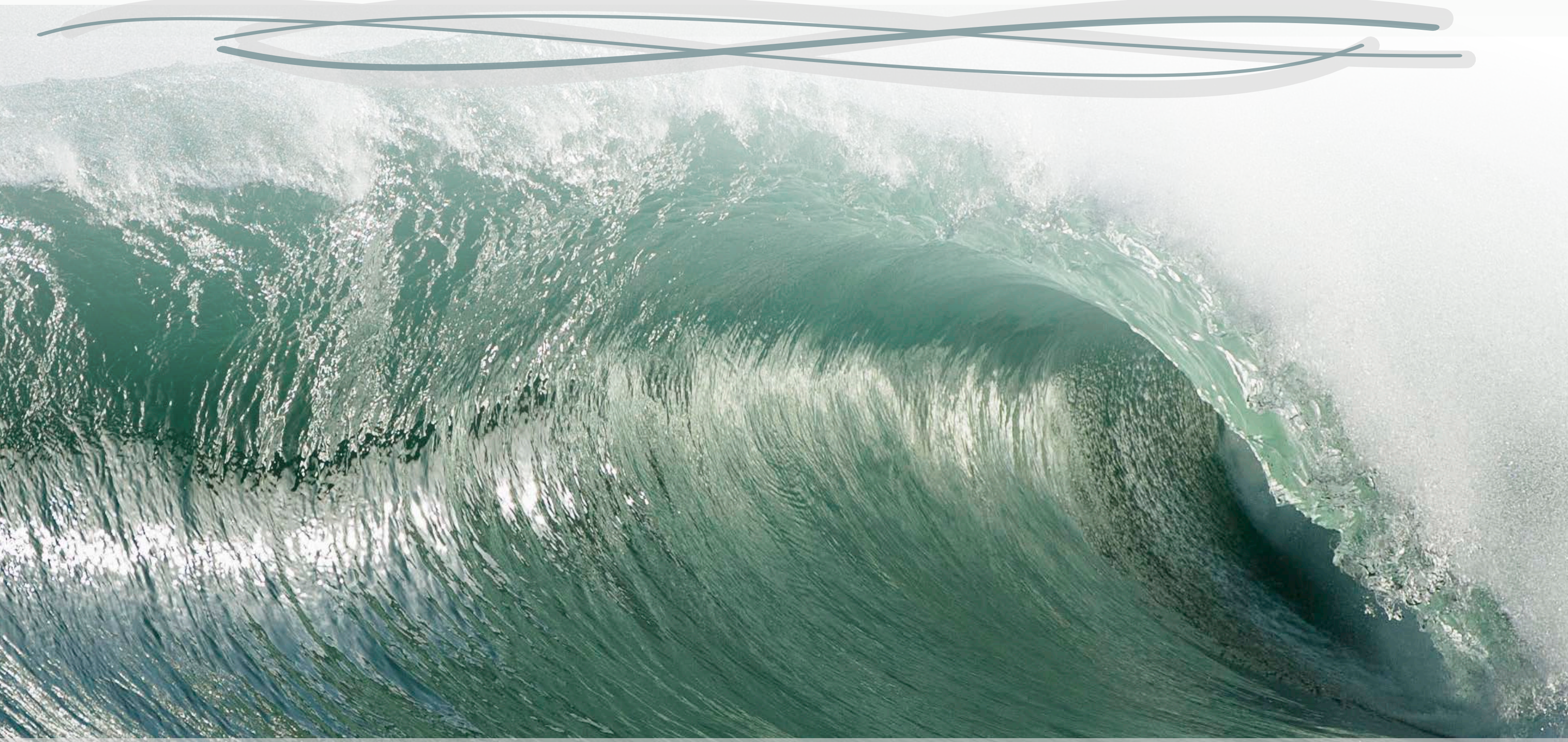
SCCWRP Technical Report 926

The West Coast Ocean Acidification and Hypoxia Science Panel

MAJOR FINDINGS, RECOMMENDATIONS, AND ACTIONS



APRIL 2016

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I. Introduction

Global carbon dioxide (CO_2) emissions over the past two centuries have altered the chemistry of the world's oceans, threatening the health of coastal ecosystems and industries that depend on the marine environment. This fundamental chemical alteration is known as ocean acidification (OA), a phenomenon driven by the oceans absorbing approximately one-third of atmospheric CO_2 generated through human activities. Scientists initially observed the impacts of OA on calcifying marine organisms that were having difficulty forming their shells, but additional evidence now indicates that growth, survival and behavioral effects linked to OA extend throughout food webs, threatening coastal ecosystems, and marine-dependent industries and human communities (see Appendix A).

Although OA is a global phenomenon, emerging research indicates that, among coastal zones around the world, the West Coast of North America will face some of the earliest, most severe changes in ocean carbon chemistry. The threats posed by OA's progression will be further compounded by other dimensions of global climate change, such as the intensification and expansion of low dissolved oxygen – or hypoxic – zones. In the coming decades, the impacts of ocean acidification and hypoxia (OAH), which are already being felt across West Coast systems, are projected to grow rapidly in intensity and extent. Even if atmospheric CO_2 emissions are stabilized today, many of the ongoing chemical changes to the ocean are already "locked in" and will continue to occur for the next several decades. Given these challenges, decision-makers must act decisively and in concert now.

In an effort to develop the scientific foundation necessary for West Coast managers to take informed action, the California Ocean Protection Council in 2013 asked the California Ocean Science Trust to establish and coordinate a scientific advisory panel in collaboration with California's ocean management counterparts in Oregon, Washington and British Columbia. The resulting West Coast Ocean Acidification and Hypoxia Science Panel, comprised of 20 leading scientific experts (see V. The Panelists, page 32), was charged with summarizing the current state of knowledge and developing scientific consensus about available management options to address OAH on the West Coast.

This document, "**Major Findings, Recommendations, and Actions"** of the Panel, summarizes the Panel's work and presents **Actions** that can be taken now to address OAH. The appendices to this document contain a series of two-page synopses that provide more detail on many of the key concepts that are mentioned in the main body. In addition to this document, the Panel has produced a number of longer supporting documents intended for agency program managers and technical audiences (see VI. Additional Panel Products Supporting the "Major Findings, Recommendations, and Actions," page 36).

Why ocean acidification AND hypoxia?

OA and hypoxia refer to distinct phenomena that trigger a wide range of marine ecosystem impacts. The Panel considered them together because they frequently co-occur and present a collective West Coast challenge. In particular, OA and hypoxia share a common set of drivers – increased atmospheric CO_2 levels and local nutrient and organic carbon inputs. Consequently, OA and hypoxia can be managed synergistically via an overlapping set of management strategies.

The Panel's products are more focused on OA because our understanding of the effects of OA and its interaction with hypoxia is only beginning to grow. In contrast, scientists have built a sizeable body of research on hypoxia, so its impacts on marine environments are better understood. Note that when the Panel uses the term OAH, it is a deliberate reference to both phenomena collectively; the terms OA, hypoxia and OAH cannot, however, always be used interchangeably.

II. Major Findings

The Panel's scientific experts reached consensus on six **Major Findings**:

1. **OAH will have severe environmental, ecological and economic consequences for the West Coast, and requires a concerted regional management focus.**

   OAH is a problem that is expected to grow in intensity with far greater impacts to come, particularly along the West Coast, where regional ocean circulation patterns dramatically heighten the potentially devastating effects of OAH. Local governments alone do not have the capability to halt fundamental, widespread changes to the chemistry of coastal waters. Decision-makers need a common core of scientific information that will enable them to use limited resources in a strategic, coordinated, regional fashion to best serve the ecological and socioeconomic needs of the entire West Coast region. Appendix B provides more detail about the trajectory of OAH-triggered change, and why the West Coast is more vulnerable than other coastal regions.

2. **Global carbon emissions are the dominant cause of OA.**

   Although this document is focused on how the West Coast is impacted by OA and the associated intensification of hypoxia, OA is a global problem that will require global solutions. Given that the dominant cause of OA is global carbon dioxide emissions, the Panel stands firmly behind multinational efforts to reduce atmospheric carbon dioxide emissions worldwide; humankind's ability to reduce the levels of CO_2 being absorbed by the world's oceans will be the single most important, effective strategy for mitigating OA. To that end, the Panel encourages West Coast leadership to develop a regional carbon management strategy, expanding on initiatives such as California's AB 32 and Washington's Climate Action Team.

3. **There are actions we can take to lessen exposure to OA.**

   Although local actions cannot wholly undo the global impacts of OA, West Coast managers can take action to improve local conditions by managing local factors that contribute to declining water quality. In particular, opportunities exist to implement better controls on nutrients and organic matter pollution that flow from land into coastal waters, as these chemicals provide nourishment for algae and bacteria that, in turn, can trigger hypoxia and exacerbate acidification. In selecting specific areas in which to implement these controls, managers should work closely with scientists, as these actions are typically costly and will not be equally effective everywhere; monitoring and modeling results can be used to inform best options.

4. **We can enhance the ability of ecosystems and organisms to cope with OA.**

   West Coast managers are not limited to mitigating OA; they also can take actions to reduce the negative biological and ecological impacts from OA. Fostering ecosystem resilience – that is, taking management actions intended to support an ecosystem's ability to withstand the impacts of OA – offers a near-term strategy for maintaining functional ecosystems along the West Coast as the environment changes. Managing for resilience can be achieved by expanding and adjusting approaches already in place along the West Coast, including the use of protected areas, ecosystem approaches to fisheries management, and integrated coastal management techniques. The concept of enhancing resilience is more thoroughly explored in Appendix C.

5. **Accelerating OA science will expand the management options available.**

   The state of knowledge about OA and its interaction with hypoxia is rapidly evolving, but is still limited and thus able to inform only a limited suite of management options to date. West Coast managers should be looking for opportunities to foster rigorous, managerially relevant research, develop coordinated cost-effective monitoring programs that continue to provide information about the projected trajectories of OAH, and integrate knowledge from multiple domains into decision-making. As scientific understanding of OAH grows, so will the options available for devising effective, fiscally prudent management strategies.

6. **Inaction now will reduce options and impose higher costs later.**

   It is becoming increasingly clear that OA will cause significant ecosystem changes, with widespread negative consequences that diminish valuable ecosystem benefits and services. Over time, OA conditions will intensify, diminishing opportunities for managers and West Coast communities to adapt to the changing marine environment. Delaying action now could render future management interventions far less effective (detailed further in Appendix D). Actions taken now based on best available science offer the possibility of forestalling at least some of the negative consequences for ecosystems and society.

III. Panel Recommendations

Consistent with these **Major Findings**, the Panel has formulated eight **Recommendations** to guide management responses. These **Recommendations** are divided among three themes:

1. Address local factors that can reduce OAH exposure;
2. Enhance the ability of biota to cope with OAH stress; and,
3. Expand and integrate knowledge about OAH.

For each **Recommendation**, the Panel provides specific **Actions** that can be implemented immediately and largely accomplished within a one-year timespan. The Panel's **Recommendations** and **Actions** highlight avenues where new science can quickly catalyze management options for addressing OAH.

By The Numbers

THREE THEMES

Eight Recommendations

Fourteen Actions

THEME 1
ADDRESS LOCAL FACTORS THAT CAN REDUCE OAH EXPOSURE

RECOMMENDATION 1 Reduce local pollutant inputs that exacerbate OAH	Action 1.1: Generate an inventory of areas where local pollutant inputs are likely to exacerbate OA. Action 1.2: Develop robust predictive models of OAH. Action 1.3: Develop an incentive-based strategy for reducing pollutant inputs.
RECOMMENDATION 2 Advance approaches that remove CO_2 from seawater	Action 2.1: Use demonstration projects to evaluate which locations are optimal for implementing CO_2 removal strategies. Action 2.2: Generate an inventory of locations where conservation or restoration of aquatic vegetated habitats can be successfully applied to mitigate OA. Action 2.3: Consider CO_2 removal during the habitat restoration planning process.
RECOMMENDATION 3 Revise water quality criteria	Action 3.1: Agree on parameters that will be part of OAH criteria.

THEME 2
ENHANCE THE ABILITY OF BIOTA TO COPE WITH OAH STRESS

RECOMMENDATION 4 Reduce co-occurring stressors on ecosystems	Action 4.1: Integrate OA effects into the management of ocean and coastal ecosystems and biological resources.
RECOMMENDATION 5 Advance the adaptive capacity of marine species and ecosystems	Action 5.1: Inventory the co-location of protected areas and areas vulnerable to OAH. Action 5.2: Evaluate the benefits and risks to active enhancement of adaptive capacity.

