Ocean Acidification and Hypoxia Research Priorities to Inform Decisions and Develop Solutions

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The West Coast Ocean Acidification and Hypoxia Science Panel

Ocean acidification and hypoxia (OAH) research is still in its infancy. Three out of every four journal articles that have been published about ocean acidification were published after 2009. From 2000 to 2013, the number of scientific journal articles focused on ocean acidification increased by 35% each year, compared to an average increase of less than 5% in other scientific fields. This lack of scientific maturity limits the options available to effectively manage for OAH. West Coast managers need an arsenal of tools and options that are grounded in sound science. The OAH research that has been conducted over the past few years has brought into focus how ocean chemistry is changing, and has begun to reveal a suite of impacts on species and ecosystems. However, many critical knowledge gaps still remain.

This document provides the Panel's vision for a recommended portfolio of five research areas that will aggressively grow available management options:

A. Understand drivers of OAH
B. Assess vulnerability to changing conditions
C. Understand evolutionary responses and adaptive capacity
D. Explore sequestration and other carbon management solutions
E. Advance living marine resources management

The research areas described below are organized around two key themes: (1) the need for foundational knowledge about OAH and its impacts to advance decision-making, and (2) the need to evaluate and optimize intervention strategies for mitigating OAH impacts. These research recommendations were developed with the assessment that absent a coordinated and strategic prioritization of research foci, current research trajectories are unlikely to meet growing needs for management-relevant knowledge. To that end, scientists must go beyond answering academically stimulating questions to maintain a relentless focus on arming managers with concrete, actionable options for immediately addressing the threats posed by OAH.

About this Document

This document prioritizes research initiatives focused on providing the knowledge needed to effectively manage the West Coast and oceans in the face of multiple stressors. It is designed to help federal, state and other research programs tasked with making more strategic funding decisions to hone in on knowledge gaps that inhibit thoughtful action on OAH.

This document was produced by a working group of the West Coast Ocean Acidification and Hypoxia Science Panel, with support from California Ocean Science Trust, as part of a suite of products to inform decision-making. The information provided reflects the best scientific thinking of the Panel.

For additional details and products from the Panel, visit www.westcoastoah.org.

West Coast Ocean Acidification & Hypoxia Science Panel

California Ocean Science Trust

California Ocean Protection Council

Institute for Natural Resources

A. Understand drivers of OAH

A prominent Panel recommendation is that managers should take actions that will reduce local nutrient and carbon inputs that can exacerbate OAH conditions. However, that recommendation is qualified by the lack of clear understanding about precisely where on the West Coast local inputs are sufficiently large to be meaningful relative to the global scale inputs that drive OAH. Furthermore, more clarity is needed on the relative importance of which local inputs (non-point source vs. wastewater discharge vs. local atmospheric inputs) should be prioritized for reduction.

An effective way to address these uncertainties, and thereby allow managers to maximize effectiveness of a local input reduction strategy, is by developing coupled physical-biogeochemical models, validated with observations, that quantify the relative impacts of various nutrient, organic carbon and carbon dioxide sources on exacerbating OAH. These coupled models include three component categories: (1) physical models that describe the movement of ocean water masses in space and time, along with their inherent properties of temperature, salinity and density, (2) biogeochemical models that describe the mass balance transport and transformation of carbon, oxygen, pH, nutrients and other biogeochemical properties in water, and (3) ecosystem models that use physical and biogeochemical properties as inputs to predict the effects on, and interactions between, organisms at scales from individuals to populations. Additionally, high temporal resolution observations can yield insights into the drivers for OAH variation and underlying mechanisms.

Multiple West Coast research groups are already engaged in various stages of developing OAH models, but additional investments are required to enhance, coordinate and link those efforts to OAH-related management decisions. Achieving that goal will be enhanced by the following five Panel research recommendations, many of which are consistent with recommendations that came out of a West Coast OAH modeling workshop in December 2013 that brought together the modeling and broader scientific communities, including eight members of the Panel.

