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

By Alexandria B. Boehm, Mark Z. Jacobson, Michael J. O'Donnell, Martha Sutula, Waldo Wakefield, Stephen B. Weisberg, and Elizabeth Whiteman

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ABSTRACT. Ocean circulation patterns along the west coast of North America periodically draw subthermocline waters that have a naturally lower pH than surface waters into shallow coastal areas. In addition, corrosive surface waters with lower pH that is caused by the ocean absorbing excess atmospheric CO_2 (called ocean acidification, or OA) are frequently present. Reduction of atmospheric CO_2 inputs is the appropriate management focus for globally decreasing OA, but there are also many management decisions made at regional to local spatial scales that can lessen the exposure to or limit the effects of atmospheric CO_2. Here, we describe these local management actions and identify the science needs that would assist local managers in deciding whether, and how best, to address local OA. Science needs are diverse, but three commonalities emerge. First, managers need a comprehensive monitoring program that expands understanding of spatial and temporal OA patterns and how OA changes influence marine ecosystems. Second, they require mechanistic, process-based models that differentiate natural from anthropogenically driven OA patterns and the extent to which local actions would affect OA conditions in context of what is largely a global atmospheric-driven phenomenon. Models present the opportunity to visualize outcomes with and without the changes in management actions included in model scenarios. Third, managers need extended models that could help to identify which locales are most and least vulnerable to future changes due to OA. Understanding vulnerability will assist managers in better siting facilities (e.g., aquaria) or protecting marine resources. These products are all achievable, with much of the necessary research and development already underway. The challenge will be to ensure good and continuing communication between the management community that requires the information and the scientific community that is often hesitant to provide recommendations while uncertainty remains high.

INTRODUCTION

Ocean acidification (OA), defined as the process whereby waters become more acidic and corrosive, poses a threat to the health of the world ocean and the significant benefits it provides (Feely et al., 2004; Orr et al., 2005; Royal Society, 2005; Doney et al., 2009). The main cause of OA is rising global atmospheric CO_2 concentrations (Doney et al., 2009). However, there is evidence that coastal processes occurring at the local to regional scale (~1 to 1,000 km) can exacerbate or alleviate OA. Some examples of exacerbating processes include coastal upwelling (Feely et al., 2008), local respiration (Feely et al., 2010), and discharge of land-based, nutrient-laden runoff, which can enhance hypoxia and acidification (Sunda and Cai, 2012). There are also local processes that can lessen acidification, such as carbon assimilation by seagrass or kelp (Hendriks et al., 2014).

The upwelling-dominated shoreline of the west coast of North America, including the California, Oregon, Washington, and British Columbia coastlines, is particularly vulnerable to OA (Barton et al., 2012, and 2015, in this issue; Feely et al., 2008, 2012; Hauri et al., 2013). Average ocean pH is about 8.2, but very nearshore waters off Oregon can exhibit pH as low as 7.7 (Feely et al., 2008; Barton et al., 2012) due to the combined effects of atmospheric CO_2 dissolution and upwelling that brings nutrient-enriched, low pH waters onshore. Declines in Oregon coast shellfish hatchery production over the last several years have been correlated with such upwelling events (Barton et al., 2012, and 2015, in this issue). In waters of Puget Sound, Washington, Feely et al. (2010) found pH as low as 7.5, owing to the combined effects of global CO_2 dissolution, upwelling of aged, low pH waters, and local respiration. Bednaršek et al. (2014) showed OA hotspots along the entire coasts of Washington and Oregon, as well as northern California, where more than 50% of the upper water column in the very nearshore was undersaturated with respect to aragonite during the summer.

Although global atmospheric CO_2 input is mainly responsible for the current OA issues along the west coast of

North America, compounding the other natural and anthropogenic causes, many management decisions made at local to regional spatial scales have the potential to slow acidification, limit its exposure, or remediate its effects. Relevant decision makers include water quality managers who regulate local discharges that may affect local carbonate chemistry, living marine resource managers who can adjust fishery limits or habitat protection in response to the additional pressures brought by acidification, coastal zone land use managers who make decisions concerning facility siting or habitat restoration activities, air quality managers who control local emissions, and coastal resource users who own and manage coastal-dependent facilities like desalination or aquaculture facilities. Local management actions are a potentially important part of a portfolio of local, regional, and global approaches to addressing OA. In many cases, local and regional management decisions are either underway or actionable now and can potentially buy time until global action on CO_2 emission reduction can be achieved.