THEME 3
EXPAND AND INTEGRATE KNOWLEDGE ABOUT OAH

RECOMMENDATION 6 Establish a coordinated research strategy	Action 6.1: Create agreement among the multiple organizations that fund OAH research to establish joint research priorities.
RECOMMENDATION 7 Build out and sustain a West Coast monitoring program that meets management needs	Action 7.1: Define gaps between monitoring efforts and management needs. Action 7.2: Enhance comparability of and access to OAH data.
RECOMMENDATION 8 Expand scientific engagement to meet evolving management needs	Action 8.1: Create a science task force.

THEME 1: ADDRESS LOCAL FACTORS THAT CAN REDUCE OAH EXPOSURE

Recommendation 1: Reduce local pollutant inputs that exacerbate OAH.

While elevated atmospheric CO_2 levels are a major driver of OA, local discharge of organic carbon and nutrients can exacerbate OA. Upon discharge, organic carbon is broken down by bacteria, which consume dissolved oxygen during the decomposition process, triggering hypoxic conditions, increasing CO_2 levels and lowering pH. When nutrients such as nitrogen and phosphorus are introduced to coastal waters, they can trigger proliferation of algae that, following their death, are decomposed by bacteria that further decrease dissolved-oxygen levels and increase acidity. The Panel's recommendation to reduce local inputs is tempered by the recognition that scientists do not yet have adequate information to precisely identify locations where reductions in local inputs can meaningfully mitigate OAH effects. In general, the effectiveness of local actions will be greatest in semi-enclosed water bodies, such as estuaries, where local processes dominate over oceanic forcing. Site-specific evaluations are needed to determine which local input(s) (wastewater discharges vs. non-point source pollution in river discharge or atmospheric deposition) should be the targets of nutrient reduction efforts. Because of uncertainties concerning which local-control strategies will be most effective in reducing OA, West Coast managers may find it advantageous to pursue more than a purely regulatory enforcement strategy. For example, upgrades to wastewater treatment plants or investment in water reuse could be incentivized to design facilities that reduce nutrient discharges. Regardless of whether incentive-based or regulation-based approaches are used to achieve desired outcomes, managers can support the expedited development of predictive OA models that will guide decisions about how to best implement local source controls.

- **Action 1.1: Generate an inventory of areas where local pollutant inputs are likely to exacerbate OA.**

  While local nutrient- or other discharge-related control programs will not be effective everywhere, there are a number of locations where local nutrient inputs are thought to exacerbate OA. West Coast managers should compile an inventory of those locations to focus their initial management efforts, as these locations can serve as testing grounds for understanding the relative successes that can be achieved by reducing local inputs.

- **Action 1.2: Develop robust predictive models of OAH.**

  One method to determine where reduction of local inputs will result in the greatest gains in water quality is through use of coupled physical-biogeochemical models. These models quantify to what degree various nutrient, carbon, and CO_2 inputs influence OAH, and project how these inputs will exacerbate OAH. Several research groups on the West Coast are in various stages of developing such models, but before they can be used to support OAH-related management decisions, further investment is required to enhance and coordinate modeling efforts, and to link them to managerially relevant endpoints. A more thorough discussion of how West Coast managers can enhance the usefulness of these modeling efforts appears in Appendix E. Once models are operational, model outputs should be made accessible for comparisons among models and with monitoring data.

- **Action 1.3: Develop an incentive-based strategy for reducing pollutant inputs.**

  West Coast managers can develop grants, loans and other programs to create financial incentives for both the public and private sector to work proactively toward reducing local inputs that can exacerbate OAH, as well as promote reductions in atmospheric CO_2 emissions.

> In general, the effectiveness of local actions will be greatest in semi-enclosed water bodies, such as estuaries, where local processes dominate over oceanic forcings.

Recommendation 2: Advance approaches that remove CO_2 from seawater.

Seagrass and kelp beds remove CO_2 from seawater as they grow. This removal of CO_2 has the potential to offset the reductions in pH from OA. Emerging research suggests that conservation or restoration of aquatic vegetation habitats may indeed act to measurably lessen the severity of OA exposure. However, important uncertainties remain about when, where and how broadly local habitat conservation and restoration will mitigate OA exposure (see Appendix F). West Coast managers should actively explore the utility of this mitigation approach.

- **Action 2.1: Use demonstration projects to evaluate which locations are optimal for implementing CO_2 removal strategies.**

  Scientists have conducted research that demonstrates substantive positive benefits from coastal aquatic vegetation on CO_2 removal from seawater. The next step is to transition from these small-scale and short-term research efforts to larger-scale proof of concept demonstration studies across a range of habitats, providing managers with the opportunity to explicitly evaluate under which conditions protection and restoration of vegetated habitats will sufficiently remove CO_2 to meaningfully mitigate OA. These demonstration projects should be accompanied by rigorous monitoring, and physical and biogeochemical modeling to evaluate efficacy of such measures in reducing exposure to OA stress.

Emerging research suggests that conservation or restoration of aquatic vegetated habitats may indeed act to measurably lessen the severity of OA exposure.

- **Action 2.2: Generate an inventory of locations where conservation or restoration of aquatic vegetation habitats can be successfully applied to mitigate OA.**

  The knowledge gained from demonstration projects in Action 2.1 can be used to identify and inventory locations across the West Coast where CO_2 removal strategies can be applied. This inventory can inform comprehensive planning for how local CO_2 removal approaches can be applied relative to other Actions to reduce local inputs of CO_2, non-OA stressors, and enhance ability of biota to cope with stressors.

- **Action 2.3: Consider CO_2 removal during the habitat restoration planning process.**

  A number of investments have already been made to promote aquatic habitat restoration. Carbon offset protocols are also under development in some instances to value the co-benefits from long-term carbon storage of such restoration. However, they do not incorporate the potential benefits of local reductions in OA stress. Accounting for this local ecosystem benefit will assist in better accounting for the full societal value of habitat restoration and management.

Recommendation 3: Revise water quality criteria.

Water quality criteria serve as the foundation for many management activities, providing managers with thresholds to objectively determine the condition of a water body and to set targets for clean-up efforts. As such, they are an initiation point for both planning and implementation activities. However, existing water quality criteria, which were created four decades ago, are not scientifically appropriate for assessing OA conditions. Even when existing water quality criteria for seawater pH are met, a wide range of severe biological impacts of OA are observed. New criteria are needed. The Panel further recommends that OA water quality criteria be expanded to include other acidification parameters, as pH is only one of several possible parameters for describing the carbonate system. One such alternative, aragonite saturation state, has been found to be biologically relevant to a number of calcifying organisms. Appendix G provides additional insight about the need for revised water quality criteria.

- **Action 3.1: Agree on parameters that will be part of OAH criteria.**

  Water quality agencies should lead efforts among water quality and acidification experts to develop scientific consensus about which parameters are most appropriate for inclusion in new water quality criteria. In the immediate future, a scientific workshop is needed to identify appropriate biologically relevant indicators and thresholds to assess OA, and prioritize short-term research needs to support criteria development.

THEME 2: ENHANCE THE ABILITY OF BIOTA TO COPE WITH OAH STRESS

Recommendation 4: Reduce co-occurring stressors on ecosystems.

The ability of marine organisms to grow, survive, and reproduce in the face of OAH is partly dependent on the number, intensity, and interactions of other, non-OAH stresses they encounter, such as physical disturbances to nearshore habitats, warming temperatures, toxic contaminants, biological invasion, and harvest. Thus, it is important for West Coast managers to consider management plans and actions in the context of these multi-stressor effects. For example, the growing adoption of ecosystem approaches to fisheries management offers opportunities to consider the potential regional effects of OAH within the context of other ecological stressors as fisheries management plans are updated.

- **Action 4.1: Integrate OA effects into the management of ocean and coastal ecosystems and biological resources.**

  OA is likely to influence ecosystems along the West Coast via impacts on fish behavior, impaired calcification of shelled organisms, and fundamental changes in food web dynamics. Managers should work to understand and incorporate the probable impacts of OA into management plans for marine managed areas and fisheries. In some instances, this will require bilateral collaboration, for example, between the U.S. and Canada. For fisheries, the most promising avenue for advancing ecosystem-based fishery management along the West Coast is the Fishery Ecosystem Plan (FEP), adopted by the Pacific Fishery Management Council in 2013. The FEP is intended to improve and coordinate fishery management within the California Current Ecosystem by informing decisions made under each individual Fishery Management Plan with broader considerations about the ecosystem. Future updates of the FEP will provide an important opportunity to integrate improved OA knowledge into fishery management decisions, including ways that individual fisheries can be better managed to enhance ecosystem resilience and adaptive capacity under OA.

Recommendation 5: Advance the adaptive capacity of marine species and ecosystems.

Marine species and ecosystems have, to varying degrees, the ability to adjust and persist in the face of changing environmental conditions, a concept known as adaptive capacity. West Coast managers can support their adaptive capacity through relatively passive measures, such as use of protected areas. Managers can also undertake more proactive approaches, such as selective breeding, translocation of organisms that have shown adaptive capacity, and direct modification of genetic material. Genetic intervention efforts are already being explored as a means to improve the adaptive capacity of marine species to OA. The Panel recognizes that these more proactive approaches raise important concerns regarding their potential unintended consequences. Thus, such strategies should only be considered when other means of maintaining and promoting genetic adaptation are infeasible, and only when safety concerns have been addressed.

- **Action 5.1: Inventory the co-location of protected areas and areas vulnerable to OAH.**

  The West Coast includes five National Marine Sanctuaries, five National Estuarine Research Reserves, 15 National Wildlife Refuges, two Canadian marine protected areas, two Canadian Areas of Interest, multiple Essential Fish Habitat conservation areas created by the Pacific Fishery Management Council, 34 Areas of Special Biological Significance established by State of California, and numerous state-managed protected areas. Most protected areas, however, were designed and are being managed without regard to their vulnerability to OAH impacts, because little was known about OAH processes or impacts when most of the areas were established. Nevertheless, some of these protected areas could serve to promote adaptive capacity to OAH. Enhanced diversity and productivity of fish and invertebrate populations and preservation of ecological function within protected areas can strengthen the ability of populations and communities to cope with future OAH impacts. This may be particularly beneficial in instances where protected areas overlap with locations that are likely to face moderated exposure to OAH stress. In contrast, protected areas that are co-located with OAH hotspots offer an environment where biota that develop genetic tolerances to OAH are preserved. Both environments are important to maintaining adaptive capacity. West Coast managers should inventory the co-location of protected areas and areas vulnerable to OAH to assess the number of locations they presently have in the two categories.

> ...protected areas that are co-located with OAH hotspots offer an environment where biota that develop genetic tolerances to OAH are preserved.

- **Action 5.2: Evaluate the benefits and risks to active enhancement of adaptive capacity.**

  West Coast managers should facilitate the establishment of a working group of scientists and managers from relevant sectors to engage in joint fact-finding about the potential risks, benefits, and costs of active genetic intervention, such as through the selection, manipulation, and/or translocation of genetic varieties as a strategy for enhancing the persistence of species in mariculture settings and in natural ecosystems under intensifying OAH. Such intervention-based options are already being explored for OA but are occurring in the absence of deliberative guidance from the scientific and management communities. Historically, introductions of new genetic varieties and species on land and in the oceans have caused unintended harmful ecological or economic consequences that outweighed their benefits. The establishment of an active genetic intervention working group will set the stage for assessing the policy context for evaluating and regulating planned genetic interventions.

THEME 3: EXPAND AND INTEGRATE KNOWLEDGE ABOUT OAH

Recommendation 6: Establish a coordinated research strategy.

OA research is still in its infancy, with 75% of all acidification science studies published in the last five years, and only a handful of studies to date that have addressed the combined effects of OA and hypoxia, or OA and temperature, or OA and any other stressor. These constraints limit the ability to formulate options for effective management actions grounded in sound science. Generating more options will require further investment in directed research on OAH and its impacts on marine ecosystems. The research should be driven by management needs and should focus on evaluating the breadth of responses available to management, including scale and cost. The Panel has developed a comprehensive set of recommendations about which research topics are most likely to yield the greatest expansion of management options (see Appendix H), and Appendix H is supported by a separate and more extensive technical document outlining recommendations for research priorities ("*Ocean Acidification and Hypoxia Research Priorities to Inform Decisions and Develop Solutions*").

- **Action 6.1: Create agreement among the multiple organizations that fund OAH research to establish joint research priorities.**

  OAH research is taking place at multiple levels – across a range of federal, state, provincial, local and nonprofit funding sources. West Coast leadership should develop a coordinated long-term vision and funding plan to achieve a sustained, leveraged OAH research strategy for the region. West Coast managers should meet with funding entities to help unify their research around focused management goals and ensure that research efforts are effectively coordinated.