Research initiatives to build foundational understanding

A1. Invest in development of coupled physical-biogeochemical models.

Although a nested set of physical and, to a lesser extent, biogeochemical models already exists for the West Coast, for most areas, these modeling efforts have primarily focused on offshore waters. Important knowledge gaps remain in scientists' ability to model OAH dynamics in the near-coastal waters, estuaries and bays – the areas that are the primary focus of potential management action – as well as linkages between these scales. Thus, West Coast managers should build capacity for downscaling physical models, better characterizing the nearshore, and coupling them with biogeochemical models to create high-resolution, coupled models that can close knowledge gaps.

A2. Evaluate models in the context of decision-making processes.

Because decisions based on model outputs will likely be costly, models should be validated with observations and scaled to the endpoint management decision in mind. Specifically, scientists should work to identify knowledge gaps and quantify uncertainty based on understanding the precision required to answer management questions. To date, the most extensive validation has been performed with physical models for the mid- to outer-shelf. Validation efforts should be expanded to focus on near-coastal areas and on biogeochemical and ecological variables, with increased emphasis on quantifying forecasting performance of the models.

A3. Collect observational data in concert with modeling.

Observations of the spatial-temporal variation in carbon chemistry and oxygen can provide invaluable insights into the drivers of OAH. For example, basic mixing curves of salinity and dissolved oxygen can be used to test the relative contributions of changes in ocean sourcewater chemistry and local respiration in strengthening coastal hypoxia. In other instances, comparing a multi-year duration time-series of carbon chemistry parameters to terrestrial nutrient inputs can provide a first order understanding of their coupling.

Projections of future changes and quantitative evaluation of different management scenarios will depend heavily on spatially explicit modeling efforts that are under development. Although scientists can begin model validation and uncertainty analysis with existing physical data, additional chemical and biological data collection is required from OAH monitoring programs for model development and refinement. Four main types of data are needed: (1) observational data for oceanic state, which describe patterns and trends in physical and biogeochemical variables. To provide effective validation, the temporal and spatial scales need to reflect the major patterns of variation observed in offshore waters, which are the source of waters upwelled onto the continental shelf, (2) data on rates of biogeochemical processes estimates (e.g., dissolution, calcification, respiration) that are specific to the local coastal ocean and local ecology, which will provide more accurate rate estimates than the globally derived estimates (mostly from open-ocean settings) presently being used; accurate rate estimates are crucial for biogeochemical models, which quantify complex biophysical interactions through model equations and their parameters, (3) data on ecological interactions, especially to inform how impacts on lower trophic level taxa that are most susceptible to OAH scale up to affect higher trophic level organisms that have commercial value, and (4) data on waters, discharge rates and constituent concentrations that feed into atmospheric and terrestrial loading models, which are needed to quantify the magnitude, timing, sources and pathways by which nutrient and carbon inputs enter the coastal ocean.

Initiatives to translate scientific understanding into management application

A4. Incentivize two-way communication and collaboration.

To link various modeling projects together, and to connect modeling scientists and observational researchers with decision-makers and other end users, West Coast managers should facilitate development of a modeling community that is focused on developing managerially relevant products. Especially because the biogeochemical drivers of OAH are complex, the diverse entities engaged in observing and modeling OAH-triggered changes will benefit from an integrated approach. A first critical action is to convene a series of workshops to summarize key regional and local management needs and identify the status of existing models to support those needs. Ultimately, an organized community of modelers, observational researchers, and managers will serve to: (1) provide a vehicle for dialogue on management goals and scenarios, (2) encourage discussion on the use of model outputs to illustrate outcomes of management options to reach those goals, (3) facilitate discussion about the level of validation needed to use models to support management decisions, and (4) coordinate modeling products among different technical specialists.

A5. Assess model effectiveness.

