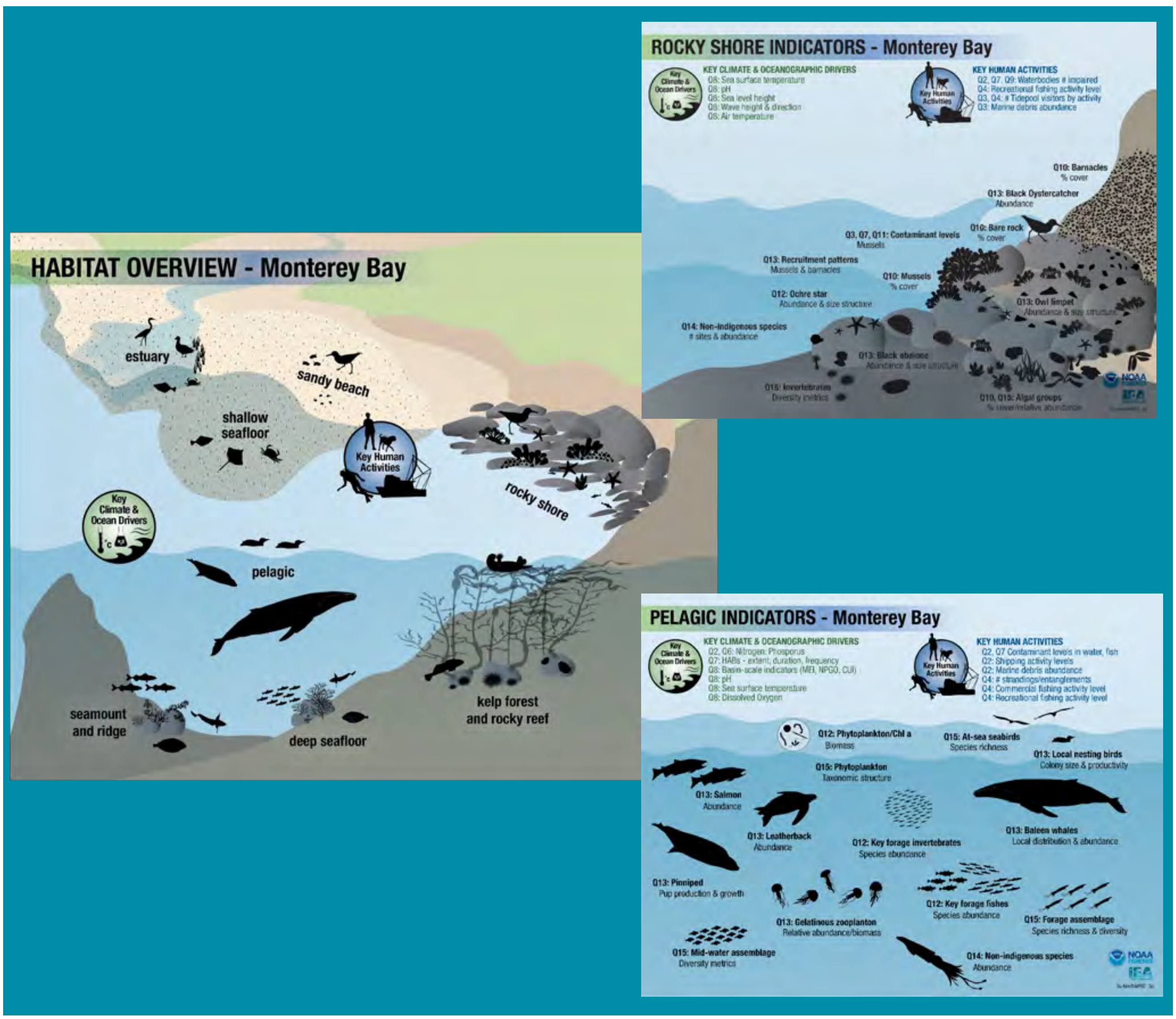
DEVELOPING SCIENCE-BASED INDICATOR PORTFOLIOS FOR NATIONAL MARINE SANCTUARY CONDITION REPORTS



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Monterey Bay National Marine Sanctuary habitat conceptual models. Image: Su Kim/NOAA

About the National Marine Sanctuaries Conservation Series

The Office of National Marine Sanctuaries, part of the National Oceanic and Atmospheric Administration, serves as the trustee for a system of underwater parks encompassing more than 620,000 square miles of ocean and Great Lakes waters. The 14 national marine sanctuaries and two marine national monuments within the National Marine Sanctuary System represent areas of America's ocean and Great Lakes environment that are of special national significance. Within their waters, giant humpback whales breed and calve their young, coral colonies flourish, and shipwrecks tell stories of our maritime history. Habitats include beautiful coral reefs, lush kelp forests, whale migration corridors, spectacular deep-sea canyons, and underwater archaeological sites. These special places also provide homes to thousands of unique or endangered species and are important to America's cultural heritage. Sites range in size from less than one square mile to more than 582,000 square miles, serve as natural classrooms and cherished recreational spots, and are home to valuable commercial industries.

Because of considerable differences in settings, resources, and threats, each marine sanctuary has a tailored management plan. Conservation, education, research, monitoring, and enforcement programs vary accordingly. The integration of these programs is fundamental to marine protected area management. The Marine Sanctuaries Conservation Series reflects and supports this integration by providing a forum for publication and discussion of the complex issues currently facing the sanctuary system. Topics of published reports vary substantially and may include descriptions of educational programs, discussions on resource management issues, and results of scientific research and monitoring projects. The series facilitates integration of natural sciences, socioeconomic and cultural sciences, education, and policy development to accomplish the diverse needs of NOAA's resource protection mandate. All publications are available on the Office of National Marine Sanctuaries website (https://www.sanctuaries.noaa.gov).

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Abstract

One of the initial challenges of ecosystem-based management centers on developing a balanced understanding of an ecosystem's "state," or the status and trends of driving forces, pressures, and resources. NOAA's Office of National Marine Sanctuaries has approached this challenge by developing condition reports, a tool that provides a standardized summary of resources, pressures, and driving forces in a sanctuary. Condition reports were developed to be site-specific, and rely heavily on expert opinion and the availability of locally relevant data. However, reviewers have called for a more transparent approach that relies more heavily on quantitative indicators derived from regional monitoring data, supplemented by the qualitative interpretations derived from expert opinion and local knowledge.

In this report, we describe the evolving collaboration between the Office of National Marine Sanctuaries' and NOAA Fisheries' scientists within the California Current Integrated Ecosystem Assessment (CCIEA) team to translate a national integrated ecosystem assessment (IEA) indicator screening and assessment framework to the scale of a sanctuary. Our goal was to create a process to identify and prioritize quantitative, habitat-based indicators of ecosystem status and trends to be incorporated into condition reports for Monterey Bay National Marine Sanctuary (MBNMS). This process compiled, categorized, and screened indicators, and resulted in indicator portfolios and conceptual models for each of the sanctuary's eight major habitat categories.

The indicator portfolios produced through this effort supported the 2015 partial update to the MBNMS condition report (ONMS 2015) and improved its transparency and rigor. Furthermore, the process highlighted a variety of useful lessons regarding: (1) the value of organizing an indicator selection framework around habitat categories; (2) using systematic methods to improve the consistency and repeatability of indicator selection; (3) using visual methods for improving the communication of key ecosystem concepts; (4) fostering broad multidisciplinary collaborations and uncovering regional data; and (5) how to highlight data gaps and future research priorities for management. These lessons were then applied in a subsequent effort at Channel Islands National Marine Sanctuary (CINMS) to select habitat-based indicators and develop conceptual models, which informed a substantially improved update to that sanctuary's condition report (ONMS 2018b). This document codifies the indicator development process in order to facilitate a more consistent approach to documenting the status and trends of driving forces, pressures, and resources in ecosystems throughout the ONMS network.

Key words

Ecosystem-based management, ecosystem, integrated ecosystem assessment (IEA), condition report, status, trends, indicator, habitat

Introduction

Ecosystem-based management is an integrated management approach that recognizes the full array of interactions within social-ecological systems (Figure 1; Levin et al. 2016), rather than considering single issues, species, sectors, or services in isolation (Arkema et al. 2006; Levin et al. 2009; Link and Browman 2014). Scientists and resource managers facing environmental challenges in coastal ecosystems see potential benefits to the ecosystem-based management approach because it emphasizes connectedness across sectors and taxa to manage water quality, species and habitats, economic and non-economic activities, conflicting uses, and the sustainability of resources. As a steward of U.S. coastal and marine ecosystems, which include coastal communities and their economies, the National Oceanic and Atmospheric Administration (NOAA) manages marine resources at a variety of spatial and temporal scales. The potential benefits of an ecosystem-based management approach have increasingly been embraced by the agency in recent years through various NOAA line offices, including the Office of National Marine Sanctuaries (ONMS; Lindholm and Pavia 2010) and NOAA National Marine Fisheries Service (NMFS or NOAA Fisheries; Levin et al. 2008, NOAA 2018).

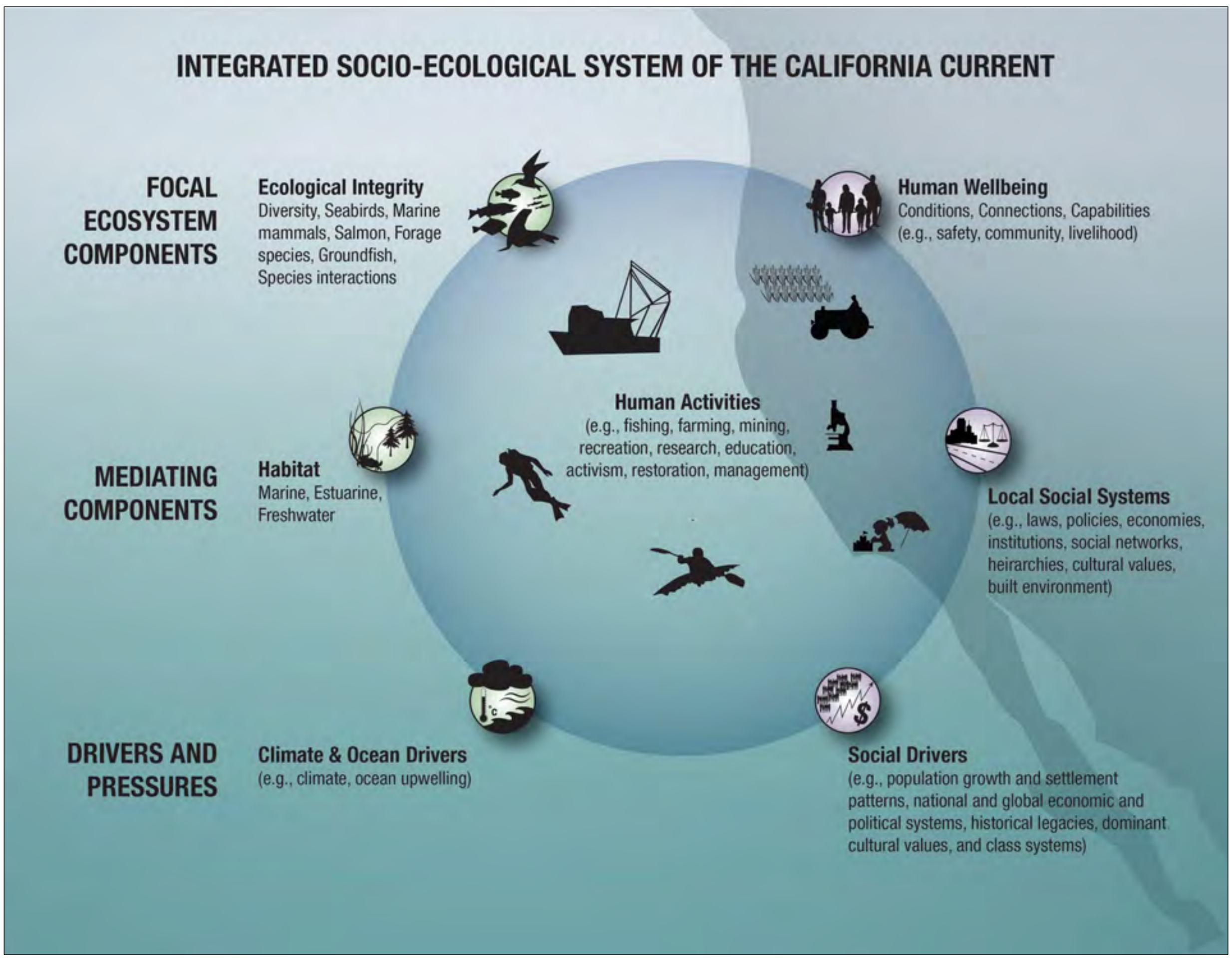

Figure 1. This conceptualization of the social-ecological system of the California Current along the U.S. West Coast shows broad biophysical and social drivers, potential mediating effects of habitat and local social systems, the management endpoints of ecological integrity and human well-being, and human activities as the central, tangible point of connection between social and ecological systems. Source: Levin et al. (2016).

NOAA's Office of National Marine Sanctuaries serves as the federal trustee for a system of 14 national marine sanctuaries and two marine national monuments in the ocean and Great Lakes. National marine sanctuaries are established for the general purpose of resource protection, research, education, and sustainable public use; this multifaceted purpose is well-aligned to the whole-system approach of ecosystem-based management. Sanctuary research and monitoring programs support management efforts by assessing changes in species and habitats. Regional monitoring information supports improved understanding of sanctuary ecosystems and helps managers address resource protection concerns. This information is used to inform decision-making, and is communicated to the public through a variety of public outreach, education, and engagement efforts.

Conditions within each sanctuary are influenced by a wide variety of ocean and climate drivers, ecological processes, human activities, and actions of adjacent and overlapping management and regulatory entities. Accurate knowledge of sanctuary conditions and the factors that affect those conditions therefore requires information from multiple disciplines at appropriate scales. One reporting tool developed by ONMS over the last decade is the sanctuary condition report, which provides a summary of resources in a sanctuary, pressures on those resources, the current condition and trends, and management responses to the pressures that threaten the integrity of the marine environment (ONMS 2018a). These reports have a standardized format and are structured around a set of 16 questions as a tool to report on the status and trends of human pressures, water quality, habitat, living resources, and maritime heritage resources. Although the structure of a condition report is standardized at the system level, the content of a report is site-specific; therefore, the information used to assess the status and trend for each question at a site is dependent on the availability of locally relevant data.

Sanctuary condition reports are a fairly new tool, and are completed at seven to 10 year intervals because of the significant amount of time and resources involved in the process. The first reports by Monterey Bay and Channel Islands national marine sanctuaries were published in 2009 (ONMS 2009a,b). These first reports relied heavily upon expert opinion to assess current resource status and recent trends in response to the standardized questions in the “state of the ecosystem” section of the report (Text Box 1). However, reviewers and both sanctuaries’ research activities panels[1] recommended that the condition report process would be improved by adopting a more transparent approach that included quantitative measures of ecosystem indicators derived from regional monitoring data, supplemented by qualitative interpretations derived from expert opinions and local knowledge.

Indicators represent key components in an ecosystem (i.e., biological, chemical, physical, social, or economic components) that serve as proxies for the condition of ecosystem attributes, such as habitat quality or community composition (Landres et al. 1988, Kurtz et al. 2001, Fleishman and Murphy 2009). While ecosystem attributes reflect the structure and function of the ecosystem, they are insufficiently specific or too logistically challenging to measure directly. Thus, indicators provide a practical means to measure changes in ecosystem attributes related to the

[1] A research activity panel is a working group of a Sanctuary Advisory Council. The panel is typically composed of representatives from regional research institutions and organizations. Administrative support of the research activity panel is provided by sanctuary staff.

achievement of management objectives, and can also be used for predicting ecosystem change and assessing risk.

Text Box 1. Sixteen standardized questions are used in the "state of sanctuary resources" section of Office of National Marine Sanctuaries condition reports (ONMS 2018a). This section serves as a summary of the current condition and recent trends of sanctuary resources within five categories: (1) human dimensions, (2) water, (3) habitat, (4) living resources, and (5) maritime heritage resources. Indicators were not developed for questions shaded gray.

Category: Human dimension

Q1. What are the states of influential human drivers and how are they changing?

Q2. What are the levels of human activities that may adversely influence water quality and how are they changing?

Q3. What are the levels of human activities that may adversely influence habitats and how are they changing?

Q4. What are the levels of human activities that may adversely influence living resources and how are they changing?

Q5. What are the levels of human activities that may adversely affect maritime heritage resources and how are they changing?

Category: Water quality

Q6. What is the eutrophic condition of sanctuary waters and how is it changing?

Q7. Do sanctuary waters pose risks to human health and how are they changing?

Q8. Have recent, accelerated changes in climate altered water conditions and how are they changing?

Q9. Are other stressors, individually or in combination, affecting water quality, and how are they changing?

Category: Habitat

Q10. What is the integrity of major habitat types and how are they changing?

Q11. What are contaminant concentrations in sanctuary habitats and how are they changing?

Category: Living resources

Q12. What is the status of keystone and foundation species and how is it changing?

Q13. What is the status of other key species and how is it changing?

Q14. What is the status of non-indigenous species and how is it changing?

Q15. What is the status of biodiversity and how is it changing?

Category: Maritime heritage resources

Q16. What is the condition of known maritime heritage resources and how is it changing?

Considerable literature is devoted to techniques for selecting, analyzing, and applying representative suites of indicators that reflect the status and trends of ecosystem components (e.g., Fulton et al. 2005; Rice and Rochet 2005; Methratta and Link 2006; Samhouri et al. 2009; Shin et al. 2010; Kershner et al. 2011). However, developing a suite of quantitative indicators for condition reporting was a relatively new process within ONMS, so sanctuary staff sought input from NOAA Fisheries scientists with NOAA's Integrated Ecosystem Assessment (IEA) Program who had experience in ecosystem indicator selection and analysis for the California Current IEA (CCIEA) region[2].

Over the past decade, the IEA approach (Figure 2) has been adopted by NOAA as a framework to provide transdisciplinary science support for ecosystem-based management (Levin et al. 2009; Samhouri et al. 2014; Harvey et al. 2017). Ecosystem indicators are fundamental building blocks of the IEA approach (Figure 2, Step 2) and an indicator evaluation framework had been developed by the CCIEA team (Kershner et al. 2011). While the missions, priorities, and spatiotemporal scales considered by the ONMS are distinct from those of NOAA Fisheries, the IEA approach is robust and transferable to ecosystem-based management needs of different NOAA line offices and scales of resource management (Harvey et al. 2017). To this end, NOAA Fisheries and ONMS scientists in the CCIEA team are collaborating to translate the CCIEA indicator evaluation framework to the scale of individual sanctuaries, with the understanding that the final indicators used by a sanctuary will reflect the different goals, scale, and information available for each sanctuary.

In this report, we describe a process for creating habitat-based indicator portfolios for new iterations of sanctuary condition reports. This process compiled, categorized, and screened indicators of human pressures on, and resource condition in, a sanctuary's major habitats, yielding indicator portfolios and visual conceptual models for each habitat. The timing of this collaborative project overlapped with a process to complete a partial update to the Monterey Bay National Marine Sanctuary (MBNMS) condition report that focused solely on the state of ecosystem resources, which was released in 2015 (ONMS 2015). While the habitat-based indicator portfolios and conceptual models described in this report were developed for the MBNMS condition report, the indicator development process is applicable to future condition report updates at sites throughout the ONMS network. To that end, we provide lessons learned from the MBNMS process, as well as examples of how this process was implemented by Channel Islands National Marine Sanctuary, that resulted in a substantially improved update to the CINMS condition report (ONMS 2018b).

[2] California Current Integrated Ecosystem Assessment Program
https://www.integratedecosystemassessment.noaa.gov/regions/california-current

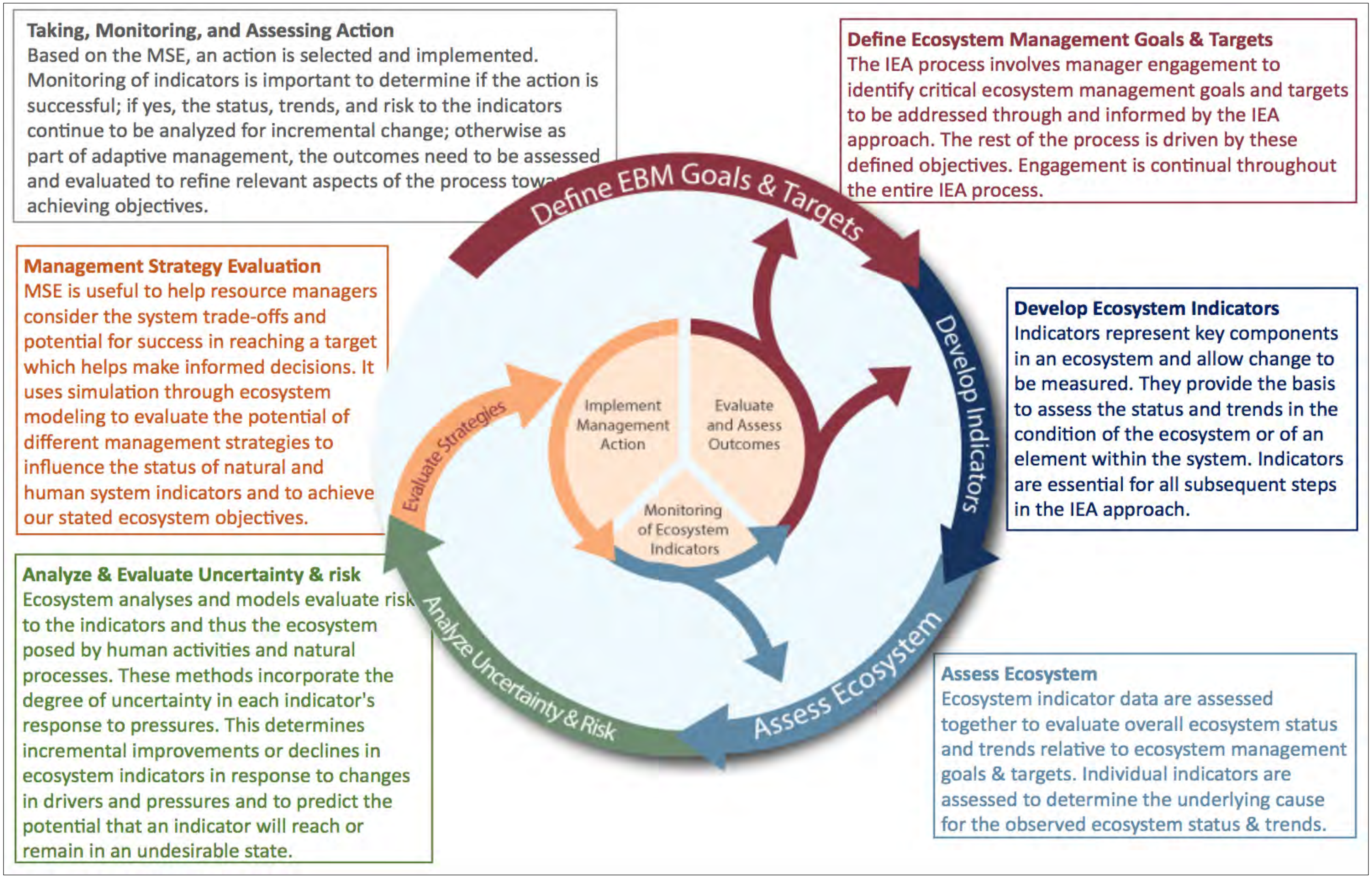

Figure 2. Schematic describing the cyclical, iterative nature of integrated ecosystem assessments at NOAA. This schematic, excerpted from Samhouri et al. 2014, is an update of the approach first depicted in Levin et al. 2009.

