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Recommendations to Inform Monitoring Strategies for Mid-Depth Rocky Reef Habitats in California

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1. INTRODUCTION

The natural wonders of the northeast Pacific Ocean off California have been variously marveled at, lived in harmony with, researched, exploited, overexploited, conserved and protected over the course of millenia. Marine habitat research and evaluation in the western scientific tradition has been conducted for decades in the state by academic and government entities, from the nearshore to the abyssal depths (e.g., Seapy and Littler 1978; Horn 1980; Bond et al. 1999; Keller et al. 2015; Bizzarro et al. 2022). This work has informed an immense body of conservation policy, culminating in the Marine Life Protection Act (MLPA) being signed into law in 1999 (CA Fish and Game Code Division 3, Chapter 10.5, § 2850-2863).

Implemented through a years-long, regionalized public process, this act resulted in the creation of a durable network of Marine Protected Areas (MPAs) designed to safeguard both habitat and biodiversity. Implementing documents include a robust monitoring framework and specific performance metrics focused on species of notable economic and/or ecological value (CDFW and OPC 2018). Recognizing that new research, novel technologies and climate-driven ecological shifts could make portions of these documents obsolete while offering unforeseen monitoring opportunities, regular ten-year evaluations of their effectiveness were planned. The final regional planning process was completed in 2012, with the first decadal evaluation scheduled for 2022. A comprehensive guidance document was created to ensure this evaluation was transparent, thorough and efficient (Hall-Arber et al. 2021).

Conducting a network-wide, comprehensive evaluation of biological, habitat, economic and social aspects of MPA effectiveness to make recommendations for adaptive management is a massive undertaking. Even so, the assessment, called the Decadal Management Review (DMR), was completed as planned (CDFW 2022). In addition to assessing progress to date, the DMR report provided high-level recommendations to strengthen scientific monitoring and administrative implementation of the MPA network. Specifically, DMR recommendation #11 aims “to improve and sustain a cost-effective long-term monitoring program.” As a subsequent step, California Sea Grant (CSG), the California Department of Fish and Wildlife (CDFW) and the California Ocean Protection Council (OPC) initiated a process to independently validate the scientific rigor and practicality of monitoring mid-depth habitat, leading to this report.

This report details the findings and recommendations of the Technical Expert Panel (TEP) convened during several meetings between July to September 2024 to evaluate methods, results, challenges and opportunities associated with scientifically assessing ecosystems in benthic, mid-depth (30-100 m), rocky habitats. Historically and contemporarily, monitoring of these species and habitats generally employs submersibles, remotely operated vehicles (ROVs), baited remote underwater video systems (BRUVs), tethered video landers, multibeam and single beam echo sounders and minimal hook-and-line sampling (see Starr et al. 2022 for a broad review, as well as Lindholm et al. 2014; 2015; Lauerman et al. 2017; for regional monitoring summaries). Panelists were selected for their experience with one or more of these tools, analysis/modeling of data collected using these (and other) survey methods and experience applying results to management of marine biota and resources under various political and social circumstances. The final panel included representatives from four countries (United States, Canada, Ecuador and Australia), with many decades of combined experience evaluating marine ecosystems.

This panel was not tasked with making policy or management recommendations; their charge focused purely on the existing and potential scientific process with regard to meeting predefined monitoring program priorities from the MPA Action Plan and Decadal Evaluation Working Group (CDFW and OPC 2018; Hall-Arber et al. 2021; CDFW 2022). Evaluation focused on four **monitoring priorities**:

1. Describing broad, ecosystem-scale species composition of fishes, invertebrates and biogenic habitat (primarily coral and sponge);
2. Obtaining accurate, repeatable estimates of abundance, density and biomass for key species that are comparable across other habitat monitoring groups (i.e., kelp and shallow rocky habitat);
3. Generating length composition data for key species, with adequate sample size to examine age structure and calculate biomass metrics;
4. Characterizing habitat in an ecologically meaningful way, on both macro and micro scales, and evaluating species-habitat association.

To perform their review, the panel was provided with several monitoring reports, MPA regional network design summaries and additional background documents specific to the California MPA network. After reviewing these documents, the panel engaged in a 90-minute orientation meeting where they had the opportunity to question CDFW and OPC experts integrally involved in monitoring efforts. Panelists then supplemented the document library by providing resources on mid-depth monitoring efforts elsewhere, allowing a detailed comparison with the approach used in California.

Over the following weeks, panelists reviewed additional documents and independently completed a tabular form provided by CSG to help organize their thoughts around monitoring priorities. This form used three **guiding questions** relevant to each of the four monitoring priorities:

1. What survey tools and methods, sampling designs (temporal and spatial) and analytical approaches would provide the most accurate and replicable results to meet this monitoring priority for California MPA Network mid-depth habitats?
2. What are the utility, effectiveness, cost considerations and complementary nature of the approaches identified in question #1 with regard to fulfilling this monitoring priority?
3. How can OPC and CDFW best evaluate cost efficiency and effectiveness among these survey tools/ methods, sampling designs and analytical approaches?

Once independent assessments were complete, panelists reconvened to compile their evaluations into a joint assessment table. CSG staff facilitated these sessions, and subject matter experts from both CDFW and OPC briefly joined to answer specific questions or concerns raised by panelists and to better define the scope of the task at hand.

During the second session, the TEP used the compiled assessment table and discussion notes from the first session to form recommendations for future monitoring of mid-depth habitats and species within the California MPA Network. CSG again provided guiding questions to structure the discussion and facilitated the session. These questions were:

1. Given the monitoring priorities and your key findings, what are the core components of a comprehensive monitoring strategy (i.e., survey tools and methods, sampling designs and analytical approaches) that will address these objectives:
    A. Evaluate MPA performance statewide, and within the network's three bioregions (North, Central and South);
    B. Inform ecological connectivity modeling;
    C. Assess and address climate change impacts;
    D. Incorporate non-fisheries and non-biological monitoring (e.g., temperature, salinity)
2. How can historical methods and datasets be best incorporated to ensure existing time series are comparable with new/additional approaches from the key findings?
3. What emerging technologies and innovative analytical approaches (e.g., artificial intelligence) could potentially complement or substitute for the approaches recommended above?

After the second session, at the TEP's request, CDFW/OPC clarified that their overall monitoring goal for California's MPA mid-depth rocky habitats is "to assess MPA effectiveness for focal species and communities". Specifically, CDFW/OPC wish to develop a monitoring strategy that enables them to effectively:

1. Measure shifts of focal species within MPAs at multiple spatial resolution — i.e., individual MPAs, bioregions and broader scales (where appropriate for the range of a focal species);
2. Detect the impacts of climate-related changes and/or other environmental stressors on focal species range distribution, depth and habitat associations and community structure;
3. Capture variation in performance metrics (i.e., density, biomass, size structure) for focal species and for community-level changes across MPAs, and assess driving factors of this variability (e.g., fishing effort, habitat quantity/quality, larval connectivity).

In doing so, CDFW/OPC wish to maintain the continuity of existing time series data and comparability to their other MPA monitoring groups targeting rocky reefs with scuba and hook-and-line sampling methods. This could be achieved, for example, by co-locating sampling points where shallow and mid-depth rock habitat co-occur.

In line with the purpose of this panel and its structured advisory process, the recommendations provided here are based on the best available science and information. They are offered with minimal bias and maximal objectivity and intended to serve as one resource among many that will be used to improve effectiveness and efficiency of the California MPA Network in coming decades. Recommendations do not represent binding edicts from any of the entities associated with the panelists and may be employed or ignored at the discretion of CSG, CDFW and OPC staff as funding, political will and other contextual factors dictate.

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2. KEY FINDINGS

2.1 WHAT APPROACHES WOULD PROVIDE THE MOST ACCURATE AND REPLICABLE RESULTS TO MEET A MONITORING PRIORITY (#1-4) FOR CALIFORNIA MPA NETWORK MID-DEPTH HABITATS?

The TEP identified survey tools, sampling designs, and analytical methods that would provide the most accurate and replicable results to address monitoring priorities. Table A1 contains the full results of this evaluation, with a summary provided here.

2.1.1 Survey Tools and Methods

Underwater camera platforms were the primary focus for survey tool evaluation. These were broadly grouped into:

- Mobile platforms that collect transect-based data;
- Stationary platforms that collect time-integrated data in a single location.

Mobile platforms included remotely operated vehicles (ROVs), autonomous underwater vehicles (AUVs), and lowered (towed) camera systems. Despite historical use in the California MPA system, manned submersibles were not included due to the low likelihood of being recommended due to very high associated operation and maintenance costs, and potential safety risks for submariners.

Stationary platforms included video landers (Matthews et al. 2024), BRUVs and long-duration stationary stereo camera systems. This list represents equipment with published applications for sampling rocky habitats on the U.S. west coast, including both established and experimental approaches.

Globally, various survey tools have been used to conduct biological surveys within mesophotic ecosystems, both within and outside Marine Protected Areas (Linfield et al. 2016; Pawlik et al. 2022). Given the technical difficulties of surveying these mid-depth ecosystems, ROVs, stationary or towed remote underwater video systems (RUVS, baited or unbaited) and AUVs have been the most widely employed survey tools (Asher et al. 2017; Turner et al. 2018; Button et al. 2021). Each one of these methodologies has unique strengths and limitations in terms of what monitoring priorities can be addressed, cost effectiveness, and temporal as well as spatial replicability.

Of the survey methods evaluated by this panel (Table A1), the use of ROVs with stereo-video cameras offers the most comprehensive approach to address the four monitoring priorities for California MPA Network mid-depth habitats. These ROVs provide accurate, replicable measurements of surveyed areas and target species lengths. With additional sensors mounted on the vehicle, they can also collect other biological and environmental data relevant to all four monitoring priorities. Given anticipated budget limitations on monitoring overall, ROV transects could be complemented by lower-cost unbaited RUVS or baited RUVS (i.e., BRUVS), at a sub-sample of selected monitoring sites (see Section 2.2.1). RUVS could be used to extend sampling beyond the existing "index sites" (see Section 2.2.2), rapidly assess regions before and after expected condition changes (e.g., heat waves) or add supplemental length data for rarely observed species that are drawn to bait, such as large mobile carnivores.

2.1.2 Sampling Designs

A sampling strategy consists of two components: (1) the sample design; and (2) the analytical approach or "estimator" (Brus and de Gruijter, 1997). Management objectives and monitoring questions should guide the sample design. To ensure representation of the wider population, sites should be chosen randomly from a clearly defined sampling frame. This applies to all monitoring priorities, so at a minimum, future monitoring programs should employ a Simple Random Sample design (Foster et al. 2024).

However, future monitoring may also benefit from stratifying the sampling frame. This could involve dividing the sampling frame into groups based on similar habitats, depths, type and duration of protection status, bioregions and/or regions based on previous levels of fishing effort. Stratification would help address the monitoring priority of assessing species associations with habitat, examine the effects of other environmental stressors and potentially provide better insight into what drives variability in focal species performance measures (as outlined in the Introduction). Therefore, a Stratified Random Sampling design should be considered, with greater sampling effort given to hard substrates that support greater biodiversity and abundance of life. The TEP notes that the current habitat mapping and bathymetry products throughout the California MPA system allow for habitat and depth stratification without additional data gathering.

Collecting samples within strata in a spatially-balanced manner may also be more cost-efficient, particularly if (as is often the case) the response variable exhibits strong spatial autocorrelation. Future monitoring programs should consider exploring the accuracy and utility of spatially balanced stratified random sampling designs (Foster et al. 2014). However, these designs may incur additional costs due to increased travel time between sample locations. Therefore, it is worth comparing the cost efficiency of this type of design with simpler designs before field implementation. See section 2.3 for a discussion on techniques for comparing the cost efficiency of different sample designs.

Regardless of the chosen design, samples should be collected on a regular schedule, for example at the same time each year. The available budget and monitoring question should guide sample frequency. To complement annual surveys, multi-annual samples could be taken within a sub-sample of sites, for example in summer and winter, if seasonal variation in focal species performance measures are potentially detectable and relevant to management agencies. Alternatively, intensive sampling could be added before or during extreme events, such as marine heat waves, to help characterize their impact.

In all cases, regular sampling should be maintained over the long term (many decades) to measure the effect of MPA protection and detect possible climate change impacts.

