Biological and Chemical Monitoring Coordination

Recommendations to the Ocean Protection Council from the California Ocean Acidification and Hypoxia Monitoring Expert Panel

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About this document

This report was produced by an expert Panel (the Panel) composed of Jim Barry, Francis Chan, Jan Newton, Su Sponaugle, with support from the California Ocean Science Trust (OST). The Panel was convened by OST on behalf of the Ocean Protection Council (OPC) from December 2020 and April 2021.

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Executive Summary

- The intensification of ocean acidification and hypoxia (OAH) will put more and more of California's productive, rich, and commercially important marine life at risk. An OAH ocean observing network is key to understanding which species of marine life will be impacted, which habitats will be altered and which fisheries will be compromised.
- California does not have a state-wide ocean observing system that can provide early warnings of the biological impacts of OAH.
- California is home to a number of long-term seagoing research programs that if coordinated can become the world's premier large-scale OAH ocean observing network.
- This report identifies five near-term recommendations for integrated biological and chemical monitoring that best leverage the opportunities and expertise of ongoing monitoring programs; projects resulting from these recommendations are likely to accelerate the understanding of potential OAH impacts and provide meaningful information for the California State of the Coast and Ocean Report.
- The recommendations were chosen to better connect the dots between exposure to stressors and changes in ocean food webs, including harmful algal blooms and the abundance and distribution of key forage taxa.
- The recommendations also prioritize the addition of capacity allowing California's nascent OAH ocean observing network to take advantage of new technologies that "future proof" and maximize the knowledge gained from observing missions.
- The ocean observing programs identified in this report are already engaged in OAH-focused observations. Infusion of funds leverages their ship time, expertise in advancing biological observations, and commitment to coordinated ocean monitoring to jump-start a statewide, decision-relevant OAH observing network.
- The five recommendations are part of a broader portfolio of observing activities that can inform the full range of increasing OAH decision-making needs. Their implementation compliments efforts such as localized or fishery-specific observations, controlled experiments and/or modeling efforts to support climate and OA-ready fishery and ecosystem management in the State.
- The new monitoring activities also represent a valuable opportunity to involve students and scientists from under-represented groups in the use of innovative ocean science technologies, and to engage ocean users from underserved communities in developing shared understanding of ocean issues.

Introduction

The coordination and integration of biological and chemical measurements has been identified as a key priority to enhance California's ocean acidification and hypoxia (OAH) monitoring network (Weisberg et al, 2020). The utility of California's OAH observing network would be maximized by such coordination and integration, allowing managers to better understand impacts of OAH exposure on marine ecosystems, and provide the State of California with the ability to act on key OAH priorities, such as developing 1) a Report Card on the state of California's Coast and Ocean (OPC Strategic Plan Target 3.6.1), 2) adaptive management approaches to assess and respond to climate-driven shifts in fish populations and fisheries (OPC Strategic Target 3.3.4), and 3) new water quality criteria for OAH, one of the priorities highlighted in the California Ocean Acidification Action Plan (Philips et al, 2018).

To this end, an expert Panel (the Panel) was convened by Ocean Science Trust (OST) on behalf of the Ocean Protection Council (OPC) to fill this management gap. Panel members were jointly selected by OPC and OST based on the following two criteria 1) experts who were not associated with the targeted monitoring programs 2) experts spanning various marine biology, geochemistry, and oceanography disciplines ensuring their expertise would be complementary to each other. The Panel was tasked to develop recommendations for projects that could enhance and standardize OAH sensitive biological measurements into ongoing OAH regional monitoring programs in California. In its latest report, the California OAH Task Force (Task Force) identified five major ongoing monitoring programs to target for this effort. These programs were recommended by the Task Force because together they provide a wide spatial range of OAH exposure conditions, necessary to achieve the desired correlation between biological condition and OAH exposure and have all expressed willingness to coordinate their efforts.

The five monitoring programs are:

1) **Applied California Current Ecosystem Studies (ACCESS):** ACCESS is a private/public partnership that supports marine wildlife conservation and healthy marine ecosystems in north-central California by conducting ocean research to inform resource managers, and policy makers. ACCESS and its partners track ocean climate to examine seasonal patterns and assess how the ecosystem is responding to large, basin-scale climate shifts among years. Ongoing cruises started in 2004, and take place from April to October on the NOAA National Marine Sanctuary Research Vessel Fulmar. Fifty-one cruises have been completed to date.
2) **California Cooperative Fisheries Investigation (CalCOFI):** CalCOFI consists of a partnership between the California Department of Fish and Wildlife, the NOAA Fisheries Service and the Scripps Institution of Oceanography. CalCOFI was formed in 1949 and

focuses on the study of the marine environment off the coast of California, the management of its living resources, and monitors the indicators of El Nino and climate change. CalCOFI conducts quarterly cruises off Southern and Central California, collecting a suite of hydrographic and biological data (at 75 stations in summer and fall, and 103 in winter and spring). In 2004, the CalCOFI surveys became part of the LTER (Long Term Ecological Research) ecological studies network as a site to understand the pelagic ecosystem of the California Current.

