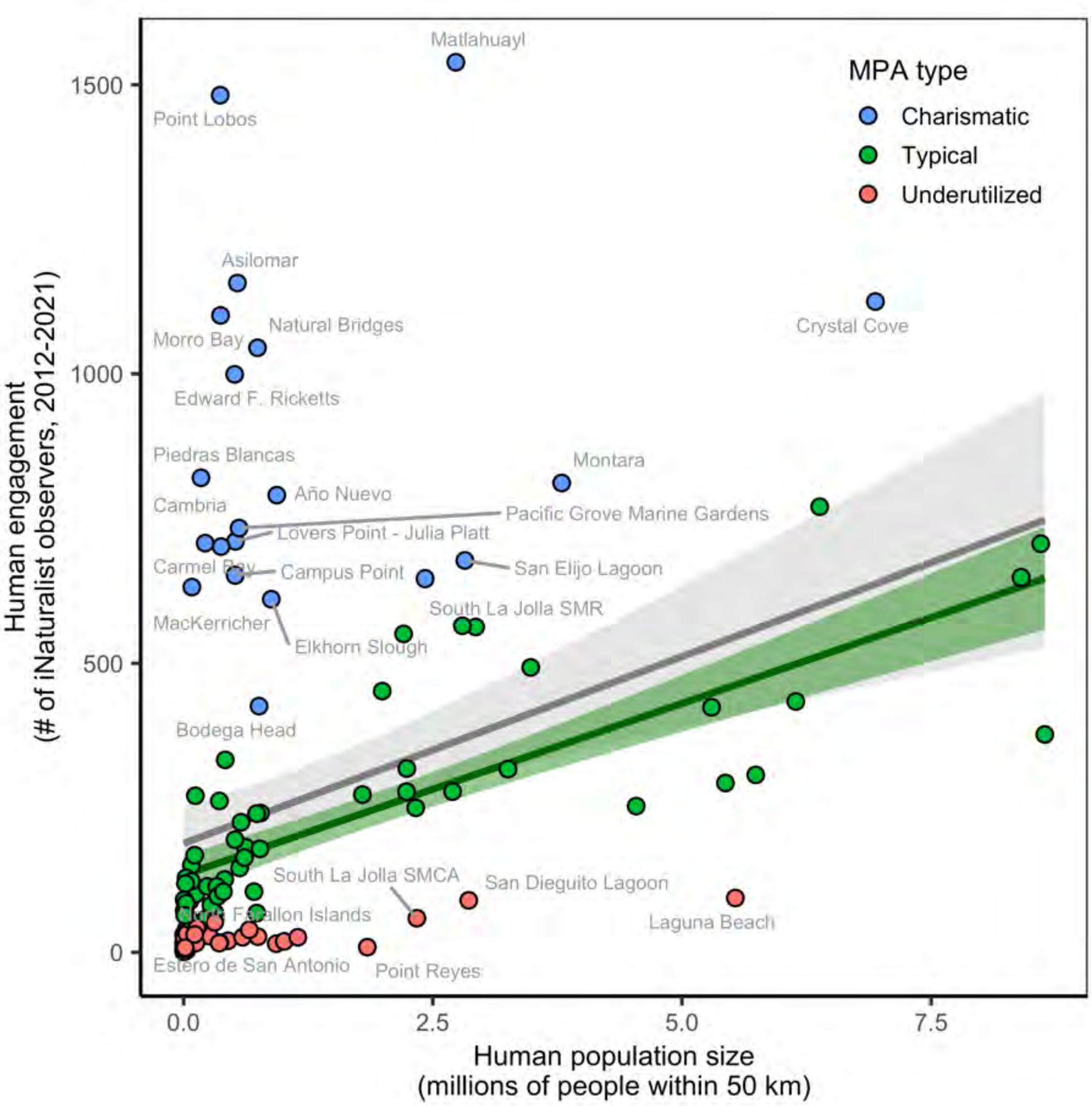


Figure 13 | *Correlation between human engagement in a marine protected area and the number of people living within 50 km of a protected area. Human engagement is measured as the number of iNaturalist observers submitting observations within 100 m of a protected area from 2012 through 2021. The gray line and 95% confidence interval illustrate a linear regression ($r^2=0.14$; $p<0.0001$) fit to all points. Blue points with residuals greater than 75% of the fitted values were classified as "charismatic" protected areas, whose engagement is higher than would be expected based on population density. Red points with residuals less than 75% of the fitted values were classified as "underutilized" protected areas, whose engagement is lower than would be expected based on population density. The charismatic and selected underutilized MPAs are labeled with their abbreviated names. The green line and 95% confidence interval illustrate a linear regression ($r^2=0.62$; $p<0.00001$) fit to the "typical" protected areas (green points), whose engagement is largely determined by population density.*

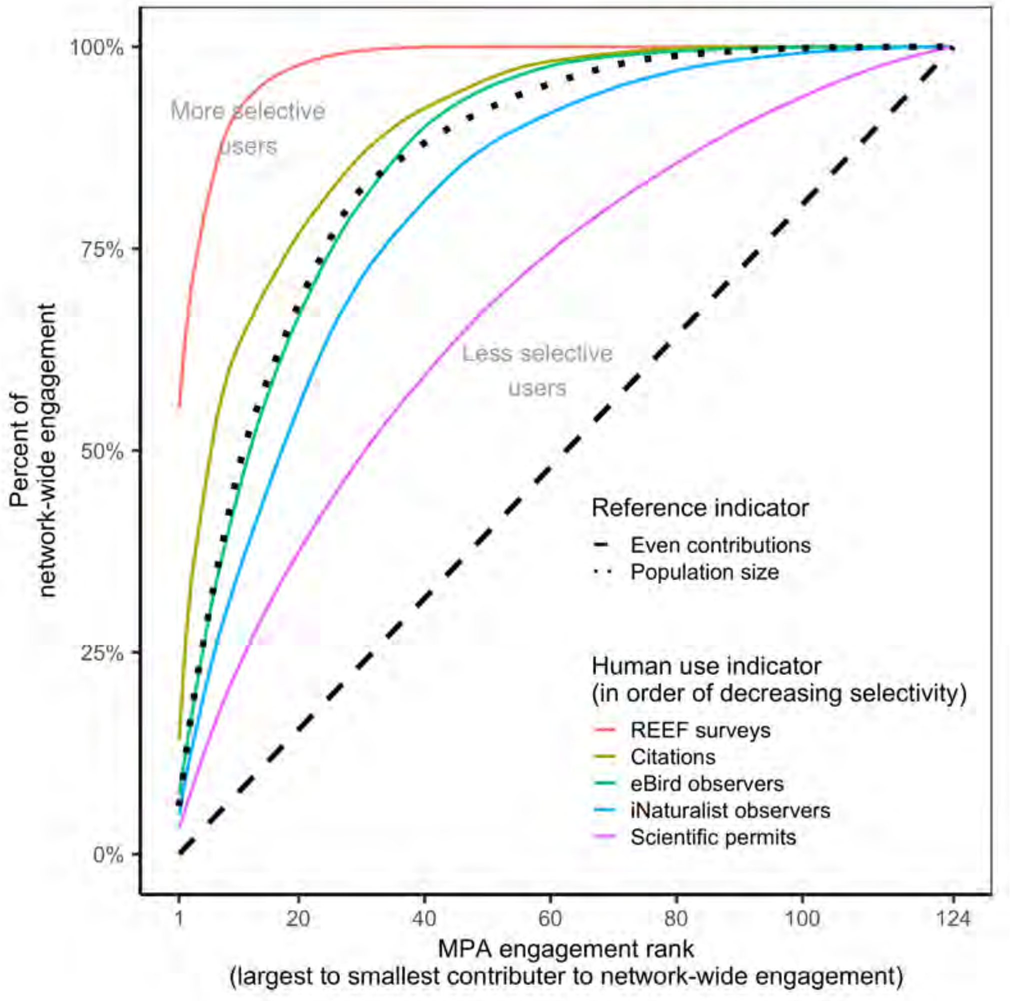


Figure 14 | *Cumulative contributions of individual marine protected areas (MPAs) to network-wide engagement based on several indicators of human use. The diagonal dashed line indicates a theoretical accumulation curve in which individual protected areas contribute equally to engagement within the overall network. Curved lines above this reference line indicate accumulation curves in which some protected areas make larger contributions (higher performers) to network-wide engagement than others (lower performers); the steeper the curve, the more network-wide engagement is dominated by a few protected areas. The accumulation curve for population size (dotted black line) provides an additional frame of reference: if human use were proportional to population size, engagement would accumulate according to this curve. Thus, curves steeper than this line indicate that benefits are more densely concentrated than would be predicted by population density (i.e., use is more selective) whereas curves shallower than this line indicate a more even distribution of benefits than would be predicted by population density (i.e., use is less selective). The MPA Watch human use indicators are excluded because they are not available for all MPAs within the network.*

Table 5 | *Attributes of "charismatic" and "underutilized" MPAs by type of engagement, based on the results of stepwise logistic regressions. Missing values indicate the best fit model does not include the associated predictors.* In each model, "typical" MPAs were set as the reference level and evaluated against charismatic or underutilized MPAs. Coefficients returned by each model are reported as odds ratio. CI = 95% confidence interval; AIC = Akaike Information Criterion.*

	Charismatic vs Typical			**Underutilized vs Total**		
Predictors	**Odds Ratios**	**CI**	**p**	**Odds Ratios**	**CI**	**p**
(Intercept)	0.00	0.00 – 0.13	0.007	0.62	0.24 – 1.53	0.302
Distance to port (km)	1.00	1.00 – 1.00	0.065	1.00	1.00 – 1.00	<0.001
MPA size (km^2)	0.94	0.87 – 1.01	0.121			
Take? (yes/no)	0.26	0.05 – 1.18	0.093			
Sandy beach (km)	1.49	1.08 – 2.19	0.022	0.61	0.39 – 0.87	0.016
MPA age (yr)	1.58	1.15 – 2.29	0.007			
# of parks within 1 km	1.28	1.09 – 1.56	0.006			
Rocky intertidal (km)				0.80	0.61 – 1.03	0.101
# of parking lots within 1 km				0.42	0.15 – 0.71	0.019
Observations	71			92		
R^2 Tjur	0.466			0.446		
AIC	59.527			84.254		

* *Predictors not included in the reduced models include: maximum kelp canopy (km^2), estuary extent (km), number of campgrounds within 1 km, number of picnic areas within 1 km (see Table S4 for details).*

Response to DEWG questions:

DEWG question N1: Which stakeholder groups are accessing MPAs and adjacent non-MPA reference sites?

