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RESEARCH ARTICLE

Using integrated, ecosystem-level management to address intensifying ocean acidification and hypoxia in the California Current large marine ecosystem

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Ocean acidification is intensifying and hypoxia is projected to expand in the California Current large marine ecosystem as a result of processes associated with the global emission of CO_2. Observed changes in the California Current outpace those in many other areas of the ocean, underscoring the pressing need to adopt management approaches that can accommodate uncertainty and the complicated dynamics forced by accelerating change. We argue that changes occurring in the California Current large marine ecosystem provide opportunities and incentives to adopt an integrated, systems-level approach to resource management to preserve existing ecosystem services and forestall abrupt change. Practical options already exist to maximize the benefits of management actions and ameliorate impending change in the California Current, for instance, adding ocean acidification and hypoxia to design criteria for marine protected areas, including consideration of ocean acidification and hypoxia in fisheries management decisions, and fully enforcing existing laws and regulations that govern water quality and land use and development.

Keywords: California Current large marine ecosystem; ocean acidification; hypoxia

Introduction

Scientific understanding of the patterns, processes, and potential impacts of ocean acidification has grown substantially over the past decade with the realization that elevated greenhouse gases not only force changes in climatic conditions but also cause changes in ocean carbonate chemistry as the seas absorb increasing amounts of carbon dioxide (CO_2) (Howes et al., 2015). Evidence of a collateral effect of climate change – deoxygenation – has similarly emerged (Levin and Breitburg, 2015). Because deoxygenation can result in hypoxia (oxygen depletion detrimental to many organisms), the combined processes are often referred to as ocean acidification and hypoxia, or simply OAH. Together they threaten contemporary coastal ecosystems. In eastern boundary current regions (regions along the eastern margins of the world's oceans), upwelling brings to the surface deep waters that are naturally enriched in carbon dioxide, and lower in dissolved oxygen. These regions show early impacts of climate change that provide a window into the broader effects of intensifying OAH and their consequences for ocean management. Here we describe ocean change and opportunities for near-term management interventions in the California Current large marine ecosystem. In doing so, we argue that diverse approaches already exist that, in combination, can help sustain ecosystem functions vital to society.

Along the West Coast of North America repeated occurrences of low-oxygen (hypoxic) and high CO_2 conditions have caused acute effects and mortality among demersal fish and invertebrates (Chan et al., 2008) and have resulted in large-scale larval mortalities in shellfish hatcheries (Barton et al., 2015). These events have alerted West Coast policy makers and managers to the potential for OAH to affect the condition, productivity, and economic vitality of ocean ecosystems significantly. In 2011, Washington State Governor Christine Gregoire convened a blue ribbon panel to identify actions to reduce the harmful effects

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of acidification on the State's multi-million dollar shellfish industry and other coastal resources (Adelsman and Whitely Binder, 2012). Subsequent to that process, a coast-wide scientific panel was convened in 2013 by the governments of the states of California, Oregon, and Washington, and the Canadian province of British Columbia to synthesize relevant information about OAH processes and impacts and to identify solutions (Chan et al., 2016). Both panels were challenged to translate an incomplete, but rapidly evolving, knowledge base about OAH into practical near-term guidance for action. Through these and other efforts, policy makers and resource managers seek to better understand the regional implications of OAH, build a scientific infrastructure for delivering policy- and management-relevant information, and identify and initiate practical interventions that could improve management outcomes as OAH progresses.

Legislatures in two west-coast states have since taken action on ocean acidification and hypoxia. The Washington State Legislature established the Marine Resources Advisory Council in 2013 to work with governmental and non-governmental entities and with scientists to deliver recommendations to the governor and state legislature regarding OA. At the same time, the Washington State Legislature established and funded the Washington Ocean Acidification Center to develop and coordinate scientific research on ocean acidification, including environmental monitoring, numerical modeling, and biological experimentation. More recently, the California State Legislature passed legislation establishing an ocean acidification and hypoxia task force and authorizing funds to support activities of the Ocean Acidification and Hypoxia Program, including those that focus on sustaining and restoring functional nearshore habitats and eelgrass beds that provide habitat for commercial species and improve water quality. Following these actions by individual states, the governors of California, Oregon, and Washington and the premier of British Columbia collectively endorsed the formation of the International Alliance to Combat Ocean Acidification to advance local and regional strategies to address ocean acidification and hypoxia. This initiative is the first such collective action of its kind. In combination, the actions described above strongly signal the concerns of state governments about the impending effects of OAH and their willingness to take pragmatic actions to address the problem.