3) **California Current Ecosystem Long-term Ecological Research (CCE LTER):** the CCE LTER site is an interdisciplinary group of scientists, students, and educators that is working to understand and communicate the effects of long-term climate variability on the California Current pelagic ecosystem. CCE LTER is based at the Scripps Institution of Oceanography but currently includes partners at four other institutions (Duke University, Georgia Institute of Technology, Point Reyes Bird Observatory Conservation Science, and the Southwest Fisheries Science Center/National Marine Fisheries Service). CCE LTER has a long-term partnership with CalCOFI, utilizing CalCOFI's cruise observations and deploying spray gliders along three CalCOFI cruise lines in Southern California.
4) **The NOAA West Coast Ocean Acidification Regional Survey Cruises** span along the North American coastlines (Atlantic, Pacific, Gulf of Mexico, and Alaskan) and in the global open ocean and focus on mapping and monitoring the distribution of key indicators of ocean acidification including carbon dioxide, pH, and carbonate mineral saturation states.
5) **SCCWRP Southern California Bight Regional Monitoring Program:** The Southern California Bight Regional Monitoring Program is an ongoing marine monitoring collaboration that examines how human activities have affected the ecological health of more than 1,500 square miles of Southern California's coastal waters. Via this partnership, facilitated by SCCWRP, dozens of participating organizations pool their resources and expertise to investigate the condition of marine ecosystems across both time and space. Both regulated and regulatory agencies, as well as non-governmental and academic organizations, come together to design studies, interpret findings, and speak with a common voice about the ecological health of the Southern California Bight.

As part of this effort, OST and OPC initially surveyed the five monitoring programs to obtain additional information on the programs, their ongoing chemical and biological measurements, and program capacity for data analysis, translation, and delivery. A summary of the survey results can be found in Table A-1.

Process

A. Standardization of ongoing chemical monitoring

The utility of California’s OAH observing network would be maximized by the use of uniform methods for chemical measurements among all monitoring programs. A comprehensive comparison of the similarity of ongoing chemical measurements among the five observing programs was difficult owing to the uneven detail in the survey results for each monitoring program. Nevertheless, the Panel noted that methodologies appear sound and have very high confidence in the caliber of the teams to determine the most suitable high-quality chemical monitoring techniques and protocols. That being said, comparisons among the teams and sharing of protocols would be valuable. For instance, are nutrient measurements included in all programs, and if so, the same ones? Such alignment may benefit interpretation over the California Current.

The Panel recommends that 1) support for chemical measurements be maintained for all observing programs, 2) attention be paid to not disrupt continuity of long term time-series observations, which are essential for detecting environmental change, 3) sampling coverage be assessed, including consideration of adding sampling over the full depth of the water column as well as closer to shore to detect horizontal and vertical OAH gradients, 4) OAH chemical spatial sampling plans be coordinated among programs to reveal potential synergies or opportunities.

B. Proposed biological indicators for integration with existing monitoring programs

The Panel considered a variety of biological indicators that could be added to or coordinated more comprehensively among ongoing monitoring programs. Some of the indicators considered are currently measured by one or more of the five monitoring programs. Other indicators were nominated for consideration by the Panel. Over thirty biological indicators were considered, ultimately grouped into seventeen activities evaluated for recommendation (Table A.2). Criteria used to rate their value for broader use across monitoring programs included:

- **Value to resource managers:** Would new or more broadly available biological observations help decision-making for resource managers in relation to OAH conditions and change?
- **Link to attribution:** Could patterns or trends in biological observations be linked strongly to OAH conditions / observations?
- **Scientific feasibility:** Are the required methods and technologies sufficiently developed and available to support the adoption of measurements across all of the monitoring programs?

- **Likelihood of adoption by monitoring programs:** Will addition of the biological observations for a 2-3 y period promote longer-term use by the monitoring programs?
- **Time period required to observe OAH signal:** What time scales of observation would be necessary for the emergence or detection of OAH-related changes?
- **Cost:** Would the estimated costs for equipment, field work, labor, and analysis be reasonable given funding constraints.

Although all criteria were important, a primary goal of the recommended actions is to improve the California OAH monitoring program in a way that provides resource managers with information and tools useful in policy decisions. Therefore, among these criteria, the perceived value to managers was weighted heavily.

Biological indicators ranked highly by the criteria above were then plotted in a value matrix (Fig.1) comparing their expected impact (y-axis) for California's OAH monitoring program in relation to the cost or effort (x-axis) required for implementation. The position of indicators among quadrants on the value matrix was key in prioritizing biological measures, and all recommended actions were located in high-impact quadrants. Ideally, the most impactful measures would also have a very low cost (i.e., "*Quick wins*"), but in some cases, high impact is expected to require high effort (*"Major Projects"*). In contrast, some very interesting biological measures are thought to have relatively low impact for the OAH observing program, regardless of cost, and were thus viewed as low in priority.

The Panel further emphasizes that prioritization of candidate projects was strongly filtered by the leveraging potential of ongoing regional OAH monitoring programs. For example, detecting and tracking the impacts of OAH on adult fish and invertebrate populations that support California's key commercial and recreational fisheries is extremely important but beyond the scope of what could be implemented easily by the programs under consideration. Likewise, efforts to monitor the impacts of hypoxia on benthic communities, - a well-recognized concern for Southern California, warrants statewide prioritization but will require attention from programs that are better positioned to expand benthic studies.

