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Ocean Acidification 2.0: Managing our Changing Coastal Ocean Chemistry

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Ocean acidification (OA) is rapidly emerging as a significant problem for organisms, ecosystems, and human societies. Globally, addressing OA and its impacts requires international agreements to reduce rising atmospheric carbon dioxide concentrations. However, the complex suite of drivers of changing carbonate chemistry in coastal environments also requires regional policy analysis, mitigation, and adaptation responses. In order to fundamentally address the threat of OA, environmental managers need to know where, when, and by how much changes in coastal ocean carbonate chemistry will influence human livelihoods and what they can reasonably do about these effects. Here, we synthesize available biogeochemical and ecological information on the problem of coastal acidification and review actions managers have undertaken thus far. We then describe nine opportunities ripe for decisionmakers to mitigate—and, where necessary, to adapt to—ocean acidification at the spatial scales relevant to their authority.

Keywords: coastal ecosystems, adaptation, monitoring and mapping, marine biology, policy and ethics

Ocean acidification (OA) is rapidly emerging as a significant problem for organisms, ecosystems, and human societies. The contemporary rates of anthropogenic carbon dioxide (CO_2)–induced chemical changes in the oceans are 100 times greater than those during the last glacial termination (Friedrich et al. 2012), and both open-ocean and coastal upwelling waters have lower pH now than they did in the preindustrial age (Orr et al. 2005, Feely et al. 2008). This global reduction of oceanic pH may be harmful to organisms dependent on calcium carbonate for shell formation—such as corals, calcareous phytoplankton, shellfish, and urchins—because the additional carbonic acid in the ocean shifts the chemical equilibrium of the carbonate system, increasing the bicarbonate ion concentration and decreasing the carbonate ion concentration. Most vulnerable are calcium carbonate shell– and skeleton–building organisms, such as economically, ecologically, and culturally important shellfish species and reef-forming corals (Kroeker et al. 2010, Branch et al. 2013).

Carbonate system equilibria in coastal waters are affected by multiple human activities operating at various spatial scales. Coastal pH variability is greater than open-ocean pH variability, and human activities can sometimes lead to a greater degree of acidification in the coastal zone than in the open ocean, causing regionally or locally enhanced coastal acidification (e.g., Cai et al. 2011). At least some organisms are already experiencing negative effects from anthropogenically altered carbonate chemistry in coastal waters (Barton et al. 2012). Managing such changes will not be simple. Not only is there a spectrum of anthropogenic perturbations of the pH in coastal waters (Duarte et al. 2013), but there are also many overlapping jurisdictional authorities that regulate human activities in the coastal zone (Kelly RP et al. 2011). Nonetheless, discussions about how to manage the threat of OA have recently begun in many jurisdictions, and several US states have started to implement management strategies to combat the regional-scale causes and effects of changing carbonate chemistry in the coastal zone. As national and regional OA governance emerges, linking our rapidly evolving scientific knowledge about the causes and impacts of the problem with current and potential management actions is imperative.

In this Overview, we present the latest biogeochemical and ecological science informing the management of OA in the coastal zone. The science of OA in coastal areas is continuing to develop, and any actions to mitigate the change in pH will require adaptive management of multiple stressors, simultaneously and on several spatial scales. Here, we link this rapidly accumulating, detailed knowledge about the dynamic drivers and biological impacts of enhanced coastal acidification with a review of what is being done about it. In light of this information, we highlight nine significant

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management opportunities for action to address changes in coastal ocean pH moving forward.

Drivers of enhanced coastal acidification

Fundamentally, environmental managers need to know where, when, and by how much changes in coastal ocean carbonate chemistry will influence human livelihoods and the coastal ecosystems on which they depend in the near and long term and what they can reasonably do about it. Obtaining this information requires understanding the human activities that drive changes in coastal ocean carbon chemistry and pH, the biological and oceanographic factors that affect the variability of coastal pH and that can attenuate or exacerbate anthropogenically driven changes, and how these changes will affect the ocean resources that fuel coastal livelihoods. As the scientific understanding of coastal pH and carbonate system dynamics continues to advance, resource managers will be able to make increasingly informed decisions about mitigation and adaptation strategies in the social–ecological systems in which they operate.

In order to begin answering the fundamental questions about coastal acidification faced by managers, we find it helpful to describe the OA problem in terms of direct and indirect mechanisms by which human actions influence the coastal ocean carbonate system (table 1a, 1b). *Direct mechanisms* refers to changes driven by anthropogenic emissions. These mechanisms include the absorption of anthropogenic CO_2 by seawater and the direct chemical discharge or deposition of other acid-forming chemicals that lower pH in the coastal ocean. Although direct acid deposition from sulfur dioxide and nitrogen oxide emissions (i.e., acid rain) may have effects on ocean surface pH, recent work has suggested that these effects are likely to be relatively minimal and short-lived (on the order of months) because of the buffering capacity of the surface ocean (Hunter et al. 2011).