While we did not evaluate which stakeholder groups were accessing adjacent non-MPA reference sites, we did find that stakeholder groups engage with MPAs in different ways. The general public that uses iNaturalist engaged strongly with MPAs, and there are particular MPAs that receive high engagement despite not being located near large population centers. Birders, identified through eBird observations, largely used MPAs that scaled positively with human population density in the region surrounding those MPAs. REEF divers were selective in which MPAs they used, more so than other stakeholders. Scientists also engaged with MPAs and did so across the MPA network.

DEWG question N4: Are there groups that disproportionately access or don't access MPAs and reference sites, and why?

We identified specific MPAs that received disproportionately high and low engagement (for the stakeholder groups for which we had data) compared to that expected if based on human population density alone. MPAs where take was allowed, presence of sandy beach, and having an MPA cited near state and county parks all contributed to increased engagement with MPAs.

DEWG question 25: Are efforts to collect long-term monitoring data coordinated sufficiently to fully evaluate MPA Network performance?

While we did not evaluate if long-term monitoring data efforts were coordinated, particularly across habitat monitoring groups, we did find that scientific permits were distributed across the entire MPA Network, confirming that monitoring data are being collected across the entire network. This suggests that a coordinated effort is possible.

Discussion:

We found that human engagement in MPAs is generally correlated with nearby population density and that site “charisma” can expand human use beyond what would be predicted by population density alone. Charismatic MPAs are located near tourist destinations and are often adjacent to beaches, state parks, and associated amenities. In addition, our analysis suggests high engagement in SMCAs where take is allowed. In contrast, underutilized MPAs were assumed to be less accessible because of their distance from densely populated areas and their lack of associated infrastructure. While some indicators of human uses scaled with population density, others were either more selective for particular MPAs or less selective than predicted. These results have important management implications. First, achieving MPA goals associated with engagement in MPAs can be promoted by developing land-based amenities that increase access to coastal MPAs or by locating new MPAs near existing amenities during the design phase.

Second, managers may prioritize monitoring, enforcement, education, and outreach programs in MPAs with traits that predict high human engagement. Lastly, while some MPAs may receive low human engagement, thus not meeting one objective, they might be important areas for preserving biodiversity, meeting other objectives.

When reflecting on MLPA Goal 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," we found high engagement in MPAs within the sectors of recreation, education, and science. Understanding the extent to which human use impacts the conservation performance of MPAs is a critical next step to designing MPAs that minimize tradeoffs among potentially competing objectives.

Equitable human use of California's MPA network should also be a critical socioeconomic objective. Unfortunately, the indicators of human engagement evaluated here do not include demographic information on the identity of human users, limiting our ability to evaluate the equity of use among different user groups. The collection of information on the identity of MPA users is thus a vital first step towards considering equity in future MPA planning and outreach. Knowledge of the representativeness of current users is necessary to design and implement programs that promote access and engagement among underrepresented groups.

Data Availability Statement

This project leveraged a very large number of published environmental and biological monitoring datasets, many of which are already collated in the OPC-funded CeNCOOS/SCCOOS MPA Monitoring Web Application and in the OPC MPA Monitoring DataONE portal. To make our work reproducible and open, we used a programmatic approach to the data processing and analytical phases of the project. Analyses were performed in R and all project code is documented and available on the GitHub code repository platform. For the dissemination of new data products generated by this project, we will preserve datasets supporting our scientific findings in a member data repository of the DataONE federation at the end of the project.

References

Ban, N. C., Gurney, G. G., Marshall, N. A., Whitney, C. K., Mills, M., Gelcich, S., ... & Breslow, S. J. (2019). Well-being outcomes of marine protected areas. Nature Sustainability, 2(6), 524-532.

Blowes, S. A., Chase, J. M., Di Franco, A., Frid, O., Gotelli, N. J., Guidetti, P., ... & Belmaker, J. (2020). Mediterranean marine protected areas have higher biodiversity via increased evenness, not abundance. Journal of Applied Ecology, 57(3), 578-589.

Bond, N. A., Cronin, M. F., Freeland, H., & Mantua, N. (2015). Causes and impacts of the 2014 warm anomaly in the NE Pacific. Geophysical Research Letters, 42(9), 3414-3420.

Botsford, L. W., White, J. W., Carr, M. H., & Caselle, J. E. (2014). Marine protected area networks in California, USA. In Advances in marine biology (Vol. 69, pp. 205-251). Academic Press.

California Department of Fish and Wildlife. (2016). California Marine Life Protection Act Master Plan for Marine Protected Areas. Adopted by the California Fish and Game Commission on August 24, 2016. Retrieved from www.wildlife.ca.gov/Conservation/Marine/MPAs/Master-Plan.

California Department of Fish and Wildlife. (2018). Marine Protected Area Monitoring Action Plan. California Department of Fish and Wildlife and
California Ocean Protection Council, California, USA. October 2018.
https://nrm.dfg.ca.gov/FileHandler.ashx?DocumentID=161738&inline

Carr, M. H., Robinson, S. P., Wahle, C., Davis, G., Kroll, S., Murray, S., ... & Williams, M. (2017). The central importance of ecological spatial connectivity to effective coastal marine protected areas and to meeting the challenges of climate change in the marine environment. Aquatic Conservation: Marine and Freshwater Ecosystems, 27, 6-29.

Carr, M.H., Caselle, J.E., Cavanaugh, K., Freiwald, J., Kroeker, K., et al. (2021). Monitoring and Evaluation of Kelp Forest Ecosystems in the MLPA Marine Protected Area Network. Technical report.

Chin, T. M., Vazquez-Cuervo, J., & Armstrong, E. M. (2017). A multi-scale high-resolution analysis of global sea surface temperature. Remote sensing of environment, 200, 154-169.

Claudet, J., Osenberg, C. W., Benedetti-Cecchi, L., Domenici, P., García-Charton, J. A., Pérez-Ruzafa, Á., ... & Planes, S. (2008). Marine reserves: size and age do matter. Ecology letters, 11(5), 481-489.

Di Lorenzo, E., & Mantua, N. (2016). Multi-year persistence of the 2014/15 North Pacific marine heatwave. Nature Climate Change, 6(11), 1042-1047.

eBird. (2022). EBird Basic Dataset. Version: EBD_relMay-2022. Cornell Lab of Ornithology. https://ebird.org/home

Edgar, G. J., Stuart-Smith, R. D., Willis, T. J., Kininmonth, S., Baker, S. C., Banks, S., ... & Thomson, R. J. (2014). Global conservation outcomes depend on marine protected areas with five key features. Nature, 506(7487), 216-220.

Erskine, E., Baillie, R., & Lusseau, D. (2021). Marine Protected Areas provide more cultural ecosystem services than other adjacent coastal areas. One Earth, 4(8), 1175-1185.

Frölicher, T. L., Fischer, E. M., & Gruber, N. (2018). Marine heatwaves under global warming. Nature, 560(7718), 360-364.

Freedman, R. M., Brown, J. A., Caldow, C., & Caselle, J. E. (2020). Marine protected areas do not prevent marine heatwave-induced fish community structure changes in a temperate transition zone. Scientific reports, 10(1), 1-8.

García-Reyes, M. and Sydeman, W.J. (2017). California Multivariate Ocean Climate Indicator (MOCI) Version V2. Farallon Institute website, http://www.faralloninstitute.org/moci. Accessed August 12, 2022.

Gentemann, C. L., Fewings, M. R., & García-Reyes, M. (2017). Satellite sea surface temperatures along the West Coast of the United States during the 2014–2016 northeast Pacific marine heat wave. Geophysical Research Letters, 44(1), 312-319.

Gerber, L. R., Botsford, L. W., Hastings, A., Possingham, H. P., Gaines, S. D., Palumbi, S. R., & Andelman, S. (2003). Population models for marine reserve design: a retrospective and prospective synthesis. Ecological Applications, 13(sp1), 47-64.

Giakoumi, S., Scianna, C., Plass-Johnson, J., Micheli, F., Grorud-Colvert, K., Thiriet, P., ... & Guidetti, P. (2017). Ecological effects of full and partial protection in the crowded Mediterranean Sea: a regional meta-analysis. Scientific reports, 7(1), 1-12.

Gleason, M., Fox, E., Ashcraft, S., Vasques, J., Whiteman, E., Serpa, P., Saarman, E., Caldwell, M. & Frimodig, A. (2013). Designing a network of marine protected areas in California: Achievements, costs, lessons learned, and challenges ahead. Ocean and Coastal Management, 74, 90-101.

Goñi, R., Hilborn, R., Díaz, D., Mallol, S., & Adlerstein, S. (2010). Net contribution of spillover from a marine reserve to fishery catches. Marine Ecology Progress Series, 400, 233-243.

Hall-Arber, M., Murray, S., Aylesworth, L., Carr, M., Field, J., Grorud-Colvert, K., Martone, R., Nickols, K., Saarman, E., Wertz, S. (2021). Scientific Guidance for California's MPA Decadal Reviews: A Report by the Ocean Protection Council Science Advisory Team Working Group and California Ocean Science Trust. https://www.oceansciencetrust.org/wp-content/uploads/2021/06/Evaluating-California%E2%80%99s-Marine-Protected-Area-Network-2021.pdf

Halpern, B. S., Lester, S. E., & McLeod, K. L. (2010). Placing marine protected areas onto the ecosystem-based management seascape. Proceedings of the National Academy of Sciences, 107(43), 18312-18317.

Harvey, B. P., Marshall, K. E., Harley, C. D., & Russell, B. D. (2021). Predicting responses to marine heatwaves using functional traits. Trends in Ecology & Evolution.

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. (2021). 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.
https://www.opc.ca.gov/webmaster/ftp/pdf/agenda_items/20210615/Item3_Climate_Resilience_and_Californias_MPA_Network_2021.pdf

Holbrook, N. J., Sen Gupta, A., Oliver, E. C., Hobday, A. J., Benthuysen, J. A., Scannell, H. A., ... & Wernberg, T. (2020). Keeping pace with marine heatwaves. Nature Reviews Earth & Environment, 1(9), 482-493.

Hopkins, C. R., Burns, N. M., Brooker, E., Dolman, S., Devenport, E., Duncan, C., & Bailey, D. M. (2020). Evaluating whether MPA management measures meet ecological principles for effective biodiversity protection. Acta Oecologica, 108, 103625.

iNaturalist. (2022). INaturalist. INaturalist. https://www.inaturalist.org/

MPA Watch. (2022a). MPA Watch. MPA Watch. https://mpawatch.org/

Jacox, M. G., Edwards, C. A., Hazen, E. L., & Bograd, S. J. (2018). Coastal upwelling revisited: Ekman, Bakun, and improved upwelling indices for the US West Coast. Journal of Geophysical Research: Oceans, 123(10), 7332-7350.

Jacox, M. G., Tommasi, D., Alexander, M. A., Hervieux, G., & Stock, C. A. (2019). Predicting the evolution of the 2014–2016 California Current System marine heatwave from an ensemble of coupled global climate forecasts. Frontiers in Marine Science, 6, 497.