The top-ranked biological indicators recommended by the Panel for broader implementation across the five monitoring programs include;

- Evaluate the extent of pteropod and crab shell dissolution and abundance.
- Measure the abundance and composition of microbial assemblages contributing to harmful algal blooms (HABs).
- Collect and analyze environmental DNA (eDNA) samples focusing on invertebrates, vertebrates, and HABs.

- Track the abundance and composition of zooplankton and ichthyoplankton.
- Track the abundance and composition of krill and forage fish assemblages.

Each of these recommendations is explained in detail in the report.

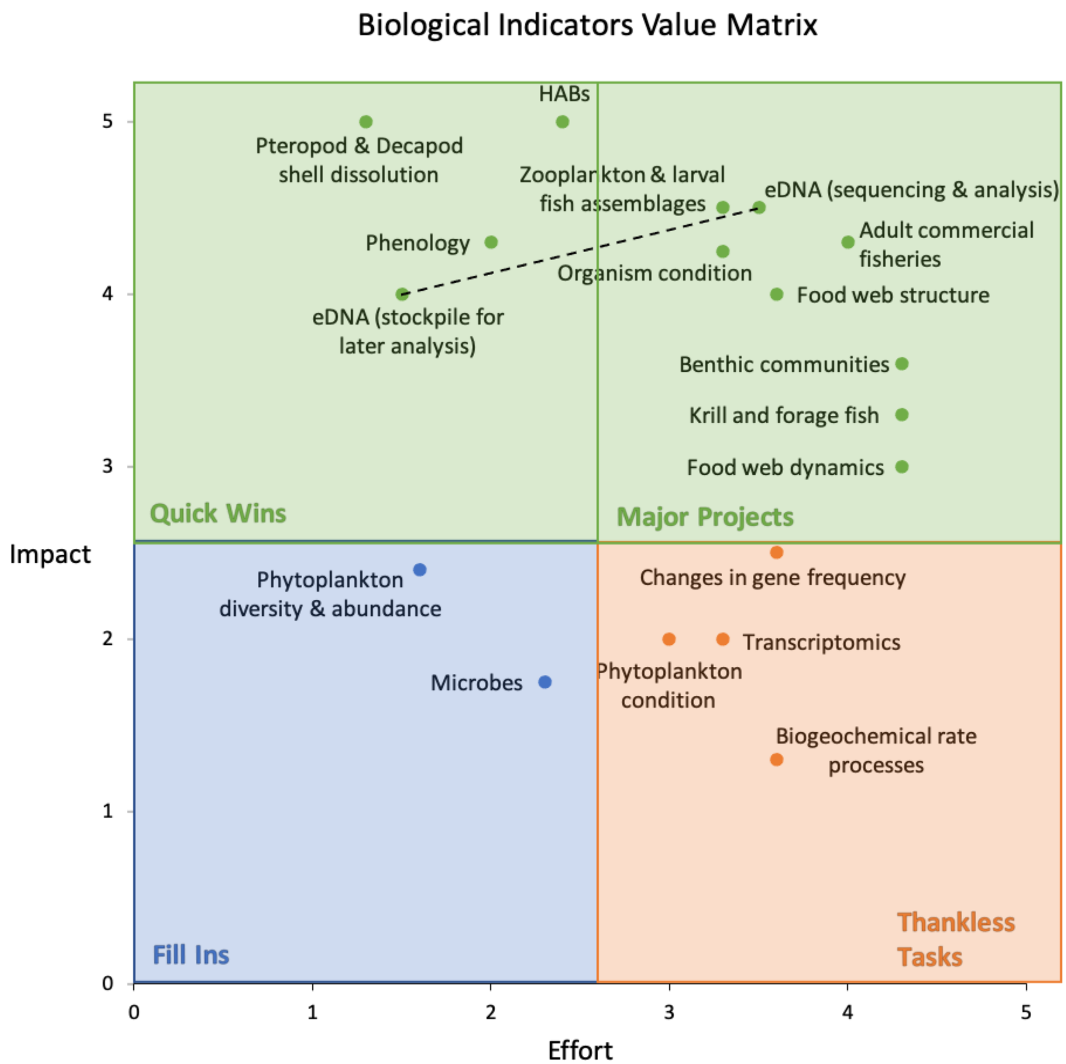

Figure 1. Value Matrix used by the Panel to prioritize biological indicators for integration in ongoing monitoring programs. *Indicators positioned in the "Quick Wins" quadrant received an average impact score of 2.5 or higher and an average effort score of 2.5 or lower; indicators positioned in the "Major Projects" quadrant received an average impact score of 2.5 or higher and an average effort score of 2.5 or higher. Indicators positioned in both of these quadrants were recommended by the Panel for implementation. In contrast, indicators that received an impact score of 2.5 or lower were either positioned in the "Fill Ins" quadrant (if they received an average effort score of 2.5 or lower), or in the "Thankless Tasks" quadrant (if they received an average effort score of 2.5 or higher).*

Programmatic considerations

In addition to recommendations for specific biological indicators to be added or expanded among monitoring programs, the Panel recommends several programmatic practices to 1) promote the accuracy, accessibility, and comparability of observations across programs, 2) develop syntheses as status reports for biological conditions in relation to OAH, and 3) actively include policies and practices to promote diversity and inclusion (DEI) within California OAH monitoring programs. These programmatic considerations include:

- **Data sharing:** Observations and measurements should be reported regularly to national data archives appropriate for biological data sets and, as possible, catalogued and made readily available through project websites to simplify access by the scientific and resource management communities, and the public.
- **Protocols/Best practices sharing:** Best practices (when available) should be used for biological measurements and observations. Project managers are encouraged to use standardized methods across all observing programs to maximize the comparability of observations among monitoring programs. For example, a 'best practices guide' for ocean acidification studies has been developed at an international level (https://www.iaea.org/sites/default/files/18/06/oa-guide-to-best-practices.pdf).
- **Pre-observation cross-check:** Any actions considered by the panel were cross-checked for alignment with the recommendations reported by the Ocean Acidification and Hypoxia Science Task Force in *Enhancing California's Ocean Acidification and Hypoxia Monitoring Network* (Weisberg et al, 2020). In particular, options to add biological monitoring to programs with currently strong chemical monitoring should address recommendation 1, to *better connect chemical and biological monitoring*.
- **Sample Location Considerations:** Although sampling locations and protocols for many recommended measurements have already been determined by monitoring programs, the Panel suggests that the horizontal and vertical scales of observations should be considered carefully so as to capture broad environmental gradients, key environmental features, and maximize statistical power for pattern or change detection. For example, shoaling of the upper edge of the oxygen minimum zone may become a crucial boundary for vertically migrating forage fishes and invertebrates. Likewise, intensifying hypoxia in the benthic boundary layer may lead to expanding mortality events in some shelf and inshore systems. Latitudinally, the Panel also notes that while waters off of southern and central California are well sampled, sampling of northern sites is substantially less regular. Modelling efforts to optimize the design of OAH chemical observing systems are currently underway. Biological monitoring efforts may benefit from exchange of information that identifies areas that are more or less chemically representative of a region or habitat. Such exchanges can also identify sampling locations that are both chemically and

biologically representative and aid in identifying priorities sites where enhancing or sustaining monitoring capabilities may yield the greatest information.

- **Multi-Stressor Considerations:** In using the term OAH, the Panel is recognizing both the importance of approaching ocean changes in a multi-stressor context, and the strong covariation of OA and hypoxia. This said, there is value in understanding the independent effects of these (and other co-occurring) stressors. Hypoxia and OA have different time horizons for impacts and progression. For example, hypoxia already organizes the distribution of marine life whereas the broader food web effects of OA may not manifest clearly for some decades to come. Near minimum DO conditions can already be found in some coastal systems but the full range of future carbonate chemistry changes remains unbounded. Models for predicting population changes due to habitat compression by hypoxia have been developed (e.g. Howard et al. 2020) and future monitoring observations can focus on readying and expanding the operational use of such tools in fishery management. For OA, such models are in development and sampling efforts can target measurements that more quickly support their growth, including expansion into a larger suite of species that are of highest management interest.
- **Synthesis for meaningful outcomes:** Syntheses of existing and new data should be an element of all recommended biological indicator projects. Rather than stockpiling data for future analysis, new observations and archived data available across monitoring programs should be integrated and synthesized periodically as a checkpoint on the status and trends in biological indicators in relation to OAH conditions.
- **Advancing Diversity Equity and Inclusion (DEI) goals:** Cognizance and action concerning justice, diversity, equity, and inclusion should be emphasized at all levels for each recommendation. From at sea research to the applications of leading-edge ocean observing and data analytics technologies, the activities involved in developing a state-wide OAH monitoring network represent an invaluable opportunity to engage students and researchers from underserved communities in experiential education, workforce training, and full participation in California’s high tech ocean research enterprise. The engagement of diverse stakeholder groups across the full research program life cycle, from identifying socially-relevant questions, communicating findings effectively, to translating new knowledge into new actions is equally important so that those most impacted by climate change are not excluded from information and decision making. The Panel places it’s highest recommendation that investments in science to ready California for ocean climate change is paired with investments in education and engagement that ensure full, equitable participation by all.

The Panel's recommendations for integrating biological measurements to ongoing OAH monitoring programs

Recommendation 1: Evaluate the extent of pteropod and crab shell dissolution and abundance across California waters; ensure that data are sufficiently high quality to inform the water quality criteria process underway.

Calcifying organisms, such as pteropods and crabs, have tests of aragonite or calcite that are susceptible to ocean acidification if saturation states of these biominerals are below or in some cases close to one. Thus, shell dissolution is a useful and common indicator of ocean acidification status. Planktonic calcifiers such as pteropods and crab megalopae are also prey items for higher trophic level species, including salmon and other fishes. While a direct linkage to hypoxia is not well known, the degree of shell dissolution is one of the more unambiguous indicators for ocean acidification.

The Panel identified collection of pteropod and crab megalopae for shell dissolution analysis as a *High Impact/Low Effort* activity (Fig.1). The utility of applying the results towards understanding spatial and temporal patterns of dissolution will enable a better understanding of where stress is highest for OA or if there are any 'refugia' where dissolution is seldom seen. Further, these results in concert with oxygen and temperature data will aid in the assessment of dissolution in a multistressor context.

A goal of this recommendation is to provide information state-wide on where ecosystem change may be anticipated. To achieve this, we recommend comparison of this indicator with the food-web dynamics observed in the system, to assess if patterns in both show any association. It would be useful to assess if severe dissolution indicates less robust food webs and/or if specific food-web structures are associated with dissolution state.
Methodology for analyzing shell dissolution has been published, primarily utilizing scanning electron microscopy (SEM) but also micron-scale computed tomography (micro-CT), a high-resolution X-ray technique providing detailed 3D information on the shell. We note that samples can be collected and preserved for analysis by another lab, if appropriate.