Site description

Monterey Bay National Marine Sanctuary was designated in 1992 and is one of the largest sites in the ONMS system (Figure 3). It covers about 15,800 km^2 of water along approximately 450 km of California's central coast. The sanctuary includes a wide range of habitats, including the Elkhorn Slough estuary, kelp forests, deep underwater canyons, and a seamount (Davidson Seamount). These various habitats support a wide diversity of flora and fauna including 36 species of marine mammals, more than 180 species of seabirds and shorebirds, at least 525 species of fishes, and an abundance of invertebrates and algae (Guerrero and Kvitek 1996; Burton and Lea 2013). The sanctuary is also responsible for the protection and management of historical and cultural resources within its boundary, including approximately 463 vessel and aircraft losses that are considered marine archaeological resources within, or adjacent to, the boundaries of MBNMS (Smith and Hunter 2003).

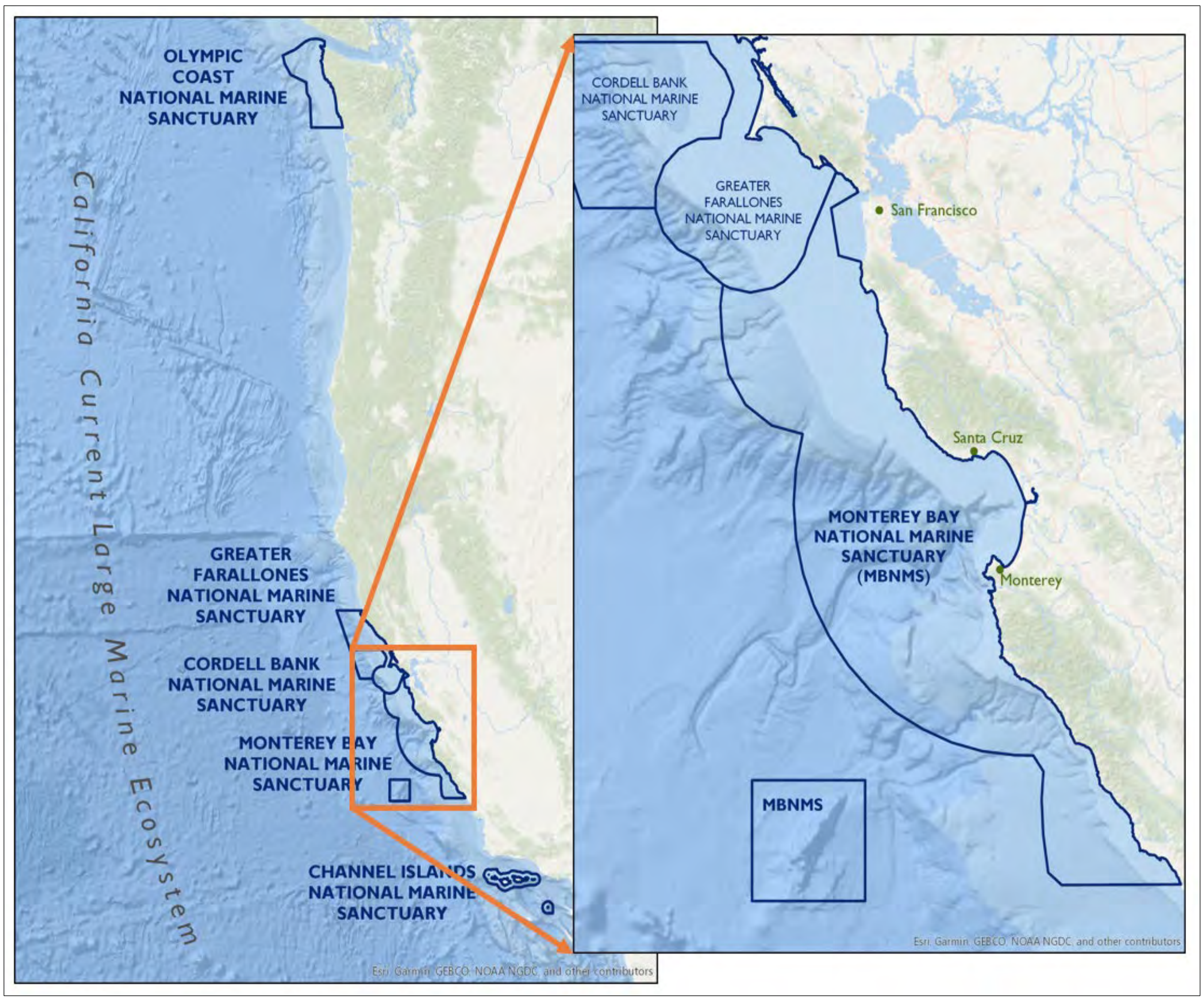

Figure 3. Map of the California Current Large Marine Ecosystem, the regional extent of the California Current Integrated Ecosystem Assessment program, and the five national marine sanctuaries along the West Coast residing therein (left). Monterey Bay National Marine Sanctuary (right) is the largest sanctuary along the West Coast; Channel Islands National Marine Sanctuary is the southernmost. Image: S. De Beukelaer/Lynker Technologies LLC, NOAA

Monterey Bay National Marine Sanctuary also has a high density of research and monitoring activity, with more than 30 research institutions located adjacent to the sanctuary.[3] There are numerous federal and state agencies monitoring resources in the sanctuary including NOAA Fisheries, the California Department of Fish and Wildlife (CDFW), United States Geological Survey (USGS), and the National Estuarine Research Reserve System (NERRS). Academic institutions include both public university systems (e.g., University of California and California State University) and private colleges (e.g., Stanford University). Additionally, there are various non-governmental marine research organizations, such as the Monterey Bay Aquarium Research Institute, Center for Ocean Solutions, and Point Blue Conservation Science. Sanctuary-specific monitoring efforts are inventoried through the Sanctuary Integrated Monitoring Network (SIMoN).[4]

Methods

The indicator development process we created for sanctuary condition reports consists of eight steps summarized in Figure 4. These steps include: defining targets for indicator development; subdividing the sanctuary into major habitat categories; a literature-based indicator survey and compilation; indicator screening and evaluation steps; an iterative, expert-based review of draft indicator lists and conceptual models; and final revisions to build indicator portfolios and

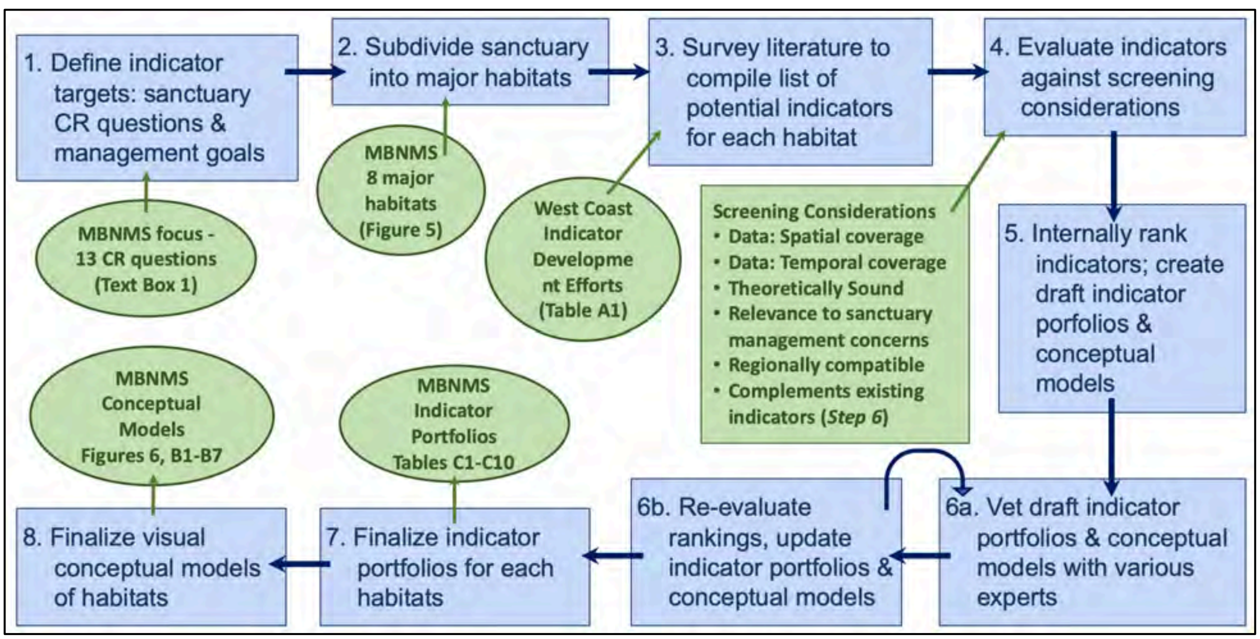

Figure 4. The process used to develop indicator portfolios and conceptual models for condition assessments of Monterey Bay National Marine Sanctuary. Blue denotes the generic process that could be applied to any site in the National Marine Sanctuary System while green denotes information specific to the process for Monterey Bay National Marine Sanctuary.

[3] Monterey Bay National Marine Sanctuary, Regional Marine Research Institutions http://montereybay.noaa.gov/research/resinstitute.html
[4] Sanctuary Integrated Monitoring Network https://sanctuarysimon.org

conceptual models for each habitat category. Details about the rationale behind and methods within each of these steps is described in the sections below.

Targeting indicators to condition report questions (management goals)

The scope of the indicator development process was informed by the first step of the IEA approach (Figure 2): defining goals and targets, or identifying the specific ecosystem goals and targets most influential to management issues. The standardized questions in ONMS condition reports (Text Box 1) were identified as the proximal target for indicator development because these questions were created in alignment with ONMS's mission and its system-wide monitoring framework (NMSP 2004).[5] Using the hierarchical framework in Kershner et al. (2011), we created an organizational table (Table 1) to illustrate how indicators align with condition report questions, and ultimately to the sanctuary program's overall management needs and goals (Figure 4, Step 1).

Table 1. How the hierarchical framework for organizing and evaluating indicators, created by Kershner et al. (2011) align with the Office of National Marine Sanctuary mission and the focal components, key attributes and indicators needed to complete assessments in sanctuary condition reports.

Tier	Definition	Sanctuary example
1. Goal	Broadest category of division that combines societal values and scientific understanding to define a desired ecosystem condition.	ONMS mission: Ensure the health and protection of essential resources in marine areas while facilitating compatible human uses and education.
2. **Focal components**	Major characteristics of an ecosystem that can be used to organize relevant information in a limited number of discrete, but not necessarily independent, categories.	Major categories of essential marine resources in condition reports (see Text Box 1): (1) **human dimensions**; (2) **water quality**; (3) **habitats**; (4) **living resources**
3. *Key attributes*	Characteristics that define the structure, composition, and function of a focal component.	(1) **Human dimensions**: *human activities*; (2) **water quality**: *climate and ocean drivers*; (3) **habitat**: *quantity* and *quality*; (4) **living resources**: *population size*, *population condition*, and *community composition*
4. <u>Indicators</u>	Quantitative biological, chemical, or physical measurements that reflect the structure, composition, or functioning of an ecological system.	(1) **Human dimensions**: *human activities* (e.g., <u>recreational fishing landings</u>); (2) **water quality**: *climate and ocean drivers,* (e.g., <u>sea surface temperature</u>); (3) **habitat**: *quantity* (e.g., <u>kelp canopy areal extent</u>); (4) **living resources**: *population size* (e.g., <u>sea otter abundance</u>); *population condition* (e.g., <u>sea urchin size structure</u>); *community composition* (e.g., <u>infaunal invertebrate diversity</u>)

[5] The ONMS condition report questions focused on human drivers and maritime heritage resources, shaded grey in Text Box 1, were outside the scope of this indicator development effort.

The ONMS mission is the highest tier, or goal, of the indicator development effort (Table 1). The next tier, or focal components, are the major categories targeted for assessment in sanctuary condition reports: human dimensions; water quality; habitats; and living resources. In the third tier, each focal component is separated into key attributes, or the characteristics that define the structure, composition, and function of a component (e.g., population size or condition of living resources). Finally, the fourth tier represented the actual indicators that serve as proxies for monitoring key attributes. Indicators focused on these standardized questions would serve to provide a summary of current conditions and trends of sanctuary resources and the driving forces and pressures on those resources.

One important note: although some of the human activities evaluated here as indicators of pressures on sanctuary resources (e.g., fishing, beach visitation) could also be framed in human dimensions as ecosystem services, or the benefits humans derive from the ecosystem, indicators for ecosystem services were not included in the scope of this project. Ecosystem services are treated in the socio-ecological model for the California Current (Figure 1), have been identified by ONMS for inclusion in future condition reports (ONMS 2018a), and are under development in other sanctuaries. For more information see Discussion, lessons learned #5).

Habitat categories

To further refine scoping for this effort, we used habitat categories within MBNMS to organize subsequent indicator development efforts (Figure 4, Step 2). Habitats within a sanctuary often form the basis for organizing ecosystem objectives, assessing status and trends, and identifying potential threats (ONMS 2009b, 2015, SIMoN[4]). Habitats can also serve as proxies for ecological communities and a variety of ecosystem processes. Other parallel or on-going indicator selection efforts in California and Washington have used this habitat-based approach effectively (e.g., COST 2014; Andrews et al. 2015), and this approach was supported by the MBNMS Research Activities Panel. A habitat-based subsetting approach also would help identify significant information gaps for future research and monitoring efforts by ONMS and science partners.

We identified eight major habitat categories in MBNMS (Figure 5) based on the habitat delineations consistently identified in past sanctuary characterizations and condition reports (Guerrero and Kvitek 1996; ONMS 2009b; Brown et al. 2013, ONMS 2015); SIMoN, and on-going indicator selection efforts in California and Washington (e.g., COST 2014; Andrews et al. 2015):

- Estuary
- Rocky shore
- Sandy beach
- Kelp forest and rocky reef (<30 m depth)
- Shallow seafloor (<30 m depth)
- Deep seafloor (shelf, slope, and canyon >30m depth)
- Seamount and ridge
- Pelagic (entire water column)

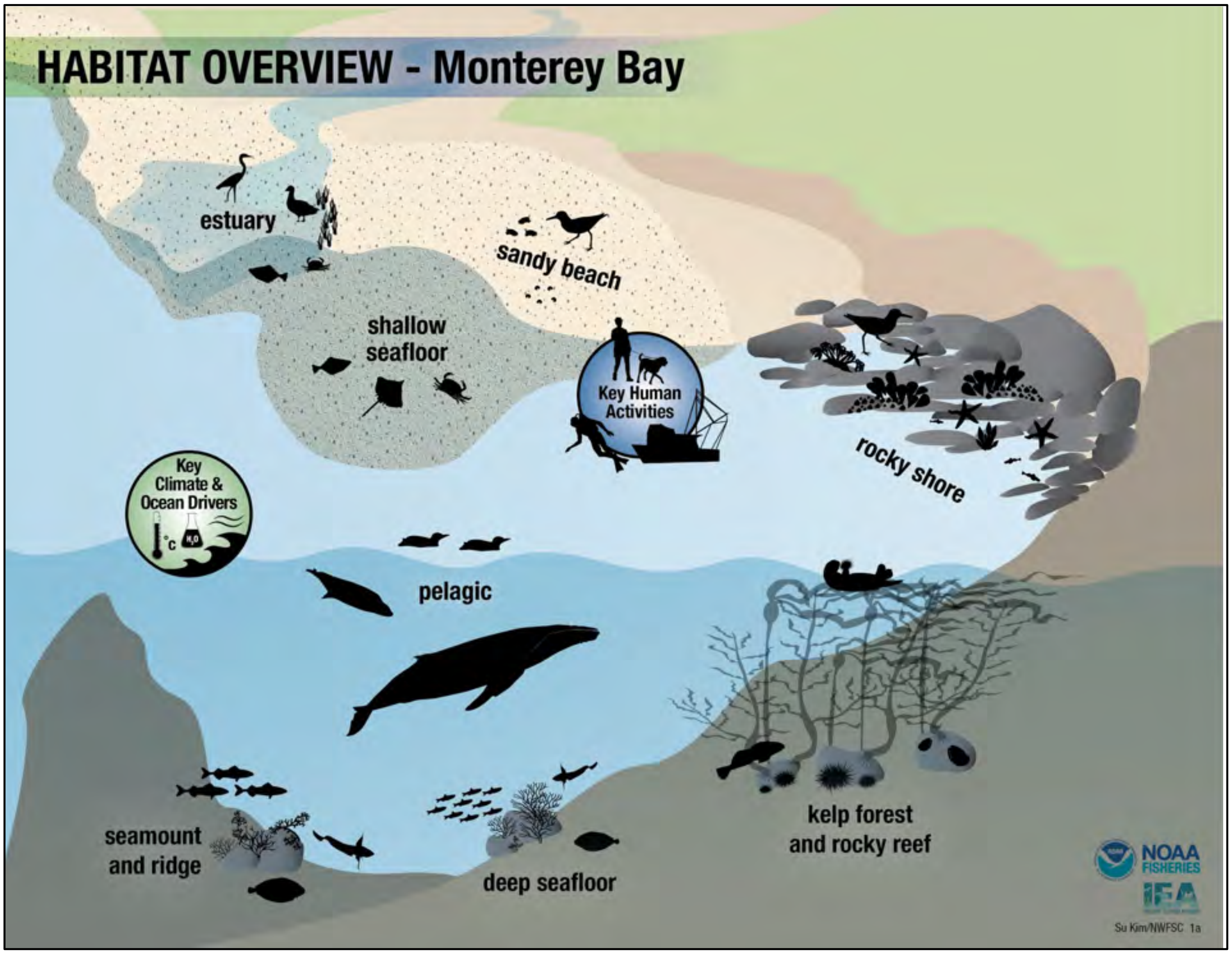

Figure 5. Overview conceptual model illustrating the eight major habitats within Monterey Bay National Marine Sanctuary, and icons representing key climate and ocean drivers and human activities. Image: S. Kim/NOAA

Indicator compilation

Next, we surveyed 10 complementary West Coast indicator development efforts (Appendix A), the 2009 MBNMS condition report (ONMS 2009b), and peer-reviewed literature for indicators relevant to resources, pressures, and drivers in MBNMS (Figure 4, Step 3). Each potential indicator was added to an indicator list for the appropriate major habitat category, in some cases repeating nonspecific indicators (e.g., demersal fish diversity, sea surface temperature) across multiple habitat lists. Indicators in the source documents that did not align with the targets identified in Tier 4 were not included as potential indicators on these lists. In all, the number of indicators across these eight habitat lists totaled almost 350 indicators, although some additional indicators were added during the expert review process (described below).

Indicator evaluations

Next, we needed to evaluate and prioritize the potential indicators within each habitat-based list (Figure 4, Step 4). Nineteen criteria were identified by Kershner et al. (2011) for evaluating and prioritizing potential ecosystem indicators. Operating under the time and resource constraints of the MBNMS condition report effort, we decided to select a subset of these criteria in consultation and consensus with sanctuary staff. Six indicator screening considerations were selected based on their weighting in previous CCIEA indicator assessments (Levin and Schwing 2011), feasibility, and utility for condition reporting and other sanctuary information needs.

Data considerations:

1. *Spatial coverage* – data available from within the spatial domain including MBNMS; coverage over a large portion of the targeted habitat preferred.
2. *Temporal coverage* – currently collected to facilitate status evaluation; long-time series preferred to allow comparison with past conditions.

Primary considerations:

3. *Theoretically sound* – scientific, peer-reviewed findings demonstrate that indicator acts as a reliable surrogate for ecosystem attribute.
4. *Relevant to management concerns* – indicator provides information related to condition report questions (Text Box 1) or sanctuary management concerns.

Other considerations:

5. *Regionally compatible* – comparable to those indicators used by partners along the West Coast to contextualize current status and changes in status relative to the region.

***Post-hoc* consideration:**

6. *Complements existing indicators* – a *post hoc* consideration, based on whether the indicator complements, and is not redundant to, others within the indicator suite.

For each habitat-based potential indicator list, we compiled available information for the first five screening considerations using the previous MBNMS condition report (ONMS 2009b), the SIMoN website[4], and reports from West Coast indicator development efforts (Appendix A), especially the CCIEA report used to assess the state of the California Current ecosystem (NMFS 2016). The team documented the screening information for each potential indicator as follows (example available in Appendix D). **Spatial and temporal coverage** of known research and monitoring efforts for an indicator were identified within the spatial domain of MBNMS, including the identification of principal investigators and temporal information. **Theoretical soundness** was captured with a citation and brief summary of literature that demonstrated the indicator could or could not act as a surrogate for its ecosystem attribute. **Management relevance** was determined by evaluating whether the indicator could be linked to one or more of the standardized ONMS condition report questions. **Regional compatibility** was noted by identifying other West Coast indicator portfolios in which the indicator had also been used.

