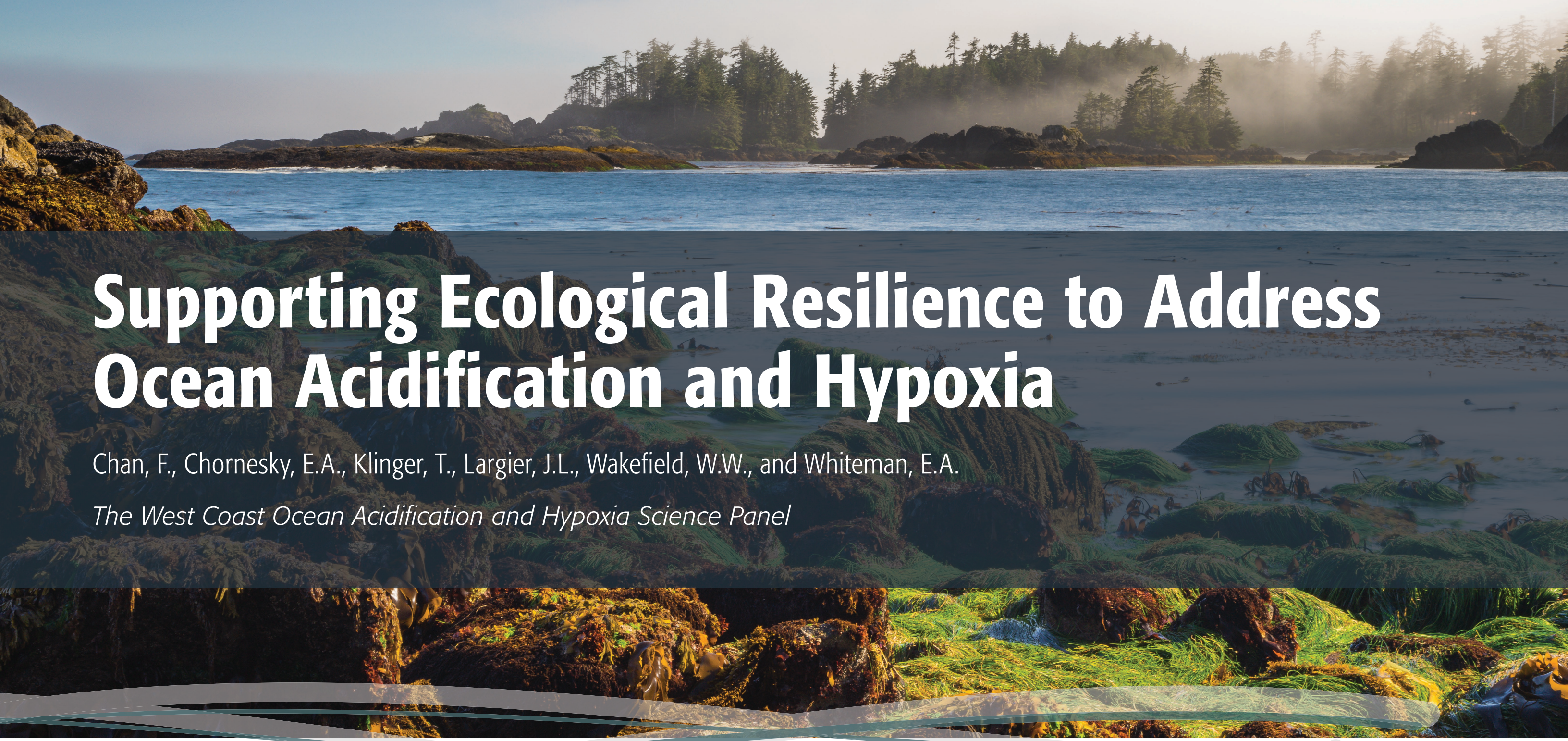

Supporting Ecological Resilience to Address Ocean Acidification and Hypoxia

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Summary

Ocean acidification and hypoxia (OAH) together are changing the chemistry of the world's oceans. Despite good evidence of species-level effects of OAH, we have little resolution regarding the scale and magnitude of ecosystem-level effects. Yet, such ecosystem effects are likely to significantly affect economically and culturally important resources, and the services and benefits that marine ecosystems provide to society. Focusing on the West Coast of North America, we first ask how insights gained from the past decade of research can inform and bound our predictions of the direction and magnitude of the ecosystem changes ahead. Although abrupt and significant ecosystem changes can reasonably be expected, predicting the timing of these changes (e.g., 1, 5, 10 years) and how they will manifest is challenging. We then propose that sustaining ecological resilience through the use of ecosystem approaches that are already embedded in natural resource management frameworks provides a pragmatic path forward and offers opportunities for decision-makers to take action now to address OAH. We illustrate this approach with three case studies from the U.S. West Coast: marine protected areas, ecosystem-based fisheries management, and coastal EBM initiatives. Such actions can potentially ameliorate OAH effects over the near-term and forestall abrupt ecosystem changes, "buying time" as scientific understanding and management options improve.