However, many coastal resource managers and users do not have the information they need for deciding whether, and how best, to deploy their management tools to regulate OA parameters directly, or to manage effectively in the face of OA. OA is a relatively new area of science where knowledge has been increasing exponentially over the last decade; more than two-thirds of all scientific articles on the topic of OA have been published since 2011 (isiknowledge web of science, accessed 9/25/14). The issue is that much of this ongoing research does not focus directly on addressing managers' needs (Yates et al., 2015, in this issue). Indeed, many scientists have limited understanding of the regulatory or decision frameworks used by managers and thus do not have the tools or information needed to prioritize research questions that can inform or improve decision making (Busch et al., 2015, in this issue; Cooley et al., 2015, in this issue).

Here, we describe the most prominent decisions that local managers already make, or could be making, under current management frameworks (summarized by Kelly et al., 2011). We then use this information to identify the science needs that must be met before managers are able to take effective action.

WATER QUALITY MANAGERS

Water quality managers employ four primary steps to address coastal ocean water quality, steps that are applicable to OA (Kelly et al., 2011): (1) develop water quality standards that define the acceptable levels of acidification parameters, (2) establish numerical limits on coastal discharges to ensure that these water quality standards are achieved, (3) assess whether discharge limits have been effective at ensuring standards are actually achieved through monitoring, and (4) if monitoring indicates that standards are not being met, manage system transitions, from developing individual discharge permits to collectively considering all discharges to the coastal ocean through establishment of a total maximum daily load (TMDL). For each of these steps, collection of scientific data could be adjusted and advanced to fully support OA management. Science needs, and the current science shortcomings for each of these steps, are delineated below.

Standards are measures that, when met, will protect the designated beneficial uses of the water body. There are two decision points for establishing a standard to protect a water body: (1) when selecting the appropriate parameter on which to base the standard, and (2) when establishing the appropriate threshold for that parameter.

All three West Coast states and the province of British Columbia presently use pH for the standard (Table 1). However, Washington's Blue Ribbon Panel on Ocean Acidification (Washington Department of Ecology, 2012) recommended that the State "evaluate the applicability of

TABLE 1. Criteria for pH water quality in the three West Coast States (US EPA, 2010) and the Province of British Columbia (Canadian Council of Ministers of the Environment, 1999).

State of Washington
For water bodies classified as exceptional waters: pH must be within the range of 7.0 to 8.5 with a human-caused variation of less than 0.2 units
For water bodies classified as excellent or good waters: pH must be within the range of 7.0 to 8.5 with a human-caused variation of less than 0.5 units
For water bodies classified as fair waters: pH must be within the range of 6.5 to 9.0 with a human-caused variation of less than 0.5 units
State of California
The pH shall not be changed at any time more than 0.2 units from that which occurs naturally
State of Oregon
For marine waters: pH must fall between 7.0 and 8.5
For estuarine waters: pH must fall between 6.5 and 8.5
Province of British Columbia
In marine and estuarine waters, the pH shall not be changed at any time more than 0.2 units from that which occurs naturally and should not fall out of the range of 7.0–8.7

other water quality criteria identified by recent research or recommended by scientific experts in the fields of ocean acidification and water quality." Moreover, the Center for Biological Diversity has petitioned the US Environmental Protection Agency (US EPA) to either add to or replace the existing national pH standard with one based on aragonite saturation state (Ω; Center for Biological Diversity, 2013), a parameter that cannot be measured directly. These recommendations result from scientific findings that biotic responses are more closely associated with a description of the carbonate system (total alkalinity, dissolved inorganic carbon, pH, pCO_2) than with pH alone (Comeau et al., 2010; Barton et al., 2012; Feely et al., 2012; Bednaršek et al., 2014; Waldbusser et al., 2015). For example, laboratory studies indicate a strong correlation between calcium carbonate formation and Ω for many calcifying species (Kroeker et al., 2010), and integrated research consortia on the US West Coast are now focusing on Ω as their primary monitoring parameter (McLaughlin et al., 2015, in this issue). However, parameter selection remains open to scientific discussion, as Ω may be the key parameter for assessing impacts on calcification processes (Waldbusser et al., 2015), but other parameters, such as pCO_2 or pH, may be more relevant for assessing biological impacts in other taxa (Tseng et al., 2013; Dixson et al., 2014).

The second step in developing standards is to establish an acceptable threshold for the chosen parameter. Current pH standards for the west coast of North America (Table 1) were developed many years ago and would benefit from reconsideration in context of more recent research. Standards for Oregon and Washington include a static range of acceptable pH condition, but the low end of that range is 6.5, and many biological studies have identified substantial biological effects at more than a full pH unit higher (Hofmann et al., 2011; Duarte et al., 2013). Washington, California, and British Columbia also require that pH should not be changed more than 0.2 units from natural conditions, and it is unclear whether that adequately buffers the detrimental effects of OA. It is also unclear what constitutes "natural." There is a great opportunity for scientists to contribute to development of new acidification-related water quality standards, but this will require more experimentation with diverse species and with realistic exposure scenarios. Research on the biological effects of OA has been concentrated on a small number of species, heavily dominated by calcifiers (e.g., Kroeker et al., 2010; Gaylord et al., 2014), and exposure studies with a wider range of biota need to be undertaken. Additionally, most studies have been short term and based on constant pH conditions expected for the open ocean rather than the fluctuating conditions observed in coastal environments (Hofmann et al., 2011).

