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-Principle Investigator

Kerry J. Nickols
California State University Northridge
Co-Principle 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.

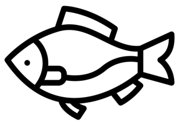
Recommendations:

- 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:

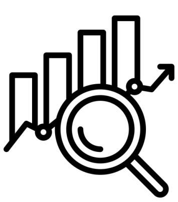


Protect the natural diversity and abundance of marine life, and the structure, function and integrity of marine ecosystems.

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	Habitat 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.

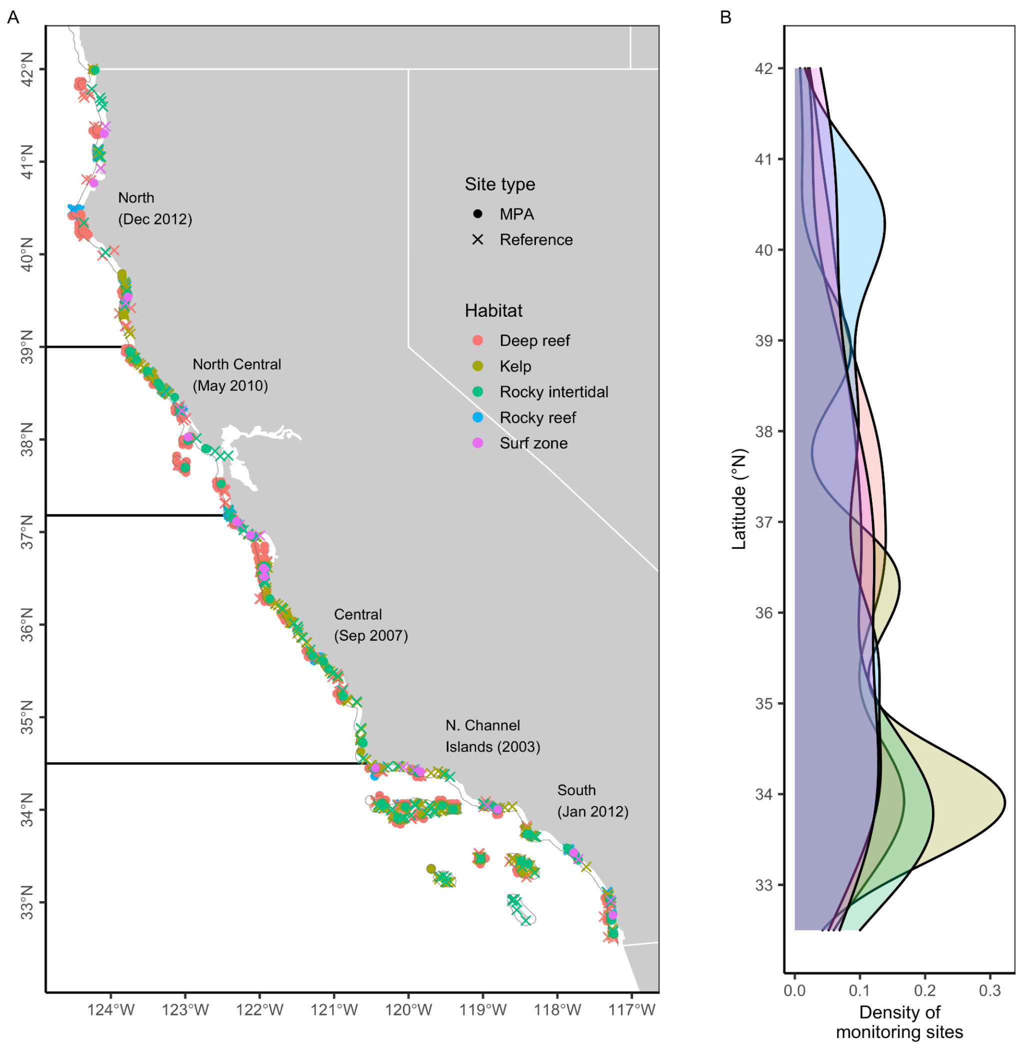
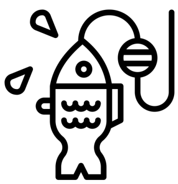


Figure 1 | *Ecological monitoring sites inside (circle) and outside (x) of marine protected areas (MPAs) along California's coast. In panel A, the dark horizontal lines delineate the four MLPA planning regions (labeled with year of implementation) and the thin gray line indicates state waters (3 nautical 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:

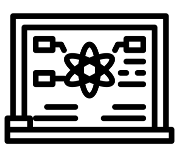
The group was tasked with building upon existing analyses stemming from the habitat-specific monitoring teams and providing new analyses as needed, to provide answers to MPA performance evaluation questions outlined in Appendix B of the Action Plan and refined by the DEWG. The broad objectives for this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

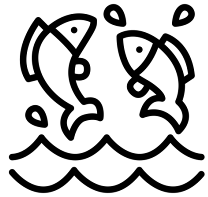
- MLPA Goal 1: To protect the natural diversity and abundance of marine life, and the structure, function, and integrity of marine ecosystems.
- MLPA Goal 2: To help sustain, conserve, and protect marine life populations, including those of economic value, and rebuild those that are depleted.
- DEWG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

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

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

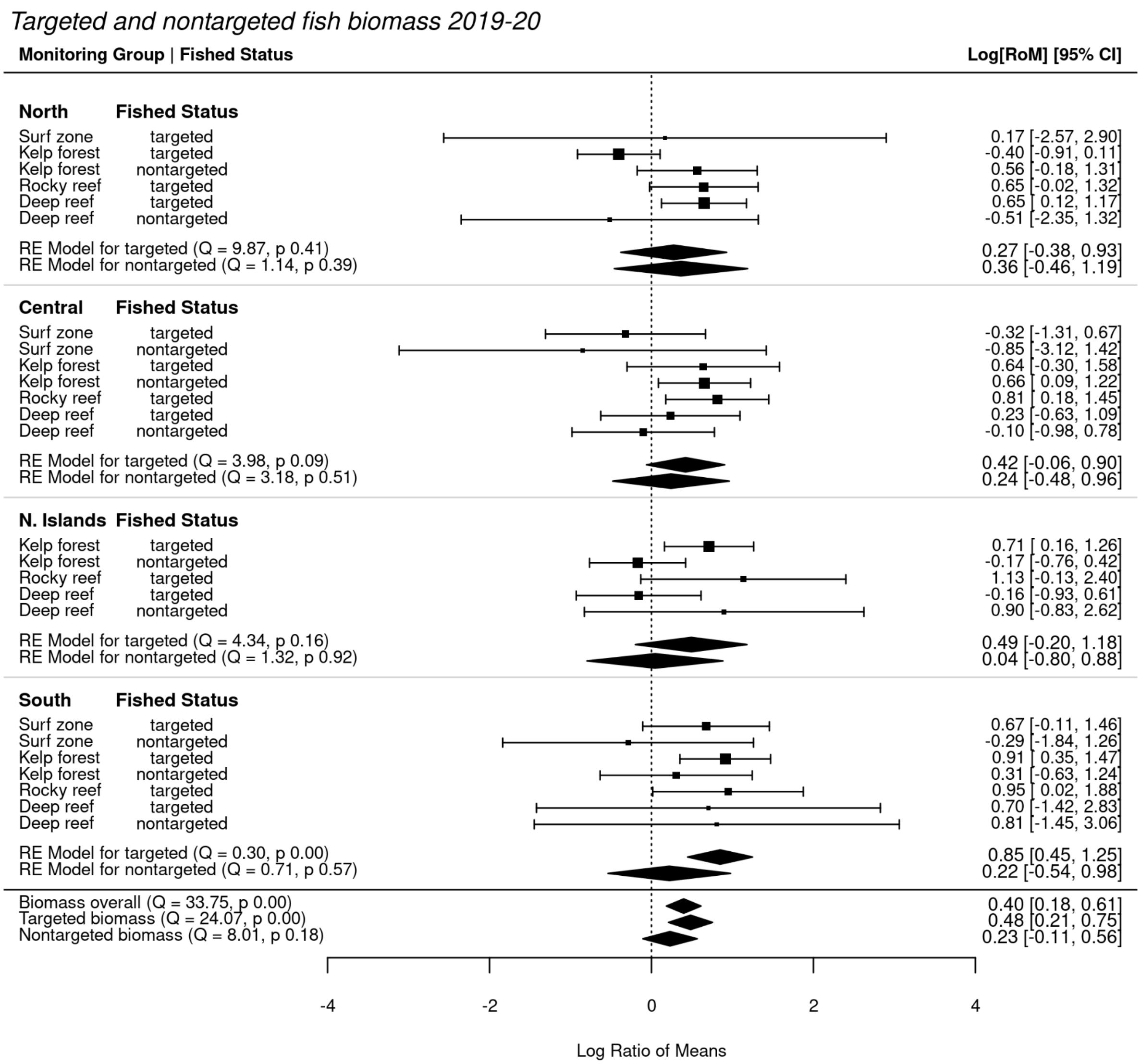


Figure 1 | *Targeted and nontargeted fish biomass response ratios across habitat monitoring groups. Each point depicts the log response ratio (SMR/reference) for a single habitat monitoring group across the 2019-20 sampling period and point sizes are scaled to their relative contribution to the regional 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.*