Globally, the phenomenon of OA is driven by anthropogenic CO_2 emissions, but in the near-shore areas where the effects of OA may be most significant for human communities, indirect anthropogenic mechanisms can strongly influence coastal pH and carbonate chemistry (Duarte et al. 2013) and, therefore, merit the attention of environmental managers. Some human activities can influence the dynamics of naturally occurring biological and oceanographic processes that control coastal ocean pH; CO_2 concentrations; and, ultimately, the saturation state of the shell- and skeleton-forming mineral aragonite, thereby acting as indirect drivers of coastal pH variability. Agriculture, water management, and energy use can often modulate the rates of naturally occurring processes affecting the partial pressure of CO_2 (pCO_2), pH, and the aragonite saturation state of coastal waters. Although the variability in the coastal ocean carbonate system is only partially controlled by anthropogenic mechanisms (Duarte et al. 2013), local and state decisionmakers are in a position to make policy and management decisions that respond to—and that, in some cases, could influence—the trajectory of coastal OA (Kelly RP et al. 2011).

We describe two salient mechanisms by which human activities can indirectly influence coastal carbonate chemistry at a local-to-regional scale. They include (1) eutrophication, through which excess anthropogenic nutrients create coastal phytoplankton blooms, which, in turn, when they have decomposed, lead to a local increase in CO_2 concentrations, and (2) changes in the amount or chemistry of riverine runoff that affect coastal carbonate chemistry, which can be affected by land use, water system management, and anthropogenic climate change. A third mechanism can also have strong local effects on coastal pH and forms the context for adaptive responses to OA: (3) Coastal upwelling can create hotspots of coastal pH change because of naturally high levels of CO_2 coupled with the increased anthropogenic CO_2 content of these waters. In some regions, an increase in the intensity of upwelling, which amplifies the effects on pH, is associated with anthropogenic climate change (table 1a, 1b).

Eutrophication. Because many coastal waters are nitrogen limited, anthropogenic nitrogen pollution from agricultural fertilizer runoff, wastewater, and atmospheric deposition from automobile tailpipe emissions is a cause of eutrophication in coastal waters around the world (Howarth et al. 2012). When light and temperature conditions are sufficient, eutrophication causes a temporary drawdown of CO_2 concentrations at the surface because of the intense biological productivity of the associated algal bloom (Borges and Gypens 2010). However, eutrophication ultimately lowers pH, because it provides conditions for greater heterotrophic respiration rates (i.e., decomposition, also referred to as *remineralization*) by organisms such as bacteria. This respiration process oxidizes organic matter, draws down local oxygen levels, releases CO_2, and—in extreme cases—can lead to hypoxic dead zones. The location of the pH change associated with anthropogenic eutrophication is a function of where organic matter is respired. In many shallow coastal shelf systems, this acidification occurs at or near the bottom sediments, where organic matter is oxidized (Waldbusser et al. 2010, Sunda and Cai 2012).

Globally, ongoing research has identified several areas of excess acidification caused by anthropogenic eutrophication. These include the East China Sea and the Gulf of Mexico (Cai et al. 2011), the Baltic Sea (Sunda and Cai 2012), and some of the coastal seas around the North Sea (Provoost et al. 2010). Recent low-pH events that may be partly attributable to eutrophication have also been observed in productive coastal estuaries, including Puget Sound (Feely et al. 2010) and the Chesapeake Bay (Waldbusser et al. 2011), although there are confounding factors in each system that may affect carbonate chemistry (e.g., the entrainment of coastal upwelled water and variable salinity regimes). Although each system is different, nitrogen inputs from agricultural fertilizer runoff, sewage, and atmospheric deposition (Howarth et al. 2012) can be a significant driver of enhanced coastal acidification, especially in hypoxic bottom waters (Sunda and Cai 2012). These local changes in pH can be substantial. For example, the measured seasonal rates of

Table 1a. Direct anthropogenic cause of enhanced coastal acidification and policy implications.