Although models will help managers determine if – and in which systems – implementing source controls will be most effective, source controls typically require large capital investment, which means West Coast managers will be seeking a higher level of certainty about whether such actions will result in a meaningful environmental response – a higher level of certainty than can be provided by one set of models alone. Thus, West Coast managers should facilitate field experiments that allow modeling predictions to be validated through small-scale source reduction of OAH stressors. Managers also should practice adaptive management, in which they commit to investing in effectiveness assessments for initial projects before expanding source controls to a wide range of habitats. It is crucial to implement an iterative process that incorporates mechanisms for evaluating progress and instituting changes as needed.

BOX 1. Linking observations, experiments, and models

The Panel has recommended the need for integrated research, monitoring, and modeling to understand how ecosystems are changing over time, and how managers can develop adaptive strategies to respond to these changes. This document focuses on the research recommendations, but these three classes of recommendations are interrelated. Laboratory and field research studies provide information on direct and indirect responses of individual species and communities to OA and hypoxia; modeling provides a quantitative assessment of the processes involved and their relative contributions to the overall impacts. Monitoring of physical, chemical and biological parameters provide real-time information on how the region is changing over time and provide validation tools for the modeling community. Research and monitoring data can also be used as inputs for short- and long-term forecast models. In turn, the models can provide information on regions of particular vulnerability and those that might serve as refugia, and can help identify new monitoring sites and sites for future research. As new information is obtained, research, modeling and monitoring activities can be adjusted to meet the needs of management teams and policymakers.

B. Assess vulnerability to changing conditions

A key management information need is understanding how fast seawater chemistry is changing, at what locations seawater chemistry will change the most, and what levels of chemical change will trigger substantial changes in biological communities. Understanding which locations will be subject to the largest and smallest changes provides opportunity for exercising and evaluating alternative management strategies.

Scientists along the West Coast are developing and expanding coordinated monitoring programs, conducting laboratory and field experiments, and refining numerical models to address such questions. These efforts are in various stages of development. To complement and add value to these efforts, Panelists identified four specific research areas as priorities: (1) expand OAH measurements at spatially-nested scales in order to resolve location-specific differences in current exposure to OAH, (2) downscale global change models to project likely rates of changes in OAH conditions along the West Coast, (3) configure coupled physical-biogeochemical models to identify localities along the West Coast that are most and least susceptible to rapid changes in OAH, and (4) expand laboratory studies to place greater emphasis on the effects of realistic exposure to environmental stress at the scale of populations and ecosystems.

Research to Enhance Foundational Understanding

B1. Expand physiology studies to understand biological response to realistic stress exposure.

Multiple stressors exposure: Experimentation to date has focused primarily on describing the response of organisms to the effects of OA or hypoxia in isolation. Further analyses of single stressor effects will be valuable, particularly where they reveal the underlying mechanistic basis for OA or hypoxia impacts. However, across many coastal ecosystems, OA and hypoxia occur as coupled stressors. They can further be expressed against a background of additional changes in factors such as temperature and environmental contaminants. As a result, increased emphasis should be placed on studies that involve multiple stressors that are reflective of changes faced by organisms in natural systems. This approach is more likely than single-stressor studies to reveal OAH effects under real world conditions, and do so more accurately than 'cumulative effect' syntheses. Recent studies have shown that effects of dual stressors of low pH and hypoxia are more severe than are predicted by the effect of either stressor alone. Consideration of OA in a multi-stressor context will be important in addressing the Panel's recommendation to develop new OA water quality criteria. Relevant thresholds for acidification criteria should account for potential interactions with co-occurring stressors such as temperature change and hypoxia.

Acute and variable stress exposure: In coastal ecosystems, exposure to OAH stress can be highly variable. As a result, the vast majority of experiments published to date that have been conducted at constant levels of pH or dissolved oxygen may be poorly representative of the conditions that organisms actually face in natural systems. This is particularly important because the intensification of OAH is projected to change not only the mean stress levels organisms are exposed to, but also the variability in stress levels. Large uncertainties remain as to the how organisms will be impacted by changes in short-term exposure to acute stress. Closing this gap in our understanding is essential for assessing ecological vulnerability and for developing relevant thresholds for acute exposure.