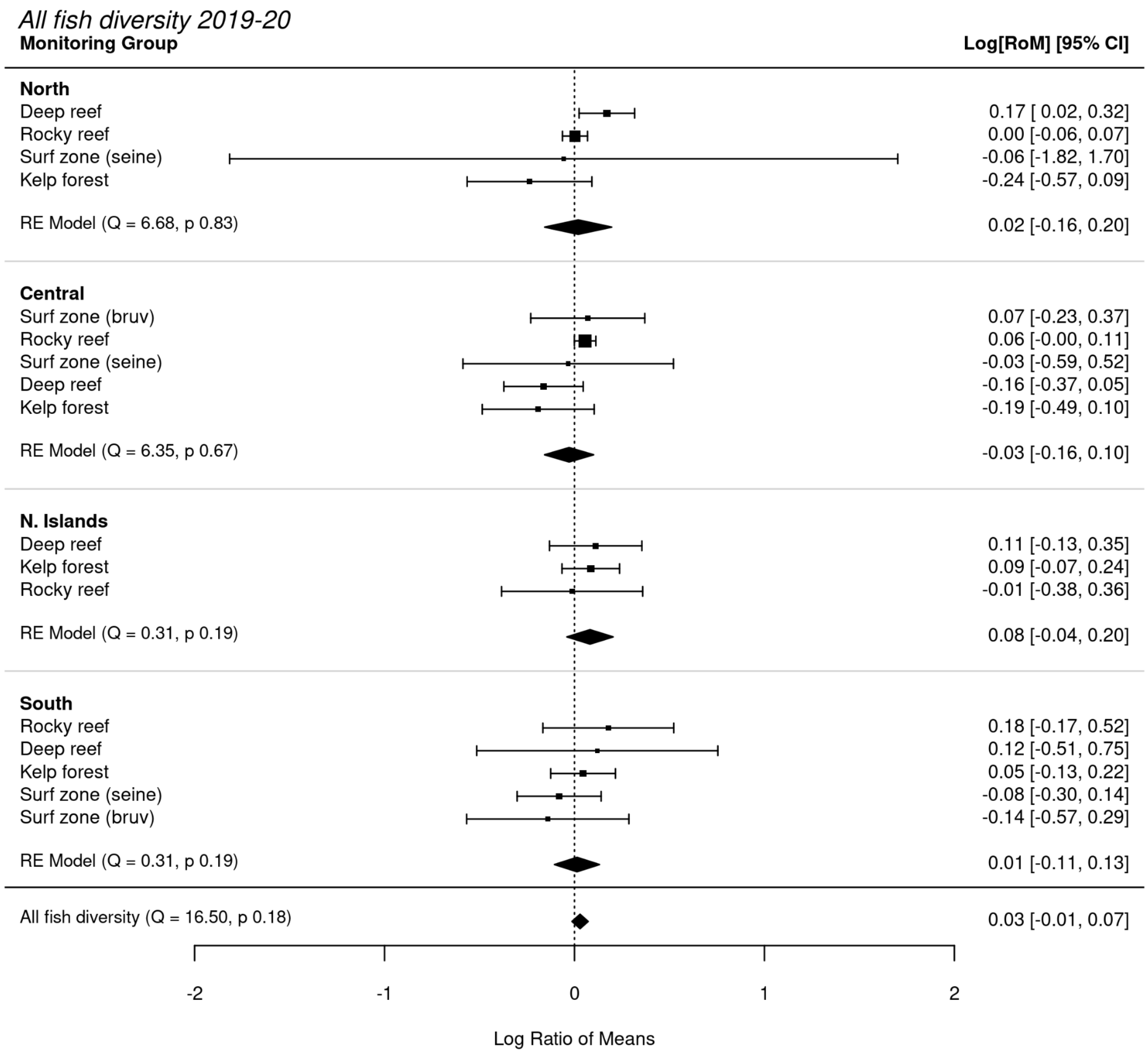


Figure 2 | *Fish diversity (Shannon-Wiener index) response ratios across habitat monitoring groups. Each point depicts the log response ratio (SMR/reference) for a single habitat monitoring group across the 2019-20 sampling period and point sizes are scaled to their relative contribution to the regional 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.*

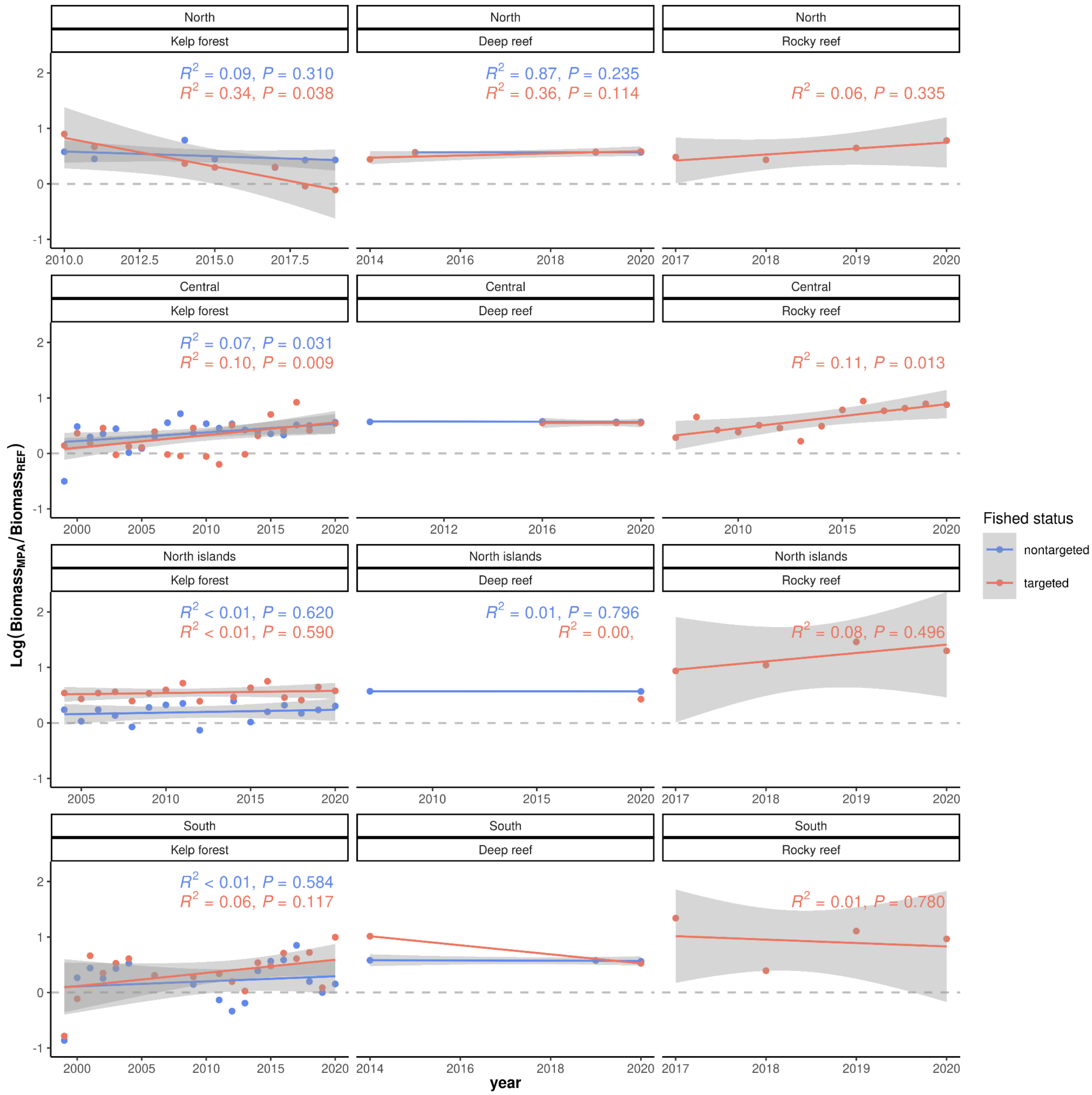


Figure 3 | *Temporal trends in response ratios for targeted and nontargeted fish biomass by monitoring group and region. Each point depicts the response ratio averaged over all MPAs sampled within a given year. Regression lines depict the trends over time for targeted (red) and nontargeted (blue) species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

