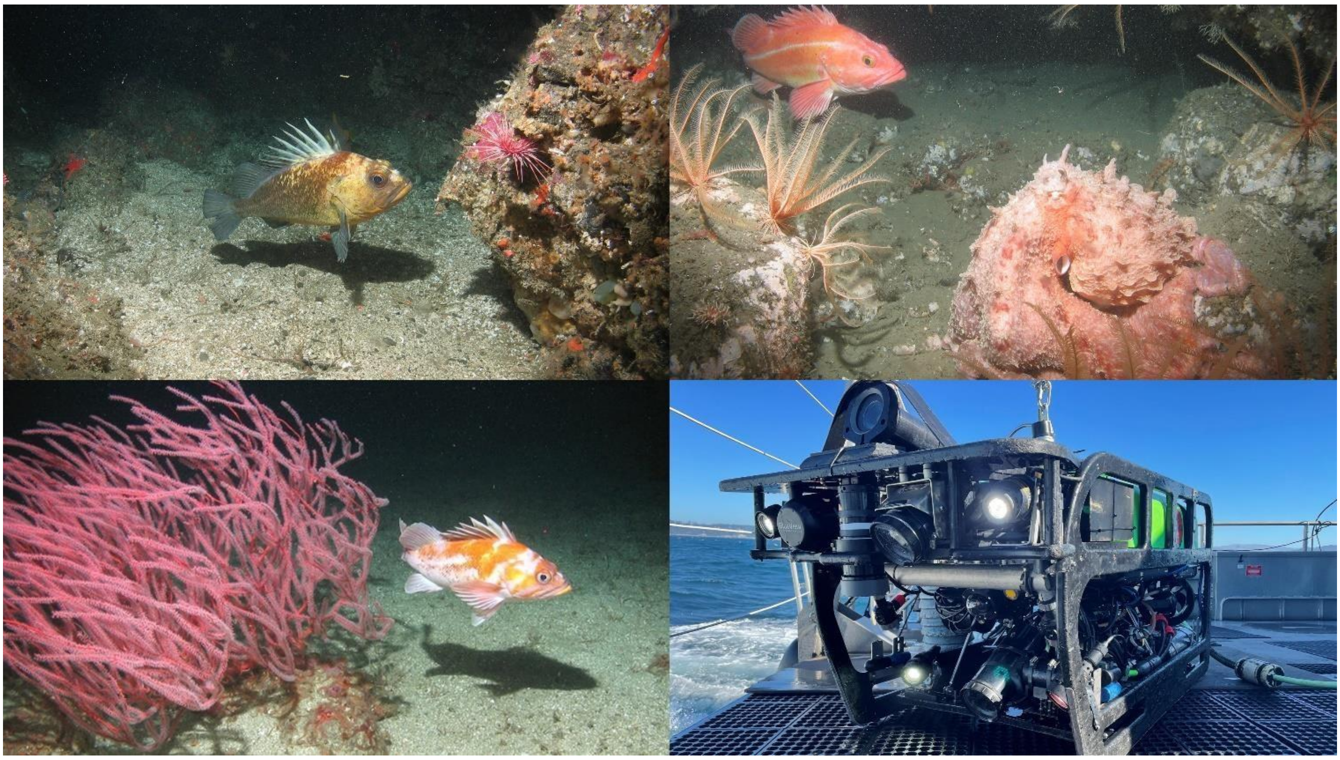
A time-series of remotely operated vehicle surveys reveals MPA effects and regional trends in mid-depth reefs across California's MPA network



Marine Applied Research and Exploration (MARE) analysis of a time-series of remotely operated vehicle (ROV) surveys in mid depth rocky reefs across California's Marine Protected Area network

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Introduction

Mid-depth habitats (30 - 100 m) comprise at least 75% of the area protected by MPAs across the California Marine Protected Area (MPA) network (Starr et al. 2021). Therefore, quantifying changes that occur in mid-depths is a crucial component of the long-term monitoring of MPA effectiveness. Remotely Operated Vehicles (ROVs) provide a powerful tool for surveying these depths, capable of covering large spatial extents, with the geo-located video footage collected able to quantify the abundance and sizes of fish and invertebrates and how they are associated with different habitats and depths. This report explores a time-series of ROV surveys conducted by California Department of Fish and Wildlife (CDFW) and Marine Applied Research and Exploration (MARE) across MPA and reference sites since shortly after the establishment of the first MPAs in the Channel Islands in 2003. Since then, CDFW and MARE have conducted 23 individual MPA surveys in all three MPA regions combined. This data set provides a unique opportunity to assess how the MPA network is performing with respect to meeting two of the specific goals of the Marine Life Protection Act (MLPA) 1999: protecting the natural abundance of marine life and rebuilding depleted stocks of previously fished species.