2.1.3 Analytical Approaches

The TEP examined various analytical approaches that could address the four monitoring priorities, summarized in Table A1. The choice of approach should be guided by the specific monitoring question as well as the expertise available to state management agencies.

These analytical approaches fall into two main categories: model-based and design-based. Dumelle et al. (2021) discuss the difference between these approaches in detail, but briefly:

- A design-based approach assumes a fixed population and relies on randomly assigning some population units to the sample (e.g., through simple or stratified random sampling) for statistical inference.
- A model-based approach assumes the population is a random realization of a stochastic process. In this case, statistical inference does not rely on (or require) random assignment of population units to the sample.

Design-based and model-based approaches each have their advantages. Design-based advantages are that:

- The estimators rely solely on the data;
- They are relatively simple to calculate;
- They are unbiased so long as the minimum sample design requirement (randomized sampling) is met.

However, design-based estimators may produce large variance estimates if sample sizes are low.

Model-based approach advantages are that:

- They can accommodate complex (especially non-linear) relationships between response variable and auxiliary variables that are either known or thought to influence the response;
- They can account for complex variance structures within the data, such as spatial autocorrelation and variability attributable to the observation platform;
- They remain robust even if randomization is not achieved;
- They can be more efficient when sample size is low.

The main drawback of model-based approaches are that the validity of the result depends on the accuracy of the chosen model.

Design-based estimators of a population mean (and associated variance) can be used in statistical models, but it is crucial to ensure that the model's underlying assumptions are met. For example, when using an analysis of variance (ANOVA) to test for significant differences in average abundance inside and outside an MPA, it is important to check that the variance within each group is the same. If variances differ, Welch's t-test can be used to assess statistical significance. Spatial autocorrelation between observations within each group, however, will violate the independent sample assumption of this test and all forms of ANOVA. If spatial autocorrelation is present, model-based estimation is recommended.

The (geo)statistical models used to account for spatial autocorrelation in model-based approaches are technically more challenging and require a higher level of statistical training to implement. However, they solve the problem highlighted above and have the potential to provide better insights into the factors that govern both the value of focal species performance measures and the variation around these measures.

For these reasons, Perkins and Lauermann (2022) recommend model-based estimators for ongoing analysis of ROV monitoring data in the California MPA Network. Their approach incorporates environmental factors such as depth, habitat type (e.g., rocky reef vs sediment) and habitat quality (e.g., reef complexity), while also accounting for spatial autocorrelation effects.

Furthermore, Perkins and Lauermann (2022) emphasize how their model-based approach can incorporate a non-linear MPA-effect function that aligns with the theoretical expectation that focal species populations within an MPA will, over time, asymptote to pre-fished levels due to density dependence. This effect is not captured by simple linear MPA-effect models, such as the response ratios utilized by Starr et al. (2022).

Finally, model-based approaches to estimation would enable CDFW/OPC to explore the use of Single Species Distribution Models (e.g., Young and Carr 2015) or Joint Species Distribution Models (e.g., Roberts et al. 2022). These models can be used to predict the range of focal species, help design sample plans for new or existing MPAs and explore the potential effect of climate change on this range, if approached carefully (Elith et al. 2010).

2.2. WHAT ARE THE UTILITY, EFFECTIVENESS, COST CONSIDERATIONS AND COMPLEMENTARY NATURE OF THE DISCUSSED APPROACHES IN MEETING EACH MONITORING PRIORITY (#1-4)?

The TEP evaluated the survey tools, sampling designs and analytical methods identified in Table A1 based on their utility, effectiveness, cost considerations and complementary nature. Table A2 contains the full results of this evaluation, with a summary provided here.

2.2.1 Survey Tools and Methods

The TEP identified several categories of survey tools, including camera-based platforms for collecting mono and stereo imagery, acoustic instrumentation, environmental DNA (eDNA) and hook-and-line surveys.

Table A2 lists major advantages and limitations of each approach. In general, mobile platforms offer advantages in survey area coverage and use established, standardized methodology for providing estimates of density, abundance and biomass. These approaches also provide more habitat information through transect-based sampling. The principal disadvantages are high initial and operational costs, and potential fish reactions to the gear (Stoner et al. 2008).

Within the mobile platform category, there is a continuum of cost levels and performance characteristics, with standard observation class ROVs providing the highest functionality and data quality. Towed/drift cameras generally have reduced operational control and lower instrument payloads, resulting in lower performance and generally lower quality imagery (Rooper et al. 2010). AUVs represent an area of rapid development and may become a viable alternative to ROV platforms in the near future. However, currently available devices do not match the cost-effectiveness of ROVs.

Stationary methods tend to be logistically simpler and more affordable, but their limited spatial coverage increases overall uncertainty. However, given the reduced effort required to deploy these platforms, they may be similarly effective to an ROV in higher-density fish habitat (Denney 2017). These platforms are also substantially more limited for habitat evaluation and fine-scale species habitat associations due to their small spatial coverage (Schramm et al. 2020).

The use of bait can improve encounter rates with bait-attracted fishes and has been used for decades for fisheries surveys in other parts of the globe (e.g., Langolis et al. 2007; Whitmarsh et al. 2017). However, the interaction of the bait dispersion plume and current can create complex and unknowable sampling footprints (Harvey et al. 2007), which reduces the reproducibility and comparability of these approaches.

Unbaited cameras have been successfully used to sample rocky habitats in California. But they often require multiple units with longer soak times to produce adequate data densities, which increases device design costs (Rooper et al. 2020). Nevertheless, this approach, when coupled with time-lapse stereo imaging, can provide density information directly comparable with transect-type data from mobile platforms. It achieves this by using volumetric density estimates of fish by leveraging stereo image analysis techniques to determine ranges to fish and the volume sampled by the camera (Williams et al. 2018).

Overall, when addressing monitoring priorities, mobile platforms can deliver more comprehensive results by definitively estimating the density, abundance and biomass of species in an absolute sense. In contrast, stationary cameras, especially BRUVs, rely on indirect abundance metrics such as MaxN (Cappo et al. 2006), defined as the maximum number of fish of a given species observed in any given video frame. While volumetric density methods have been developed for unbaited stereo-based camera systems (Denney et al. 2017; Williams et al. 2018), these are not yet established in the fisheries survey community.

Mobile platforms are also a better choice compared to stationary cameras with regard to the second monitoring priority of habitat monitoring/assessment, due to their increased spatial coverage. However, for the monitoring priorities of assessing species composition and fish length, stationary cameras can provide similar data to mobile camera platforms.

It is worthwhile considering the complementary nature of these camera approaches. For example, in scenarios where the sample frame contains medium to highly mobile fish species with regular movements across the surveyed area, mobile and stationary gear may have similar encounter rates. This can provide comparable data, potentially at a lower cost with stationary cameras. On the other hand, for epibenthic fishes with limited movement or lower abundance species, stationary cameras may have inadequate encounter rates because their survey sampling fraction is much lower, and extended temporal sampling at a station does not translate into higher efficiency (Rooper et al. 2020).

Other non-optic marine surveying tools were identified, including acoustic instrumentation, eDNA and hook-and-line surveys. While these approaches have established utility in marine living resource surveying and habitat characterization, each is less able to singlehandedly address the four monitoring priorities compared with camera-based tools.

Multibeam acoustics approaches, for example, offer large spatial coverage and established broad category habitat categorization methodology, but are not suitable for direct fish species-specific density and size estimation. Hook-and-line methods can provide data on fish size and an abundance index, but do not offer any habitat information. eDNA approaches show great potential for cost-effective assessments of species composition, and possibly abundance, but do not provide fish length or habitat data. An overview of these methods is provided in Table A2. While they could help to augment data streams, they do not represent viable primary survey approaches for California's mid-depth rocky reefs.

2.2.2 Sampling Designs

The ROV sampling designs used in the baseline and subsequent surveys of mid-depth reefs in the North, North-Central and South bioregions can be generally summarized as follows:

- North: (i) fixed, qualitatively paired as similar (inside and outside MPAs) "index" sites, 500 m wide and 1000 m long, orientated downslope and chosen to represent "general rocky reef habitat" within which six, 500 m long transects (across the width of the site) are selected using a systematic random approach; (ii) between two and six additional 1000 m long "characterization" transects, selected to capture habitat (reef and soft bottom) and sometimes depth differences.
- North-Central and South (baseline surveys 2011–2015): Various number of exploratory transects, of lengths up to 2 km, inside and outside of MPAs, whose start and direction are preferentially selected to capture habitat (reef and soft bottom) and depth differences.
- North-Central and South (2015–onwards): Adopted the fixed, paired, index site design initially implemented in the Northern Channel Islands (2004 –onwards), Central (2007–onwards) and North (2012–onwards) coast MPAs (Perkins et al. 2024).

After 2011, ROV transects within the index sites were allocated using a stratified random approach. However, in the Californian MPA ROV design, the locations of the index sites (and characterisation transects) were chosen purposely and considered "typical" of the mid-depth rocky-reef habitat. Therefore, any randomization within the index site is conditional on this initial choice.

Prior to the deployment of stereo BRUVs, MPA and reference sites were stratified by depth and proportion of hard habitat within 100 m x 100 m grid cells (using habitat maps from the California Seafloor Mapping Programme). Suitable BRUV sites were designated as cells containing more than 15% (30-50 m and 50-70 m depth) and more than 5% (70-100 m depth) hard habitat. BRUV were subsequently deployed "haphazardly" in cells that met these suitability criteria.

Perkins et al. (2024) demonstrate that the current ROV index site sampling design can clearly discern MPA effects — that is, changes in performance metrics for focal species attributable to the exclusion of fishing activity within MPAs. Importantly, this design was chosen for efficiency and ease of operation, maximizing ROV time in surveying transects (rather than in transit between them).

However, the preferential selection of the index site locations assumes that these sites are representative of non-sampled locations — an assumption difficult to justify in highly spatial and temporal variable regions such as the California MPA network (Perkins and Lauermann 2022). Moreover, preferential designs may not be effective when studying shifts in focal species or the impacts of climate change and/or other environmental stressors on community structure or species range and habitat associations.

These more complex questions may require a more sophisticated, stratified and perhaps spatially balanced design. Such a design would select sample sites that ensure a balanced coverage across auxiliary variables — i.e., factors such as fishing pressure, depth, habitat type and habitat quality that are thought to influence the response variable reflected in the management questions (Robertson et al. 2013; Brown et al. 2015). Starr et al. (2022), for example, recommend using the CDFW seafloor habitat analysis (https://apps.wildlife.ca.gov/marine/) to stratify future ROV and BRUV survey efforts by habitat quality and reef patch size, thereby accounting for habitat and depth effects on response variables.

Importantly, existing “legacy sites” can be incorporated into stratified and spatially balanced designs (Foster et al. 2017; Dumelle et al. 2023). Doing so would, for example, allow state management agencies to maintain time series observations for some or all the existing index sites — thereby potentially addressing longer-term, multi-decadal changes such as climate change-induced shifts in species distribution — while adopting more sophisticated designs to target this and other management questions.

The haphazard selection of BRUV sites may also be inadequate to address more complex management questions. In this context it may be worth noting that several factors have likely contributed to researchers “searching” for suitable sample sites within cells, rather than using a strictly randomized approach. These factors include the size of the sampling raster (100 m x 100 m), the patchiness of rocky habitat in the selected depth-ranges and the desire to place BRUVS on rocky habitats. This has ultimately resulted in a directed placement of BRUVs.

2.2.3 Analytical Approaches

In general, efficiency and cost are not major factors in the analysis component of a sampling strategy. However, as noted above, model-based approaches typically require a higher level of statistical expertise, which may incur additional subcontracting costs if this capability is not available within state management agencies. Similarly, using ecosystem models to address issues such as connectivity may impose a larger external data overhead.

Most analysis methods are tailored to address specific monitoring properties. For example, multivariate models that describe community structure address priority #1 (broad ecosystem-scale species composition); standard ROV density estimation addresses priority #2 (abundance, density and biomass metrics); and stereo image fish length estimation addresses priority #3 (length composition data). Model-based estimators can be considered complementary, as a single model may be able to address several management questions simultaneously by quantifying the effect of multiple auxiliary variables (such as habitat type, depth, fishing effort) within the same model.