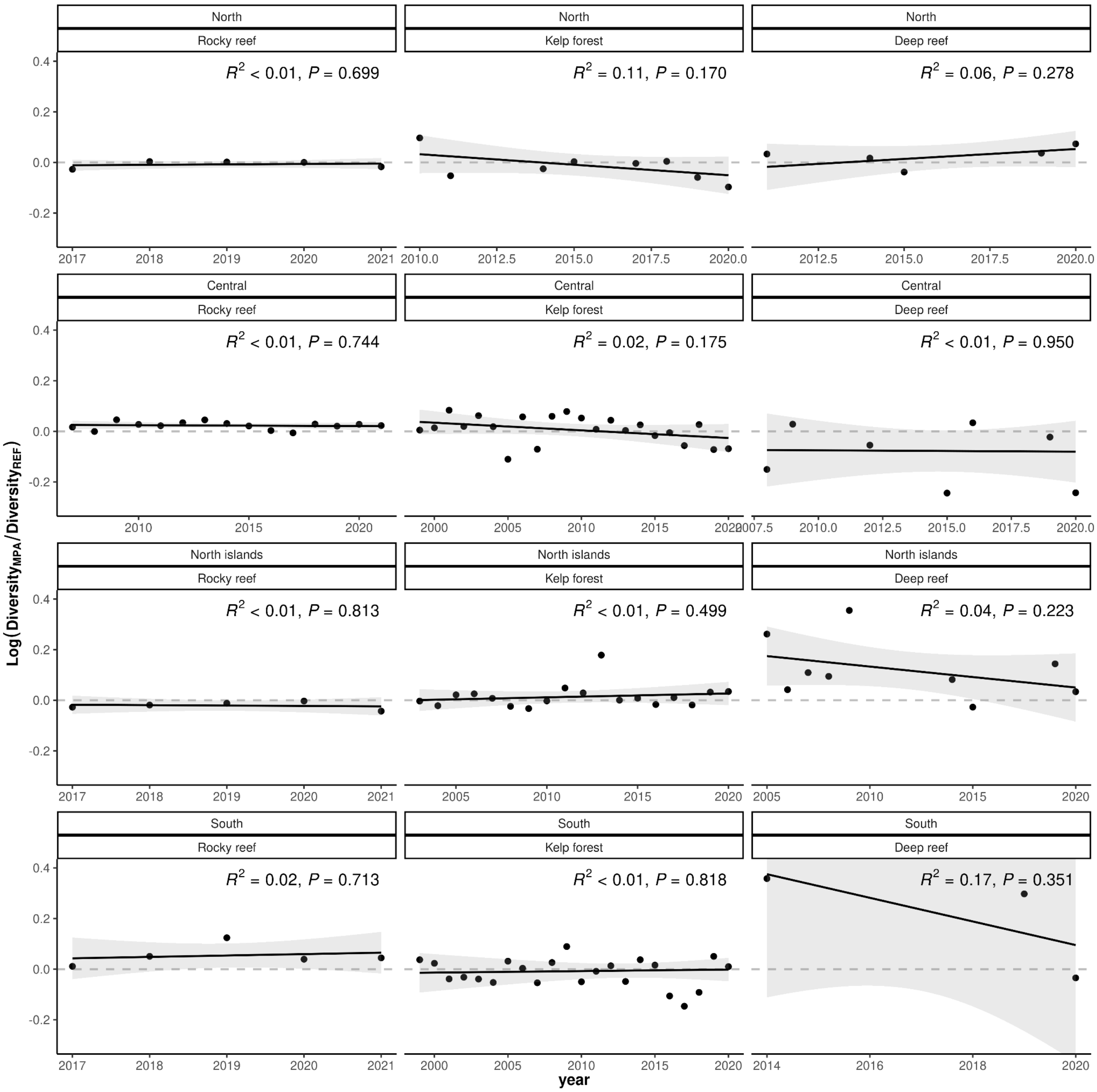


Figure 4 | *All fish diversity response ratios by monitoring group and region. Each point depicts the response ratio averaged over all MPAs sampled within a given year. Also included are regression lines that depict the trends over time with 95% confidence intervals shaded in gray.*

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 results 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

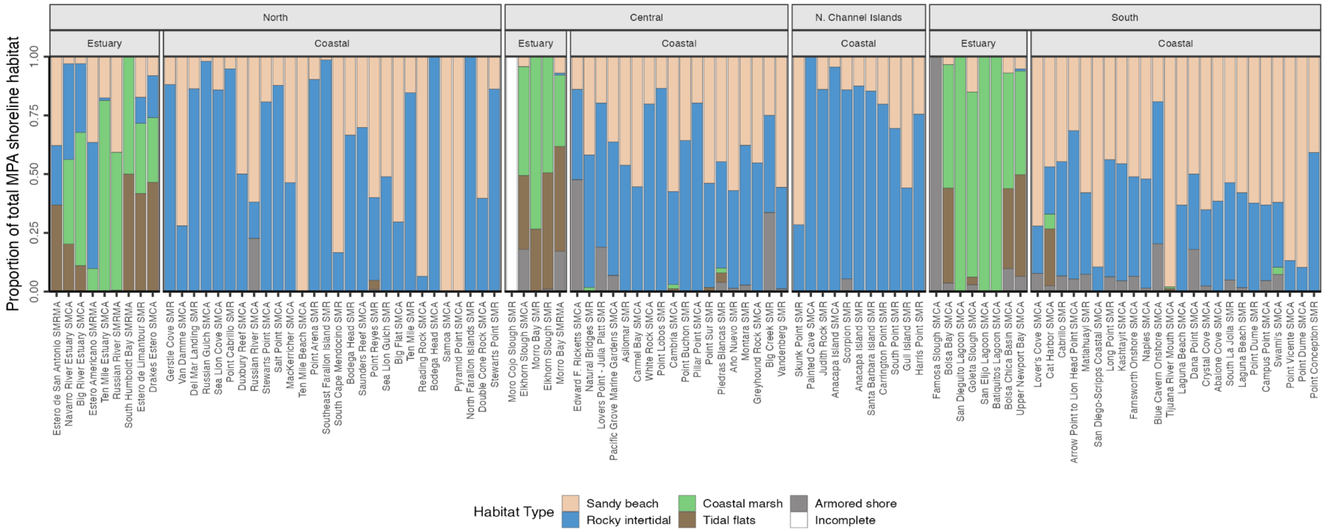


Figure 5 | *Shoreline habitat composition of estuary and coastal MPAs, calculated relative to the total amount of shoreline habitat (km). Estuary MPAs only contain shoreline habitat, by definition. Coastal MPAs are adjacent to a shoreline and also contain offshore habitats. Offshore MPAs are not shown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

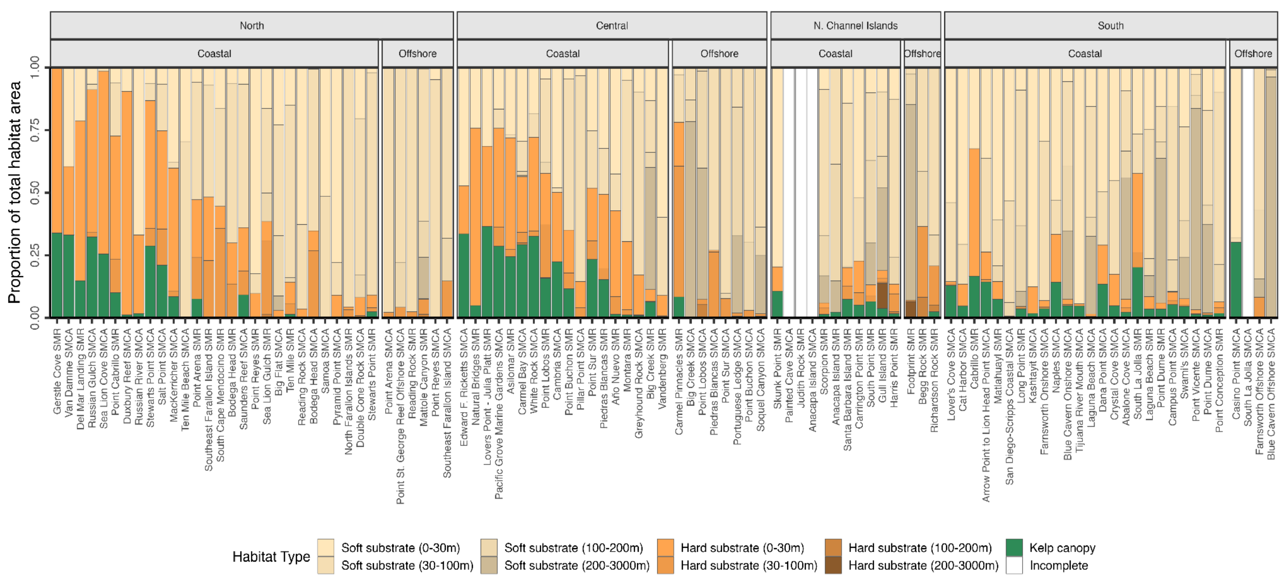


Figure 6 | *Nearshore/offshore habitat composition of coastal and offshore MPAs, calculated relative to the total amount of nearshore/offshore habitat within that MPA (km²). Coastal MPAs are adjacent to a shoreline and also contain offshore habitats, whereas offshore MPAs have no shoreline and therefore 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.*