B2. Expand physiology studies to place greater emphasis on scaling up to ecosystem level impacts.

Physiology experiments provide fundamental mechanistic understanding of the biological impacts of ocean changes. At the same time, there is a strong need for studies that can inform how responses at the organism or sub-organism scale translate into population and ecosystem level changes. Future physiology experiments can help meet this need in a number of ways. First, studies can focus on

elucidating the functional responses of organismal performance to OAH. Such information is vital for parameterizing ecological models and requires a focus on studies that resolve potential non-linear, or threshold, responses that are common in biological systems. Second, studies to date have been successful at identifying diverse behavioral and physiological responses to OA including increases in anxiety in fishes, increases and decreases in calcified mass in coccolithophores, and altered settlement behavior in corals, among many others. How such information translates into projections of changes in organismal performance or fitness in natural settings is less clear. Efforts that can integrate the diverse potential pathways of physiological impacts into predictive models of organism responses and involve coordinated laboratory and field studies will be invaluable in bridging this gap. Third, efforts to more accurately model ecosystem impacts of OAH will require information to parameterize key components of ecological interaction webs. In spite of the rapid growth in OA organismal studies, the overlap between what has been studied and what is required to parameterize ecosystem models is exceedingly poor for many systems. Absent a strategic approach in targeting taxa for investigations, missing information for key taxa is likely to remain a bottleneck for the development of predictive ecosystem models. We note that the information gap for functionally important taxa is also often mirrored by the information gap for taxa that are of the greatest management concern. As a consequence, management considerations can at times require considerable extrapolation from studied taxa whose physiologies may differ considerably from those of managed species. A strategic prioritization of future organismal studies, and their translation to population and ecosystem-scale projections, will be essential in providing a firmer basis for management decisions.

Initiatives to translate scientific understanding into management application

B3. Develop models to identify areas most and least prone to rapid changes in carbon chemistry.

The Panel has recommended that West Coast managers explore the use of protected areas as an OAH management tool, allowing species and genotypes to persist in regions where conditions remain favorable, even as conditions in other regions become intolerable. Properly scaled, observations and coupled physical-biogeochemical models can be used to help identify those areas most and least likely to undergo rapid change, and to select the most appropriate locations where protection will be beneficial. We further note that vulnerability ultimately reflects the interaction between changes in exposure and biology sensitivity to those changes. Identifying areas that are most and least prone to rapid changes in carbon chemistry is needed to inform managers as to the distribution of spatial protection measures relative to exposure risk. In the future, advances in our understanding of how physiological impacts scale up to population and ecosystem changes can be applied in conjunction with exposure projections to better guide the effective use of spatial management tools to address OAH over time.

C. Understand evolutionary response to OAH

Marine organisms have three options for responding to OAH stress: (1) behavioral responses, e.g., migration out of the stressful areas; (2) acclimatization–changing physiological capacities during an individual's lifetime ("phenotypic plasticity"); or (3) genetic adaptation–selection for genotypes with a potential for improved capacities for coping with OAH. The accessibility of these three strategies differs widely among species with different locomotory abilities, capacities for acclimatization, and levels of genetic variation. Life history characteristics like generation time and reproductive output also will affect abilities to adapt.

While the potential for evolutionary adaptation to OAH is recognized, scientists have insufficient information to predict whether, where, and how fast genetic adaptation to OAH will occur. Thus, research is needed to understand rates of natural genetic change in response to OAH, and how evolutionary potential is distributed among taxa and localities. Moreover, West Coast managers need to understand the feasibility of incorporating adaptation into management strategies.