2.3 HOW CAN COST EFFICIENCY AND EFFECTIVENESS BE EVALUATED BETWEEN THESE MONITORING APPROACHES?

Evaluating the cost efficiency and effectiveness of MPA monitoring methods should focus on the management authority’s goals, as reflected in the monitoring strategy objectives and the data needed to meet them. Trade-offs are often necessary when monitoring objectives compete or are addressed in parallel. For example, an ROV might be most cost effective for monitoring fish density, while hook-and-line sampling could be cheapest per sample for monitoring fish size. However, if both fish density and size are needed a towed stereo camera might meet both objectives at the lowest cost (Rooper et al. 2012).

For some monitoring objectives, particularly those requiring observations across time and space, a slightly less effective or cost-efficient method may be preferred to maintain data integrity for time series analysis. While considerable information on the effectiveness of most survey tools is available in published literature (Starr et al. 2022), state management agencies should be wary of analyses that attempt to identify optimal cost efficiency since some factors, such as familiarity with and reliability of survey tools, are important for successful outcomes but may be difficult to quantify. Additionally, sampling design can crucially influence statistical inference power, depending on the encounter rate of high-priority target species (Lowry et al. 2022).

2.3.1 Survey Tools and Methods

Underwater image surveys generally provide similar data types and face comparable strengths and weaknesses. The main differences seem to lie in fish avoidance behavior and survey cost/time (e.g., drop cameras are inexpensive and comparatively easy to use, ROVs are costlier but may cause avoidance/attraction behavior, AUVs are very expensive but potentially elicit minimal avoidance). Despite rapid evolution of visual survey tools and methods in recent decades, many deployment costs remain fundamentally tied to offshore ship operations and the use of sensitive electronics in marine environments. Consequently, all visual tools and methods share certain challenges, which can be met in various ways. Numerous researchers have assessed these challenges, seeking to optimize survey efficacy (e.g., O'Connell and Carlile 1994; Cappo et al. 2003; Yoklavich et al. 2015).

Specific cost considerations include the initial technology investment, outfitting a support vessel for deployment, hiring subcontractors to run the equipment or cultivating in-house expertise, the technological infrastructure for data storage, field equipment storage and maintenance and costs associated with video annotation software and staff time. Other relevant cost factors include data collection hours, the sampling design's effects on total survey effort, staff safety at sea and both equipment and vessel depreciation (O'Connell and Carlile 1994; Yoklavich et al. 2015; Pacunski et al. 2020). Each sampling tool, vessel, crew and data storage system varies in efficiency, making a comprehensive review unfeasible. Therefore, consideration of survey assets and methods must be closely tied to sampling goals, specific to regional support infrastructure and aligned with expected financial support. For existing sampling programs, any tool and method alteration must be accompanied by a direct comparative analysis of these cost considerations specific to the proposed changes.

The metrics for evaluating the cost effectiveness and efficiency of different survey tools vary with the nuances of different monitoring objectives. However, a generic set of metrics can account for costs such as capital investment, maintenance, personnel and vessel expenses for data replication and processing costs. These can then be balanced against the number of priority objectives that are addressed, the data's usefulness in addressing these priorities and the number of replicate samples needed for statistical power. Using this common set of metrics, costs can thus be compared among survey tools (e.g., Table A2 in Ohayon et al. [2023]).

2.3.2 Sampling Designs

The efficacy and cost effectiveness of sampling designs should be evaluated based on their ability to: (a) produce unbiased statistics that are applicable to the monitoring questions; (b) provide precise estimates; and (c) detect changes given a sample size where an "effect size" is relevant to the monitoring question.

However, no single design is optimal for all research questions (Kermorvant et al. 2019a; Lowry et al. 2022). More complex sampling designs for ROV and RUVs — such as stratified, spatially balanced, random sampling — may entail additional travel time between deployments, potentially increasing the overall monitoring program cost. Conversely, spatially balanced designs typically require fewer samples to achieve the sample level of precision, potentially reducing overall costs. Consequently, trade-offs are likely when considering sampling designs that meet the needs of different monitoring questions.

Simulation studies (see also Section 2.3.3) provide a mechanism to investigate these trade-offs by:

1. Deliberately degrading existing data sets. This can be done by sequentially removing data collected from individual transects at index sites and/or sampling years, applying a model- or design-based estimator to the degraded data set and identifying (for example) how quickly species accumulation curves degrade or at what point pre-specified effect sizes (such as differences between control and MPA sites in focal species and/or community metrics) are no longer detectable.

2. Using existing data sets and a spatial or spatio-temporal statistical model to estimate population metrics (presence/absence, abundance, density) across a relevant sampling frame. This involves simulating observations from this population using different sampling designs and/or survey tools, applying model or design based estimates to these simulated observations and testing their ability to answer specific management questions and detect trends or pre-specified effect sizes.

3. Evaluating the utility of different sampling platforms by incorporating species-specific fish movements, schooling behaviors and potential responses to sampling gear into a model environment to generate simulated gear-specific samples, which can be statistically tested for bias and precision. For example, simulated populations that move throughout a given sampling domain will have an increased encounter rate with stationary platforms that can sample for an extended time (time-lapse). Conversely, dispersed, localized non-mobile simulated targets would be better sampled by the greater spatial coverage of a transect-based mobile gear. The trade-offs between these sampling platforms can be evaluated given sufficient knowledge of different key species in the survey domain.

The outcomes of these analyses can be coupled to estimates of the person-hours, boat-hours, mobilization costs, consumables, etc. associated with each simulated sample design, estimator and survey method. This approach helps to identify the most cost-effective sampling strategy, defined as the strategy that achieves the requisite power and/or precision to answer a specific management question at the lowest cost.

Foster et al. (2014) and Perkins et al. (2021) provide examples of how to conduct the second type of simulation study for AUV and ROV survey methods, respectively. Kermorvant et al. (2019) also show how to conduct this type of simulation study for a sediment grab survey method, dividing costs into “fixed” (per survey) and “variable” (per sample) components.

Foster et al. (2014) conducted an analysis using AUV imagery of benthic habitat-forming species (Ecklonia radiata) and morphotypes (e.g., Cup sponges), collected with a “Clustered Sparse Grid” design that is similar to the index site design used in the Californian MPAs. They employed a geostatical model to estimate the population abundance of species and morphotypes across the sampling frame. The model accounted for the effects of depth, seabed rugosity and spatial autocorrelation. This model was then used to test the bias (measured against the original model) and precision of simulated observations under various sampling designs. Adding the theoretical cost of collecting simulated observations under different sampling designs would be a relatively straightforward extension of this type of analysis.

Perkins et al. (2021) combined elements of the first and second approach. They fit a geostatistical model to brown rockfish counts collected under the Californian MPA ROV index site design, coupled to an Integral Project Model (IPM) to simulate the population dynamics (recruitment, mortality and growth of fish over time) at each site. The geostatistical model accounted for important environmental covariates and spatial autocorrelation, while changes to the IPM simulated the effect of protection from fishing-related mortality within MPA sites. Simpler statistical models were then fitted to simulated observations, collected using different numbers of ROV transects placed randomly within sites. These models were tested for their ability to detect differences between MPA and non-MPA sites. Again, including survey cost components, informed by the known costs associated with CDFW-funded ROV surveys, would be a relatively simple addition to this analysis. This approach could also be extended to examine the effects of alternative sample designs (as per Foster et al. 2014), survey methods and design-based estimators.

While these simulation studies are potentially powerful, it is important to recognize that their results depend on the modeled population characteristics. Without representative input data spanning a variety of relevant conditions, simulations may fail to adequately predict biologically plausible outcomes. Moreover, if environmental conditions reach unprecedented levels (e.g., during prolonged marine heat waves), such simulations lack a basis for making accurate predictions.

2.3.3 Analytical Approaches

As noted previously, cost efficiency is generally not a primary consideration when selecting an analytical approach. However, the accuracy of model-based estimators and their ability to detect change and answer monitoring questions depend heavily on the analyst's assumptions regarding the most suitable model structure.

The first step in choosing an appropriate model is to consider the statistical (e.g., categorical or continuous) and mathematical (e.g. counts are positive integers, ratios range from 0 and 1) characteristics of the response variable. For example, count data can be assumed to follow a Poisson or Negative Binomial distribution, with an "offset" used to account for the effect of different survey areas.

After considering the basic properties of the response variable, analysts must then choose from a potentially very large set of options regarding:

1. The covariates believed to influence the expected value of the response variable;
2. The structure of the relationship between these covariates and the expected value;
3. The specific nature of the spatial (or temporal) autocorrelation between response variables.

These choices often have a large effect on the model outcomes and, consequently, analysis conclusions. They must therefore be made carefully. Ideally, plausible alternative models should be tested using within-sample procedures (Yates et al. 2023) or by assessing their ability to accurately predict to hold out (testing) data sets (Roberts et al. 2017; Valavi et al. 2019).

Fitting model-based estimators that account for spatial and/or temporal autocorrelation, as well as potentially complex interactions between the expected value of the response variable and auxiliary variables, also often requires familiarity with advanced statistical methods and associated software, such as spBayes (Finley et al. 2007), R-INLA (Lindgren and Rue 2015) or sdmTMB (Anderson et al. 2024). If the management agencies lack the necessary in-house statistical expertise, they also need to consider the cost of either contracting out sample data analysis or developing internal capabilities through staff training.

03

3. RECOMMENDATIONS

3.1 WHAT ARE THE CORE COMPONENTS OF A COMPREHENSIVE MONITORING STRATEGY THAT WILL ADDRESS THE STATE'S MONITORING OBJECTIVES?

3.1.1 Comprehensive Monitoring Strategy Recommendations

The TEP recommends identifying and consistently collecting a data stream for each monitoring priority over several years. For example, if the objective is to monitor fish abundance and size inside and outside an MPA, consistent collection of length and density data are needed. One effective method to collect this type of data would be stereo cameras mounted on an ROV, following a stratified random design, with annual surveys conducted at the same time each year. This approach would provide samples that can be used in a design-based or model-based estimate of abundance, while the stereo images could be used to produce annual size estimates. Once established, the core sampling program should persist long enough to meet long-term monitoring network goals.

Similar data could be collected using other vehicles (e.g., AUVs or towed camera systems with stereo camera capabilities), utilizing alternative sampling designs (e.g., simple random sampling or spatially balanced sampling). The key recommendation is to select a tool and sampling design capable of collecting the data needed to address the research priority. Extrinsic factors will likely influence the final choice of monitoring approaches. For instance, there might be an existing time series of stereo camera data collected via ROVs, or towed stereo cameras might be the most cost-effective option for collecting density data. However, these external factors should be primarily considered in terms of their ability to provide data that adequately informs the key monitoring priority.

A comprehensive monitoring strategy should include several core components:

1. **Management questions:** A limited set of specific management and science questions. State management agencies should review which of the Decadal Evaluation Working Group (DEWG) questions remain pertinent. They may also consider using existing data and analysis to quantify MPA performance targets. These targets could help set condition categories for key focal species metrics within MPAs and enable the use of control chart methods to demonstrate MPA performance over time (refer to Section 3.1.4).

2. **Survey tools and methods:** A stereo-camera equipped mobile platform, such as an ROV, AUV or towed camera device. This parimary monitoring approach is critical for generating area-swept density, length composition and habitat assessment, while maintaining comparability with existing long-term time series.

   Lower-cost stationary platforms can complement this primary method in lower-priority sites, expected low fish density sites or for initial exploratory deployments in previously unsampled sites. While these stationary platforms provide a reduced suite of data and do not address the entire set of monitoring priorities (see Section 2.2.1), they require less specialized operators than ROVs and may allow for multiple, simultaneous deployments. BRUVs offer higher encounter rates with rarer and larger predatory fishes, providing more opportunities for estimating length composition. However, BRUVs have potential biases associated with bait use (Taylor et al. 2013) and difficulties in estimating the effective area sampled due to complexities with bait scent dispersion. Video landers present an unbaited stationary platform alternative, likely yielding unbiased density estimates. These range in system complexity from simple consumer-off-the-shelf (COTS) systems (Hannah and Blume 2012; Longolis et al. 2020) to custom-built, specialized devices that require collaborations with a suitable fabricator (Rooper et al. 2020; Matthews et al. 2024). Unbaited platforms may require higher effort in terms of sampling duration or number of deployments to match observed fish densities in BRUVs and transecting mobile platforms. The TEP recommends considering lower-cost, baited or unbaited simple stereo camera platforms to complement primary monitoring efforts in less critical areas, to facilitate collection of length data for mobile predators or as alternatives where the primary method is cost-prohibitive.