Analysis of ROV data provides several challenges. MPAs and reference sites are unlikely to be perfectly balanced in terms of depths and quantity of habitats, and thus survey data is also unlikely to be balanced across these important factors. This makes comparisons of MPAs and paired reference sites with traditional statistical methods (e.g., analysis of variance) problematic. Also, counts of fish are unlikely to follow statistical assumptions about normality of error distributions. Generalized Linear Models (GLMs) provide a tool for analyzing such data, with models being able to account for non-normal data distributions while also incorporating and estimating the importance of variables such as depth and habitat. GLMs can be extended to also include spatial autocorrelation present in the data, further reducing biases and improving confidence in the conclusions drawn.

Spatial autocorrelation (SAC) refers to systematic spatial variation, for example in the counts of fish, with positive correlation indicating the tendency for sampling units closer together to have similar values. SAC can be driven by habitat preferences that are not accounted for in the model, or by biological factors such as home ranges and larval dispersal distances. Many statistical analyses assume that the data being used is a true random sample, which is unlikely to be the case with spatial survey data collected across a region. Failure to account for SAC can lead to biases in estimates, under-estimation of errors and confounding of subsequent conclusions drawn. Previous work has shown that for the majority of ecological data, the magnitude, direction, and error associated with estimates can be dramatically altered when not accounting for spatial autocorrelation (e.g., Dormann 2007). Therefore, models that incorporate SAC present in the data should be preferred. The modeling approach used in this report explicitly models SAC by using a GLM approach that incorporates the location of each sampling unit and estimates the SAC present in the data for each species.

Here we explore the effect of MPA protection within each management region (South, Central and North) for a subset of focal fish species and for a grouping of key benthic species by analyzing the 15-year time series of ROV data collected by MARE and CDFW. We report on the impact of MPA protection on the density of these focal species and on the density of larger fish, which are expected to increase in abundance following protection. Our overarching aims are to explore the evidence to date for MPAs meeting goals of increasing the abundance and rebuilding of depleted stocks of previously targeted fish, and to make recommendations for the ongoing long-term monitoring of California’s MPA network.

Methods

Data collection and conditioning for analysis

ROV data collection and post processing methods used were developed and tested by CDFW and MARE from 2003-2004 and formalized starting in 2005. ROV survey sites were identified using high resolution seafloor maps and were placed perpendicular to the prevailing depth contour, were 500 m wide and spanned the targeted rocky substrate from deep to shallow. Within MPAs and reference sites, the 500-meter transect lines starting points were randomly generated and distributed to maximize the area sampled within each site. The number of transects selected at each site was based on the total rocky habitat present and the amount of survey time allotted to each study area. Collected video imagery was analyzed to characterize substrate types present and to identify and estimate all demersal and epibenthic finfish and macro-invertebrate species. A full description of data collection and conditioning methods used can be found in Lauermann et al. (2017).

Associations between fish and preferred habitat are likely to be on a smaller scale than 500 m transects. Therefore, it is standard practice to break longer transects into sub-units for analysis. Previously, sub-units of 50m^2 area have been used (Karpov et al. 2012) as well as sub-units of 20 m length (Budrick et al. 2019). Exploratory analysis showed that habitat tends to be patchy on scales of 10's of meters. Also, seafloor mapping data in California is usually at either 2 m or 5 m resolution. Therefore, a sub-unit length of 10 m was chosen for analysis as this captures potential fine-scale habitat associations and allows a sub-unit length that can be matched back to seafloor mapping data at both 2 m and 5 m scales. In total 125,629 10 m sub-units were used in the final analyses across all regions.

Modeling

All modeling was conducted using the Integrated Nested Laplace Approximation (INLA; see Lindgren et al. 2011) approach, which allows the incorporation of SAC. The approach is Bayesian, so the output for each estimate is a distribution (known as a posterior). Rather than using p-values, the strength of an effect is determined by how far the posterior distribution is away from zero, with 95% credible intervals including zero generally being considered "non-significant" in the traditional sense.

Analyses were conducted for a subset of species and one species grouping for two metrics: (i) density; and (ii) the density of larger fish (> 30 cm for rockfish species and > 55 cm for lingcod). Data was available on size structure for ROV surveys from 2014 onwards. These two metrics were chosen as they are both expected to be positively affected by MPAs. Expectations are that differences in abundance between MPAs and fished areas may take longer to detect, whereas the filling in of the size structure of larger size classes is likely to be detectable in a shorter time (e.g., Kaplan et al. 2019). Species chosen for modeling were copper rockfish, vermilion rockfish, California sheephead, canary rockfish, gopher rockfish, quillback rockfish, yelloweye rockfish, brown rockfish, lingcod, and kelp greenling. These species were chosen as they are benthic species whose presence are likely to be captured consistently by the ROV survey methodology and are species that are actively targeted by fishers. Analysis of the density of larger fish was not conducted for gopher rockfish due to the much smaller length at maturity, and California sheephead because of their diandric nature. The species treated as grouped species were copper rockfish, vermilion rockfish, china rockfish, quillback rockfish, gopher rockfish, canary rockfish, yelloweye rockfish, treefish, brown rockfish, flag rockfish, kelp rockfish, and tiger rockfish.