About this Document

This document offers a perspective developed by a working group of the West Coast Ocean Acidification and Hypoxia Science Panel (Panel) intended for a broad audience. It provides pragmatic guidance about the opportunities to incorporate ocean acidification and hypoxia into existing ecosystem-based management frameworks as an important near-term and actionable strategy to ameliorate the likely impacts of OAH on marine resources and ecosystems. The document is part of a suite of Panel products to inform decision-making, and has received input and review from the full Panel. The information provided reflects the best scientific thinking of the Panel.

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

Introduction

Elevated greenhouse gases will not only alter climatic conditions, but also lead to acidification of the ocean and more frequent hypoxic conditions as the seas absorb carbon dioxide (CO_2) and surface waters warm. Scientific understanding of the patterns, processes, and potential impacts of ocean acidification and hypoxia (OAH) have grown substantially over the past decade (Gruber 2011). Together, these stressors are changing the chemistry of the world's oceans and are likely to cause widespread ecosystem effects. However, our ability to predict these ecosystem-level effects or to fully anticipate how OAH will interact with other drivers of ecosystem change, such as rising temperatures, is likely to be characterized by persistent uncertainties for some time (IPCC 2014).

Despite such uncertainties, recent declines in the survivorship of larval shellfish in hatcheries and hypoxia-induced crab mortality events have alerted policy makers and managers to the potential for OAH to significantly affect the condition and productivity of ecosystems along the West Coast of North America. These decision-makers are seeking to better understand the implications of OAH, to build a scientific infrastructure for delivering policy- and management-relevant information, and to initiate actions now for improving management outcomes under conditions of intensifying OAH.

This paper builds upon our existing understanding of organismal effects to examine the incomplete but evolving knowledge base about the effects of OAH on ocean ecosystems along the West Coast of North America. We translate this knowledge into near-term guidance for policy-makers and resource managers by illustrating how supporting ecological resilience offers a path forward now despite incomplete understanding and associated uncertainties. We highlight application of the approach by describing how OAH can be incorporated into existing management frameworks - i.e., marine protected areas, ecosystem-based fisheries management, and coastal EBM initiatives on the U.S. West Coast.

Understanding ecosystem impacts of OAH

The California Current Large Marine Ecosystem (CCLME) extends from southern British Columbia, Canada to Baja California, Mexico, and includes the coastal ocean, the coastal land-sea interface, and connections to adjacent watersheds. This ecosystem provides the large-scale context for understanding of OAH impacts along the West Coast of North America. The expression of OAH in the CCLME varies from place to place and over time, reflecting complex interactions among biophysical processes that include the uptake of anthropogenic carbon dioxide, upwelling of colder deeper waters naturally lower in pH and dissolved oxygen, and local processes that can intensify OAH (e.g., breakdown of organic matter and land runoff). These already complex interactions potentially will be further complicated as upwelling, precipitation, freshwater inputs, and other factors shift in ways that are not yet fully understood as the climate changes.

As a result of interacting natural (e.g., upwelling) and anthropogenic (e.g., uptake of enhanced atmospheric CO_2) factors, at certain times and sites, surface waters of the CCLME already show CO_2 values three times higher than the current global mean (1200 versus ~400 µatm; Harris et al. 2013), and conditions corrosive to calcified marine organisms have increased in frequency, severity, duration, and spatial extent due to anthropogenic CO_2 increases (Feely et al. 2008; Harris et al. 2013). Moreover, patterns of ocean circulation impose decadal-scale time lags between CO_2 uptake and altered pH of upwelled waters. Consequently, the chemical changes observed today do not yet reflect the full impact of the amount of CO_2 already in the atmosphere (Feely et al. 2008); even with immediate stabilization of today's atmospheric CO_2 levels, acidification will further intensify over the coming decades.

Climate change is also reducing dissolved oxygen concentrations in the CCLME through solubility declines caused by warming and through stratification and circulation changes that diminish the resupply of oxygen to the ocean interior (Keeling et al. 2010). While the exact scope of climate-driven oxygen declines remains uncertain, observed fluctuations in dissolved oxygen in response to climate change, evidence of long-term oxygen declines, and complex near-shore anoxia dynamics in the CCLME have further highlighted a need for understanding and managing the impacts of ocean acidification and hypoxia as coupled stressors.

Despite good evidence of the biogeochemical effects of OAH in the CCLME, the effects of OAH on ocean and coastal ecosystems are not well understood. Yet, ecosystems are the fundamental unit for organizing our understanding of ecological dynamics including food-web interactions, biogeochemical cycles, and population replenishment and connectivity, and are also increasingly viewed as an important context for managing fisheries and the impacts of global change on marine systems (Mcleod & Leslie 2009). Indeed, habitats and ecosystems in the CCLME support highly productive food webs that sustain commercial and recreational fisheries vital to local and regional economies.

Although the number of ecosystem studies is growing, current understanding of OA impacts rests heavily on single species laboratory studies of organism physiology and survival. The full ecological and ecosystem impacts of OAH cannot be directly inferred from studies of individual species. Ecological processes and interactions within populations and among species can intensify or dampen biological responses to OAH and influence the pace and variability of changes in carbon and oxygen chemistry. Thus, while an understanding of the ecosystem consequences of OAH is essential, achieving such an understanding presents a significant challenge. Furthermore, such documentation is unlikely to be available until OAH has caused substantial environmental or economic change.