To preserve the evolutionary processes that determine how organisms and ecosystems adapt to OAH, scientists need better understanding of the scope and distribution of the natural genetic variation that leads to adaptation. By incorporating an evolutionary perspective into West Coast planning and management, managers can help foster ecological resilience to OAH, increase the likelihood that key species will persist, and smooth out inevitable transitions to novel environmental states. With sufficient knowledge, evolutionary potential can be considered in adaptive management strategies going forward. Moreover, evaluating the potential value and consequences of purposeful interventions, such as selective breeding and translocation, will help determine whether and where opportunities exist to use evolutionary potential to address OAH's impacts on biological communities.

Research to enhance foundational understanding

C1. Evaluate the adaptive capacity of diverse organisms to OAH.

Of major importance in efforts to predict the effects of OAH is the need to characterize natural phenotypic variability and sensitivity, and the genetic determinants of that variability in natural populations. For organisms and locations where standing variation is high, relatively rapid adaptation to OAH is theoretically possible. A combination of laboratory studies, field studies, and numerical modeling can improve understanding of these mechanisms and the likely outcomes of evolutionary responses of organisms exposed to OAH.

C2. Identify the geographic distribution of adaptive capacity.

Over time, local populations can adapt to localized conditions, allowing individuals to persist under conditions that might not be tolerated by individuals from other locations. Such populations offer important insights into the scope of OAH adaptation potential. Moreover, locally adapted populations may serve as important reservoirs of genetic variation as OAH intensifies. One way to enhance understanding about the capacity for natural genetic adaptation is to characterize genetic variation and genetic expression responses at locations where OAH stress is high or increasing. Such measurements could identify populations with abilities to cope relatively well with OAH; such data can be integrated into OAH monitoring programs that track genetic changes over time and space.

C3. Use experimental evolution, or artificial selection, to infer adaptive response and identify the limits of adaptive evolution.

Experimental evolution uses controlled experiments to explore organisms' scope for evolution in response to OAH. Traits that increase the rate of evolution in response to OAH are likely to contribute to persistence of the species over time. The identity of such traits is not well characterized within and among most taxa, nor have the constraints and limitations of ability to evolve been demonstrated. By better understanding whether, how, and how fast evolution can occur in response to OAH, scientists will be able to project long-term changes and weigh the urgency for, and likely success of, management options.

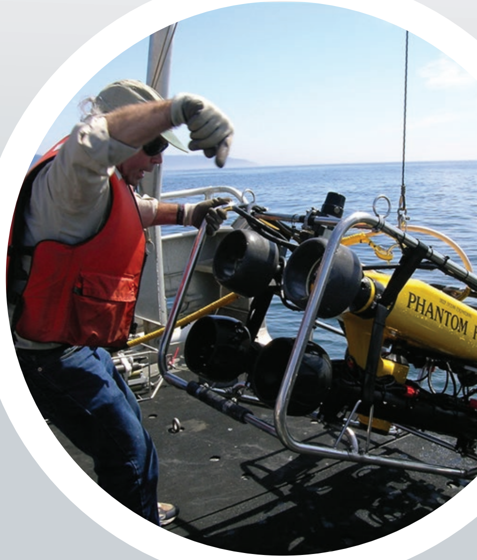
Initiatives to translate scientific understanding into management application

C4. Explore the use of evolutionary refugia.

Refugia have played critical roles in recovery following extreme environmental perturbations in the past by allowing species and genotypes to persist in local areas where conditions remain favorable, even as global conditions become intolerable. In the context of OAH, refugia can refer to areas where harvest or other cofounding local stressors are minimized to ensure the persistence and productivity of populations, as well as locations where exposure to OAH stressors is naturally moderated by ocean currents and topography. However, the use of refugia to address OAH has not been studied. Thus, projects should be developed in coordination with some of the many West Coast protected areas to determine whether they effectively protect species of high sensitivity in areas exposed to low levels of OAH, or whether they protect more tolerant species in areas exposed to high or varying levels of OAH. Both scenarios are important to preserving biodiversity in the face of increasing OAH. Research to describe connectivity and gene flow between populations will help determine whether refugia contribute more broadly to adaptive potential among populations and will help managers optimize opportunities for natural gene flow. As OAH conditions grow in space and time, understanding these gene movements could be critical in using refugia to foster adaption.