To quantify the "MPA effect", the cumulative effect of years of MPA implementation (YSI) on density was estimated. All samples outside of MPAs (i.e., in reference areas) have zero years of implementation throughout the time-series, whereas samples within MPAs were attributed the number of years since the MPA was established, which ranged from zero (surveys conducted in the first year after establishment) to 17 years (MPAs in the Channel Islands established in 2003 and last surveyed in 2020). The response was modelled using a log (τ +1) transformation, where τ is the number of years since implementation. Thus, for surveys in an MPA in the first year of implementation this formulation will set the cumulative effect at zero as log (0 + 1) = 0. The MPA effect (β) is thus quantified by a power relationship: YSI^{β}. A linear term for survey year was also included to quantify the general trends for decrease/increase in density across a region. Modeling the MPA effect in this way means that the additional cumulative effect of MPA implementation is quantified on top of any overall regional trend. Thus, the MPA effect may have an exponentially increasing effect early in implementation (green line Fig. 1), but is expected asymptote through time (e.g., black line in Fig. 1), whereas negative effects (red line Fig. 1) are not expected.

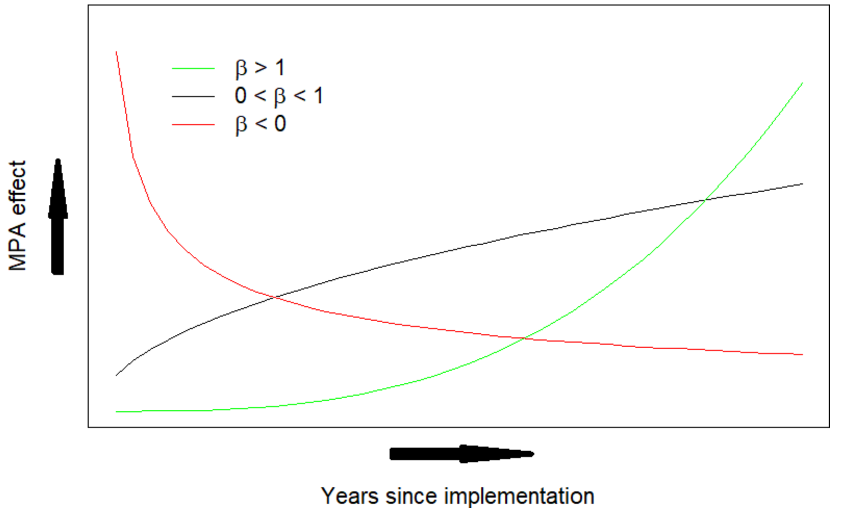

Figure 1 *Illustration of model specification used for the "MPA effect". The coefficient for the MPA effect (β) when > 1 results in an increasing trend bounded at zero below with no upper limit; when 0 < β < 1 results in an increasing trend bounded by zero below and tending to an asymptote; and when β < 0 resulting in a decreasing trend with an asymptote at zero.*

Environmental covariates included in the models were depth, $depth^2$ (to quantify non-linear depth distribution of species), proportion hard habitat, and proportion mixed habitat. As proportions of habitat (hard, mixed, and soft) sum to 1, including proportion soft habitat was redundant. The area of each sub-unit was included as a model offset, resulting in the response variable being modeled as density (i.e., number of fish per unit area).

The response (density of focal species or larger individuals) was modeled using a negative binomial likelihood. SAC was modeled across a triangular "mesh" created within a bounding polygon within each management region using the coastline (including islands) and a buffer of 40 km. SAC is quantified by two estimated parameters: the spatial standard deviation, which quantifies the magnitude of the correlation, and the spatial range, which quantifies the distance over which SAC occurs. To illustrate the importance of accounting for SAC vermilion rockfish density data from the southern region was used in two regional models for the south: (i) a non-spatial model incorporating depth and habitat covariates, and (ii) a spatial model with the same covariates but also accounting for SAC.

Plots of model- based estimates of effects and calculation of density differences between MPA and reference sites within regions were made by taking 5000 joint posterior sample draws from the model and then calculating mean trends and credible intervals across all draws. Mean depth and habitat within the survey data for each region were used for all calculations.