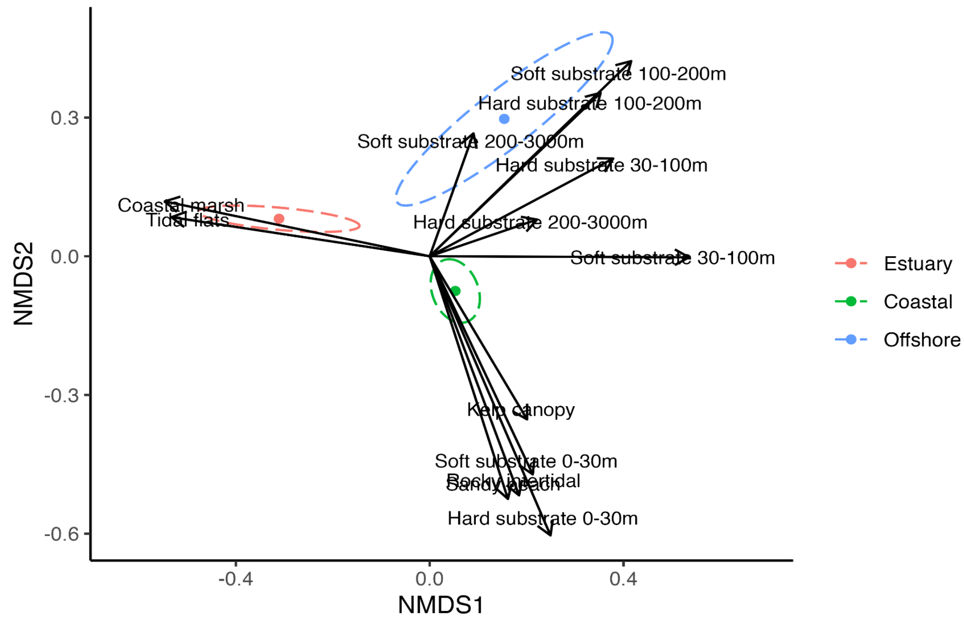


Figure 7 | *Relative differences in MPA habitat composition among estuarine, coastal, and offshore MPAs. from non-metric multidimensional scaling (NMDS) ordination of all MPAs. Dashed lines represent 95% confidence ellipses calculated around the mean position for each region. Vectors are displayed for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

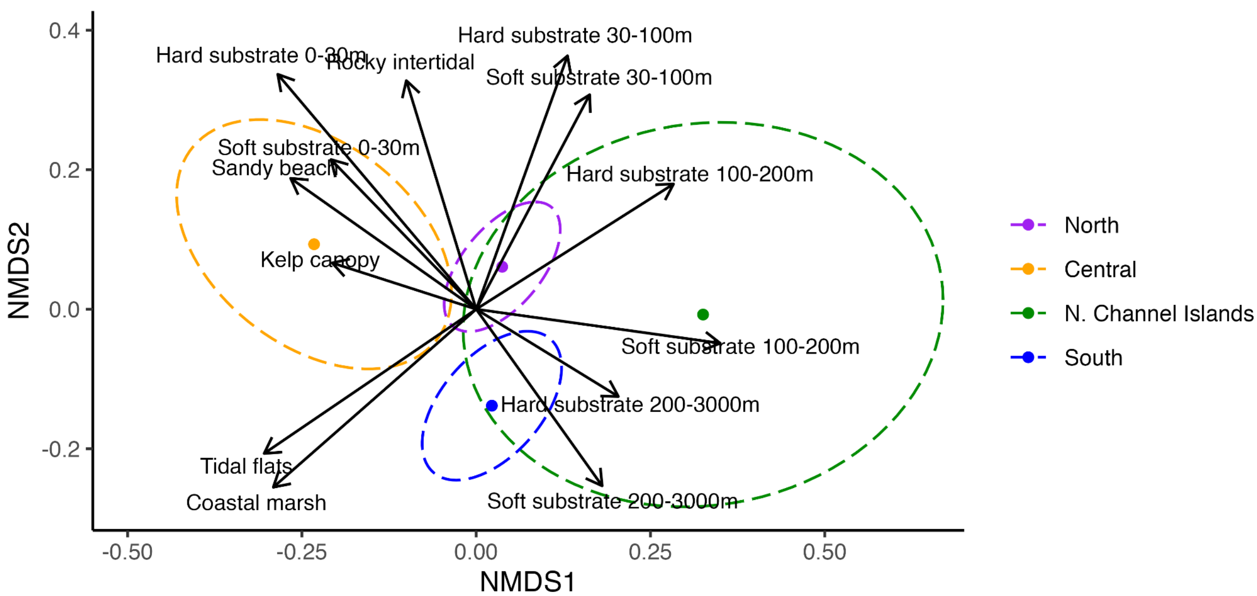


Figure 8 | *Relative differences in MPA habitat composition among planning regions from non-metric multidimensional scaling (NMDS) ordination of only coastal MPAs. Colors represent different MPA regions. Dashed lines represent 95% confidence ellipses calculated around the mean position for each region.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

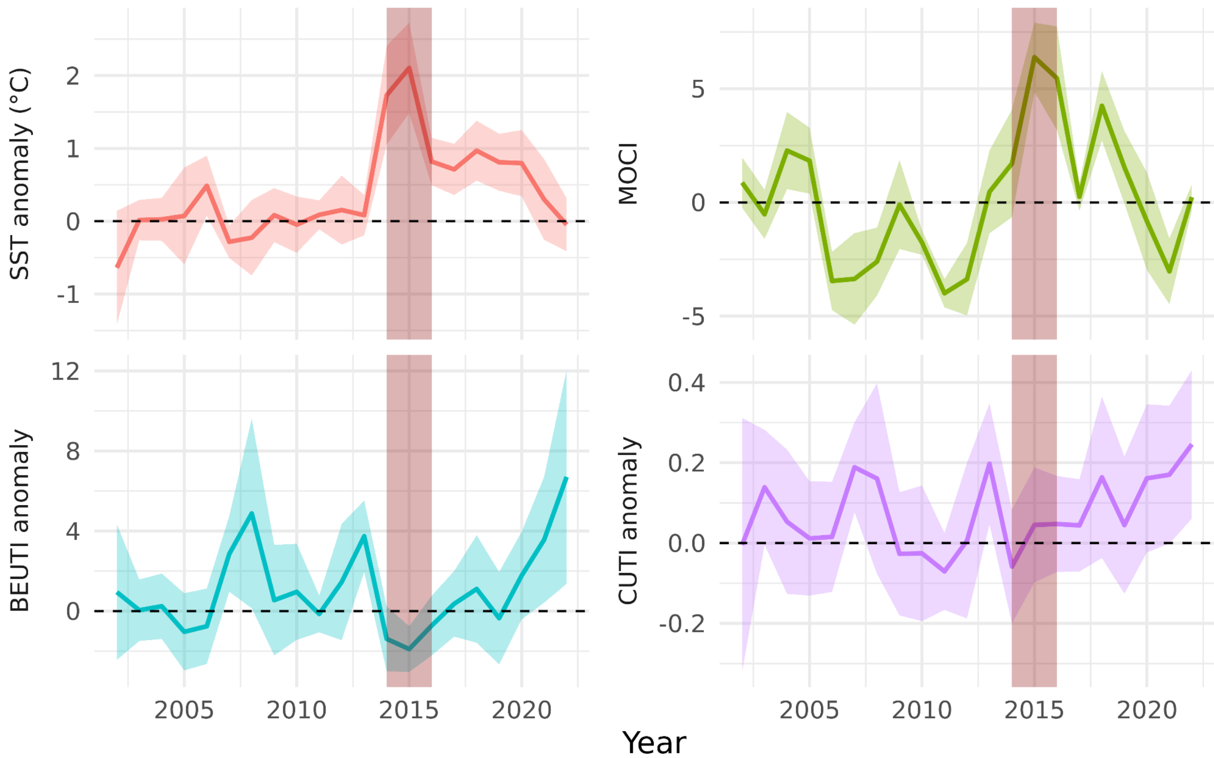


Figure 9 | *Oceanographic conditions from 2000-2022. Each panel depicts a single indicator (annual monthly mean Sea Surface Temperature, SST; Multivariate Oceanographic Climate Index, MOCI; Coastal Upwelling Transport Index, CUTI; Biologically Effective Upwelling Index, BEUTI) with annual trends (lines). 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.*