Several alternative lines of evidence, discussed in the sections that follow, suggest the potential range and magnitude of impacts and can be used to project the likely trajectories of coastal ecosystems. This understanding provides a basis for considering how OAH will intersect with management objectives, how OAH ranks relative to other marine management priorities, and the efficacy of present and future management targets and tools in light of OAH.

a. Organism-level studies

Controlled laboratory studies provide the best evidence for the organismal effects of acidification (e.g., Kroeker et al. 2013). Such studies have shown that diverse taxa and functional groups are vulnerable to current and near-future changes in ocean chemistry, with acidification affecting multiple aspects of organismal physiology and behavior in addition to calcification. Extensive research on hypoxia has demonstrated effects on organismal physiology and success across broad taxonomic categories (Vaquer-Sunyer & Duarte 2008), the potential for some taxa to acclimate to reduced oxygen (Grieshaber et al. 1994), and interactions between hypoxia and stress from acidification and temperature (Somero et al., In Press).

Laboratory studies have provided a critical early warning of potential OAH impacts, and looking ahead, will provide needed insights into the mechanistic action of these stressors. However, the results of laboratory studies generally cannot be directly translated into real-world effects on organisms in situ or on ecological communities or ecosystems (Gaylord et al. 2015). Most experiments necessarily focus on single species, often a single life stage, and are brief relative to the lifespan of the study organisms. Although researchers have recently developed tools and methods to investigate OAH within laboratory contexts more reflective of real-world exposures (Hofmann et al. 2014), under conditions of multiple stressors, and across multiple life-stages (Hettinger et al. 2012) and generations (Tatters et al. 2013), laboratory studies still are not yet able to replicate high levels of temporal variability in exposure, such as that resulting from upwelling events.

b. Ecological theory and inference

Our understanding of individual organism's responses combined with our understanding of ecological relationships and ecosystem processes can further inform and bound basic expectations of future ecosystem changes. For example, based on ecological theory and observation, rates of survivorship and reproduction will determine whether or not populations will persist and grow. To the extent that OAH directly affects survivorship and reproduction, these chemical changes will influence population persistence and growth.

Interactions among species – competition, predation, and facilitation – in combination with the physical environment, determine the structure of ecological communities and the distributions and abundance of organisms. Kroeker et al. 2014 used empirical evidence to create a conceptual model of potential changes in predator-prey relationships among coastal molluscs (e.g., oysters, snails), illustrating the numerous complex connections between individual physiology and predator-prey interactions (Kroeker et al. 2014). These indirect effects are likely to be important in determining the overall ecological effects of OAH (Gaylord et al. 2015), yet also are likely to be the most difficult to predict a priori. Moreover, response strength and effect size will vary in space and time, with some effects being large and persistent.

Taking a different approach, Doney et al. combined empirical observations with theory to hypothesize likely changes in the CCLME in response to climate change (Doney et al. 2012). Based on a conceptual model, these authors argue that reductions in primary production due to climate change will propagate through the food web, from lower to upper trophic levels, and that climate change will influence both the mean and the variance of production at lower trophic levels. Taken together, the work of Kroeker et al. (2014), Gaylord et al. (2015), and Doney et al. (2012) suggest that direct and indirect interactions between species will determine the ultimate effects of OAH on nearshore communities, and that these effects will be modulated through changes in primary production and higher trophic relationships.

c. Inferential evidence from mesocosms and models

In experimental ecology, mesocosms provide a tool for addressing some of the inherent challenges of interpreting the results of physiological assays in terms of potential effects on ecological communities and ecosystems. When scaled appropriately, mesocosms can allow direct observation of key processes, such as species interactions and biogeochemical feedbacks. To date, relatively few mesocosm experiments have addressed OA. Those studies highlight the important role that indirect effects, such as food web changes and competition, will play in regulating the community and ecosystem effects of OA (e.g., Kuffner et al. 2007; Riebesell et al. 2013).

Ecological interaction models offer another tool for considering the potential direct and indirect effects of OAH on ecosystem structure and function. Creating appropriate ecosystem models for OAH has proven difficult thus far (Blackford 2010), because of limited understanding of how best to parameterize the functional response of diverse suites of organisms to OAH, model uncertainty in capturing coupled physical-ecological dynamics, and availability of suitable data required to verify model performance. Nevertheless, several quantitative models have examined the direct and indirect effects of acidification on ecosystem structure and function. Some treat acidification as a perturbation that incrementally reduces the growth of susceptible taxa or functional groups in food webs (e.g., Ainsworth et al. 2011; Busch et al. 2013), while others use coupled biophysical models to explore outcomes and management responses (e.g., Kaplan et al. 2010). Results suggest that ecological interactions can amplify or dampen impacts on ecosystem service provision (e.g., fishery yields), depending on how acidification impacts are distributed among species and functional groups. While such models lack information needed to parameterize the functional response of organisms to OA and hypoxia, they offer opportunities to evaluate the direction and scale of changes associated with alternative scenarios of organismal sensitivity.