Joh, Y., & Di Lorenzo, E. (2017). Increasing coupling between NPGO and PDO leads to prolonged marine heatwaves in the Northeast Pacific. Geophysical Research Letters, 44(22), 11-663.

Kirlin, J., Caldwell, M., Gleason, M., Weber, M., Ugoretz, J., Fox, E., & Miller-Henson, M. (2013). California's Marine Life Protection Act Initiative: supporting implementation of legislation establishing a statewide network of marine protected areas. Ocean & Coastal Management, 74, 3-13.

Lester, S. E., & Halpern, B. S. (2008). Biological responses in marine no-take reserves versus partially protected areas. Marine Ecology Progress Series, 367, 49-56.

McPherson, M. L., Finger, D. J., Houskeeper, H. F., Bell, T. W., Carr, M. H., Rogers-Bennett, L., & Kudela, R. M. (2021). Large-scale shift in the structure of a kelp forest ecosystem co-occurs with an epizootic and marine heatwave. Communications biology, 4(1), 1-9.

Naidoo, R., Gerkey, D., Hole, D., Pfaff, A., Ellis, A. M., Golden, C. D., ... & Fisher, B. (2019). Evaluating the impacts of protected areas on human well-being across the developing world. Science Advances, 5(4), eaav3006

Nickols, K. J., White, J. W., Malone, D., Carr, M. H., Starr, R. M., Baskett, M. L., ... & Botsford, L. W. (2019). Setting ecological expectations for adaptive management of marine protected areas. Journal of Applied Ecology, 56(10), 2376-2385.

Reed, D., Washburn, L., Rassweiler, A., Miller, R., Bell, T., & Harrer, S. (2016). Extreme warming challenges sentinel status of kelp forests as indicators of climate change. Nature Communications, 7(1), 1-7.

Ramírez-Ortiz, G., Reyes-Bonilla, H., Balart, E. F., Olivier, D., Huato-Soberanis, L., Micheli, F., & Edgar, G. J. (2020). Reduced fish diversity despite increased fish biomass in a Gulf of California Marine Protected Area. PeerJ, 8, e8885.

REEF. (2022). Reef Environmental Education Foundation. www.REEF.org

Rogers-Bennett, L., & Catton, C. A. (2019). Marine heat wave and multiple stressors tip bull kelp forest to sea urchin barrens. Scientific reports, 9(1), 1-9.

Saarman, E., Gleason, M., Ugoretz, J., Airamé, S., Carr, M., Fox, E., ... & Vasques, J. (2013). The role of science in supporting marine protected area network planning and design in California. Ocean & Coastal Management, 74, 45-56.

Sala, E., & Giakoumi, S. (2018). No-take marine reserves are the most effective protected areas in the ocean. ICES Journal of Marine Science, 75(3), 1166-1168.

Sciberras, M., Jenkins, S. R., Kaiser, M. J., Hawkins, S. J., & Pullin, A. S. (2013). Evaluating the biological effectiveness of fully and partially protected marine areas. Environmental Evidence, 2(1), 1-31.

Smith, J. G., & Tinker, M. T. (2022). Alternations in the foraging behaviour of a primary consumer drive patch transition dynamics in a temperate rocky reef ecosystem. Ecology Letters, 25(8), 1827-1838.

Stobart, B., Warwick, R., González, C., Mallol, S., Díaz, D., Reñones, O., & Goñi, R. (2009). Long-term and spillover effects of a marine protected area on an exploited fish community. Marine ecology progress series, 384, 47-60.

Wilson, K. L., Tittensor, D. P., Worm, B., & Lotze, H. K. (2020). Incorporating climate change adaptation into marine protected area planning. Global Change Biology, 26(6), 3251-3267.

Young, M., & Carr, M. (2015). Assessment of habitat representation across a network of marine protected areas with implications for the spatial design of monitoring. PLoS One, 10(3), e0116200.

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Listed in alphabetical order after working group co-chairs, report authors, and data analysts

California Ocean Landscapes Courtesy of Alexandra A Phillips

NCEAS
National Center for Ecological Analysis and Synthesis

UC SANTA BARBARA

Appendix

Table S1 | *State MPAs and reference sites sampled by five habitat monitoring groups. 'Total groups' indicates the number of habitat monitoring groups that sampled a given MPA at any point in time. The numbers for each habitat monitoring group indicate the total number of years that site was sampled as of 2021.*

Region	MPA	Designation	Total Groups	Kelp Forest	Intertidal	CCFRP	Deep Reef	Beach	Surf
NORTH	BODEGA HEAD	REFERENCE	3			4	5	1	
		SMCA	1				5		
		SMR	4		21	4	5	2	
	DEL MAR LANDING	REFERENCE	1	2					
		SMR	2	2	4				
	DOUBLE CONE ROCK	SMCA	1	3					
	DUXBURY REEF	SMCA	1		17				
	GERSTLE COVE	SMR	1		6				
	MACKERRICHER	SMCA	2		3		2		
	MATTOLE CANYON	REFERENCE	1				2		
		SMR	1				2		

MCKERRICHER	REFERENCE	1				2	
	SMCA	2				2	3
NORTH FARALLON ISLANDS	SMR	1			5		
PILLAR POINT	REFERENCE	1			4		
	SMCA	1			4		
POINT ARENA	REFERENCE	2	2		3		
	SMCA	1			3		
	SMR	3	2	5	3		
POINT CABRILLO	REFERENCE	1	5				
	SMR	1	5				
POINT REYES	REFERENCE	2				1	3
	SMCA	1			3		
	SMR	4		3	3	2	3
POINT ST. GEORGE REEF OFFSHORE	REFERENCE	1			3		
	SMCA	1			3		
PYRAMID POINT	REFERENCE	1	2				
	SMCA	2	3	2			

READING ROCK	REFERENCE	3				3	2	3
	SMCA	1				3		
	SMR	3				3	2	3
RUSSIAN RIVER	SMCA	1		2				
SALT POINT	REFERENCE	1	2					
	SMCA	2	2	3				
SAMOA	REFERENCE	1						3
	SMR	1						3
SAMOA DUNES	REFERENCE	1					2	
	SMR	1					2	
SAUNDERS REEF	REFERENCE	1	7					
	SMCA	3	7	4		1		
SEA LION COVE	REFERENCE	1	2					
	SMCA	2	2	17				
SEA LION GULCH	REFERENCE	1				3		
	SMR	1				3		
SOUTH CAPE MENDOCINO	REFERENCE	1			4			

		SMCA	1				1		
		SMR	1			4			
	SOUTHEAST FARALLON ISLAND	REFERENCE	2			2	5		
		SMCA	1				5		
		SMR	2			2	5		
	STEWARTS POINT	REFERENCE	2	5		4			
		SMR	4	5	2	4	1		
	TEN MILE	REFERENCE	3	5		4		2	
		SMR	5	6	2	4		1	3
	TRINIDAD	REFERENCE	1			2			
CENTRAL	ANO NUEVO	REFERENCE	3			14	4	1	
		SMR	5		19	14	4	1	3
	ASILOMAR	REFERENCE	2	3				1	
		SMR	4	3	15			1	3
	BIG CREEK	REFERENCE	2	11			2		
		SMCA	1				2		
		SMR	2	11			2		

CAMBRIA	REFERENCE	1	4					
	SMCA	2	9	17				
CARMEL BAY	REFERENCE	2	3				1	
	SMCA	5	20	22		2	1	3
CARMEL PINNACLES	SMR	1	4					
EDWARD F. RICKETTS	SMCA	1	19					
GREYHOUND ROCK	SMCA	2		23				3
LOVERS POINT - JULIA PLATT	SMR	2	21	23				
MONTARA	REFERENCE	1					1	
	SMR	3		6		4	2	
NATURAL BRIDGES	REFERENCE	2	12					3
	SMR	3	11	23				3
PACIFIC GROVE MARINE GARDENS	SMCA	1	13					
PIEDRAS BLANCAS	REFERENCE	3	5		12	2		
	SMR	4	5	23	12	2		
POINT BUCHON	REFERENCE	3	10		14	5		

	POINT LOBOS	SMR	4	10	5	14	5		
		REFERENCE	3	17		14	5		
		SMCA	1				5		
	POINT SUR	SMR	5	21	23	14	5		3
		REFERENCE	2	12			4		
		SMCA	1				4		
	PORTUGUESE LEDGE	SMR	3	13	23		4		
		REFERENCE	1				3		
		SMCA	1				3		
	SOQUEL CANYON	SMCA	1				1		
	SOUTHEAST FARALLON ISLAND	SMR	1		4				
	VANDENBERG	REFERENCE	2	14				1	
	WHITE ROCK	SMR	3	9	22			1	
		REFERENCE	1	9					
		SMCA	2	9	21				
SOUTH	ABALONE COVE	REFERENCE	1	12					

	SMCA	2	11	2				
ARROW POINT TO LION HEAD POINT	SMCA	1	6					
BEGG ROCK	REFERENCE	1	1					
	SMR	1	2					
BLUE CAVERN ONSHORE	REFERENCE	1	6					
	SMCA	2	6	22				
CABRILLO	REFERENCE	1	1					
	SMR	2	2	22				
CAMPUS POINT	REFERENCE	4	12			2	3	3
	SMCA	5	12	23		2	3	3
CAT HARBOR	REFERENCE	1	6					
	SMCA	1	5					
CRYSTAL COVE	REFERENCE	1	4					
	SMCA	2	3	22				
DANA POINT	REFERENCE	1	4					
	SMCA	3	4	22				3

FARNSWORTH OFFSHORE	REFERENCE	1				4		
	SMCA	1				4		
FARNSWORTH ONSHORE	REFERENCE	1	5					
	SMCA	1	3					
LAGUNA BEACH	REFERENCE	2	4		1			
	SMCA	1		22				
	SMR	4	4	23	1			3
LONG POINT	REFERENCE	1	4					
	SMR	2	4	4				
LOVER'S COVE	REFERENCE	1	2					
	SMCA	1	2					
MATLAHUAYL	REFERENCE	1	4					
	SMR	2	4	5				
NAPLES	REFERENCE	1	12					
	SMCA	2	22			1		
POINT CONCEPTION	REFERENCE	5	15		1	2	1	3
	SMR	6	14	15	1	2	1	3

	POINT DUME	REFERENCE	4	8			1	3	3
		SMCA	2	6	4				
		SMR	5	7	23		1	3	3
	POINT VICENTE	REFERENCE	1	15					
		SMCA	2	15	3				
	SANTA BARBARA ISLAND	REFERENCE	2	8			1		
		SMR	3	8	17		1		
	SCRIPPS/MATLAHUAYL	REFERENCE	1					3	
		SMCA	1		21				
		SMR	2					3	3
	SOUTH LA JOLLA	REFERENCE	3	4		4	2		
		SMCA	1				2		
		SMR	4	4	5	4	2		
	SWAMI'S	REFERENCE	4	4		4	2	1	
		SMCA	6	4	4	4	2	3	3
SOUTH - CI	ANACAPA ISLAND	REFERENCE	3	17		4	11		
		SC	1		19				