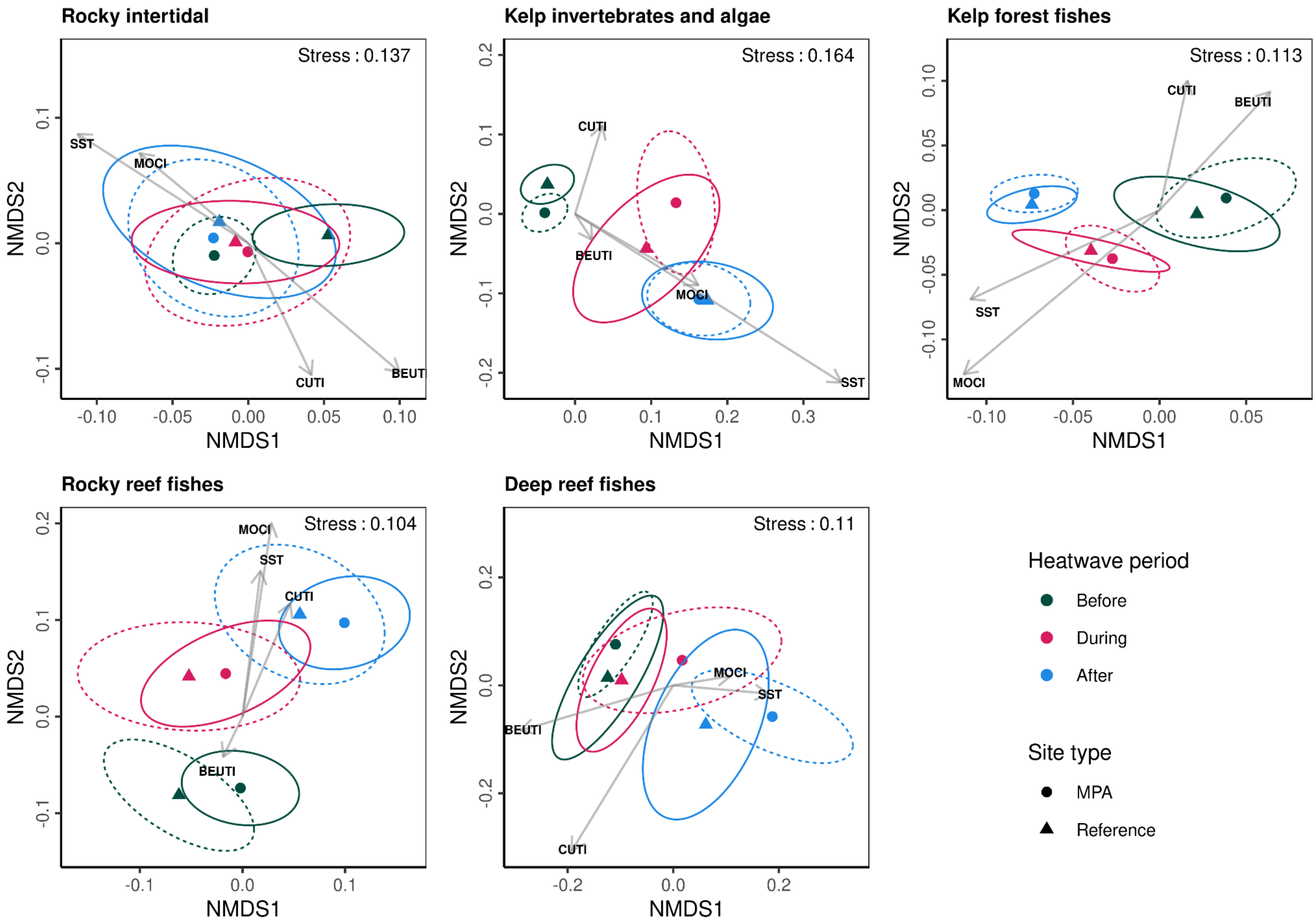


Figure 10 | *Community structure before (green), during (red), and after (blue) the marine heatwave event inside of SMRs (circles) and reference sites (triangles) in the central coast. Each panel represents a different monitoring program or subprogram. Each point depicts the centroid position, which 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).*

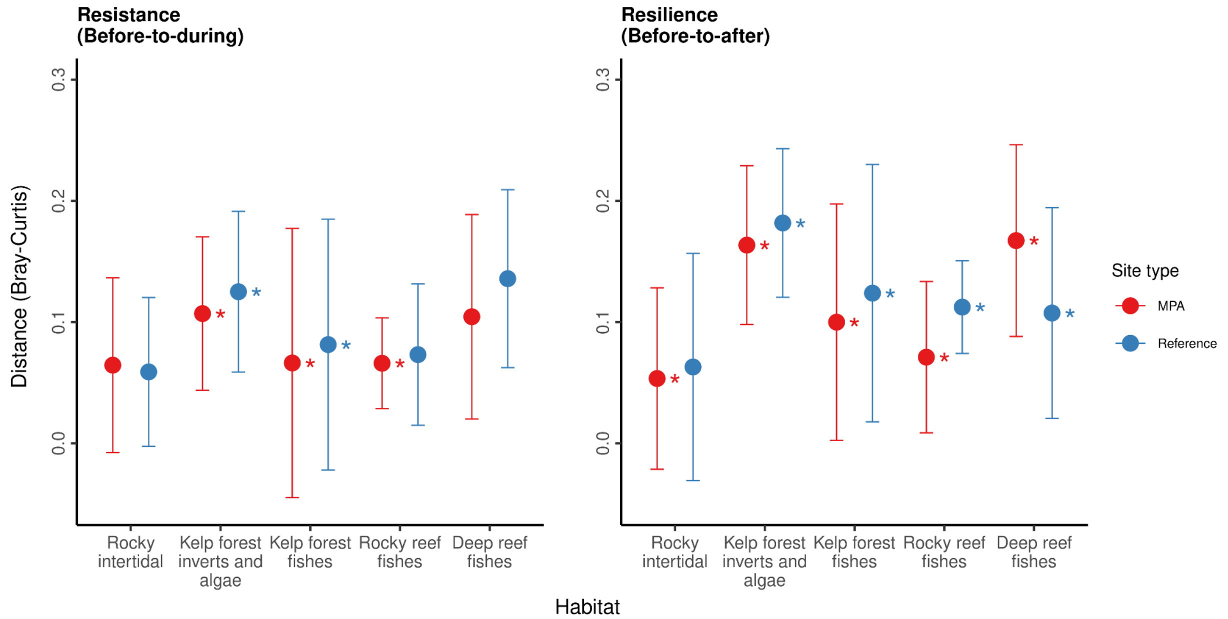


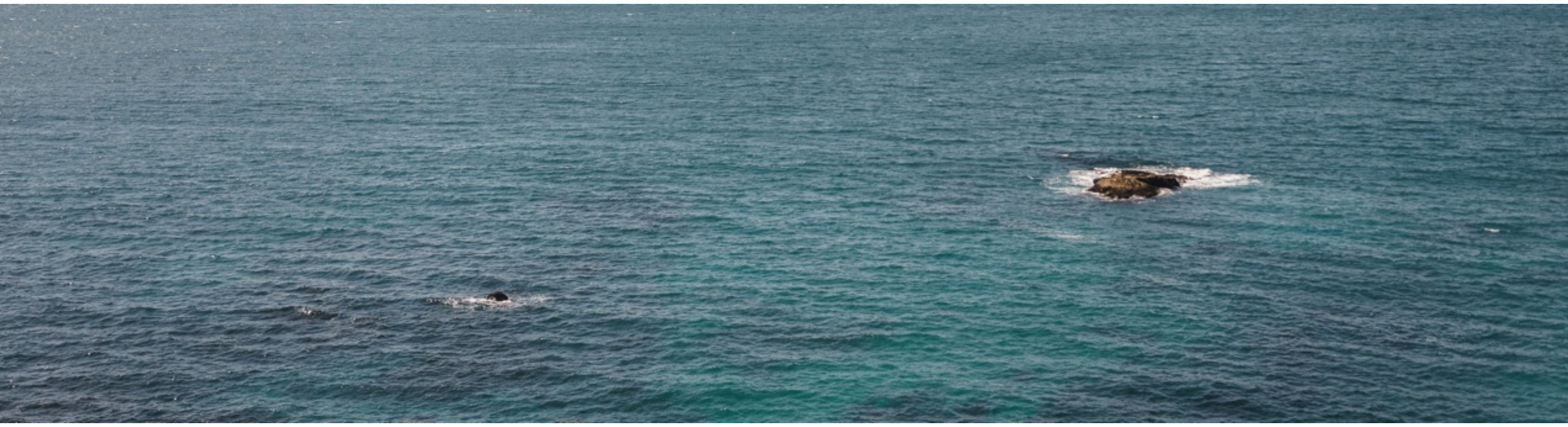
Figure 11 | *Community resistance (before-to-during) and resilience (before-to-after) as measured by distance between centroids for each habitat. Each point depicts the distance between the pre-heatwave centroid (before) and the during-heatwave or the post-heatwave centroid outside and inside of MPAs. 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. 2019). 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 separate from 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 programs 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) and “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.