3. **Sampling designs:** Future sampling locations should be chosen randomly from a clearly defined sampling frame. The TEP agrees with previous recommendations (e.g. Perkins and Lauermann 2022; Starr et al. 2022) that sampling designs should be stratified, at minimum by habitat type and depth. The stratification scheme should utilize existing bathymetric, habitat type and habitat- or season-specific species encounter data to divide the sampling frame into discrete regions over which population estimates will be expanded. Stratification need not be restricted to environmental covariates but can also include anthropogenic pressures, such as previous or current fishing effort. Hall-Alber et al. (2021) and Perkins and Lauermann (2022), for example, recommend considering historic and on-going fishing pressure when analyzing MPA performance. The TEP recommends reflecting this covariate in the sample design, rather than relying on post-survey analysis to reveal its effect. This could be achieved by allocating sampling effort across the MPA prioritization described in the MPA Monitoring Action Plan (CDFW and OPC 2018) as well as ecologically comparable sites (as defined by the stratification process) outside of the MPA network.

The TEP recognizes the importance of maintaining at least some existing index sites within any future sample design (see Long-term monitoring bullet below). However, the preferential selection of these sites may mean that the observations collected there are not representative of the mid-depth rocky reef environment across the California coast.

4. **Analytical approaches:** Unbiased, design-based estimators of population metrics are available for simple random samples, stratified random samples and spatially balanced stratified random samples, provided randomization is achieved in the field. These estimators are relatively simple to calculate and may suffice for some management questions. However, model-based estimators using (for example) spatial point-process models will be necessary in certain instances:
   A. When spatial autocorrelation violates the assumptions of statistical tests used in conjunction with design-based estimators;
   B. To examine how spatial autocorrelation affects sample designs efficiency;
   C. When investigating complex non-linear effects of environmental covariates and anthropogenic activity on the abundance and distribution of key focal species, such as the possibility of MPA effects reaching an asymptote.

   Perkins and Lauermann (2022) and Perkins et al. (2024) provide evidence that focal species abundance within the California MPA network exhibits strong spatial autocorrelation. They caution that model-based estimates of MPA effects can be substantially incorrect, even in direction (e.g., indicating worse instead of better outcomes), if spatial autocorrelation is not incorporated into the model-based analysis. The TEP recommends that spatial autocorrelation is measured in all future observations and, if present, accounted for in future analytical approaches.

5. **Long-term monitoring:** Future surveys should include a subset of previously surveyed index sites to maintain long-term datasets. Alternative survey tools with comparable capabilities (i.e., AUVs, other lowered mobile camera platforms) can be considered, provided they yield the same data types as the historically used transect-based ROV surveys.

   When using alternate tools to collect complementary data (e.g., obtaining length distributions of rarely encountered mobile predators with a BRUV rather than an ROV) extensive evaluation of selectivity and encounter rate is unnecessary, as these parameters are expected to vary and the data sets inform different metrics.

   If combining data from different platforms into a single index, a side-by-side comparison should be made between the ROV and any proposed supplemental or replacement tool. This comparison would help understand platform-specific variation in detectability of key species and habitats (e.g. Rooper et al. 2012; 2020, Laidig et al. 2013; Somerton et al. 2017). NOAA's Untrawlable Habitat Strategic Initiative provides a good example of this approach, using test beds with different optical and acoustic methods to document differences in gear catchability/detectability.

   While such exhaustive evaluations of differences in bias and catchability/detectability are costly and time-consuming, especially given low encounter rates for rare species, the results are important for creating long-term indices based on multiple data series (Pacunski et al. 2016; Somerton et al. 2017). Alternatively, if spatiotemporally overlapping data sets are available from different sampling tools, methods such as multivariate autoregressive state space (MARSS) modeling may be used to combine information into a single index and evaluate information content afforded by each input (Tolimieri et al. 2017; Holmes et al. 2021).

Index sites retained within future surveys may be revisited annually or over longer periods, within a rotating-panel design. This approach would enable the inclusion of a greater variety of sites in the monitoring programme without incurring substantial additional costs.

6. **Standardized protocols:** Recordings from ROVs and other survey tools should be reviewed and annotated following standardized protocols by technicians and biologists who receive adequate ongoing training and evaluation to ensure data collection consistency. Quality assurance and control protocols should include an independent review of a portion of videos by a secondary reviewer, the addition of a species identification confidence field in the database (at minimum for high-priority species) and the establishment of a final vetting process for all specimens not confidently identified during initial review.

   Once extracted from video recordings, data should be analyzed using multivariate techniques to determine assemblages and environmental drivers. If spatial autocorrelation is evident in the observations, this should be accounted for. This can be done, for example, by using spatial point process models (via supported software packages such as VAST or sdmTMB) to generate abundance indices, and by using species distribution models to generate overall distributions by size and species for the region, as well as to predict climate change impacts (Simpson et al. 2017; Laman et al. 2018). When implemented within a randomized, stratified design, this approach will provide a representative time series of comparable abundance inside/outside MPAs, a time series of size inside/outside MPAs, a time series of diversity inside/outside MPAs, habitat mapping, and habitat utilization inside and outside MPAs.

7. **Data curation and FAIR (Findability, Accessibility, Interoperability, Reuse) access:** Video and image recordings serve as long-term observation records. The original recordings should be stored on site, with a copy banked in a secure, off-site facility for future research. It is crucial to identify ongoing funding for the maintenance of these stored recordings, even if regular access is not anticipated.

   Given that the data streams needed to address program objectives will likely be common across multiple projects (e.g., density estimates), state management agencies should consider developing a relational database. This database would allow data submission, implement quality control measures, provide permanent housing for data and make it easily accessible for future re-analysis.

   An efficient database would include both the metadata (e.g., the survey vehicle, sample frame, date/time, sample design and site inclusion probability if appropriate) and the derived data (e.g., density, size distribution) for each funded project. An example of a national database housing common data from multiple projects, collected with multiple platforms over many years, can be found at NOAAs Deep Sea Research and Technology Program (https://deepseacoraldata.noaa.gov/; Hourigan et al. 2015).

3.1.2 Additional Monitoring

While the recommended primary sampling approach is not dependent on any other methodology to accomplish the main monitoring goals, the overall monitoring may benefit from additional data collection — for example, augmenting the main data collection with stationary stereo camera deployments at a subset of randomly selected stations.

These stationary camera deployments could be analyzed using the same tools as the primary surveys, allowing for a comparison of the results between the transect surveys and the stationary deployments. Stationary stereo cameras can be baited or unbaited, each with its own trade-offs. Unbaited cameras may yield data more comparable to ROV surveys (e.g., fish density per square meter). However, they potentially require greater cost, longer deployments and more analysis time compared to baited alternatives.

This supplementary sampling could offer additional insights, providing a time series of seasonal habitat use and abundance. Such data could be helpful to interpret the ecological context of the transect surveys described above.

The lower potential cost of stationary camera surveys compared to ROV surveys could be used to increase the number of locations sampled across the MPA Network. This cost effectiveness stems from the ability to perform these surveys quickly and efficiently from smaller vessels, allowing for broader coverage as a “snapshot” of the marine environment. For example, Rooper et al. (2012; 2020) demonstrate that stationary camera systems and towed camera systems can provide density estimates comparable to ROV and AUV surveys across various species, including rockfishes. Both of these systems are not only less expensive to construct (e.g., < $10,000) but also more efficient to deploy (sample sizes in tens per day over a given area) compared to ROV surveys that involve larger construction and deployment costs in terms of both funds and time (Rooper 2008).

The camera systems used in transect and stationary sampling can serve additional purposes beyond visual observation. They can be equipped to collect data on temperature, salinity, oceanography, and even conduct zooplankton sampling. Furthermore, water sampling for eDNA could be integrated into these systems or incorporated into the overall sampling plans. These data would provide a time series of environmental parameters that would be linked to the survey data.

For certain monitoring questions, it may be necessary to validate these surveys using alternative methods. For example, limited exploitative/take surveys such as hook-and-line could be used to obtain biological data beyond length. This additional data may be important, as length-based estimates of biomass, reproductive output and other parameters assume a constant relationship. However, with climate change we have already observed non-stationarity in these biological parameters (Matta et al. 2018). Consequently, these biological assumptions need periodic validation, perhaps on a 5-10 year cycle, given the relative longevity of mid-depth reef fish.

3.1.3 Connectivity

Maintaining biological connectivity among MPAs within the network is crucial to minimize extinction risk due to various factors, including habitat fragmentation, demographic stochasticity, climate shifts and catastrophic events. Evaluating connectivity requires regular, systematic characterization of parameters such as movement patterns, genetic variation, demographic variation and patterns in parasite loading. Models based on fine-scale water movement patterns can inform the design of connectivity studies. Additionally, tools such as eDNA may prove fruitful in these evaluations. MPA network managers and their partners could determine which species are of most interest or value within the network. They could then create a prioritized list of explicit connectivity evaluations needed for the next decadal cycle. This would provide academic and governmental entities clear validation to pursue funding for this work.

3.1.4 Future Directions

Spatially balanced designs

The current evidence suggests that spatial autocorrelation operates at scales of 2 to 15 km for many species and 2 to 300 km for large fish (Perkins and Lauernamm 2022, Perkins et al. 2024). This finding indicates that cost efficiencies might be achieved by moving to stratified, spatially balanced sampling designs. Several freely available software tools, particularly MBHDesign (Foster, 2020) and spsurvey (Dumelle et al. 2023), currently support this transition.

These types of designs have been used successfully in Australia, but can entail additional travel time between sites. For BRUVs, this may necessitate relatively complex, two-stage designs if the transit time between sites exceeds the soak duration (Hill et al. 2018). Therefore, any decision to shift to this type of design should be preceded and supported by a cost-efficiency analysis (see Section 2.3.2).

Spatial balance and stratification in these designs are achieved by adjusting sampling inclusion probabilities. Although conceptually more complex, inclusion probabilities are a more general and flexible way to achieve stratification, and they open the door to potentially more efficient and informative sampling strategies that can be explicitly tailored to address complex management questions. However, this tool can be misused, leading to poorer outcomes. For an informative summary see https://survey-design-field-manual.github.io/efficient-designs. Given the complexity of these designs, the TEP recommends that state management agencies seek statistical advice before implementing spatially balanced designs.

Condition assessments and control charts

As California's MPA monitoring strategy matures, state management agencies may also wish to explore performance thresholds, condition assessments and control chart methods to help demonstrate the conservation outcomes being achieved throughout the MPA Network. A central requirement for this type of approach is a quantitative and unambiguous specification of the desired ecological condition — the performance target — that state management agencies seek to achieve within each MPA.

Specifying performance targets for protected areas is a challenging task (Hilton and Cook 2022). For example, determining what constitutes a good, healthy or desirable abundance at maturity for key rockfish species within an MPA can be complex However, this challenge can be tackled in various ways (Hilton et al. 2021).

Once achieved, these targets can serve multiple purposes. They can help identify the bounds within which managers seek to maintain natural values. Additionally, through the use of control charts, they can demonstrate when management is successful and what condition values should trigger management intervention (Anderson and Thompson 2004). Control charts have been successfully used in Victorian MPAs for many years (Edmunds 2017; Ierodiaconou et al. 2020), providing a practical tool for communicating management effectiveness.

In the case of the California MPA Network, analysis conducted by Perkins et al. (2024) provides evidence that fisheries management measures and the protection afforded by the network have led to strong increases in density for most focal species. This information, combined with the reported asymptotic "MPA effect," may help guide the development of performance targets for key focal species within each MPA. Ultimately, this type of analysis prompts state management agencies to consider the desired future state they aim to achieve for key focal species that inhabit mid-depth rocky reef habitats off the Californian coast.