Although coupled biophysical models specifically addressing OAH effects are relatively new, similar models have been broadly applied to climate change. For example, numerical models exploring the effects of fishing and climate change in the CCLME show that each stressor causes negative effects, and these are magnified when the two stressors are combined (Blanchard et al. 2012). For the CCLME, many of the changes due to OAH may be in the same direction as those due to climate, with generally negative trends in primary production propagating through the food web to the highest trophic levels, causing observable changes in secondary production, food web structure, and community structure.

Taken together, the results of mesocosm studies and numerical models suggest that the ecosystem-level effects of OAH will be sensitive to a number of factors, including starting conditions and duration and intensity of exposure. Consequently, while we might anticipate general negative effects at the ecosystem level over time, the predictability of specific ecosystem responses remains low.

d. Observations of natural OAH gradients and temporal changes

Empirical studies of spatial gradients in OAH conditions provide correlative understanding of how organisms, populations, and ecological interactions respond to altered ocean chemistry in situ. Examination of natural CO_2 vents in areas other than the CCLME has shown that calcifying taxa decline relative to non-calcifiers with proximity to the vents, as CO_2 increases and pH declines (Hall-Spencer et al. 2008). Importantly, vulnerability in situ can exceed predictions based on laboratory experiments. Persistent spatial gradients in dissolved oxygen are also known to organize broad shifts in benthic community structure (Levin & Sibuet 2012). On the Oregon shelf, declines in fisheries catch per unit effort correspond to observed declines in dissolved oxygen along spatial gradients that form seasonally (Keller et al. 2010). Recent work combining organismal assays with field sampling across OAH gradients revealed that in situ calcification of pteropods - a prey item for salmonids, herring and mackerel - is already being compromised by anthropogenic CO_2 (Bednaršek et al. 2014).

Moreover, temporal dynamics provide insights on ecosystem response to OAH. Observations such as changes in zooplankton and salmon production resulting from decadal climate cycles (Peterson 2003), inter-annual declines in ocean productivity and replenishment of coastal invertebrates (Barth et al. 2007), and rapid climate-mediated range shifts of top predators (Zeidberg & Robison 2007) demonstrate the potential for rapid reorganization of ocean food webs through bottom-up propagation of changes in productivity as well as changes in consumer performance and distribution. The seasonal formation of hypoxic zones can compress habitats and alter predator-prey interactions, and hypoxia attributable to human causes has caused wholesale shifts in benthic community structure (Breitburg et al. 2009), further demonstrating the potential for indirect effects to drive substantial ecosystem changes.

Over longer time-scales, paleontological records similarly suggest reorganization of marine food webs in response to climate-mediated transitions in dissolved oxygen. Paleo-records from the Humboldt Current (an eastern boundary current system analogous to the California Current) suggest that rapid climate-mediated transition from higher oxygen to semi-permanent suboxic or anoxic states could have occurred during the 19th century (Salvatteci et al. 2014). This ecosystem transition was accompanied by reorganization of coastal food-webs including increased abundance of pelagic fish species that benefited from increases in upwelling and primary production (Gutiérrez et al. 2009).

Projections of future ecosystem change

These lines of evidence combined can bound expectations regarding the direction and magnitude of the ecosystem changes ahead. OAH conditions will intensify over time and consequently ecological impacts are unlikely to plateau in the coming decades. Moreover, today's understanding of organismal effects, derived largely from single factor studies, provides an incomplete, and in some cases overly simplistic, picture of how OAH will affect marine species and populations.

We also know that ecosystem-level changes will not scale simply from organismal responses, but instead that dynamic interactions among species will determine outcomes at the level of ecosystems. These ecosystem impacts will grow over time causing important thresholds to be crossed in which ecosystems switch to new and different states. However, these changes cannot be predicted with precision or strong confidence. Mechanistic interactions between acidification and hypoxia, and between OAH and other factors (e.g., temperature, fisheries) remain poorly understood. From a policy and management perspective, OAH thus can be characterized as "high impact – high uncertainty," posing challenges similar to other dimensions of climate change that are expected to have multiple effects on ecosystem patterns and processes that are difficult to predict (IPCC 2014).

At the same time, the choices made now about how to manage the effects of OAH on coastal and marine ecosystems will significantly affect future ecosystem conditions and management options. Considerable progress has been made over the past decade in identifying practical steps that managers can take to start addressing climate change despite uncertainties, and general operating principles have begun to emerge that are being embedded into approaches for managing wildlife, ecosystems, and the ocean (e.g., NFWPCAP 2012; Stein et al. 2013). Some climate-adaptation approaches for coastal and marine systems already include ocean acidification as an element of climate change impacts (e.g., Bernhardt & Leslie 2013).

Here, we propose an approach that embeds consideration of OAH into existing management frameworks, focusing on those grounded in the principles of ecosystem-based management. Our approach is pragmatic; uncertainties in scientific knowledge and those that result from complex system dynamics can stifle or delay management responses. In the face of such uncertainties, a resilience approach can be used to guide management actions in the near term.