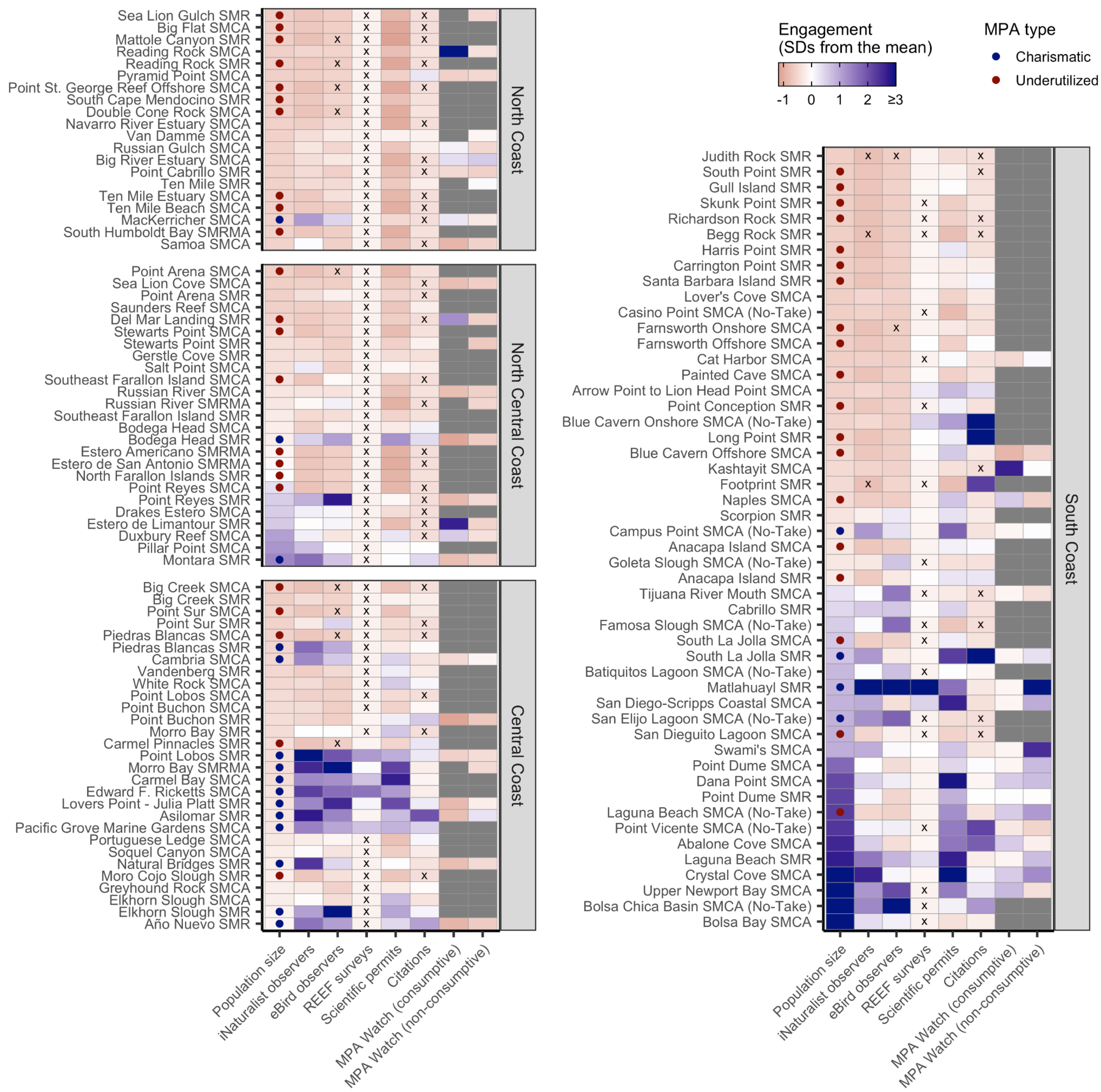


Figure 12 | *A synthesis of human use indicators within California's state marine protected areas (MPAs). MPAs are organized by region and are sorted by population density within 50 km (first column of each plot). Human use indicators are centered and scaled to ease comparison across indicators; thus, 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).*

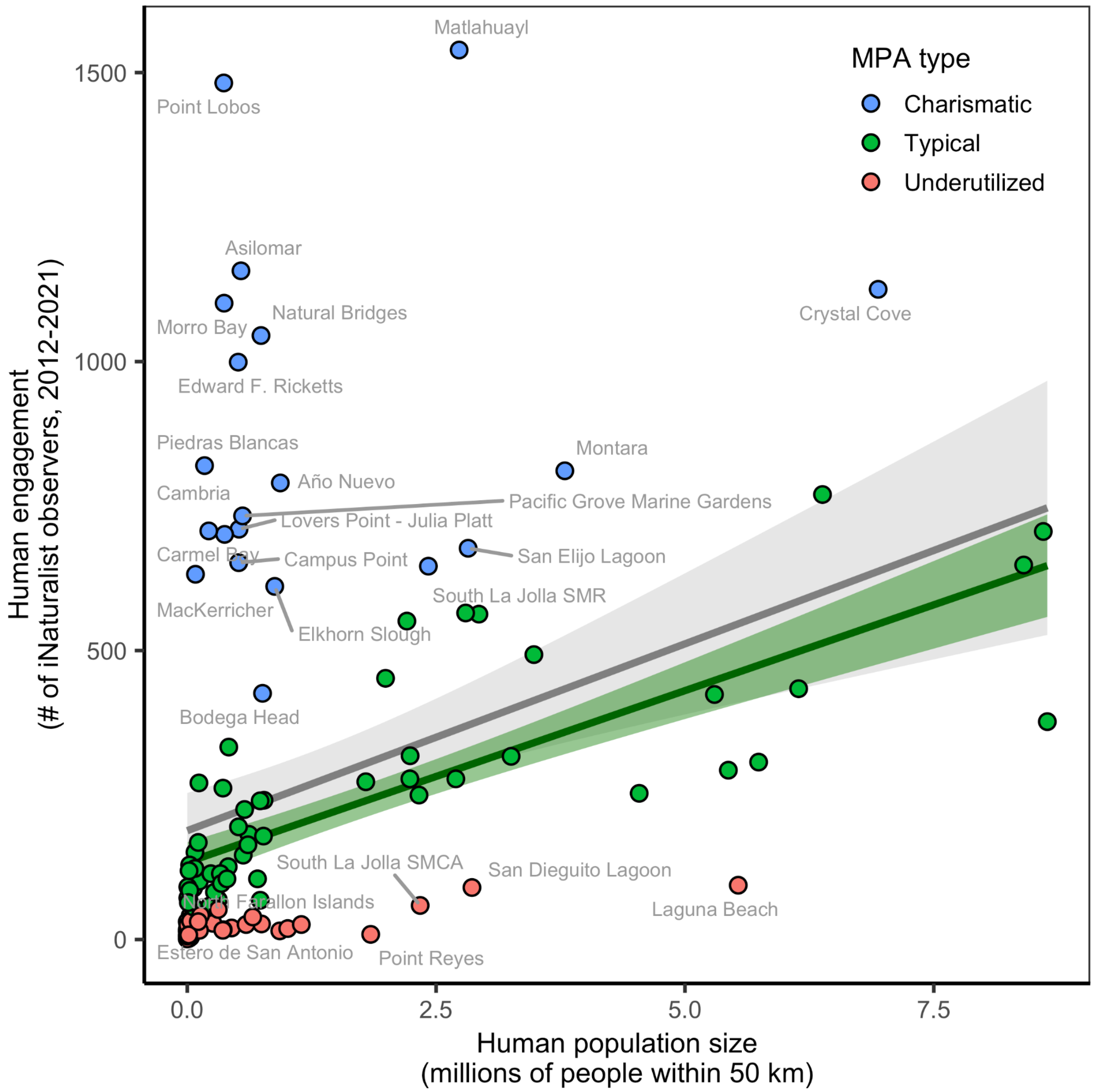


Figure 13 | *Correlation between human engagement in a marine protected area and the number of people living within 50 km of a protected area. Human engagement is measured as the number of iNaturalist observers submitting observations within 100 m of a protected area from 2012 through 2021. The gray 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.*

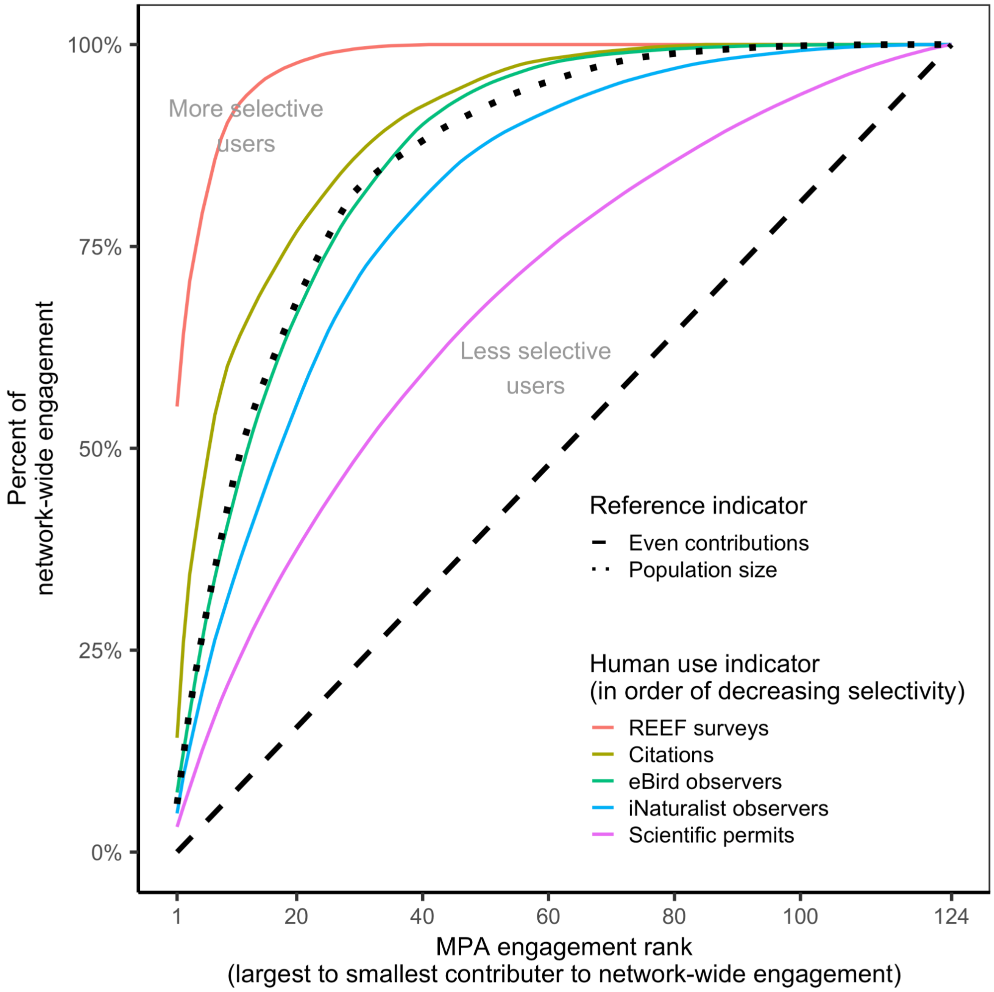


Figure 14 | *Cumulative contributions of individual marine protected areas (MPAs) to network-wide engagement based on several indicators of human use. The diagonal dashed line indicates a theoretical accumulation curve in which individual protected areas contribute equally to engagement within the overall 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: maxim 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 use of 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.