Mechanism	What happens	Effect on pH	Link to management	Sources
Atmospheric CO_2	Forms carbonic acid, which dissociates, resulting in increased ratio of bicarbonate to carbonate.	Decrease	Areas more vulnerable to ocean acidification, such as coastal, resource-dependent nations, will have greater incentive to push for an international accord to reduce atmospheric CO_2. Subnational policy options exist but have a limited role in mitigating global CO_2 emissions.	Orr et al. 2005, Doney et al. 2009
SO_X and NO_X; direct acid deposition	Deposited as sulfuric acid, dissociates in water; deposited as nitric acid, dissociates to NO_3^- and H^+.	Decrease, dependent on buffering and time frame	Short residence times tend to internalize incentives for action; the existing regulatory structure in United States under the Clean Air Act is one avenue to address this driver. The net effect on pH may be minimal.	Doney et al. 2007, Hunter et al. 2011

Abbreviations: CO_2, carbon dioxide; H^+, hydrogen ion; NO_3^-, nitrate; NO_x, nitrogen oxide; SO_x, sulfur oxide.

Table 1b. Indirect anthropogenic cause of enhanced coastal acidification and policy implications.

Mechanism	What happens	Effect on pH	Link to management	Sources
Anthropogenic nutrients	Runoff as NO_3^- and NH_4^+ from agricultural fertilizers, treatment works, urban areas, deposition from cars stimulates phytoplankton growth and decomposition, particularly in nitrogen-limited estuaries.	Decrease in deeper waters with eutrophication	Local jurisdictions have some ability to control these drivers. There are particularly strong incentives for action in regions where the driver (the source of nutrient pollution) and the harm (the effect on coastal livelihoods) are located within the same jurisdiction.	Borges and Gypens 2010, Feely et al. 2010, Cai et al. 2011, Waldbusser et al. 2011, Sunda and Cai 2012, Hu and Cai 2013
Freshwater delivery	Can increase or decrease carbonate ion concentrations. Generally lowers total alkalinity, reducing buffering capacity of coastal water to pH change.	Variable, can lower pH	Local jurisdictions may have some ability to control the driver; a spatially heterogeneous effect requires an area-by-area analysis to determine the likely impacts on coastal ecosystems.	Salisbury et al. 2008, Aufdenkampe et al. 2011
Upwelling	The duration and frequency of upwelling increase of low-pH waters with a high anthropogenic CO_2 content can lower the aragonite saturation state.	Decrease	Local jurisdictions do not have the ability to control the driver but can focus on adaptation to changing pH in upwelling hotspots; a spatially heterogeneous effect requires an area-by-area analysis to determine the likely impacts on coastal ecosystems.	Feely et al. 2008, Gruber et al. 2012

Abbreviations: CO_2, carbon dioxide; NH_4^+, ammonium; NO_3^-, nitrate.

pH change in the North Sea were an order of magnitude greater than those already induced by global CO_2 changes (Provoost et al. 2010).

Influences of freshwater delivery. Human land-use practices can strongly influence the carbonate chemistry of riverine waters, with consequent effects on the coastal ocean through changes in total freshwater delivery (which may be occurring because of anthropogenic climate change) or through human actions that alter the flux of calcium ions, bicarbonate ions, and carbonate ions in riverine waters transported to the coastal ocean (Aufdenkampe et al. 2011). Riverine dynamics can have both positive and negative effects on coastal ocean pH. For example, agricultural practices in the Mississippi River watershed have, over time, increased the total flux of carbonate alkalinity (bicarbonate and carbonate ions) from rivers to the ocean, resulting in a slight increase in the water aragonite saturation state (Aufdenkampe et al. 2011). In other regions, recent work has demonstrated the link between the coastal aragonite saturation state and the seasonal variability of terrestrial river runoff (Salisbury et al. 2008). In the Gulf of Maine, for example, evidence suggests that spring snow-melt waters with relatively lower carbonate ion concentrations reduced the aragonite saturation state of coastal waters, which resulted in a potential threat to the commercially and culturally important soft-shell clam (Salisbury et al. 2008).

In the Bering Sea, both freshwater delivery from the Yukon River and respiration of phytoplankton biomass have been shown to drive lower saturation states in bottom waters, an area that already has naturally low aragonite saturation (Mathis et al. 2011). The effects of melting glaciers can also affect coastal carbonate chemistry: Tidewater glacial melt in Prince William Sound has been linked with an undersaturation of aragonite due to the delivery of water with low total alkalinity, which reduces the aragonite saturation state (Evans et al. 2014). Shifts in pH due to riverine inputs are likely to be greatest wherever coastal systems are heavily influenced by river hydrography and wherever rivers deliver low-alkalinity water to the coastal system. However, the effect of riverine inputs on coastal pH change can vary substantially, depending on coastal mixing, upwelling, and the salinity regime.