Next, we internally evaluated indicator performance against the screening considerations and ranked them as strongly, moderately, or weakly supported (Figure 4, Step 5). Strongly supported indicators met all or most screening considerations while moderately supported indicators were lacking against one or more considerations. Weakly supported indicators were lacking in most considerations. We then created the first round of indicator portfolios for the eight habitats with the goal of balancing inclusion of the higher-ranking indicators while also creating a portfolio that provided information for as many condition report questions as possible without the portfolio becoming too large (e.g., >25 indicators). In general, we considered a portfolio of 15 to 25 indicators to be a reasonable size given the 13 condition report questions for which we were selecting indicators. This meant we included most of the strongly supported indicators, but not necessarily all if there was substantial overlap or redundancy between them. Moderately supported indicators were selected to fill gaps in the portfolio for each condition report question or to include habitat components, living resource groups, oceanographic drivers, or human pressures that link to resource issues of high management interest.[6] Weakly supported indicators were not included in the portfolios.

Conceptual models

Conceptual models have proven valuable as a means for stakeholders, managers, policymakers, and scientists to describe their perceptions of ecosystems and develop clear communication and consensus around what components, linkages, and processes are most important to ecosystem function (Orians et al. 2012). We decided that conceptual models of the draft indicator portfolio for each habitat could be a useful a visual aid and communication tool during the review process because they could enhance a reviewer's ability to map specific indicators to condition report questions and to quickly assess redundancies or gaps in the indicator portfolio for each habitat. Our conceptual models (Figure 6 and Appendix B) followed the examples created by Andrews et al. (2013; 2015) to support spatial management efforts in coastal Washington state.

Expert review process

Upon completion of the indicator evaluation and conceptual model development by the core project team, we conducted an iterative review process of the draft indicator portfolios and conceptual models (Figure 4, Step 6). The review process began by gathering input from additional MBNMS research staff on the data availability, management relevance, regional compatibility, and overall complementarity of the eight draft indicator portfolios. This additional information and guidance resulted in some indicators being added and removed from each portfolio as well as changes to the relative ranking of some indicators.

Next, a second draft of the indicator portfolios and conceptual models was reviewed by the MBNMS research activities panel[7], which is a science advisory group composed of 23 representatives from regional research institutions and organizations covering a wide variety of research disciplines (e.g., biological oceanography, deep sea ecology, water quality). At this same time, the indicator portfolios and conceptual models were sent to additional regional science and monitoring experts identified by MBNMS staff or research activities panel members to supplement the expertise of research activities panel members. All experts were asked to provide the following input:

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[6] Monterey Bay National Marine Sanctuary, Resource Issues https://montereybay.noaa.gov/resourcepro/resmanissues/issues.html

[7]Monterey Bay National Marine Sanctuary, Sanctuary Advisory Council, research activities panel overview http://montereybay.noaa.gov/sac/rap/objectives.html

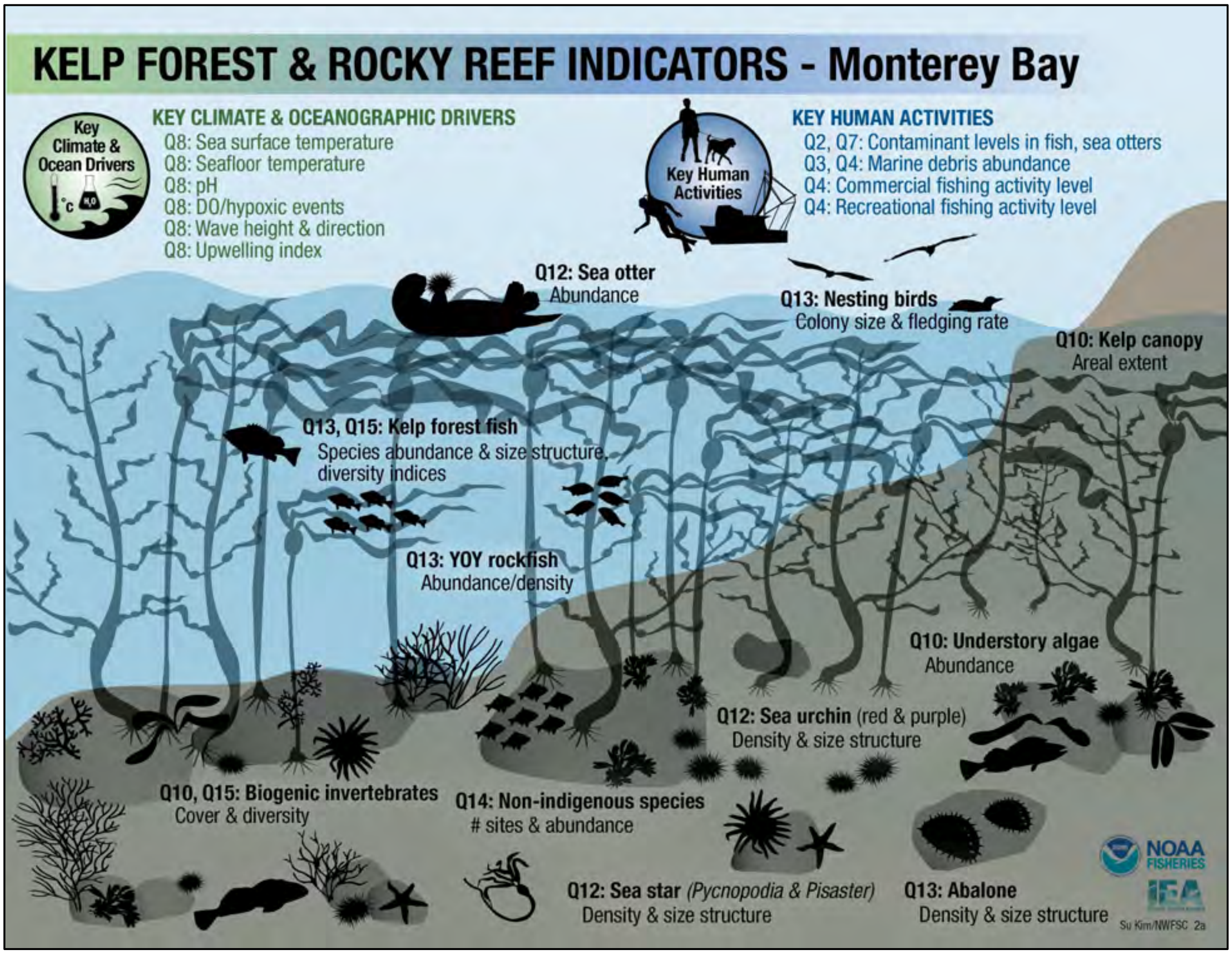

Figure 6. Conceptual model depicting the portfolio of indicators of ecosystem components (black font), climate and ocean drivers (green font), and human pressures (blue font) for the kelp forest and rocky reef habitat in Monterey Bay National Marine Sanctuary. Q numbers align with the standardized questions in Office of National Marine Sanctuaries condition reports (Text Box 1). Image: S. Kim/NOAA

- Are we missing important indicators? Why?
- Do you recommend removing any indicators? Why?
- Are we focused on the best metric (e.g., biomass vs. size structure)? Why?
- Do you disagree with our rankings of indicators? Why?
- Do you disagree with our assessment of data availability? Why?

Input was received from 21 expert reviewers in this second iteration of the review step. Comments were compiled in the potential indicator table and included suggested additions and removals from the indicator portfolio as well as changes in ranking and data availability. We then reassessed the indicators against the screening considerations and the combined internal and external reviews to create a third version of the indicator portfolios and conceptual models.

The opportunity for further refinement of the MBNMS indicator portfolios emerged when Channel Islands National Marine Sanctuary (CINMS) joined the indicator development collaboration with MBNMS and the CCIEA team. Using the MBNMS indicator lists as a starting point, CINMS began its own effort to compile and evaluate indicators. Due to regional differences in species assemblages, human activities, and oceanographic processes, some potential indicators were added to or removed from the CINMS lists, but a large portion of indicators from the MBNMS lists were considered and evaluated again during the CINMS process. Additional information and input were gathered for some indicators, including new or additional data sources and guidance on theoretical soundness and complementarity, during vetting by the CINMS research team, the CINMS research activities panel,[8] and the CCIEA science team. For indicators in the MBNMS portfolio for whisch new information and expert input was available from the CINMS process, we completed a *post hoc* evaluation of its relevance to the MBNMS indicator portfolios and conceptual models. Though much of the MBNMS portfolios remained unchanged, we made some selected refinements to clarify the preferred indicator metric (e.g., aerial extent vs. density measures), modify or expand available data sources, and to improve cross-regional compatibility and complementarity of the portfolios. The most recent versions (version 4) of the MBNMS indicator portfolios and conceptual models are those made available in this report (Figure 6, Appendix B, Appendix C).

Results

Below we describe the results of the indicator evaluation and the portfolio development process for the eight major habitats in MBNMS. To provide some spatial context, we first describe the makeup and distribution of those eight major habitats within the sanctuary. To help illustrate the intermediate outputs during the indicator compilation and screening process, we provide a case study with more detailed results specific to the kelp forest and rocky reef habitat category. This same process was completed for each of the other seven habitats and the final products for all eight habitats are shown in Appendices B and C. Finally, we summarize the aggregate results for living resources, habitats, climate and ocean drivers, and human activities, which relate to the standard condition report questions outlined in Text Box 1.

Habitat distributions within MBNMS

We identified eight habitat categories in MBNMS: Elkhorn Slough estuary, four nearshore habitats (rocky shore, sandy beach, kelp forest and rocky reef, and shallow seafloor), and three offshore habitats (deep seafloor; seamount and ridge; pelagic zone). The overwhelming majority of MBNMS is in the three habitats in the offshore environment (Table 2). Approximately 92.6% of subtidal benthic habitat in MBNMS is categorized as deep seafloor (purple shaded area in Figure 7). Based on the available seafloor mapping data, most of this is composed of soft sediments with various mixtures of sand, mud, and silt. Hard substrates, such as deep reef, rock, and gravel, occur in patches of various sizes, but tend to become less abundant in the deeper portions of the sanctuary (ONMS 2009b; Brown et al. 2013). The offshore environment also

[8] Channel Islands National Marine Sanctuary, Advisory Council, working groups, and subcommittees https://channelislands.noaa.gov/sac/working_groups.html

contains two very large rocky formations, Davidson Seamount and Sur Ridge (Figure 7), which make up the seamount and ridge habitat category. In addition, the three-dimensional pelagic habitat includes all the water not associated with the seafloor and comprises the most voluminous portion (approximately 18,670 km^3; Brown et al. 2013) of the sanctuary.

The five remaining habitat categories comprise a much smaller relative proportion of MBNMS' area (Table 2). Elkhorn Slough, the only tidal slough and estuary occurring within the boundaries of MBNMS (yellow shaded left panel, Figure 7), is the smallest of these, with an area of only 1.49 km^2 (<0.01% of MBNMS area). The nearshore environment, which extends from mean high water line out to a depth of 30 m, includes four other habitats: two intertidal (shoreline) and two subtidal. Of the sanctuary's approximately 450 km of shoreline, sandy beach habitat composes 48% of the shoreline while rocky shoreline composes 39%, with the remainder classified as mixed type or man-made structures[9] (right panel Figure 7). Finally, nearshore subtidal habitats compose only 3.62% of the total seafloor area in MBNMS, with about 76% represented by shallow soft seafloor and 24% by kelp forest and rocky reef (Table 2).

Table 2. Areal extent and relative abundance (%) of the five subtidal benthic habitat categories. Research publications and density indicate the number of peer-reviewed publications available electronically and conducted within boundaries of MBNMS that were classified by key study habitats by Alvarado et at. (2017).

Habitat Category	Area (sq mi)	Area (sq km)	% sanctuary	# research publications	Research density (# per sq km)
Estuary	0.58	1.49	0.01	98	65.77
Shallow seafloor (< 30 m)	167.21	433.06	2.75	31	0.07
Kelp forest and rocky reef (< 30 m)	52.71	136.51	0.87	149	1.09
Deep seafloor (>30m)	5,641.21	14,610.66	92.6	430	0.03
Seamount and ridge	195.05	505.17	3.20	23	0.05
Sur Ridge	14.12	36.57	0.23		
Davidson Seamount	180.93	468.60	2.97		
Unknown	33.31	86.28	0.55		
TOTAL	6,090.00	15,773.00	100	731	0.05

[9] from SIMoN http://www.sanctuarysimon.org/monterey/sections/rockyShores/overview.php

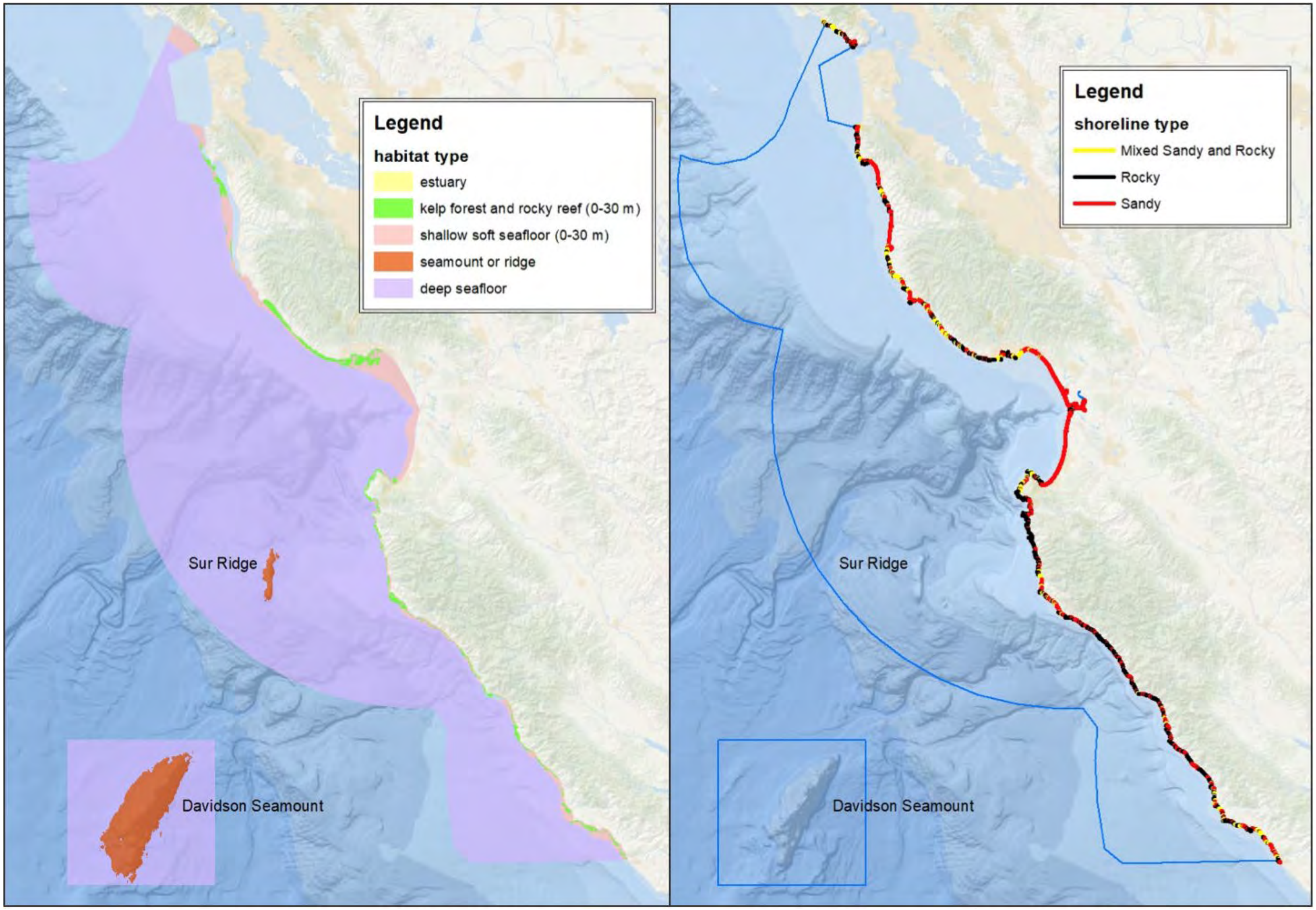

Figure 7. Monterey Bay National Marine Sanctuary was subdivided into eight major habitats, seven of which were based on substrate type and depth. The geographic extent of those seven habitats are shown. Right panel: rocky shore (black), sandy beach (red), mixed sandy and rocky (yellow); left panel: estuary (yellow), kelp forest and rocky reef (green), shallow soft seafloor (pink), seamount or ridge (orange); and deep seafloor (purple). Image: C. King/NOAA

Case study: Indicator development in kelp forest and rocky reef habitat

We began the indicator development process by compiling a list of 57 potential indicators for tracking the condition of kelp forest and rocky reef habitat and associated living resources, as well as the human activities and climate and ocean drivers (water quality) that may influence them (Appendix D). Only indicators that could be linked to one or more of the standardized ONMS condition report questions were included in this list.

Based on the hierarchical framework shown in Table 1, the potential indicators were categorized by: habitat quantity (e.g., kelp canopy cover, areal extent of rocky reef habitat); habitat quality (e.g., kelp size structure, substrate rugosity); population size of focal species (e.g., sea urchin density, sea star density, young-of-the-year rockfish abundance, sea otter population status); population condition of focal species (e.g., sea urchin size structure, rockfish size structure, sea otter health/condition); community composition (e.g., demersal fish diversity, biogenic invertebrate diversity, mean trophic level); human activities (e.g., recreation fishing landings, marine debris abundance); and climate and ocean drivers (e.g., sea surface temperature, dissolved oxygen concentration). Every potential indicator on this list was internally reviewed and qualitatively ranked by the authors, with input from the MBNMS research team, based on the six indicator screening considerations (Appendix D), as described above. Additionally, a visual representation of the habitats and species was created as an initial conceptual model that attempted to portray key ecosystem components as well as the important ocean and climate drivers and human activities that influence ecosystem components.

This internal evaluation and ranking step resulted in an initial portfolio of 20 indicators, which included 13 highly ranked indicators and seven moderately ranked indicators. This relatively large number of highly ranked indicators was due to: (1) a history of research studies focused on understanding water quality issues, climate drivers, and ecological interactions that strongly influence the structure and function of the kelp forest ecosystem and (2) availability of long-term monitoring data collected by Partnership for Interdisciplinary Studies of Coastal Oceans (PISCO) scuba surveys (algae, fish, demersal invertebrates), California Department of Fish and Wildlife (kelp, harvest species), and U.S. Geological Survey (sea otters). Seven moderately supported indicators were added to the indicator portfolio to help fill in gaps for population condition, community composition, and water quality. These indicators were not considered highly supported because either it was uncertain if the data was collected consistently (e.g., size structure data) or the indicator was a composite that would require input and data analysis in partnership with data providers (e.g., top predator biomass, water quality index). This list, accompanied by a parallel version of the refined conceptual model, was then sent to external experts for review.

Based on their area of expertise, external reviewers suggested additions and removals from the kelp forest and rocky reef indicator portfolio as well as changes in relative ranking and data availability. We compiled this information and then reassessed the indicators against the selection considerations and evaluated the combined internal and external reviews. Examples of adjustments to the portfolio included: adding pH and dissolved oxygen as important indicators for tracking water quality and a changing climate; changing the data source for kelp canopy extent from diver surveys to aerial extent from Landsat data; adding wave height and direction because frequent large storms can reduce kelp abundance; and removing land-based nutrient-loading as an indicator of eutrophication because naturally high nitrate levels from upwelling likely swamp out land-based sources. This re-evaluation and vetting resulted in a next iteration of the portfolio and conceptual model for kelp forest and rocky reef habitats.

As described in the methods above, the indicator information compiled from the MBNMS process served as the starting point for the indicator development process for CINMS. Through vetting by the CINMS research team, the research activities panel, and the CCIEA science team, additional expert input was gathered on potential indicators for this habitat. Information gained during the CINMS review of kelp forest and rocky reef indicators led us to make a few revisions to the MBNMS conceptual model. For example, we added a non-indigenous species indicator focused on both the number of sites with non-indigenous species present and the abundance of non-indigenous species at those sites. Two non-indigenous species, *Sargassum horneri* and *Undaria pinnatifida*, are spreading in kelp forests in CINMS. It is important to monitor for these species, or others, that may eventually arrive in MBNMS. Additionally, adding this indicator helps improve coordination and comparison of indicators across these two California national marine sanctuaries.

The version of the kelp and rocky reef conceptual model available in this report (Figure 6) and indicator portfolio (Table C4) reflects the revisions made during the CINMS process. We completed parallel indicator development efforts for the seven other habitat categories following the approach described in this case study. These habitat-specific portfolios ultimately led to the full MBNMS indicator portfolio described in the next section.

MBNMS indicator portfolios across all habitats

Summary indicator evaluation information is provided for the final portfolios of ecosystem components (i.e., habitats and living resources indicators) for the eight major habitats in Tables C1-C8. Because many water quality and human dimensions indicators were identified as important in two or more major habitats, these portfolios are shown separately in cross-habitat summary tables, Tables 4 and 5, respectively, with additional indicator evaluation information provided in Appendix C (Tables C9 and C10). Earlier, more detailed versions of these tables were the foundation of the indicator evaluation effort, serving first as a simple checklist to assure that the critical elements were in place, and then as the object of review and vetting (see case study and Appendix D for an example).

While more than 350 potential indicators were initially identified across eight MBNMS habitats, the indicator evaluation and expert review process were able to reduce this to a more manageable number of 17 to 26 indicators per habitat (Figures 6 and B1-B7). Considered collectively, and given that many of the water quality and human dimension indicators were shared across multiple habitats, these eight portfolios contain a total of 120 indicators, a reduction of approximately 66%.

Living resources and habitat

The condition of habitats and living resource ecosystem components in MBNMS were represented by indicators of habitat quantity, habitat quality, population size, population condition, and community composition. Keystone, foundation, and focal species were the primary focus of species-specific indicators, while community composition was represented by indices of species richness, diversity, and non-indigenous species (Table 1; Appendix C).