Box 2: Intersection between ocean acidification and hypoxia research

Hypoxia and acidification result from some of the same drivers. As upwelling brings cold, low pH, and hypoxic waters to coastal regions, nutrient additions from land can lead to eutrophication and exacerbate hypoxia and acidification. Moreover, acidification, hypoxia and temperature all interact to affect biotic response. Falling pH can impede an animal's ability to obtain oxygen and transport it to tissues. Changing temperature affects metabolic rates and the amount of dissolved oxygen available to support metabolism. Studies and models of OAH/temperature effects must integrate all three variables, though this can be challenging. The effects of acidification may require protracted experimental periods to study ontogeny or growth, whereas the effects of dissolved oxygen or temperature generally manifest more quickly. Scientists must design laboratory and field studies that take into account the temporal patterning of changes in pH, dissolved oxygen and temperature in order to understand how concurrent changes in these three interacting stressors affect individual species and the ecosystems in which they are embedded. The interaction among these parameters is further described in the Panel's foundational product: *What changes in the carbonate system, oxygen, and temperature portend for the Northeastern Pacific Ocean: A physiological perspective.*



C5. Explore the utility and consequences of purposeful interventions, such as selective breeding and translocation.

Selective breeding of organisms that will tolerate OAH, and purposeful translocation of locally adapted organisms that have demonstrated tolerance to OAH, could potentially help managers preserve key species. However, research is needed to determine for which approaches and which species these active adaptation approaches work most effectively, as well as the extent to which these approaches improve upon less active interventions, such as the use of refugia. Moreover, breeding and translocation strategies must be carefully evaluated for unintended negative consequences, such as species extirpation via competition or predation, or the likelihood of species loss through introgression.

D. Explore CO_2 reduction solutions

The international community has recently made excellent progress in committing to CO_2 emission reductions in the coming decades; in Paris, the COP21 agreement demonstrated unprecedented acknowledgement of the impacts of atmospheric CO_2 loading. While this is an important step, the Paris agreements will only slow the rate of increase of atmospheric CO_2 levels, and will be insufficient to reverse growing CO_2 concentrations in the ocean. We should simultaneously advance science that may uncover strategies for lessening acidification exposure.

There are two main approaches to local CO_2 reduction. The first is biologically-based, making use of the natural ability of the ocean's photosynthetic organisms (algae and plants) to capture CO_2. Seagrasses, algae and kelp remove CO_2 from seawater and convert it into living tissue. This CO_2 uptake can occur at sufficiently rapid rates to improve water quality. Although a substantial fraction of this organic carbon is remineralized to CO_2 when the tissues die, active photosynthesis offers a means to lessen the impacts of OA in surrounding waters, particularly in systems with limited circulation, such as embayments. Because vegetated coastal habitats can also sequester carbon, they have the potential to contribute to the mitigation of greenhouse gas emissions. Consequently, their conservation and restoration could one day become eligible as carbon offsets in carbon trading markets, such as the one established in California, or for other funding that promotes carbon sequestration.

Emerging research suggests that conservation or restoration of these vegetated habitats may indeed act to measurably lessen the severity of OA exposure. However, important uncertainties remain about when, where and how broadly local CO_2 uptake by vegetated marine habitats can remediate OA exposure. West Coast managers should actively explore the utility of this remediation approach. They should also advance the development of carbon offset protocols for restored wetlands and marine vegetated habitats, and should explore the potential for including local OA mitigation benefits in these protocols. Accounting for long-term carbon sequestration and local OA mitigation benefits will assist in better accounting for the full societal value of habitat restoration and management.