OAH in the California Current large marine ecosystem

Ocean and coastal environments from southern British Columbia, Canada, to Baja California, Mexico, are part of the California Current large marine ecosystem (CCLME). Surface waters of the CCLME already show CO_2 values that can be three times higher than the current global mean (~1200 μatm *versus* ~400 μatm; Harris et al., 2013) due to the upwelling of CO_2-rich waters. Over recent decades, conditions corrosive to calcified marine organisms have increased in frequency, severity, duration, and spatial extent (Feely et al., 2008; Harris et al., 2013) Moreover, changes observed in the ocean today do not reflect the full amount of anthropogenic CO_2 already in the atmosphere, because ocean circulation imposes decadal-scale time lags between CO_2 uptake at the ocean surface and subsequent upwelling of deeper CO_2-enriched waters (Feely et al., 2008) Even if today's atmospheric CO_2 levels were stabilized, acidification would further intensify over the coming decades, reflecting increases in atmospheric CO_2 concentrations that have occurred over the past decades.

At the same time, climate change is exposing the CCLME to increased risk of larger, more frequent and more severe hypoxia events as changes in oxygen solubility, stratification and circulation diminish the resupply of oxygen to the ocean interior (Keeling et al., 2010). Due to deoxygenation of source waters and intensification of upwelling (Garcia-Reyes and Largier, 2010; Sydeman et al., 2014), low-oxygen waters are spreading onto the continental shelf in some regions of the CCLME, bringing them in contact with valuable commercial fisheries (Keller et al., 2015). Moreover, deoxygenation and acidification are linked through biological processes: as organic matter is decomposed, microbial respiration consumes oxygen and produces CO_2, adding to the burden of CO_2 in seawater that lowers pH and saturation states of carbonate minerals. This biological link explains the co-occurrence of hypoxia and low pH in upwelled waters and may result in local intensification in highly productive zones of the CCLME, increasing the risk of exposure to both hypoxia and acidification (Keeling et al., 2010).

Patterns of ocean acidification and hypoxia in the CCLME are spatially and temporally complex, because they reflect geographically and temporally variable upwelling currents that bring naturally CO_2-rich and dissolved oxygen-poor waters to the coast. This dynamic physical setting in turn interacts with localized processes such as primary production and respiration, land-based inputs of nutrients and acidifying chemical constituents, and freshwater inflows to intensify the coastal expression of OAH (**Figure 1**; Hales et al., 2016). These time-variant expressions of OAH in the CCLME will shift as climate-induced changes progress and intensify, contributing to the dynamism of the system and creating some amount of irreducible uncertainty (Busch et al., 2015).

Effects on ecosystems

Based on what we already know about potential biological and ecological effects, OAH in the CCMLE has the potential to alter critical processes, such as nutrient cycling and food-web interactions, that determine the dynamics, diversity, and biological productivity of coastal and marine ecosystems (Gaylord et al., 2015). However, relatively few projections yet exist concerning OAH effects on the ecology of the CCLME or its societal benefits, which include valuable commercial and recreational fisheries, recreational industries, and coastal wetlands and shoreline habitats. Instead, evidence from laboratory and field studies and projections based on numerical modeling serve as key sources of information for anticipating and bounding expectations about the potential range, magnitude, and predictability of the ecosystem changes ahead (Blackford, 2010; Kroeker et al., 2013).