A few of the habitats in MBNMS, including Elkhorn Slough estuary (Figure B1), rocky shores (Figure B2), and kelp forest and rocky reefs (Figure 6), had fairly extensive lists of indicators that scored well and met many, if not all, of our six screening considerations. Each of these habitats have been the focus of extensive research and numerous long-term monitoring efforts (summarized in DeVogelaere 1996; Edwards and Foster 1996; Alvarado et al. 2017; Wasson et al. 2015), which provided a wealth of information for tracking status over time and for identifying which species, or groups of species, are useful indicators of condition (Tables C1, C2, C4). For these well-studied habitats, some higher ranked indicators were culled from the final indicator portfolio to make it a manageable size (~ 25 or fewer indicators) based on our complementarity screening consideration. For example, the Multi-Agency Rocky Intertidal Network (MARINe) monitoring program identifies 27 long-term monitoring target species, also called indicator species, for which they collect data at sites throughout MBNMS.[10] Although each of these target species had extensive monitoring data of high cross-regional value, we limited our final portfolio to three species (ochre sea star, *Pisaster ochraceus*; black abalone, *Haliotis cracherodii;* and owl limpet, *Lottia gigantea*) with the highest relative ranking due to high management interest, as well as four measures of habitat quantity (bare rock, mussels, barnacles, and algae), and one measure of community composition (species diversity).

The disparity in available information between particular habitat categories is supported by a recent literature review by Alvarado and colleagues (2017), which analyzed the key study habitats and organisms targeted by peer-reviewed research studies in MBNMS. They found that among the five subtidal habitat categories in MBNMS, the estuary habitat had a much higher study density per unit area (65.77 studies km^{-2}) than any other subtidal habitat type in MBNMS (Table 2). Subtidal kelp forest and rocky reef habitat was the next most intensely studied with 1.09 studies km^{-2}. Seamount and ridge was the habitat category with the fewest studies (23 studies) while the deep seafloor habitat exhibited the lowest research study density (0.03 studies km^{-2}). Among shoreline habitats, more than twice as many studies were focused on rocky shores than sandy beaches (371 vs. 161 studies; Alvarado et al. 2017), even though beach habitat is the more abundant shoreline habitat in MBNMS.

One potential reason for the abundance of research studies, and thus high-ranking indicators, in estuary, rocky shore, and kelp forest habitats is their relative accessibility to researchers doing field studies. However, despite the same ease of access, sandy beaches and shallow sandy seafloor habitats had far fewer high-ranking indicators than the other nearshore habitats. Though many potentially useful indicators of habitat or ecosystem condition were identified, few had long-term monitoring data or directed research studies at sites in MBNMS. Despite these

[10] MARINe Long-Term Monitoring Target Species
https://www.eeb.ucsc.edu/pacificrockyintertidal/target/index.html

shortcomings, we were able to include indicators that could satisfy some condition report questions and were tracked by partner agencies in central California (e.g., COST 2011, 2014). For example, abundance of sand crabs and snowy plover abundance and reproductive success were included for the sandy beach portfolio; California halibut and Dungeness crab abundance and size structure were included for sandy seafloor habitat (Table C3 and C5). In addition, we selected some indicators that are current data gaps (e.g., non-indigenous infaunal species, contaminant levels in sediments) as targets for potential future research and monitoring efforts to better answer specific condition report questions across the variety of habitats and resources in the sanctuary.

Seafloor habitat deeper than 30 m is the most abundant benthic habitat in MBNMS (Figure 7), but with the exception of the NMFS groundfish trawl survey, it receives relatively little repeated monitoring attention (0.3 studies km^{-2}) relative to its abundance (Table 2). Similar monitoring data deficiency issues apply to seamount and ridge habitats. Although Davidson Seamount and Sur Ridge have been the subject of recent exploration and characterization surveys,[11,12] little repeated monitoring has occurred that could be used to track status and trends. These data deficiencies resulted in portfolios with few high-ranking indicators (Figures B5, B6, and Tables C6, C7). Additionally, some potential indicators were dropped because there was little guidance available on which species, taxonomic groups, or functional groups are the most reliable indicators of ecosystem attributes. We retained indicators that covered many of the condition report questions and have cross-habitat relevance, high interest to managers or the public, or are the focus of research expeditions to characterize these more remote portions of the sanctuary (e.g., Burton and Lundsten 2008; Newton and DeVogelaere 2013; Burton et al. 2017).

The pelagic habitat indicator portfolio (Figure B7) includes indicators spanning a range of data availability (Table C8). Indicators that can be monitored through satellite-based observing and surface-based sampling methods tend to rank higher for the data considerations. For example, there is long-term monitoring data available through satellites for physical characteristics and chlorophyll, net sampling for forage fish and zooplankton, and visual surveys for seabirds and mammals. However, indicators of abundance, condition, and community composition for species found in the deeper water column (e.g., mesopelagic fishes, gelatinous zooplankton) tended to be data deficient. In addition, less information was available to help evaluate which species or taxonomic groups are good indicators of ecosystem condition for these deeper portions of the water column.

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[11] SIMoN Monitoring Project Summary, Davidson Seamount 2015: Characterization of Mammals, Birds, and Midwater Fishes Above and Adjacent to Davidson Seamount http://www.sanctuarysimon.org/projects/project_info.php?projectID=100421&site=true; SIMoN Monitoring Project Summary, Davidson Seamount: 2006 Expedition to Ancient Coral Gardens http://www.sanctuarysimon.org/projects/project_info.php?projectID=100307&site=true

[12] SIMoN Monitoring Project Summary, Exploration of Sur Ridge http://sanctuarymonitoring.org.previewc28.carrierzone.com/projects/project_info.php?projectID=100449&site=true

Water quality: Climate and ocean drivers

Sixteen climate and ocean drivers were selected as important indicators for one or more habitats (Tables 4 and C9). Three drivers applied to most, or all, of the eight major habitats (Table 3), and their importance was stressed by many reviewers. For example, temperature, either at the surface or seafloor, has a strong influence on condition of all habitats through interaction with physiological preferences and tolerances of the organisms, and is a key indicator of changing climate (summarized in Duncan et al. 2014; Andrews et al. 2015). Other indicators of changing ocean conditions (e.g., dissolved oxygen, pH) were selected due to their importance in assessing water quality and habitat suitability for a wide variety of organisms (summarized in Duncan et al. 2014; Andrews et al. 2015).

Conversely, some drivers were selected due to their relative influence on particular habitats. For example, sea level and wave height were selected because of their potential to strongly influence shoreline and nearshore kelp forest habitats of the sanctuary. Similarly, nutrient concentration and eutrophication are key drivers influencing water quality and habitat conditions in the Elkhorn Slough estuary (Hughes et al. 2011; Wasson et al. 2015). Finally, basin-scale indices such as the Pacific Decadal Oscillation (PDO) and Multivariate ENSO [El Niño-Southern Oscillation] Index (MEI), though broadly influential, are most easily understood in the context of

Table 3. Indicators of climate and ocean conditions that can be drivers of change in sanctuary water quality were evaluated for each of the eight major habitat categories, and 16 drivers were selected as important indicators for one or more habitats.

Climate and ocean drivers indicator	Habitat category							
	Estuary	Rocky shore	Sandy beach	Kelp forest & reef	Sandy seafloor	Deep seafloor	Seamount & ridge	Pelagic
Eutrophic status/nutrient concentration	X							
Aerial extent sea lettuce	X							
Dissolved oxygen/hypoxic events	X		X	X	X	X	X	X
Sea surface temperature	X	X	X	X			X	X
pH	X	X	X	X	X	X	X	X
Sea level height	X	X	X					
Freshwater inflow	X							
(Max) wave height & direction		X	X	X				
Air temperature		X						
Seafloor temperature				X	X	X	X	
Upwelling Index				X				
Depth of anoxic layer					X	X		
Harmful algal boomss/domoic acid – extent, duration, frequency					X			X
Nitrogen: Phosphorus					X			X
Internal tides/currents							X	
Basin-scale indices (e.g., PDO)								X

the pelagic environment and set the stage for understanding how background physical conditions may be influencing conditions in the other habitats (Andrews et al. 2015; Leising et al. 2015).

Data availability for climate and ocean drivers varied widely in its spatial and temporal coverage and was one of the primary factors influencing selection of these indicators. In general, data collected by satellite, surface buoys, and *in situ* shoreline sensors were the most readily available, especially when funded and maintained by federal agencies (e.g., NOAA satellites and buoys, NERRS). Data collected by non-government entities or involving subsurface or seafloor deployments, especially when far from shore, were less readily and/or publicly available.

Human dimensions: Human activities

Humans engage in a wide variety of land- and ocean-based activities that exert pressure on, and yield benefits from, marine ecosystems (Halpern et al. 2009). For this effort we focused on indicators of human activities which were explicitly considered pressures to the ecosystem, as described in questions two through four of the ONMS condition report. As previously noted, human benefits are an acknowledged gap in this and prior iterations of the assessment, but are an implied part of the modern socio-ecological system conceptual model (Figure 1) and a focus area that will be addressed in future condition reports that assess the status of ecosystem services (ONMS 2018a).

Table 4. Indicators of human activities that can exert pressures on sanctuary resources were evaluated for each of the eight major habitat categories, and 13 were selected as important indicators for one or more habitats.

Human activity indicator	Habitat category							
	Estuary	Rocky shore	Sandy beach	Kelp forest & reef	Sandy seafloor	Deep seafloor	Seamount & ridge	Pelagic
Indicator bacterial levels	X		X					
Waterbodies #/area impaired	X	X	X					
Watershed activities	X							
Contaminant levels – water, sediments, infauna, shellfish, fish, mammals	X	X		X	X	X	X	X
Recreational fishing activity level	X	X		X	X	X	X	X
# visitors by activity		X	X					
Marine debris abundance		X	X	X	X	X	X	X
Amount of beach grooming			X					
Erosion/deposition rate			X					
Commercial fishing activity level				X	X	X	X	X
Bottom-contact gear distance disturbed					X	X	X	
Shipping activity level							X	X
# strandings/entanglements								X

In MBNMS, human activities include recreational activities (e.g., beach-going, diving, boating, collecting), commercial activities (shipping, fishing), and various land uses (agriculture, shoreline development) (Weinstein 1996). Unfortunately, there were few data available to characterize either spatial or temporal patterns for many of these human activities. These data limitations hindered the indicator selection process and should be prioritized as an area of emphasis in future condition reporting. The final portfolio includes 13 types of human activity indicators, with data availability ranging from good to data-deficient (Tables 4 and C10).

Similar to the physical drivers, a handful of human activities were identified as strong indicators of human pressure across most, or all, major habitats (Table 4). Biomass extraction for human consumption, represented by commercial and recreational fishing removals, occurs throughout the sanctuary. Tracking the levels of these activities is important to understanding condition of both targeted and non-targeted species as well as benthic habitats. Although land-based activities are the main sources of marine debris and chemical contaminants that enter the sanctuary (Davis et al. 2012; Stevenson et al. 2011), water circulation and sediment movements extend the impacts of these pressures from nearshore to both offshore pelagic and deep benthic habitats in the sanctuary (Hartwell 2008; Watters et al. 2010; Schlining et al. 2013).

The remaining human activity indicators help track other impacts across one or a few sanctuary habitats. For instance, bacterial levels and the number of impaired water bodies are strong indicators of human activities in the watershed that affect the condition of estuarine and nearshore habitats, as well as associated human wellbeing benefits. Additionally, shoreline recreation such as beach visitation may have strong direct impact on shoreline habitats, especially in rocky intertidal areas where trampling may occur (Van De Werfhorst and Pearse 2007; Micheli et al. 2016). Shipping activity[13] represented a range of potential impacts to pelagic communities, from acoustic impacts[14] (Redfern et al. 2017) to ship strikes on whales[15] (Redfern et al. 2013; Hazen et al. 2016). Bottom-contact fishing represents a potential impact to deep seafloor habitats and living resources in the offshore environment of the sanctuary where this activity is allowed (de Marignac 2009; PFMC 2012 Appendix J; Lindholm et al. 2015).

[13] Monterey Bay National Marine Sanctuary, Resource Issues: Vessel Traffic http://montereybay.noaa.gov/resourcepro/resmanissues/vessels.html
[14] Monterey Bay National Marine Sanctuary, Resource Issues: Acoustic (Noise) Impacts http://montereybay.noaa.gov/resourcepro/resmanissues/acoustic.html
[15] Monterey Bay National Marine Sanctuary, Resource Issues: Whale Strikes http://montereybay.noaa.gov/resourcepro/resmanissues/whalestrikes.html

Discussion

In this report, we have presented a process to identify portfolios of indicators to enhance the value of national marine sanctuary condition reports in support of ecosystem-based management at the sanctuary scale. This process addresses recommendations from regional experts and reviewers that the MBNMS condition report rely more on quantitative information derived through transparent and repeatable methods and less on expert opinion, which while valuable, is also more subjective.

Our approach relies on several key components. It uses major habitat types within a national marine sanctuary as an organizing principle for focusing the standardized management questions (Text Box 1) and for assessing information. It uses visually compelling conceptual models as tools for establishing and communicating how each major habitat type is structured, and what indicators are relevant to key ecosystem components. Finally, it adapts a hierarchical indicator screening method, described by Kershner et al. (2011) and applied extensively by the CCIEA team (e.g., Levin et al. 2013), to identify and screen indicators that can be traced back to specific objectives (Table 1).

The process outlined here (Figure 4) is consistent with the first few steps of the IEA framework displayed in Figure 2. The initial IEA step, "defining ecosystem-based management goals and targets," is essential to ensuring that scientists, stakeholders, managers, and policymakers have a common understanding of key overarching elements such as the scale, scope, and structure of the ecosystem; the diverse and interacting objectives of different user groups; and the key risks and threats faced by the system (Levin et al. 2009). Those elements are all embodied in the sanctuary condition report process, specifically: the use of the standardized questions for assessing sanctuary condition which link directly ONMS program goals; the choice to divide the sanctuary into discrete major habitat types, each with its own conceptual model that links to those questions; and the use of established MBNMS goals as the top tier of the hierarchical indicator screening process.

The second step in the IEA approach is to develop indicators (Figure 2). Developing robust indicators is essential for effectively tracking the status and trends of focal ecosystem components (Levin et al. 2009). This step is represented in our process (Figure 4) by compiling candidate indicators and screening them using methods adapted from Kershner et al. (2011), which results in indicator portfolios specific to each major habitat type. The method evaluates and prioritizes potential indicators based on theoretical soundness, management relevance, data availability, and other considerations at spatial scales relevant to the sanctuary. After integrating feedback from various reviewer groups, the resulting indicator portfolios become the basis for the next sanctuary condition report assessment, in alignment with the third step of the IEA approach, "assessing the ecosystem" (Figure 2).

This indicator portfolio development process provides a structured yet flexible framework that can accommodate many voices. The repeatable structure of this approach ensures a well-documented process that sustains institutional knowledge and is designed to increase the efficiency and speed of subsequent efforts. The reviewable transparency of the data-driven screening process helps temper the subjective input of experts that may bias indicator selection outcome. Together, these traits should improve the consistency and rigor of subsequent condition reports, especially because turnover within the contributing pool of sanctuary staff and experts can be high within the typical seven-to-10 year spacing of condition report updates. The screening process itself can be revisited and new indicators and time series can be incorporated, for example as data gaps are filled through new monitoring efforts, or as new sanctuary priorities arise that require additional indicators. We further emphasize that although the indicator screening and prioritization process is designed to provide a rigorous and systematic framework, it should not produce static and immutable results; rather, it should be viewed as a template with room for adaptations to particular sanctuary needs, resource constraints, and expert insights (see below: lessons learned #2, systematic framework).

In addition to improving indicator development and ecosystem assessment methods, the indicators and time series identified here will be critical for subsequent steps in the IEA approach ("assessing risk and uncertainty," and "evaluating strategies"; Figure 2). Indicators of stressor and response variables are essential to assessing risk in a system; similarly, the error structure around quantitative indicators, and data gaps identified through the indicator screening process, can help us to assess uncertainty about the ecosystem (Levin et al. 2009). Finally, robust indicators are needed in the step of "evaluating strategies," because they will be important in measuring how the system responds to management actions and help us to understand if the system is moving toward the goals and objectives identified in the initial step of the IEA framework (Levin et al. 2009). These final aspects of the IEA framework, which are built upon the solid foundation of a robust portfolio of indicators, could be useful for setting management targets for some indicators and condition report questions (Text Box 1) and for identifying and evaluating potential new strategies for use in sanctuary management plans.

Key lessons learned

In the course of developing this approach and applying it to indicator development for MBNMS and subsequently for CINMS, we came away with several overarching lessons which we summarize below in the hope of helping science and management teams of other protected areas adopt this approach for their own ecosystem assessments and condition reporting.

1. Major habitat categories are a useful organizing principle for developing representative sanctuary indicator portfolios.

National marine sanctuaries are special places, established not only for their diverse mosaic of habitats, but also for their unique natural attributes. Indeed, MBNMS contains one of the world's most geologically diverse and complex seafloors and continental margins, and its natural resources include one of the nation's largest contiguous kelp forest and one of North America's largest underwater canyons (MBNMS Final Management Plan 2008[16]). However, these

[16] Monterey Bay National Marine Sanctuary, MBNMS Management Plan Documents https://montereybay.noaa.gov/intro/mp/welcome.html

superlative features also present competing challenges when assessing the sanctuary's condition. Specifically, how does one acknowledge the contributions of seemingly minor habitats that contribute to this diversity (sum of the parts) while also recognizing the inherent value of rare or unique habitats? Without an organizing principle to guide the process, condition ratings of a marine sanctuary could be overly reliant on indicators in habitats that receive disproportionate study, or alternatively, could fail to properly highlight indicators that represent the most "valued" features within the sanctuary landscape.

Documenting and understanding habitat-based inequities in the pool of potential ecosystem indicators is important for two main reasons. First, these inequities point out gaps in available data and research effort (see lesson learned #5, below). Second, the imbalance highlights potential biases about how we may value and prioritize particular habitats or species groups within the sanctuary. As noted above, some habitats in the sanctuary, like Elkhorn Slough estuary, tide pools in the rocky intertidal, and kelp forests, are relatively scare, but receive significant public interest and management action within MBNMS (e.g., DeVogelaere 1996; Edwards and Foster 1996; Wasson et al. 2015; Alvarado et al. 2017). These highly visible and accessible habitats provide popular recreational destinations in the Monterey Bay region, and contain relatively high densities of charismatic and protected species (e.g., sea otters, seabirds, intertidal invertebrates) that elicit public interest and concern. Additionally, research hotspots are concentrated around established marine research institutions and coastal access points near Santa Cruz, Monterey, and Moss Landing/Elkhorn Slough, which further enhance accessibility, monitoring, and research by agency, academic, and citizen scientists (Alvarado et al. 2017).

In contrast, a very small portion of the vast deep seafloor habitat in MBNMS has been imaged and characterized, let alone repeatedly monitored (Alvarado et al. 2017). Most deep seafloor habitat is located far from population centers and extends into very deep waters, which are more logistically challenging and expensive to study; furthermore, the faunal biomass of these habitats is concentrated in the sediments and not easily viewed. These patterns extend to pelagic habitats, where research studies show a strong bias towards surface waters and larger charismatic megafauna or species that are the subject of active management (e.g., seabirds, cetaceans, turtles; Alvarado et al. 2017) while deeper portions of the water column receive much less study (Robison 2004, 2009).

We recommend using major habitat categories as an initial organizing principle for assessing and selecting indicators within sanctuary condition reports. This approach can reveal potential biases in the geophysical and taxonomic distribution of research effort within a particular sanctuary and facilitate open communication about the limits of available information. Being transparent about these inequities and communicating them clearly at the outset should similarly influence how sanctuaries approach condition report conclusions. For example, a sanctuary may want to clearly communicate at the outset of their condition report how particularly valued habitats (e.g., coral reefs, kelp forests, cetacean habitat) are the cornerstone of their designation, and therefore represent the main focus of their assessment. Alternatively, one could use a weighting system to influence the indicator scores of particular habitat categories, acknowledging that "weighting" should be set in a transparent and repeatable process guided by expert opinion (see Kershner at al. 2011).

2. Adapting a systematic framework increases the rigor, transparency, and consistency of the indicator selection process.

The initial 2009 condition reports for Monterey Bay and Channel Islands national marine sanctuaries were guided heavily by expert opinion for assessing the status and trends of water quality, habitats, living resources, and the human activities that put pressure on those resources. While expert opinion is a valuable approach for making rapid assessments, it can be difficult to recreate, may vary considerably at the scale of an individual's experience, and often suffers from unquantifiable biases. Guided by advice to address the shortcomings of the expert-driven model, we looked to the IEA approach (Levin et al. 2009; Harvey et al. 2017) to create an indicator development process that increases transparency, while also increasing consistency of the evaluation and the likelihood that the best indicators emerge as finalists in any portfolio. It also establishes some baseline standards and considerations for indicator inclusion or exclusion, thereby defusing potential conflicts with experts who may have hidden biases or a vested interest in elevating a particular dataset. When paired with habitat as an organizing principle (lesson #1, above), we found the indicator evaluation and screening step served as a helpful checklist—an established tool that provides a simple solution for managing complex problems (Gawande 2009) and assures that the critical elements are in place and vetted before expert opinion finally weighs in on the remaining uncertainties.

In contrast to the expert model, the indicator evaluation framework in its original form (Kershner et al. 2011; CCIEA) requires a comprehensive, literature-based evaluation of 19 criteria with a quantitative scoring protocol. We initially sought to replicate this rigorous approach, but found that the time and resource requirements for completion far exceeded our staffing and budget, and its findings were often overly prescriptive. We therefore sought a middle ground, developing a more condensed evaluation process that balanced the benefits of the screening tool (e.g., transparency, repeatability, peer-review data standards), with some of the flexibility and rapidity offered by the expert-driven approach.

Our modified approach reduced the list of potential indicators by two-thirds, identified highest-ranked indicators, and highlighted habitats and questions for which there was insufficient monitoring data. However, the final eight habitats portfolios still contained a combined total of 120 indicators, a considerable number which will require substantial staff time and attention to track and update in future condition reports. The relatively large size of MBNMS, as well as its resource diversity and abundance of affiliated research institutions, likely contributed to this substantial number of indicators; however, this number will likely change in the future as discussion continues on the optimal number of indicators for a sanctuary. Smaller or more remote sanctuaries and sanctuaries with fewer major habitat types will likely be able to further reduce their final indicator list to a smaller and even more manageable number.