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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		

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

		SMR	2	2	2	2	2	1	2	2	4	4	4	3	3	3	3	3	3	4	3	3	5	4	2
	POINT SUR	REFERENCE							1	1	1	2		1	1	2				2	1	1	2	1	
		SMCA										1				1				1			1		
		SMR	2	1	1	1	2	1	2	2	2	3	2	2	2	2	1	1	1	3	2	1	3	2	1
	PORTUGUESE LEDGE	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		
		SMR	2	2	2	2	2	2	2	2	1	2	1	1	1	1	1	1	1	1	1	1	2	1	
	WHITE ROCK	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

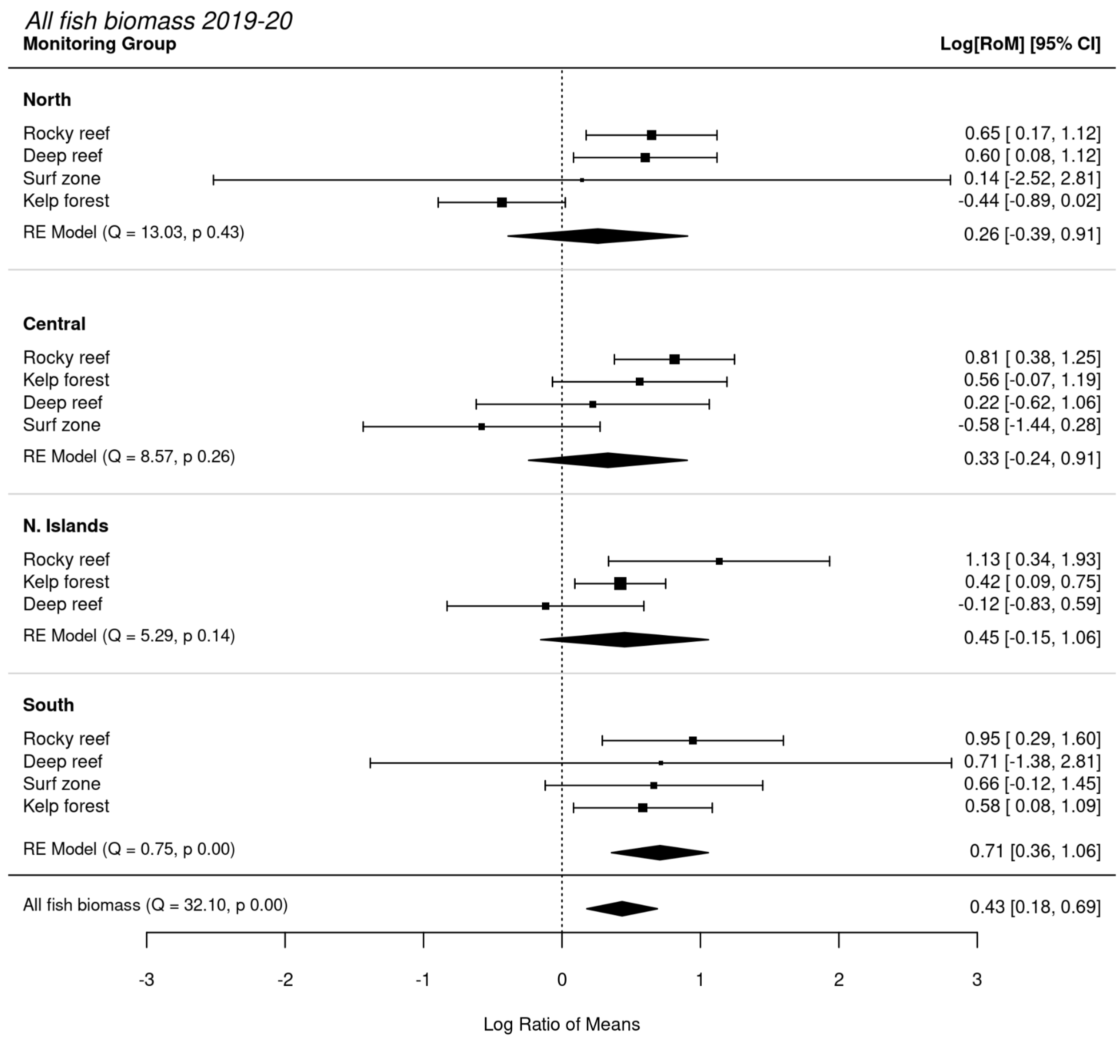

Figure S1 | *All fish biomass response ratios across habitat monitoring groups. Each point depicts the log response ratio (SMR/reference) for a single habitat monitoring group across the 2019-20 sampling period and point sizes are scaled to their relative contribution to the regional pooled effect (across 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.*

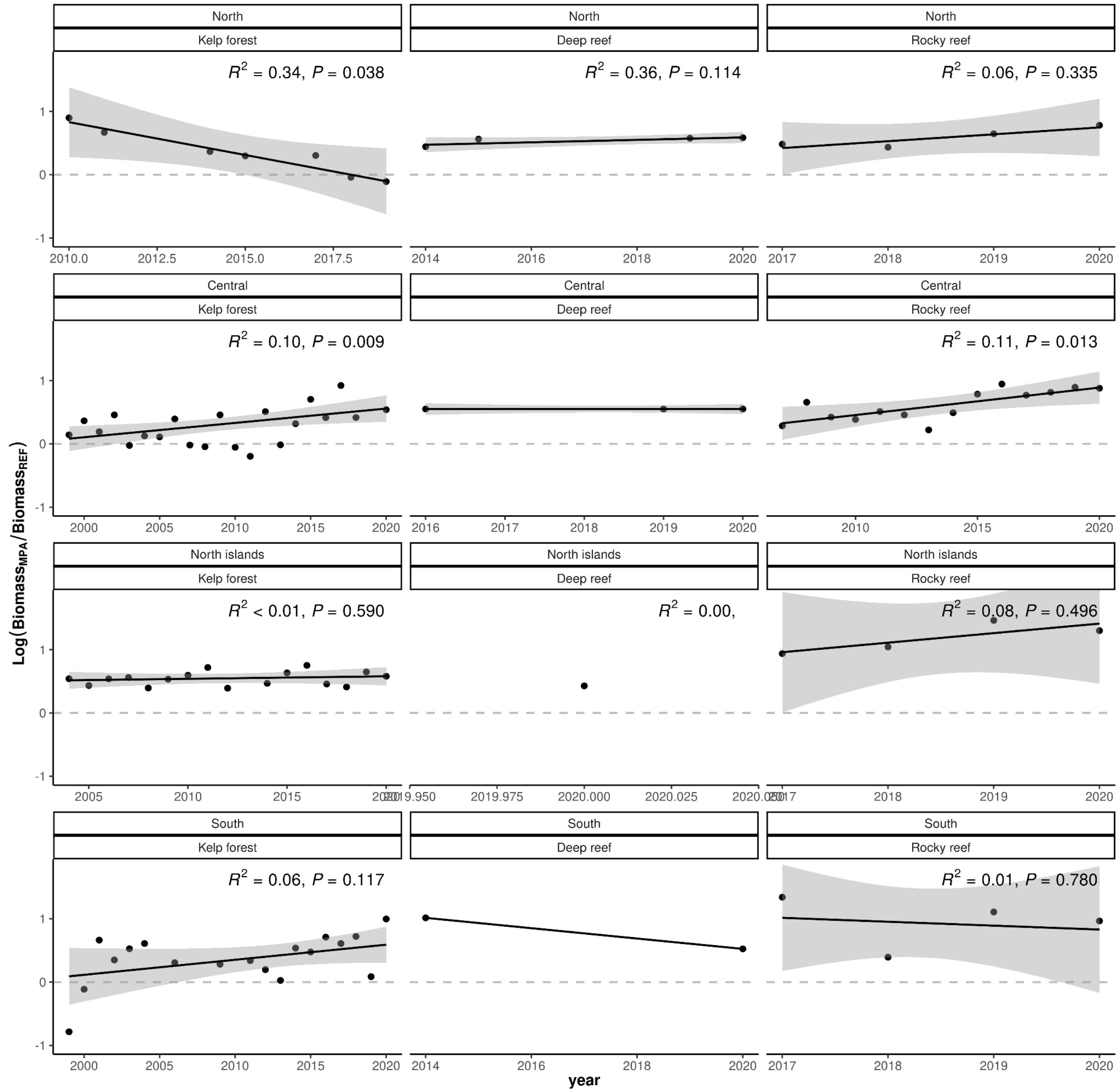

Figure S2 | *Targeted fish biomass response ratios by monitoring group and region. Each point depicts the response ratio averaged over all MPAs sampled within a given year. Regression lines depict the trends over time with 95% confidence intervals shaded in grey.*