Highlights and Key Findings

Density of focal species

The density of many of the focal species exhibited a positive response to protection, with estimates of the cumulative effect of protection being positive for 11 out of 25 of the species/management region combinations modeled (MPA effect, Table 1). There were no negative regional MPA effects on density on the species tested, with the need for longer time-series indicated in the uncertainty around MPA effects for other species. There were also increasing trends in the density of all focal species across the survey period, except for lingcod in the north (Year effect, Table 1), indicating a strong trajectory of increasing abundance through time in both MPA and fished areas across the state. The general trend for recovery is likely to indicate a combination of successful recruitment years and other management efforts (e.g., harvest limits and rockfish conservation areas) to restore previously depleted stocks.

Table 1 *Model-based estimates of the MPA effect and year effect for the density of focal species within each management region (South, Central and North). Estimates are the mean estimated effect size with 95% credible intervals given in brackets. Effects highlighted green show a positive response, red a negative response and not highlighted an indeterminate effect. Light blue shading with an "N/A" indicates that the species did not occur in that region in sufficient densities for modeling.*

Species	MPA effect South	MPA effect Central	MPA effect North	Year effect South	Year effect Central	Year effect North
Grouped species	-0.010 (-0.090, 0.070)	0.077 (-0.077, 0.232)	0.301 (0.182, 0.419)	0.091 (0.083, 0.099)	0.168 (0.148, 0.188)	0.137 (0.119, 0.155)
Copper Rockfish	0.375 (0.242, 0.509)	0.144 (-0.119, 0.408)	0.347 (0.058, 0.636)	0.107 (0.094, 0.119)	0.218 (0.171, 0.267)	0.094 (0.045, 0.142)
Vermilion Rockfish	-0.074 (-0.182, 0.033)	0.072 (-0.147, 0.293)	0.127 (-0.055, 0.310)	0.062 (0.051, 0.072)	0.135 (0.106, 0.164)	0.189 (0.156, 0.223)
California Sheephead	0.354 (0.221, 0.486)	N/A	N/A	0.116 (0.104, 0.129)	N/A	N/A
Canary Rockfish	N/A	0.081 (-0.309, 0.473)	0.416 (0.212, 0.621)	N/A	0.094 (0.037, 0.153)	0.107 (0.076, 0.138)
Gopher Rockfish	-0.073 (-0.248, 0.102)	0.148 (-0.076, 0.374)	0.326 (-0.086, 0.746)	0.170 (0.154, 0.185)	0.245 (0.217, 0.274)	0.194 (0.140, 0.250)
Quillback Rockfish	N/A	N/A	0.233 (0.031, 0.435)	N/A	N/A	0.145 (0.111, 0.179)
Yelloweye rockfish	N/A	-0.059 (-0.375, 0.256)	0.020 (-0.200, 0.241)	N/A	0.215 (0.140, 0.294)	0.111 (0.066, 0.156)
Brown Rockfish	N/A	-0.437 (-1.210, 0.341)	0.688 (0.313, 1.062)	N/A	0.213 (0.111, 0.317)	0.155 (0.104, 0.208)
Lingcod	0.211 (0.047, 0.375)	0.386 (0.180, 0.594)	0.221 (0.079, 0.363)	0.064 (0.049, 0.080)	0.058 (0.031, 0.084)	-0.050 (-0.073, -0.027)
Kelp Greenling	N/A	0.021 (-0.093, 0.135)	0.124 (0.004, 0.244)	N/A	-0.007 (-0.036, 0.021)	-0.011 (-0.030, 0.008)

Notably, there was a lack of an MPA effect found in the central region, except for lingcod, with large credible intervals in estimates signaling uncertainty in trends related to protection in the data collected so far. The reason for this is currently unclear and is surprising given the positive effects shown in the north despite the north having a shorter length of MPA implementation compared to the central region. One possible reason is the historically high proportion of rocky reef habitat protected by rockfish conservation area (RCA) depth closures north of Point Conception, which protected larger proportions of rocky reef than

MPAs between 2003-2016 (CDFW 2021). RCAs are likely to have had a strong influence on density across the region making differences less distinct. The lack of an effect found for grouped species and vermilion rockfish in the south is interesting and could be related to ontogenic shifts to deeper water that are known to occur for vermilion rockfish (Caselle and Cabral 2018). It should also be noted that vermilion rockfish accounted for almost 50% of the abundance in the grouped species in the south and patterns for this species are likely driving patterns observed for the grouped species in the south.

Species that showed particularly strong responses to protection were copper rockfish (Figure 2) and California sheephead in the south, lingcod in the central region, and grouped species, canary rockfish and brown rockfish in the north. Model-based estimates show that densities in the south for California sheephead are approximately 2.8 times higher, densities of copper rockfish 2.9 times higher; and densities of lingcod in the central region 2.3 times higher in the last survey (2020) compared to reference areas. Positive effects were also found for lingcod in the south (2.8 times higher in 2020), and copper rockfish (2.2 times higher in 2020), quillback rockfish (1.7 times higher in 2020), lingcod (1.6 times higher in 2020), and kelp greenling (1.3 times higher in 2020) in the north. Responses to protection were positive and suggest an MPA effect (although the posterior still included zero) for vermilion rockfish in the north and gopher rockfish in the central and north regions. Yelloweye rockfish showed overall increases in density in the north and central regions, suggesting a recovery in abundance; however, MPAs do not appear to have higher densities than fished areas for this species.