	SMCA	3	17		4	11
	SMR	4	22	19	4	11
CARRINGTON POINT	REFERENCE	3	5		4	2
	SMR	4	5	1	4	11
GULL ISLAND	REFERENCE	2	19			10
	SMR	2	17			10
HARRIS POINT	REFERENCE	2	15			8
	SMR	3	15	19		8
PAINTED CAVE	REFERENCE	1	21			
	SMCA	1	17			
SCORPION	REFERENCE	2	21			1
	SMR	3	17	19		1
SOUTH POINT	REFERENCE	2	17			10
	SMR	3	18	1		10

Table S2 | *MPA sampling effort by survey year. The total number of habitat monitoring groups (of the five analyzed in this report) that sampled a given MPA is indicated for each year, starting in 1999.*

Region	MPA	Designation	99	00	01	02	03	04	05	06	07	08	09	10	11	12	13	14	15	16	17	18	19	20	21
NORTH	BODEGA HEAD	REFERENCE												1	1				1		1	1	3	2	
		SMCA												1	1				1				1	1	
		SMR			1	1	1	1	1	1	1	1	1	3	2	1	1	1	2	1	2	2	4	3	1
	DEL MAR LANDING	REFERENCE												1	1										
		SMR												2	2						1			1	
	DOUBLE CONE ROCK	SMCA																1	1				1		
	DUXBURY REEF	SMCA				1			1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	
	GERSTLE COVE	SMR												1	1						1		1	1	1
	MACKERRICHER	SMCA						1										1	1			1		1	
	MATTOLE CANYON	REFERENCE																1	1						
		SMR																1	1						
	MCKERRICHER	REFERENCE																1					1		
		SMCA																1					2	1	1
	NORTH FARALLON ISLANDS	SMR												1	1				1				1	1	

PILLAR POINT	REFERENCE		1	1				1					1	
	SMCA		1	1				1					1	
POINT ARENA	REFERENCE		1	2				1					1	
	SMCA			1				1					1	
	SMR		2	3				1		1			2	1
POINT CABRILLO	REFERENCE						1	1		1	1	1		
	SMR						1	1		1	1	1		
POINT REYES	REFERENCE											2	1	1
	SMCA	1	1	1										
	SMR	1	3	2						1		2	1	1
POINT ST. GEORGE REEF OFFSHORE	REFERENCE						1	1					1	
	SMCA						1	1					1	
PYRAMID POINT	REFERENCE						1				1			
	SMCA						1	1			2	1		
READING ROCK	REFERENCE						2	1				2	2	1
	SMCA						1	1					1	
	SMR						2	1				2	2	1

RUSSIAN RIVER	SMCA							1	1										
SALT POINT	REFERENCE							1	1										
	SMCA							2	2									1	
SAMOA	REFERENCE																1	1	1
	SMR																1	1	1
SAMOA DUNES	REFERENCE											1					1		
	SMR											1					1		
SAUNDERS REEF	REFERENCE							1	1					1	1	1	1	1	
	SMCA							2	2			1	1	1	1	1	1	2	
SEA LION COVE	REFERENCE							1	1										
	SMCA	1	1	1	1	1	1	2	2		1	1	1	1	1	1	1	1	1
SEA LION GULCH	REFERENCE											1	1					1	
	SMR											1	1					1	
SOUTH CAPE MENDOCINO	REFERENCE														1	1	1	1	
	SMCA											1							
	SMR														1	1	1	1	
	REFERENCE							1	1				1		1	1	1	1	

	SOUTHEAST FARALLON ISLAND	SMCA										1	1				1				1	1	
		SMR										1	1				1		1	1	1	1	
	STEWARTS POINT	REFERENCE										1	1						2	2	2	1	
		SMR										1	1				1		3	2	2	1	1
	TEN MILE	REFERENCE														2	1		1	2	3	2	
		SMR														1	2		2	3	4	3	1
	TRINIDAD	REFERENCE																		1	1		
CENTRAL	ANO NUEVO	REFERENCE							2	2	1	1	1	1	1	1	2	1	1	1	3	1	
		SMR		1		1	1	1	3	3	2	2	2	2	2	2	3	2	2	2	5	3	2
	ASILOMAR	REFERENCE							1	1			1								1		
		SMR							2	2	1	1	2	1	1	1	1	1	1	1	3	2	2
	BIG CREEK	REFERENCE	1	1	1		1	1	1	1	1	1	1				1	1				1	
		SMCA																1				1	
		SMR	1	1	1		1	1	1	1	1	1	1				1	1				1	
	CAMBRIA	REFERENCE			1		1		1	1													
		SMCA		1	1	1	2	2	2	2	2	2	2	1	1	1	1	1	1	1		1	1
	CARMEL BAY	REFERENCE	1	1	1																1		

	SMCA	1	2	2	2	2	1	2	2	2	3	2	2	2	1	2	2	2	3	2	2	4	3	2
CARMEL PINNACLES	SMR									1	1		1	1										
EDWARD F. RICKETTS	SMCA	1	1	1	1	1		1	1	1	1	1		1	1	1	1	1	1	1	1		1	
GREYHOUND ROCK	SMCA	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	2	2	2
LOVERS POINT - JULIA PLATT	SMR	2	2	2	2	2	1	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	1
MONTARA	REFERENCE																					1		
	SMR				1				1				2	2			1	1		1		1	2	
NATURAL BRIDGES	REFERENCE	1	1	1	1	1		1	1	1	1	1	1	1								1	1	1
	SMR	1	2	2	2	2	1	2	2	2	2	2	2	2	1	1	1	1	1	1	1	2	2	2
PACIFIC GROVE MARINE GARDENS	SMCA								1	1	1			1	1	1	1	1	1	1	1	1	1	
PIEDRAS BLANCAS	REFERENCE					1		1	1	1	2	1	1	1	1	1	1		2	1	1	1	2	
	SMR	1	1	1	1	2	1	2	2	2	3	2	2	2	2	2	2	1	3	2	2	2	3	1
POINT BUCHON	REFERENCE									2	3	3	2	2	2	1	1	1	3	2	2	3	2	
	SMR									3	4	4	2	3	2	1	1	1	3	3	2	3	2	
POINT LOBOS	REFERENCE					1		1	1	3	3	3	2	2	2	2	2	2	3	2	2	3	2	
	SMCA									1	1	1							1			1		

	POINT SUR	SMR	2	2	2	2	2	1	2	2	4	4	4	3	3	3	3	3	3	4	3	3	5	4	2
		REFERENCE							1	1	1	2		1	1	2				2	1	1	2	1	
		SMCA										1				1				1			1		
	PORTUGUESE LEDGE	SMR	2	1	1	1	2	1	2	2	2	3	2	2	2	2	1	1	1	3	2	1	3	2	1
		REFERENCE																	1	1			1		
		SMCA																	1	1			1		
	SOQUEL CANYON	SMCA																		1					
	SOUTHEAST FARALLON ISLAND	SMR							1												1	1		1	
	VANDENBERG	REFERENCE	1	1	1	1	1	1	1	1	1	1	1	1	1	1							1		
	WHITE ROCK	SMR	2	2	2	2	2	2	2	2	1	2	1	1	1	1	1	1	1	1	1	1	2	1	
		REFERENCE					1		1	1	1	1	1		1								1	1	
		SMCA			1	2	2	1	2	2	2	2	2	2	2	1	1	1	1	1	1	1	1	1	1
SOUTH	ABALONE COVE	REFERENCE									1	1			1	1	1	1	1	1	1	1	1	1	
		SMCA											1	1	1	2	1	1	1	1	1	1	1	1	
	ARROW POINT TO LION HEAD POINT	SMCA						1				1			1	1							1	1	
	BEGG ROCK	REFERENCE														1									

	SMR										1				1									
BLUE CAVERN ONSHORE	REFERENCE						1				1			1	1							1	1	
	SMCA	1	1	1	1	1	2	2	1	1	1	1	1	2	2	1	1	1	1	1	1	2	2	
CABRILLO	REFERENCE														1									
	SMR	1	1	1	1	1	1	1	1	1	1	1	1	2	2	1	1	1	1	1	1	1	1	
CAMPUS POINT	REFERENCE										1		1	1	2	2	2	1	1	1	1	4	2	1
	SMCA	1	1	1	1	1	1	1	1	1	1	2	2	2	3	3	3	2	2	2	2	5	3	2
CAT HARBOR	REFERENCE						1				1			1	1							1	1	
	SMCA						1							1	1							1	1	
CRYSTAL COVE	REFERENCE													1	1							1	1	
	SMCA	1	1	1	1	1	1	1	1	1	1	1	1	2	2	1	1	1	1	1	1	2	1	
DANA POINT	REFERENCE													1	1							1	1	
	SMCA	1	1	1	1	1	1	1	1	1	1	1	1	2	2	1	1	1	1	1	1	3	3	1
FARNSWORTH OFFSHORE	REFERENCE													1	1		1						1	
	SMCA													1	1		1						1	
FARNSWORTH ONSHORE	REFERENCE						1				1			1	1							1		
	SMCA													1	1							1		

LAGUNA BEACH	REFERENCE													1	1					1		1	1	
	SMCA	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	
	SMR	1	1	1	1	1	1	1	1	1	1	1	1	2	2	1	1	1	1	2	1	3	3	2
LONG POINT	REFERENCE													1	1							1	1	
	SMR												1	1	1	1					1	1	2	
LOVER'S COVE	REFERENCE						1				1													
	SMCA													1	1									
MATLAHUAYL	REFERENCE													1	1							1	1	
	SMR											1		1	2	1						1	2	1
NAPLES	REFERENCE											1	1	1	1	1	1	1	1	1	1	1	1	
	SMCA	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	2	1	1	1	1	1	1	
POINT CONCEPTION	REFERENCE	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1				1	3	1	1
	SMR	2	2	2	2	2	2	2	2	1	1	1	1	1	1		2	1	1	1	2	4	2	1
POINT DUME	REFERENCE						1				1		1	1	2	2	1					3	2	1
	SMCA											1	1	1	2	2					1	1	1	
	SMR	1	1	1	1	1	1	1	1	1	2	1	2	2	3	3	2	1	1	1	1	4	3	2
POINT VICENTE	REFERENCE						1			1	1	1	1	1	1	1	1	1	1	1	1	1	1	