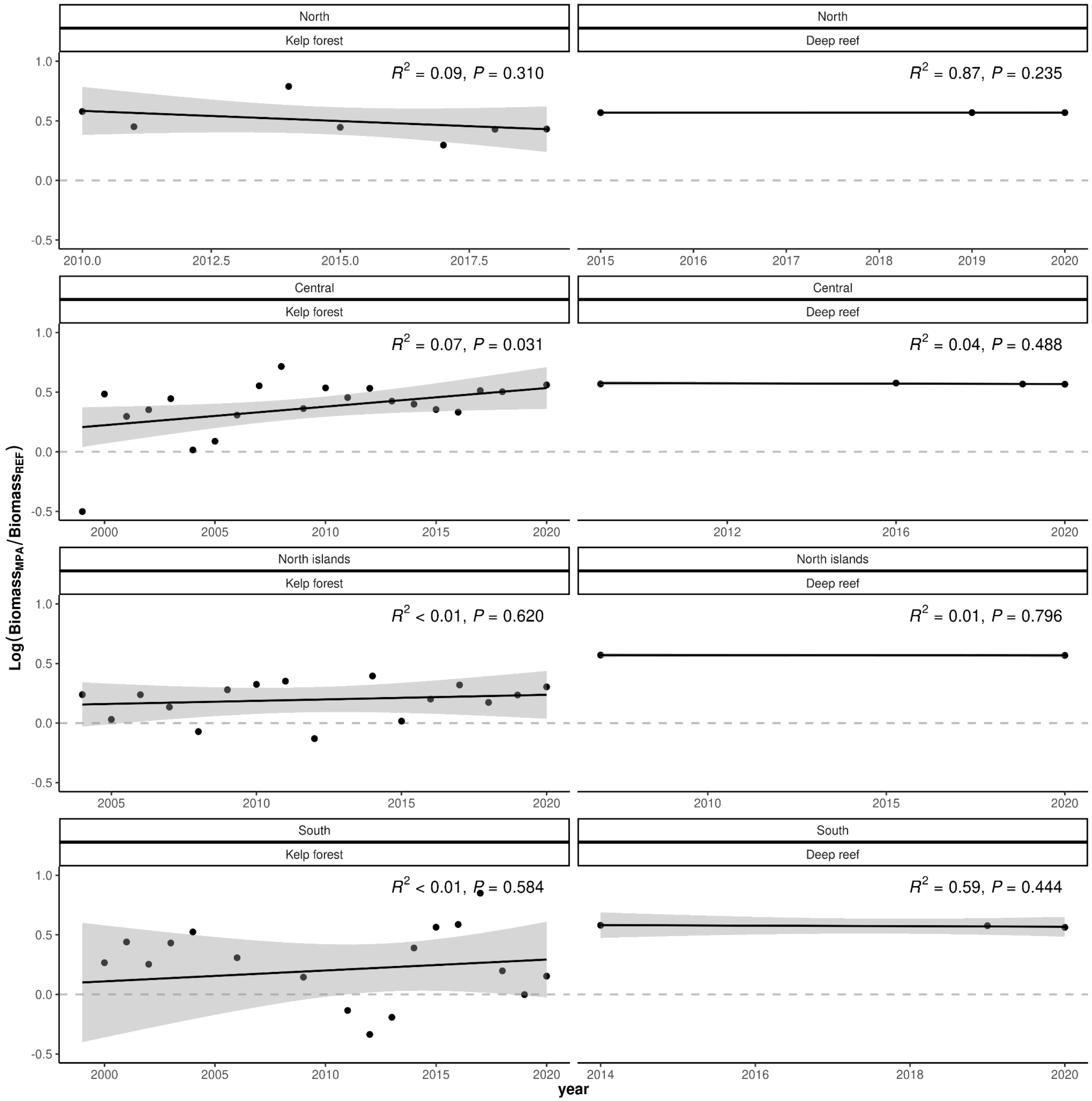

Figure S3 | *Nontargeted fish biomass response ratios by monitoring group and region. Each point depicts the response ratio averaged over all MPAs sampled within a given year. Regression lines depict the trends over time with 95% confidence intervals shaded in grey.*

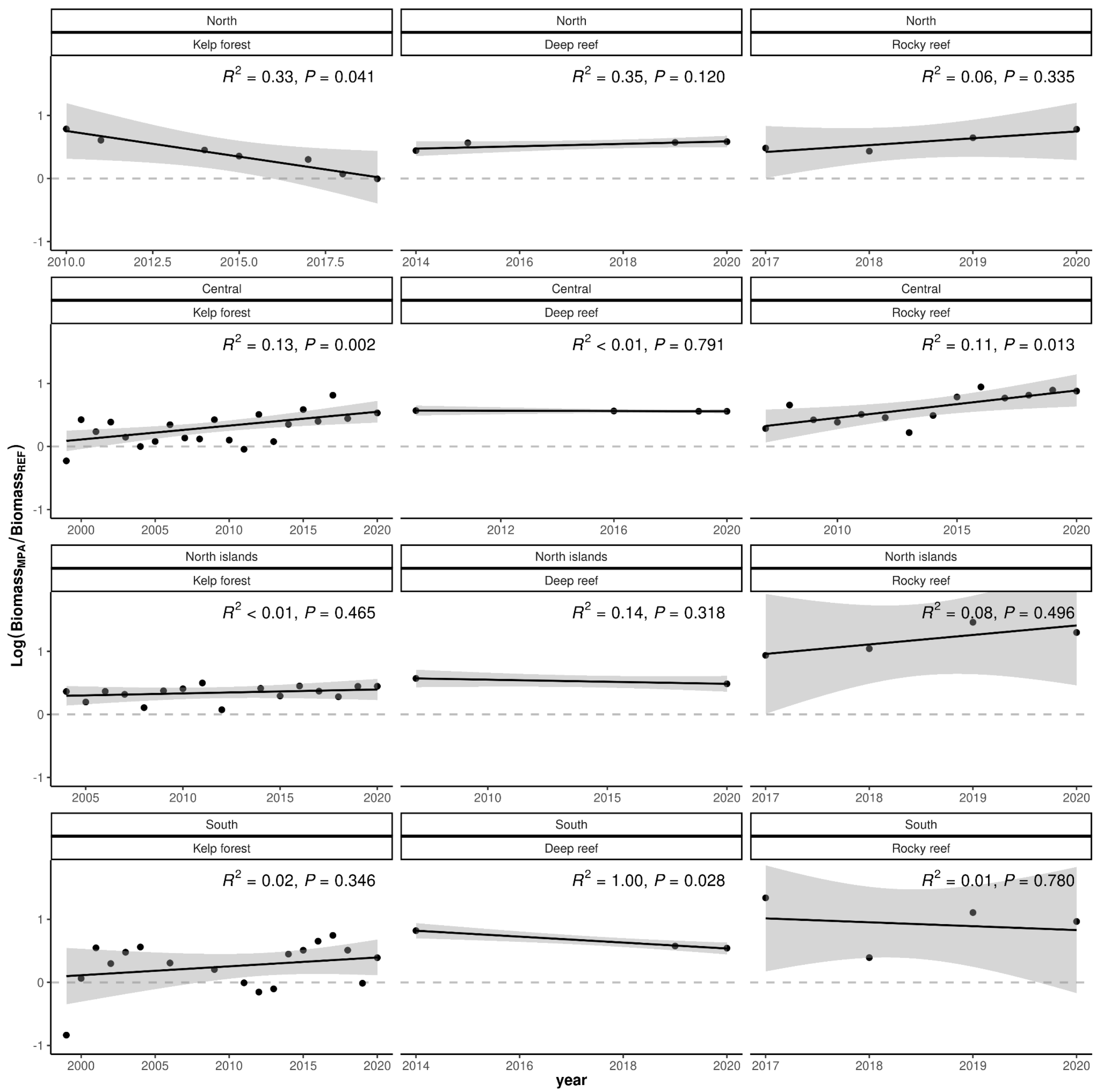

Figure S4 | *Total fish biomass response ratios by monitoring group and region. Each point depicts the response ratio averaged over all MPAs sampled within a given year. Regression lines depict the trends over time with 95% confidence intervals shaded in grey.*