Recommendation 7: Build out and sustain a West Coast monitoring program that meets management needs.

Monitoring is a cornerstone of effective environmental management, highlighting spatial differences in OAH condition, and revealing the trajectory of conditions and providing a means for assessing effectiveness of management actions. OAH monitoring programs have often focused on measuring chemical parameters – such as pH and dissolved oxygen – but managers need a comprehensive program that assesses an array of interrelated physical oceanographic, chemical and biological variables and indices. Moreover, most West Coast monitoring is focused on addressing local issues, but these can readily be coordinated to achieve a regional-level program that addresses management needs coast-wide. A more thorough description about the need and opportunities for enhanced monitoring appears in Appendix I and in a supporting Panel technical document that describes a desired monitoring framework ("*Ocean Acidification and Hypoxia Monitoring Network: Tracking the Impacts of Changing Ocean Chemistry to Inform Decisions*").

> ...research should be driven by management needs and should focus on evaluating the breadth of responses available to management, including scale and cost.

- **Action 7.1: Define gaps between monitoring efforts and management needs.**

  West Coast managers should cultivate partnerships between monitoring practitioners and decision-makers to better define OAH information needs across ecosystem types and for diverse uses. First, they should build on existing efforts to complete a comprehensive inventory of existing oceanographic and ecological monitoring programs on the West Coast; the goal being to identify what monitoring is being conducted, what management questions these efforts address, what synergies and enhancements could be achieved, what measurements are missing, and what geographic areas have inadequate coverage to meet management needs.

- **Action 7.2: Enhance comparability of and access to OAH data.**

  Data comparability among disparate programs is necessary to achieve an understanding of OAH. West Coast managers should facilitate training and quality assurance procedures that will enhance comparability among programs. Furthermore, managers should work toward a consistent level of data discoverability, ensuring that the OAH community can make effective use of OAH data. Development of centralized portals for OAH monitoring data will allow this key information to be linked and shared, ensuring that monitoring can be used effectively to inform further research and ultimately management actions. This portal can also be used to access OAH model outputs.

Recommendation 8: Expand scientific engagement to meet evolving management needs.

Over the past two years, the Panel has not only created a set of written products outlining its "**Major Findings, Recommendations, and Actions**," but has also taken advantage of an unprecedented opportunity to network, convey relevant scientific perspectives, and build a community within a relatively nascent research area. Going forward, the region will benefit from this continued thoughtful interaction among scientists that is simultaneously focused and region-wide, and enhanced dialogue between scientists and managers. This is a rapidly evolving field, so cross-boundary communication is crucial to ensuring that new science products developed from research initiatives are appropriately vetted and communicated for use by the management community.

- **Action 8.1: Create a science task force.**

  West Coast managers will need a highly qualified body of scientists to advise them as new science develops in this rapidly evolving field. Given our West Coast-wide scientific commitment, investment, and momentum, this should remain a West Coast regional body with representation from California, Oregon, Washington, British Columbia, Alaska and Mexico as this issue will transcend state and federal geographic boundaries. The task force can evolve from the existing OAH Panel, but it should be refined to focus expertise on topic areas that align with management needs. A West Coast science task force will ensure that managers and legislators continue to be equipped with the most up-to-date information to make important decisions to protect the West Coast.

A West Coast science task force will ensure that managers and legislators continue to be equipped with the most up-to-date information to make important decisions to protect the West Coast.

IV. Appendices

APPENDIX A:
Why West Coast managers should care about ocean acidification

APPENDIX B:
Why the West Coast is vulnerable to ocean acidification - and what we can learn from it

APPENDIX C:
Managing for resilience to address ocean acidification and hypoxia

APPENDIX D:
The cost of inaction

APPENDIX E:
Using modeling to enhance understanding

APPENDIX F:
Approaches to reduce CO_2 in seawater

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APPENDIX H:
Establishing ocean acidification and hypoxia research priorities

APPENDIX I:
Tracking changing ocean chemistry through an ocean acidification and hypoxia monitoring network

APPENDIX A

Why West Coast managers should care about ocean acidification

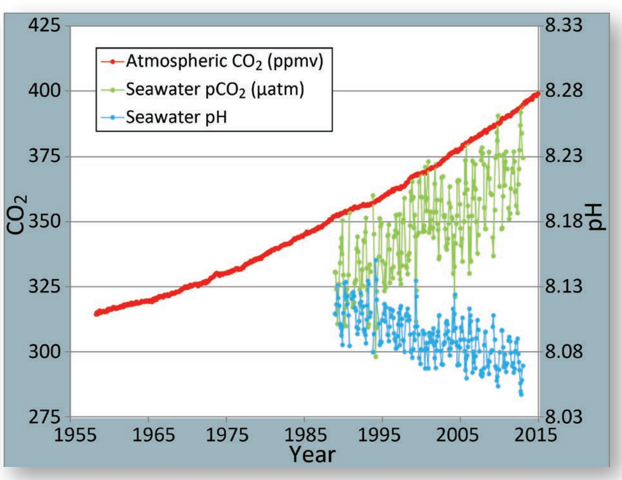
Ocean acidification is already posing a substantial threat, even if it's just beginning to enter the public consciousness.

In the same way that legacy pollutants in the marine environment inspired a generation of environmental activism in the 1970s and 80s, ocean acidification (OA) will define West Coast environmental management in the coming decades. OA endangers not only the biological health of marine organisms but also the numerous economic and societal benefits that stem from the West Coast's dependence on its coastal waters. The Panel unanimously and vigorously affirms that acidification of coastal waters is an undeniable, pervasive issue whose impacts have only begun to be felt.

1. Ocean chemistry is changing at an alarming rate, with no projected end or slowdown in sight.

- **Rapid change:** The fundamental alteration of the ocean's chemistry from continued absorption of atmospheric CO_2 is indisputable. At the current rate of global CO_2 emissions, the average acidity of the surface ocean is expected to double over pre-industrial levels by the end of this century.
- **Consequential change:** Seemingly small changes in ocean pH – which serves as a measure of acidification – are anything but small, as pH is expressed on a logarithmic scale. The 0.1 pH units of change that the ocean has recently experienced is equivalent to a 30% increase in acidity. For some organisms, this can be the difference between being able to grow a shell and having their shell dissolved.

> ...the average acidity of the surface ocean is expected to double over pre-industrial levels by the end of this century.



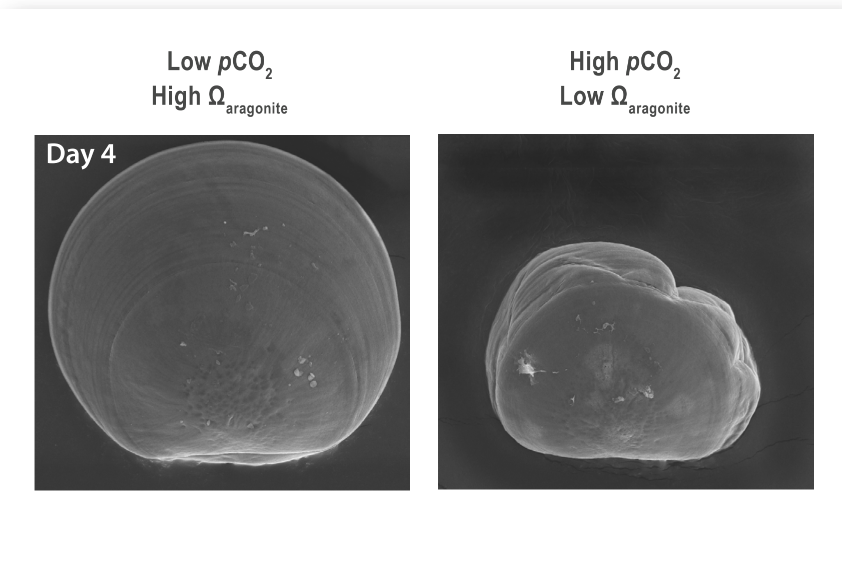
Credit: Modified after R.A. Feely, Bulletin of the Meteorological Society, July 2008.

2. West Coast ecosystems are already facing the pervasive impacts of OA.

- **Shell-forming abilities crippled:** Even small increases in acidity of the local water can dramatically reduce the ability of marine organisms to properly grow shell or skeletal structures. Shellfisheries are particularly vulnerable. Oyster hatcheries are seeing high mortality rates during early life stages when shell formation is critical. In 2007, hatchery managers began to experience a severe loss of oyster seed stock as a consequence of OA, which led to acute shortages available to oyster growers up and down the West Coast.
- **Reverberation through food webs:** Microscopic algae and zooplankton that form carbonate structures during their life cycle are at risk, resulting in consequences for marine food webs. For example, swimming sea snails known as pteropods, serve as an important food source for many West Coast fisheries species, including herring, mackerel and salmon. In some locations, more than 50% of these sea snails are already showing signs of shell dissolution. The evidence is compelling, with studies demonstrating that the percentage of pteropods affected by shell dissolution corresponds with local acidity levels.
- **Effects extend beyond shelled organisms:** Rising CO_2 in seawater has been found to disrupt basic neural function and sensitive skeleton structure in marine fishes. These disruptions adversely affect critical behaviors such as orientation, distinguishing predators from prey, finding food, and identifying appropriate habitats. Scientists' understanding of how OA impacts organisms and ecosystems continuously expands, so effects will likely extend beyond those described here.

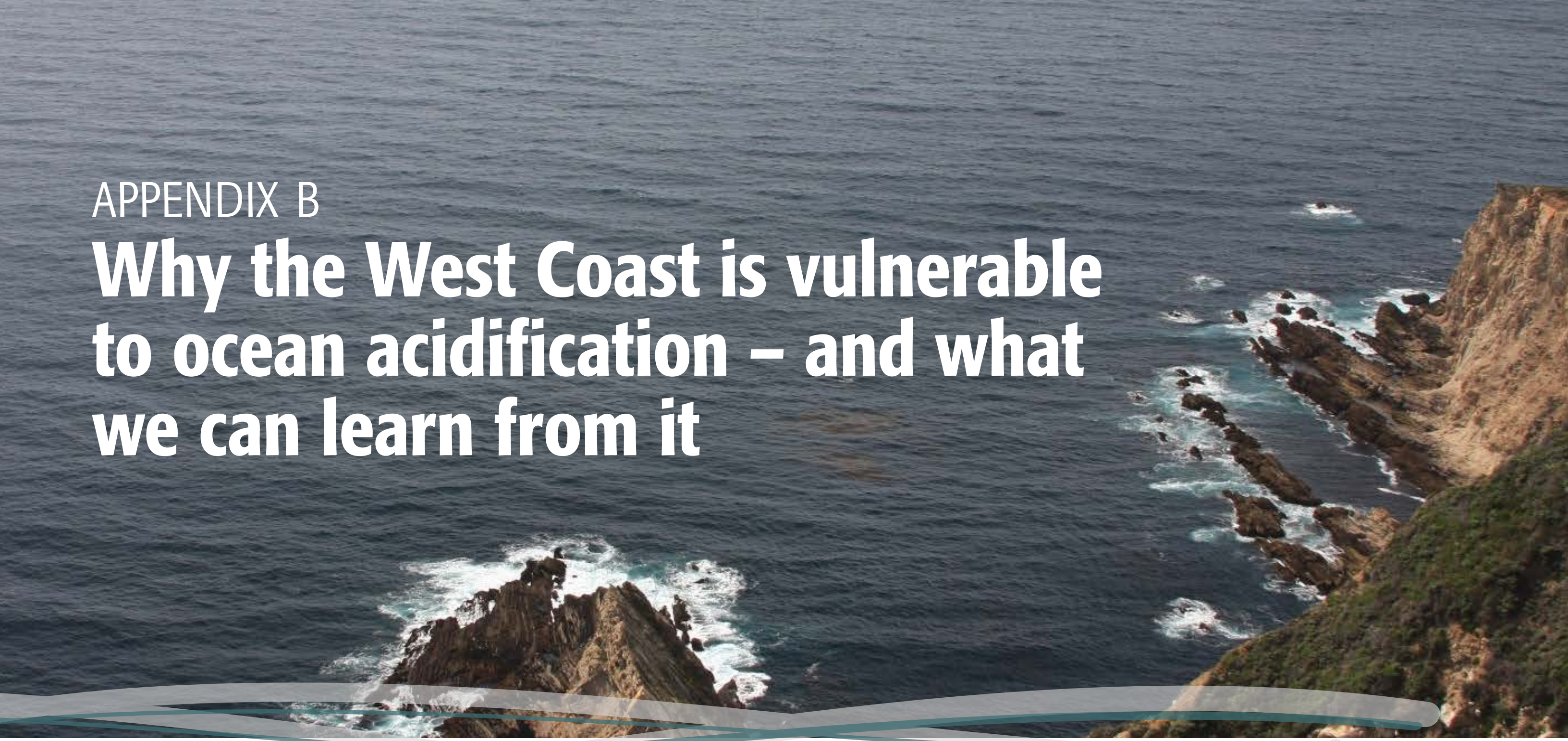
3. The consequences of OA are affecting ocean industries, with effects projected to worsen over time.