Potential outcomes of this recommendation include:

- Identify spatial patterns of dissolution
- Ability to assess dissolution in context of OA, hypoxia, and temperature
- Synergy with informing food web dynamics and vice versa

Recommendation 2: Provide a robust understanding of how OAH exposure risks are distributed relative to Harmful Algal Blooms across dynamic coastal ocean environments.

Harmful algal blooms (HABs) have broad-reaching impacts on coastal ecosystems and fisheries. The frequency and size of HABs have been projected to increase with climate change. Laboratory studies have further highlighted the potential for OA to increase the prevalence or toxicity of HABs. In circumstances where HABs become particularly abundant, they can exacerbate the risks and intensity of OAH exposure. Consequently, managing the risks of increasing OAH exposure will require a clear understanding of how HABs intersect with ocean chemistry changes in time and space**.** For California, such understanding remains largely localized in scope. Important uncertainties as to where and when these multiple stressors may overlap, or how laboratory results scale up to whole ecosystems thus remain.

The Panel identified the expansion of coordinated OAH and HABs monitoring as a *High Impact/Low Effort* activity (Fig.1). Understanding if areas and habitats that face the greatest exposure to OAH stressors are also subject to enhanced risks of HAB exposure, or if the intensification of OAH will further amplify the risk of damaging HAB events and vice versa is likely to have important decision-making consequences. For example, such information can identify locations and fisheries where managers are likely to have to manage for low oxygen, acidification, and biotoxin stressors, and when planning will need to account for the accelerated expansion of HAB exposure. The goals of new investments would be to provide state-wide information to resolve the likelihood of OAH and HAB co-occurrence, and whether OAH and HABs will interact to quicken the pace of ecosystem change.

Sampling for HABs can be readily incorporated into existing seagoing monitoring efforts. In most instances, additional wire time would be minimal. We considered this to be a *Low Effort* activity for three additional reasons: 1) conventional approaches for standardized enumeration of HAB taxa and toxicity are well developed, 2) eDNA-based approaches (see Rec. 3) for detection and classification of HAB taxa have advanced considerably, and 3) optical imaging and AI-based enumeration technologies for preserved samples and underway analyses are already at hand and can greatly transform the volume of information available absolutely and relative to per data cost. The Panel recognized that HABs represent an important research priority independently of OAH concerns. Resolving drivers of HAB, fully characterizing their ecological and socio-economic impacts, building meaningful predictions, and developing effective mitigation and adaptation tools require important attention. The recommendation of adding HAB monitoring can benefit those efforts but the focus here is specific to answering questions of OAH and HABs in a multi-stressor context.

Potential outcomes of this recommendation include:

- Resolving the 1) distribution of HAB and OAH exposure risk in space and time, and 2) potential for interactions between OAH and HABs to amplify their co-occurrence and/or their impacts on ocean food webs (e.g. as characterized by other coupled chemical-biological observations).
- Standardization of eDNA and optical imaging-based sampling and analysis techniques
- Formal evaluation and comparisons of statistical power and information content among conventional, eDNA-based, and optical imaging-based techniques for HABs sampling to guide which approach or mix of approaches can maximize decision-making value going forward

Recommendation 3: Collect an environmental DNA dataset across broad spatial and depth gradients to document the status and change in the biodiversity of major groups (vertebrates, invertebrates, harmful algae) in relation to OAH exposure

Increasing the use of environmental DNA (eDNA) methods was recommended for use across all monitoring programs owing to its potential for characterizing biodiversity and tracking species of interest in California waters in relation to OAH conditions. eDNA was ranked as having high impact and utility to resource managers. Cost/effort is expected to range from low to high depending on the level of investment. At a minimum, sampling eDNA can be as simple as filtering a water sample then freezing the filter for later analysis; several monitoring programs are already investing in eDNA at this level. Effort and costs increase depending upon the number and complexity of samples processed, sequenced, and analyzed.

Although eDNA is still considered an emerging technology, it has been a tool for assessing biodiversity for over 30 years, first used in the late 1980s and early 1990s (Ogram et al 1987 and others). Briefly, DNA strands deposited in seawater from organisms by excretion, sloughing, or other means can be easily sampled by filtration. DNA retained on a filter is then amplified using a polymerase chain reaction (PCR) to increase the volume of targeted DNA for analysis, and then sequenced to determine its genetic identity. Amplification uses primers (short sections of RNA or DNA) targeting major phylogenetic groups (e.g., vertebrates), or can be species specific to target DNA of individual species (e.g., for invasive or rare species). Advances in high-throughput sequencing technology (next generation sequencing; NGS) is reducing the cost of DNA sequencing (e.g., metabarcoding) for characterizing the biodiversity of marine environments. Although eDNA has limitations (e.g., no physical sample of individuals, limited inference concerning the abundance of identified taxa), there is growing support for its broader use in conservation, and biodiversity estimates using eDNA have been shown to correlate well with estimates from traditional net-sampling methods. For example, Djurhuus et al. (2020) used eDNA from filtered water samples to characterize variation over two years in Monterey Bay of more than 600 taxa spanning microbes to marine mammals, concluding that eDNA is a useful tool to sense ecosystem change and inform conservation strategies.