The next water quality management step is to establish permit limits for dischargers that ensure the water quality standard in the receiving water body will be achieved. This step presents an interesting challenge for OA as compared to traditional pollutants. For chemical contaminants such as copper, the typical permit discharge limit is determined by considering the dilution of the discharge where it enters the ambient environment; the permit limit concentration is set such that the anticipated dilution will reduce the copper concentration below the water quality standard. This management mechanism is problematic for setting pH and other carbonate system parameters because their levels in the discharge stream are not the concern. Rather, the concern is the discharge of nutrients or organics, which, through their effects on biological respiration, can cause carbonate chemistry to change at spatial and temporal scales beyond the area immediately adjacent to a discharge (Sunda and Cai, 2012).

An obvious approach for developing effluent limits for parameters such as nutrients that indirectly affect OA is to develop models that predict and quantify their effects. These models must couple the anthropogenically influenced direct acidification (from atmospheric dissolution) and enhanced biological productivity (from anthropogenic nutrient and organic matter input) with the physical transport of that productivity to determine whether those effects are acceptably diluted over a larger spatial range. Such coupled models, particularly ones that operate close to the coastline and at spatial resolution necessary for water quality management (1–10 km), are only beginning to be developed (Borges and Gypens, 2010). Validation of the models with measurements of carbonate parameters will be necessary.

Once permit limits are issued, dischargers are typically required to monitor the ambient environment to ensure that standards are being met. In some cases, monitoring programs are specific to the area immediately adjacent to the discharge; increasingly, however, dischargers are being asked to participate in regional monitoring programs that assess the cumulative effects of multiple discharges. Such regional monitoring efforts are extensive in larger water bodies of the west coast of North America such as Puget Sound (Moore et al., 2013), San Francisco Bay (Hoenicke et al., 2003), and the Southern California Bight (Bernstein and Weisberg, 2003).

A larger problem, though, is that most existing measurement approaches are less sensitive and reproducible than needed to assess discharge effects on carbonate chemistry in coastal waters. Some standards (Table 1) require that there be no more than 0.2 pH unit deviation from natural conditions, which is less than the measurement variability of the glass electrode sensors that are typically used in regulatory monitoring programs. Newer instruments are becoming available, such as Durafet sensors that are repeatable to ~0.1 pH unit (Martz et al., 2010; McLaughlin et al., 2015, in this issue). XPrize, a nonprofit organization that designs and manages public competitions with the intension of encouraging technological development that could benefit humankind, has incentivized the community to develop even better instrumentation, with a multimillion dollar prize for instruments that meet reliability and performance standards relevant to water quality management (Xprize, 2014). The US Integrated Ocean Observing System (IOOS), in collaboration with the National Oceanic and Atmospheric Administration's (NOAA's) Ocean Acidification Program, is sponsoring an Ocean Technology Transfer program to develop better OA monitoring sensors (IOOS, 2014).

There are also similar advances in devices that measure other relevant parameters, including $p\mathrm{CO}_2$ and alkalinity (Byrne, 2014). Water quality managers can identify, as part of a discharger's monitoring requirements, precision and accuracy minimums that will lead them to adopt newer technologies, but those requirements must be achievable by commercial and standardized methods. They cannot require dischargers to either develop or use experimental technologies as part of their permit based measurements. This constraint challenges the scientific community to reach consensus about the effectiveness of new measurement technologies as they become available, to standardize implementation practices, to conduct inter-calibration exercises, and to help regulatory agencies develop laboratory certification programs. Such steps are necessary before new technologies can be recognized as routinely available and be required by regulators for routine measurements.

When monitoring indicates that a water quality standard is not being met in the United States, the state may list the water body as "impaired" through the Clean Water Act Section 303d listing process. Ultimately, this step can lead to a TMDL allocation that reconsiders the discharge limits for all facilities cumulatively. The Ministry of the Environment in British Columbia has enacted a similar process. However, a recent court case determined that the pH data being routinely collected are of insufficient quality to make such a determination (Center for Biological Diversity, 2015). Beyond the incongruity between instrument precision and the water quality standard, the standard requires definition of "natural" water quality so that impaired water quality can be properly assessed. A major shortcoming is that there are few temporally extensive acidification data in the region to determine which areas have changed relative to their historic conditions. Alternatively, managers can list water bodies as impaired based on definition of a spatial reference condition, but broad-scale regional monitoring data that allow description of spatial patterns are rare.