3.2 HOW CAN HISTORICAL METHODS AND DATASETS BE BEST INCORPORATED TO ENSURE EXISTING TIME SERIES ARE COMPARABLE WITH NEW/ADDITIONAL APPROACHES FROM THE KEY FINDINGS?

3.2.1 Overview

The simplest way to ensure ongoing time series can incorporate historical data is to maintain the same methodology for sampling design and survey tools as was used for historical data collection. This continuity approach is commonly used in fields such as fisheries stock assessment surveys, where preserving the integrity of the time series is paramount (see for example the standardization of methods described in Stauffer 2004). By using the historical methods for ongoing surveys, researchers can maintain continuity in the data streams used to analyze time trends.

However, the continuity approach for long-term monitoring comes with trade-offs. The initial methods are often built off pilot studies with limited goals or spatial coverage, which may not be suitable for longer-term or system-wide monitoring approaches (Tolimieri et al. 2008; Lochead et al. 2023). Historical data sets provide examples of limited approaches taken as pilot studies (Starr et al. 2022) that may or may not translate to a system-wide approach.

The initial survey tools may also become outdated, or sampling tools may break down and require replacement or updating. This is common in ROV and underwater image-based surveys, as the technology is continually improving (e.g., Mallet and Pelletier 2014). Many of these technological improvements allow for better or more efficient data collection, such as transitioning from paired lasers to stereo-images or AI-assisted image analysis. Ongoing surveys should be able to take advantage of new technologies and efficiencies as they become available. Inevitably, "technological creep" will occur in any survey or data collection method. Even routine component replacements, such as improved ROV tracking or higher quality cameras, will introduce changes.

The main goal should be to maintain the same or at least compatible data streams from historical and ongoing data collections, ensuring that historical data remains useful in ongoing time series. For example, ROV surveys should be maintained and expanded to maximize long-term data series, as they provide the best data to answer objectives 1-4. To facilitate comparison, direct evaluations between ROV and RUVS (unbaited and baited) and/or drop cameras can be conducted. This calibration allows these potentially more cost-effective methods to supplement or complement ROV surveys at other sites.

3.2.2 Survey Tools and Methods

There are several ways to ensure ongoing data streams remain compatible or complementary to historical data. One common method is to intercalibrate changes in survey tools and methods by overlapping old and new techniques for a year or two, or by setting up experimental intercalibrations (Kingsley et al. 2008; De Robertis and Wilson 2011). This approach is recommended as the best way to maintain continuity of data streams across changes in sampling tools. However, such intercalibrations are rarely implemented. In some cases, this is because equipment breaks down and needs to be replaced immediately, which prevents intercalibration from being performed. But more frequently, these experiments are not conducted due to their costly nature. Calibrations essentially require funding for two (at least partial) surveys within a single funding cycle. Additionally, the sample sizes needed for meaningful comparisons can be prohibitively large (Thiess et al. 2018).

An alternative approach is to ensure that survey tools provide complementary data, or at least somewhat complementary data (Nephin et al. 2023). If the output data is similar, modeling techniques can be used to overcome the absence of intercalibration. Each tool and method has its own inherent biases, which can be addressed using hierarchical models that allow for different "catch efficiencies."

For example, spatial point process models can integrate observations from different platforms (with different catch efficiency) into a single analysis. However, these types of models often require complex inference methods, resulting in a capability overhead (e.g., Thorson et al. 2013; Gruss and Thorson 2019).

A key challenge in this context is obtaining reliable estimates of survey effort, defined as survey area per unit time. This challenge is compounded by potential avoidance (or attraction) behaviors across different observation platforms. These issues influence the catch efficiency of different gear types and can make it difficult to distinguish between gear-specific effects and genuine spatio-temporal trends. Hence, experimental intercalibration among tools and methods should be done whenever possible. When experimental cross-validation is not possible, statistical methods must be used to demonstrate either comparable or consistently varying information capability across different survey approaches.

3.2.3 Sampling Designs

Most statistical sampling designs that output the same measure (e.g. density across an area) are complementary and can be combined. If data or spatial coverage differs, one approach is to address this through a simulation study. For example Gemmell et al. (in press) compared two sampling designs (one effective and one ineffective) to determine their respective biases. Similarly, examining sources of bias in estimates can provide insight into potential solutions for estimating relative abundance of fish species (e.g., Kotwicki and Ono 2019)

As mentioned in section 3.1.1, a selection (sub-sample) of the existing index sites with long data series could be maintained and resampled using the same methodology to ensure year-to-year or multi-annual comparability. This can be integrated into a rotating-panel, randomized, stratified design that balances MPA and non-MPA sites among other important covariates such as depth, habitat size and/or type and previous fishing effort. These legacy sites can be incorporated into spatially-balanced designs (even if these sites were not spatially balanced), allowing historical locations to be integrated into new designs, thereby maintaining and extending time series of observations (Foster et al. 2017).

3.2.4 Analytical Approaches

There are many options for modeling approaches that can help to integrate different historical and modern data points. As this is a common problem, there is typically an analytical approach to be found that allows at least some combination of historical and modern data. For example, Bayesian methods have been used to combine Indigenous Traditional Knowledge (ITK) and trawl survey data.

Spatial point process models should be able to incorporate legacy data provided that survey effort is recorded, thus allowing counts to be standardized per unit of survey effort. However, standardizing survey effort across some platforms may prove challenging. For instance, the area surveyed by BRUVs remains uncertain (Harvey et al. 2011), making it difficult to integrate BRUV observations (typically measured in MaxN/hr) with observations from platforms such as AUVs or ROVs (which are usually measured in abundance or density per hour).

3.3 WHAT EMERGING TECHNOLOGIES AND INNOVATIVE ANALYTICAL APPROACHES FOR MONITORING MID-DEPTH HABITATS COULD POTENTIALLY COMPLEMENT OR SUBSTITUTE FOR THE APPROACHES RECOMMENDED?

The TEP has identified several areas and activities in the MPA monitoring program that are likely to be impacted by imminent technological advancements and the use of Artificial Intelligence (AI) and Machine Learning (ML). While specific examples are listed in Table 1, the rapid emergence of AI makes it impossible to create a comprehensive inventory of options. As much as practicable, MPA network managers should investigate, experiment with, and invest in technologies that have the potential to increase efficiency in data capture, processing and analysis. These may include automated image processing algorithms, advanced statistical packages and autonomous sampling platforms. However, such efforts should not come at the expense of core monitoring and information dissemination efforts but should be funded through parallel innovation funds.

The most immediate probable impacts on MPA monitoring include continued advancements and cost reduction in eDNA approaches, which have the potential to revolutionize certain aspects of monitoring, such as species composition evaluation, detection of rare or cryptic species and broad ecosystem assessments. Ongoing miniaturization and cost reduction of instruments, particularly underwater cameras, are also likely to impact future efficiencies.

The rapid progression of AUV capabilities could reduce reliance on ROVs and improve cost efficiency for surveying MPAs, with added AI/ML capacities opening the door to autonomous adaptive sampling designs. Components of MPA monitoring that rely on video review are likely to benefit in the near term from AI/ML-based automated image analysis. However, these approaches should still include a human element (human-in-the-loop) to ensure stability and reliability of outputs, such as fish detection and species classification.

The TEP cautions that incorporating technological improvements can complicate survey standardization and the comparability of results over time. Care must be taken when adopting new survey tools and analysis methods to preserve the ability to assess changes on decadal scales.

See Table 1 on next page.

Table 1.

	Emerging monitoring approaches and how they complement or substitute for recommended approaches
Survey tools and methods	· Autonomous robotic technologies employing AI/ML for navigation or adaptive sampling · Tagging studies with smaller, more precise tags · Environmental DNA (eDNA) · Continued reduction in camera instrumentation size and cost and increased capability may allow increased capacity for the same level of effort or longer sampling times.
Sampling designs (temporal and spatial)	· Persistent monitoring approaches that operate year-round (e.g. acoustic moorings, long-duration cameras) to extend sampling windows for surveys. These approaches address questions about the representativeness of field sampling relative to year-round conditions at a site. · Spatially-balanced designs are not new or emerging but their application to the Californian MPA monitoring program may be novel. · Innovation is great, stability is important. New technologies must be incorporated judiciously to avoid biasing time series data. If approaches change substantially, an intercalibration experiment may be necessary. When considering density estimation, maintaining the same core methodology and data outputs when changing/upgrading gear is important. For example, if switching from an ROV to an AUV platform, both should implement absolute areal density measurement estimates using transect methods to ensure consistency.
Analytical approaches	· Increased use of simulation approaches in hypothesis testing, while not particularly new, is being applied in novel ways. For example, simulations can be used to determine the number of samples needed or to identify the best sampling strategy for estimating changes in size over years. They can also be employed to test sampling designs based on SDM outputs (Gemmell study). · Automated image review has the potential to greatly reduce processing cost. It can also be semi-automated to increase analyst efficiency. · AI/ML techniques for habitat and species distribution models. Reef cloud (https://reefcloud.ai/) for example is pioneering AI methods to automate the production of coral reef composition data from imagery.

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4.CONCLUSIONS

In the preceding sections, the TEP has identified a number of recommendations, ranging from specific (e.g., using a randomized sampling design to allocate effort) to more general (e.g., using numerical and statistical approaches to reconcile different sources of data). A key conclusion of the TEP is that, regardless of the tools used, it is important to have data collection methods that can address specific monitoring objectives and that there are multiple options available to meet the current objectives.

Over the last decade, mid-depth rocky reef monitoring programs have collected a large amount of valid and valuable data. For many combinations of focal species and MPA, this data has demonstrated a clear MPA effect which in some cases may have reached a theoretically supported limit. However, it is important to note that this data has been collected at a (spatially) limited number of sites inside and outside MPAs, using a preferential rather than randomized approach. Therefore, it may not be representative of the mid-depth habitats that occur more broadly across the MPA network.

The TEP recognizes the importance of maintaining the current time series and using it efficiently moving forward. This involves:

1. Maintaining the consistent types of data generated to date;
2. Adding new data where appropriate and where monitoring gaps exist;
3. Using model-based estimates, simulations and statistical techniques to help connect historical and ongoing data collections and test the cost efficiency of alternative sampling designs and methods.

Given the value of the existing time series, the management questions posed by state management agencies, the previous preferential sampling design and the possibility of potentially comparable, lower-cost survey methods, the TEP notes that a strong case can be made for:

1. Continuation of the existing index sites;
2. Transitioning toward a stratified random design;
3. Complementing the current use of mobile ROV platforms with stationary baited and/or unbaited RUVs.

The TEP emphasizes that these recommendations should be considered jointly but are also conscious of the cost implications. Given the anticipated annual budget for monitoring mid-depth rocky reef habitats in the MPA Network , implementing all of these recommendations will likely mean that only a subset of the existing index sites can be continued in any given year, allowing some existing mobile effort to be re-allocated to new (stratified randomly allocated) sites and additional stationary effort to be allocated in a similar manner. Returning to existing index sites on a multi-annual basis may allow a greater number of these sites to be continued without jeopardizing the utility of the overall data set.

The TEP notes that future developments, such as improvements in AUV technology, may provide opportunities to improve the cost efficiency of sampling efforts for both mobile and stationary observation platforms. However, any decision to replace the existing ROV platform with an alternative should be taken carefully, ideally supported by an intercalibration experiment and accompanied by a clear understanding of the statistical methods that will ensure continuity of the time series gathered to date.

Future analyses should also seek to compare the consistency and relative precision of estimators derived from mobile and stationary observation platforms and identify discrepancies that may occur due to factors such as avoidance or rarity. These analyses should help guide decisions regarding the allocation of the total survey effort across the two types of observation methods. Additionally, they may prove useful when considering potential efficiencies that could be gained by moving to spatially-balanced designs.

The TEP also recommends that future plans should include the development of an adequate database to house the data generated from funded projects. This database should allow for storage of metadata, derived data and raw data (such as images), and ideally enable all data and data products to meet the FAIR principles for research data management.

Finally, the TEP takes this opportunity to support the decadal evaluation established under the Californian MPA regional planning process. This evaluation provides a process for periodic review, reflection, comparison and the validation that data streams continue to meet state management requirements.