Managing for ecological resilience

Ocean policy-makers and managers over the past decade have increasingly emphasized sustaining ecological resilience as a strategy for maintaining the productivity and benefits of coastal and marine ecosystems in a changing and uncertain world (e.g., Mcleod et al. 2011). In this context, resilience refers to the capacity of an ecosystem to tolerate and recover from disruptions, thereby sustaining key functions, processes, and feedbacks. Resilient ecosystems exhibit variation over time while retaining their fundamental attributes, functions, and services. Resilient coastal and marine ecosystems are characterized by biological diversity, functional diversity, food web complexity, and spatial connectivity (Bernhardt & Leslie 2013).

Management actions that maintain diversity, complexity, and connectivity in marine systems can thus be expected to support the resilience of ecosystems exposed to OAH, thereby ameliorating the effects of OAH over the near-term, "buying time" as scientific understanding and management options improve. Delayed action, conversely, will constrain future options as ecosystem change accelerates and resilience erodes. Maintaining ecosystem resilience should yield benefits under a wide range of alternative future scenarios by forestalling abrupt ecosystem change while smoothing transitions to new states (e.g., Billé et al. 2013).

a. Conceptual framework for managers

Box 1 provides a conceptual framework to assist managers in taking action. This framework is built upon the expectation that supporting the resilience of coastal and marine ecosystems provides the single best available strategy for taking actions now. This strategy is both pragmatic and precautionary; near-term practical opportunities exist within numerous, ecosystem-based frameworks for natural resource management that could help to support ecological resilience in an uncertain future.

This conceptual framework will be intuitive for many coastal and marine resource managers, because the key ingredients –legislative mandates to protect ecosystems, monitoring and evaluation programs, adaptive management processes – are in place or under development in many locations. Three examples are provided below and in Table 1 – marine protected areas, ecosystem-based fisheries management and coastal EBM projects – to illustrate applications of the framework. In each case the narrative below provides the management context and discussion of OAH in this context while Table 1 provides sample strategies to address OAH. Not all listed strategies or actions will be timely or appropriate in all places. Rather the table illustrates actions that can be taken and which should be evaluated from within the specific management context of a particular location. A portfolio of actions within an ecosystem-based management context offers the best path to support ecological resilience and address OAH.

b. Marine protected areas

Over the past several decades, coastal communities and local, state, and federal governments have increasingly turned to marine protected areas (MPAs) as a tool for conserving and restoring places of special ecological, cultural, and economic significance. MPAs established along the West Coast of North America now include five large National Marine Sanctuaries, five National Estuarine Research Reserves, 15 National Wildlife Refuges, large Essential Fish Habitat (EFH) conservation areas created by the Pacific Fisheries Management Council, 34 Areas of Special Biological Significance (ASBS) established by State of California Water Resources Control Board, numerous state-managed MPAs in Oregon and Washington, and the new statewide network of MPAs in California (NMPAC 2013). These collectively cover more than 114,000 square nm and 40% of the US Exclusive Economic Zone (EEZ) along the US West Coast.

These MPAs fall under diverse designations and vary in their specific goals. About two thirds seek in some way to sustain biodiversity, ecosystems, or protected species (NMPAC 2013), and interest is growing in protecting reserve networks and large ocean areas that encompass functioning ecosystems. Many MPAs are expected to provide benefit not only to species and ecosystems within the MPA, but also to surrounding marine populations and ecological communities, for example by providing source populations to restore depleted fish stocks or by supporting complex food webs. The state MPA network in California, which covers about 16 % of that state's waters, was designed to help improve the health of the state's nearshore ecosystems and to function as a network that provides habitat, adult movement and larval connectivity among individual MPAs.

Within this management context there are several possible actions and strategies to address OAH by supporting ecological resilience (Table 1). Some MPAs could potentially enhance the resilience and adaptive capacity of local ecosystems exposed to OAH through beneficial effects on biodiversity, food webs, and connectivity (Micheli et al. 2012). The evidence of how MPAs enhance resilience under OAH has thus far been inferential and based on the existence of ecosystem attributes thought to affect OAH conditions. For example, preliminary evidence from the Padilla Bay National Estuarine Research Reserve – home to the largest stand of eelgrass (Zostera marina) in Washington State – suggests that pH is higher and pCO_2 is lower within the bed, and thus eelgrass beds may help moderate local acidification.

At the same time, OAH has the potential to significantly alter or degrade the biological and ecological assets that many of these MPAs were designed to protect, for example through changes to physiology, behavior, and relative abundance that propagate through communities and food webs. OAH thus