A second shortcoming is that implementation of a TMDL requires source attribution, and it is unclear how to separate the degree to which global versus local processes contribute to coastal OA. While global CO_2 emissions are the main cause of OA, local inputs of nutrients can also affect local OA conditions (Sunda and Cai, 2012). From a water quality manager's perspective, four main sources of nutrients may contribute to OA: (1) end-of-pipe discharges, such as wastewater outfalls, (2) surface runoff from rivers and streams, which comprise nonpoint and point sources, (3) atmospheric deposition, and (4) upwelling from the ocean's interior. The latter two are either mostly natural (oceanic input) or primarily driven by factors that operate beyond the control of a water quality manager (atmospheric deposition). The first two are more readily regulated, but managers need scientific data to determine whether these sources are large enough that their reduction will lead to meaningful change in the relevant carbonate system parameters. To make that assessment, managers would benefit from coupled physical-biogeochemical models, described above, that are validated by monitoring data to a known level of skill. Such models are still in early stages of development (Borges and Gypens, 2010).

LIVING MARINE RESOURCE MANAGERS

Local, state, provincial, and federal living marine resource managers—encompassing fisheries, habitat, and protected area managers—make day-to-day management decisions that balance the conservation of marine resources with human use and recreation. Management processes or decisions often incorporate, or have subsequent implications for, multiple jurisdictions, recognizing that the living marine resources often span governance boundaries. For this group of managers, the immediate challenge is to incorporate scientific understanding of the impacts of OA into existing decision processes, rather than to directly regulate OA parameters. Compared to other management arenas, the broad mandates of most living marine resource managers provide less guidance to those charged with making resource decisions in the face of OA. In general, matching the spatial and temporal scales of OA scientific understanding to the scales of management decisions and jurisdictions is a first-order need. More specifically, three types of decisions made by living resource managers highlight current science gaps and approaches that can provide new knowledge to effectively inform decisions: fisheries harvest, ecosystem conservation and management, and habitat creation and restoration.

Fisheries Harvest

Within most jurisdictions, the largest number of decisions are related to setting levels of allowable extraction, for example, deciding how much and what kinds of fishes, invertebrates, or plants may be harvested through adjustments to harvest season length, size limits, trip and/or bag limits, and bycatch limits. Such decisions are typically made with consideration of biological parameters that form the basis of stock assessments, together with knowledge of socioeconomic impacts and implications for the day-to-day management of the fishery. Given the hundreds of species currently harvested (commercially, recreationally, or for cultural uses) along the North American west coast, a deeper scientific understanding of the relative vulnerability of individual fisheries to OA can inform the first step of fisheries management decision making: prioritizing fisheries for regulatory and management action. Research that deepens our understanding of individual and population impacts and vulnerabilities, and that can be expressed in a spatially explicit form, can be fed directly into existing vulnerability assessment models. For example, OA is a key determinant of species rank in NOAA's developing Fisheries Vulnerability Assessment process. For prioritized fisheries, increased scientific understanding of the effects of OA on individual and population parameters, such as growth rates or fecundity, can provide greater confidence in stock assessment results—the scientific basis of most regulatory decisions. Moreover, as fisheries managers grapple with uncertain socioeconomic impacts of alternative management scenarios, coupled physical and ecological monitoring programs that link changes in ocean chemistry with ecological and economic effects, and that feed into adaptive management processes, are needed.

Legislative mandates over the last decade, including the Magnuson-Stevens Act and the California Marine Life Management Act, embed ecosystem approaches in the development of fishery management frameworks and regulations. These mandates have broadened the range of information considered in making ecosystem-based fishery management decisions (Pacific Fishery Management Council, 2013). In most cases, decisions are still based primarily on traditional stock assessment models, which often tie future harvest regulations to past ocean conditions, but these broad mandates create the window to integrate OA into the decision matrix. For example, a deeper understanding of the spatial variability of vulnerability, at individual and population levels, can guide decisions about how to define a stock for purposes of developing harvest control rules. Similarly, assessments of species impacts could be fed into food web models that modify the effects of harvest scenarios. Moreover, the ecosystem context of existing mandates has instigated the development of new coupled modeling approaches that link environmental variation with ecosystem effects (Levin et al., 2009; Griffith et al., 2012). Continued modeling efforts to understand the sensitivity of fisheries to OA, to project impacts expressed in social and economic terms, and to understand the extent to which adaptive capacity enables these potential impacts to be offset have been identified as science needs to effectively design fishery management approaches under acidified conditions (Pacific Fishery Management Council, 2013).