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5.CITATIONS

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Table A1

	Broad ecosystem-scale species composition	Abundance, Density, and Biomass metrics	Length composition	In situ habitat characterization
Survey tools and methods	·Stereo Remotely Operated Vehicle (s-ROV) ·Video landers (e.g., benthic observation survey system [BOSS]) ·Stereo-Baited Remote Underwater Video Stations (s-BRUVS) ·Unbaited stereo stationary cameras (long duration) ·Small Autonomous Underwater Vehicles (AUVs) (e.g., boxfish) ·Lowered drift/tow camera ·Community Temperature Index (CTI)	·s-ROV ·Video landers ·s-BRUVS (relative abundance only) ·Lowered drift/tow camera (no bottom contact) ·Small AUV (e.g., boxfish) ·Acoustics for pelagic species, with target verification via trawl ·Seafloor mounted acoustics to observe seasonal patterns. ·Towed camera sled (Kodiak work) for soft bottom to ensure target species are not using unexpected habitats	·s-ROV ·Landers ·s-BRUVS ·Hook-and-line ·non-baited, long duration stereo cameras ·other hands on (i.e., extractive) data when possible	·s-ROV ·Video Landers ·s-BRUVS ·AUV mapping with photomosaic capacity ·Multibeam echosounder (MBES), and backscatter analysis for bathymetry and benthic composition ·Side scan sonar ·Single/Split beam Acoustics ·Tagging studies ·Species distribution modeling
Sampling designs (temporal and spatial)	·Spatially balanced designs can be more efficient for any response variable that exhibits spatial autocorrelation (SAC) ·Model-based designs ·Stratified random, with strata based on habitat metrics (e.g., depth, rugosity, benthic hardness) ·Balanced effort across seasons ·Prioritization of sites based on ecological/management value SPATIAL ·Bioregion - 3 levels (N, C, S) - but could be continuous by latitude ·Protection - 2 levels (Inside, Outside of MPA) ·Substrate type - 4 levels (Hard, Hard Mixed, Soft, Soft Mixed) - with final categories depending on habtiat modeling ·Depth - could be continuous or in bins TEMPORAL ·Annual (Tier 1 sites) ·Multi-annual (Other sites)	·Stratified random ·Prioritize primary species of concern without spending too much time trying to flesh out data for rare species ·Ensure reference sites are representative of “background” or “target” environment, as appropriate ·Habitat stratification - effort allocation based on historic variability within strata	·Stratified random, with varying methods (cameras, hook-and-line, BRUV, etc.) to ensure bait, etc. are not introducing bias ·Will need to exclude certain life stages due to habitat use and/or detectability, then clearly state this shortcoming ·Should include stereo - analysis of range (from camera) dependence of length ·For partial images of target species, identify isometric scaling relationships to maximize ability to obtain total length ·Ensure sufficient sampling per species, need to ensure representativeness over time and space, including depth	·Likely remote sensing supplemented by location-specific validation ·May need to plan for deep-water deployments to obtain water quality data (temp, O2, etc.) rather than relying on surface readings ·For overall habitat mapping, stratified random again, but perhaps stratified by backscatter ·Scale is important (on the level of individual fish). Different than population perhaps. ·Stratification by habitat important ·Seasonality of measurements ·A systematic, transect-based mobile survey to cover all habitat types ·Spatially balanced stratified sample designs can be more efficient than stratified random
Analytical approaches	·Species Richness ·Shannon Diversity Index ·Evaluation of species-specific SAC ·Geostatistical models such as the Poisson point process models described by Perkins et al. (2020) for model-based analysis (could also be used in model-based survey design) ·Control chart methods ·Dashboard type methods ·FAIR data products ·Tracking key biodiversity quantities over time (i. e., simply trend analysis) ·Ecosystem models and/or dynamic factor analysis (DFA) or other approaches currently used/developed for ecosystem indicators ·Multivariate models (NMDS, SIMPER) to describe community structure and relationships	·ANOVA, PERMANOVA using desing based-estimators - check that model assumptions are met ·Model based estimation methods (sdmTMB, VAST) that can supplement Design Based estimates ·Stationary gears can use established MaxN or mean count from video or use volumetric density approaches for absolute abundance ·Condition assessments by identifying (either empirically or via expert judgment) quantitative definition of “good” versus “poor” condition for key indicators in each reserve; ·Control chart methods ·Dashboard type methods	·Length frequency distributions and growth curves ·Proportions above maturity ·Froese 3 indicators ·Percent above maturity size ·Percent within optimum length ·Percent of megaspawners ·Condition assessments ·Age, fecundity ·Control chart methods ·Dashboard type methods	·High resolution maps ·Species distributions models ·Validation via visual survey tools (e.g., ROV, AUV) ·Individual Based Modeling ·Coastal and Marine Ecological Classification Standard (CMECS) marine classification system ·Artifical intelligence and/or machine learning (AI/ML) approach for habitat classification ·Bayesian multinomial habitat models

Table A2

Survey Tools and Methods

	Utility (i.e., What are the strengths and limitations of this tool/method?)	Effectiveness (e.g., accuracy, repeatability)	Cost considerations (e.g., infrastructure, personnel, logistical support)	Complementary nature (i.e., Does this tool/method address limitations of other tools/methods?)	To what degree does this tool/method address each of the four monitoring priorities?
ROV	STRENGTHS • No bottom time limit • High number of replicates. • Video library can be revisited • Not consumptive or disruptive • Collect species and habitat data simultaneously • Variable payload to carry cameras, sonars, CTDs, Niskin bottles for eDNA LIMITATIONS • Cost and time to train pilots and operate • Logistical challenges with access to sites and boat operation • Video analysis time and expense • Biased against detection of small and/or cryptic species • Limited by water clarity • Selectivity can be hard to estimate without expensive validation	• ROV transects produce replicable and accurate abundance, density and biomass metrics per unit area across larger areas than other methods (lander, BRUVs) • Standardized methodology well established and employed in a variety of habitats worldwide • Established track record for effective data collection • Combined survey of fish and benthos in single deployment	• HIGH investment in ROV equipment • HIGH ship operational cost • HIGH ROV pilot cost • HIGH maintenance costs • Lower risk relative to manned submersibles • Area sampled is smaller than AUVs, etc. • Time intensive, but can provide a huge amount of data and videos that can be post-processed in various ways • Video processing is extensive unless trained AI is used, and that also needs cross-check and validation/supervision	• Works best in complex habitat (ROV) and moderately complex (sled) • Not best option for flats	• It addresses all four priorities to some extent. This method is good for 1 once sufficient data is collected, is best for 2 and 3, and supplements MBES for 4.
AUV (small and large)	STRENGTHS • Higher resolution • (small AUV) Newest technology, removes human operators and constant vessel support • (small AUV) Some equipment (e.g. boxfish) can charge/download for persistent unmanned deployments (probably not applicable here) • (large AUV) Established track record for rocky habitat work LIMITATIONS • Lower area covered • Higher costs • (small AUV) Higher operational risk to gear. Possible vehicle avoidance issues are similar to ROV/large AUV, possibly less due to smaller sized platform • (large AUV) High operational complexity and intermediate cost • (large AUV) Requires attendant vessel, more complex deployment and retrieval	• Potential endurance issues, reduced operating time compared with ROV resulting in smaller area sampled • (small AUV) Similar in operation to ROV, can use ROV methodology, while potentially being smaller and without accompanying vessel effect • Current iterations primarily use a down facing cameras, more limited sampling domain	• (small AUV) Very high initial cost and high expertise for setup, but less for operations • (small AUV) Potentially lower vessel costs, depending on endurance, possibility of docking setup, etc. • (large AUV) Requires a high initial investment, maintenance and specialized crew similar to the ROV. This is essentially an untethered ROV. • Full spectrum of types, sizes, varying technologies of AUVs	• It complements biological surveys • (small AUV) Shares a lot with other AUV ROV platforms, great for spatial coverage, should provide similar data to existing ROV based time series • (large AUV) Similar to the ROV, with possibly greater risk profile	• (small AUV) As with the ROV/large AUV, while species composition and length estimation are achievable, the real strength is in spatial coverage, abundance/density estimation, habitat characterization. • (large AUV) Habitat assessment is the real strength of this approach. It is better suited for benthic and epibenthic biota.

Stereo BRUVS	STRENGTHS ● Lower cost ● Replicable and comparable to other global studies ● Can deploy multiple units from the same vessel at the same time LIMITATIONS ● Abundance limited to MaxN (no density for now compared to ROV) ● Limited biomass estimations ● Biased towards carnivore fish, no attraction by inverts (but can be recorded in background field of view) ● Video analysis time and cost ● With multiple units with line to the surface, requires line management ● Very localized, but can stack up points to validate habitat, etc.	● Very effective for carnivore fish, but not as good for other fish, macro invertebrates and benthos compared to ROV ● Depletion bias as bait is consumed ● Small area sampled relative to some other methods (ROV, sled) ● Captures localized snapshots that need to be stacked up to have utility ● Very limited bottom time	● LOW investment in BRUVS ● LOW ship operational costs ● LOW maintenance costs ● Higher data density (but potentially biased), so lower effort. ● Video processing is extensive unless using trained AI, and that also needs cross-check and validation/supervision	● Can complement other methodologies to sample macroinvertebrates and benthos (i.e. landers, towed camera surveys) ● Cost-efficient because platforms are already being deployed to monitor other indicators. Can potentially reduce or eliminate need for drop cameras, particularly if rear-facing camera is added to stereo BRUVs frame. ● Works best in complex habitat but can also be used for flats/low relief. ● Can be used for fish assessments, habitat assessments,or just validation of remote sensing. ● Any type of stereo underwater imaging tool that can produce metrics of count and effort (area sampled) coupled with something else (eDNA) to confirm rare/avoidance behavior.	● Adequate for 2, 3, and 4 on limited basis. ● Not great for 1 because it misses non-predator, non-hungry, skittish species (can be good for many target spp though) and there is a depletion effect as bait is used up
Long duration stationary unbaited stereo cameras	STRENGTHS ● Unbiased (for the most part), except fish size and cryptics ● Easy to target (e.g. habitat) ● Can deploy multiple units from the same vessel at the same time LIMITATIONS ● Need large sample sizes (small area sampled) ● Often taking pictures of empty water ● Image analysis time ● Not so easy to get density ● With multiple units with line to the surface, requires line management ● Abundance limited to MaxN (density may be able to be estimated with range analyses)	● Can be repeated (BRUV surveys used for stock assessment in SE and PI, Australia, others . Canada exploring for monitoring MPAs) ● Accurate for the species viewed ● Easy to get large sample size	● Relatively cheap and easy to build and operate, but few off-the-shelf options ● Requires more soak time/video footage/image stills/analysis since there is no bait; more effort needed. Longer soak time can increase encounter rates for roving fish. ● All frames need annotation to get volumetric density. ● Requires more technical setup compared to baited (can't use simple gopro setup); ● Cost in between BRUV and ROV	● Could complement other image based methods ● Not as good for species that don't move ● Couple with ROV potentially to reduce soak time ● Any type of stereo underwater imaging tool that can produce metrics of count and effort (area sampled) coupled with something else (eDNA) to confirm rare/avoidance behavior	● can get 1, 2, 3, 4 (but need lots of samples); lots of image processing required for #2
Video Landers	STRENGTHS ● Lower cost, short duration ● Unbaited which removes issues with plumes ● Samples a larger area than BRUVS LIMITATIONS ● Density estimates are possible with volumetric analysis of stereo images (MaxN is also possible for comparisons with BRUV's) ● Limited biomass estimations ● Video analysis ● Lower fish density without bait	● Effective for fish and benthos depending on the camera set-up (needs to be stereo to be effective), but much less area covered than ROV. Is essentially quadrat sampling ● With stereo, could estimate density	● MEDIUM investment in equipment ($30 - 50k) ● MEDIUM ship operational costs ● MEDIUM maintenance costs ●Can use multiple cameras to try to get 360 degrees, but can be challenging to light evenly	● Could be used to spot check ROV methods or "scout" new areas ● Could be combined with eDNA water samplers to obtain samples at depth for cross-validation of visual surveys	● It addresses all four, but on a more limited basis ● Since your sample area is so small, the number of samples needed to estimate these things is probably cost-prohibitive (for drop cameras, less so with the BOSS)