Coastal upwelling. Coastal upwelling is a wind-driven oceanographic process that brings relatively saltier, lower-pH, deep-ocean waters rich in CO_2, nitrate, and phosphate up to the surface, thereby providing the inorganic nutrients that fuel and sustain phytoplankton production in these regions (Feely et al. 2008). In the California Current system (CCS), for example, seasonal upwelling largely controls pH variability (Gruber et al. 2012). Although wind-driven upwelling occurs naturally, the frequency and duration of upwelling events has increased in the CCS over the last 30 years, at least in part because of climate change (Garcia-Reyes and Largier 2010). Stronger upwelling increases the delivery rate of high-CO_2 deep waters to the surface, thereby enhancing near-surface acidification, and models predict that this intensification is likely to continue with future ocean warming (Snyder et al. 2003).

In addition to the increase in upwelling intensity, the CO_2 content of upwelled waters is increasing because of anthropogenic emissions. Globally, the ocean has already absorbed between 20% and 35% of anthropogenic CO_2 emissions, which has been transported to the deep ocean by global circulation patterns (Sabine et al. 2004). Depending on the particular source waters, in some coastal regions, this anthropogenic CO_2 returns to the surface through upwelling (Feely et al. 2008), which may further exacerbate near-surface acidification. For example, regional-scale ecosystem–ocean circulation models show that the upper 60 meters of the CCS water column will become seasonally undersaturated with aragonite in the next 30 years because of the increased anthropogenic CO_2 content of upwelled waters in the CCS (Gruber et al. 2012). Recent observations off the northern California coast have shown that some upwelled waters are already undersaturated with aragonite and, therefore, corrosive to calcium carbonate shell–forming organisms (Feely et al. 2008). Accounting for the impact of upwelling is an essential component of current and future monitoring and attribution efforts, because changes in upwelling intensity have the potential to significantly amplify the effects of OA in the coastal zone.

Managing multiple drivers: Linking knowledge to action. Although pH variability in certain coastal systems may be most significantly modulated by either direct or indirect mechanisms, there are locations where both types of mechanisms exist simultaneously, driving hotspots of acidification. For example, Hu and Cai (2013) recently highlighted how high-CO_2 ocean water can mix with low-alkalinity riverine water in areas of high respiration of organic material to create hotspots of pH-change vulnerability in some estuaries (Hu and Cai 2013). Such hotspots represent particular challenges and opportunities for management responses. In figure 1, we highlight some of the mechanisms of change that are likely to be significant drivers in key regional areas around the United States.

Successful management of the threat of coastal acidification requires understanding the dynamics of eutrophication, upwelling, and changes in riverine runoff and their interactions. On the basis of the science described above, it is clear that comprehensive management responses to OA will require coordinated new and improved institutional frameworks, as well as specific management actions (see table 2). Enhanced data collection and monitoring, at varying spatial scales, will be crucial to the work of attributing observed changes in pH to these multiple stressors (see table 2).

Impacts of enhanced coastal acidification on species, ecosystems, and economies

Knowledge of coastal pH drivers and the dynamics of change holds tremendous value to fisheries and coastal resource managers in the context of seafood economies and relevant species population shifts due to pH change. There are numerous reviews of the ecological effects of OA (Doney et al. 2009, Kroeker et al. 2010, 2013); here, we briefly review emerging trends and focus on the latest research most salient to managers concerned about populations of species and to decisionmakers assessing the economic threat posed by OA.

Generally, species that build their shells or skeletons from calcium carbonate are highly vulnerable to OA; this vulnerability is attributable to increased energetic costs needed to maintain net calcification (Kroeker et al. 2010, 2013). In contrast, noncalcareous marine plants may benefit slightly from OA (Koch et al. 2013), and fish and other highly mobile species may suffer less-obvious effects, such as neurological changes that alter behavior (Nilsson et al. 2012). OA effects may also vary over the course of an organism's life span, with vulnerability most pronounced at specific growth phases (e.g., the larval stage for oysters; Waldbusser et al. 2011), although the effects incurred at one life stage may persist into other stages (Hettinger et al. 2012). Although some calcifying species may have mechanisms to upregulate their internal pH to resist OA (McCulloch et al. 2012), this may come at a metabolic cost to the organism (Melzner et al. 2011), especially in warming conditions (Dove et al. 2013). In short, some species may benefit from OA, but many commercially and culturally important species of shellfish and corals are likely to suffer significant negative outcomes.