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Ecosystem Conservation and Management

Spatial area management has long complemented resource-specific actions along the West Coast. Historically designated to protect a specific habitat, species, or place, protected areas now exist throughout the region as scientifically designed networks with broad ecosystem and biodiversity protection goals. Managers charged with meeting these broad goals seek scientific knowledge to inform decisions about where to site protected areas, how to manage activities (such as recreational access, educational use, or fishing) within protected areas, and how and what to monitor to evaluate progress towards legal and policy goals. Indeed, monitoring is regularly articulated as a key science need that can, for example, provide the information required to make or adjust protected area siting decisions, or adjust allowed activities within a protected area on the basis of progress toward accomplishing ecosystem protection goals.

Siting protected areas or, more importantly, refining management goals for existing protected areas, will depend on having a better understanding of which locales are most and least susceptible to future changes in OA exposure. Achieving this understanding is a logical extension of the coupled physical-biogeochemical models. However, application of those models to protected area management raises an additional scientific need: should protected areas serve as refugia from OA or serve as sources for physiologically tolerant populations (e.g., Hofmann et al., 2014)? What size scales are needed? The answers to these questions can be pursued through coupled experimental and monitoring programs. Indeed, protected areas will serve as experimental designs where research can identify and quantify the ecosystem impacts of OA and begin to distinguish among stressors as well as the effectiveness of different management scenarios.

Habitat Creation and Restoration

Whether charged with creating new habitat under an artificial reef program, restoring estuarine habitats within an ecosystem mitigation program, or planting kelp to create new habitat, "active" habitat conservation and management typically fall under the purview of state or federal natural resource agencies and departments. On the surface, the decisions made mirror those for the categories above—designing management intervention (e.g., where to site an artificial reef for population replenishment goals), developing a management plan (e.g., building a boardwalk to limit seagrass trampling in a restoration zone), and implementing a monitoring and evaluation program. Science that tests management scenarios in light of OA, and evaluates actions post-hoc, can significantly inform these decisions. This category of decision making also highlights some of the most scientifically controversial and uncertain topics within the current OA dialogue. There has been significant discussion about the potential of seagrasses, kelps, and other plants to serve as "blue carbon"—actively mitigating the effects of greenhouse gas emissions through carbon uptake—but the effectiveness of such actions to affect local OA conditions in light of larger-scale influences is poorly understood. Coupled mechanistic physical-biogeochemical models (i.e., models that examine the individual parts or processes and how they interact in order to understand the complex system) that can quantify the effects of local actions in the context of global processes and identify areas where local influences on biogeochemical processes warrant investment could provide the science needed to move past the current seeming impasse. Such modeling will also provide the information necessary to discern which restoration or mitigation measures are most effective at reducing OA stress, given a particular set of local circumstances.

COASTAL ZONE LAND MANAGERS

Land managers consist of federal, state/provincial, and local jurisdictions that have regulatory control over siting of new development, local land-use zoning changes, and approval of restoration and mitigation plans within the coastal zone. Generally, regulatory approval for modification of coastal zone land use is granted if alternative locations are infeasible or more environmentally damaging, and adverse environmental effects are mitigated to the maximum extent feasible. Land managers need to know whether the siting of new, or the expansion of existing, developments or operations will affect or be affected by OA. They also need to determine what mitigation or restoration measures should be required as conditions to issuing permits as well as what monitoring should be required.

Coastal zone land managers would benefit from improved understanding of (1) the coastal locations that are the most susceptible to OA as a threat to coastal-dependent uses, (2) the extent to which land use changes contribute to OA in the adjacent coastal ecosystem, and (3) cost-effective restoration or mitigation measures that can reduce OA effects.

Decisions on siting, quantifying the effects of land use changes, and identifying cost-effective restoration and mitigation measures require much of the same information required by water quality and living marine resource managers: (1) improved monitoring to provide spatially detailed understanding of carbonate system status and trends over time, and (2) coupled physical-biogeochemical models to forecast OA changes associated with land use changes and coastal development.

Maps of current and future OA hotspots (e.g., Gruber et al., 2012, and Bednaršek et al., 2014, but on smaller scales) would assist land use managers in making decisions regarding the siting and investments in restoration. Coupled physical-biogeochemical models have the potential to fill gaps in OA monitoring data and provide forecasts of corrosive conditions. The utility of models lies not only in prediction of hotspots but also in scenario analyses. Models can be used in alternatives analyses for siting and/or expansion, and permit conditions requiring mitigation can quantify how the planned use influences OA at the local scale. Discharges from coastal facilities (e.g., power plant cooling water or brine from desalination facilities) can be included in these models to assess their potential impacts on OA.