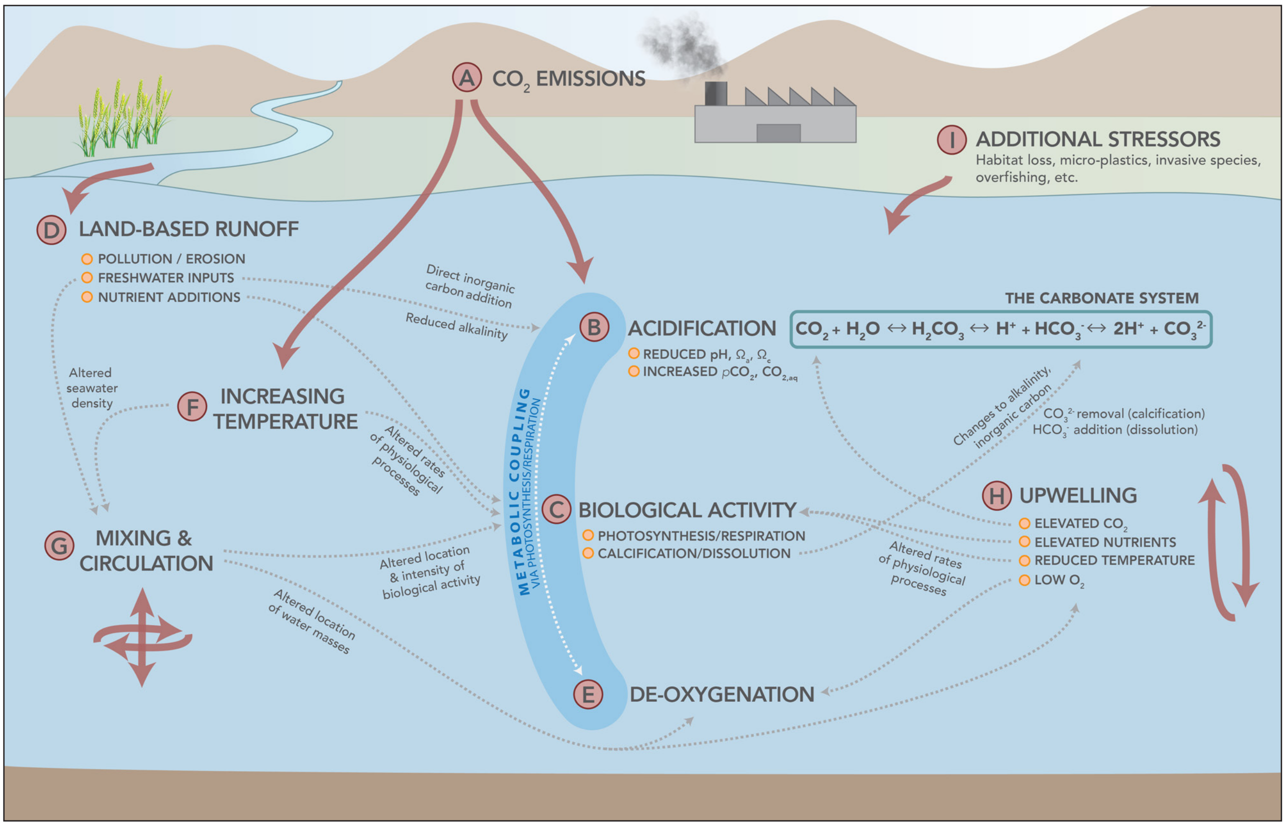

Figure 1: Graphical representation of major processes affecting the expression of OAH in coastal waters. CO$_2$ emissions **(A)** cause acidification of coastal waters **(B)** that is further influenced by biological activity **(C)**, runoff from land **(D)**, deoxygenation **(E)**, ocean warming **(F)**, mixing and circulation **(G)**, upwelling **(H)**, and additional stressors related to human activities **(I)**. Note that the actual location of processes in the water column varies in space and time. Figure taken from Hales et al. (2016); used with permission. DOI: https://doi.org/10.1525/elementa.198.f1

Controlled laboratory experiments have provided a critical warning that changing ocean chemistry could significantly affect populations of many marine species through effects on physiology and behavior that impair growth, reproduction, and survivorship (e.g., Kroeker et al., 2013; Somero et al., 2016). Diverse taxa and functional groups are vulnerable to current and near-future levels of acidification and hypoxia, with stronger impacts likely where the two stresses co-occur with each other and with a third stressor, increased temperature (Vaquer-Synyer and Duarte, 2008; Somero et al., 2016). Negatively affected species are likely to include those that play critical roles in pelagic food webs (e.g., calcified plankton), in biogenic construction of benthic habitats (e.g., corals, oysters), and in direct support of valuable fisheries (e.g., crabs, demersal and pelagic fishes).

Empirical observations of spatial gradients and temporal patterns suggest that intensifying OAH is associated with declining abundance of calcified taxa, altered ecological communities and food webs, and diminished fishery catches. Detailed studies of the pteropod *Limacina helicina* along the US west coast have shown that current levels of anthropogenic CO$_2$ are already compromising calcification by this important food source for pink salmon, mackerel, and herring (Bednaršek et al., 2014). Diminished fishery catches have been associated with seasonal spatial gradients in dissolved oxygen along the Oregon shelf (Keller et al., 2010, 2015). Moreover, poor survival of oyster larvae in an Oregon hatchery has been associated with corrosive waters (Barton et al., 2015), and reorganized coastal food webs and increased abundances of pelagic fishes have been associated with historical shifts to lower oxygen conditions in the oceanographically analogous Humboldt Current (Gutiérrez et al., 2009; Salvatteci et al., 2014). Evidence from other marine ecosystems shows that calcifying taxa become less abundant as pH declines in proximity to natural CO$_2$ vents (Hall-Spencer et al., 2008; Fabricius et al., 2014), and that hypoxic zones can cause habitat compression, altered predator-prey interactions, and wholesale shifts in benthic community structure (Breitburg et al., 2009; Levin and Sibuet, 2012).