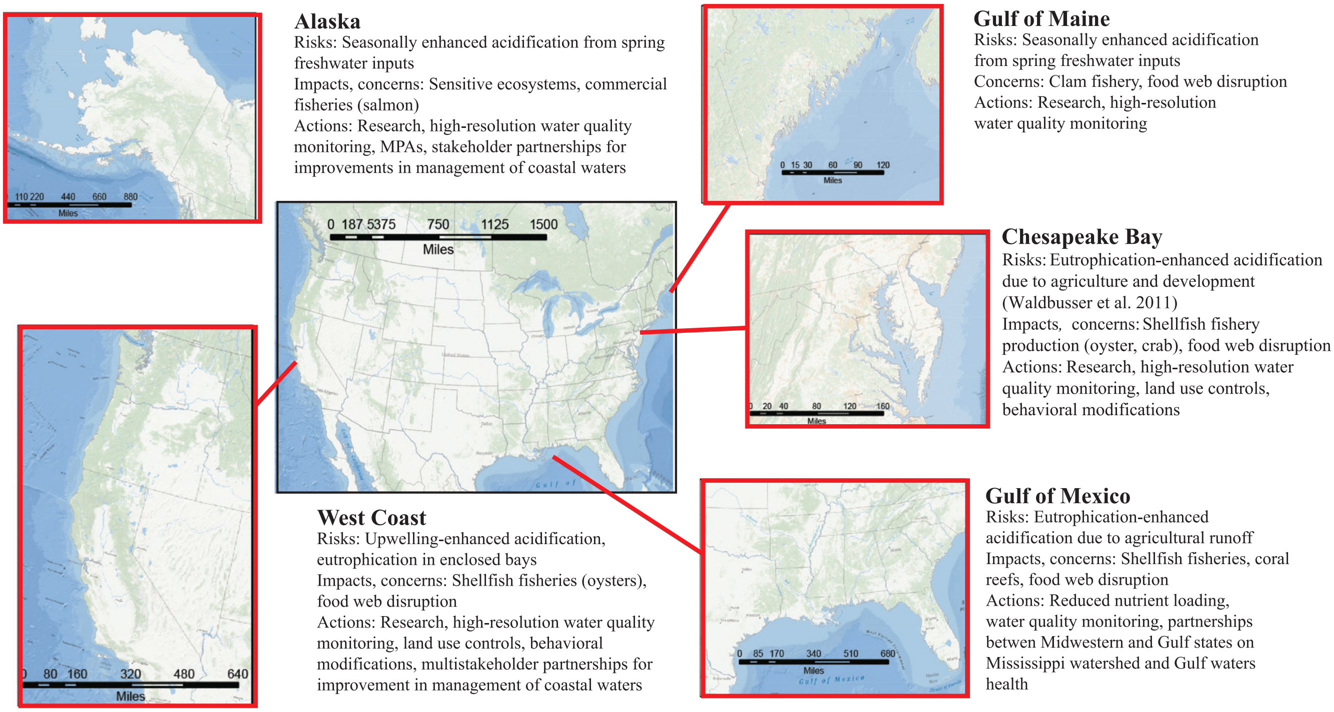

Figure 1. Some of the drivers and impacts of pH change in several potential hotspots of coastal acidification around the United States that have been highlighted in recent literature. Because of their varying geographic, ecological, and socioeconomic positions, different regions will experience acidification to different degrees. Abbreviation: MPA, marine protected area.

The potential for evolutionary adaptation. The potential for acclimatization and evolutionary adaptation in response to OA, as well as human actions that could promote adaptation, are important considerations for resource management. By necessity, most OA experiments have occurred over relatively short time frames and have not addressed the capacity for species to acclimatize or adapt to OA. Although evolution is often thought of as occurring over very long time frames, evolutionary changes over time frames relevant to present-day OA are possible and could substantially improve a species' performance under future pH change (Hoffmann and Sgrò 2011). However, OA is not happening in isolation, and it is still unclear whether species will be able to adapt to concurrent changes in multiple environmental factors.

Plasticity is a phenotypic response to environmental conditions, often caused by changes in gene expression within the same species. Recent evidence indicates that variations in individuals' responses to OA that are due to plasticity can be similar in magnitude to variation among entirely different species (Schaum et al. 2013). In a pertinent example involving phytoplankton, Schaum and colleagues (2013) found that the most plastic individuals originated from locations with highly variable environmental conditions, such as the variable pCO_2 conditions at the sea surface. Such results suggest that an entire species' response to OA cannot be predicted on the basis of a single population and that populations previously exposed to substantial variability in pCO_2 may be more capable of acclimatizing to future OA.

Evidence also suggests that some individuals may be better able to cope with OA because of underlying genetic differences. Parker and colleagues (2011) demonstrated that particular populations of the economically important Sydney rock oyster, *Saccostrea glomerata*, that were selectively bred for fast growth and disease resistance were less vulnerable to experimental acidification (Parker et al. 2011). A similar response has also been shown for bred lines of juvenile hard clams (Waldbusser et al. 2010), which highlights the potential for both natural and artificial selection for acidification-tolerant individuals. Furthermore, there is evidence that some wild populations of marine species, such as the purple sea urchin, *Strongylocentrotus purpuratus*, are better adapted to cope with OA than are others because of existing genetic differences (Kelly MW et al. 2013, Pespeni et al. 2013). Given the rate of OA, evolutionary adaptation for long-lived species is most likely to result from the selection of existing genetic variation than from novel genetic mutations. In contrast, adaptation from novel mutations is most likely to occur among short-lived species with rapid generation times (Sunday et al. 2011, Lohbeck et al. 2012).