At a minimum, the Panel felt that ongoing efforts to archive frozen filters from water samples collected for future eDNA sequencing was worth investment across all observing programs. This effort is already ongoing for most programs, and any additional sampling should ideally be coordinated among programs to standardize sampling methods (e.g., liters of seawater filtered, filter type, and mesh size). The spatial and temporal coverage of eDNA sampling would likely have to match the protocols for each observing program, but coordination among programs, if possible, would strengthen the value of eDNA (and other) analyses for a California-wide OAH observing system; broad coverage of samples across gradients in space and depth is an important consideration.

A more comprehensive project would include processing of eDNA samples to target invertebrates, vertebrates, and microbes associated with harmful algal blooms (HABs); this would likely require parallel PCR and/or sequencing of subsamples from eDNA filters using the appropriate primers. Fully implemented, metabarcoding of eDNA samples to characterize the composition and abundance (quasi-estimated from the number of sequences detected for a particular taxon) of targeted taxa could provide a wealth of information for scientists and resource managers concerning the presence of organisms from microbes to whales. Coupled with OAH sampling, eDNA could become an important and robust future tool for tracking changes in biological patterns in concert with environmental change.

The addition of eDNA studies will increase the uniformity of biodiversity sampling across the California OAH observing network and provide some 'future-proofing' for monitoring programs as the costs of ship-time and traditional sampling and analysis increase. Among monitoring programs there are differences in the optical, net, and acoustic sampling methods used to characterize plankton & nekton communities. If samples are collected and processed using near-identical protocols with a suite of primers targeting major microbial (including phytoplankton), zooplankton, and nekton groups, eDNA has the potential to provide a consistent, system-wide approach for estimating biodiversity that complements traditional sampling methods.

Among the biological indicators recommended by the Panel, tracking biodiversity by eDNA analyses ranks lowest for readiness. Though it has demonstrable value for biodiversity assessment in marine and freshwater systems, it may not yet be considered a suitable substitute for traditional methods. Nevertheless, its promise for future monitoring protocols and greater automation in biodiversity assessment elevate its importance as a tool for California's OAH monitoring program.

Potential outcomes of this recommendation include:

- Initiation and/or expansion of eDNA-based assessment and monitoring of invertebrate, vertebrate, and phytoplankton biodiversity across the California OAH observing system.
- Evaluation and demonstration of the value of eDNA sampling & assessment in understanding linkages between ocean ecosystems and OAH.
- Stockpiling samples of eDNA (frozen filters) is feasible and would be valuable if the capacity for analysis is currently limited.

Recommendation 4: Track changes in abundance and composition of zooplankton and ichthyoplankton assemblages on horizontal and vertical scales over time to characterize coherence with patterns of OAH.

The characterization and monitoring of spatial and temporal patterns of zoo- and ichthyoplankton assemblages was viewed as having a *High Impact* to management yet also requiring a *High Effort* to accomplish. This *"Major Project"* (Fig. 1) should entail quarterly measurements of the abundance and diversity of both zooplankton and ichthyoplankton. The spatial resolution of the data is critical for OAH purposes as correlative 'attribution' requires spatial overlap with hypoxic and acidified waters.

Traditionally and historically, zoo- and ichthyoplankton sampling has been conducted by towing nets from a research vessel. Oblique nets transitioned to bongo nets in the 1970s and this method continues to be used today. Paired bongo nets are lowered to a maximum depth and retrieved obliquely through the water column. Thus, the abundance and diversity of taxa retrieved from such net sampling are integrated over the entire sampled water column. Other specialized nets are used to sample the surface waters for neustonic organisms. More recently, underwater imaging has been introduced as a method of rapidly quantifying both zooplankton and ichthyoplankton. Such cameras can also be towed behind vessels or deployed on gliders; in both cases, data are collected continuously over all depths. This method continues to evolve, with major technological advances in image processing (i.e., via machine learning techniques) occurring rapidly. Thus, underwater imaging provides very high-resolution spatial data, and is increasingly cost-effective, both major considerations for maintaining long-term time-series. Its primary weakness is that no biological samples are collected, limiting the additional data (eDNA; specimens for analysis of shell dissolution; otolith-based growth and condition data for ichthyoplankton) that can be obtained from this sampling method.

Several of the five focal monitoring programs were initially designed to focus on ichthyoplankton assemblages and thus require no additional changes in sampling to accomplish this goal. CalCOFI has one of the world's longest time-series of larval fish collections and the longer the time series extends, the more valuable it becomes for informing scientists and managers of the ecosystem-wide changes that occur both cyclically with large scale oceanographic processes (e.g., Pacific Decadal Oscillation) or progressively in relation to increasing effects of climate change. Further, the partnership of CCE LTER has introduced underwater imaging into this plankton sampling, creating an effective combination of biological sample collection and high-resolution spatial distributions. The expansion of the geographic extent of this sampling (both net and imagery) through the engagement of other monitoring programs would provide a valuable time-series of data along the California coast to evaluate the effects of OAH on biological communities. Of critical note is the preservation and storage of the biological samples. Both aspects of the sampling program need to be selected carefully to maximize utility of the biological specimens into the future.