BOX 1. Example of OA Being Used to Inform Coastal Zone Land Management in California

The California Coastal Commission (CCC) oversees development within the state's coastal zone and enforcement of the Coastal Act. Among other regulations, the Coastal Act requires that new developments should not violate provisions of the Federal Clean Water and Clean Air Acts, as well as other local and federal statutes. In 2007, the CCC finalized a decision that construction of a BHP Billiton liquefied natural gas terminal, which was to be sited offshore in federal southern California waters, with offloading facilities in Ventura County, was not consistent with the Coastal Act and thus could not be constructed. The decision was based primarily on concerns regarding air emissions. In particular, CCC staff found that the facility would have significant adverse effects on coastal resources through its emission of air pollutants (specifically NO_x and reactive organic compounds—precursors to ozone) in excess of public health thresholds, and its emission of greenhouse gases that would result in adverse effects to coastal resources, including OA (California Coastal Commission, 2007).

New coastal developments adjacent to or within environmentally sensitive habitat areas (including but not limited to wetlands, estuaries, and seagrass beds) might impair the restorative effects these areas might have on OA. Restoration of wetlands and seagrass habitats have been suggested as mitigation for development elsewhere along the coast; however, their mitigatory effects need to be better documented (Hendriks et al., 2014).

AIR QUALITY MANAGERS

Air quality managers include federal and state/provincial managers who have regulatory control over the quantity and siting of air emissions. Anthropogenic air emissions generally are grouped into four source categories: point sources, on-road and non-road mobile sources, area sources, and biogenic sources. Anthropogenic emissions are controlled through a combination of air pollutant emission standards, mandates for fuel efficiency, and requirements for replacing fossil-fuel combustion with clean, renewable energy sources.

Federal regulatory authority over CO_2 emissions is the major management lever that can be wielded to combat climate change, and OA in particular. The US EPA made a determination that six well-mixed greenhouse gases (GHG), including CO_2, constitute a threat to public health and welfare (US EPA, 2014), paving the way for regulatory initiatives to control CO_2. These initiatives include standards to reduce GHG emissions from new motor vehicles and engines, expansion targets for renewable fuels, carbon pollution standards for power plants, landfill and oil and gas emission standards, and emissions reporting. Canadian regulatory initiatives mirror those of the United States (Environment Canada, 2014).

California, in particular, has taken the lead nationally in advancing requirements, strategies, and incentives. Assembly Bill 32 (California State Assembly, 2006) mandates GHG reductions, to be accomplished through direct regulations, alternative compliance mechanisms, monetary and non-monetary incentives, voluntary actions, and market-based mechanisms such as a cap-and-trade system. One justification for the US EPA allowing California to control its own CO_2 emissions was evidence that local emissions of CO_2 may lead to local increases in ozone in polluted cities where ozone levels are already high (Jacobson, 2010).

The extent to which local emissions affect local coastal OA is presently uncertain. Thus, the quantity and siting of air emissions are not presently informed by the potential for localized OA impacts. Models with fine spatial and temporal scales would allow managers to investigate the utility of reducing local sulfur, nitrogen, and chlorine emissions (Doney et al., 2007) in order to control coastal OA locally (Jacobson, 2005)2005. While models such as the Community Multi-scale Air Quality Model (CMAQ; Eder and Yu, 2006) exist for this sort of application, models would need to be tuned to finer scales applicable for local emissions source assessment, and direct measures of air deposition data at similarly fine scales would be needed to validate model predictions.

USERS OF MARINE RESOURCES

This paper focuses largely on the decisions and information needs of the government sector, but commercial enterprises must also make decisions about use that can be greatly impacted by changing ocean chemistry. Primary OA information needs of some user groups, such as commercial fishermen, may be met, or at least prescribed, by regulatory agencies. Others, however, have specific operational needs that are independent of those required by regulatory mandates; these include water intake for aquaculture facilities, marine research labs, public aquaria, and other operators of coastal dependent uses (power plants and desalination plants). These user groups are place-based, often requiring substantial investments in land acquisitions and the infrastructure to support them, and are vulnerable to OA because their operations are not mobile. An example of this vulnerability is evidenced by the shellfish industry. Only a handful of oyster hatcheries, such as Whiskey Creek Hatchery Inc. and Taylor Shellfish Inc., supply the majority of US West Coast oyster farmers with "seed." These hatcheries have experienced massive oyster larvae mortalities linked to low pH water. Similarly, British Columbia-based Island Scallops has seen a dramatic rise in scallop mortality coincident with decreasing pH levels in waters of Qualicum Bay where its operations are located (Haluschak, 2014). A Washington-based hatchery has moved some of its operations to the Big Island of Hawai'i to reduce economic losses associated with OA exposure. However, grow-out operations generally do not have this flexibility; many commercial farms in the Pacific Northwest have experienced 80–90 % mortality in their oyster and scallop crops over the past several years, pushing these businesses to the brink of failure (Welch, 2013).