Without being overly prescriptive ourselves, we recommend other national marine sanctuaries strive to attain high indicator evaluation standards demonstrated by Kershner et al. (2011), while working within the bounds of their available staff time and financial resources. In this case, MBNMS staff time and resources were augmented via collaboration with the CCIEA science team. This collaboration was also able to leverage support from prior indicator evaluation efforts in the California Current region, the coastal waters of Washington State, and the state waters of California. We recommend future efforts seek to incorporate similar collaborative strategies to expand available resources and expertise by working with state and federal partners with complementary interests or experience.

3. Conceptual models are an effective visual tool for communicating indicator portfolios.

The visual appeal of habitat-based conceptual models was broadly acknowledged and provided a clear communication tool for a range of audiences, from scientists and managers to educators and laypeople (pers. observation, J. Brown). Visual imagery conveys a critical element missing from the data matrices that result from the Kershner et al. (2011) indicator framework (i.e., data matrices; Appendix C). They more readily translate the same information to those not versed, or not interested, in the details of the screening process. Foremost, the imagery provides the proverbial "thousand words" necessary to convey the complexity inherent in marine systems, and allows rapid sharing of common indicators (Tofte 1997). We should also note that professional-quality graphics should not be a prerequisite to building these models; much of our work was started with rough sketches and clip-art (e.g., free web-based graphics repositories such as IAN/UMCES Symbol and Image Libraries, http://ian.umces.edu/imagelibrary/), before we enlisted the assistance of a graphic designer.

We found the conceptual models to be a useful complementary tool for gathering expert input on the draft habitat-based indicator portfolios. During the review process, subject experts were asked to provide comments on both the indicator summary tables (Appendix C) and the visual conceptual models (Appendix B), often helping to drive consensus on what the defining components and processes were in each habitat. Although both the indicator tables and conceptual models were available, the models were most often used by experts when providing feedback regarding indicator gaps or suggested changes. While comments on the indicator tables were often focused on identifying additional data sources or clarifying their temporal or spatial coverage within the sanctuary, the conceptual models allowed a more holistic visual consideration of the indicator portfolio and convenient platform for suggesting indicator additions/removals or additional ideas of improvement.

The conceptual models also have been helpful for communicating the value of condition report indicator portfolios throughout the National Marine Sanctuary System. As previously noted, CINMS started their condition report (ONMS 2018b) where MBNMS left off, adapting the original versions of the MBNMS indicator selection matrices and conceptual models. These draft models served as a key tool during meetings of the sanctuary's research activities panel to gather expert input on indicator portfolios. Currently, these visuals are under consideration for incorporation into web-based education and outreach efforts. The web-based versions will be linked to indicator data, which could be updated on a more regular basis than the seven-to-10 year condition report cycle and thus provide more timely updates on ecosystem status and trends information for condition reporting. As part of a Sanctuaries Marine Biodiversity Observation Network demonstration project, which began in 2014, we have started to convert the static conceptual models into 'live' interactive infographics.[17] In these live infographics, the

[17] Sanctuaries MBON project, New Interactive Visualizations Show Sanctuary Data

silhouettes of indicators serve as clickable portals to real-time data products for the indicators. The education team at CINMS is also providing input on how to customize these web-based data products for use in outreach to middle and high school students and teachers and interactive exhibits at sanctuary visitor centers.

4. An iterative expert review process fosters collaboration and communication of ideas and data.

Expert review at all stages of the indicator evaluation process not only provided essential insights that refined the final indicator portfolios, but it also built relationships and enhanced collaboration that strengthened the final condition report. The staged review process was iterative, which allowed inclusion of more expert opinions and fine-tuning of the indicator portfolios over time. In addition, revising the MBNMS portfolio and conceptual models following the CINMS indicator development process was valuable for *post hoc* prioritization and cross-regional alignment. While the key to a successful project cannot be distilled into a simple recipe or formula, its success is often predicated on the expertise of the leaders and team members. In our case, having a dedicated condition report leader with extensive knowledge of prior and ongoing research in the sanctuary provided an initial boost to identifying and assessing data considerations, recruiting contributors and reviewers, and facilitating collaboration.

Expert reviewers in both MBNMS and CINMS regions highlighted the need for additional indicators of biodiversity, an observation that fostered development of new biodiversity indicators supported by Marine Biodiversity Observation Network (MBON) demonstration projects. The Sanctuaries MBON project[18] developed indicators that help track impacts of ocean climate variability on biodiversity of the pelagic forage species (Santora et al. 2017), which may also influence distribution and abundance of higher-trophic levels species. The Santa Barbara Channel MBON project[19] developed biodiversity metrics for kelp forest fish and invertebrates, deep water fish, and the pelagic forage community, which improved the sanctuary's assessment of how biodiversity had changed in the updated CINMS condition report (ONMS 2018b).

The collaborations engendered by this project have facilitated communication between scientists at NOAA science centers (Northwest Fisheries Science Center and Southwest Fisheries Science Center) and national marine sanctuaries along the West Coast. These interactions expanded opportunities for sharing ideas and data in support of both NOAA Fisheries and ONMS management goals. Idea-sharing has resulted in an ongoing expansion of the conceptual model design, including an interactive website that facilitates online access to indicator time-series,[20] as well as communication and outreach to educators and the public. In addition, a variety of CCIEA indicator data sets, including basin-scale oceanographic indices, abundance estimates of key forage groups and groundfish species, pinniped reproductive success, and select human activities or pressures, were used and in some cases (e.g., groundfish trawl surveys) downscaled from

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http://sanctuaries.marinebon.org/products/developing-new-interactive-visualizations-to-show-sanctuary-data/

[18] Sanctuaries Marine Biodiversity Observation Network project http://sanctuaries.marinebon.org/

[19] Santa Barbara Channel, Marine Biodiversity Observation Network project http://sbc.marinebon.org/

[20] California Current IEA, West Coast Sanctuary Project https://www.integratedecosystemassessment.noaa.gov/regions/california-current/cc-projects-west-coast-sanctuaries

NOAA regional science centers (Northwest, Southwest, and Alaska fisheries science centers) to sanctuary condition reports. CCIEA science is progressively responding to more requests for finely scaled products from management partners and end users, and we anticipate local or regional downscaling and forecasting will only increase in priority at the level of the NMFS science centers. We recommend sanctuaries use this as an opportunity to actively seek collaboration and partnerships with NMFS science centers to conduct indicator analyses at the regional scales that highlight their spatially-based management objectives.

Enhanced interaction has not only established a conduit for science center support and analysis to national marine sanctuaries; it is also bringing to light some monitoring priorities and data sets that could scale up from national marine sanctuaries along the West Coast to the broader California Current ecosystem (e.g., Kaplan et al. 2012). These include long-term monitoring data sets that are currently collected (often at the regional scale) and are highly relevant to CCIEA and sanctuary indicator needs, but not readily available for analysis and display in CCIEA or sanctuary reports. Targets of particular interest to both programs include MARINe[21] rocky shores long-term monitoring data, PISCO[22] kelp forest monitoring data, satellite-based kelp forest canopy data, eelgrass spatial extent, nesting seabird colony surveys, ocean acidification and other climate change indicators, and some human activities data.

The iterative review and refinement process we adopted reinforced the iterative nature of the IEA approach (Figure 3) and the concept that indicator portfolios are rarely static. It is important to emphasize that available information related to the screening considerations is likely to change in the future with changes in data availability, research into theoretical soundness, and management needs. For example, data consideration likely will change as new monitoring programs are created to fill the identified data gaps or existing monitoring programs are discontinued. It will be important to periodically reevaluate indicator portfolios, especially after the implementation of an indicator development effort at a new site within a region, or even across the National Marine Sanctuary System. Efforts at new sites will likely highlight opportunities to further improve cross-site and cross-program indicator alignment.

5. The entire indicator vetting process reveals data gaps and highlights future research priorities.

The indicator evaluation and prioritization process displays a range of tangible outcomes and sets the stage for highlighting research and monitoring priorities that inform future sanctuary management plans and associated science needs assessments[23]. By design the process elevates indicators with readily available data that meet all other screening considerations (i.e., high management priority; upper right, Figure 8). For example, abundance of sea otters, a keystone predator, is monitored closely in both estuary and kelp habitats by the USGS Western Ecological Research Center due to its threatened listing under the Endangered Species Act. The process can also be used to identify high priority, data-rich indicators that nonetheless require additional

[21] Multi-Agency Rocky Intertidal Network (MARINe) http://www.marine.gov/

[22] Partnership for Interdisciplinary Studies of Coastal Oceans (PISCO) http://www.piscoweb.org/

[23] Science Needs Assessment for NOAA's Office of National Marine Sanctuaries https://sanctuaries.noaa.gov/science/assessment/

analysis in collaboration with partners. As one example, groundfish diversity and abundance estimates conducted annually by the Northwest Fisheries Science Center over the entire West Coast need to be spatially downscaled to be very meaningful to assessment of conditions at the sanctuary scale.

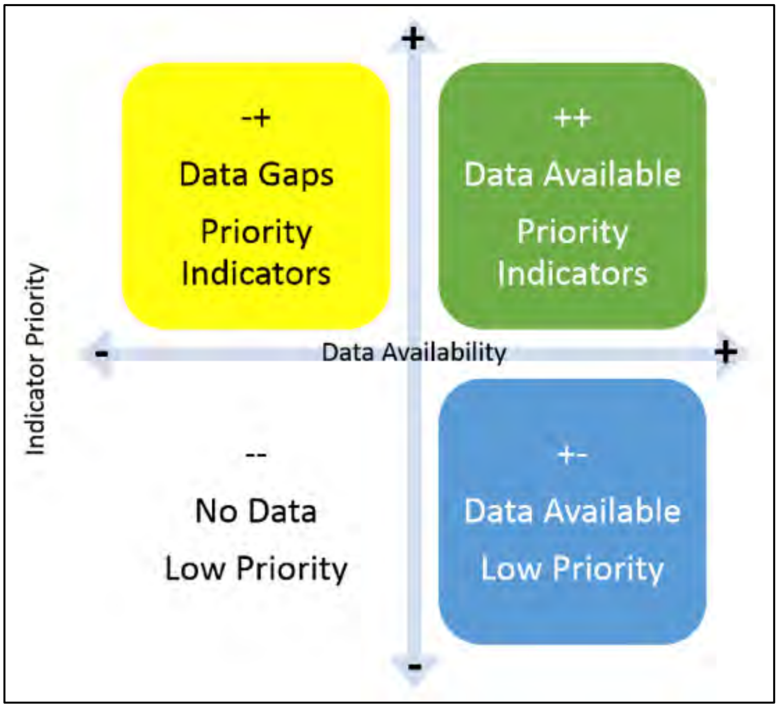

Figure 8. General quadrants where ecosystem indicators classify when evaluated with regard to management priority and data availability.

High priority indicators without associated data (upper left, Figure 8) highlight significant data gaps in existing monitoring and may ultimately play a role in determining the path of future sanctuary research. The standardized indicator evaluation process helped to identify these key data gaps and provides an opportunity for developing proposals in partnership with other partners (e.g., federal and state agencies, universities, and others) to collect these data in the future for inclusion of these data in future reports. As one example, research studies and volunteer surveys indicate that marine debris is a pervasive pressure on resources in most, if not all, habitats in the sanctuary (Stevenson et al. 2011; Rosevelt et al. 2013; Schlining et al. 2013' Donnelly-Greenan et al. 2014; Nevins et al. 2014; Taylor et al. 2014). However, there are limited long-term monitoring data available to quantify the abundance and distribution of marine debris, especially on the seafloor and in the water column. Having identified this data gap for a key indicator of human pressures, MBNMS has convened a working group as part of reviewing the existing management plan and begun working with partners to implement monitoring of plastics in sanctuary waters. We also recommend work to supplement knowledge on the spatial and temporal patterns of human activities in the sanctuary, a current data gap which hinders our basic understanding of potential pressures and how they may be changing over time, as well as the status and trends of living resources in soft sediment habitats (e.g., beaches, shallow and deep seafloor), which are comparatively ignored given their spatial extent.

Indicators positioned in the opposite quadrant (lower right, Figure 8), represent those for which data are available but may not necessarily be a sanctuary management priority (e.g. densities of some fish species collected in kelp habitats using PISCO surveys) or are duplicative of other efforts. There are numerous examples where monitoring goals of other researchers do not align with those of the sanctuary, and these data will continue to be collected to fill those information needs. However, the indicator screening framework can provide a transparent, unbiased justification for why the sanctuary prioritizes some indicators and associated data sets over others for inclusion in condition report assessments.

This iteration of the assessment has significant and acknowledged gaps in human well-being indicators, which measure the benefits humans derive from the natural environment. These benefits are a focus area that is currently being addressed using an ecosystem services approach driven by social scientists from ONMS headquarters (https://coast.noaa.gov/digitalcoast/topics/ecosystem-services.html). Olympic Coast National Marine Sanctuary is currently leading an effort that will evaluate how these human well-being indicators can be folded into our systematic evaluation framework.

Conclusions

We propose that the approach described in this report is an effective way for NOAA's Office of National Marine Sanctuaries to transition condition reports from relatively qualitative assessments guided by expert opinion to more quantitative assessments that include robust ecosystem indicators linked back to sanctuary management objectives specific to different major habitats. Importantly, this approach is relatively new: it was first developed in parallel with the most recent MBNMS condition report update (ONMS 2015), and was applied more formally in the recent update of the CINMS condition report (ONMS 2018b). Thus, the approach will likely evolve considerably, particularly each time it is applied to a new national marine sanctuary, and increase efficiency in terms of both cost and time savings. Each sanctuary's unique set of habitats, species, human uses, cultural components, and management objectives will lead to new lessons learned, recommendations, and prioritizations of needs and gaps. Ideally, the collective, shared experiences of individual sanctuaries will improve condition reporting throughout the entire ONMS network. At the same time, science programs such as regional IEA efforts and ecosystem monitoring efforts at local, state, tribal, and federal levels will also evolve; we are hopeful that these efforts will do so in a manner that maintains or enhances quantitative indicator-based ecosystem assessment, although that will depend heavily on how finite research funds and person-hours are allocated in the future.

The approach we outline will be informed perhaps most of all by future iterations of national marine sanctuary management plans. A sanctuary management plan is shaped by combinations of legal mandates, agency goals and objectives, and stakeholder engagement in the sanctuary region. As a plan's priorities and objectives evolve, the indicators needed to track progress toward those priorities and objectives will have to evolve in parallel through appropriate monitoring and assessment. In addition, the value of a quantitative process as compared to a more qualitative, expert-opinion-driven process will be tested as the quantitative approach is applied in the context of a management plan. Robust indicators of key sanctuary components and processes could serve as performance measures to show if management actions are guiding the sanctuary away from risk-related thresholds and toward reference points defined by goals and objectives (Sainsbury et al. 2000; Himes-Cornell and Kasperski 2015; Lederhouse and Link 2016). We should assume that additional recommendations and lessons learned will emerge from that real-world application of this approach to a management system. It therefore stands to reason that this report should be updated after more sanctuaries have applied the approach to condition reports and management plans, in order to update the framework, explore additional lessons learned, and make new recommendations for moving forward.

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Glossary of acronyms

Beach COMBERS – Coastal Ocean Mammal and Bird Education and Research Surveys
CalCOFI – California Cooperative Oceanic Fisheries Investigations
CCIEA – California Current Integrated Ecosystem Assessment
CCLEAN – Central Coast Long-term Environmental Assessment Network
CCMP – Central Coast MPA Monitoring Plan
CCWG – Central Coast Wetlands Group
CDFW – California Department of Fish & Wildlife
CeNCOOS – Central and Northern California Ocean Observing System
CINMS – Channel Islands National Marine Sanctuary
COST – California Ocean Science Trust
CPUE – Catch Per Unit Effort
CRAM – California Rapid Assessment Method
CRFS – California Recreational Fisheries Survey
ENSO – El Niño Southern Oscillation
EPA – Environmental Protection Agency
ESA – Endangered Species Act
ESI – Environmental Sensitivity Index maps
ESNERR – Elkhorn Slough National Estuarine Research Reserve
GFNMS-OCI – Greater Farallones National Marine Sanctuary - Ocean Climate Indicators
IEA – Integrated ecosystem assessment
LiMPETS – Long-term Monitoring Program and Experiential Training for Students
MARINe – Multi-Agency Rocky Intertidal Network
MBARI – Monterey Bay Aquarium Research Institute
MBNMS – Monterey Bay National Marine Sanctuary
MBON – Marine Biodiversity Observation Network
MEI – Multivariate ENSO Index
MLML – Moss Landing Marine Laboratory
MLPA – Marine Life Protection Act
MMPS – Marine Mammal Protection Act
MPA – Marine protected area
NADP – National Atmospheric Deposition Program
NAIS – Nationwide Automatic Identification System
NCCMP – North Central Coast MPA Monitoring Plan
NCCOS – National Centers for Coastal Ocean Science
NERRS – National Estuarine Research Reserve System
NMFS – National Marine Fisheries Service
NOAA – National Oceanic and Atmospheric Administration
NPS AIS – Naval Postgraduate School Automatic Identification System data (http://www.oc.nps.edu/~cwmiller/AIS/)
NWFSC – Northwest Fisheries Science Center
ONMS – Office of National Marine Sanctuaries
PacFIN – Pacific Fisheries Information Network (https://pacfin.psmfc.org/)
PDO – Pacific Decadal Oscillation

PFMC – Pacific Fishery Management Council
PFMC CCE – Pacific Fisheries Management Council Annual State of the California Current Ecosystem Report
PISCO – Partnership for the Interdisciplinary Studies of Coastal Oceans
PRBO – Point Reyes Bird Observatory
PRD – Protected Resources Division
PSP – Puget Sound Partnership
RecFIN – Recreational Fisheries Information Network (https://www.recfin.org/)
RREAS – Rockfish Recruitment and Ecosystem Assessment Survey
SBC-LTER – Santa Barbara Coastal Long-Term Ecological Research Project
SCMP – South Coast MPA Monitoring Plan
SFBAY – The State of San Francisco Bay Report
SIMoN – Sanctuary Integrated Monitoring Network
SWAMP – (California) State Water Resources Control Board's Surface Water Ambient Monitoring Program
SWFSC – Southwest Fisheries Science Center
USGS – United States Geological Survey
WAMSP – Washington State Marine Spatial Planning

Appendices

Appendix A: West Coast indicator development efforts

Table A1. Complementary efforts to develop indicators of ecosystem status, human pressures, and environmental drivers along the U.S. West Coast.

West Coast indicator development effort	Report	Acronym	Online Access
Pacific Fisheries Management Council Annual State of the California Current Ecosystem Report	NMFS 2016	PFMC CCE	http://www.pcouncil.org/ecosystem-based-management/annual-state-of-the-california-current-ecosystem
North Central Coast MPA Monitoring Plan	COST 2010	NCCMP	http://www.oceansciencetrust.org/wp-content/uploads/2018/12/NorthCentralCoastMonitoringPlan.pdf
Central Coast MPA Monitoring Plan	COST 2014	CCMP	http://www.oceansciencetrust.org/resources/central-coast-mpa-monitoring-plan-2014/
South Coast MPA Monitoring Plan	COST 2011	SCMP	http://www.oceansciencetrust.org/wp-content/uploads/2018/12/SouthCoastMonitoringPlan.pdf
Gulf of the Farallones National Marine Sanctuary Ocean Climate Indicators	Duncan et al. 2014	GFNMS-OCI	https://sanctuaries.noaa.gov/science/conservation/ocean-climate-indicators.html
Washington State Marine Spatial Planning Process (Ecological indicators for Washington state's outer coastal waters)	Andrews et al. 2015	WAMSP	http://www.msp.wa.gov/wp-content/uploads/2015/03/NWFSC_EcosystemIndicatorReport.pdf
The State of San Francisco Bay Report	SFEP 2015	SFBAY	http://www.sfestuary.org/wp-content/uploads/2015/10/SOTER_2.pdf
Puget Sound Partnership Vital Signs	Hamel et al. 2015	PSP	http://www.psp.wa.gov/vitalsigns/
Elkhorn Slough National Estuarine Research Reserve State of the Estuary Report	Wasson et al. 2015	ESNERR	http://www.elkhornslough.org/research/PDF/State_of_Estuary_2015.pdf
CalCOFI: CalCOFI State of the California Current and State of California Current: Live supplement	Leising et al. 2015	CalCOFI	http://calcofi.org/ccpublications/state-of-the-california-current-live-supplement.html