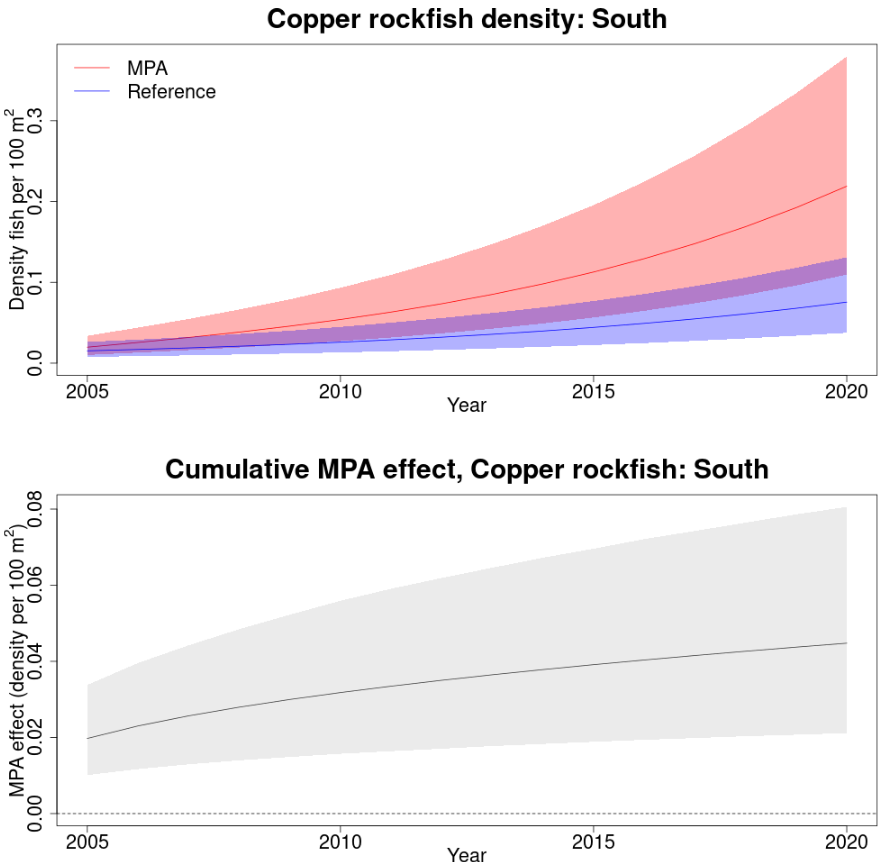

Figure 2 *Model-based estimates of the trajectory of the density (expressed in fish per 100 m^2) of copper rockfish in MPAs and reference areas in the southern region (top) and of the cumulative MPA effect on the density of copper rockfish in MPAs in the southern region (bottom). Solid lines show mean modeled responses and shaded areas 95% credible intervals.*

Lingcod displayed a small but statistically significant decline in overall density in the north when considering both MPA and fished areas. However, the positive MPA effect in the north suggests this was largely driven by declines in density in the fished areas rather than MPAs.

Strong associations with both depth and habitat were found for all species, with preferences for hard substrate, and to a lesser extent mixed substrate types. Depth and habitat trends followed those expected for each species but are not presented here for brevity of results.

SAC was high (spatial standard deviation of 3 – 4) for most species and occurred over ranges of 2.5 – 7.5 km. This indicates that SAC is important on the approximate scale of individual MPA and reference site pairs, and that densities and effects can be quite different between neighboring MPAs. The high spatial standard deviation over several kilometers shows that 10 m sub-units and 500 m long transect lines can not be considered as independent samples when quantifying regional MPA effects.

Density of larger focal species

Positive MPA effects were found for the density of larger fish in six out of the 21 combinations of species/management regions tested (Table 2). The strongest and most definitive effects (posterior distributions farther from zero) were found in the south for all species tested except lingcod. Notably, and in concurrence with the density results, no significant MPA effects were found for the density of larger fish in the central region in the time series to date, with wide credible intervals in the estimates indicating uncertainty around the current data. However, estimates for copper rockfish and lingcod suggest that these species are showing signs of rebuilding larger size classes in the central region.