- **Operational disruption:** A West Coast shellfish farmer has relocated his hatchery to Hawaii, where exposure to low-pH marine waters is less than along the West Coast. Other hatcheries have invested in building expensive monitoring and water conditioning systems as necessary to maintain their West Coast operations.
- **Economic loss:** Oyster production in the Pacific Northwest declined 22% between 2005 and 2009 (13% decline in gross sales). In Washington and Oregon alone, two of the three major West Coast oyster seed hatcheries experienced production declines of up to 80% from 2006 to 2009. A Canadian company reported that it lost $10 million during its scallop harvest in 2014 in part due to OA. As the OA trajectory continues, a range of shellfish industries, including those for oysters, mussels and crabs, will be subject to economically devastating losses.
- **Domino effects of job losses:** Washington State's commercial and recreational fishing industries generate $8 billion in sales and 65,000 in jobs annually. In Oregon, the commercial and recreational fishing industries generate $1.5 billion in sales, and 19,000 jobs annually. Lastly, sales generated by the commercial and recreational fishing industries in California are $25.7 billion, and 158,000 jobs generated annually. As these industries endure future increases in acidification, the impacts could set off a domino effect of job losses throughout coastal communities, particularly in places where the fishing industry and coastal tourism provide the economic base.



Even small increases in acidity of the local water can dramatically reduce the ability of marine organisms to properly grow shell or skeletal structures.

Figure. Pacific oyster larvae from the same spawn, raised by the Taylor Shellfish Hatchery in natural waters of Dabob Bay, WA having favorable (left, pCO_2 = 403 ppm, $\Omega_{aragonite}$ = 1.64, and pH (total) = 8.00) and unfavorable (right column, pCO_2 = 1418 ppm, $\Omega_{aragonite}$ = 0.47, and pH (total) = 7.49) carbonate chemistry during the spawning period.
Photo credit: Brunner/Waldbusser.



APPENDIX B

Why the West Coast is vulnerable to ocean acidification – and what we can learn from it

Ocean acidification (OA) is a global problem triggered by the world's oceans absorbing society's CO_2 emissions from the atmosphere, but the effects of OA will manifest unevenly in different regions of the world. The West Coast of North America – among the first and most prominent regions being impacted by OA – is especially vulnerable because of a confluence of factors affecting this ecologically and economically significant region. However, as OA's global impacts intensify, other regions of North America – from the fisheries-dependent Gulf Coast to the slow-flowing embayments of New England – also will be altered by OA. Thus, the West Coast can and should serve both as a harbinger of OA's impacts worldwide and as a case study on how to develop a highly effective, region-specific science strategy for reducing the threat of OA on the West Coast and other regions of North America.

A confluence of factors makes the West Coast particularly vulnerable to ocean acidification; a regional, coordinated science approach is the best strategy to mitigate impacts.

A confluence of factors makes the West Coast especially vulnerable to OA

OA along the West Coast is being driven by a confluence of conditions that will create increasingly severe impacts over the foreseeable future. There are two primary natural phenomena that work in concert to heighten the region's vulnerability to global CO_2 emissions:

1. **Ocean currents:** Acidification of West Coast waters originates with oceanic currents that transport waters across the northern Pacific Ocean from Asia to the West Coast. The journey for these waters – which takes about 30 years but can be as long as 50 years – begins off the coast of Japan, where surface waters absorb atmospheric CO_2 produced through global human activity and then sink hundreds of feet beneath the ocean's surface. As these subsurface waters move toward the West Coast, CO_2 levels rise even more as natural respiration processes break down sinking organic matter (and deplete dissolved oxygen). Because these deep waters are naturally enriched in CO_2, the added CO_2 from atmospheric emissions has a disproportionately large impact on ocean chemistry.
2. **Coastal upwelling:** Along the West Coast, winds that blow southward push surface waters away from the coastline. As surface waters are displaced, the deep waters rich in CO_2 and poor in dissolved oxygen (DO) are pulled to the surface in a process known as upwelling. Upwelling spreads CO_2–enriched waters across the entire continental shelf, pushing chemical conditions past biological thresholds for harm in many coastal zones.

Because these physical and biogeochemical processes play out over a multi-decade timeframe, the effects of West Coast OA are projected to become increasingly severe over time. Three decades ago, atmospheric CO_2 levels were about 16% lower than they are today. Thus, the waters already in transit to the West Coast will carry an increasingly heavy anthropogenic CO_2 burden as they arrive on West Coast shores. In fact, even if atmospheric CO_2 emissions could immediately be stabilized, the West Coast would still be grappling with increasingly CO_2-rich waters for at least the next three decades.

Compounding these challenges is global climate change, which is also triggered by rising CO_2 emissions. As the world's oceans warm, seawater will become less able to hold DO, and the difference in temperatures between surface waters and deeper waters will grow bigger, reducing the oxygen resupply to deeper waters. Both trends will result in larger and more severe low oxygen, or hypoxic zones. Meanwhile, West Coast upwelling is projected to intensify as the winds that drive upwelling strengthen in response to global warming. Because upwelled waters are also depleted in DO, the progression of OA in many parts of the West Coast will take place against a backdrop of increasing risk of hypoxia events. This co-occurrence of hypoxia poses further challenges for organisms already subject to OA stress, increasing the vulnerability of the West Coast region to the effects of rising CO_2 emissions.

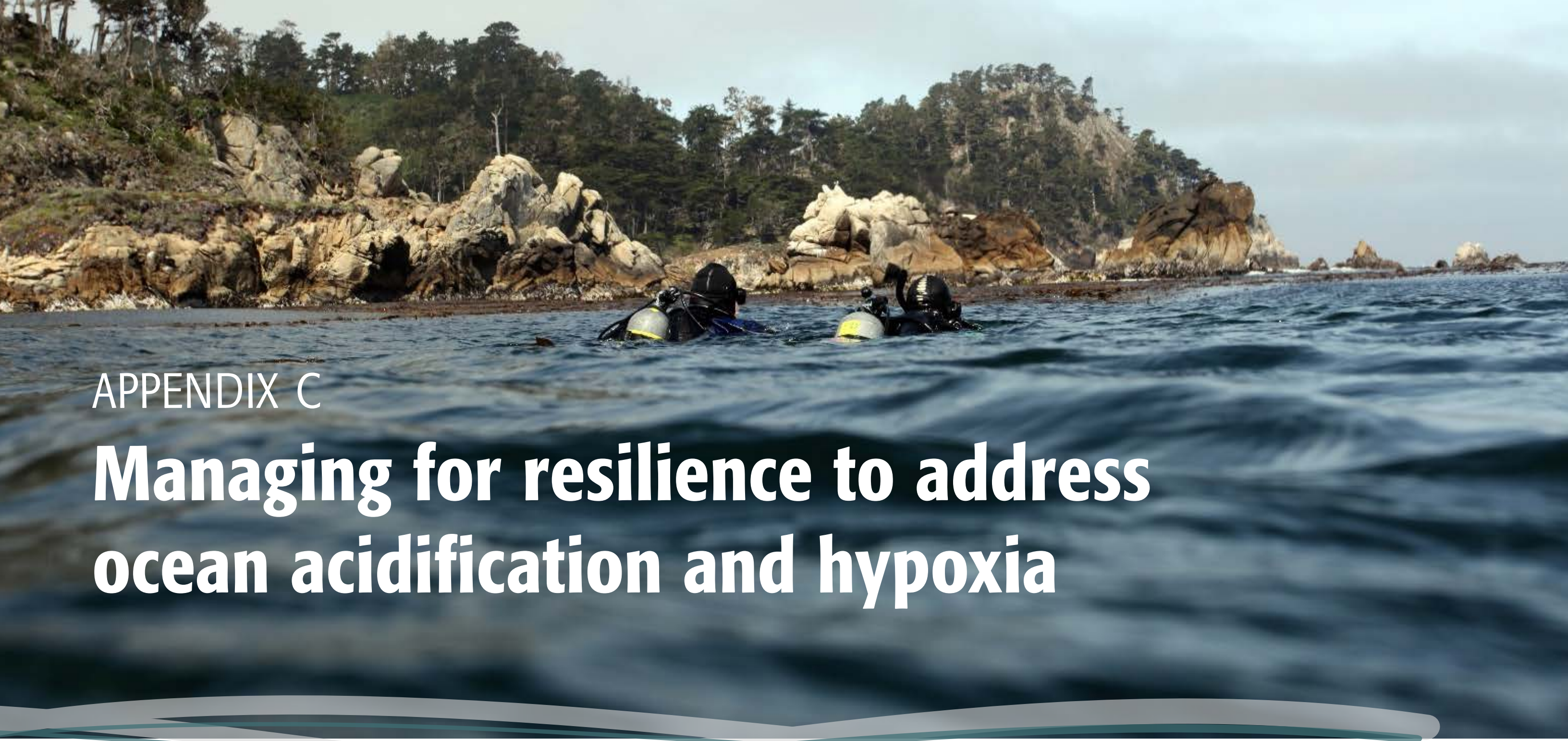
The most effective way to reduce West Coast vulnerability is through coordinated science

Because OA is a regional problem for the West Coast, the best way to mitigate OA's impacts is a regionally coordinated scientific research and monitoring strategy. Scientists and managers from across the West Coast can work together toward reducing OA's impacts on coastal ecosystems. A coordinated approach can take advantage of scientific commonalities that link the geographically and ecologically disparate areas that make up the West Coast region. For example, while Southern California's highly urbanized coastline may bear little resemblance to the minimally developed outer coast of Washington, they share many species of marine life in common. In fact, many important fishery species such as hake, tuna, and sardines move readily across state and national borders. Even for bottom-dwelling invertebrates such as Dungeness crabs, clams, and mussels, local populations can be genetically connected over large distances by the dispersal of planktonic young on ocean currents. Insights into biological vulnerability gained from one region can thus quickly inform information needs in another. Likewise, projections of ocean chemistry changes in any local ecosystem will require input from coast-wide models that set the stage for broader-scale patterns and trends in exposure. The development of such crucial coast-wide models is already underway and offers another avenue to accelerate access to knowledge needed across the region.

While local modeling and monitoring efforts are critical, they can have tremendous added value when they are linked together in a region-wide context that matches the regional scope of West Coast OA. By forming collaborative partnerships that leverage regional expertise and resources, and reduce redundancies, the West Coast can take advantage of economies of scale to mount a strong defense against this intensifying region-wide problem. OA knows no political boundaries and cannot be managed within defined jurisdictional borders, underscoring the value of highly coordinated, leveraged science.

The West Coast can serve as a proving grounds for strategic OA management

The West Coast will be a harbinger for the types of OA impacts that will be widely felt across coastal North America in the coming decades. By working in a coordinated fashion, scientists can provide managers with useable knowledge and information that informs and supports their OA management decisions. Just as importantly, the West Coast can serve as a proving ground for strategic OA management in other regions of North America and the world. Even within the West Coast region, "one size fits all" approaches are unlikely to be successful, as local factors that amplify or dampen OA vulnerability will differ with geography. Consequently, the vast and varied West Coast region offers the opportunity to test and compare diverse strategies, models and guides that can be transferred to other regions of North America.



APPENDIX C

Managing for resilience to address ocean acidification and hypoxia

The term "resilience," as applied here, refers to the adaptive capacity of ecological systems to cope with and recover from the impacts of ocean acidification and hypoxia (OAH) and other stressors. Here we provide the Panel's suggestions for how the management community can support ecological resilience under conditions of intensifying OAH by undertaking targeted actions that preserve or enhance the capacity for ecological systems to cope with and recover from OAH. Managing for resilience includes adaptation measures that seek to proactively lessen the impacts of OAH, and mitigation approaches that reduce exposure to co-occurring stressors. Such actions can be applied now to address impending changes in ocean chemistry. While intensifying OAH conditions may eventually cause some ecosystems to change substantially or irreversibly, over the near-term, managing for resilience represents an important strategy for "buying time" to slow the onset and reduce the scope of harmful ecosystem changes.