Appendix B: Monterey Bay National Marine Sanctuary habitat conceptual models

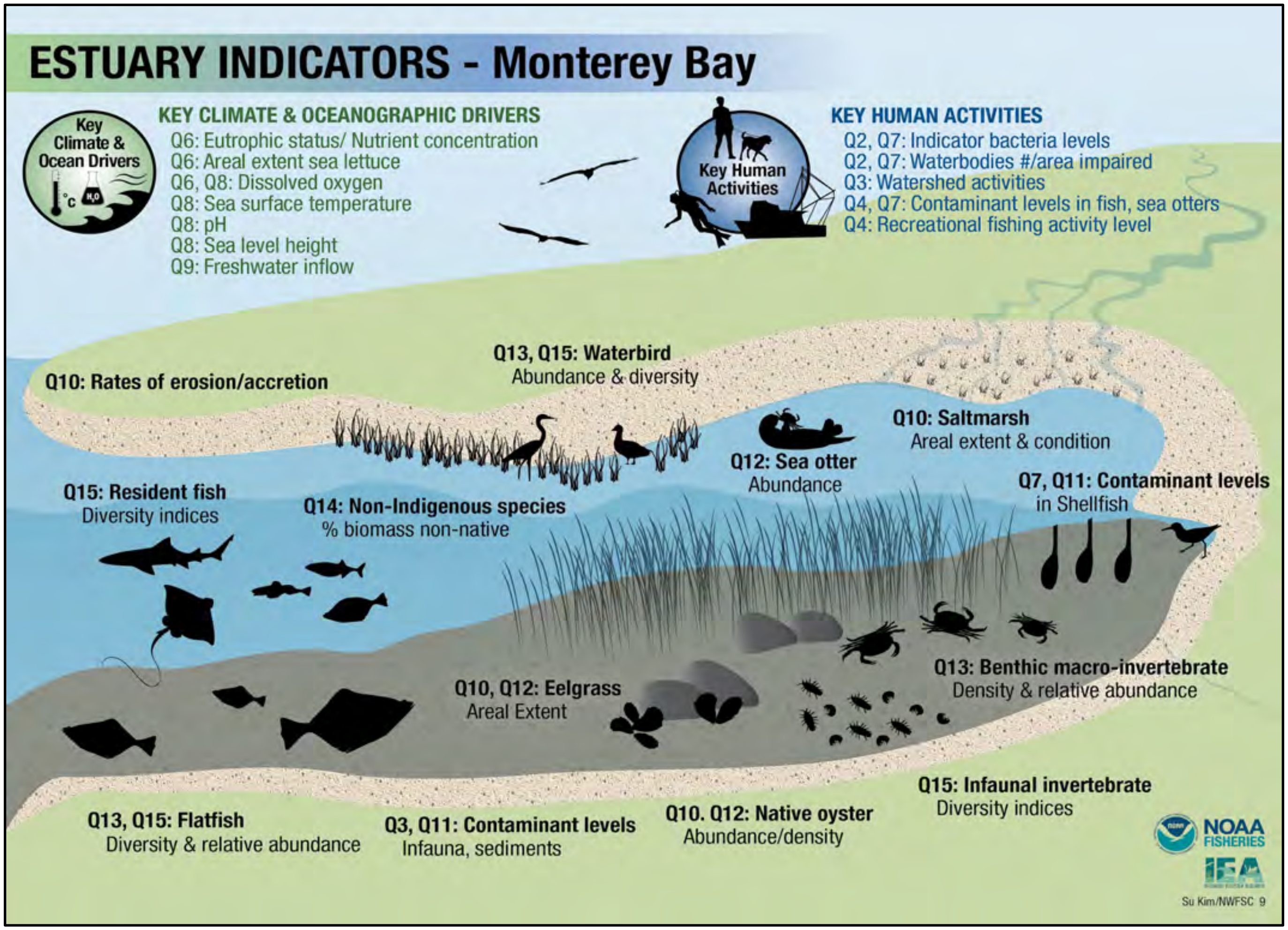

Figure B1. Conceptual model depicting the portfolio of indicators of ecosystem components (black font), climate and ocean drivers (green font), and human pressures (blue font) for Elkhorn Slough. Elkhorn Slough is the only estuary habitat within the boundaries of Monterey Bay National Marine Sanctuary. Q numbers align with the standardized questions in Office of National Marine Sanctuaries condition reports (Text Box 1). Image: Su Kim/NOAA

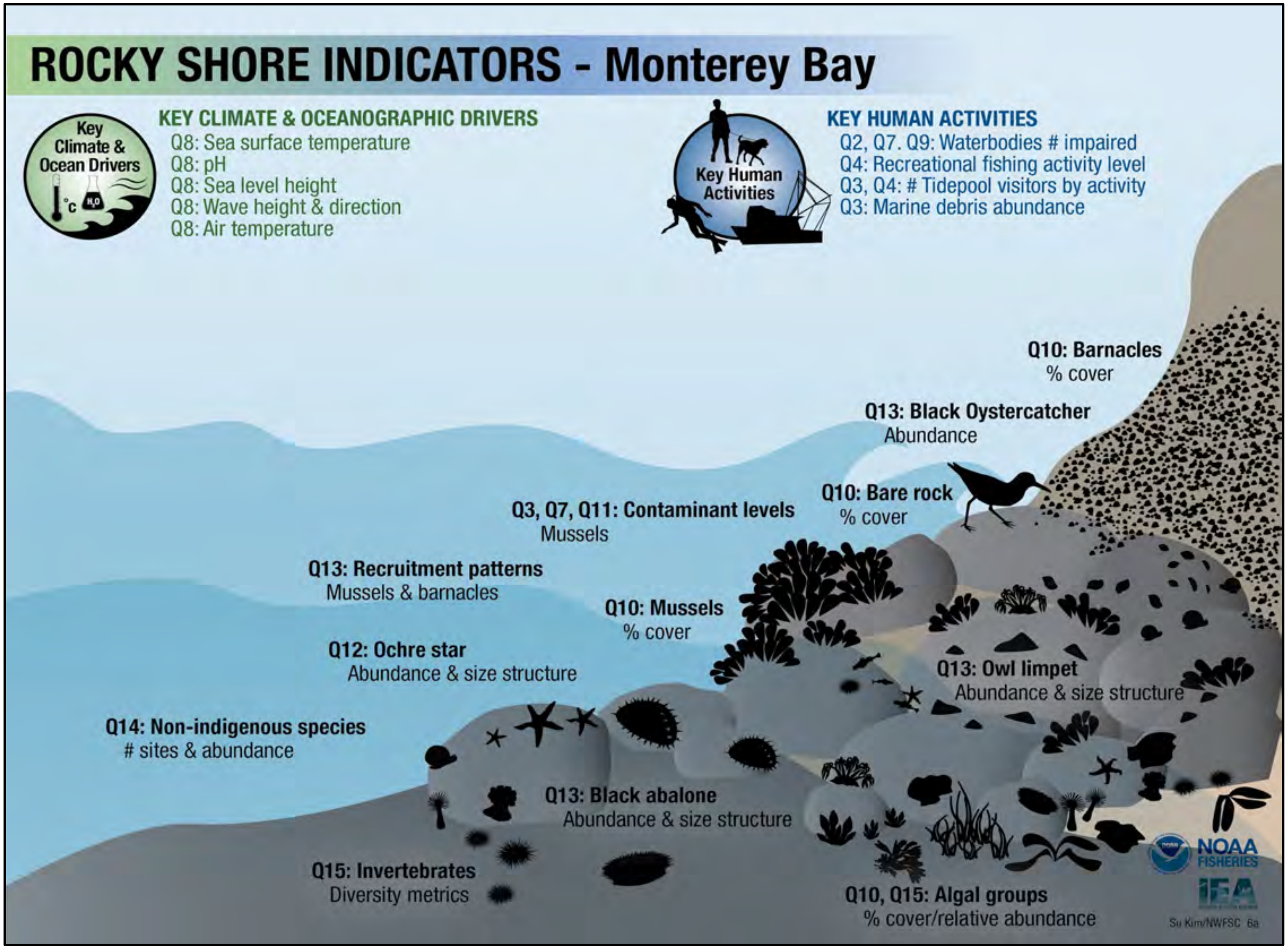

Figure B2. Conceptual model depicting the portfolio of indicators of ecosystem components (black font), climate and ocean drivers (green font), and human pressures (blue font) for the rocky shore habitat in Monterey Bay National Marine Sanctuary. Q numbers align with the standardized questions in Office of National Marine Sanctuaries condition reports (Text Box 1). Image: Su Kim/NOAA

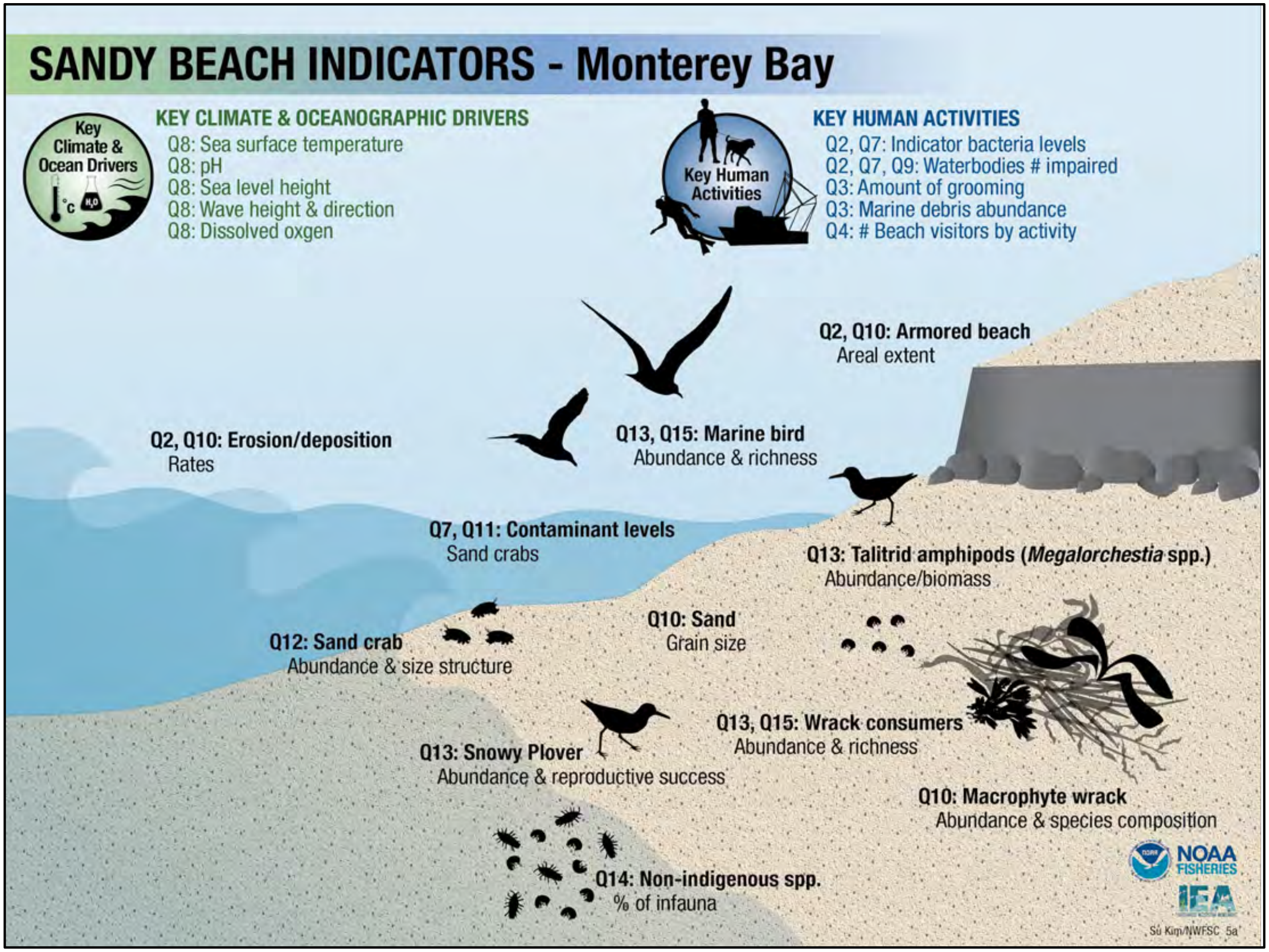

Figure B3. Conceptual model depicting the portfolio of indicators of ecosystem components (black font), climate and ocean drivers (green font), and human pressures (blue font) for the sandy beach habitat in Monterey Bay National Marine Sanctuary. Q numbers align with the standardized questions in Office of National Marine Sanctuaries condition reports (Text Box 1). Image: Su Kim/NOAA

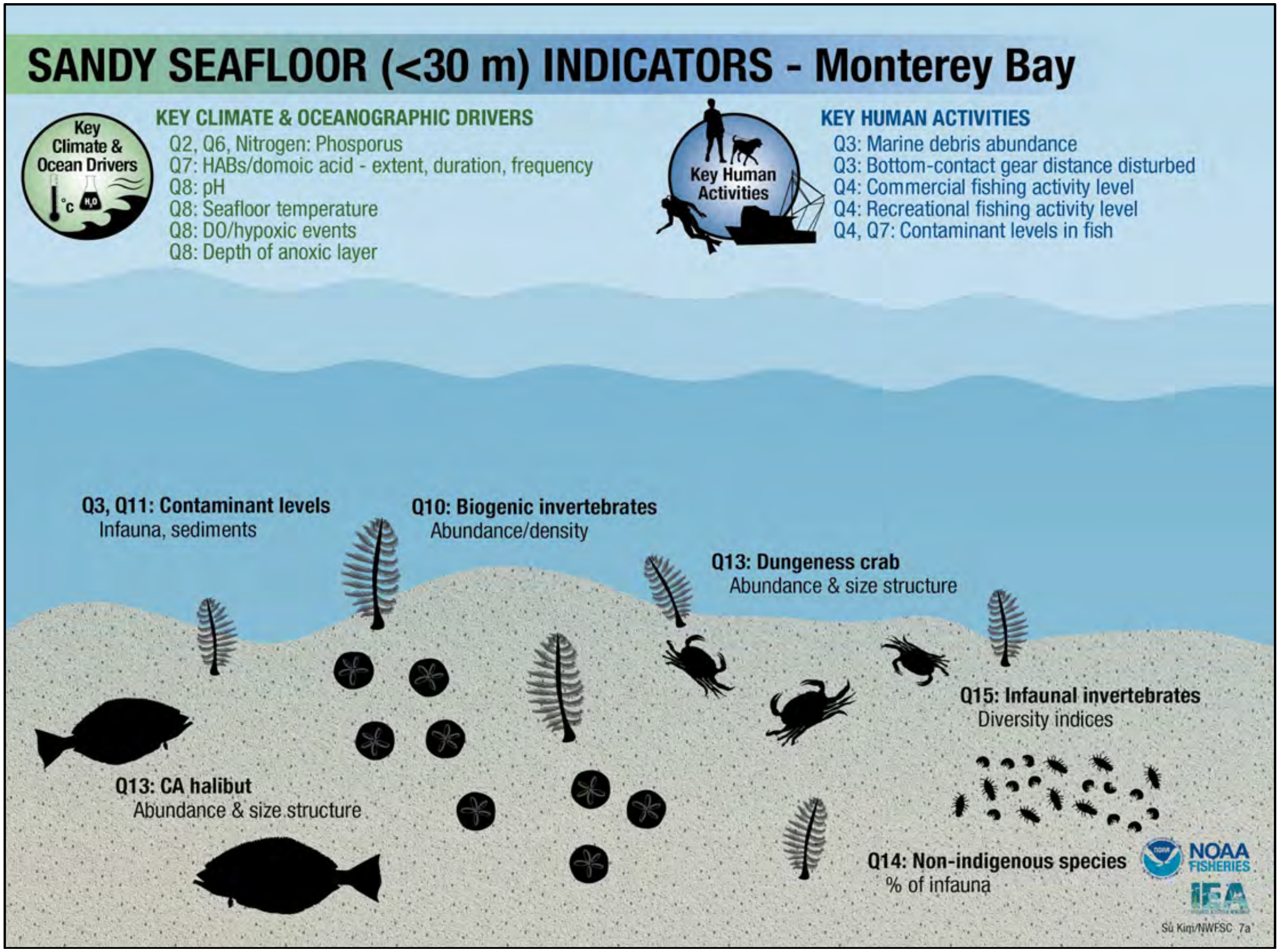

Figure B4. Conceptual model depicting the portfolio of indicators of ecosystem components (black font), climate and ocean drivers (green font), and human pressures (blue font) for the sandy seafloor habitat in Monterey Bay National Marine Sanctuary. Q numbers align with the standardized questions in Office of National Marine Sanctuaries condition reports (Text Box 1). Image: Su Kim/NOAA

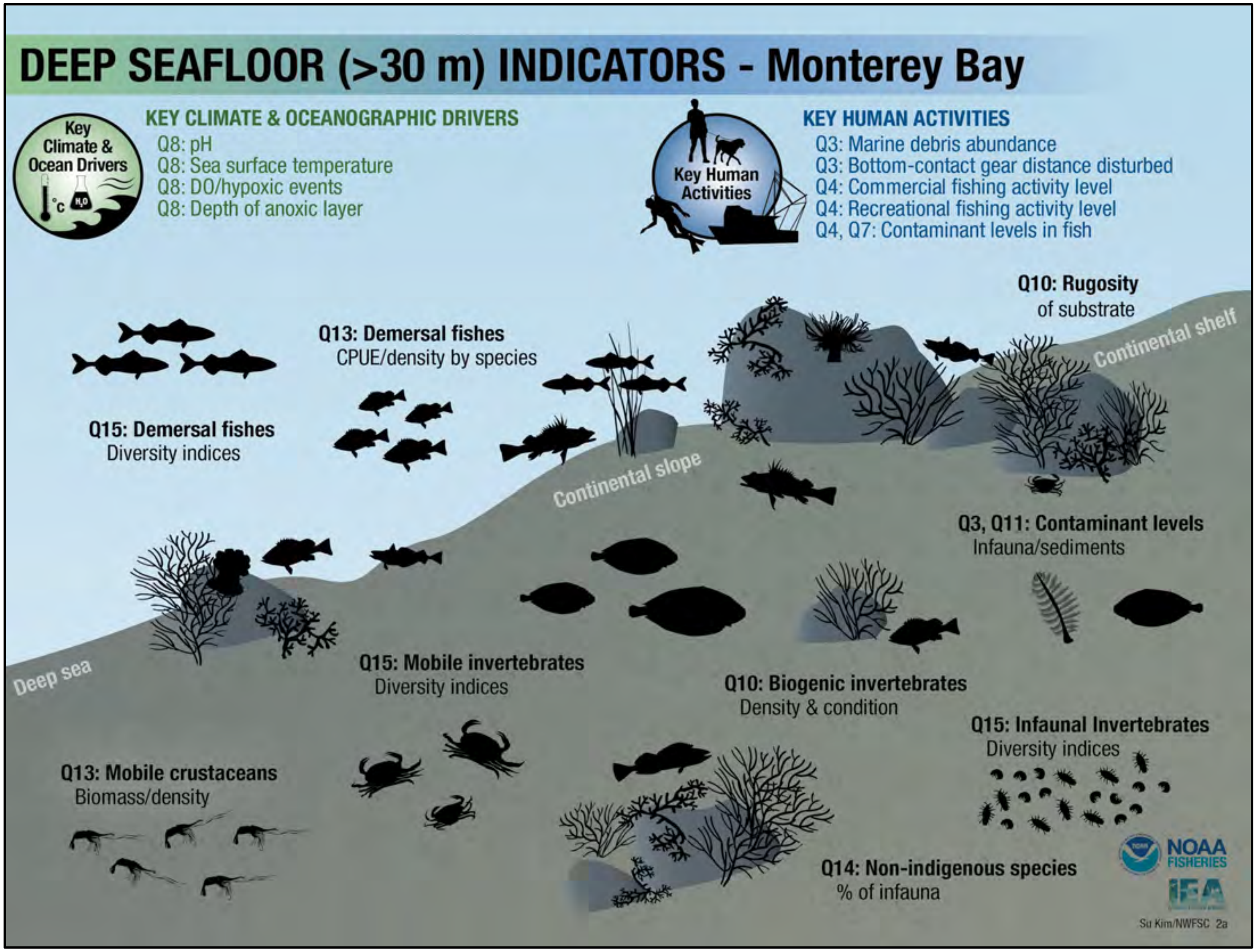

Figure B5. Conceptual model depicting the portfolio of indicators of ecosystem components (black font), climate and ocean drivers (green font), and human pressures (blue font) for the extensive deep seafloor habitat in Monterey Bay National Marine Sanctuary. Q numbers align with the standardized questions in Office of National Marine Sanctuaries condition reports (Text Box 1). Image: Su Kim/NOAA

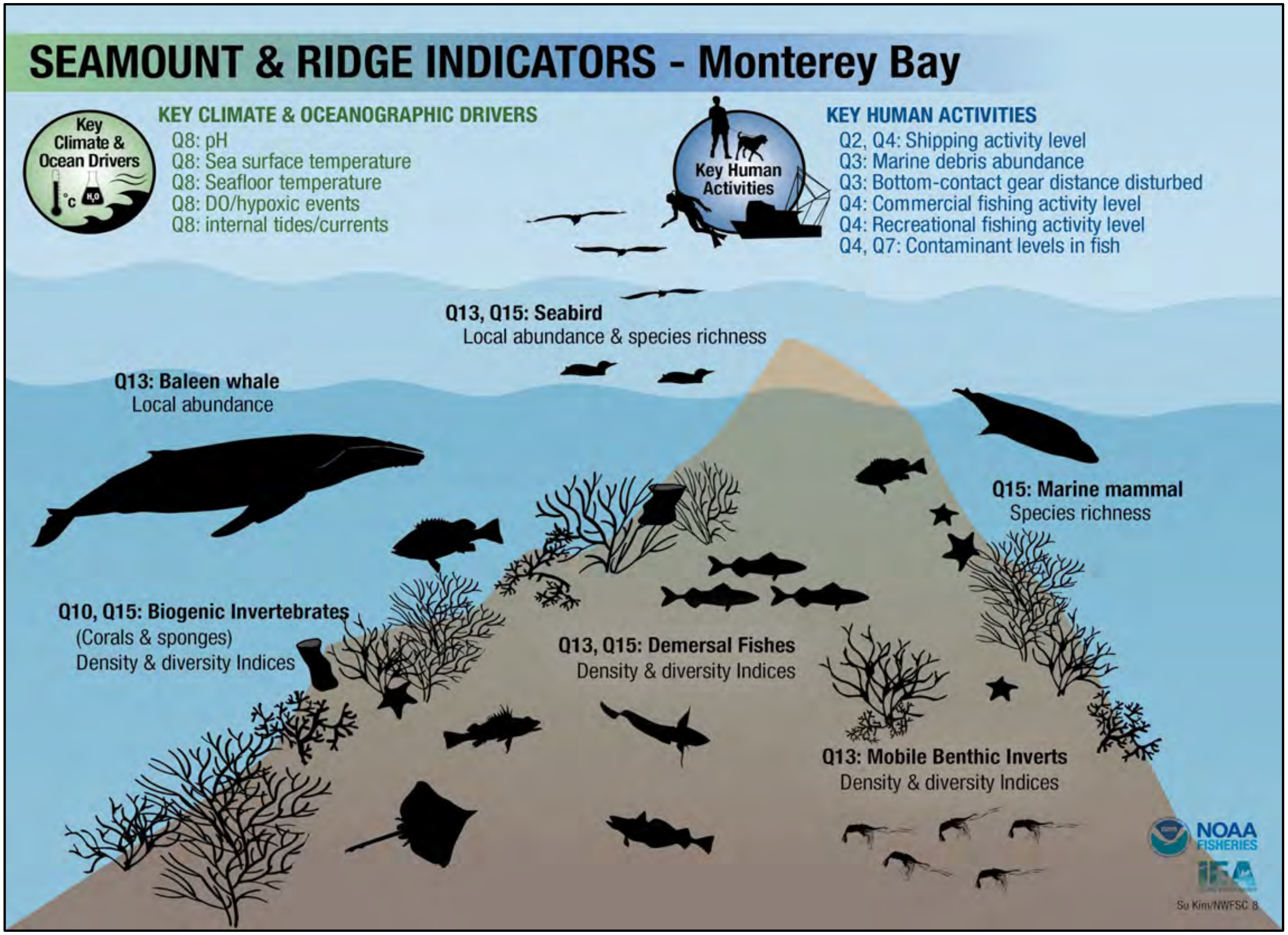

Figure B6. Conceptual model depicting the portfolio of indicators of ecosystem components (black font), climate and ocean drivers (green font), and human pressures (blue font) for the seamount and ridge habitat in Monterey Bay National Marine Sanctuary. Q numbers align with the standardized questions in Office of National Marine Sanctuaries condition reports (Text Box 1). Image: Su Kim/NOAA