Potential outcomes of this recommendation include

- Quarterly net collection of **biological samples** from specific locations to enable assessment of growth and condition of particular taxa of interest
- Quarterly collection of **imagery data** throughout the sampling range to enable high-resolution spatial data, especially, increased vertical resolution
- Collection of comparable data across programs for broad spatial and temporal coverage
- Synthesis of data across programs to assess whether the data are useful for water quality and fisheries management related to OAH

Recommendation 5: Track changes in abundance and composition of krill and forage fish communities on horizontal and vertical scales over time to characterize the coherence with patterns of OAH.

Krill and forage fishes are critical components of the pelagic food web, supporting higher trophic levels, including major commercial and recreational fisheries, marine mammals, and seabirds. The abundance of krill off California is not continuous, but fluctuates with oceanographic conditions, with carry-on effects on the oceanic food web. For example, the relative abundance of krill influences the magnitude of juvenile rockfish recruitment, with corresponding effects on adult rockfish populations. Likewise, forage fishes play a major ecological role in many marine ecosystems. Despite the central role of krill and forage fishes, they are not regularly surveyed off the coast of California by all five of the focal monitoring programs. The measurement and monitoring of spatial and temporal patterns of krill and forage fishes was viewed as having a *High Impact* to management yet also requiring a moderately *High Effort* to accomplish. This *"Major Project"* (Fig. 1) should entail quarterly measurements of the abundance of krill and forage fishes.

While krill can be sampled by plankton nets, forage fishes cannot as they are able to swim to evade the approach of nets. Further, nets must be large in size, such as mid-water trawl nets, requiring a large expanse of deck space for net deployment and retrieval, and sufficient lab space (and onboard taxonomic expertise) for sample processing while underway. Further, mid-water trawls integrate horizontal water masses, reducing the spatial resolution of the resulting abundance data. An easier and more effective method for sampling these two groups of organisms is via hydroacoustics which can be installed on any sized vessel, including autonomous underwater vehicles (AUVs). Hydroacoustics can simultaneously sample both krill and forage fishes, providing a record of abundances in the water column along the vessel track. Where biogeochemical data are simultaneously collected, this spatial resolution of the distribution of krill and forage fishes will allow abundances to be related to water characteristics. While it is not time-consuming nor expensive to deploy these acoustical techniques from underway research vessels, interpretation of the data requires specialized training. A catalog of 'best practices' should be drafted by those currently using the method, together with consultation with acoustics experts. Sharing of this document among the monitoring groups would facilitate incorporation of a hydroacoustics sampling program into each program's quarterly sampling.

Hydroacoustic sampling of krill and forage fishes occurs regularly by at least one of the five focal monitoring programs (ACCESS). Expansion of this sampling to the other California monitoring programs would expand the geographic extent of information on krill and forage fish distributions to ultimately generate a valuable time-series of data to evaluate the effects of OAH on these critical food web taxa.

Potential outcomes of this recommendation include:

- Quarterly collection of comparable krill and forage fish data across programs for broad spatial and temporal coverage
- Determination of whether the abundance of krill and forage fish overlaps OAH 'hot spots'
- Synthesis of krill and forage fish abundance data across programs to assess whether these data are useful for water quality and fisheries management related to OAH

Appendices

Table A.1. Collated information on the five targeted monitoring programs.

Monitoring Program Name	Program Lead(s)*	Spatial Extent (also see Fig A.1)	Ongoing Biological Measurements
ACCESS (Applied California Current Ecosystem Studies)	Jaime Jahncke	From Point Arena to San Mateo	Phytoplankton, pteropods, copepods, decapods, euphausiids and seabirds, euphausiids and forage fish via hydroacoustic, eDNA, HABs
CalCOFI (California Cooperative Fisheries Investigation)	Brice Semmens	From San Francisco to San Diego	Phytoplankton, ichthyoplankton and zooplankton (from oblique ring and then paired Bongo), Continuous Underway Fish Egg Sampling, observer-based data on seabirds and marine mammals, eDNA samples of bacterial, phytoplankton and zooplankton
CCE LTER (California Current Ecosystem Long-term Ecological Research)	Mark Ohman	CalCOFI cruise lines for quarterly ship-based observation Glider lines off of the Farallones Islands, Monterey, Point Conception and San Diego Moorings off of Point Conception	Characterization of the planktonic food web by genomic, morphological methods and in situ imaging, in addition to CalCOFI's ongoing biological measurements
NOAA West Coast Ocean Acidification Regional Survey Cruises	Richard Feely	From Alaska to the Gulf of Mexico	Phytoplankton, zooplankton, ichthyoplankton (vertical tows, and oblique tows with Bongo nets), dungeness crab megalopae (Neuston nets), eDNA
SCCWRP (Southern California Coastal Water Research Project Authority) – Southern California Bight Regional Monitoring Program	Steve Weisberg Martha Sutula	From Oxnard to San Diego	Pteropods (shell condition) and crab larvae (carapace condition), DNA meta barcoding for species distributions, genetic markers for stress

* Additional staff from these monitoring programs were consulted by the panel including: Keith Sakuma (NOAA Fisheries), Karen McLaughlin (SCCWRP), Nina Bednarsek (SCCWRP), Andrew Thompson (CalCOFI)