The second approach involves engineering methods that directly remove CO_2 or reduces the effects of rising CO_2 by the addition of base minerals, such as carbonates or silicates that neutralize acidity to the ocean. CO_2 can be physically removed from seawater using methods such as electrochemistry, electrodialysis, vacuum extraction, and aeration with a CO_2-depleted gas. These removal methods can be energy intensive and further research is needed to better understand their carbon footprints and cost-effectiveness when applied at larger scales. The effects of rising CO_2 can also be countered by increases in seawater alkalinity. Whatever alkalinity is added, the effect is to consume acidity and convert some resident CO_2 to dissolved bicarbonate and carbonate via equilibrium reactions. Alkalinity can be introduced in the form of synthetic base chemicals such as soluble hydroxides, carbonates and/or bicarbonates, or it could be alkalinity derived from the addition of inexpensive and naturally abundant base minerals, such as carbonates or silicates. The West Coast shellfish industry has begun to add sodium carbonate to counter the decrease in carbonate saturation from OA and its negative impact on shell formation in hatchery settings. However, the range of conditions and scales where alkalinity manipulation can be applied remains to be determined. For example, the addition of carbonate minerals is only effective when seawater is undersaturated in calcium carbonate. In addition, the dissolution rate of silicate minerals in seawater is exceedingly slow, requiring the addition of large masses of finely ground material or other methods of hastening dissolution. Human interventions to accelerate local abiotic removal of CO_2 its effects from seawater are still in early development and the effective scale, cost-effectiveness, and ecological consequences of such efforts remain uncertain. Whether abiotic approaches prove to be a more widely applicable and effective management tool remains to be determined empirically. The Panel recommends supporting research on the type, capacity, cost- effectiveness, and safety of these removal processes as a means to determine which, if any, of these could become part of an effective marine management strategy.

Research to enhance foundational understanding

D1. Explore abiotic intervention approaches to consume excess ocean CO_2 and acidity.

Investigation into consumption of excess CO_2 and acidity via enhancement of abiotic processes should also be explored. This could include the addition of base minerals in the form of waste shell material, or natural carbonate or silicate mineral substrates, the addition of artificially produced chemical bases, and physical/chemical CO_2 extraction methods. With all of these approaches, the cost and any negative impacts of such proposed mitigation efforts will need to be quantified to help managers weigh these against the benefits of such actions before considering conservation-relevant applications.

Initiatives to translate scientific understanding into management application

D2. Estimate the mitigation potential of marine vegetated aquatic habitats for CO_2 reduction.

Determining the potential for marine vegetated aquatic habitats to locally mitigate OA involves several steps. The first is scaling up from pilot studies conducted to date to explicitly identifying the conditions under which marine vegetated aquatic habitat can effectively reduce local CO_2 concentrations in seawater. Scientists have conducted pilot studies that demonstrate substantive increases in pH and associated carbonate chemistry changes resulting from photosynthesis, but we need to transition from these small-scale and short-termed research efforts to larger-scale proof of concept demonstration studies across a range of habitats. This involves strategically expanding research to habitats and locations across broad ecological, geomorphic and oceanographic gradients. These demonstration projects should be accompanied by intensive monitoring, and physical and biogeochemical modeling to evaluate efficacy of such measures on organismal exposure to OA. Once CO_2 reduction efficacy has been assessed, solicitations for scientific/experimental evaluation of methods of operational implementation should be conducted, including determination of scales, costs and potential negative impacts. Evaluations of the potential co-benefits of vegetated habitats management in terms of OAH adaptation and carbon sequestration should be included in these efforts. For example, restoration of key nursery habitats can improve the capacity of fish and invertebrate populations to better cope with the progression of OAH. In vegetated habitats where carbon may be sequestered over long time scales, their protection and restoration can be important contributions to management of carbon footprints. From these efforts, state and region-wide inventories can be generated that identify the areas where habitat protection and restoration are available as a management option for local CO_2 reduction, their likely efficacy and range of co-benefits.