Based on results from numerical models and incubation experiments, indirect ecological effects – mediated, for example, by changes in biogeochemical cycles and species interactions – are likely to play a critical role in regulating the impacts of OAH on biological communities in the CCLME (Busch et al., 2013, 2014). Acidification has been shown to alter predator-prey relationships of coastal molluscs (Kroeker et al., 2014) and may cause modifications in primary production that propagate through food webs (Nagelkerken and Connell, 2015). Food web and multi-species fishery models developed for the CCLME show that the distribution of impacts among species and functional groups will determine whether ecological interactions among species amplify or dampen acidification impacts on fishery yields (Busch et al., 2013). Models also suggest that interactions among acidification, hypoxia, other climate-related changes, and/or fishing will cause additive and synergistic effects (Kaplan et al., 2010; Ainsworth et al., 2011). Some of these indirect effects could be large and persistent (Benedetti-Cecchi, 2003; Ainsworth et al., 2011).

Opportunities for pragmatic action

From a policy and management perspective, ongoing OAH in the CCLME can be characterized as a phenomenon of high impact and high uncertainty, posing challenges similar to other dimensions of climate change that are expected to have multiple and wide-ranging effects on ecosystem structure and process, leading to transitions that are difficult to predict with confidence. Coastal and marine ecosystem managers can, nevertheless, take steps now to support the long-term productivity and benefits of the CCLME under uncertain and rapidly changing conditions by sustaining ecological resilience (e.g., Bernhardt and Leslie, 2013; Billé et al., 2013; Cooley et al., 2016; Seidl, 2014; Weins, 2016).

Here we use the term 'resilience' to mean the capacity of a system to maintain key ecological functions, processes, and feedbacks in the face of perturbations and disruptions (e.g., Levin and Lubchenco, 2008; Billé et al., 2013; Seidl, 2014). Biological diversity (including genetic and functional diversity), food web complexity, habitat diversity, modularity, and spatial connectivity all can contribute to the resilience of coastal and marine ecosystems and can be sustained or restored by coordinated management actions (Bernhardt and Leslie, 2013). Current levels of ecological resilience in the CCLME result from a combination of intrinsic and extrinsic factors such as oceanographic processes, biogeographical history, past disturbances, and human inputs and actions.

Resilience approaches to the problem of OAH should yield benefits under a wide range of alternative future scenarios by delaying abrupt ecosystem change and smoothing transitions to new states when those transitions become inevitable (Bernhardt and Leslie, 2013; Seidl, 2014). Delaying action to address OAH, conversely, will constrain future management options as ecosystem change accelerates and ecosystem function is eroded or lost (Scheffer et al., 2015; Gattuso et al., 2015).

In the policy domain, resilience has gained traction as a goal for ecosystem management more generally (Standish et al., 2014). It has recently been proposed as a goal for regulatory and non-regulatory actions for ameliorating OA in the U.S., such as by restoring oyster beds, considering OA in fisheries management decisions, and changing land use and land development practices in ways that alleviate OA (Cooley et al., 2016). Resilience resonates with decision-makers because it presents a way to maintain or restore ecological states that are desirable or beneficial in a socio-economic context. The adoption of resilience as a credible goal for environmental management has grown as indicators, metrics, and tools for its implementation continue to be developed, tested, and refined (Spears et al., 2015). Ecologists, notably, have for decades recognized resilience as a property of natural systems that persist under conditions of environmental variation; persistence requires resilience (Weins, 2016).

We argue that, with respect to OAH, sustaining or restoring ecological resilience offers a near-term or bridging strategy to slow, ease or even avert ecosystem transitions while scientific understanding grows and new management options emerge. At the same time, we recognize that over the longer term, the progressive intensification of OAH in CCLME ecosystems will increase the risks of crossing critical thresholds that can lead to highly altered states that no longer provide goods and services important to society, including, for example, productive fisheries. The possibility of critical transitions to undesirable states underscores the importance of continuing to mitigate CO_2 and other greenhouse gas emissions to limit OAH intensification and effects.