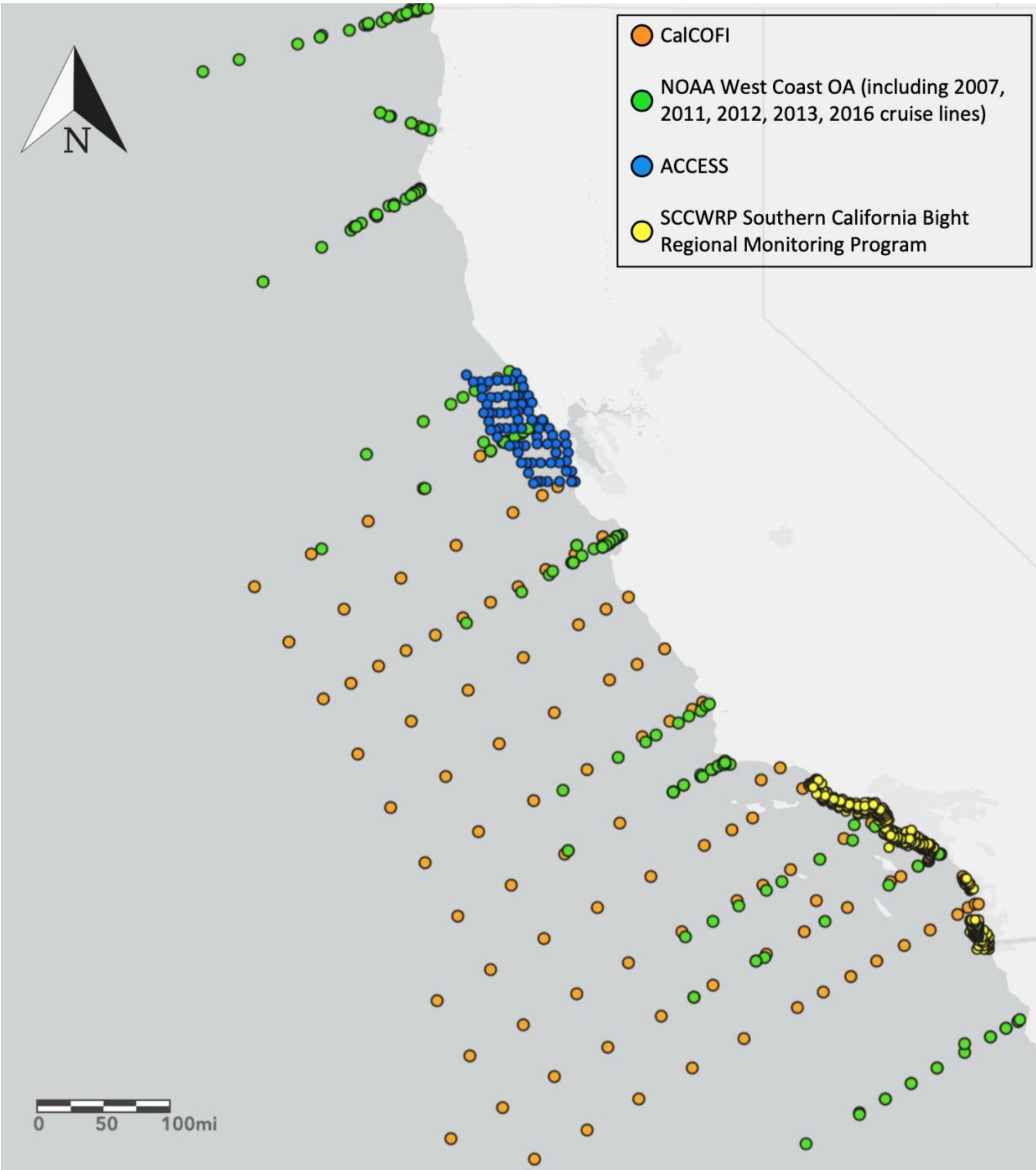

Figure A.1. *Rapid assessment map of four monitoring programs (NOAA OA cruises, CalCOFI, the SCCWRP Southern California Bight Regional Monitoring Program and the Applied California Current Ecosystem Studies (ACCESS)) cruise lines along the California coast. Cruise lines coordinates were sourced from the West Coast OAH Inventory [1] and the ACCESS mapping tool [2], this map is not intended to be comprehensive but rather a decision-support tool.*

[1] https://www.arcgis.com/apps/webappviewer/index.html?id=a8b5c0ecfbe7451e950def767c55335e

[2] http://www.accessoceans.org/?page_id=219

Table A.2. Full list of biological indicators evaluated for recommendation. Indicators with denoted with an asterisk (*) were determined to be a high priority and listed in the report (p.9)

Biological Indicators
Phytoplankton diversity and abundance
Phytoplankton condition (including lipid/carb content, cell condition, etc…)
Pteropod and decapod shell dissolution *
Zooplankton & larval fish assemblages (including abundance, diversity, larval fish growth & condition) *
HABs species *
Microbes
Transcriptomics
Organism condition of focal species (including pteropods, decapods, , echinoid larvae, larval fishes) *
Biogeochemical rate processes (including photosynthesis, respiration, event scale information, productivity/yield)
Food web structure *
Food web dynamics, including predation, reproduction, and competition rates *
Changes in gene frequency
Phenology
eDNA *
Krill and forage fish *
Adult commercial fisheries (including groundfish, market squid, spiny lobster, Dungeness crab, red sea urchin etc..)
Benthic communities

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