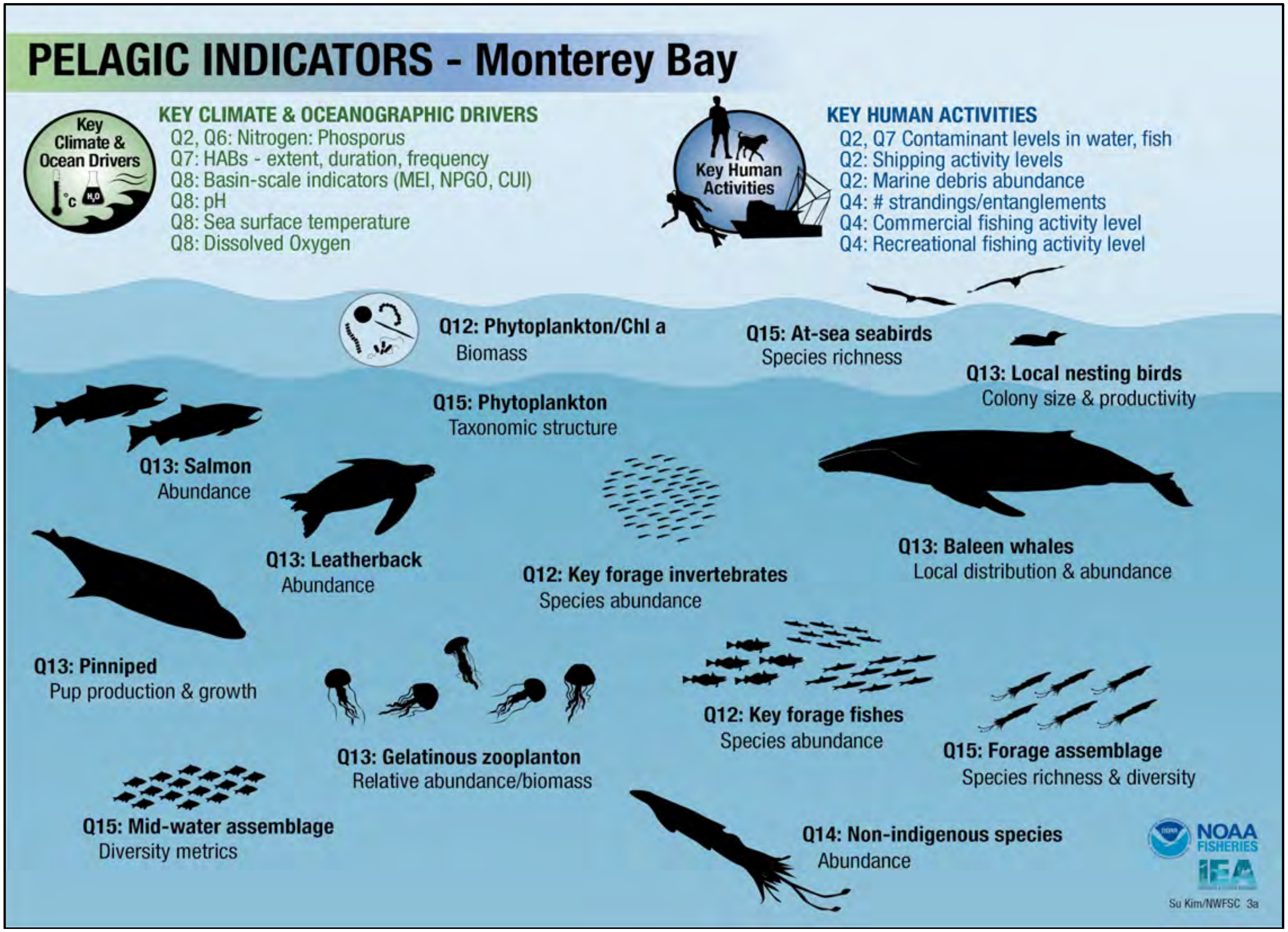

Figure B7. Conceptual model depicting the portfolio of indicators of ecosystem components (black font), climate and ocean drivers (green font), and human pressures (blue font) for the extensive pelagic habitat in Monterey Bay National Marine Sanctuary. Q numbers align with the standardized questions in Office of National Marine Sanctuaries condition reports (Text Box 1). Image: Su Kim/NOAA

Appendix C: Monterey Bay National Marine Sanctuary final indicator portfolios

Table C1. Portfolio of ecosystem component indicators for the estuary habitat in Monterey Bay National Marine Sanctuary.

Key attribute	Indicator	Condition report question	Used in MBNMS 2015 report?	West Coast indicator portfolios	Available data in MBNMS	Other comments
Habitat quantity	Rates of erosion/ accretion	Q10: Major habitats	No	ESNERR; WAMSP	**Good** - ESNERR main channel bank erosion rate time series since 2002	Vulnerability/resilience to sea level rise; related to salt marsh and eelgrass health
Habitat quantity	Native oyster - abundance/ density	Q10: Major habitats; Q12: Foundation species	Yes	CCMP; NCCMP; WAMSP; ESNERR	**Good** - ESNERR monitoring of oyster cover/density since 2007	Management priority, biogenic habitat value, native species
Habitat quantity	Eelgrass - areal extent	Q10: Major habitats; Q12: Foundation species	Yes	CCMP; NCCMP; PSP; CCIEA, WAMSP; GFNMS-OCI; ESNERR	**Good** - ESNERR time series since 1965 (every other year since 2000)	Management priority (essential fish habitat), internationally compatible, linkable to targets, biogenic habitat
Habitat quantity & quality	Saltmarsh - areal extent and condition	Q10: Major habitats	Yes	NCCMP; SCMP; CCIEA; GFNMS-OCI; ESNERR; SFBAY	**Good** - ESNERR time series for aerial extent (but only some years); on-going monitoring; **Limited:** recent CRAM scores of saltmarsh condition (CCWG)	Historic data set and on-going monitoring; management priority, linkable to targets, understood by public
Habitat quantity	Contaminant levels in tissues - shellfish	Q11: Contaminants in habitats; Q7: Human health	Yes		**Limited** - NOAA Mussel Watch data (1986-present); State Mussel Watch; CCLEAN monitoring	National indicator; federal guidelines for some contaminants; no monitoring for some contaminants; cross-habitat indicator
Habitat quantity	Contaminants in tissues - infauna, sediments	Q11: Contaminants in habitats; Q3: Human activities & habitats	No	WAMSP	**Data deficient** - no current monitoring program; some studies in the past	Cross-habitat indicator; management relevance; national standards
Population size	Sea otter - abundance	Q12: Keystone & foundation species	Yes	ESNERR	**Good** - USGS Western Ecological Research Center census counts in Elkhorn Slough since 1985; ESNERR monitoring since 2009	Cross-habitat indicator; management relevance (ESA listed), understood by public; keystone spp/trophic cascade in estuary (Hughes et al. 2013)

Key attribute	Indicator	Condition report question	Used in MBNMS 2015 report?	West Coast indicator portfolios	Available data in MBNMS	Other comments
Population size	Waterbirds - abundance target species	Q13: Other key species	No	CCMP; NCCMP; SCMP; ESNERR; SFBAY; PSP; WAMSP	**Limited** - ESNERR annual surveys of abundance of shorebirds (since 2003); Audubon Christmas bird count data	Management relevance (Migratory Bird Act), understood by public
Population size	Benthic macro-invertebrates - density, relative abundance	Q13: Other key species	Yes	CCMP; NCCMP; SCMP; GFNMS-OCI; ESNERR; SFBAY	**Good** - ESNERR density of fat innkeeper worm, gaper and butter clams annual time series since 2002	Important mid-trophic levels species; existing monitoring program
Population size	Flatfishes - diversity, relative abundance	Q13: Other key species; Q15: Biodiversity	No	CCMP; NCCMP; SCMP; ESNERR;	**Data deficient** - no current monitoring program; time-series pieced together by Hughes et al. 2012	Theoretically sound, relevant to management concerns (important fisheries species); little to no data available
Community composition	Non-indigenous species - % biomass non-native	Q14: Non-indigenous species	No	SFBay	**Limited** - ESNERR invasive species monitoring program; MLML surveys of infaunal community repeated infrequently	Theoretically sound, linkable to targets, understood by public; cross-habitat indicator
Community composition	Infaunal invertebrates - diversity indices	Q15: Biodiversity	No		**Data deficient** - MLML collected samples in the 1970s, 2003-2006 (main channel of ES), 2007-2009 (tidal wetlands)	Indicator of pollution, invasions, habitat change, but very limited data available.
Community composition	Resident fish - diversity indices	Q15: Biodiversity	No	CCMP; NCCMP; SCMP; ESNERR; SFBAY	**Data deficient** - no current monitoring program in Elkhorn Slough; time-series cobbled together recently by Hughes et al. 2012	Theoretically sound, relevant to management concerns (important fisheries species)
Community composition	Waterbirds - diversity indices	Q15: Biodiversity	No	CCMP; NCCMP; SCMP; ESNERR; SFBAY; PSP	**Limited** - ESNERR annual surveys of abundance of shorebirds (since 2003); some Audubon Christmas bird count data	Management relevance, history of reporting, cost-effective, nationally compatible

Table C2. Portfolio of ecosystem component indicators for the rocky shore habitat in Monterey Bay National Marine Sanctuary.

Key attribute	Indicator	Condition report question	Used in MBNMS 2015 report?	West Coast indicator portfolios	Available data in MBNMS	Other comments
Habitat quantity	Bare rock - % cover	Q10: Major habitats	No	WAMSP	**Good** - MARINe monitoring data	Indicator of physical habitat quantity and disturbance
Habitat quantity	Algal groups (e.g., *Ulva, Porphyra, Endocladia, Silvetia, Hesperophycus*) - % cover/ relative abundance	Q10: Major habitats; Q15 Biodiversity	Yes	CCMP; NCCMP; SCMP; WAMSP; GFNMS-OCI	**Good** - MARINe monitoring data	Community composition, responds to climate/ ecological change, different species indicators of high vs. low levels of natural and human disturbance (Murray et al. 2016)
Habitat quantity	Mussels (*Mytilus californianus*) - % cover	Q10: Major habitats; Q12: Foundation species	Yes	CC, NCC & SCMP; WAMSP; GFNMS- OCI	**Good** - MARINe monitoring data; LiMPETS monitoring data	Habitat-forming, fisheries, trophic structure; monitoring for contaminants, climate change
Habitat quantity	Barnacles (*Tetraclita, Balanus/ Chthamalus, Pollicipes*) - % cover	Q10: Major habitats	No	SCMP; WAMSP; GFNMS- OCI	**Good** - MARINe monitoring data	Important colonizer and space competitor, distribution and abundance may respond to climate change or other factors
Habitat quantity	Contaminant levels in tissues - mussels	Q11: Contaminants in habitats; Q7: Human health	Yes		**Limited** – NOAA Mussel Watch (10 sites); State Mussel Watch (5 sites); CCLEAN monitoring	National indicator; federal guidelines for some contaminants; no monitoring for some contaminants; cross-habitat indicator
Population size & condition	*Pisaster ochraceus* - abundance & size structure	Q12: Keystone species	Yes	CC, NCC & SCMP; GFNMS-OCI; WAMSP	**Good** - MARINe monitoring data (count and size data)	Keystone species, mid-trophic level indicator of trophic structure, sensitive to disease outbreaks
Population size & condition	Black abalone - abundance & size structure	Q13: Other key species	Yes	CCMP; NCCMP; SCMP	**Good** - MARINe monitoring data (count and size data)	Management priority (ESA), sensitive, ecosystem engineer, indicator of low disturbance sites (Murray et al. 2016)
Population size & condition	Owl limpet - abundance & size structure	Q13: Other key species	Yes	CC, NCC & SCMP; WAMSP	**Good** - MARINe monitoring data (count and size data)	Sensitive, harvested, indicator of low disturbance sites (Murray et al. 2016)

Key attribute	Indicator	Condition report question	Used in MBNMS 2015 report?	West Coast indicator portfolios	Available data in MBNMS	Other comments
Population size	Black Oystercatcher - abundance	Q13: Other key species	Yes	CCMP; NCCMP; WAMSP	**Data deficient** - Audubon Christmas Bird Count, one-time study (Weinstein et al. 2014)	Prominent, important predator, sensitive to human activity
Population size & condition	Mussels & barnacles - recruitment	Q13: Other key species; Q10: Major habitats	No	CCMP, WAMSP	**Limited** - MARINe recruitment data (settlement plates)	Measures supply of new individuals to population; can help determine mechanism driving change in adult population
Population size	Non-indigenous species - # sites (spread) & abundance	Q14: Non-indigenous species	Yes		**Limited** - some MARINe biodiversity monitoring data; some one-time surveys (e.g., Zabin et al. 2018)	Management priority, sensitive to human activities, ecological impacts to habitat/community. Species of concern include *Watersipora* spp., *Sargassum muticum, Caulacanthus ustulatus* (Zabin et al. 2018)
Community composition	Invertebrates - diversity indices	Q15: Biodiversity	No	CC, NCC & SCMP; WAMSP	**Good** - MARINe biodiversity monitoring data	Working with MARINe to identify metrics that best inform changes in ecological condition

Table C3. Portfolio of ecosystem component indicators for the sandy beach habitat in Monterey Bay National Marine Sanctuary.

Key attribute	Indicator	Condition report question	Used in MBNMS 2015 report?	West Coast indicator portfolios	Available data in MBNMS	Other comments
Habitat quantity	Armored beach - areal extent	Q10: Major habitats; Q3: Human activities & habitats	Yes	CCIEA; PSP; WAMSP	**Limited** - 2006 ESI (not a time series); # permits for shoreline modification	Relevant to management issues (habitat conversion, sand/sediment processes)
Habitat quantity	Rates of erosion/ sediment deposition	Q10: Major habitats	Yes	WAMSP	**Limited** - some locations with measurements; no time series	Relevant to management issues (sand mining, road construction, landslide impacts)
Habitat quantity	Macrophyte wrack - abundance & species composition	Q10: Major habitats	No	CCMP; SCMP, WAMSP	**Limited** - only from northern management area (Beach Watch, Nielsen et al. 2013)	Food source; biogenic habitat; influences invertebrate community composition; impacted by human activities (e.g., beach grooming)
Habitat quantity	Sand grain size	Q10: Major habitats	No		**Data deficient**	Influences invertebrate community composition (Dugan et al. 2015)
Habitat quantity	Contaminant levels in sand crabs	Q11: Contaminants in habitats	No	PSP	**Data deficient**	Indicator of coastal contaminants (Dugan et al. 2005)
Population size & condition	Sand crab (*Emerita analoga*) abundance & size structure	Q12: Keystone & foundation species	No	CCMP, NCCMP & SCMP; GFNMS- OCI	**Limited** - LiMPETS monitoring program (data quality may improve with recent changes in methods - see Nielsen et al. 2013; Dugan et al. 2015)	Indicator of beach condition; changes in mid-trophic level abundance/biomass can indicate changes in health of the food web (Dugan et al. 2015, Nielsen et al. 2013)
Population size	Talitrid amphipods (*Megalorchestia*) abundance	Q13: Other key species	No	SCMP	**Data deficient** - a little data available for beaches in north central CA MPA region only (Nielsen et al. 2013)	Good indicator of beach condition and trophic structure (Dugan et al. 2015, Nielsen et al. 2013)
Population size & condition	Snowy plover – abundance & reproductive success	Q13: Other key species	Yes	CCMP	**Good** - annual abundance at nesting beaches (since 1997 by Point Blue/PRBO)	Management priority (Migratory Bird Act & ESA listed), sensitive to habitat disturbance; responds to management, public interest
Population size	Marine birds - Abundance	Q13: Other key species	No	CCMP, NCCMP & SCMP;	**Data deficient** - Audubon Christmas Bird Count (few locations); some data in	Recommended as indicator in Nielsen et al. 2013 and Dugan et al. 2015. Could be a good indicator if data is available

Key attribute	Indicator	Condition report question	Used in MBNMS 2015 report?	West Coast indicator portfolios	Available data in MBNMS	Other comments
				WAMSP, SFBay	northern management area (Nielsen et al. 2013)	
Community composition	Non-indigenous species - % of infauna	Q14: Non-indigenous species	No		**Data deficient** - no current monitoring; baseline data (MLML Benthic Lab surveys in 1970s, 1990s, 2000s)	Should be tracked in case non-indigenous species of concern emerges
Community composition	Marine birds - species richness	Q15: Biodiversity	No	CCMP, NCCMP & SCMP; WAMSP; CCIEA	**Data deficient** - Audubon Christmas Bird Count - few locations; some data in northern management area (Nielsen et al. 2013)	Tightly correlated with the species richness and abundance of intertidal invertebrates (Schlacher et al. 2014, Dugan et al. 2015)
Community composition	Wrack consumers - abundance & species richness	Q13: Other key species; Q15: Biodiversity	No	SCMP; CCMP; WAMSP	**Data deficient** - some data in northern management area (Nielsen et al. 2013)	Scavenger/detritivore biomass is correlated with several measures of diversity and total biomass

Table C4. Portfolio of habitat and living resources key attribute indicators for kelp forest and rocky reef habitat (0-30 m depth) in Monterey Bay National Marine Sanctuary.

Key attribute	Indicator	Condition report question	Used in MBNMS 2015 report?	West Coast indicator portfolios	Available data in MBNMS	Other comments
Habitat quantity	Kelp canopy - Areal extent	Q10: Major habitats; Q12: Foundation species	Yes	CC, NCC & SCMP; WAMSP; GFNMS-OCI, CCIEA	**Good** - from Landsat data (SBC-LTER); some CDFW aerial overflights (not every year)	Critical, foundational species; good monitoring data; understood by public, management relevance (Essential Fish Habitat)
Habitat quantity	Understory algae - Abundance	Q10: Major habitats	Yes	CC, NCC & SCMP; WAMSP; GFNMS-OCI,	**Good** - PISCO monitoring - stipe count data and point contact data	Important habitat component especially when kelp absent; PISCO suggested reporting on *Pterygophora* and erect red algae
Population size and condition	*Pisaster* & *Pycnopodia* - Density & size structure	Q12: Keystone species	Yes	CC, NCC & SCMP; WAMSP; GFNMS-OCI	**Good** - PISCO monitoring; Reef Check CA monitoring	Cross-habitat indicator, target of extensive survey effort due to sea star wasting syndrome; important benthic predators
Population size and condition	Sea urchin - Density & size structure	Q12: Keystone species	Yes	CC, NCC & SCMP; WAMSP; GFNMS-OCI; WAMSP	**Good** – PISCO monitoring; Reef Check CA monitoring (red and purple urchins)	Keystone species with critical effects on kelp canopy; good monitoring data; management relevance (harvested)
Population size	Sea otter - Abundance	Q12: Keystone species	Yes	SCMP; WAMSP	**Good** – USGS Western Ecological Research Center biannual survey data	Keystone species; cross-habitat indicator; management relevance (ESA protected), understood by public; history of reporting
Population size and condition	Abalone - Density & size structure	Q13: Other key species	Yes	NCCMP; SCMP; WAMSP; GFNMS-OCI	**Good** – PISCO monitoring; Reef Check CA monitoring	management relevance (ESA protected); economically important (harvest/aquaculture); disease; good monitoring data
Population size	Kelp forest fish - species abundance, size structure	Q13: Other key species	Yes	CC, NCC & SCMP; WAMSP, CCIEA	**Good** – PISCO monitoring; Reef Check CA monitoring (lingcod, black RF, blue RF, cabezon, kelp greenling, striped surfperch)	Management relevance (some fished and unfished species); trophic structure; responds to management changes
Population size	young-of-the-year Rockfish - abundance/ density (recruitment)	Q13: Other key species	Yes	CCMP; WAMSP; CCIEA	**Good** – PISCO monitoring; Reef Check CA monitoring	Linked to oceanographic conditions; important prey, management relevance; sensitive to ecosystem attributes.

Key attribute	Indicator	Condition report question	Used in MBNMS 2015 report?	West Coast indicator portfolios	Available data in MBNMS	Other comments
Population size & condition	Nesting seabirds - colony size & fledging rate	Q13: Other key species	Yes	CCMP, SCMP, CCIEA	**Limited** - Brandt's and pelagic cormorant, pigeon guillemot - data for Año Nuevo and Farallon Islands	Indicator of ecosystem condition and prey availability
Community composition	Non-indigenous species - # sites & abundance	Q14: Non-indigenous species	Yes	SFBay	**Limited** - some PISCO/ MBNMS monitoring data; some one-time surveys; (*Sargassum muticum, Undaria, Watersipora*)	Management priority, sensitive to human activities, responds to management changes, ecological impacts to habitat/community, data available
Community composition	Kelp forest fish - diversity indices	Q15: Biodiversity	Yes	CC, NCC & SCMP; WAMSP; CCIEA	**Good** – can be calculated using PISCO data	Cross habitat indicator; composite indicator; work with MBON to determine most informative metrics
Community composition	Biogenic invertebrates - cover & diversity indices	Q15: Biodiversity	No	CCMP; NCCMP; WAMSP	**Good** – should be able to calculate using PISCO data (corals, sponges, anemones, etc.)	Cross habitat indicator, important habitat, sensitive to human activities and climate change

Table C5. Portfolio of ecosystem component indicators for the sandy seafloor habitat (0-30 m depth) in Monterey Bay National Marine Sanctuary.