Management options

Here we identify practices that can be adopted by managers now to enhance near-term ecological resilience and adaptive capacity in the CCLME. We provide specific examples demonstrating how these approaches already are being implemented under existing legislative mandates, institutions, and decision-making processes (**Table 1**). Our set of examples is not exhaustive; instead we focus on several of the most obvious and appropriate management tools specific to the CCLME.

Marine Protected Areas. Marine protected areas (MPAs) are a spatial management tool widely used to sustain living marine resources. MPAs in the CCLME region are established under a number of authorities and differ in their specific objectives, regulations, and levels of protection (Gleason et al. 2013); collectively, they cover more than 114,000 square nm and 40% of the US Exclusive Economic Zone (National Marine Protected Areas Center, 2013). Of these, the most restrictive MPAs are designated as fully no-take areas. Other MPAs allow the take of a restricted set of species while affording substantial protection to most resident species and the benthic habitat. Still other MPAs, for example, the National Marine Sanctuaries, focus on education, outreach, and research, while limiting some human uses. Many of these MPAs, especially those that limit the extraction of living marine resources and protect benthic habitat, are expected to provide ecological benefits both within and beyond their boundaries, such as protecting biodiversity, maintaining food web functions, and sustaining larval production and connectivity (Micheli et al., 2012; Barnett and Baskett, 2015). Existing MPAs and MPA networks and those established in the future thus have the potential to help support regional ecological resilience and adaptive capacity as OAH intensifies.

At the same time, OAH threatens to significantly change or degrade the biological and ecological attributes and processes that many of these MPAs were designed to protect, for example, through negative effects on physiology, behavior, and abundance that propagate through populations and communities. As a consequence, the

Table 1: Examples of strategies and existing applications that can be used to help support ecological resilience to ocean acidification and hypoxia (OAH). DOI: https://doi.org/10.1525/elementa.198.t1

Strategies[a]	**Example applications**[b]
1. Marine Protected Areas (MPAs)	
Incorporate OAH considerations into MPA site 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 could help attenuate local or regional OAH through biogeochemical cycling.	Existing MPAs in Washington State are regularly exposed to OA; they can serve as test areas to evaluate physiological tolerance to OA. National Estuarine Research Reserves may function as 'buffering MPAs' and can serve as test areas to evaluate changes in carbon dynamics and biogeochemical cycling under intensifying 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. · Move away from species-based goals and metrics towards those focused on ecological resilience and adaptive capacity. · Identify and implement management actions to reduce MPA vulnerability to OAH, such as by reducing local land-based contributions to OAH (e.g., nutrient inputs).	The Gulf of the Farallones National Marine Sanctuary is integrating acidification into a climate change vulnerability assessment to inform future management evaluations. This vulnerability assessment is now available (http://sanctuaries.noaa.gov/science/conservation/vulnerability-assessment-gfnms.html). Some MPAs within the California statewide network are co-located with existing Areas of Special Biological Significance – 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 and monitoring.	
· Improve understanding of whether, where, and how MPAs can contribute to ecological 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 resilience goals. · Implement MPA monitoring to track changing ocean chemistry and ecological impacts. Develop metrics and methods to monitor ecological resilience.	Researchers at the University of California Santa Barbara are evaluating spatial scales of OAH variability relative to MPAs in the South Coast regional MPA network (G. Hofmann, pers. comm.), and piloting a coupled MPA monitoring – OA sensor network. The West Coast Ocean Acidification and Hypoxia Science Panel developed a monitoring framework that prioritizes management relevant questions and couples biological and chemical data collection (http://www.westcoastOAH.org). The California Ocean Science Trust is leading development of an OAH hotspots inventory, with support from California Ocean Protection Council, to map locations of vulnerability and potential adaptive capacity, align these with existing MPA, fisheries and habitat protections, and inform long-term monitoring design.
2. Fisheries Management	
Advance ecosystem-based policies to guide management.	
· Integrate OAH considerations into ecosystem approaches to fisheries management. · Periodically update state and federal fishery management plans to incorporate improved understanding of the impacts and feedbacks among OAH, ecological processes, and fisheries management. Periodically re-evaluate ways in which individual fisheries could be managed to enhance ecological resilience 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 include considerations of OAH into plans that guide management of >115 species by the National Marine Fisheries Service. The 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).
Build decision-maker understanding.	
· Improve understanding of OAH among key fisheries decision-makers and regulators in the private and public sectors through increased communication about OAH processes, impacts, and responses. · Provide forecasts of OAH conditions to decision-makers and users at spatial and temporal scales that are relevant to their management needs.	The California Current Ecosystem Assessment has begun to include OA 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., http://nvs.nanoos.org/ShellfishGrowers).

contd.