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Ecological concepts that underlie managing for resilience

Resilience spans many scales of biological organization, ranging from short-term physiological adjustments that take place within individual organisms, expression of adaptive capacity through evolutionary changes in populations, to the maintenance of ecological function by species turnover at the scale of ecosystems. Despite the number and complexity of biological and ecological processes that contribute to ecological resilience, scientists have been able to identify a specific set of desired attributes of resilient systems that are well-suited for protection or enhancement via management intervention. These general attributes include diversity, redundancy, modularity, connectivity, and adaptive capacity. For example, diversity in the form of a species-rich and functionally-redundant community of aquatic vegetation can be fostered by habitat protection measures. The resilience of fish populations can be promoted through harvest regulations that maintain broad distributions in age class structure and the contribution of sub-populations to a fishery. Population connectivity and, to a lesser extent, modularity, are already central elements in the design of coastal protected area networks.

Managers can also develop solutions that foster resilience by focusing on stressors that co-occur with OAH, such as physical disturbances to nearshore habitats, warming temperatures, toxic contaminants, biological invasion, and harvest. Co-occurring stressors can diminish the ability of ecological systems to cope with OAH, but may be amenable to control through management action.

Maximizing benefits from managing for resilience

Although managing for resilience is a useful near-term management strategy for coping with OAH, the adaptive capacity of West Coast ecosystems is not limitless. Managing for resilience is likely to become less and less effective as OAH intensifies and degrades precisely the biological and ecological attributes that confer resilience to populations, communities, and ecosystems. Where and when managing for resilience is likely to be most successful is also likely to vary greatly among systems and from place to place, but understanding of this variation is poorly developed for OAH. Identifying priority candidate fisheries or systems where the development and implementation of resilience-focused management plans are most likely to be beneficial would be an important first step in managing for resilience across the region.

Resilience management can involve actions to prevent the loss of resilience from status quo conditions, or interventions that enhance the resilience of a system in the face of intensifying OAH stress. The effectiveness of either approach will depend on establishing metrics of resilience, defining targets and goals, and developing the ability to track changes in resilience and intervene adaptively if goals are not met. Because preserving and enhancing resilience to OAH are not currently explicit goals of natural resource management, metrics to quantify resilience, targets for those metrics and approaches to monitor changes in resilience have yet to be fully developed.

Increasing the capacity to hone such tools is an important opportunity to advance managing for resilience from conceptual strategy to concrete implementation. For now, managers will need to work with scientists to develop, test, and refine such approaches in real world applications.

Resilience management can involve actions to prevent the loss of resilience from status quo conditions, or interventions that enhance the resilience of a system in the face of intensifying OAH stress.

APPENDIX D
The cost of inaction

Failure to take action will reduce management options and trigger more severe ecological harm

Marine ecosystems, and the industries that depend on them, face growing risks of widespread harm that will become increasingly difficult to reverse as rising CO_2 emissions intensify ocean acidification and hypoxia (OAH). Thus, the cost of inaction on OAH, in the form of reduced management options and wider ecological changes, will rise over time. Scientists are working to understand where and when OAH's aggregate impacts will cross thresholds, or "tipping points," where ecosystems switch to significantly degraded or altered states from which recovery becomes increasingly unlikely. Scientists also are continuing to evaluate what actions West Coast managers can take now to slow the progression of OAH and mitigate its most ecologically and economically threatening impacts.

The full scope of ecological changes ahead is not yet well understood or described, and, as with any area of scientific projection, understanding will come qualified by caveats about scientific and statistical uncertainty. While skeptics might argue that West Coast managers should wait to take action until these uncertainties are resolved, the Panel strongly disagrees with that assessment. OAH science allows researchers to link various observational and modeling data to develop reasoned, informed projections that can help bound expectations about what the world might look like in 1 year, in 10 years, in 50 years. These projections will change as scientific understanding of OAH improves, but the general trends are clear.

...the cost of inaction on ocean acidification and hypoxia, in the form of reduced management options and wider ecological changes, will rise over time.

Science supports the decision to act now to start addressing OAH

The Panel's rationale for why West Coast managers should take action now includes:

1. Larger and more rapid changes in ocean chemistry lie ahead.

Continued atmospheric CO_2 emissions will alter the chemistry of coastal waters in ways that will fundamentally make it more difficult to support ecosystems and the benefits that they provide to humans today. These changes in ocean chemistry are not projected to occur in a simple incremental fashion, as non-linearities in the carbonate system amplify the impacts of future rise in seawater CO_2 content. Larger and more rapid changes can also arise from processes associated with climate change and nutrient inputs that enhance inorganic carbon loading and the intensity of ocean hypoxia.

2. The risk of crossing biological and ecological thresholds will increase as OAH stress intensifies.

In addition to non-linear changes in ocean chemistry, scientists also expect impacts on marine life populations and ecological communities will rise non-linearly as the intensification of OAH stress exceeds the physiological tolerance of an increasingly large suite of species that interact within coastal food webs.

3. Predictive power will decrease as the effects of OAH move deeper into uncharted territory.

As the West Coast moves away from presently observable states of ocean chemistry and ecology, it will become harder for scientists to predict with confidence how ecological systems will be affected by OAH. Thus, West Coast managers will benefit from slowing OAH's impacts, as it will help to preserve access to the best-constrained assessments of risks and options.

4. Degraded systems may become less resilient to OAH stress.

Emerging science suggests that as ecosystems become degraded by OAH and other stressors, they become less resilient and less able to withstand increased OAH stress going forward. This suggests that taking actions now to prevent the loss of resilience can lessen the impacts of OAH in the future.

5. Reversing OAH degradation later will involve greater effort and/or longer lag times.

Preventing declines in populations or ecosystems is often more tractable and less costly than reversing declines once they have occurred. For example, challenges in rebuilding fish populations once genetic diversity is lost, or restoring habitats once they have shifted into a less desired state, illustrate the difficulty of reversing ecological degradation. By allowing more changes to manifest before taking management action, OAH effects may become more difficult and perhaps impossible to reverse.

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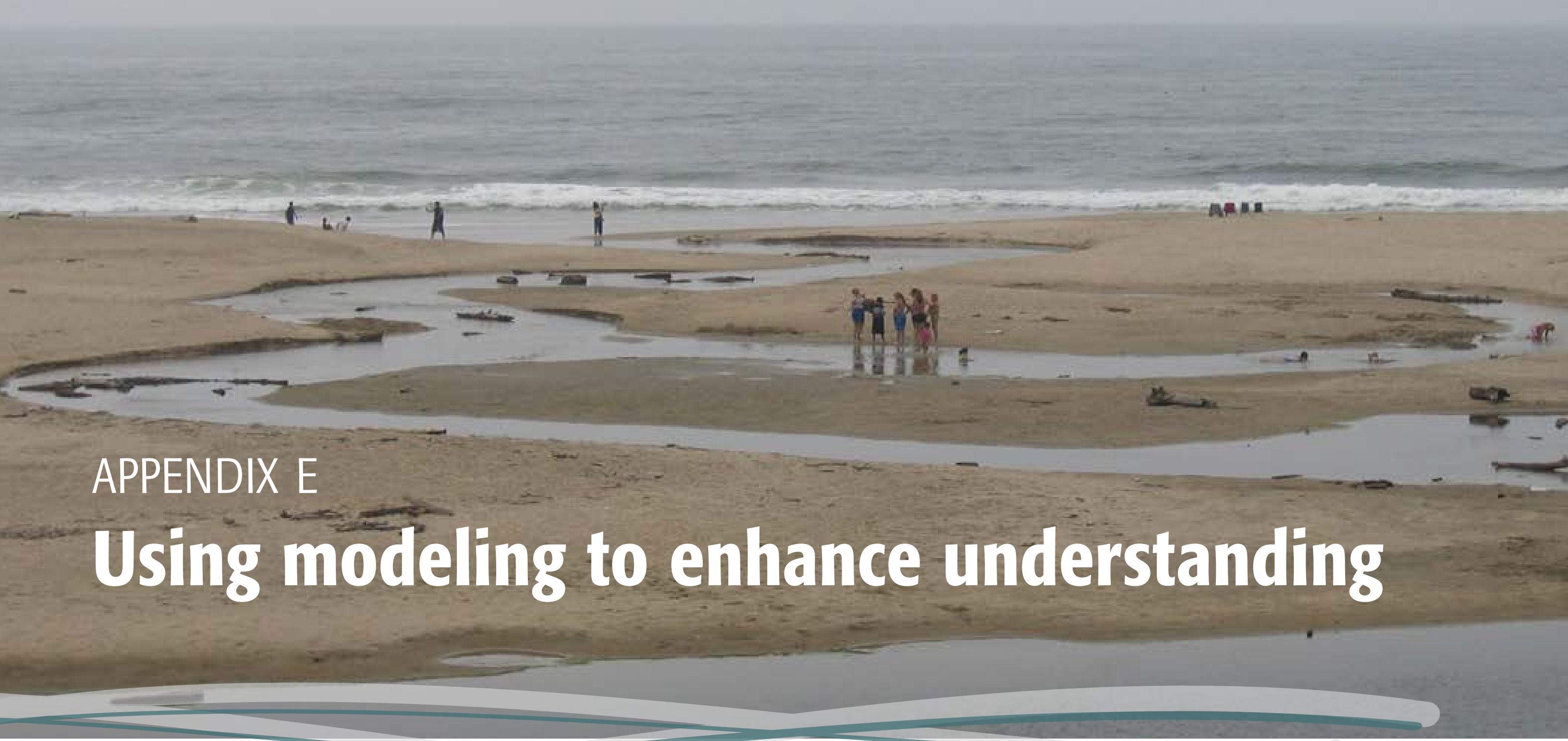


APPENDIX E
Using modeling to enhance understanding

Predictive mathematical models that provide insight into the potential ramifications of ocean acidification and hypoxia (OAH) play an instrumental role in scientists' ability to offer a suite of management options that address OAH in an informed, scientifically defensible fashion. Modeling tools allow scientists to forecast what future conditions will look like, to interpolate limited data sets to build a comprehensive picture of conditions, to evaluate likely success of potential management actions, to prioritize data gaps, and to evaluate monitoring plans.

OAH models will allow coastal managers to make better-informed decisions about implementing controls on local pollution sources that are exacerbating OAH, and to engage in ecosystem-scale resource management planning. Multiple research groups are already in various stages of developing such models, but efforts to date are limited in several respects. First, OAH model development has primarily focused on large oceanic scales, leaving important knowledge gaps in scientists' ability to predict OAH dynamics in near-coastal waters, estuaries and bays that are the primary focus of potential management action. Second, physical models that describe the movement of ocean water across space and time have not yet been systematically coupled with biogeochemical models, which describe how various environmental elements together exert collective effects on OAH chemistry, or with ecosystem models that integrate physical, biogeochemical and ecological properties to predict effects on marine life populations and whole ecosystems.

Thus, additional investments in OAH modeling work are needed to enhance, coordinate and link existing modeling efforts to OAH-related management decisions. The Panel recommends that West Coast managers and the scientific community move forward by building and improving upon both coupled physical-biogeochemical models and fishery and ecosystem models. These models should be validated with management endpoints in mind and against various settings. The modeling community would also benefit from a modeling forum to promote collaboration and interaction with managers. These recommendations are outlined in greater detail here.

OAH models will allow coastal managers to make better-informed decisions about implementing controls on local pollution sources...

OAH Modeling Recommendations

1. Invest in a suite of coupled ocean-margin physical and biogeochemical models.

Although a nested set of physical and, to a lesser extent, biogeochemical models has already been developed for the West Coast, these models have coarse resolution that inhibits their application in areas that are the focus of management concern. West Coast managers should build capacity for downscaling these physical models, extending them closer to shore, and integrating them with biogeochemical models to create high-resolution, coupled models.

2. Improve fishery and ecosystem models.

Although a broad suite of models are currently employed to inform fishery management and predictions of ecosystem changes along the West Coast, the objectives of these efforts have generally fallen outside the scope of OAH management needs. Fishery and ecosystem models will be crucial for understanding and predicting the full extent of OAH impacts. The utility of these models, however, will depend on how biological and ecological responses of OAH are parameterized, and how outputs from coupled physical-biogeochemical models are utilized. To better support marine resource decisions, scientists should prioritize research that yields parameterize-able understanding of the biological and ecological impacts of OAH, and improvement in the capability of fishery and ecosystem models to be informed by advances in coupled physical-biogeochemical models.