		SMCA						1			1	1	1	1	1	2	2	1	2	1	1	1	1	1	
	SANTA BARBARA ISLAND	REFERENCE						1	1	1	1	1			1	1		1					1		
		SMR			1	1	1	2	1	2	2	2	1	1	2	2	1	1	1	1	1		2	1	
	SCRIPPS/MATLAHUAYL	REFERENCE														1	1						1		
		SMCA	1	1	1	1	1	1	1	1		1	1	1	1	1	1	1	1	1	1	1	1	1	
		SMR														1	1						2	1	1
	SOUTH LA JOLLA	REFERENCE													1	1		1			1	1	2	3	
		SMCA																1						1	
		SMR													1	2	1	1			2	1	2	4	1
	SWAMI'S	REFERENCE													1	1		1			1	1	3	3	
		SMCA													1	2	1	1			2	2	5	5	1
SOUTH - CI	ANACAPA ISLAND	REFERENCE	1				1	2	2	2	2	2	2	1	1	1		2	2	1	2	2	3	3	
		SC	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1		1			
		SMCA					2	2	2	2	2	2	2	1	1	1		2	2	1	2	2	3	3	
		SMR	2	2	2	2	3	3	3	3	3	3	3	2	2	2	2	3	3	2	2	3	3	3	
	CARRINGTON POINT	REFERENCE					1	1	1		1	2								1	1	1	1	1	
		SMR					2	2	2	1	2	2	1					1	1		2	1	2	2	

GULL ISLAND	REFERENCE			1	1	2	2	2	2	2	2	2	1	1	1		2	1	1	1	2	1	2
	SMR					2	2	2	2	2	2	2	1	1	1		2	1	1	1	2	1	2
HARRIS POINT	REFERENCE					1	1	2	2	2	2	2	1	1	1		2		1		1	2	2
	SMR	1	1	1	1	2	2	3	3	3	3	3	2	2	2	1	3		2	1	1	3	2
PAINTED CAVE	REFERENCE		1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
	SMCA					1	1	1	1	1	1	1	1	1	1		1	1	1	1	1	1	1
SCORPION	REFERENCE		1	1	1	1	1	1	1	1	1	1	1	1	1	1	2	1	1	1	1	1	1
	SMR	1	1	1	1	1	2	2	2	2	2	2	2	2	2	2	3	2	2	1	2	1	1
SOUTH POINT	REFERENCE						2	2	2	2	2	2	1	1	1	1	2	2	1	1	1	2	2
	SMR					1	2	2	2	2	2	2	1	1	1	1	2	2	1	2	1	2	2

Table S3 | *State MPA and monitoring de facto status. The gray column 'mpa type' contains the state-designated MPA status and each habitat-specific status is included as separate columns. Red text indicates de facto SMRs as determined by habitat group PIs (see Chapter 1 Methods). Missing values represent MPAs that are not surveyed by a given habitat monitoring group.*

	MPA type	Kelp Forest	Rocky Intertidal	Surf Zone	Deep Reef	CCFRP
north						
pyramid point smca	*SMCA*	SMCA	SMCA			
point st. george reef offshore smca	*SMCA*				SMCA	
reading rock smca	*SMCA*			SMCA		
reading rock smr	*SMR*				SMR	
samoa smca	*SMCA*			SMCA		
south cape mendocino smr	*SMR*				SMR	SMR
mattole canyon smr	*SMR*				SMR	
sea lion gulch smr	*SMR*				SMR	
double cone rock smca	*SMCA*	SMCA				
ten mile smr	*SMR*	SMR	SMR	SMR	SMR	SMR
mackerricher smca	*SMCA*		SMR		SMCA	
point cabrillo smr	*SMR*	SMR				
van damme smca	*SMCA*	SMCA				
point arena smr	*SMR*	SMR	SMR		SMR	
point arena smca	*SMCA*				SMR	

	MPA type	Kelp Forest	Rocky Intertidal	Surf Zone	Deep Reef	CCFRP
sea lion cove smca	*SMCA*	SMCA	SMR			
saunders reef smca	*SMCA*	SMCA	SMR		SMR	
del mar landing smr	*SMR*	SMR	SMR			
stewarts point smca	*SMCA*				SMCA	
stewarts point smr	*SMR*	SMR	SMR		SMR	SMR
salt point smca	*SMCA*	SMCA	SMCA			
gerstle cove smr	*SMR*		SMR			
russian river smca	*SMCA*		SMR			
bodega head smr	*SMR*		SMR		SMR	SMR
bodega head smca	*SMCA*				SMCA	
point reyes smr	*SMR*		SMR	SMR	SMR	
point reyes smca	*SMCA*				SMR	
duxbury reef smca	*SMCA*		SMCA			
north farallon islands smr	*SMR*				SMR	
southeast farallon island smr	*SMR*		SMR		SMR	SMR
southeast farallon island smca	*SMCA*				SMR	
central						
montara smr	*SMR*		SMR		SMR	
pillar point smca	*SMCA*				SMCA	

	MPA type	Kelp Forest	Rocky Intertidal	Surf Zone	Deep Reef	CCFRP
ano nuevo smr	*SMR*		SMR	SMR	SMR	SMR
greyhound rock smca	*SMCA*		SMR			
natural bridges smr	*SMR*	SMR	SMR	SMR		
soquel canyon smca	*SMCA*				SMR	
portuguese ledge smca	*SMCA*				SMR	
asilomar smr	*SMR*	SMR	SMR	SMR	SMR	
lovers point - julia platt smr	*SMR*	SMR	SMR			
carmel pinnacles smr	*SMR*	SMR				
carmel bay smca	*SMCA*	SMCA	SMR		SMCA	
point lobos smr	*SMR*	SMR	SMR	SMR	SMR	SMR
point sur smr	*SMR*	SMR	SMR		SMR	
point sur smca	*SMCA*				SMR	
big creek smr	*SMR*	SMR			SMR	
big creek smca	*SMCA*				SMR	
piedras blancas smr	*SMR*	SMR	SMR		SMR	SMR
piedras blancas smca	*SMCA*				SMR	
cambria smca	*SMCA*	SMCA	SMCA			
white rock smca	*SMCA*	SMR	SMR			
point buchon smr	*SMR*	SMR	SMR			SMR

	MPA type	Kelp Forest	Rocky Intertidal	Surf Zone	Deep Reef	CCFRP
vandenberg smr	*SMR*	SMR	SMR			
north islands						
harris point smr	*SMR*	SMR	SMR		SMR	
painted cave smca	*SMCA*	SMCA				
scorpion smr	*SMR*	SMR	SMR		SMR	
carrington point smr	*SMR*	SMR	SMR		SMR	SMR
anacapa island smca	*SMCA*	SMCA			SMCA	
anacapa island smr	*SMR*	SMR	SMR		SMR	SMR
gull island smr	*SMR*	SMR			SMR	
south point smr	*SMR*	SMR	SMR		SMR	
santa barbara island smr	*SMR*	SMR	SMR			
begg rock smr	*SMR*	SMR				
south						
naples smca	*SMCA*	SMCA			SMCA	
point conception smr	*SMR*	SMR	SMR	SMR	SMR	SMR
campus point smca	*SMCA*	SMR	SMR	SMR	SMR	
point dume smca	*SMCA*	SMR	SMR			
point dume smr	*SMR*	SMR	SMR	SMR	SMR	
point vicente smca	*SMCA*	SMR	SMR			

	MPA type	Kelp Forest	Rocky Intertidal	Surf Zone	Deep Reef	CCFRP
abalone cove smca	*SMCA*	SMR	SMR			
crystal cove smca	*SMCA*	SMCA	SMR			
laguna beach smr	*SMR*	SMR	SMR	SMR		SMR
laguna beach smca	*SMCA*		SMR			
dana point smca	*SMCA*	SMCA	SMR			
blue cavern onshore smca	*SMCA*	SMR	SMR			
cat harbor smca	*SMCA*	SMCA				
long point smr	*SMR*	SMR	SMR			
lover's cove smca	*SMCA*	SMCA				
farnsworth offshore smca	*SMCA*				SMCA	
farnsworth onshore smca	*SMCA*	SMR				
swami's smca	*SMCA*	SMR	SMR		SMCA	SMR
san diego-scripps coastal smca	*SMCA*		SMR			
matlahuayl smr	*SMR*	SMR	SMR	SMR		
south la jolla smr	*SMR*	SMR	SMR		SMR	SMR
south la jolla smca	*SMCA*				SMCA	
cabrillo smr	*SMR*	SMR	SMR			

Table S4 | *Taxa recorded by each long-term monitoring group used in the climate community change analyses (Chapter 3). An "X" indicates taxa recorded by an individual group (RI=rocky intertidal, KF-I/A=kelp forest invertebrates/algae, KF-F=kelp forest fish, RR=rocky reef, DR=deep reef).*

Common Name	Scientific name	RI	KF-I/A	KF-F	RR	DR
Alaria	*Alaria marginata*		X			
Aggregating anemone	*Anthopleura elegantissima*		X			
Sunburst anemone	*Anthopleura sola*		X			
Giant green anemone	*Anthopleura xanthogrammica*		X			
California brown sea hare	*Aplysia californica*		X			
Black sea hare	*Aplysia vaccaria*		X			
California sea cucumber	*Apostichopus californicus*		X			
Warty sea cucumber	*Apostichopus parvimensis*		X			
Barnacle	*Balanus nubilus*		X			
Cancer crab			X			
Leafy hornmouth	*Ceratostoma foliatum*		X			
Costaria	*Costaria costata*		X			
Grey tennis ball sponge	*Craniella arb*		X			
Rock scallop	*Crassadoma gigantea*		X			
White-spotted rose anemone	*Cribrinopsis albopunctata*		X			
Gumboot chiton	*Cryptochiton stelleri*		X			

Umbrella crab	*Cryptolithodes sitchensis*	X
Orange sea cucumber	*Cucumaria miniata*	X
Leather star	*Dermasterias imbricata*	X
Rough keyhole limpet	*Diodora aspera*	X
Southern sea palm	*Eisenia arborea*	X
Pinto abalone	*Haliotis kamtschatkana*	X
Red abalone	*Haliotis rufescens*	X
Flat abalone	*Haliotis walallensis*	X
Blood star	*Henricia leviuscula*	X
Kellet's whelk	*Kelletia kelletii*	X
Oar weed	*Laminaria farlowii*	X
Laminaria farlowii sub-canopy (layer above primary spaceholder)	*Laminaria farlowii*	X
Setchell's kelp	*Laminaria setchellii*	X
Six arm star	*Leptasterias hexactis*	X
Red gorgonian	*Leptogorgia chilensis*	X
Fragile star	*Linckia columbiae*	X
Decorator crab, moss crab	*Loxorhynchus/Scyra crispatus/acutifrons*	X
Sheep crab	*Loxorhynchus grandis*	X
White urchin	*Lytechinus pictus*	X