These and other studies suggest that human activities that limit genetic diversity or create bottlenecks in populations—through overfishing, for example—might decrease the ability

Table 2. Nine opportunities for action: Developing coastal ocean acidification management strategies.

Ocean acidification (OA) management strategy	Institutional capacity	Financial investment required	Progress	Actors
(1) Set up initiatives in each coastal state to assess the threat of OA to ecosystem health and human livelihoods in state waters and evaluate strategies to mitigate local drivers.	Partial	Less than $1 million	Moderate	State agencies, science and policy NGOs, universities
(2) For regional OA issues, leverage existing interstate coalitions or form new interstate task forces to facilitate multistakeholder solutions.	Absent	$1 million to $5 million	Some	State agencies, advocacy or policy NGOs, universities
(3) Continue developing a coordinated regional network of monitoring stations to map the vulnerability of coastal areas to OA, extend monitoring to near-shore systems relevant to management jurisdictions, and determine easy-to-measure biological indicators as proxies for ecosystem health.	Adequate	More than $5 million	Some	State agencies, universities
(4) Launch public education programs around OA and its causes to foster public awareness and stakeholder engagement.	Adequate	Less than $1 million	Some	State agencies, community-building and science-education NGOs
(5) Coordinate domestic research and communication efforts with international programs to amplify attention to OA, increase international collaboration, and standardize global monitoring.	Partial	Less than $1 million	Moderate	State agencies, international science and policy NGOs, universities
(6) Integrate the threat of OA into existing and new climate change programs and state-level coastal programs under the Coastal Zone Management Act.	Partial	$1 million to $5 million	Some	State agencies
(7) Enforce existing regulatory measures to regulate water quality that affects enhanced coastal OA.	Absent	More than $5 million	None	State agencies, advocacy or policy NGOs
(8) Include the impact of permitting actions on OA when conducting environmental impact assessments under the National Environmental Policy Act or under state-level environmental policy acts, such as the California Environmental Quality Act.	Partial	Less than $1 million	None	State agencies, universities, industry
(9) Consider and incorporate information about marine genetic diversity within OA hotspots into marine protected area planning processes.	Partial	Less than $1 million	None	State agencies, universities, science and policy NGOs

Note: All of the relevant jurisdictions have full authority to address local OA as specified in the recommendation. The assessments are based on qualitative research of existing infrastructure and authority, the costs of corollary programs, and prior OA management assessments. The cost assessments reflect the costs of coordination and organizing, rather than full implementation of the findings. For example, coordinating a network to standardize global monitoring might cost less than $1 million dollars, but actually doing that monitoring would cost a different party much more than $1 million. *Abbreviations:* NGO, nongovernmental organization.

of some species to adapt to OA. Although small populations are often associated with low genetic diversity and, therefore, with limited evolutionary potential, locally adapted populations that naturally experience more acidic conditions or high natural variability in pCO_2 might also harbor important acidification-tolerant individuals with alleles crucial for the persistence of the species (Kelly MW et al. 2013). Locally adapted acidification-tolerant genotypes could then function as important reservoirs of evolutionary potential (see table 2).

Ecosystem-scale impacts. Because the majority of OA researchers have examined direct effects on single species, the consequences of OA on ecosystem functioning are less understood (Fabricius et al. 2011, Kroeker et al. 2011). Naturally acidified ecosystems, including CO_2 vents and high-pCO_2 upwelling zones, lend some insight into the emergent effects of OA. The few examples available suggest that OA could result in ecosystems with fewer calcareous species and an overall reduction in species diversity (Fabricius et al. 2011). Seaweeds are more abundant in these ecosystems, including rocky intertidal, rocky reef, and coral reef ecosystems, which indicates that there could be shifts toward algae-dominated ecosystems in an acidified ocean (Connell et al. 2013).

The careful management of local stressors, such as overfishing and eutrophication, could potentially improve species' and ecosystems' resilience to acidification-related phase shifts toward algae at a local scale (Falkenberg et al. 2013). However, some recent ecological research suggests opportunities for proactive management. For example, marine plants have been shown to play a potentially important role in creating OA refugia. The Florida Reef Tract is one example in which vast seagrass meadows may be attenuating OA experienced downstream in coral reef habitats (Manzello et al. 2012). Experiments in Papua New Guinea suggest that large tracts of seagrasses can sequester carbon, which reduces the concentration of CO_2 in ambient seawater (Russell et al. 2013). Such research findings can help inform adaptive management where OA is threatening species that have limited adaptive capacity (see table 2).