Box 1. Conceptual framework for applying a resilience strategy to address OAH

1. **OAH will undermine existing management goals for coastal and ocean ecosystems.** Many key ecosystem attributes are routinely addressed in many existing planning and management methodologies, such as the design of marine protected area (MPA) networks and ecosystem approaches to fishery management. However, OAH will affect these attributes in ways that will alter the ability of resource managers and policy makers to accomplish their goals.
2. **Effects of OAH will be context dependent, requiring context-specific solutions.** The ecological effects of OAH in any particular locale will depend on drivers and interactions that vary with oceanographic setting, land-based inputs, human uses, and other factors. Consequently, OAH will need to be addressed within the specific contexts of place, species, and ecological system.
3. **The best available management approach now is to focus on supporting ecosystem resilience and adaptive capacity.** Ecosystem resilience and adaptive capacity of the natural system will improve the potential for sustaining desired ecosystem conditions or supporting ecosystem transitions as OAH conditions change in the future.
4. **A resilience approach is possible within existing management approaches, so start now.** Managing for ecosystem resilience is increasingly a cornerstone of marine and coastal ecosystem management (e.g., "ecosystem-based management," "ecosystem approaches to fisheries management," and spatial management of human uses). Consequently, existing planning and management authorities and methods provide good opportunities for anticipating and addressing the potential effects of OAH.
5. **Review, refine, and revise operating approaches and policy guidance as new scientific information and tools become available.** For the foreseeable future, managers will be "learning by doing" as they address OAH. Well-developed methods for adaptive management are available to assist managers in explicitly identifying, prioritizing, and filling information gaps and then using improved knowledge to adapt and improve future management choices. These methods have been adopted in many types of coastal and marine ecosystem management.

has the potential to overwhelm or obscure the beneficial effects of MPAs in some places. Certain MPAs may be especially vulnerable due to their particular ecological and oceanographic attributes or their proximity to land-based inputs (e.g., freshwater, pollutants, and suspended sediments). Certain areas off the coast of Oregon, for example, have already been hit hard by extreme low oxygen events (Chan et al. 2008) and appear particularly vulnerable to acidification (Harris et al. 2013).

Although likely to differ in priority and efficacy between locations, pursuing a portfolio of actions can help managers to realize the broader ecosystem benefits of MPAs or minimize the harm to biological resources within MPAs exposed to OAH (see Table 1).

c. Ecosystem-based fisheries management

National, international, state, and tribal government entities manage fisheries along the West Coast of North America. The National Marine Fisheries Service (NMFS) manages the majority of the coast's living marine resources, in cooperation with state authority or by international commission, under fishery management plans (FMPs) or as protected species under the Marine Mammal Protection Act or the Endangered Species Act. These FMPs are the responsibility of the Pacific Fishery Management Council, acting on behalf of the Federal Government (NMFS) in managing fishery resources within the U.S. EEZ. Coastal states or tribal fishery agencies, with cooperation from NMFS, manage diverse commercial and recreational nearshore and estuarine species that are neither included in an FMP nor federally protected, including shrimps, crabs, abalones, clams, squids, sea urchins, sea cucumbers, and both cartilaginous and bony fishes.

Historically, the sustainable harvest of any given fish stock was guided by its respective management plan (including multi-species fisheries, like groundfish). However, this situation is now starting to change. Responding to evolving U.S. laws and policies, improved ecological understanding, and concerns about fishery depletions, federal fishery scientists and managers in the U.S. over the past decade have been developing new plans, analytical tools, and scientific syntheses to support management within an ecosystem context that better accounts for ecological interactions and dynamics (e.g., Field & Francis 2006; PFMC 2013). While many of these approaches are nascent, they provide opportunities to consider time-dependent environmental influences on fishery performance and thus how OAH effects can potentially be assessed and addressed within ecosystem-based fisheries management.

Although relatively little is yet known about how OAH will impact west coast fisheries, inferential evidence and preliminary modeling simulations suggest the potential for significant impacts on fishery yields due to altered fish behavior, impaired calcification of prey items, and altered ecological interactions and food web dynamics (e.g., Branch et al. 2013; Busch et al. 2013). Of particular concern is the potential for OAH to harm species that are economically important (e.g., crabs) or that play important but as yet incompletely understood roles in fishery food webs as grazers and prey (e.g., pteropods, krill, and copepods) or in providing biogenic fish habitat (e.g., deep sea corals and sponges). Such effects could become amplified as OAH interacts with altered oceanographic processes and other climate change processes.

Given this combination of potentially serious impacts and high uncertainty, the best approaches available today for addressing OAH in west coast fisheries management are to generally advance ecosystem-based fisheries management, to improve decision-maker understanding of OAH processes and impacts, and to build new scientific knowledge and decision-support tools (see Table 1).

d. Coastal ecosystem-based management

Coastal and estuarine waters that are partly enclosed and not rapidly flushed by offshore waters are likely to be susceptible to acidification and hypoxia effects resulting from land-based nutrient and/or organic pollution. Upstream land uses and water quality can have significant downstream impacts on coastal ecosystems. At the same time, choices about ecosystem protection and management in estuaries and nearshore systems influence the vulnerability of these ecosystems and their capacity to buffer OAH impacts from upstream.

For example, nutrients released to coastal waters from upland areas can contribute to OAH by fueling phytoplankton growth, which leads to increased OAH from the subsequent decay of the organic matter produced. Microbial degradation of the dead phytoplankton releases CO_2 and contributes to local acidification while consuming oxygen and inducing hypoxia. Like phytoplankton, seagrasses and kelps also take up nutrients and CO_2 (or related carbonate compounds) from surrounding waters for use in growth and reproduction, but some portion of the biomass they produce can be sequestered by burial or transported to deep areas. Consequently, the effects of coastal nutrient enhancement on OAH may be reduced in places where currents and bathymetry facilitate offshore transport of phytoplankton and detritus from kelps and seagrasses.