Macrocystis	*Macrocystis pyrifera*	X
Macrosystis holdfast (alive)	*Macrocystis pyrifera*	X
Red star	*Mediaster aequalis*	X
Wavy turban snail	*Megastraea undosa*	X
Giant key-hole limpet	*Megathura crenulata*	X
Red urchin - all sizes	*Mesocentrotus franciscanus*	X
Red urchin adult	*Mesocentrotus franciscanus*	X
Red urchin recruit	*Mesocentrotus franciscanus*	X
White plumed anemones	*Metridium* spp	X
Chestnut cowrie	*Neobernaya spadicea*	X
Nereocystis, bull kelp	*Nereocystis luetkeana*	X
Nereocystis holdfast (alive)	*Nereocystis luetkeana*	X
Rainbow star	*Orthasterias koehleri*	X
Burrowing anemone	*Pachycerianthus fimbriatus*	X
Bat star	*Patiria miniata*	X
Short spined star	*Pisaster brevispinus*	X
Giant spined star	*Pisaster giganteus*	X
Ochre star	*Pisaster ochraceus*	X
Pleurophycus	*Pleurophycus gardneri*	X
Red turban snail	*Pomaulax gibberosus*	X

Pterygophora	*Pterygophora californica*	X
Winged kelp	*Pterygophora californica*	X
Mimicking crab	*Pugettia foliata*	X
Northern kelp crab	*Pugettia producta*	X
Cryptic kelp crab	*Pugettia richii*	X
Sunflower star	*Pycnopodia helianthoides*	X
Dawson's sun star	*Solaster dawsoni*	X
Chain-bladder kelp adult	*Stephanocystis osmundacea*	X
Chain-bladder kelp	*Stephanocystis osmundacea*	X
Purple urchin	*Strongylocentrotus purpuratus*	X
Purple urchin adult	*Strongylocentrotus purpuratus*	X
Purple urchin recruit	*Strongylocentrotus purpuratus*	X
Stalked tunicate	*Styela montereyensis*	X
California hydrocoral	*Stylaster californicus*	X
Orange puff-ball sponge	*Tethya californiana*	X
Urticina spp.	*Urticina spp*	X
Bryozoan		X
Strawberry anemone	*Corynactis californica*	X
Acidic seaweed	*Desmarestia spp*	X
Ornate tube worm	*Diopatra/Chaetopterus spp*	X

Hydroid		X
Brown algae		X
Colonial sand tube worm	*Phragmatopoma californica*	X
Sponge		X
Dictyoneurum	*Dictyoneurum californicum/reticulatum*	X
Surfgrass	*Phyllospadix* spp	X
Tube snail, scaled worm shell	*Thylacodes/Petaloconchus squamigerus/montereyensis*	X
Clam		X
Dodecaceria	*Dodecaceria fewkesi*	X
Green algae		X
Tubeworm		X
Barnacle		X
Sea cucumber (embedded, non-mobile)	*Cucumaria* spp	X
Dictyotales	*Dictyotales* spp	X
Egregia	*Egregia menziesii*	X
Cup coral		X
Diatom layer		X
Fragile tube worms	*Salmacina tribranchiata*	X
Tubeworm mat		X

Red filamentous turf		X			
Scallop		X			
Southern staghorn bryozoan	*Diaperoforma californica*	X			
Worm snail	*Petaloconchus montereyensis*	X			
Tube snail, scaled worm shell	*Thylacodes squamigerus*	X			
Mussel	*Mytilus*	X			
Encrusting purple hydrocoral	*Stylantheca papillosa*	X			
Wolf eel	*Anarrhichthys ocellatus*		X		
Ronquils	*Bathymasteridae* spp		X		
Kelp surfperch	*Brachyistius frenatus*		X		
Monkeyface eel	*Cebidichthys violaceus*		X		
Swell shark	*Cephaloscyllium ventriosum*		X		
Blacksmith	*Chromis punctipinnis*		X		
Sanddabs	*Citharichthys* spp		X	X	
Shiner surfperch	*Cymatogaster aggregata*		X		
Black surfperch	*Embiotoca jacksoni*		X		X
Striped surfperch	*Embiotoca lateralis*		X	X	X
Masked prickleback	*Ernogrammus walkeri*		X		
Opaleye	*Girella nigricans*		X		
California moray	*Gymnothorax mordax*		X		

Horn shark	*Heterodontus francisci*	X		
Giant kelpfish	*Heterostichus rostratus*	X		
Kelp greenling	*Hexagrammos decagrammus*	X	X	X
Rock greenling	*Hexagrammos lagocephalus*	X	X	X
Rainbow surfperch	*Hypsurus caryi*	X		X
Halfmoon	*Medialuna californiensis*	X		
Ocean sunfish	*Mola mola*	X		
Bat ray	*Myliobatis californica*	X		X
Lingcod	*Ophiodon elongatus*	X	X	X
Senorita	*Oxyjulis californica*	X		X
Painted greenling	*Oxylebius pictus*	X	X	X
Kelp bass, calico bass	*Paralabrax clathratus*	X		
California halibut	*Paralichthys californicus*	X	X	X
Sharpnose surfperch	*Phanerodon atripes*	X		
White surfperch	*Phanerodon furcatus*	X		X
Thornback	*Platyrhinoidis triseriata*	X		
C-o turbot	*Pleuronichthys coenosus*	X		
Plainfin midshipman	*Porichthys notatus*	X		X
Blue shark	*Prionace glauca*	X		
Starry skate	*Raja stellulata*	X		X

Rubberlip surfperch	*Rhacochilus toxotes*	X		X
Pile surfperch	*Rhacochilus vacca*	X		X
Blackeye goby	*Rhinogobiops nicholsii*	X		
California scorpionfish	*Scorpaena guttata*	X		
Cabezon	*Scorpaenichthys marmoratus*	X	X	X
Kelp rockfish	*Sebastes atrovirens*	X	X	X
Brown rockfish	*Sebastes auriculatus*	X	X	X
Gopher rockfish	*Sebastes carnatus*	X	X	X
Copper rockfish	*Sebastes caurinus*	X	X	X
Black and yellow rockfish	*Sebastes chrysomelas*	X	X	
Gopher and black and yellow rockfish young of year	*Sebastes chrysomelas/carnatus* young of year	X		
Calico rockfish	*Sebastes dallii*	X	X	X
Splitnose rockfish	*Sebastes diploproa*	X		
Widow rockfish	*Sebastes entomelas*	X		X
Squarespot rockfish	*Sebastes hopkinsi*	X	X	X
Black rockfish	*Sebastes melanops*	X	X	X
Vermilion rockfish	*Sebastes miniatus*	X	X	X
Blue rockfish	*Sebastes mystinus*	X	X	
China rockfish	*Sebastes nebulosus*	X	X	X

Bocaccio	*Sebastes paucispinis*	X	X	X
Canary rockfish	*Sebastes pinniger*	X	X	X
Grass rockfish	*Sebastes rastrelliger*	X	X	
Rosy rockfish	*Sebastes rosaceus*	X	X	X
Stripetail rockfish	*Sebastes saxicola*	X		
Halfbanded rockfish	*Sebastes semicinctus*	X		X
Olive or yellowtail rockfish	*Sebastes serranoides,flavidus*	X	X	
Olive, yellowtail, and black rockfish young of year	*Sebastes serranoides,flavidus,melanops*	X		
Treefish	*Sebastes serriceps*	X	X	X
California sheephead	*Semicossyphus pulcher*	X	X	X
Spiny dogfish	*Squalus acanthias*	X		
Pacific angel shark	*Squatina californica*	X		
Pacific electric ray	*Tetronarce californica*	X		
Leopard shark	*Triakis semifasciata*	X		
Pink surfperch	*Zalembius rosaceus*	X		X
California lizardfish	*Synodus lucioceps*		X	
Grunion, topsmelt or jacksmelt	*Atherinopsidae* spp		X	
Pacific mackerel, greenback mackerel	*Scomber japonicus*		X	
Ocean whitefish	*Caulolatilus princeps*		X	X

Eastern pacific bonito	*Sarda chiliensis chiliensis*	X	
Quillback rockfish	*Sebastes maliger*	X	X
Scaleyhead sculpin	*Artedius harringtoni*	X	
Rock sole	*Lepidopsetta bilineata*	X	
Starry rockfish	*Sebastes constellatus*	X	X
White croaker	*Genyonemus lineatus*	X	
Barred surfperch	*Amphistichus argenteus*		X
Big skate	*Raja binoculata*		X
Smooth ronquil	*Rathbunella hypoplecta*		X
Flag rockfish	*Sebastes rubrivinctus*		X
Pacific hagfish	*Eptatretus stoutii*		X
Rex sole	*Glyptocephalus zachirus*		X
Spotted ratfish	*Hydrolagus colliei*		X
English sole	*Parophrys vetulus*		X
Longnose skate	*Raja rhina*		X
Greenspotted rockfish	*Sebastes chlorostictus*		X
Greenstriped rockfish	*Sebastes elongatus*		X
Rosethorn rockfish	*Sebastes helvomaculatus*		X
Shortbelly rockfish	*Sebastes jordani*		X
Cowcod	*Sebastes levis*		X

Blue/deacon rockfish	*Sebastes mystinus or diaconus*		X
Tiger rockfish	*Sebastes nigrocinctus*		X
Speckled rockfish	*Sebastes ovalis*		X
Yelloweye rockfish	*Sebastes ruberrimus*		X
Pygmy rockfish	*Sebastes wilsoni*		X
Combfish complex	*Zaniolepis* complex		X
Anthopleura elegantissima; anthopleura sola	*Anthopleura* elegantissima, sola	X	
Articulated corallines		X	
Barnacles		X	
Chitons		X	
Chondracanthus canaliculatus	*Chondracanthus canaliculatus*	X	
Chthamalus dalli; fissus; balanus glandula		X	
Cladophora columbiana	*Cladophora columbiana*	X	
Crustose corallines		X	
Egregia menziesii	*Egregia menziesii*	X	
Endocladia muricata	*Endocladia muricata*	X	
Endarachne spp; petalonia spp; phaeostrophion spp		X	
Fucus distichus	*Fucus distichus*	X	

Stephanocystis spp	*Stephanocystis* spp	X
Pelvetiopsis californica	*Hesperophycus californicus*	X
Limpets		X
Lottia gigantea	*Lottia gigantea*	X
Mastocarpus spp	*Mastocarpus* spp	X
Mazzaella affinis	*Mazzaella affinis*	X
Mazzaella spp	*Mazzaella* spp	X
Mytilus californianus	*Mytilus californianus*	X
Mytilus trossulus; galloprovincialis; edulis	*Mytilus* spp	X
Neorhodomela larix	*Neorhodomela larix*	X
Non-coralline crusts		X
Other algae; other plants		X
Other brown algae		X
Other green algae		X
Other invertebrates		X
Other red algae		X
Other substrate		X
Pelvetiopsis limitata	*Pelvetiopsis limitata*	X
Phragmatopoma spp; sabellaria spp		X