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 ecological 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 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). NOAA's Integrated Ecosystem Assessment provides scientific support for ecosystem approaches through the development of tools for assessment. 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.
3. Coastal Management	
Protect ecosystems that sequester carbon.	
· Protect habitats that support beneficial ecological and biogeochemical processes. · Protect seagrass and kelp beds that have the potential to ameliorate local pH through carbon assimilation and sequestration.	Protection and restoration of eelgrass meadows have been recommended as management actions to address OAH in Washington state and California (Washington State Blue Ribbon Panel on Ocean Acidification, 2012; West Coast Ocean Acidification and Hypoxia Science Panel: Major Findings, Recommendations and Actions, 2016).
Integrate OAH into coastal ecosystem management frameworks and actions.	
· Advocate for resources to assist local and regional coastal managers in addressing OAH, for example through cooperative research and demonstration projects. · Work with water quality regulators to develop and refine indicators and metrics of OAH. · Update place-based management plans and models to include OAH. Manage water circulation, stratification and retention in coastal areas via management of flow rates, water column depth and structures. · 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 by 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). In Washington State, OA monitoring data from multiple sources have been shared with state and federal water quality regulators.
Support research to advance management approaches.	
· Conduct research and assessments to inform local plans and actions, including research to evaluate the efficacy of carbon assimilation and sequestration as a means of addressing local OAH. · 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.	The California Ocean Protection Council is supporting research to develop coupled oceanographic and biogeochemical models to understand the role of nutrient discharges and coastal oceanography 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 effort includes investiging the role of nutrient pollution from land-based sources. In Washington State, the Puget Sound Restoration Fund is investigating the utility of kelp culture to ameliorate local OA conditions. In California, management of hypoxia in Pescadero Lagoon is being attempted via management of flow rate and mouth state.

[a] General strategies that can be adopted 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.

[b] Real-world examples of tools and practices now in place within the California Current region illustrating how each strategy could be implemented within existing management frameworks.

performance of some MPAs may not meet expectations established at the time of their designation. Some MPAs may be especially vulnerable to ecological disruption if they are exposed to local environmental stressors; for example, some areas along the Oregon coast periodically experience fish and invertebrate mortality during hypoxic events (Chan et al., 2008) and appear particularly susceptible to acidification (Harris et al., 2013).

Going forward, designation of new MPAs and refinements to existing MPA networks will require consideration of current and future OAH conditions. MPAs established in areas less exposed to OAH can potentially serve as temporal or spatial refugia that provide habitat for vulnerable species and as source populations for repopulating areas subject to transient OAH intensification (Strong et al., 2014). Alternatively, MPAs established in areas that are naturally subject to more intense or more variable OAH conditions could serve to protect populations that have developed greater physiological tolerance or that are more genetically diverse in traits that confer such tolerance, and therefore have the potential for rapid evolutionary adaptation (Strong et al., 2014). By explicitly considering the adaptive capacity of species and incorporating evolutionary perspectives into MPA planning and management, managers can increase the likelihood that the behavioral, physiological, or evolutionary responses of key species to changing environmental conditions will shift in ways that promote their persistence and abundance under novel environmental conditions (Beever et al., 2016). While the adaptive capacity of populations or species may be difficult to assess quantitatively, a useful approximation can be obtained from observations of OAH variability in locations where focal species persist, based on the assumption that persistence under conditions of extreme variability indicates genetically-based capacity to tolerate extreme conditions.

Goals and performance metrics for many MPAs may need to be recalibrated in light of OAH. Performance metrics based on the status of current species assemblages will become less meaningful as systems undergo OAH-related transitions. Alternative or additional metrics that assess the functions, services, and attributes of the system vis-à-vis ecological resilience (e.g., food web complexity, biodiversity, connectivity), but that are independent of particular species assemblages, may become more useful and can be developed; in some cases, these metrics already are under development. Clearly acknowledging the potential magnitude and uncertainty of ongoing changes due to OAH will generate more realistic expectations about MPA performance among policy-makers, managers, and stakeholders.