Over the past few decades, a variety of local and regional organizations have emerged that take a place-based approach to understanding, managing, and delivering public education related to the health of watersheds and ecosystems at the land-sea interface. Many involve partnerships that draw members from the public and private sectors, NGOs, and academic or research organizations. Along the west coast, these include six National Estuary Programs (e.g., Santa Monica Bay; Columbia River), five National Estuarine Research Reserves (e.g., South Slough, OR; San Francisco Bay), and a variety of coastal ecosystem-based management initiatives (e.g., Puget Sound; Morro Bay) and other local and regional planning activities. Most of these efforts have developed plans that generally identify key ecological and socioeconomic processes affecting local ecosystems and strategies to sustain or restore ecosystem health and services to local communities.

The organizations working at the land-sea interface provide a good foundation for building local understanding of OAH processes and impacts and, potentially, for taking local actions under the umbrella of a place-based and ecosystem-based management framework (see Table 1).

Looking Ahead

The intensification of OAH along the West Coast of North America over the next century has enormous potential implications for the region's coastal and ocean ecosystems and the benefits they provide to society. While evidence suggests that impacts will be significant, specific predictions are difficult to make with confidence. Nevertheless, actions taken now to enhance ecological resilience under existing management authorities and planning processes can potentially dampen OAH effects over the near-term and forestall abrupt ecosystem changes. Such actions should be designed in ways that allow critical evaluation of how they affect ecological resilience and how sustaining resilience modulates OAH effects.

Advancing science in the following areas will speed progress: (1) mapping current and projected spatial patterns of OAH and its impacts; (2) developing models and scenario tools for exploring OAH ecosystem effects, OAH interactions with other ecosystem drivers, and the effectiveness of alternative management interventions; and (3) implementing monitoring to track changing ocean chemistry and ecosystem resilience. Collectively, these will improve our ability to distinguish among likely future trajectories of ecosystem change and, as such, illuminate and select among new management options. The urgency and significance of OAH will require mechanisms to support coordination and information sharing and integration as experience grows and new scientific knowledge is developed.

Table 1. Examples of strategies that can be used within the context of existing ecosystem-based management frameworks for addressing ocean acidification and hypoxia (OAH) by supporting ecosystem resilience. The first column identifies strategies that can generally help to support ecological resilience despite current uncertainties about the timing, scale and magnitude of OAH ecosystem impacts. Whether, where, and how each strategy might be implemented will depend on the specific management situation: Some strategies will be more appropriate in certain situations than others. The second column provides real-world examples of tools and practices now in place along the West Coast of North America to illustrate how each strategy could be implemented under existing management frameworks.

Strategy to Address OAH	Example Application
Marine Protected Areas	
Incorporate OAH considerations into MPA selection and/or network design or refinement	
• Locate some MPAs in areas less exposed to OAH where vulnerability to OAH-caused ecological change is lower. • Locate some MPAs in areas that naturally experience OAH stress; populations in such areas may have greater physiological tolerance to OAH or greater potential for evolutionary adaptation. • Locate some MPAs to protect ecosystems that may help buffer local or regional OAH shifts through biogeochemical cycling.	*Scientists advising the Pacific Fishery Management Council are considering how to ensure that Rockfish Conservation Areas (fishery closure areas) are not located along bathymetric "tipping points" for hypoxia that could experience rapid and significant change (Wakefield pers. comm.).* *National Estuarine Research Reserves may function as 'buffering MPAs' and can serve as test cases for evaluating the contribution of local solutions to OAH.*
Update management goals and evaluation	
• Ensure that management goals and performance evaluations accurately reflect the potential for significant ecological change associated with changes in ocean chemistry. • Transition away from species based goals and metrics to ones focused on ecological resilience and adaptive capacity. • Implement management where possible to reduce MPA vulnerability to OAH, such as by reducing local contributions to OAH (e.g., nutrient inputs).	*The Gulf of the Farallones National Marine Sanctuary is integrating acidification into a climate change vulnerability assessment (EcoAdapt 2014, http://ecoadapt.org/workshops/ca-coast-va-workshop) to inform future management evaluations.* *Some MPAs within the California statewide network are co-located with existing Areas of Special Biological Significance (ASBS) – areas monitored and maintained for water quality by the State Water Resources Control Board (http://www.swrcb.ca.gov/water_issues/programs/ocean/asbs.shtml)*
Support management-relevant science & monitoring	
• Improve understanding of whether, where, and how MPAs can contribute to regional ecosystem resilience under OAH. • Improve understanding of OAH effects on the structures, functions, and processes of protected ecosystems. • Develop modeling and scenario analysis tools to identify potential ecosystem trajectories and test alternative management interventions under projected OAH changes; Use this information to develop tools to integrate OAH considerations into MPA policies, siting, and design to support MPA-specific or regional ecosystem resilience goals. • Implement MPA monitoring to track changing ocean chemistry and attribute ecosystem impacts; develop methods to monitor ecosystem resilience and adaptive capacity.	*California Ocean Science Trust is advancing methods for evaluating ecosystem resilience as a key element of the statewide MPA monitoring program (http://oceanspaces.org/monitoring/regions/central-coast/planning).* *Researchers at University of California Santa Barbara are evaluating spatial scales of OAH variability relative to MPAs in the South Coast regional MPA network (Hofmann, pers. comm.), and piloting a coupled MPA monitoring – OA sensor network.* *The West Coast Ocean Acidification and Hypoxia Science Panel is developing a monitoring framework that prioritizes management relevant questions and couples biological and chemical data collection (www.westcoastOAH.org).*
Ecosystem-based Fisheries Management	
Advance ecosystem-based policies to guide management	
• Implement, and integrate OAH considerations into, ecosystem approaches to fisheries management that seek to sustain the broader set of ecological systems and processes that generate fishery yields. • Periodically update state and federal fishery management plans to incorporate improved understanding of the impacts and feedbacks among OAH, ecosystems, and fishery management choices as well as the ways individual fisheries could be managed to enhance ecological resilience and adaptive capacity under OAH.	*The Fishery Ecosystem Plan (FEP) adopted by the Pacific Fishery Management Council in 2013 includes summary information on OAH (PFMC 2013) Future updates to the FEP will assist in integrating considerations of OAH into the plans that guide management of >115 species by the National Marine Fisheries Service.* *The recently-released NOAA Fisheries Climate Science Strategy provides complementary guidance and stresses the importance of identifying and tracking climate impacts on ecosystems within an adaptive management context (http://www.st.nmfs.noaa.gov/ecosystems/climate/national-climate-strategy)*