Table 2 *Model-based estimates of the MPA effect and year effect for the density of large focal species (> 30 cm for rockfish and kelp greenling and > 55 cm for lingcod) within each management region (South, Central and North). Estimates are the mean estimated effect size with 95% credible intervals given in brackets. Effects highlighted green show a positive response, red a negative response and not highlighted an indeterminate effect. Light blue shading with an "N/A" indicates that the species did not occur in that region in sufficient densities for modeling.*

Species	MPA effect South	MPA effect Central	MPA effect North	Year effect South	Year effect Central	Year effect North
Grouped species	0.473 (0.247, 0.700)	-0.185 (-0.680, 0.309)	0.193 (0.057, 0.365)	0.076 (0.058, 0.098)	0.144 (0.021, 0.186)	0.092 (0.066, 0.118)
Copper Rockfish	0.654 (0.337, 0.975)	0.251 (-0.016, 0.519)	0.462 (0.076, 0.848)	0.073 (0.044, 0.102)	0.038 (-0.045, 0.122)	0.036 (-0.027, 0.100)
Vermilion Rockfish	0.472 (0.203, 0.744)	0.054 (-0.292, 0.399)	0.101 (-0.105, 0.307)	0.070 (0.012, 0.093)	0.209 (0.162, 0.803)	0.124 (0.081, 0.167)
Canary Rockfish	N/A	-0.083 (-0.457, 0.289)	0.029 (-0.244, 0.302)	N/A	-0.180 (-0.275, -0.088)	0.103 (0.056, 0.150)
Quillback Rockfish	N/A	N/A	0.316 (0.010, 0.622)	N/A	N/A	0.028 (-0.024, 0.080)
Yelloweye rockfish	N/A	-0.074 (-0.480, 0.331)	0.067 (-0.139, 0.275)	N/A	-0.299 (-0.497, -0.114)	0.100 (0.038, 0.162)
Brown Rockfish	N/A	0.071 (-0.391, 0.536)	0.167 (-0.503, 0.838)	N/A	0.166 (0.068, 0.266)	0.146 (0.049, 0.244)
Lingcod	0.116 (-0.399, 0.636)	0.214 (-0.094,0.522)	-0.043 (-0.278, 0.191)	-0.196 (-0.249, -0.144)	-0.247 (-0.308, -0.187)	0.038 (-0.004, 0.081)
Kelp Greenling	N/A	-0.052 (-0.259, 0.155)	0.023 (-0.125, 0.171)	N/A	-0.262 (-0.336, -0.191)	-0.071 (-0.099, -0.042)

Species that showed a definitive response in terms of an increase in larger fish due to protection included copper rockfish (Figure 3), grouped species and vermilion rockfish in the south. In the last survey in the south (2020), model-based estimates indicate the mean density of large copper rockfish was 6.4 times higher, large grouped species was 3.8 times higher, and large vermilion rockfish 3.8 times higher in the south compared to reference areas. The effect size for copper rockfish in the south was much larger when considering the density of large fish compared to density of all fish (Fig. 3 vs Fig. 2). Also, an MPA effect on the density of large fish was detected for grouped species and vermilion rockfish in the south, while no effect was found when considering density alone for those species. This reinforces previous work that shows data regarding the size structure of fish, such as the density of larger fish used here, or other measures that incorporate size such as biomass are likely to provide a stronger and earlier signal of MPA effects than density. The density of large lingcod in the south didn't display a definitive response and could be related to ontogenic movement patterns of lingcod and the higher likelihood that they will range outside MPA boundaries (Bassett et al. 2017).