Informing the design of future policy or management interventions with an understanding of how ecosystems could change under OAH will require the development of targeted, context-specific models and scenario analyses. Scenarios can be based on model simulations and used to reflect alternative outcomes under differing conditions. Sustained environmental monitoring of OAH conditions can provide the data to inform, improve, and validate such models and scenarios. More generally, monitoring within and adjacent to MPAs can be used to assess OAH in ways that are management-relevant, such as by illuminating potential associations between changing ocean chemistry and ecosystem effects or by evaluating whether or how MPAs contribute to regional ecological resilience under OAH.

The value of using MPAs as research reserves to control for human-use variables is likely to grow as OAH progresses. Such research reserves can help test management interventions beyond the effects of fishing. For example, MPAs that protect submerged aquatic vegetation and other forms of blue carbon (i.e., carbon naturally stored in coastal ecosystems) may help us quantify the value of such resources for achieving greenhouse gas reduction targets and could serve as important additions to a larger portfolio of strategies designed to foster ecological resilience.

Fisheries management. National, tribal, and state governments all participate in managing commercial and recreational fisheries in the CCLME. While OAH effects on fisheries in the CCLME are not yet well understood, the potential exists for significant impacts on fishery yields due to changes in behavior, growth, and survivorship among target and non-target species (e.g., Branch et al., 2013; Busch et al., 2013).

The recent move towards managing fisheries within an ecosystem context provides what may be the best opportunity for realistically considering OAH in fishery management decisions. Although stock-specific management plans historically guided fishery harvests, US fishery scientists and managers have been moving over the past decade towards better accounting for ecological interactions and dynamics (e.g., Field and Francis, 2006; Pacific Fishery Management Council, 2013). Ecosystem-based fishery management plans seek to sustain the full range of functional groups in fisheries ecosystems (i.e., producers to consumers and habitat-providers), account for key processes and feedbacks, and allow consideration of more environmental variables and uncertainties (including OAH) to be part of the management planning process (Collie et al., 2016). As a consequence, ecosystem-based fishery management plans are more likely to support ecosystem resilience (e.g., Levin and Lubchenco, 2008) and maintain productive fisheries under intensifying OAH.

Within the CCLME, the Pacific Fishery Management Council in 2013 adopted the Fishery Ecosystem Plan to move ecosystem science into planning and policies and to provide a general framework for addressing uncertainties that stem from consideration of natural and anthropogenic changes in fishery management decisions. However, most fishery decision-makers and stakeholders do not yet have a good understanding of how the potential impacts and uncertainties of OAH might be integrated into setting harvest control rules, designing stock rebuilding strategies, or establishing other fishery policies. Building this understanding is essential.

Some of the decision-support tools that inform fisheries decisions can be adjusted to better integrate OAH considerations. Assessments of the vulnerability of benthic habitats to trawling, for example, could be enhanced to address the susceptibility of benthic organisms that create biogenic habitats (e.g., corals and sponges) to changing OAH conditions. The siting of MPAs established for the protection of fish species could be improved by considering the spatial arrangement of areas that are more or less vulnerable to acidification or hypoxia. The growing use of integrated modeling frameworks to run simulations and compare alternative management strategies (e.g., management strategy evaluation) presents an opportunity for incorporating OAH into fisheries decisions by adjusting how the models treat uncertainty and environmental variation (Collie et al., 2014; Punt et al., 2014). At the same time, scenario-based models are being used to explore the effects of OAH on fishery yields, food webs, and biodiversity in the CCLME (e.g., Kaplan et al., 2010; Busch et al., 2013). Continuing development and refinement of such models can help to determine how alternative OAH scenarios or management choices affect fisheries impacts and yields; they can also reveal specific indicators with which to measure progress.

Convincing policy makers to incorporate OAH into the potentially costly and sometimes contentious decisions that guide fishery harvests in the CCLME will require a clearer understanding of OAH impacts and better appraisal of management choices that can optimize fishery yields under OAH. Given the need for clear evidence on which to base decisions, indicators that reflect OAH conditions and their effects on fisheries and ecosystems should be viewed as integral components of monitoring programs.