Lowered drift/tow camera (no bottom contact)	STRENGTHS ● Non-lethal ● Can be cheap ● Simple, low requirements ● Very repeatable ● Easy to get density/abundance ● Direct real time feedback LIMITATIONS ● Tradeoff between goals (nice pictures/good tracking/brute force survey) ● Low maneuverability, difficult to control position in the water ● Avoidance behavior for some species ● Dependent on vessel and current for heading	● Provides generally similar transect type data as ROV/AUV approaches, but less able to sample specific directions and lower quality data due to altitude fluctuations ● Possible higher operational risk due to entanglement with the sea floor in high relief areas ● Possibly less fish reactions compared to ROV/large AUV due to smaller size	● Image analysis costs/time ● Need to have some technical expertise on staff or contracted ● More attainable than in the past ● HIGH cost for capital, but can be manageable ● LOW initial system cost ● LOW maintenance cost low ● Technical expertise lower than ROV and AUV ● Vessel time similar to ROV, potentially smaller class vessel can be used	● Similar to ROV/AUV	● Good method for priorities 2-4 ● Bias against some cryptic or species with avoidance, so does not entirely capture #1 ● Similar to the ROV/AUV, with perhaps less precision for fish density estimation as the transect width ("swath") is more complex due to fluctuation platform altitude.
Multi-beam and Side scan acoustics	STRENGTHS ● Particularly effective in deeper environments as swath width increases with depth. Hence can potentially map large areas cost effectively ● Excellent for habitat characterization and pelagic fish (different frequencies and configurations) LIMITATIONS ● Lower resolution for habitat mapping ● Needs careful calibration ● Need a vessel with proper equipment and schedule availability. Vessel is captive during deployment ● Costly, intensive processing	● Can map larger areas, but with a lower resolution. ● Has been used in successfully in Australia to map continental shelf and shallow reef habitats ● Effective when calibrated. ● Highly repeatable and filterable	● Gear, calibration, and image processing can be costly. ● Time and ship intensive methods	● Complements biological surveys ● Can in theory map entire shelf habitats with backscatter - still requires a model to translate backscatter signal into habitat category but data gathered over much larger area than visual methods. ● Defines strata. ● Broad-scale evaluation that can be refined by other tools for modeling and population estimation (based on strata)	● Best for 4 and somewhat for 1, not suited for 2 and 3, except as it informs modeling
Single beam/split beam acoustics	STRENGTHS ● With calibration, capable of deriving density ● Large volume sampled and range (100s of m away) ● Established techniques for fish population estimation LIMITATIONS ● Limited close to sea floor (acoustic dead zone) ● Requires independent target validation (from cameras or trawls) for full abundance estimation	● This tool is specifically targeted at pelagic/semi-pelagic fish aggregations, a secondary MPA monitoring objective ● Effective in certain situations, may be more useful as a broad system index ● Additional frequencies would allow separation of zooplankton from fish backscatter ● Would provide insight into pelagic and semi-pelagic fish presence over MPA grounds, useful for generic comparisons	● High initial cost of equipment, unless a chartered vessel already is instrumented ● A systematic set of transects would add vessel time, but due to the small nature of the MPA grounds, it would not be substantial ● Requires expertise in analysis to generate useful data products	● This data stream could be complimentary in several ways by adding information on the presence and density of semi-pelagic rockfish or other fish and in addressing potential limitations in vertical sampling domain of most of the camera platforms	● Best for non-specific fish/plankton density ● Generally not very useful for habitat assessment (possible exceptions for classification) ● Not useful for size/species composition

eDNA	STRENGTHS ● Non-consumptive/invasive ● Relatively inexpensive to process ● Not visually-based, so has a different set of biases from other tools proposed ● Will detect small/cryptic species. May detect rare species LIMITATIONS ● Variability in dispersion and degradation of material not well known on a species-specific basis ● Signal strength is dependent on environmental parameters ● Data resolution depends on flow patterns (which need to be modeled)	● Can be effective at broad scale characterization of community without intense video review time, etc. ● Results will differ with sampling depth, so samples must be taken from near the bottom (but can also be used for pelagic species)	● Comparatively inexpensive for a large return on detections ● Processing is getting relatively inexpensive but costs MEDIUM to gear up	● Complementary to other tools, and addresses biases of visual survey methods ● Hard to cross-validate	● Useful for 1 and 2, but not 3 or 4
Hook-and-line	STRENGTHS ● Samples in hand for identification and measurement ● Information on the length/height of individual species is fundamental to almost all of the ecological indicators of MPA performance ● The data used to derive abundance, density, and biomass indicators can also be used to estimate biomass (based on length-weight relationships) or abundance by maturity status (based on length at maturity relationships) that can reflect differences across depths or bioregions. LIMITATIONS ● Biased to larger/more predatory fish ● Invasive, with some associated mortality	● Can be an excellent outreach tool/method or citizen science opportunity ● Can provide additional biodata other methods don't provide (age structures, fin clips, fecundity, species validation)	● Trade-off between, take/mortality and education and outreach value for public engagement (safe handling, descending devices, etc.) ● Minimal infrastructure and investment ● Less lab processing, basically walk off the boat with data	● Augments observation (image) data by allowing biological samples to be taken	● Hard to get density/biomass without some assumptions ● Likely the best for 3 and doesn't get 1 or 4

Sampling Designs

	Utility (i.e., What are the strengths and limitations of this sampling design?)	Effectiveness (e.g., accuracy, repeatability)	Cost considerations (e.g., infrastructure, personnel, logistical support)	Complementary nature (i.e., Does this sampling design address limitations of other sampling designs?)	To what degree does this sampling design address each of the four monitoring priorities?
Stratified (by habitat) random station/transect assignment	STRENGTHS • Unbiased to most metrics • Mimics standard approach to full population surveying for large areas • Effort allocation per stratum can be tailored according to known fish densities in different habitats • If representative, station count can be comparatively lower and still have good variance • Allows separation of effort and stats across strata LIMITATIONS • Requires high quality habitat maps identifying all relevant types • Can require large number of samples (depending on how many strata)	• One of the best approaches for reducing variance detecting time trends, accurate and repeatable, with lowest CV • Can be used to provide a species specific abundance / population structure for each MPA • Need to repeat design, but not specific stations • Strata can be refined year to year, but total estimates still comparable if survey area remains static	• Sample size drives the cost and support needed • Higher effort may be required, depending on the size of the MPA. • Vessel would need to cover more ground carry out more deployments/retrieval than an index area approach • Cheaper than systematic, usually • Random stations are not efficient to visit without careful planning. Inconvenient stations shouldn't be ignored.	• This approach would be complementary to an index site approach, but not with other stratification schemes • Serves as core design and is augmented by others	• Unbiased for population level abundance, size, diversity. With an SDM, can have limited coverage of some habitats where sample sizes are smaller. • This approach would meet all goals, potentially with lowest uncertainty depending on survey gear used. Requires habitat characterization in advance to stratify well.
Seasonal (with stratified or repeat sampling)	• Retains a standard sampling design, but reduces variability due to site differences to focus on seasonal changes • Benthic species at least might not move much seasonally (except during spawning migrations).	• Easily repeated • Seasonality may affect quality or ease of sampling (e.g., summer is easiest to sample)	• Sample size drives the cost and support needed	• Can be performed once or twice in various seasons then used as a correction factor or model parameter for other estimates based on SRD	• Unbiased for population level abundance, size, diversity. With an SDM, can have limited coverage of some habitats where sample sizes are smaller.
index area (for comps through time)	STRENGTHS • If population abundance/structure is not required for the entire MPA, index sites provide a fixed, reduced effort base for comparisons on local density/abundance • Can be readily explainable to the public LIMITATIONS • Limitations include potential shifts of population within the MPA which could reduce representativeness of index, or even short term movements of fish in and out of the index area (eg daily, diel) • Can become biased over time, if sampling extractive • Can result in high variability if repeated transects are slightly dissimilar from year to year.	• Accuracy depends on consistency of habitat within the MPA and choice of index area. It may not include a representative set/similar ratio of all habitat types in MPA. Species have tight associations with habitat, thus index area would not accurately represent entire MPA • If effort is limited, index areas may be the only method of achieving goals of monitoring a larger number of MPAs • If purely passive monitoring, can be excellent. • Must validate representativeness with broader surveys periodically • Need to monitor environment to avoid misinterpretation that change is due to specific effect	• Likely lowest cost option • Could be implemented with any gear. • Size of index area can be tailored to available resources, but for comparability it should not change afterwards regardless of changes in resources.	• This approach can be included with other more comprehensive efforts. Potentially a full MPA survey can occur at larger intervals or different survey equipment than the index area • Can be integrated into stratified random, or supplement	• Good for all, with explicit understanding of regional variability and representativeness of index to broader picture • An index area can provide local site level abundance species and length compositions and habitat assessments (depending on gear used) but these would not be representative of the MPA

full MPA systematic	STRENGTHS ● Mimics standard fixed station surveys with equal effort in all areas ● Simple to design and may be simpler to execute depending on samping gear LIMITATIONS ● Possibly not as efficient (more sites with low fish densities sampled) possibly higher uncertainty than stratified designs	● Unbiased approach but possibly not as efficient (more sites with low fish densities sampled) possibly higher uncertainty than stratified designs ● Does not require any prior knowledge of habitats	● Higher effort may be required, depending on the size of the MPA. ● Vessel would need to cover more ground carry out more deployments/retrieval than an index area approach ● Similar effort allocation to stratified random sampling, but possibly less efficiency	● Not really compatible with another full area approach, densities would be comparable among different sampling grids or stratifications across years or MPA's	● This approach would meet all goals, potentially with higher uncertainty than stratification depending on survey gear used.
Model-based, spatially balanced designs (perhaps within a rotating panel set-up)	STRENGTHS ● Spatial balance has shown to increase sample efficiency. ● Model based survey design leads naturally to model based analysis of MPA performance and also facilitates power analysis by simulation. Note if implemented within a Bayesian framework then posterior distribution of indicator metrics can be routinely updated LIMITATIONS ● At the moment these types of designs don't seem to be employed in the Californian MPA monitoring. ● Can lead to increased travel times (e.g. BRUVs), but this can to some extent be ameliorated with careful planning.	● Considered to be good practice in Australia. Spatially balanced designs now routinely implemented in commonwealth MPA surveys. Not so well adopted in state MPAs (reflects influence of NESP in Commonwealth waters)	● Can lead to increased travel times (e.g. BRUVs) which could increase survey costs. ● Some sample design costs (e.g. training in relevant concepts and software).	● Specifically addresses spatial auto-correlation (SAC) between sample sites - a well known phenomena that decreases the efficiency of a survey and invalidates the assumptions of many common statistical tests (e.g. ANOVA)	● Relevant to all four monitoring priorities
Validation	STRENGTHS ● Helps to ensure the model is working ● Microhabitats can be crucial to certain species, so groundtruthing is crucial. LIMITATIONS ● May need dedicated validation studies for SDMs that are aside from population estimation surveys.	● Doesn't need to be repeated, but can be as desired to prove long-term stability of estimates	● Can be piecework amenable to contractors or academics	● Ensures stratified random design is hitting what it should in a defensible way ● Could be used for developing correction factors	● Good for 4, depending on scale, and used to cross-check others as needed on a very local basis