E. Advance living marine resources management

Among the Panel's key findings are that managers should undertake actions that enhance the ability of organisms to cope with increasing OAH stress. This is critically important in the context of managing living marine resources, such as commercial fisheries. The growing adoption of ecosystem approaches to fisheries management offers opportunities for fisheries managers to consider the potential regional effects of OAH as they update fisheries management plans. The Panel offers three recommendations to help advance the management of living marine resources in the face of growing OAH.

Research initiatives to build foundational understanding

E1. Develop biological time series that reveal trends and unanticipated effects.

Long-term biological time series are typically rare or not coupled with physical or chemical data. Managers should invest in research to identify where biological time series are needed, if existing biological time series should be augmented with physical or chemical measurements, and what can be learned from existing records especially in MPAs or other environments where human disturbance is low. While models are essential, long-term time series have revealed unanticipated responses that can guide model development about processes we did not know were operative.

Box 3: Linking research with action

Many of the research activities that the Panel has suggested investing in are complex and will need to be vetted before they can be used to guide future management. The Panel recommends creating continuing mechanisms for communication among scientists, and between scientists and managers, to ensure that the new scientific products that are produced through the research initiatives outlined in this document are useful to the management community. As part of that, the Panel recommends that funding agencies create expectations of their grantees for frequent and early interaction with the management clients for their work, while also encouraging creation of advisory panels early in the project that enhance community engagement.

E2. Develop and validate ecosystem models.

Ecosystem models are a broad class of models that are intended to describe the attributes, interactions, and dynamics that shape the ecosystem in question. Ecosystem models are used to advance foundational understanding of ecosystem function and to guide strategic decisions required of managers. These models can help support ecosystem-based fisheries management by: (1) identifying mechanistic linkages between OAH and fisheries production; (2) predicting the response of species and ecosystems to OAH; and (3) evaluating the response of species and ecosystems to management interventions. Ecosystem models can be used to compare alternative management strategies, explore food web impacts of declines in sensitive species, and to evaluate risk and vulnerability under conditions of growing OAH. Such models are being developed for the West Coast, but do not yet include biogeochemical algorithms for OAH and data are not available to fully parameterize the relevant ecological interactions. Four types of investment will advance development of ecosystem models: (1) research to better parameterize biogeochemical process rates, which are presently based on globally derived estimates from open-ocean settings, rather than being specific to the nearshore ocean and local ecology; (2) research to better understand ecological interactions, (3) development of ecosystem models that can be coupled to physical-biogeochemical models to predict effects on key species or assemblages, and (4) additional data collection to support model validation.

E3. Conduct ecological risk assessments to increase understanding of fishery vulnerabilities.

Ecological risk assessments (ERAs) are frameworks for assessing the likelihood of a fishery, species, or ecosystem facing significant impacts due to multiple stressors (e.g., fishing activities, climate change, OA, impaired water quality). ERAs can provide insight for fisheries managers faced with competing priorities and multiple fisheries, and have the potential to help managers move way from single species or habitat management and towards ecosystem-based management. Early applications of ERAs were developed primarily to assess risk from fishing pressure, but have more recently been used to evaluate vulnerability to climate related stressors. Those models need to be extended to address the impacts that managed species might experience due to OAH, the mechanisms underpinning those impacts, and management actions available to mitigate those impacts.

Initiatives to translate scientific understanding into management application

E4. Enhance OAH considerations in fishery models.

West Coast managers will benefit from the development of fisheries management plans that account for reduced fisheries reproduction through altered fish behavior, impaired calcification of the organisms that fish feed on, and fundamental changes in food web dynamics associated with OAH. Fisheries decisions are largely based on traditional stock assessment models, which often tie future harvest regulations to past ocean conditions. Continued modeling efforts to understand sensitivity of fisheries to OAH, project impacts expressed in social and economic terms, and understand the extent to which adaptive capacity enables these potential impacts to be offset have been identified as science needs to effectively design fishery management approaches under acidified conditions. Opportunities to integrate OAH into the decision matrix already exist, and should be more actively explored.

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