Socioeconomic impacts. The ecological effects of OA will have cascading impacts on human economic systems and ecosystem service provision (Branch et al. 2013). Quantifying and valuing the socioeconomic impacts of OA is an area of active research, and current estimates of the economic value of OA-induced losses are nonexistent for many regions. Below, we highlight some of what is known about the economic effects on fisheries and coral reef–based economies.

Although not economically quantified, ecosystem models suggest that declines in the abundance of calcareous species, including bivalves, snails, and sea urchins, could cause declines in groundfish species that derive a large proportion of their diet from shelled species (Kaplan et al. 2010). Nongroundfish fisheries may also be at risk: For example, adverse impacts on *pteropods* (pelagic marine snails) due to OA could affect juvenile pink salmon, whose diet is 60% pteropods (Comeau et al. 2012). Pink salmon, themselves, represent 68% of the $818 million annual North Pacific salmon fishery, which indicates a potentially significant economic impact of OA (Comeau et al. 2012).

Cooley and Doney (2009) highlighted a substantial risk of economic loss, on the order of hundreds of millions of dollars annually by 2060, due to OA's effects on mollusk shellfish fisheries in the United States (Cooley and Doney 2009). Globally, losses from declining mollusk production could exceed $100 billion by 2100 under scenarios of business-as-usual greenhouse gas emissions, with most of the impacts (and the uncertainty in production losses) occurring in China (Narita et al. 2012).

Beyond the economic risks to mollusk and groundfish fisheries, millions of people around the world depend on coral reefs for their livelihoods, and these ecosystems provide services worth billions of dollars annually. The predicted economic impacts of OA's harm to coral reefs have been estimated at $870 billion lost annually by 2100 under the Intergovernmental Panel on Climate Change's A1 emissions scenario (Brander et al. 2012).

These economic models highlight the potential for significant socioeconomic impacts due to OA in regions that are dependent on shellfish fisheries and coral reefs. The impacts are not demonstrated only within future projections. In 2008, the US Pacific Coast oyster industry, worth $84 million annually, saw harvests at one major supply site drop by 80% (NOAA 2011). OA has already begun to take its toll on oyster growth in Oregon, where researchers found that reduced aragonite saturation states limited successful oyster larval development in a coastal hatchery (Barton et al. 2012). These significant impacts highlight the need for accounting for the threat of OA into new and existing coastal management frameworks (see table 2).

Management responses to ocean acidification

The United Nations Framework Convention on Climate Change (UNFCCC) is the international treaty system under which protocols for limiting global greenhouse gas emissions, such as the Kyoto Protocol, are negotiated. Despite global attention to OA, the UNFCCC has not adopted any treaty instruments that directly address OA, nor has any other multilateral environmental agreement on OA been negotiated. Despite the lack of a multilateral action on OA, various international organizations have begun to organize around this issue. The International Oceanographic Commission, the Scientific Committee on Oceanic Research, and the International Geosphere–Biosphere Programme have cosponsored the triennial Symposium on the Oceans in a High-CO_2 World to initiate and coordinate the discussion of the OA problem, and the United Nations Open-Ended Informal Consultative Process on the Oceans and the Law of the Sea organized a high-level conference on the impacts of OA on the marine environment in 2013.

We now assess ongoing national-scale OA governance strategies, focusing specifically on the United States. (For a recent review of international governance responses and opportunities for action on global OA, see Billé et al. 2013.) In March 2009, the Federal Ocean Acidification Research and Monitoring (FOARAM) Act of 2009, which was introduced by State of Washington Representative Brian Baird and was cosponsored by representatives from Maine, Washington, Michigan, Massachusetts, and Guam, passed in Congress and was signed into law by President Obama. Among other actions designed to spur federal agency collaboration and research on the challenges of OA, the passage of the FOARAM Act created an Interagency Working Group on OA. In 2012, as a result of the Interagency Working Group's recommendations, the National Oceanic and Atmospheric Administration (NOAA) created its Ocean Acidification Program, organized around six core issues: monitoring carbonate chemistry changes, measuring biological impacts, assessing socioeconomic impacts, managing and coordinating OA data, coordinating education and outreach, and engaging directly in the process of developing adaptation strategies.