Analytical Approaches

	Utility (i.e., What are the strengths and limitations of this analytical approach?)	Effectiveness (e.g., accuracy, repeatability)	Cost considerations (e.g., infrastructure, personnel, logistical support)	Complementary nature (i.e., Does this analytical approach address limitations of other analytical approaches?)	To what degree does this analytical approach address each of the four monitoring priorities?
Species Richness (e.g. Shannon Diversity Index)	STRENGTHS • Simple, understandable metric LIMITATIONS • Often biased and incomplete. • Requires high sample sizes to detect rare species • Often difficult to interpret - see comments regarding functional diversity versus taxonomic diversity in Appendix E of MPA Monitoring Action Plan	• Relatively good "first cut" metric, but needs deeper analysis to be really useful	• LOW investment to use	• Relatively good "first cut" metric, but needs deeper analysis to be really useful	• Ok for 1, N/A for others
Condition assessments and control chart methods	STRENGTHS • Provide the basis for adaptive management (management responds when signal reaches pre-determined metric) • Clear communication of MPA outcomes • Power calculations for achieving quantitative outcomes • Control chart methods can be used to track the status and trend of indicators in relation to these conditions LIMITATIONS • Not currently used for Californian MPAs to power calculations for achieving quantitative outcomes	• This approach may be good practice – but may not be widely used	• Specifying quantitative condition metrics for all relevant indicators may be a difficult task - there could be reasonably cost-overhead associated with specifying these (e.g. expert workshops)	• Addresses a fundamental question: what are managers trying to achieve - e. g. is any improvement inside an MPA (relative to a control) good enough or should managers strive to reach a target for MPA performance?	• Relevant to broad ecosystem-scale species composition, abundance, density, and biomass metrics. • Relevant to length composition so long as quantitative condition metrics can be specified for each indicator
Ecosystem models and/or DFA or other approaches currently used/developed for ecosystem indicators	STRENGTHS • Can help to define linkages in the community (trophic) and can identify indicators that are useful for monitoring LIMITATIONS • Data-intensive and more complex	• Can be updated as new data come in, definitely repeatable and accurate	• Ecosystem models require a lot of information about trophic links to parameterize. In the best case scenario, these data are spatially explicit.	• Can be combined with other analyses	• These statistical techniques can be used to monitor changes and address 1-3

Multivariate models to describe community structure and relationships with specific habitat strata (e.g., Bray Curtis NMDS, SIMPER, etc)	STRENGTHS ● Can be used to correlate with environmental covariates, define assemblages, cluster into groups for more effective monitoring ● Complex, outputs are more accessible using graphical methods to reduce dimensionality (e.g. principal components analysis) LIMITATIONS ● Correlative in nature, can hard to interpret sometimes, may be driven by species/areas where you have more data	● Can be updated as new data come in ● Repeatable and accurate ● Captures base similarity and difference well, but can be thrown out of whack by rare species	● LOW cost ● Requires basic R package or PRIMER-E	● Can be combined with other analyses ● More complex, but more complete	● These statistical techniques can be used to monitor changes and address 1-3
Time series analysis (DSEM, DFA, etc.)	STRENGTHS ● Can be used to detect step changes ● Measure the strength of relationships ● Define drivers of change LIMITATIONS ● Correlative, hard to interpret	● Can be updated as new data come in, definitely repeatable and accurate	● LOW cost ● Easily implemented using packages such as R	● Complementary to other statistical approaches (such as indicator analysis and multivariate techniques). They should be used in tandem to answer related questions about trends over time.	● These statistical techniques can be used to monitor changes and address 1-3
Model-based estimation methods (sdmTMB, VAST, spatial point process models)	STRENGTHS ● State of the art/best practices for “count-based” indicators (e.g. number or density of fish). ● Flexible and accommodate many types of explanatory covariates (discrete and continuous) as well spatial correlation. ● Can be used to link data from different surveys, methods, etc in a straightforward way ● Can be used to create standardized indices of abundance (or other y variables). Becoming widely used, allow explicit use of positional data and estimation of spatial autocorrelation (both pros and cons to this) LIMITATIONS ● Require relatively advanced training and software, ● Requires a consistent survey methodology to meet model assumptions (e.g., constant mean-variance structure)	● Can be updated as new data come in, definitely repeatable and accurate ● Would be considered best practice for count-based observations	● Needs spatially explicit data ● Can generally be learned by most biologists ● LOW cost, potentially only for training, software and staff time, similar to other model-based analysis	● Complements design-based statistics ● Can be combined with more traditional SDM to improve inference ● Can address spatial structure in the data (through spatial covariance terms) and accommodate large range of potentially important covariates	● Can be used to address 1-4 ● Relevant to abundance and density metrics
Standard ROV density estimation	STRENGTHS ● Provides absolute areal density (with some “catchability”, e.g. behavioral bias, avoidance/attraction)	● Comparable across years and locations as long as protocols for estimation critical values are followed, even if different platforms are used ● Possible behavior bias due to reactivity to moving large lighted object	● Analysis requires full review of video data, possibly specialized software for annotations ● Experienced personnel needed for tracking individual fish and habitat classification	● By providing absolute density, this method is then comparable to all other approaches ● Well suited for infrequently encountered species with high site fidelity ● would complement well with image analysis of Stationary Cameras, using stereo density methods	● Data on species composition, size composition and density available from this approach, also suitable for habitat analyses

MaxN or mean count from video data on stationary platforms	STRENGTHS ● Conservative, easy to extract and accessible from most video data LIMITATIONS ● Biased data with complex relationship to true abundance, generally asymptotic (limited at high densities) ● Bait improves data density (increase in fish) but may introduce more bias in species composition	● Because there are potential biases in the relationship between true density and MaxN, greatest value is in a relative index, which can be compared amongst standardized equipment/deployment methods (e.g., bait) ● Baited systems will further depend on bait plume situations	● Easy to implement, simple annotation tools sufficient for video review ● Time effective in that not all of the data needs annotation	● This data is not really comparable to other sources, such as ROV areal density ● If used with bait, can result in higher number of individuals sighted than the ROV approach, without any avoidance reactions	● While size and species compositions can be extracted, potential biases make general inferences on density harder to make ● Not useful for habitat
Image analysis of stationary cameras, using stereo density methods	STRENGTHS ● Absolute volumetric density, comparable across camera systems, years, locations ● Unbiased, range compensated species composition LIMITATIONS ● requires calibrated stereo camera images	● As it provides absolute density, it is effective for estimating unbiased abundance when used without bait ● Repeatable and theoretically immune to issues due to changing camera gear, view angles, lighting	● This approach requires specialized software to extract ranges from all fish targets in view ● The annotation time is likely higher than MaxN, but the frequency of frame analysis can be set according to available resources	● This approach makes comparable estimates to areas density from mobile platforms, although sampling in the temporal domain rather than spatial ● Better suited for species that move around the survey area, as it increases the encounter rates with longer term deployments	● Data on species composition, size composition and density available from this approach, not really suitable for habitat
Length frequency distributions from stereo image analysis	STRENGTHS ● Primary method for evaluating MPA effects on population demographics LIMITATIONS ● Tracking mean size is the obvious choice, but can be impacted by large recruitment events. ● Lower precision than physical measurements ● Depends highly on stereo camera calibration/standardized methods	● The standard for non-lethal sizing of marine animals ● Uncertainty can be established though repeat measurements of individuals or known size targets	● In addition to specialized calibrated stereo camera systems, requires analytical software for manual measurements such as SEAGis, which can be expensive ● Intermediate level of proficiency and experience with analysists required	● Highly complementary with abundance estimation ● Local abundance can be used to derive more accurate MPA-wide mean sizes using density-weighted length averaging.	● Addresses #2
Species distributions models	STRENGTHS ● Effective at predicting important areas for species, groups of species, other variables ● Very easy to communicate to management and identify areas of concern (lots of good guidelines out there). ● Can give great results based on very little input (but data quality going in, relates to quality of output) ● Will need to use rugosity, slope, derivative of slope, etc. LIMITATIONS ● Often proxy variables are required ● Demonstrating variability is not always done/straightforward ● Need a fair amount of expertise ● Need adequate encounters over sufficient space	● Can be updated as new data come in, definitely repeatable and accurate ● Excellent, for scoping and statistical expansion	● A bit more technically demanding (more choices have to be made) ● Field is changing quite rapidly, so difficult to keep up with sometimes (e.g. joint species distribution modeling or archetypal species distribution modeling) ● Remotely sensed information can be used to generate quick and dirty models	● Can complement many other methods ● Can help transition from design-based to model-based at various levels. ● Can have iterations.	● Can be used to address 1-4, best for #4

Coastal and Marine Ecological Classification Standard (CMECS)	STRENGTHS • Widely used and originates from CA. LIMITATIONS • Varies widely by user and becomes challenging with more hierarchies	• Can be fairly standardized and repeatable when consistently applied	• Some automated GIS tools already exist to process remotely sensed data and produce CMECS layers • Layers may already exist for CA	• Habitat characterization provides the basis for many other analyses	• Addresses 4 only
AI/ML approach for habitat classification	STRENGTHS • Provides an alternative to CMECS LIMITATIONS • Consistent habitat classification can be challenging, AI/ML approach can be useful to remove human subjectivity	• Can be very effective and has known, stable accuracy and precision	• Requires expertise in AI/ML methods • Highly efficient (reduced human interaction required)	• Habitat characterization provides the basis for many other analyses	• Addresses 4 only
Bayesian multinomial habitat models	STRENGTHS • Relatively simple, adaptable (priors/posteriors coherently updated) and flexible model for categorical data types (such as habitat types). • Can capture uncertainty in habitat predictions • These have recently been developed in Australia to provide habitat maps with improved resolution - i.e. probability of habitat forming species or probability of different types of reef, rather than binomial reef/no-reef models previously employed. • Alternative to CMECS	• Used effectively in Australia	• Similar to other modeling approaches - capability overhead	• Improves over binomial model predictions (reef/non-reef)	• Relevant to all priorities, primarily addresses 4
Community temperature index	STRENGTHS • Well established index for measuring impact of climate change in terrestrial and marine ecosystems (e.g. https://www.nature.com/articles/nature16144#Sec4) LIMITATIONS • Developing a CTI for sessile inverts may not be possible due to the difficulty of scoring sessile invertebrate imagery to species level but may be possible for morpho-species.	• Effectiveness reflected by its incorporation into CBD Aichi Targets (Target 10) (https://dart.informea.org/taxonomy/term/3878)	• LOW cost if data required to construct the index is already collected - but may require recording of data beyond key indicator species	• Could be used to complement other signals of climate induced change	• Addresses 1
Use of AUV/BRUV/ROV background image to characterize habitat	STRENGTHS • can be used to help in the derivation of habitat distribution models (done successfully in AUS) or to train AI/ML algorithms for backscatter analysis LIMITATIONS • Field of view changes between platforms and can vary dramatically depending on visibility	• Effective if visibility is good	• LOW cost because platforms are already being deployed to monitor other indicators • Can potentially reduce or eliminate need for drop cameras - particularly if rear-facing camera is added to stereo BRUVs frame	• Can be used to produce (or ground truth) habitat distribution models along with similar observations from drop cameras etc. • Can be used to ground truth habitat maps produced by multibeam backscatter	• Addresses 4

Use of multibeam backscatter data to map seabed habitats	STRENGTHS ● Particularly effective in deeper environments as swath width increases with depth - hence can potentially map large areas cost effectively - does however need careful calibration ● Bathymetry metrics (BPI, VRM, curvature, slope, etc..) are derived as environmental covariates ● Multibeam backscatter data can be processed to provide hi-resolution seabed maps - this can be done “manually” (hand digitisation - as per NSW Marine Park mapping) or using AI/ML techniques (e.g. https://www. sciencedirect. com/science/article/pii/S0003682X2030 832X) LIMITATIONS ● Trade-off between swath width and resolution of map	● Has been used in successfully in Australia to map continental shelf and shallow reef habitats	● Can be relatively cost effective in deeper waters	● Can in theory map entire shelf habitats with backscatter - still requires a model to translate backscatter signal into habitat category but data gathered over much larger area than visual methods.	● Addresses 4
Dashboard type methods	STRENGTHS ● use dashboard type methods to help disseminate (among stakeholders and rights holders) and publicize the performance of each MPA	● Makes complex data and analytical outputs broadly accessible	● LOW cost	● Primarily a communication approach, not an analysis per se, but complements other analyses by communicating results	● Relevant to all priorities
FAIR data products	STRENGTHS ● Many Australian and international agencies are adopting a “whole of data product” perspective that sets minimum standards for all stages of a data product life-cycle (from sample design and data collection) to data analysis, curation and re-use (see for example: https://ardc.edu. au/resource/shared-analytic-framework-for-the-environment-safe-2-0/)	● The panel might consider these approaches with an eventual view to adopting similar approaches for data products that are developed by the Californian MPA monitoring program - this would facilitate national and international integration and analysis.	● Recommend that managers consider how the results from the Californian MPA monitoring program can be made broadly available to the scientific/management/stakeholder community with a particular emphasis on developing FAIR data products that enable larger-scale (regional, national, global) analysis.	● Complementary to others listed in the table	● Relevant to all as an overarching framework for environmental data collection, analysis curation and re-use