Strategy to Address OAH	Example Application
Build decision-maker understanding	
• Improve understanding of OAH among key fisheries decision-makers and regulators in the public and private sectors through increased communication about OAH processes, impacts, and responses. • Provide forecasts of OAH conditions to decision-makers and end-users at geographic scales and time frames that are relevant to their management needs.	*The California Current Ecosystem Assessment has begun addressing acidification in information it synthesizes for fishery decision-makers (http://www.noaa.gov/iea/regions/california-current-region).* *Pacific coast shellfish growers use data, including those provided by NOAA, US IOOS, and regional partners to adjust their culture practices. Many data are served through the regional ocean observing systems (e.g., NANOOS: http://nvs.nanoos.org/ShellfishGrowers)*
Invest in expanding scientific knowledge and tools	
• Develop scenario-based simulation models and risk assessment frameworks to explore interactions and feedbacks among OAH, fisheries management, and ecological resilience • Develop and implement indicators of resilience and of OAH impacts on fisheries and the ecosystems on which they depend; Use indicators to track and report trends. • Coordinate sharing and integration of new information as it is developed and make it useful and available for fishery management applications.	*Scenario-based simulation models for Puget Sound have begun to explore OAH impacts (on fisheries yields, food webs, and biodiversity), how management choices affect impacts, and the feedbacks among OAH, fisheries management, and ecosystem resilience (see Kaplan et al 2010; Busch et al 2013).* *In California, new research is exploring ecological risk assessments as a mechanism to integrate climate, OAH and other risks and uncertainties into state fishery management decisions.*
Coastal Ecosystem Management	
Protect ecosystems that sequester carbon	
• Protect habitats where they contribute to sustaining ecological and biogeochemical functions; Protect seagrass beds and kelp forests where they may ameliorate local pH through carbon sequestration.	*Protection and restoration of eelgrass meadows have been recommended as management actions to address OAH in Washington state (Washington State Blue Ribbon Panel on Ocean Acidification, 2012)*
Integrate OAH into coastal ecosystem management frameworks and actions	
• Advise federal and state agencies to provide resources to assist local and regional coastal managers in addressing OAH and to consider OAH in water quality regulations and cooperative programs. • Update place-based management plans and models to include OAH; manage circulation, water stratification and water retention in local coastal areas e.g., via dams and/or dykes. • Include OAH in public education; Provide information to diversify and broaden the audiences who understand the implications of OAH for the places and ecosystems that matter to them	*In Washington State collaborative projects with the Puget Sound Restoration Fund are underway to rebuild Olympia oyster populations by providing critical habitat and water quality characteristics that also enhance local ecosystem functioning (http://www.restorationfund.org/projects/olympiaoyster).*
Support research to advance management approaches	
• Conduct research and assessments to inform local plans and actions, including research to evaluate the efficacy of carbon sequestration in local habitats as a local OAH solution. • Improve understanding of the role of retention and stratification in coastal waters for use in mitigating local OAH effects. • Support monitoring to assess status and trends of OAH in coastal and estuarine waters and promote open sharing of the data	*California Ocean Protection Council is supporting research to develop coupled oceanographic and biogeochemical models to understand the role of nutrient discharges on OAH in the Southern California Bight* *The Washington Department of Ecology is working to quantify the role of key natural and human-influenced processes that contribute to acidification, as recommended by the Blue Ribbon Panel on Ocean Acidification. This includes investigation of the role of nutrient pollution from land-based sources.*

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