3. Validate the models.

The management decisions that will be based on model outputs are likely to be costly. As such, models should be validated and improved with endpoint management decisions in mind, and with a focus on identifying knowledge gaps and quantifying uncertainty. Validation efforts should extend explicitly into near-coastal areas where temporal and spatial variability are the highest, and where a large number of management decisions are concentrated. Scientists should first seek to validate existing models using observational data for a broad range of climate and ecosystem states, with a focus on quantifying uncertainties and identifying key gaps in data and modeling infrastructure. Second, scientists should compare the outputs of multiple models to constrain uncertainty in their projections, which could ultimately pave the way for development of the next generation of models.

4. Collect data to support model development and refinement.

The ability of models to make accurate predictions of future ecosystem changes – be it aragonite saturation state, dissolved oxygen, biodiversity, or fish populations – is limited by the availability of data that can be used to parameterize those key attributes. In turn, confidence in model outputs will depend on a clear understanding of the ability of models to accurately reproduce features of the ecosystem that are of greatest management interests. This understanding will require diverse datasets that test model performance across different regions or habitats, and across different seasons and years as ocean and ecosystem conditions change. Investments in the sustained collection of integrated oceanographic and ecological data sets will be crucial for refining the performance of predictive models and their utility in informing decisions. There also should be effort to create a central repository for observational data and model output so that they are used effectively to inform further research, and ultimately management action.

5. Establish a forum to advance coastal ocean modeling.

The West Coast would benefit from creation of a forum that brings scientists and managers together to synthesize local and regional management needs, and to ensure that scientists are working in a coordinated, synergistic fashion to address those management needs. 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. 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.

APPENDIX F

Approaches to reduce CO_2 in seawater

The impacts of rising atmospheric CO_2 concentrations on seawater carbonate chemistry can be reduced using two possible approaches. The first is biologically-based, making use of the natural ability of the ocean's photosynthetic organisms (algae and plants) to capture CO_2. For example, seagrasses, kelps and other macrophytes remove CO_2 from seawater and convert it into living tissue. This CO_2 uptake can occur at sufficiently rapid rates to significantly improve water quality for organisms sensitive to carbon chemistry changes. Although a substantial fraction of this organic carbon is released as CO_2 when plant tissue decomposes, active photosynthesis may offer a means to locally reduce CO_2 in shallow coastal environments.

There has been considerable interest along the West Coast in protecting and restoring aquatic vegetation as a means to reduce CO_2 in coastal aquatic ecosystems. Seagrass beds and kelp forests are among the world's most productive habitats, with rates of net primary production that can exceed those of tropical forests. The ability of aquatic vegetation to influence coastal chemistry is evident from estuarine monitoring data that show day to night swings in pH whose magnitude can exceed near-term declines projected from OA.

The second approach uses abiotic methods to mitigate OA exposure. Abiotic methods can be used to increase chemical buffering capacity (alkalinity) of seawater or physically remove CO_2. Synthetic base chemicals or natural base minerals can be added to seawater to increase its alkalinity. This in turn neutralizes seawater acidity and buffers against the effects of increasing CO_2 on seawater chemistry. CO_2 can be directly removed from seawater using engineered approaches such as electrochemistry, electrodialysis, vacuum extraction, and aeration with a CO_2-depleted gas.

...coastal vegetated habitats hold some of the highest concentration of organic carbon of any ecosystem on the planet, and serve as a globally important sink for carbon (i.e., blue carbon).

There are potential co-benefits of habitat protection and restoration

While one potential benefit of protecting and enhancing aquatic vegetation is reducing CO_2 in seawater, additional co-benefits may also be realized. A portion of the CO_2 converted into vegetation can be buried in sediments. This process represents the potential long-term storage or sequestration of CO_2. On an areal basis, coastal vegetated habitats hold some of the highest concentration of organic carbon of any ecosystem on the planet, and serve as a globally important sink for carbon (i.e., blue carbon). Consequently, their conservation and restoration could one day become eligible for carbon offsets in carbon trading markets, such as the one established in California, or for other funding that promotes carbon sequestration. We also note the distinction between short-term removal of CO_2 and the long-term sequestration of CO_2 by vegetated habitats. For example, kelp forests, while highly productive and active in CO_2 removal on a daily and seasonal basis, grow on hard bottom habitats where local sediment burial and the potential for long-term carbon sequestration may be minimal. In contrast, emergent marsh vegetation uses CO_2 from the atmosphere for photosynthesis and releases CO_2 to surrounding waters through root respiration. Yet, these systems can be highly effective in trapping and sequestering carbon-rich sediments, or removing nutrients that may otherwise contribute to acidification or hypoxia in downstream habitats.

Another benefit of protecting and enhancing aquatic vegetation is the creation of habitat for fish and other biota. One of the Panel's **Actions** is considering the ability of aquatic vegetation to remove CO_2 from seawater in addition to its habitat value during habitat restoration planning. Accounting for both of these ecosystem benefits will assist in better achieving the full societal value of habitat restoration and management.

Advancing research to increase management options

Across the West Coast, researchers are actively investigating approaches for restoring aquatic vegetation, their role in locally modifying coastal seawater chemistry, and the daily to seasonal patterns of carbon uptake of these environments. In the K'ómoks Estuary on Eastern-central Vancouver Island, the transplanting of eelgrass from donor beds to previously disturbed estuaries has been successful in establishing new beds. Dive surveys have confirmed a transplant success rate of 95%. In Washington, pilot studies have reported elevated daytime pH in waters over seagrass beds relative to bare sediment habitats. In Oregon, oyster hatchery managers at Netarts Bay have begun to selectively draw seawater into the hatchery during hours when photosynthesis in the seagrass-rich system has reduced CO_2 to levels acceptable for their operations.

These examples highlight the potential applications of aquatic vegetation protection and restoration as actions to reduce CO_2 and ameliorate, if not offset, OA in local ecosystems. If successful, such actions can increase the range of options available to managers to address OA. Important questions nonetheless remain as to the effectiveness of aquatic vegetation CO_2 reduction as an OA mitigation strategy and must be answered before implementation. For example: Will the benefits of photosynthesis be offset by increases in the daily and seasonal swings in carbon chemistry? How far does the spatial "footprint" of such effects extend? What are the range of settings and locations where vegetation protection and restoration will be most successful and beneficial? Can such measures be employed in concert with other management actions to maximize conservation benefits? These questions can be addressed directly in larger-scale, proof-of-concept demonstration studies. When conducted across a range of habitats, these efforts can provide managers with new, useable knowledge of if and where protection and restoration of vegetated habitats will sufficiently remove CO_2 to meaningfully mitigate OA.

Options from engineering approaches

Human intervention to mitigate OA through engineering addition of basic materials and removal of aqueous CO_2 is still in early development. The effective scale, ecological consequences, and carbon footprint of such efforts remain uncertain but can offer important options for impacted industries. For example, shellfish growers on the West Coast have begun to use alkalinity management to offset the increase in carbonate mineral corrosivity from OA in hatchery settings. Although currently available approaches remain likely tractable only at localized scales and in controlled environments, future technological advances may broaden the applications of engineering approaches. Further research will be needed to determine the safety, cost effectiveness and potential scale of such efforts in countering the ongoing global progression of OA and its regional expression on vulnerable West Coast ecosystems.

APPENDIX G

Existing water quality criteria are inadequate to protect marine ecosystems

Water quality criteria are the management foundation of the Clean Water Act. They provide a basis for assessing water body condition, determining the level of discharge that will maintain a water body in an ecologically acceptable condition, and objectively determining when a water body is impaired. Most importantly, water quality criteria serve as targets for water body planning and mitigation projects, even outside of the regulatory framework.

Unfortunately, the existing water quality criteria for pH are not scientifically valid for application to ocean acidification (OA). They were developed 40 years ago, and the Panel has determined that they are neither based on current science nor are they ecologically relevant. Damage to ocean biological communities has been documented at thresholds that are well within the criteria's legally permissible range.

...the existing water quality criteria for pH are not scientifically valid for application to ocean acidification.

Shortcomings of existing criteria

Existing OA criteria are based on two types of pH thresholds: a requirement that pH should not fall below 6.5, and a requirement that pH should deviate no more than 0.2 pH units from natural conditions. Both types of thresholds are flawed for the purposes of application to acidification.

The minimum pH of 6.5 is inadequate because numerous studies have shown diverse biological impacts routinely manifest at pH levels well above 7.5, at which acidity (hydrogen ion concentration) is an order of magnitude higher than pH 6.5 (pH is on a logarithmic scale). The Panel's publication, "*What changes in the carbonate system, oxygen, and temperature portend for the northeastern Pacific Ocean: a physiological perspective*," provides more detail about the range of biological responses that occurs even as existing pH criteria are met.

The second part of the criteria, which calls for a deviation of no more than 0.2 pH units from natural, is flawed because it is impractical to apply. "Natural" conditions cannot be established spatially because the entire West Coast region is undergoing change due to global atmospheric inputs, and it is difficult to establish temporally because there are few long-term data sets with enough precision and accuracy to capture this level of change. This is compounded because measurement imprecision of the technology used in discharge monitoring programs is greater than 0.2 pH units, creating a margin of error that can mask ecologically relevant pH changes. Criteria inadequacies regarding establishing "natural" conditions are further described in the Panel supporting document "*Water quality criteria for acidifying oceans: Challenges and opportunities.*"

Water quality criteria should be expanded to encompass other acidification parameters

Although developing an alternative pH criteria represents an important first step, revisions to water quality criteria should be expanded to include other biologically relevant acidification parameters. pH is only one of several possible parameters for describing effects of acidification, and it is unclear if pH is even the most biologically relevant variable for many species. Aragonite saturation state, another viable candidate indicator, has been found to be more biologically relevant than pH for shell-building in calcifying organisms. Considerable scientific evidence, particularly from studies of oysters and pteropods – a shelled zooplankton at the base of the food web – is already available for establishing both chronic and acute thresholds for aragonite saturation state. In addition, parameters such as pCO_2 have been found to be biologically relevant for fish, affecting their behavior and ability to navigate.

In developing ecologically relevant thresholds for OA parameters, managers should account for potential interactions of OA with co-occurring stressors such as hypoxia. There is a growing recognition that the most acidified regions of the ocean are also low in oxygen, with recent studies showing that dual effects of low pH and hypoxia are more severe than the predicted effects of either stressor alone. In the immediate future, a scientific workshop is needed to identify appropriate biologically relevant indicators and thresholds to assess OA, and to prioritize short-term research needs for informing criteria and threshold development.

…revisions to water quality criteria should be expanded to include other biologically relevant acidification parameters.

Development of biological criteria will improve assessment of acidification effects

The Clean Water Act provides an opportunity for assessing ocean health by examining condition of the biological communities that live within it, which has advantages over using pH or other chemical criteria alone. Traditional chemistry thresholds and associated monitoring are limited because they provide information about a relatively narrow portion of the environment at a discrete point in time. In contrast, bioassessment accounts for exposure to multiple stressors over extended time periods, and provides a more integrated reflection of aquatic ecosystem condition.

Incorporating biological criteria into a management context requires linking population and community effects with specific stressors. Effective biological criteria should provide early-warning management cues, before significant ecosystem alteration has already taken place. However, biological criteria also need to relate to effects on growth, survival, reproductive success or other metabolic functions that have repercussions at the population level, as opposed to simply quantifying exposure to a stressor. For example, pteropods might prove useful as a biologically relevant criterion for linking acidification stress to biological response, as they are an important food source for economically important fish and are among the first organisms to be affected by acidification in a marine ecosystem. Pteropods have thin aragonitic shells and narrow optimum windows for calcification, leading them to display rapid responses to corrosive waters. Acidification effects on their calcification have been studied under both field and laboratory circumstances and such indicators could offer a more integrated understanding of acidification effects.

Using ecologically relevant criteria to support OA management

Water quality criteria are typically used as regulatory tools, such as making decisions under the Clean Water Act Section 303(d) regarding whether a water body is impaired. The Panel recognizes that this is one application of water quality criteria, but the Panel also recognizes that credible water quality criteria can be effective in other decision-making contexts. For example, water quality criteria provide essential context for interpreting monitoring data or the output of model predictions about the likely effects of potential management actions. They also become part of a shared toolkit with managers from other sectors, providing a common framework for discussions about appropriate actions for fisheries and marine reserves. Additionally, scientifically-founded OA criteria can also be used to educate the public about OA and its effects on local waters.