Collectively, these industry groups have two main requirements to make them sustainable: (1) tools that detect water quality problems and allow them to optimize operations or business practices in order to mitigate the effects of OA, and (2) modeling tools that allow them to site facilities in areas least vulnerable to OA. A third requirement, directed specifically at aquaculture facilities, is the need for seed stock (native and cultivated shell and finfish populations) with enhanced tolerance to OA.

One principal challenge to the users is that corrosive waters may periodically reach intake pipes, or encroach upon aquaculture grow-out facilities located in the intertidal or subtidal zones (Barton et al., 2012). Carbonate chemistry can be highly variable, including pH and aragonite saturation state, with a large range occurring over the course of a tidal cycle (Hofmann et al., 2011; Barton et al., 2012). Thus, procedures must be put in place to react on short notice should such an event occur. To address this challenge in the long term, managers need tools to move from a reactive, crisis response to proactive management of water quality in their facilities. To accomplish this level of management, four scientific components are needed: (1) real-time monitoring data on water quality reaching their facilities, (2) guidance on indicators and thresholds that should trigger adaptive action, (3) validated models that can provide short-term forecasts (one to two weeks) of corrosive conditions, and (4) science supporting evaluation of cost-effective mitigation measures.

Progress is being made on monitoring and modeling in Washington's Puget Sound, where shellfisheries are a primary source of coastal monitoring data, and models are under development that directly apply to shellfish growers and hatcheries (http://coenv.washington.edu/research/major-initiatives/ocean-acidification. A major challenge is that model spatial scales must be fine enough to be informative at the scale of the facilities (~100 m), and the temporal scale must be hourly to daily in order to capture extremes caused by semidiurnal and diurnal variability. Although the short temporal scales are currently considered in many hydrodynamic models, the required fine spatial scales are technically challenging. Models ultimately have the potential to improve long-term planning and investment strategies by identifying coastal stretches that are least susceptible to OA. This type of vulnerability mapping is similar to that needed by living marine resource and land-use managers.

DISCUSSION

Although the different types of coastal resource managers and users have a wide array of responsibilities and make diverse decisions, they have common needs regarding the kinds of scientific tools and information that would assist them in integrating OA considerations into their actions (Table 2):

1. A comprehensive monitoring program could allow resource managers to better understand spatial and temporal patterns in OA. Management decisions require understanding patterns that occur in the nearshore and how land-based activities potentially influence them. OA monitoring needs to be of sufficient temporal length to assess trends and variables relevant to organisms, a measure that is often lacking in nearshore waters and further complicated by sensor limitations (Hofmann et al., 2011; McLaughlin et al., 2015, in this issue).

2. Coastal, mechanistic, process-based models that operate at small spatial and temporal scales would help many managers assess whether a proposed action will have the desired effect and, importantly, whether local actions will be substantial enough, in the context of what is largely an international atmospheric-driven phenomenon, to warrant local investment. Mechanistic models that

TABLE 2. Classes of managers and users of coastal resources and the monitoring and models needed to consider ocean acidification (OA) in their decision making. Example uses of information obtained from monitoring and models is also provided.

Managers / Users	Monitoring	Models	Example uses of information obtained from monitoring and models
Water quality managers	Water chemistry in the nearshore: pH, Ω, other carbonate-system parameters	Coupled physical-biochemical models that consider land-based discharges (water chemistry parameters as dependent variables)	Identify trends in OA parameters and elucidate information on deviation from baseline conditions; identify OA hotspots; determine how land-based discharges affect local OA conditions to inform management decisions
Living marine resource managers	Water chemistry in nearshore, reserve, and offshore regions; biomass of key estuarine and coastal biota; ecosystem health indicators	Coupled physical-biochemical and population models (biotic populations as dependent variables)	Identify trends in OA and living resource populations to inform placement of reserves or catch limits; project OA effects on biota and ecosystem health for proactive management
Land managers	Water chemistry adjacent to shoreline	Coupled physical-biochemical models that consider land-based discharges as well as potential mitigation efforts (water chemistry parameters as dependent variables)	Identify trends in OA and OA hotspots for siting of coastal-dependent facilities and reserves adversely affected by or capable of affecting (negatively or positively) nearshore OA; project effects of siting decisions and restoration efforts on nearshore OA
Users	Water chemistry near regions affecting their coastal water intakes	Coupled physical-biochemical models operating at spatial scale of intakes (water chemistry parameters as dependent variables; some may require specific species populations as dependent parameters)	Proactively identify time periods and locations when low pH waters might affect quality of intakes and operations based on real time monitoring as well as models
Air quality managers	Water chemistry	Coupled physical-biochemical coastal models that consider inputs from local atmospheric deposition at fine spatial scales (water chemistry parameters as dependent variables)	Determine whether changes to local emissions will have a positive influence on local OA to inform decision making

allow a manager to visualize carbonate chemistry outcomes with and without changes in management actions will be particularly useful. Monitoring data are essential for parameterizing and validating model skill, and until these models are evaluated, trust in these tools will be limited. Modeling efforts are underway in some regions, but more experimental, microcosm, and field observations will be needed to fully parameterize the models.