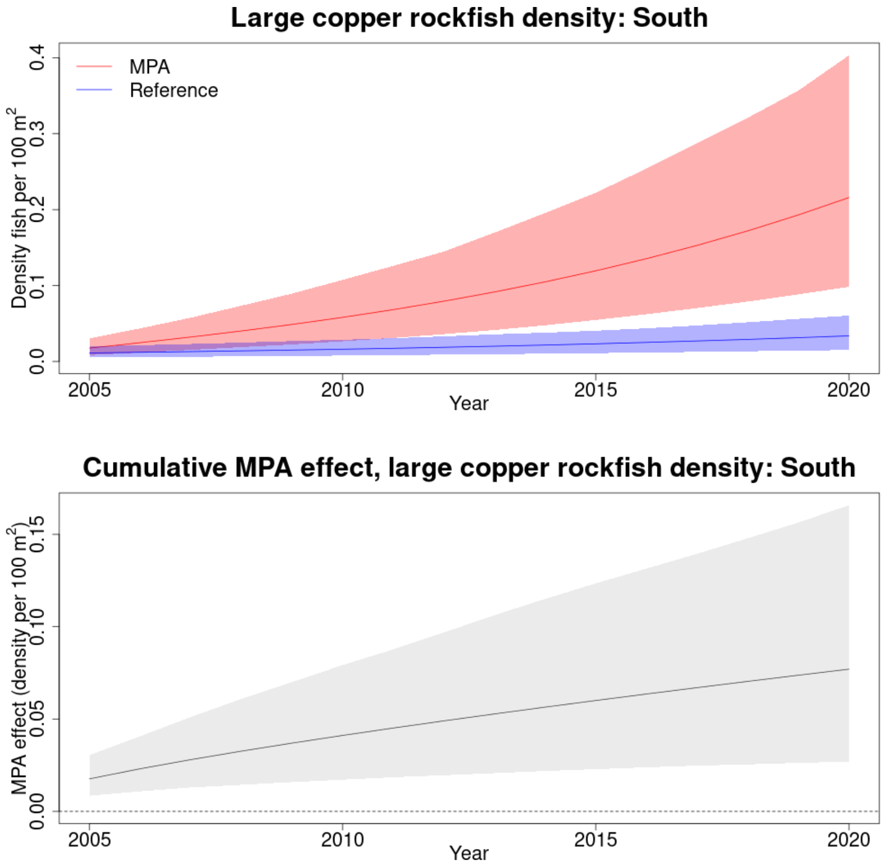

Figure 3 *Model-based estimates of the trajectory of the density (expressed in fish per 100 m^2) of large copper rockfish (> 30 cm) in MPAs and reference areas in the southern region (top) and of the cumulative MPA effect on the density of large copper rockfish in MPAs in the southern region (bottom). Solid lines show mean modeled responses and shaded areas 95% credible intervals.*

Positive effects were also found for grouped species (1.7 times higher in 2020), copper rockfish (3.8 times higher in 2020) and quillback rockfish (2.5 times higher in 2020) in the north, although posterior distributions for the MPA effect were closer to zero than those in the south, likely reflecting the shorter time span of MPA establishment in the north and the earlier stages of the filling in of the size structure of fish inside MPAs.

Overall increases (i.e., regional, including both MPA and fished areas) in the density of large fish were found for grouped species in all regions, vermilion rockfish in all regions, copper rockfish in the south, brown rockfish in the central and north regions and canary and yelloweye rockfish in the north. Overall decreases in the density of large fish were observed for lingcod in the south; canary rockfish, yelloweye rockfish, lingcod and kelp greenling in the central region and kelp greenling in the north. However, the lack of significant negative effects in the MPAs for these species implies that this may be driven more by changes in reference areas than MPAs.

SAC estimates for the density of large fish tended to have longer spatial ranges (~ 4 – 20 km), indicating SAC was important over larger spatial scales for large fish.

The importance of spatial autocorrelation

For the density of vermilion rockfish in the south, conclusions drawn from non-spatial and spatial models would be quite different regarding the MPA effect, with the non-spatial model coefficient for the MPA effect showing a positive effect, and the spatial model no definitive effect (Table 3). Ecological conclusions regarding the overall importance of depth and habitat associations would be similar; however, the magnitude of effects differs between the two models, with the spatial model implying a stronger effect of habitat and a smaller effect of depth than the non-spatial model. Furthermore, credible intervals around all estimates are larger in the spatial model, implying an over confidence in estimates in the non-spatial model. The Bayes factor, a diagnostic used to determine how well the model fits the data indicate “extreme evidence” (Kass and Raferty 1995) for the improved fit of the spatial model.

Table 3 *Model summaries of coefficient estimates and 95% credible intervals for non-spatial and spatial models for the density of vermilion rockfish across the southern region. Effects highlighted green are positive, red negative and not highlighted show no evidence of an effect.*

Fixed effects	**Non-spatial model**	**Spatial model**
Intercept	**-6.229 (-6.304, -6.155)**	**-6.555 (-7.319, -5.793)**
Survey Year	**0.055 (0.048, 0.061)**	**0.062 (0.051, 0.072)**
MPA effect (years since implementation)	**0.130 (0.098, 0.162)**	**-0.074 (-0.182, 0.033)**
Depth	**0.657 (0.611, 0.704)**	**0.410 (0.232, 0.588)**
Depth	**-0.340 (-0.373, -3.07)**	**-0.321 (-0.409, -0.234)**
Proportion hard habitat	**0.775 (0.738, 0.813)**	**0.869 (0.828, 0.911)**
Proportion mixed habitat	**0.757 (0.718, 0.796)**	**0.807 (0.766, 0.848)**

For the spatial model, a strong spatial effect for the density of vermilion rockfish was found, with high spatial correlation (spatial standard deviation = 3.325 (2.621, 4.229)) occurring over a relatively short spatial range (mean 2.596 km (1.797, 3.601)). This implies that strong SAC occurs on the scale of individual MPAs, and that densities and effects can change over relatively small scales. Large aggregation of vermilion rockfish (> 20 fish in a 10 m sub-unit) were observed in some sites/surveys and may be partly responsible for high SAC. It is also possible that there are spillover effects, with MPAs playing a role in the density and size structure of fish in nearby reference areas.