Phyllospadix spp	*Phyllospadix* spp	X
Pisaster ochraceus	*Pisaster ochraceus*	X
Pollicipes polymerus	*Pollicipes polymerus*	X
Pyropia spp	*Pyropia*	X
Sargassum muticum	*Sargassum muticum*	X
Scytosiphon spp; melanosiphon spp		X
Semibalanus cariosus	*Semibalanus cariosus*	X
Mytilisepta bifurcata; b rachidontes adamsianus		X
Silvetia compressa	*Silvetia compressa*	X
Tetraclita rubescens	*Tetraclita squamosa*	X
Ulva spp; kornmannia spp; monostroma spp		X

Table S5 | *Indicators of human use evaluated in this paper. The bolded metric indicates the metric used in the scorecard analysis.*

Indicator and source	Description	Metrics
MPA Watch (www.mpawatch.org)	Recreation: MPA Watch is a community science program that trains volunteers to observe and collect data on human uses of protected areas (MPA Watch, 2022a). Volunteers use a standardized survey protocol (MPA Watch, 2022b) to record consumptive (e.g., fishing) and non-consumptive (e.g., surfing, boating, tidepooling, running, etc.) activities occurring offshore and onshore of coastal sampling sites.	**(1) the median number of activities observed per hour for surveys in which activities were observed (i.e., zeroes excluded);** (2) percent of surveys in which an activity was observed
iNaturalist (www.inaturalist.org)	Recreation/education: iNaturalist is a web- and app-based platform that allows observers to submit wildlife photos for identification by amateur and professional naturalists (iNaturalist, 2022).	**(1) number of iNaturalist users who submitted observations**; (2) number of submitted observations
eBird (www.ebird.org)	Recreation/education: eBird is a global citizen science program that collates observations of birds submitted by birdwatchers (eBird, 2022).	**(1) number of eBird users who submitted observations;** (2) number of submitted observations
REEF (www.reef.org)	Recreation/education: REEF is an international marine conservation organization that trains volunteer divers and snorkelers to collect and report information on marine fish and selected invertebrate and algae species (REEF, 2022).	**(1) number of surveys conducted;** (2) number of years in which a survey was conducted
Scientific permits (CA Dept. Fish & Wildlife)	Scientific research: Permits issued by CDFW for scientific research provide an indicator of scientific research activity throughout California's MPA network.	**(1) number of permits issued;** (2) number of years in which permits were issued.

Law enforcement citations (CA Dept. Fish & Wildlife)	Non-compliance: Regulatory citations from CDFW's Law Enforcement Division provide an indicator of where non-compliance occurs throughout California's MPA network.	(1) number of citations issued; (2) number of years in which citations were issued.

Table S5 | *List of explanatory variables included in the full logistic model. *denotes inclusion in the reduced best-fit model. **denotes significance in the reduced model.*

Variable
Population density (no. people living within 50 km)
MPA size (km^2)*
Shore span (km)
Take allowed (yes/no; take of any kind)**
MPA age
Park density (no. state and county parks within 1 km) **
Park area (total area of state and county parks)*
Number of parking lots*
Number of picnic areas

MPA within national marine sanctuary

Distance to nearest port

Nearest port size (very small, small, medium, large, very large)

Sandy beach extent (km)**

Rocky intertidal extent (km)

Estuary area (km^2)*

Depth range (m)

Max kelp canopy (km^2)

Fish diversity (Shannon-Wiener)

Total fish biomass

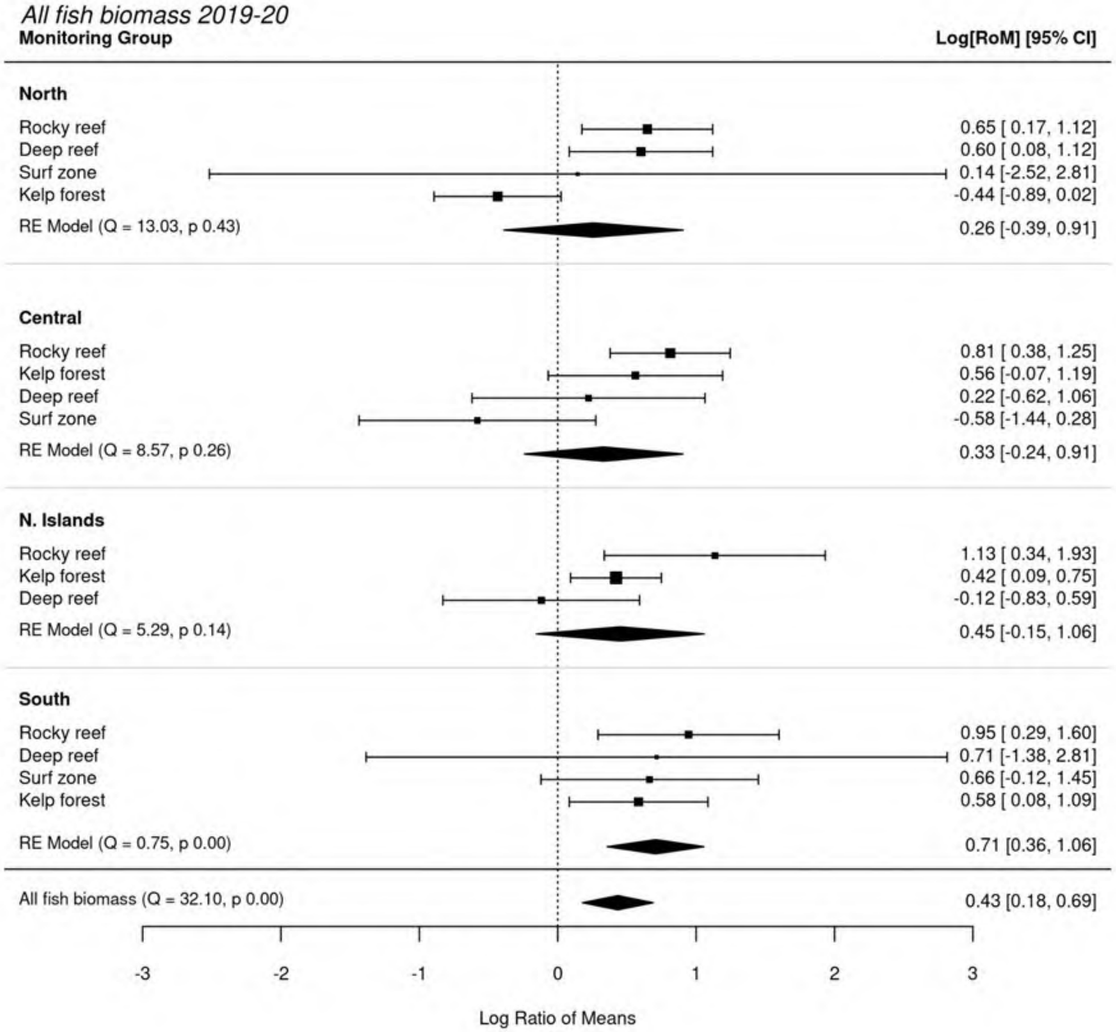

Figure S1 | *All fish biomass response ratios across habitat monitoring groups. Each point depicts the log response ratio (SMR/reference) for a single habitat monitoring group across the 2019-20 sampling period and point sizes are scaled to their relative contribution to the regional pooled effect (across habitats; black diamond). Error bars represent 95% confidence intervals surrounding the response ratio. The vertical dashed line indicates a non-significant effect - where there is no difference in biomass between no-take MPAs and reference sites. Therefore, points with whiskers that do not overlap the line are statistically significant. Similarly, the edges of the pooled effect diamonds represent 95% confidence regions. Finally, each region includes results from a random effects model (RE Model) evaluating the significance of the pooled effect size.*

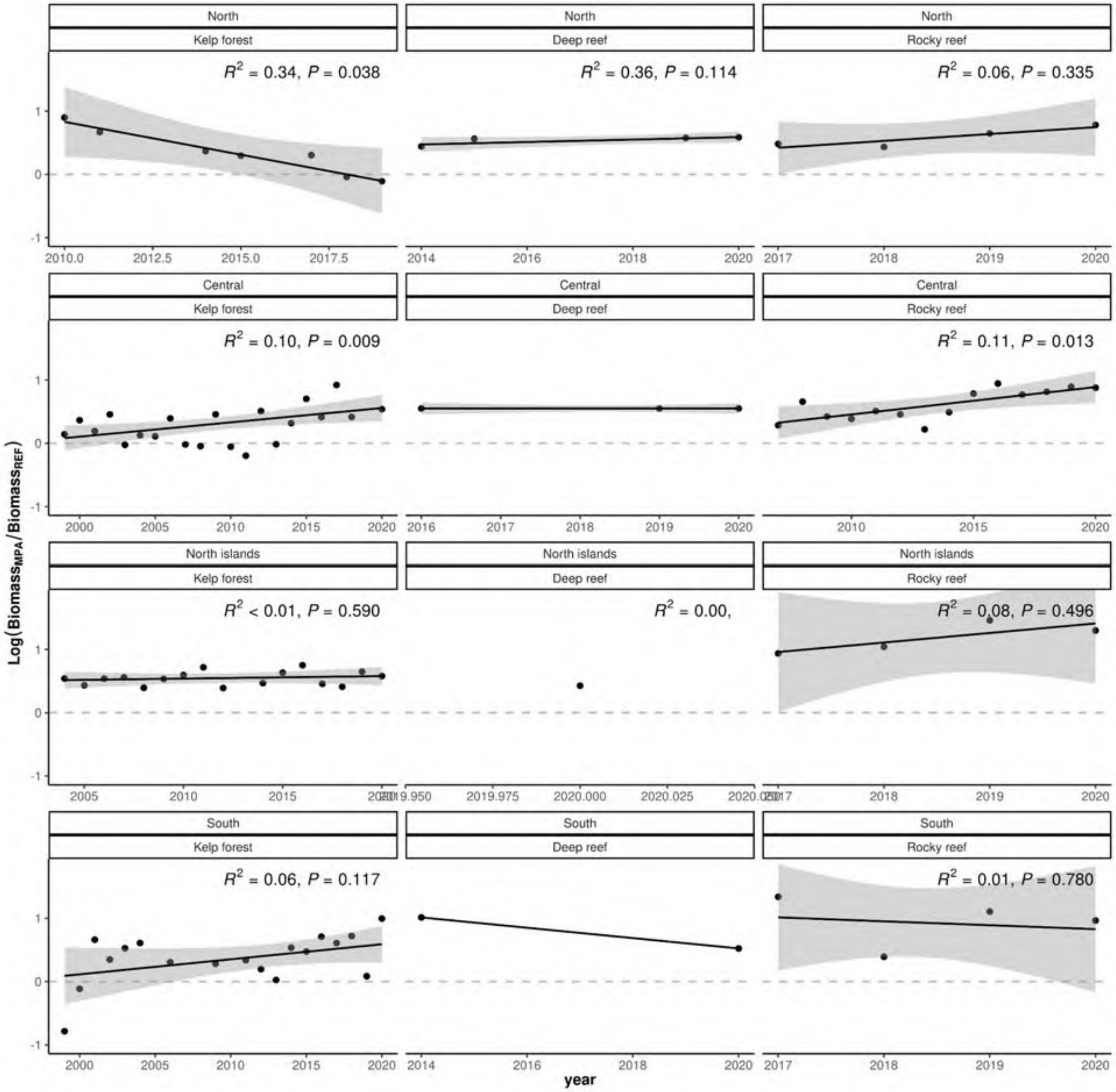

Figure S2 | *Targeted fish biomass response ratios by monitoring group and region. Each point depicts the response ratio averaged over all MPAs sampled within a given year. Regression lines depict the trends over time with 95% confidence intervals shaded in grey.*