3. There is a need to predict which areas of the coast are most and least vulnerable to future changes in carbonate chemistry. This need is less about knowing how to limit the exposure that comes with global changes in CO_2, and more about how to adapt to it. Many decision makers are interested in understanding how quickly conditions will change and which areas are most/least vulnerable to those changes. This understanding would allow managers to better site facilities or protect vulnerable biological resources.

All of these science needs, including others described in this document, are achievable. Many are even presently advancing toward accomplishment. Regional working groups, such as the California Current Acidification Network and the US IOOS regional ocean observing systems, are developing principles for and early implementation of a coordinated regional monitoring effort, which will be further enhanced by growth in technology through efforts such as that of XPrize. Along the west coast of North America, the States of California and Washington are both investing in modeling efforts intended to assess the extent to which contributions from local nutrient sources are contributing to local acidification. These modeling efforts will take time and even further investment, as there are technical challenges in moving oceanographic models closer to shore, operating them on spatial and temporal scales relevant to nearshore processes and human activities, and coupling OA and other biogeochemistry within those models. In addition, the scientists building the models recognize their logical extension as tools to identify the relatively vulnerability of different areas of the coastal and inland waters and to link biogeochemical changes to marine ecosystem health.

Addressing these science needs requires funding, and one of the messages provided by managers and legislators alike is that they must weigh the urgency of this issue relative to other issues when making funding decisions (Cooley et al., 2015, in this issue). The challenge for the OA science community is appropriately communicating the urgency of the issue, even though the repercussions of inaction will be felt over a much longer time frame than most of the other environmental issues decision makers must consider. Part of that communication requires increased collaboration between physical scientists and social scientists to translate OA effects into societal impacts and place them into economic context.

This paper focuses on OA science needs within existing management frameworks, many of which were designed to address local issues and may not be the most appropriate frameworks for managing large-scale, global problems like OA. We hope that the science needs identified here, when met, will shed light on the appropriateness of current management frameworks. However, addressing OA and managing marine resources in the face of likely continuing acidifying conditions requires a portfolio of management approaches to augment the options available today. In particular, natural resource managers are increasingly adopting ecosystem-based management principles, broadening management focus to consideration of species in an ecosystem context. Decisions that enhance ecosystem resilience also offer a path forward. The scientific community has an important role to play in helping to develop and test these new approaches.

While this paper identifies numerous science needs, managers already have some information that can be used to address OA. The issue is primarily one concerning the level of acceptable scientific certainty that managers require, and it highlights the need for good and continuing communication between the scientific and management communities. OA science is evolving rapidly, but the scientific questions managers are asking require establishing monitoring networks and developing extensive, interdisciplinary models, both of which will take time to achieve. Moreover, scientific advances are incremental and scientists are often hesitant to communicate their results until they have high certainty, whereas managers often want the most current information, even if it is uncertain, as long as the certainty level is also communicated. Establishing mutual understanding of these expectations will yield improved collaborations into the future. For the West Coast, groups like the West Coast Ocean Acidification and Hypoxia Science Panel provide an appropriate forum for scientists to develop consensus in communicating the state of the science, and the uncertainties that remain, to the management community.

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AUTHORS. Alexandria B. Boehm (aboehm@stanford.edu) is Associate Professor, Environmental and Water Studies, Civil and Environmental Engineering, Stanford University, Stanford, CA, USA, and a member of the West Coast Ocean Acidification and Hypoxia Science Panel. **Mark Z. Jacobson** is Professor, Environmental and Water Studies, Civil and Environmental Engineering, Stanford University, Stanford, CA, USA. **Michael J. O'Donnell** is Senior Scientist, California Ocean Science Trust, Oakland, CA, USA. **Martha Sutula** is Head, Biochemistry Department, Southern California Coastal Water Research Project, Costa Mesa, CA, USA, and a member of the West Coast Ocean Acidification and Hypoxia Science Panel. **Waldo Wakefield** is Habitat Team Leader, Fishery Resource Analysis and Monitoring Division, Northwest Fisheries Science Center, National Marine Fisheries Service, National Oceanic and Atmospheric Administration, Newport, OR, USA, and a member of the West Coast Ocean Acidification and Hypoxia Science Panel. **Stephen B. Weisberg** is Executive Director, Southern California Coastal Water Research Project, Costa Mesa, CA, USA, and a member of the West Coast Ocean Acidification and Hypoxia Science Panel. **Elizabeth Whiteman** is Program Director, California Ocean Science Trust, Oakland, CA, USA, and a member of the West Coast Ocean Acidification and Hypoxia Science Panel.

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