Initial exploratory analysis suggests that some individual MPAs within the south such as Harris Point and Gull Island MPAs are contributing disproportionately to positive MPA effects for the density of vermilion rockfish, while other MPAs are showing little response. This spatial dependence across the region is being captured in the spatial model but is ignored when all the data is pooled regionally. This points to the danger of treating management regions as homogenous units when quantifying MPA effects. Models should therefore incorporate spatial dependence, as the spatial models outlined here do, when making inferences across management regions. Exploration of the performance of individual MPAs will be incorporated into ongoing work on the ROV survey data set.

Challenges

The data set analyzed in this report was large, spatially explicit and spanned 17 years of data collection. The modeling approach was sophisticated and required significant time and computing resources to undertake. We found that initial state-wide model specification with nested management regions ran into computational issues, particularly where species distributions made data sparse, necessitating region-based models. When analyzing size structure, size information was only available from 2014 onwards, and used visual laser sizing which has been shown to underestimate the lengths of the larger sized fish (Starr et al. 2021). Given the strong signal found in the size structure for many species within this report, a longer time-series would have been useful, and size data should be a focus of ongoing work. Stereo imagery was captured in surveys from 2014, but to date has not been processed for sizing information.

Knowledge gaps and recommendations

Knowledge gaps

Several important factors that are likely to influence the magnitude and detectability of MPA effects were not incorporated into the current analysis:

- The timing of recruitment events and how they coincide with MPA establishment plays a crucial role in determining the length of time taken to detect the effects of protection (Hopf et al. 2021) and would therefore aid in interpreting patterns seen.
- Measures of fishing effort, both prior to MPA establishment and ongoing effort in reference areas are crucial to informing magnitudes and rates of recovery.
- Previous work has shown that some species have ontogenic depth shifts (e.g. Caselle and Cabral 2018). Incorporating data from a wider depth range may be necessary to understand how MPAs may be affecting the entire populations.
- Measures such as rugosity and slope derived from seafloor mapping may help further refine models and account for differences seen.
- MPA area and habitat quality may also influence MPA performance and could be included in future analyses.

Recommendations

Key recommendations for ongoing monitoring:

- Continuation of important time-series requires careful consideration of the revisit schedule, striking a balance between spatial and temporal revisits. Current evidence points to high spatial variability between MPAs. Therefore, capturing this spatial variability is important if reporting is required at the regional level.
- To aid in designing future monitoring, clear management reporting goals should be defined. For example, optimal monitoring designs may be quite different if reporting is required at a regional, state-wide, or individual MPA levels.
- Data regarding the density and size structure of focal species in deeper habitats adjacent to MPAs would be useful in tracking the effect of MPAs and could be collected by the ROV survey methodology.
- Results presented in this report show that SAC is an important consideration for ROV (and likely other) survey tools and therefore should be included in modeling efforts.
- Given the strong signal of MPA effects found in size-structure data, sizes of fish should continue to be collected, preferably with stereo-imagery which provides higher accuracy than laser sizing that has been used previously. Funds should be allocated to sizing from stereo imagery collected since 2014.

Conclusions

Analysis of a spatially and temporally extensive data set of ROV surveys spanning mid-depths across the California MPA network has revealed encouraging signs of regional recovery and the ability of MPAs to increase the density and size structure of a number of focal species. We found that densities of focal species were up to 2.9 times higher, and denisites of larger fish up to 6.4 times higher in MPAs than reference areas across management regions. Previous work has suggested that MPA effects may take in excess of 20 years to detect, particularly for slow-growing species such as many of the rockfish species analyzed in this report (Starr et al. 2015), but that incorporating data from multiple MPAs across a region is likely to increase the power to detect change (Perkins et al. 2020). The results here support these findings, with stronger regional effects generally seen in the south, where MPAs have been established the longest and fishing mortality in reference areas is highest (Miller et al. 2014). Also, we found that the density of larger fish provided a stronger response signal of MPA effects, especially in the south where longer time periods have allowed the accrual of more large fish. Signs of rebuilding and MPA effects were also observed for a number of species in the north region. However, MPA effects were largely not currently detectable in the central region, with the reasons for this currently unclear and requiring further investigation. Having data collected in a consistent and standardized manner in mid-depths across the entire California MPA network allows for robust conclusions to be drawn across the network and highlights the utility of such data for long-term monitoring.

Next steps

Analysis of the MARE/CDFW ROV data set is still underway. Results presented in this report will be built upon with a more detailed report to follow later in 2022. Ongoing work will incorporate the latest round of 2021 surveys and encompass a wider range of species, including non-targeted species and invertebrate species. Modeling will also be conducted at the individual MPA scale for selected species/MPAs to explore the performance of individual MPAs. There are also plans to address a number of identified knowldege gaps in this report, including the incorporation of seafloor mapping products in future analyses, and the exploration of proxies of fishing effort and how they may help in interpretting MPA effects.

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