Coastal management. Coastal regions of the CCLME experience more intense and variable OAH conditions than those farther offshore (Harris et al., 2013). Partially enclosed embayments and estuarine waters where local drivers of eutrophication-enhanced OAH are strong, such as parts of Puget Sound, are especially susceptible (Feely et al., 2010). In such places, effective management of water quality can help reduce local intensification of OAH. For example, nutrients released to coastal waters from upland areas contribute to OAH by fueling phytoplankton growth. Where phytoplankton are abundant (e.g., in eutrophic waters), microbial decay of the organic matter produced by phytoplankton contributes to local acidification by increasing CO_2 concentrations while inducing hypoxia. Coastal eutrophication is a problem familiar to water quality managers, who have developed means to control nutrient pollution through laws and regulations. Fully implementing existing laws and regulations, and modifying existing water quality standards and thresholds to better address OAH, can help managers tackle the emerging problem of OAH (Boehm et al., 2015; Weisberg et al., 2016).

Stratification, tides, and river forcing combine to control how long land-based nutrients and organic matter remain in estuarine and coastal waters, and thus determine the net effects of photosynthesis, respiration, and decomposition on the chemistry of these waters. In areas experiencing strong stratification, photosynthesis in the surface layer may become uncoupled from decomposition in lower layers, exacerbating deoxygenation and acidification at depth. Opportunities may exist in some estuaries and bays to restore coastal features in ways that mitigate local OAH, such as by altering built structures or other impediments that limit flushing.

Opportunities are emerging for coastal managers to include carbon management as a growing part of their portfolio. In this regard, avoiding conversion of coastal systems to low-carbon systems — those that store less carbon — can be an important first step, for example, by preventing the release of carbon now stored in coastal sediments and preserving carbon stored as living biomass. First critical steps in this regard are to inventory carbon stocks in nearshore environments and amend management strategies to protect or enhance valuable carbon reservoirs. Such practices can be integrated with broader climate change policies, for example, those that encourage sequestration or establish a market value for carbon via offset credits, for greater effect.

Considerable interest now centers on the potential for submerged aquatic vegetation (e.g., seagrasses, kelp) to improve local OAH conditions in the near term, and to sequester carbon in the longer term (Mcleod et al., 2011). Although this potential is an area of active investigation, a scientific consensus does not yet exist on the general efficacy of such approaches. However, vegetation management is already part of coastal management in many areas of the CCLME, and often is required by law or regulation. The organic matter produced by seagrasses, kelps, and other macroalgae typically is more resistant to microbial decay than that produced by phytoplankton. It therefore is more likely to become buried in sediments or be transported to deeper areas offshore, effectively removing carbon from the local system in areas where rates of deposition or offshore transport are high. Managing submerged aquatic vegetation to slow or reduce OAH by promoting carbon sequestration is, for now, experimental; further research is required to evaluate its effectiveness. Nevertheless, protecting submerged vegetation to the extent now specified by law or regulation has the potential to produce benefits while preserving options for future management actions related to carbon storage.

Diverse organizations and institutions in the CCLME – including the National Estuary Program, National Estuarine Research Reserves, and various local and regional initiatives – now help manage watersheds and ecosystems at the land-sea interface by convening interested parties, developing place-based scientific knowledge and plans, and delivering public education. These organizations provide a means for building local understanding and for spurring local actions to improve OAH conditions by reducing land-based inputs, protecting submerged aquatic vegetation, and/or modifying coastal structures. National, regional, and state organizations that provide technical assistance, develop public education materials, and fund applied science can help speed such local and regional efforts.

Conclusion

Along the west coasts of the USA, Canada, and Mexico, the highly productive California Current large marine ecosystem provides goods and services that contribute to one of the world's largest regional economies. At the same time, the CCLME is experiencing rapid changes in environmental conditions. Ocean acidification in the CCLME already is more intense than those in many other coastal regions, and hypoxic events are occurring more widely and more often; both of these changes threaten the natural productivity of this system and serve as indications of larger changes that will be associated with climate change in the future.

Despite these rapid changes, practical options are available now to help ameliorate their effects on populations and ecosystems. Managers on the US west coast have the opportunity to use established practices in new and more coordinated ways to help foster ecosystem resilience under conditions of persistent uncertainty. The approaches we have identified comprise a suite of adaptive responses that can be evaluated and modified as ocean conditions progressively move beyond the range experienced over recent centuries and millennia. The early impacts of ocean change in the CCLME offer an important and perhaps unparalleled learning opportunity for human adaptation to rapid ocean change.

Data accessibility

No original data were generated.

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Competing interests

The authors have no competing interests to declare.

Author contributions

- Contributed to conceptual framing: all authors
- Contributed to writing: all authors
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