APPENDIX H

Establishing ocean acidification and hypoxia research priorities

A strategy for aggressively expanding options for management action

To manage effectively for ocean acidification and hypoxia (OAH), West Coast managers need an arsenal of tools and options that are grounded in sound science. However, OAH research is still largely in its infancy, generally limiting the management options available. While the amount of OAH research being conducted has exploded over the past decade, many critical knowledge gaps remain. This document outlines the Panel's recommendations for aggressively expanding the breadth and depth of OAH research in order to meet the demands for management-relevant information on the West Coast and beyond. Organized around five major research areas, this research portfolio has been designed 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; they also must maintain a relentless focus on providing managers with concrete, actionable options for immediately combatting the threats posed by OAH. Scientists are invested in seeing their OAH work translated into viable management options, but need help from West Coast managers in coalescing around a shared research vision and coordinating efforts for maximum impact and efficiency. The recommendations outlined in this Appendix are expanded in the Panel's more detailed document "*Research Priorities to Inform Decisions and Develop Solutions.*"

While the amount of OAH research being conducted has exploded over the past decade, many critical knowledge gaps remain.

Understand drivers of OAH

Scientists understand at a conceptual level that local nutrient and carbon inputs can exacerbate the impacts of OAH. However, management recommendations about reducing these local inputs are 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 about the relative importance among local inputs (non-point source vs. wastewater discharge vs. local atmospheric inputs) to prioritize for reduction. Thus, the Panel recommends investing in research that enhances our understanding of the relative importance of local vs. global contributions to OAH. West Coast managers should focus on developing key datasets, and coupled physical-biogeochemical models, validated with observations, that quantify the relative impacts of various nutrient, carbon and carbon dioxide sources on exacerbating OAH. Investments should also continue in developing new, accurate, cost-effective and easily deployed ocean sensors for OAH parameters. These models should be evaluated in the context of decision-making processes, and observational data should be collected to enhance model validation. As scientists learn more, they can adjust and adapt strategy options for source reduction that will maximize effectiveness and minimize cost.

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. Scientists along the West Coast are in various stages of developing coordinated monitoring programs, conducting laboratory and field experiments, and refining numerical models to address such questions. However, additional research is needed to transition these studies from individual research projects to more concerted, connected sets of research activities that address the underlying management questions. In addition, current efforts need to be expanded to downscale global models to project change along the West Coast, elucidate the biological effects of multiple stressors within the context of real-world exposure conditions and enhance the translation of physiology-scale findings to population- and ecosystem-scale projections.

Understand evolutionary response to OAH

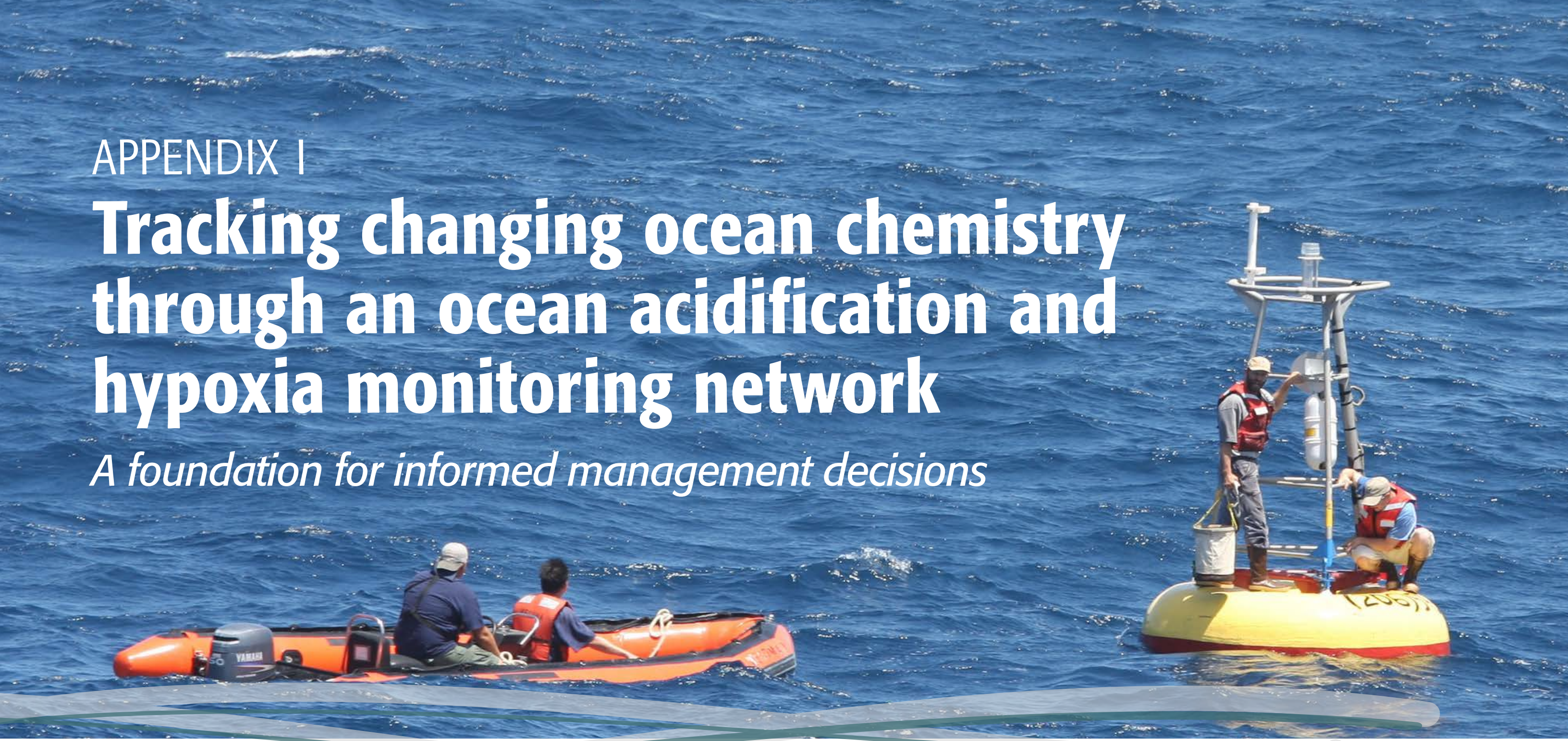
Although organisms have the potential for evolutionary adaptation to cope with OAH stress, scientists have insufficient information to predict whether, where, and how fast that genetic adaptation will occur. Thus, research is needed to understand rates of natural genetic change in response to OAH, and how evolutionary potential is distributed among taxa and localities. Moreover, West Coast managers need to understand how this potential for adaptation can best be incorporated into management strategies, such as use of refugia to protect the genetic diversity that now exists in local biota, especially those that are routinely exposed to high levels of OAH stress. Research will also allow assessment of the potential value and consequences of purposeful interventions, such as selective breeding and translocation. With sufficient knowledge, managers can determine whether and where opportunities exist to use evolutionary potential to address OAH's impacts on biological communities.

Explore sequestration and other carbon removal solutions

The acidification of seawater can be mitigated in two main ways: a) a biologically-based approach, in which seagrasses, kelp and other vegetation remove carbon dioxide from seawater and convert it into living tissues, and b) a chemically-based approach, in which the addition of base minerals such as carbonates is used to neutralize acidity. These approaches are appealing because they operate at the local level, but their applications to date have been limited and focused mostly on laboratory or small-scale settings. 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 conservation strategy.

Advance living marine resources management

Because the Panel has recommended that managers undertake actions that enhance the ability of organisms to cope with increasing OAH stress – 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. Critical to understanding OAH in an ecosystems context is that different areas are more vulnerable or resistant than others. Ecosystem models that support ecosystem-based fisheries management need to be developed and validated on local scales, and ecological risk assessments that increase understanding of fisheries vulnerabilities need to be conducted.



APPENDIX I

Tracking changing ocean chemistry through an ocean acidification and hypoxia monitoring network

A foundation for informed management decisions

Ocean acidification and hypoxia (OAH) monitoring programs dot the West Coast, as monitoring plays an invaluable role in scoping the severity of OAH-related problems, determining the trajectory of the problem (i.e., is it getting worse, and at what rate?), and assessing the effectiveness of past and planned management actions. Many monitoring programs were developed to address specific research or management needs. As a consequence, they do not adequately operate on the spatial and temporal scales over which OAH is occurring. Furthermore, traditional OAH monitoring focuses on measuring basic chemical parameters, such as pH and dissolved oxygen, rather than the full array of interrelated variables that collectively define OAH's impacts.

The Panel recommends establishment of a sustained, strategic and adaptive monitoring network that is founded on integration, coordination, and harmonization of existing efforts and their expansion in ways that will inform policy and management decisions. A regional OAH monitoring network will link decision-makers with a common pool of scientific data that will enable them to evaluate how, when, and where to act to serve the best interests of the region and society as a whole.

The monitoring network envisioned by the Panel explicitly includes physical, chemical, biological, and ecological monitoring to track change, understand impacts, and evaluate management actions. It leverages and enhances existing assets (e.g., observing systems, ecological time-series), technologies, protocols, partnerships, data systems and management frameworks (e.g., protected areas) to achieve a strategic, efficient network. The Panel's foundational requirements for a rigorous regional monitoring program are provided in a separate technical document entitled "*Ocean Acidification and Hypoxia Monitoring Network: Tracking the Impacts of Changing Ocean Chemistry to Inform Decisions.*"

A regional OAH monitoring network will link decision-makers with a common pool of scientific data that will enable them to evaluate how, when, and where to act...

Here we describe the key actions needed to achieve that desired monitoring network.

1. Define management needs from OAH monitoring.

Cultivate and enhance existing partnerships between monitoring practitioners, modelers, and decision-making users to better define OAH information needs across ecosystem types, and for diverse uses.

2. Assess how well existing monitoring efforts meet those management information needs.

Complete a comprehensive inventory of the geographic distribution, data quality, and operational status of existing monitoring programs that provide information relevant to OAH management. Use this inventory to address how well these monitoring assets are positioned to address management questions and support OAH forecast models. Use OAH model outputs to evaluate the information value of existing and proposed monitoring locations.

3. Evaluate and prioritize needs for new investment.

Enhance existing monitoring efforts to fully address management questions. Assess the feasibility of adding new measurements and analytical capacity to existing monitoring efforts. Establish regular communication and connections among managers, scientists, system operators, and end-users to iteratively assess the strength of alignment between monitoring activities and decision-making needs.

4. Enhance consistency among programs through training and quality assurance.

Many monitoring programs on the West Coast were established independently and thus have unique procedures for data procurement and management. Measurement techniques and data archiving should be harmonized among monitoring efforts. Staff involved in monitoring requires training in these procedures, and quality assurance activities should be performed to ensure reliability and comparability of data.

5. Develop a centralized portal for accessing OAH monitoring data.

Develop a simple means for accessing diverse monitoring data sets as well as OAH model output that inform OAH management. This will allow data to be catalogued, combined, compared, and shared, ensuring that monitoring data and model output are used effectively to inform further research, and ultimately management action. Establish community protocols for submitting new data into common data portals.

6. Develop and sustain intellectual capacity.

It is not enough to just make measurements and run models - it is also critical to maintain the intellectual capacity to interpret and communicate the findings. Investments in data analysis and data distribution are critical pieces of a monitoring network, as they will ensure the data are used to inform the management decisions the program was designed to support.

7. Communicate information widely.

Develop tools and technologies to promote greater two-way communication regarding observations and analyses, and data synthesis products. Incentivize regular information exchange activities that engage the broader user community.

Enhance existing monitoring efforts to fully address management questions.

V. The Panelists

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Dr. Alexandria Boehm is a Professor in the Department of Civil and Environmental Engineering, and a Senior Fellow of the Woods Institute for the Environment at Stanford University. Her area of expertise is coastal water quality, with a focus on knowledge that is crucial to directing new policies, and management and engineering practices that protect human and ecosystem health along the coastal margin. Dr. Boehm received her M.S., and later her Ph.D., in Environmental Engineering from University of California, Irvine.

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Dr. John “Jack” Barth is a Professor of Oceanography and Associate Dean for Research in the College of Earth, Ocean, and Atmospheric Sciences at Oregon State University. An expert in the physics of oceans and atmospheres, Dr. Barth specializes in understanding spatially and temporally variable circulation, water mass structure and ecosystem response in coastal waters. He received his Ph.D. from the Massachusetts Institute of Technology and Woods Hole Oceanographic Institution Joint Program in Oceanography.

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Dr. Francis Chan is an Associate Professor, Senior Research in the Department of Integrative Biology at Oregon State University. He is also a scientist with PISCO – the Partnership for the Interdisciplinary Studies of Coastal Oceans. Dr. Chan is an expert in interactions between biogeochemistry and ecological patterns and processes in coastal oceans, including the drivers and consequences of changing ocean chemistry from hypoxia and ocean acidification. Dr. Chan received his Ph.D. from Cornell University in the Department of Ecology and Evolutionary Biology.