Key attribute	Indicator	Condition report question	Used in MBNMS 2015 report?	West Coast indicator portfolios	Available data in MBNMS	Other comments
Habitat quantity	Biogenic invertebrates (e.g., sea whips, sea pens, sand dollars) - abundance/ density	Q10: Major habitats	No	CC, NCC & SCMP; GFNMS-OCI, CCIEA	**Data deficient** - No monitoring of biogenic species; some characterization studies (see trawling pressures for possible indicator related to the inverse of this)	Cross habitat indicator, management concern, sensitive to human activities and climate change
Habitat quality	Contaminant levels - in infauna or sediments	Q11: Contaminants in habitats; Q3: Human activities & habitat	Yes		**Data deficient** - no current monitoring program; possibly some CCLEAN or EPA data	Management concern, public interest, sensitive to human activities; regulatory standards; cross habitat indicator
Population condition	Contaminant levels - in demersal fish	Q7: Human health; Q4: Human activities & LR	Yes	SFBay	**Data deficient** - SWAMP data on contaminant levels in nearshore fishes (intermittent samples - no regular time series)	Management concern, public interest, integrated response desirable; sensitive to human activities; regulatory standards; cross habitat indicator
Population size & condition	Dungeness crab - abundance/ biomass & size structure	Q13: Other key species	No	CC, NCC & SCMP	**Limited** - no monitoring of biomass/density; fisheries-dependent data on crab landings could be used to calculate CPUE and abundance of crabs; size data?	Commercially and ecologically important member of community; management concern, public interest, sensitive to human activities
Population size & condition	California halibut - abundance/ biomass & size structure	Q13: Other key species	No	CC, NCC & SCMP; CCIEA	**Limited** - no monitoring of biomass/density; commercial (CDFW) and recreational (CRFS) fisheries-dependent data on crab landings could be used to calculate CPUE and abundance of crabs; size data?	Commercially and ecologically important member of community, management concern, public interest, sensitive to human activities
Community composition	Non-indigenous species - % of infaunal invertebrates	Q14: Non-indigenous species	No	SFBay	**Data deficient** - CCLEAN sampling; MLML surveys of infaunal community repeated infrequently (1971-75, 97-98, 2014-15; K Hammerstrom pers com); EPA sampling?	Cross habitat indicator, management concern. When ecosystems lose native benthic diversity, they can be less productive, less resilient, and provide fewer ecological services

Key attribute	Indicator	Condition report question	Used in MBNMS 2015 report?	West Coast indicator portfolios	Available data in MBNMS	Other comments
Community composition	Infaunal invertebrates - functional/ taxonomic diversity	Q15: Biodiversity	No	CC, NCC & SCMP	**Data deficient** - CCLEAN sampling; MLML surveys of infaunal community repeated infrequently (1971-75, 97-98, 2014-15; K Hammerstrom pers com); EPA sampling?	Benthic invertebrates are localized indicators of condition; changes in benthic community patterns can indicate large recent changes in nutrient loading, toxic substances, or sedimentation patterns.

Table C6. Portfolio of ecosystem component indicators for the deep seafloor habitat (>30 m depth) in Monterey Bay National Marine Sanctuary.

Key attribute	Indicator	Condition report question	Used in MBNMS 2015 report?	West Coast indicator portfolios	Available data in MBNMS	Other comments
Habitat quality	Rugosity of substrate	Q10: Major habitats	No	CCIEA	**Limited** - finescale substrate data for some of MBNMS >30 m (CA seafloor mapping)	Theoretically good, often used as proxy for habitat complexity, explains variation in species abundance
Habitat quantity & quality	Biogenic invertebrates (Corals, *Metridium*, sponges, sea pens) - density and condition	Q10: Major habitats	Yes	CC, NCC & SCMP; WAMSP; GFNMS-OCI	**Limited** - some monitoring in MLPA MPAs (to 365 m); some MBARI deep sea transects (mostly characterization)	Sensitive to human activities and climate change, cross habitat indicator, management interest, habitat-forming
Habitat quality	Contaminant levels in sediments/ infaunal community	Q11: Contaminant in habitats; Q3: Human activities & habitats	Yes	PSP	**Limited** - CCLEAN data at a few sites in Monterey Bay; some EPA and/or NCCOS data	Management concern, public interest, sensitive to human activities; regulatory standards, cross habitat indicator
Habitat quality	Contaminants levels in tissues - demersal fishes	Q7: human health; Q4: Human activities & LR	Yes		**Data deficient** - SWAMP data for shallower species (only a few years)	Management concern, public interest, sensitive to human activities; regulatory standards, cross habitat indicator
Population size	Mobile crustaceans - Population biomass / density	Q13: Other key species	No	CC, NCC & SCMP; WAMSP	**Limited** - monitoring in MLPA MPAs (to 365 m); landings info for commercial spp.; NMFS groundfish trawl surveys	Management concern (harvested), public interest
Population size	Demersal fishes – density/CPUE by species	Q13: Other key species	Yes	CCMP; SCMP; WAMSP, CCIEA	**Limited** - NMFS groundfish trawl surveys; landings info for commercial spp.; monitoring in MLPA MPAs (to 365 m)	Management concern, public interest, sensitive to human activities
Community composition	Non-indigenous species - % of infaunal invertebrates	Q14: Non-indigenous species	No	SFBay	**Data deficient** – some baseline data (CCLEAN, MLML); EPA & NCCOS?	Biodiversity, sensitive to human activities (e.g., contaminants, climate change), cross habitat indicator, management concern
Community composition	Infaunal invertebrates - functional/taxonomic diversity	Q15: Biodiversity	No	CCMP; NCCMP; SCMP	**Limited** - baseline data from CCLEAN and MLML sampling; EPA & NCCOS?	Sensitive to human activities, cross habitat indicator; loss of native benthic diversity can reduce productivity, resilience, and ecological services.

Key attribute	Indicator	Condition report question	Used in MBNMS 2015 report?	West Coast indicator portfolios	Available data in MBNMS	Other comments
Community composition	Mobile invertebrates - diversity indices	Q15: Biodiversity	No	CC, NCC & SCMP; WAMSP	**Limited** - monitoring in MLPA MPAs; landings/ CPUE info for commercial spp.; NMFS groundfish trawl surveys	Integrative indicator, compatible, management importance, influenced by human activities (harvest)
Community composition	Demersal fishes - diversity indices	Q15: Biodiversity	No	CC, NCC & SCMP; WAMSP, CCIEA	**Limited** - NMFS groundfish trawl; monitoring in MLPA MPAs	Integrative indicator, compatible, management importance, influenced by human activities (harvest)

Table C7. Portfolio of ecosystem component indicators for the seamount and ridge habitat in Monterey Bay National Marine Sanctuary.

Key attribute	Indicator	Condition report question	Used in MBNMS 2015 report?	West Coast indicator portfolios	Available data in MBNMS	Other comments
Habitat quantity	Biogenic invertebrates (corals & sponges) - density	Q10: Major habitats	Yes		**Data deficient** - MBARI/MBNMS characterization studies but not repeated sampling	Sensitive to anthropogenic activities and climate change, habitat-forming, public interest, island biogeography, data shortcomings
Population size	Mobile benthic invertebrates - density	Q13: Other key species	No		**Data deficient** - characterization studies but not repeated sampling	Management relevance (crustaceans), public interest, cross habitat indicator, data shortcomings
Population size	Demersal fishes - density	Q13: Other key species	Yes	CCIEA	**Limited** - characterization studies only; CCIEA data for seafloor surrounding seamounts/ridges	Management relevance (harvested species), public interest, responds to management, cross habitat indicator, data shortcomings
Population size	Seabirds - local abundance	Q13: Other key species	Yes	CCIEA	**Limited** - aerial and shipboard surveys of spp occurrence/ abundance; population trends for some species (not seamount specific data)	Public interest, management relevance, cross habitat indicator, data shortcomings
Population size	Baleen whales - local abundance	Q13: Other key species	Yes		**Limited** - aerial and shipboard surveys of spp occurrence/ abundance; stock assessments for status and trend info (not seamount specific data)	Good indicator for evaluating associations with these habitat features, public interest, management relevance, data shortcomings
Community composition	Biogenic invertebrates - diversity indices	Q15: Biodiversity	Yes		**Data deficient** - some diversity info McClain et a. 2010 (but only one time)	Sensitive to anthropogenic activities and climate change, habitat-forming, public interest, island biogeography
Community composition	Mobile benthic invertebrates - diversity indices	Q15: Biodiversity	No		**Data deficient** - no monitoring data; some diversity info McClain et a. 2010 (but only one time)	Management relevance (crustaceans), public interest, data shortcomings, cross habitat indicator
Community composition	Demersal fishes - diversity indices	Q15: Biodiversity	No	CCIEA	**Limited** – ROV characterization studies; CCIEA data for seafloor surrounding seamounts and ridges	Management relevance (harvested species, public interest, responds to management, data shortcomings, cross habitat indicator
Community composition	Marine mammals - species richness	Q15: Biodiversity	Yes		**Data deficient** - no LT monitoring data; some aerial and shipboard surveys of spp occurrence/ abundance	Good indicator for evaluating associations with these habitat features, public interest, management relevance, data shortcomings
Community composition	Seabirds - species richness	Q15: Biodiversity	Yes	CCIEA	**Data deficient** - no LT monitoring data; some aerial and shipboard surveys of spp occurrence/ abundance	Public interest, management relevance, cross habitat indicator, data shortcomings,

Table C8. Portfolio of ecosystem component indicators for the pelagic habitat in Monterey Bay National Marine Sanctuary.

Key attribute	Indicator	Condition report question	Used in MBNMS 2015 report?	West Coast indicator portfolios	Available data in MBNMS	Other comments
Population size	Phytoplankton/Chlorophyll a - biomass	Q12: Keystone & foundation species	Yes	WAMSP; CalCOFI, CCIEA	**Good** - MBARI stations; satellite-based time series data (CeNCOOS)	Foundation of food web, sensitive to ocean drivers and climate change
Population size and condition	Key forage invertebrates (krill, market squid) - species abundance	Q12: Keystone & foundation species	Yes	SCMP; CalCOFI-CCS; PaCOOS; CCIEA	**Good** - NMFS-SWFSC RREAS mid-water trawl surveys; CDFW landings	Management relevance, links to upper trophic levels, sensitive to ocean drivers
Population size and condition	Key forage fishes (sanddabs, anchovy, sardine, hake, rockfish, myctophids) - species abundance	Q12: Keystone & foundation species	Yes	CCMP; NCCMP; SCMP; WAMSP; GFNMS-OCI; CalCOFI-CCS; CCIEA	**Good** - NMFS-SWFSC RREAS mid-water trawl surveys); CDFW landings	Management relevance, links to upper trophic levels, sensitive to ocean drivers
Population size	Gelatinous zooplankton - relative abundance/biomass	Q13: Other key species	No	SCMP; WAMSP; CalCOFI-CCS; CCIEA	**Limited** - NMFS-SWFSC midwater trawl surveys; MBARI midwater ROV surveys	Trophic structure, ecosystem, increasingly understood by public
Population size & condition	Salmon - abundance	Q13: Other key species	No	CCIEA	**Good** - NMFS-SWFSC salmon surveys; CDFW CPUE from landings	Public interest, management concern, sensitive to ocean drivers
Population size and condition	Nesting seabirds - colony size & productivity - (pigeon guillemot, cormorants, common murre, Cassin's auklet, rhinoceros auklet)	Q13: Other key species	Yes	NCCMP; SCMP; PSP; SFBay; WAMSP; GFNMS-OCI; CalCOFI, CCIEA	**Good** - annual surveys of nesting colony size at SFI (Point Blue Conservation) & ANO (Oikonos)	Management relevance, public interest, some cross-habitat value, early indicators of ecosystem conditions
Population size and condition	Pinnipeds - population size & reproductive performance	Q13: Other key species	Yes	WAMSP; PFMC-CCE; CalCOFI-CCS; CCIEA	**Good** - NMFS-SWFSC annual pinniped surveys and California sea lion pups at San Miguel Is.	Linkable to ecosystem change, public interest, management concern
Population size	Baleen whales - local distribution & abundance	Q13: Other key species	No	WAMSP; CCIEA	**Limited** - periodic at-sea surveys in MBNMS; NMFS stock assessments	Management relevance, public interest, protected species

Key attribute	Indicator	Condition report question	Used in MBNMS 2015 report?	West Coast indicator portfolios	Available data in MBNMS	Other comments
Population size	Leatherback sea turtle - local distribution & abundance	Q13: Other key species	No		**Good** - NMFS aerials surveys (data collected in some form every year)	Protected species, public interest, local abundance linked to ecosystem attributes
Community composition	Humboldt squid - abundance	Q14: Non-indigenous species	Yes		**Good** - NMFS-SWFSC catch data; MBARI midwater ROV surveys	non-indigenous species, predator, strong food web impacts, responds to climate (but not predictably)
Community composition	Phytoplankton - Taxonomic structure	Q15: Biodiversity	Yes	WAMSP; PaCCOOS	**Good** - MBARI phytoplankton monitoring	Dinoflagellate:diatom ratio good indicator of conditions at the base of food web
Community composition	Forage assemblage - species richness & diversity	Q15: Biodiversity	Yes	CCIEA	**Good** - NMFS-SWFSC RREAS mid-water trawl surveys	Biodiversity, management interest, influenced by oceanographic drivers
Community composition	Mid-water assemblage - species composition & relative abundance	Q15: Biodiversity	No		**Limited** - MBARI midwater ROV surveys but time series not readily available	Biodiversity, influenced by oceanographic drivers, climate change
Community composition	At-sea seabirds - species richness	Q15: Biodiversity	No	PFMC-CCE; CalCOFI, CCIEA	**Limited** - at-sea surveys in MBNMS but time series not readily available	Biodiversity, management interest, influenced by oceanographic drivers

Table C9. Portfolio of indicators of ocean and climate drivers in all habitats in Monterey Bay National Marine Sanctuary.

Indicator	Habitat								Condition report question	Used in MBNMS 2015 condition report?	West Coast indicator portfolios	Available data in MBNMS	Other comments
	Estuary	Rocky Shore	Sandy Beach	Kelp forest & Reef	Sandy Seafloor	Deep Seafloor	Seamount & Ridge	Pelagic					
Eutrophic status/ Nutrient concentration	X								Q6: Eutrophic condition	Yes	GFNMS-OCI; ESNERR	**Good** - ESNERR monitoring since 1998	Habitat suitability, primary productivity, human impacts, responds to management
Aerial extent sea lettuce	X								Q6: Eutrophic condition	Yes	ESNERR	**Good** - ESNERR monitoring since 2010	Indicator for primary production, linked to eutrophication
Dissolved oxygen/ hypoxic events	X		X	X	X	X	X	X	Q6: Eutrophic condition; Q8: Climate change	Yes	CCIEA; WAMSP; GFNMS-OCI; PSP; PFMC-CCE; ESNERR	**Good** (estuary) - ESNERR monitoring; **Limited** - (for some habitats/locations) CeNCOOS; MBARI	Habitat suitability, water quality, degradation of organic matter, primary productivity
Sea surface temperature	X	X	X	X			X	X	Q8: Climate change	Yes	WAMSP; GFNMS-OCI; CalCOFI; PFMC-CCE; ESNERR	**Good** - ESNERR monitoring; CeNCOOS; MBARI moorings	Indicates changes in upwelling, water transport, habitat suitability, water quality
pH	X	X	X	X	X	X	X	X	Q8: Climate change	Yes	WAMSP; GFNMS-OCI; ESNERR	**Good** (estuary) - ESNERR monitoring; **Limited** - (for some habitats/locations) CeNCOOS; MBARI	Climate change. cross-habitat indicator
Sea level height	X	X	X						Q8: Climate change; Q10: Major habitats	No	GFNMS-OCI; WAMSP; ESNERR	**Good** - ESNERR monitoring; in situ tide gauge data	Habitat extent & exposure time, relevant to management, understood by public
Freshwater inflow	X								Q9: Other stressors; Q2: Human activity & WQ	No		**Limited** - USGS stream gages	Actual and unimpaired freshwater inflow to estuary
(Max) wave height & direction		X	X	X					Q8: Climate change	No	GFNMS-OCI; WAMSP	**Good:** National Data Buoy Center	Indicator of shoreline erosion, inundation time, beach condition

Indicator	Habitat								Condition report question	Used in MBNMS 2015 condition report?	West Coast indicator portfolios	Available data in MBNMS	Other comments
	Estuary	Rocky Shore	Sandy Beach	Kelp forest & Reef	Sandy Seafloor	Deep Seafloor	Seamount & Ridge	Pelagic					
Air temperature		X							Q8: Climate change; Q10: Major habitats	No		**Good:** CeNCOOS shore stations	Indicator of habitat suitability & exposure stress
Seafloor temperature				X	X	X	X		Q8: Climate change; Q10: Major habitats	No	CCIEA	**Data deficient**	Indicator of subtidal habitat quality
Upwelling Index				X					Q8: Climate change	No	CCIEA	**Good:** CCIEA indicator status and trend webpage	CUI estimate of the net influence of upwelling on ecosystem structure and productivity
Depth of anoxic layer					X	X			Q8: Climate change	No			
Harmful algal blooms/domoic acid – extent, duration, frequency					X			X	Q7: Human health	Yes	SFBay	**Limited –** in situ monitoring at two piers; prediction models for surface waters (CeNCOOS)	
Nitrogen: Phosphorus					X			X	Q6: Eutrophic condition; Q8: Climate change	No	CCIEA; WAMSP; PFMC-CCE	**Limited** - USGS, NADP; Halpern et al. 2009; CCIEA time series for CCE	Habitat quality, water quality and eutrophication; cross habitat
Internal tides/ currents							X		Q8: Climate change;	No		**Data deficient** - no *in situ* monitoring near features	A primary reason for biological productivity at seamounts and ridges
Basin-scale indices (e.g., PDO)								X	Q8: Climate change; Q9: Other stressors	Yes	WAMSP; CCIEA; CalCOFI; PFMC-CCE	**Good** - CCIEA indicator status and trend webpage	Timing, frequency, duration, intensity of oceanographic processes and phenomena

Table C10. Portfolio of indicators of human activities across all habitats in Monterey Bay National Marine Sanctuary.

Indicator	Habitats								Condition report question	Used in MBNMS 2015 condition report?	West Coast indicator portfolios	Available data in MBNMS	Other comments
	Estuary	Rocky Shore	Sandy Beach	Kelp forest & Reef	Sandy Seafloor	Deep Seafloor	Seamount & Ridge	Pelagic					
Indicator bacterial levels	X		X						Q2: Human activities & WQ; Q7: Human health	Yes	CCIEA	**Good** - AB411 testing at beaches with >50,000 visitors since 1999; Heal the Bay annual report cards	Responds to management, history of reporting, compatible nationally, understood by pubic
Waterbodies #/area impaired	X	X	X						Q2: Human activities & WQ; Q7: Human health	Yes	WAMSP	**Good** - Regional Water Quality Control Board 303(d) list of impaired waterbodies	Human impacts; responds to management, history of reporting, compatible regionally
Watershed activities	X								Q3: Human activities & habitats	Yes		**Limited** - Land use tracked by Elkhorn Slough Foundation	Human impacts; responds to management, understood by public
Contaminants – in water, sediments, infauna, shellfish, fish, mammals	X	X		X	X	X	X	X	Q2: Human activities & WQ; Q3: Human activities & habitats; Q4: Human activities & LR; Q7: Human health	Yes	PSP, CCIEA	**Limited** - some data available for some habitats/species - NOAA Mussel Watch; SWAMP, CCLEAN	Human impacts, responds to changes in management, history of reporting, nationally compatible, cross-habitat indicator
Recreational fishing – activity level	X	X		X	X	X	X	X	Q4: Human activities & living resources	Yes	WAMSP; PFMC-CCE; SCMP; CCIEA	**Good** - CDFW & NMFS data; RecFIN database	Human impacts; history of reporting; responds to management; cross-habitat indicator
# visitors by activity		X	X						Q3: Human activities & habitats; Q4: Human activities & LR	Yes	CCIEA; SCMP	**Limited** - MPA Watch citizen science (since 2011); CA State Park System Annual Statistical Report	Human impacts; non-consumptive uses, understood by public
Marine debris abundance		X	X	X	X	X	X	X	Q2: Human activities & WQ; Q3: Human activities & habitats;	Yes	CCIEA	**Limited** - Save Our Shores beach cleanup data since 2007; various studies but no	Human impacts, responds to management, history of reporting, compatible

Indicator	Habitats								Condition report question	Used in MBNMS 2015 condition report?	West Coast indicator portfolios	Available data in MBNMS	Other comments
	Estuary	Rocky Shore	Sandy Beach	Kelp forest & Reef	Sandy Seafloor	Deep Seafloor	Seamount & Ridge	Pelagic					
									Q4: Human activities & LR			regular monitoring in other habitats	nationally, understood by public
Amount of grooming			X						Q3: Human activities & habitats	No		**Data deficient**- no known database	Theoretically sound, human impacts to biodiversity
Erosion/ deposition rates			X						Q3: Human activities & habitats	Yes	WAMSP	**Limited** - available in some locations from USGS	Human impacts
Commercial fishing activity level				X	X	X	X	X	Q4: Human activities & LR	Yes	WAMSP; CCIEA; SCMP; PFMC-CCE	**Good** - CDFW & NMFS data; PacFIN database	Human impacts; history of reporting; responds to management; cross-habitat indicator
Bottom-contact gear distance disturbed					X	X	X		Q3: Human activities & habitats	Yes	WAMSP; PFMC-CCE; CCIEA	**Good** - California logbook trawl data	Human impacts; history of reporting; responds to management; cross-regional
Shipping activity level							X	X	Q2: Human activities & WQ; Q4: Human activities & LR	Yes	WAMSP; PFMC-CCE; CCIEA	**Good** - U.S. Coast Guard NAIS data, NPS AIS data via CeNCOOS portal	Human impacts, responds to management; cross-regional
# strandings/ entanglements								X	Q4: Human activities & LR	Yes	CCIEA	**Good** - Beach COMBERS); TMMC data (stranded mammals); NMFS PRD data (mammals)	Human impacts, responds to management, history of reporting, compatible nationally, understood by public

Appendix D: MBNMS kelp forest and rocky reef habitat interim indicator screening table

Due to sizing constraints, a PDF version of Appendix D is available for download on the Office of National Marine Sanctuaries website at https://sanctuaries.noaa.gov/science/conservation/2019-science-based-indicator-portfolios.html.

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