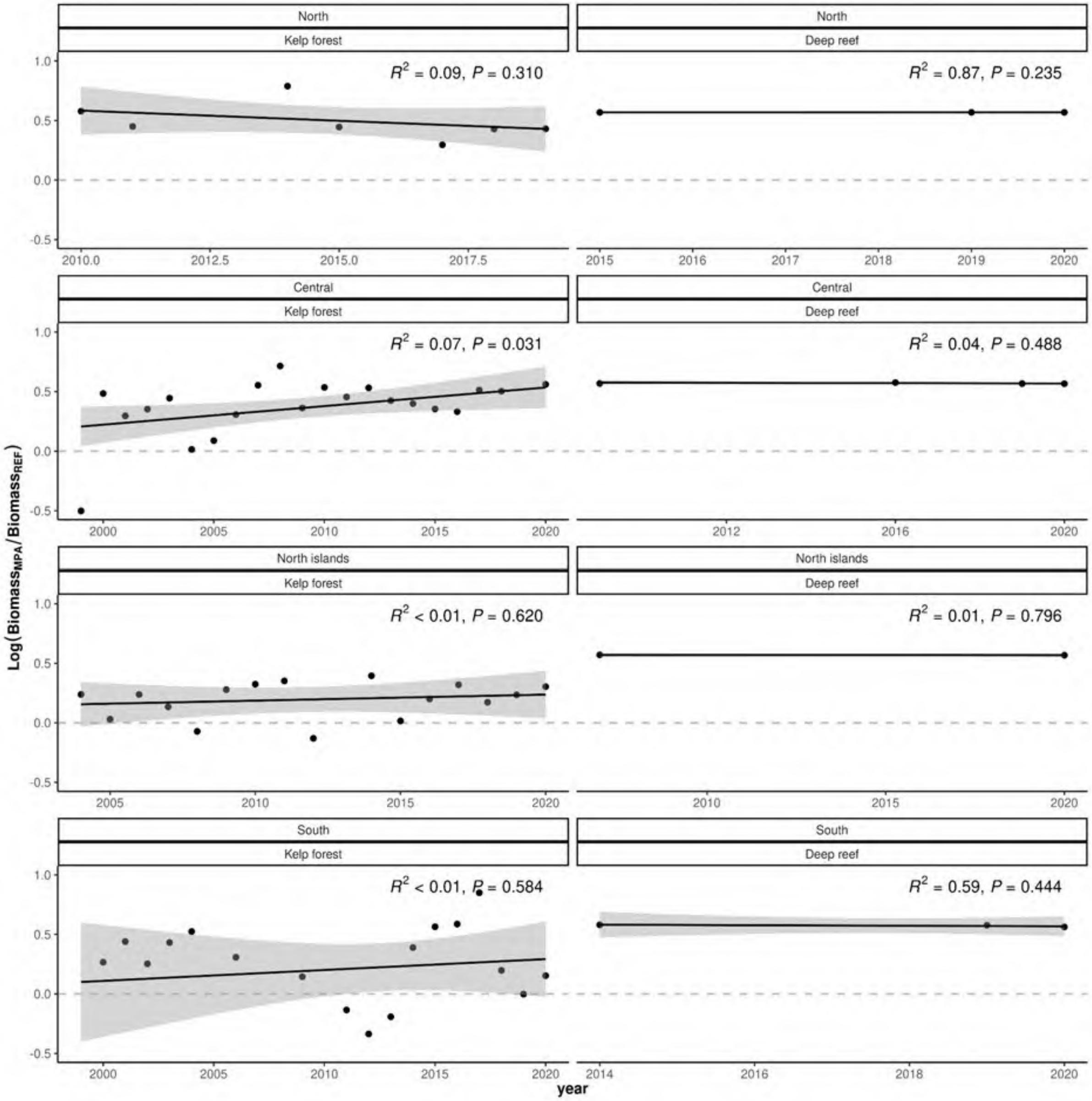

Figure S3 | *Nontargeted fish biomass response ratios by monitoring group and region. Each point depicts the response ratio averaged over all MPAs sampled within a given year. Regression lines depict the trends over time with 95% confidence intervals shaded in grey.*

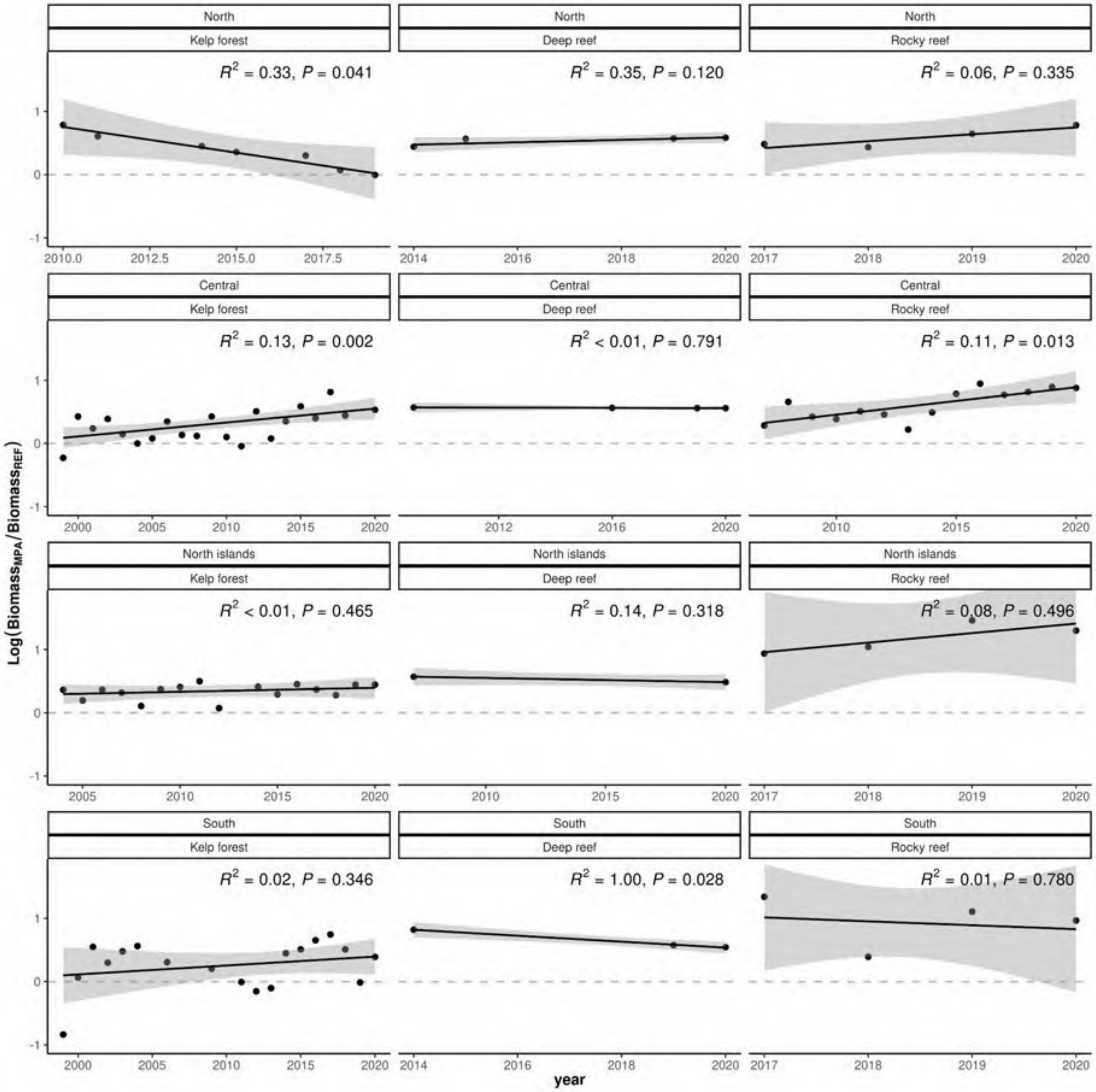

Figure S4 | *Total fish biomass response ratios by monitoring group and region. Each point depicts the response ratio averaged over all MPAs sampled within a given year. Regression lines depict the trends over time with 95% confidence intervals shaded in grey.*

From: Patrick Spalding <[redacted]>
Sent: Wednesday, April 22, 2026 12:53 PM
To: FGC <FGC@fgc.ca.gov>
Subject: Opposition to Petition 2023-23 MPA_AM1

Dear Commission,

I appreciate your work and thank you for giving me the opportunity to engage in the discussion about the best ways to protect our precious ocean resources. My name is Patrick Spalding, I am a father, husband, educator and diver. For the last 16 years I have been harvesting fish from the SMCAs located in Monterey, Pacific Grove and Carmel via freedive spearfishing. I urge the Commission to deny Petition 2023-23 and oppose upgrading existing SMCAs to SMRs or creating new SMRs in the Monterey and Carmel area. There are several reasons for this:

(1) The Monterey/Carmel area is already highly regulated, with several existing no-take areas

(2) The Petitioner's state goal of encouraging kelp restoration and the means of achieving it, eliminating the take of fin fish in designated areas, are tenuously connected at best. It is not surprising that they have offered no scientific evidence of a causal relationship between the rejuvenation of kelp and the take of fin fish.

(3) The likely benefits to kelp restoration caused by the Petition are questionable and run a strong risk of producing little to no return. The damage done to the Community by the Petitioner's proposal will be significant and immediate. Over 100,000 residents will be denied responsible use of a resource they have had for generations.

Therefore, I encourage you to follow the DFW recommendation and deny Petition 2023-23. Thank you for your time and consideration .

Take care,

Patrick Spalding