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Dr. Elizabeth Chornesky is an Independent Consultant who assists non-profit organizations, philanthropies, and public agencies in designing science, policy, investment, and organizational strategies. Dr. Chornesky’s areas of expertise include ecosystem management, sustainability, and global change, focusing on the integration of science with applied policies and practices to achieve societal goals. She earned her Ph.D. in Marine Ecology from the University of Texas at Austin.

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Dr. Andrew Dickson is a Professor of Marine Chemistry in the Marine Physical Laboratory Division at the Scripps Institution of Oceanography, University of California, San Diego. Playing a key role in providing quality control for oceanic carbon dioxide measurements, he is an expert in the chemistry of carbon dioxide in seawater, with an emphasis on ocean acidification and its effects on marine organisms. Dr. Dickson received his Ph.D. from the University of Liverpool.

Richard A. Feely
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Dr. Richard A. Feely is a Senior Scientist at the National Oceanic and Atmospheric Administration (NOAA) Pacific Marine Environmental Laboratory in Seattle, WA. He also holds an Affiliate Full Professor faculty position at the University of Washington School of Oceanography. Dr. Feely's area of expertise are carbon cycling and ocean acidification processes in the oceans. He received his M.S., and later his Ph.D., in the field of Chemical Oceanography from Texas A&M University.

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Dr. Burke Hales is a Professor in Ocean Ecology and Biogeochemistry in the College of Earth, Ocean, and Atmospheric Sciences at Oregon State University. He is a chemical oceanographer specializing in carbon cycling at the sea-floor, air-sea, and land-sea interfaces, and in the topics of carbon sequestration, ocean acidification, and de-oxygenation, as well as the analytical and physical chemistry of carbon dioxide in natural waters. He received his Ph.D. in Chemical Oceanography from the University of Washington.

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Dr. Tessa Hill is Associate Professor and Chancellor's Fellow at University of California, Davis, in the Department of Earth & Planetary Sciences. She is also affiliated with UC Davis Bodega Marine Laboratory, a research station on the Northern California Coast. Dr. Hill's expertise is in marine geochemistry, and the response of marine organisms to climate change, including the impacts of ocean acidification on California coastal environments. She earned her Ph.D. in Marine Science from University of California, Santa Barbara.

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Dr. Gretchen Hofmann is a Professor in the Department of Ecology, Evolution, and Marine Biology at University of California, Santa Barbara. Dr. Hofmann is an eco-physiologist whose research focuses on the effects of climate and climate change on the performance of marine species, with a focus on how such environmental changes influence the regulation of mechanisms within the body that impact development, geographic distribution and survival. She received an M.S. and Ph.D. from the University of Colorado at Boulder in Environmental, Population and Organismal Biology.

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Dr. Terrie Klinger is the Director of the School of Marine and Environmental Affairs, Co-Director of the Washington Ocean Acidification Center (alongside Dr. Jan Newton), and holds the Stan and Alta Barer Endowed Professorship in Sustainability Science in Honor of Edward J. Miles. She is a marine ecologist focused on applying ecological theory to practical management solutions. Dr. Klinger received her Ph.D. in Biological Oceanography from Scripps Institution of Oceanography, University of California, San Diego.

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Dr. Debby Ianson is an Oceanographer and a Fisheries and Oceans Canada Research Scientist at the Institute of Ocean Sciences in Sidney, B.C., as well as an Adjunct Professor at the School of Earth and Ocean Sciences, University of Victoria, Victoria, B.C. An interdisciplinary expert in chemical and physical oceanography, she focuses on the impact of climate change on biogeochemical cycles along continental margins and their influence on the global ocean. Dr. Ianson received her Ph.D. in Physical Oceanography from University of British Columbia.

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Dr. John Largier is Professor of Coastal Oceanography and Associate Director for Research of the Coastal and Marine Sciences Institute at the University of California Davis. Within the Department of Environmental Science and Policy, and resident at Bodega Marine Laboratory, he is an expert in the role of transport in ocean, bay, nearshore, and estuarine waters, including transport of plankton, contaminants, pathogens, nutrients, oxygen, and sediment. He places this work in the context of environmental issues as diverse as marine reserves, fisheries, mariculture, beach pollution, sea-level rise, wastewater discharge, and wildlife health, just to name a few. He earned his Ph.D. in Oceanography, from the University of Cape Town.

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Dr. Jan Newton is a Principal Oceanographer with the Applied Physics Laboratory of the University of Washington (UW) and affiliate faculty with the UW School of Oceanography and the School of Marine and Environmental Affairs, both in the UW College of the Environment. She is the Executive Director of the Northwest Association of Networked Ocean Observing Systems (NANOOS), the U.S. IOOS Regional Association for the Pacific Northwest, and Co-Director (alongside Dr. Terrie Klinger) of the Washington Ocean Acidification Center. A biological oceanographer, Dr. Newton is an expert in the physical, chemical, and biological dynamics of Puget Sound and coastal Washington, including understanding effects from climate and humans on water properties. She holds a Ph.D. in Biological Oceanography from the University of Washington.

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Dr. Thomas Pedersen is Professor of Oceanography at the University of Victoria. He is an internationally recognized authority on ocean chemistry, has published extensively in the field of paleoceanography, and has longstanding interests in climate change issues and the application of government policy to climate-change mitigation and adaptation. Dr. Pedersen holds a Ph.D. in Marine Geochemistry from the University of Edinburgh.

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Dr. George Somero is the David & Lucile Packard Professor Emeritus in Marine Sciences at Stanford University. He studies the effects of environmental factors, such as temperature, salinity, hydrostatic pressure, and oxygen availability on the physiology of marine animals. Dr. Somero received his Ph.D. in Biology from Stanford University.

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Dr. Sutula is a Principal Scientist at the Southern California Coastal Water Research Project (SCCWRP), where she is head of the Biogeochemistry Department. An expert in aquatic biogeochemistry and habitat assessment, Dr. Sutula oversees a variety of projects related to eutrophication and harmful algal blooms in streams, estuaries and nearshore waters, including studies of biogeochemical cycling and their linkage to anthropogenic activities and climate change. Beyond her research activities, she focuses on linking science to management, examples of which include her work as lead scientist to water quality agencies developing nutrient management strategies. Dr. Sutula received her Ph.D. in Coastal Oceanography from Louisiana State University.

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Dr. Steve Weisberg is Executive Director of the Southern California Coastal Water Research Project (SCCWRP), a research agency created to provide the scientific foundation for water quality management in California. A biologist who specializes in the design of environmental monitoring programs, Dr. Weisberg's present efforts focus on the development of coordinated, integrated, cost-effective regional monitoring in the Southern California Bight. He received his Ph.D. in Biology from the University of Delaware.

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Dr. Liz Whiteman is the Program Director for the California Ocean Science Trust, a non-profit organization dedicated to advancing science-informed ocean resource management and stewardship decisions. An expert in coral reef ecology, conservation, fisheries management, and the links between science and decision-making, Dr. Whiteman has worked throughout the Caribbean and U.S. West Coast studying the effectiveness of marine protected areas and providing recommendations to policymakers from several countries. Dr. Whiteman earned her Ph.D. in Marine Evolutionary Ecology from the University of East Anglia, U.K.

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In May 2015, Skyli joined The Nature Conservancy as the Director of the North America Oceans and Coasts Program. She previously served as the Executive Director of the California Ocean Science Trust supporting California coastal and ocean resource managers by providing them with sound science to help inform decisions. She also served as the Science Advisor to the California Ocean Protection Council. In both roles, she built partnerships for science, decision-making and resource management in California.

VI. Additional Panel products supporting the "Major Findings, Recommendations, and Actions"

The Panel has produced a series of products that anchor the Panel's "**Major Findings, Recommendations, and Actions**" and attached appendices on a foundation of the best available science. The documents fall into two categories: technical guidance documents targeted for program managers, and foundational science documents targeted for subject-matter experts. For Panel products, visit www.westcoastOAH.org.

Technical guidance documents

The primary audience for Technical guidance documents is program managers who are responsible for programmatic implementation. These documents are intended to help program managers translate the "**Major Findings, Recommendations, and Actions**" into initiatives and policy.

- **Ocean Acidification and Hypoxia Monitoring Network: Tracking the Impacts of Changing Ocean Chemistry to Inform Decisions**

  The Panel has outlined a strategic framework for ocean acidification and hypoxia (OAH) related monitoring intended to provide rigorous decision-support to policymakers and managers at a West Coast-wide regional scale. This document describes key attributes of an OAH monitoring network, and recommends practical steps for implementing a West Coast network.

- **Modeling Tools: Summary of Needs to Enhance Understanding of Ocean Acidification and Hypoxia in Coastal Oceans**

  Numerous Panel discussions have underscored the need for improved modeling tools to assess the effectiveness of any potential OAH-related management action. This document outlines specific modeling needs for coupled oceanic physical and biogeochemical models as well as for ecosystem models. This document also outlines specific steps that will help build on existing infrastructure and enhance prioritization and coordination within the modeling community for meeting management needs.

- **Multiple Stressor Considerations: Ocean Acidification in a Deoxygenating Ocean and Warming Climate**

  The Panel recognizes that understanding changes to ocean chemistry is confounded by factors that may co-vary or counter-vary with OA. The outcomes of interacting environmental changes are likely to exert important compounding effects on species and ecosystems. This document describes the need for considering acidification in the context of multiple stressors to marine ecosystems.

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

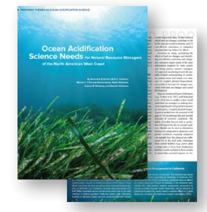
  This document prioritizes research initiatives focused on providing the knowledge needed to effectively manage the West Coast and oceans in the face of multiple stressors. This document is designed to help decision-makers to strategically hone in on knowledge gaps that inhibit thoughtful action on OAH.

Foundational science documents

The Panel has authored a series of in-depth scientific documents intended for subject-matter experts that summarize the state of the science on which the Panel has developed its recommendations. These documents are intended for publication as scientific journal articles, with several of them already published.

- **Ocean Acidification Science Needs for Natural Resource Managers of the North American West Coast** *(published in the journal Oceanography)*

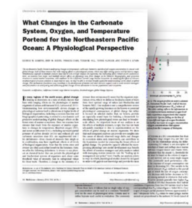
  This document describes potential management actions and associated science needs that will assist managers in making decisions around whether and how best to address OA. Although decision-makers with a role to play in responding to OA come from diverse sectors, some commonalities emerge in their information needs, including a need for a comprehensive monitoring program and a range of models that identify areas that are most and least vulnerable to future OA-triggered changes.



Ocean Acidification Science Needs for Natural Resource Managers of the North American West Coast

- **What Changes in the Carbonate System, Oxygen, and Temperature Portend for the Northeastern Pacific Ocean: A Physiological Perspective** *(published in the journal BioScience)*

  The northeastern Pacific Ocean is undergoing changes in temperature, carbonate chemistry, and dissolved oxygen concentration. Here, the Panel examines how single- and multiple-stressor effects on physiology may drive changes in individual or species behavior, and the structure of marine ecosystems.



What Changes in the Carbonate System, Oxygen, and Temperature Portend for the Northeastern Pacific Ocean: A Physiological Perspective

- **Water Quality Criteria for an Acidifying Ocean: Challenges and Opportunities** (*in press in the journal Ocean and Coastal Management*)

  When monitoring data indicate that water quality standards are not being met, management agencies have the option under Section 303(d) of the Clean Water Act to list the water body as impaired. This document describes the state of the science for making an impairment assessment in the context of this Clean Water Act process, and in cases where data needed to perform assessments are limited. The document also recommends strategies for improving monitoring programs and water quality criteria.

- **Supporting Ecosystem Resilience to Address Ocean Acidification and Hypoxia**

  This product provides practical guidance about the opportunities to incorporate OAH management strategies into existing ecosystem-based management frameworks – an important near-term, actionable management approach intended to ameliorate the likely impacts of OAH on marine resources and ecosystems.

Supporting Ecological Resilience to Address Ocean Acidification and Hypoxia

Support: The West Coast Ocean Acidification and Hypoxia Science Panel, convened by California Ocean Science Trust, is funded by the Ocean Science Trust, the California Ocean Protection Council, and Coastal Impact Assistance Program. The Institute for Natural Resources in Oregon, working in collaboration with California, is supported by the Oregon Governor's Office, the Oregon Department of Fish and Wildlife, the Oregon Department of Agriculture, the Oregon Department of Environmental Quality, the Oregon Department of Land Conservation and Development, and the OSU Research Office. The participation of the Washington Ocean Acidification Center was supported by Washington State and the University of Washington.

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The West Coast Ocean Acidification and Hypoxia Science Panel, April 2016

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