Several states have also initiated substantial efforts to address the problem of OA, including Alaska, Maine, Washington, California, and Oregon. In Alaska, the nongovernmental Alaska Marine Conservation Council reported on the risks of OA in several hotspot areas with important fisheries in the Gulf of Alaska and called for support for a state legislative budget request for the Ocean Acidification Research Center, which led to nearly $3 million for OA research in the 2013 budget (AMCC 2012). In Maine, local coastal advocacy organizations have initiated discussions about addressing OA, with an emphasis on reducing the nitrogen loading associated with enhanced coastal OA (Friends of Casco Bay 2012). In early 2013, the state legislature adopted a resolution officially recognizing OA as a threat to Maine's coastal economy and way of life, emphasizing the impacts of OA on the state's shellfish industry.

In 2012, Washington State established the Blue Ribbon Panel on Ocean Acidification in response to concerns about the vulnerability of oyster fisheries to OA (WSBRPOA 2012). This panel's recommendations led to legislation that both funded a center for OA research at the University of Washington and formed the Washington Marine Resources Advisory Council in the Office of the Governor, which is focused, in part, on OA.

For the state of California, in 2010, the Southern California Coastal Water Research Project convened the Ocean Acidification Impacts on Shellfish Workshop, which spawned the California Current Acidification Network (C-CAN). C-CAN is a consortium of scientific researchers and shellfish industry partners that explores the causes of and potential adaptive measures to shellfish losses on the US West Coast. C-CAN recently released a report outlining a set of core principles for monitoring near-shore acidification and its biological impacts (McLaughlin et al. 2013). In 2013, the California Ocean Science Trust—a scientific advisory group established by state law—launched the West Coast Ocean Acidification and Hypoxia Science Panel (in partnership with the state of Oregon and with collaborators representing Washington and British Columbia, as well), which is intended to advance decision-makers' understanding of OA and hypoxia by synthesizing the current state of the science, focused on the causes of, effects of, and potential solutions to the problem of OA along the Pacific Coast.

Governmental efforts have primarily been focused on how to encourage and foster adaptation to OA and monitor its effects, with the exception of Washington State's legislation, which addresses certain forms of coastal runoff that may drive coastal OA. Adaptation to OA is already occurring; shellfish growers have changed the timing of oyster larvae release in Puget Sound to minimize harmful low-pH effects (WSBRPOA 2012), and clam diggers have moved clam flats toward higher-pH areas and are closing those in low-pH areas in Maine (Koenig 2011).

Over the last 5 years, there has been a marked shift in the management conversation around OA in the United States. The discussion has evolved from initial reports presenting OA as a global problem with the same fundamental cause as climate change (i.e., the other-CO_2-problem paradigm) to local and regional conversations about mitigation and adaptation solutions involving single-estuary-based conservation organizations, stormwater managers, shellfish producers, and other state and local officials.

R. P. Kelly and colleagues (2011) highlighted opportunities within current legal frameworks to incorporate OA at the local scale. However, much of what is being done—and much of what can be done—to adapt to and manage enhanced coastal OA and its drivers involves opportunities for action across many and varied contexts of governance, including comanagement, scientific monitoring, education, and outreach. It is the collective efforts within all these contexts that will ultimately determine the effectiveness of coastal OA governance.

Below and summarized in table 2, on the basis of the scientific literature described above, we highlight nine significant opportunities for the development of further management strategies in the context of increasing state and local action on OA.

(1) Set up initiatives in each coastal state to assess the threat of OA to ecosystem health and human livelihoods in state waters and to evaluate strategies to mitigate local drivers. Building on the success of the Washington State Blue Ribbon Panel and its role in spurring the West Coast Ocean Acidification and Hypoxia Science Panel, all coastal states can convene relevant stakeholders to assess and plan for OA impacts and to examine opportunities for mitigating the direct and indirect OA drivers within their coastal waters. The assessments can evaluate the local nature of coastal OA, contextualizing the effects of eutrophication, upwelling, and changes in riverine discharge, as well as the biological impacts of acidification. Initiatives can be led by state government executive agencies in partnership with science and policy nongovernmental organization (NGO) coalitions, as was the case in Washington State.

(2) Leverage existing interstate coalitions or create new interstate task forces to facilitate strategic interactions in the context of regional OA issues. Building on the example of California and Oregon's joint initiative on OA and hypoxia in the CCS, other sets of states facing regional-scale OA drivers or regional impacts (such as shellfish declines) could either form new interstate partnerships or build on interstate marine collaborative efforts that are already in place. Organizations ripe for integrating OA into their agendas might include the Gulf of Maine Council on the Marine Environment, the West Coast Governors Alliance on Ocean Health, the Gulf of Mexico Alliance, the Governors South Atlantic Alliance, and the Northeast Regional Ocean Council. Each of these institutions strives to create policy solutions for a breadth of marine health issues, but none has yet addressed OA, although the threat of OA explicitly falls within the purview of their stated objectives. Regional NGO coalitions may also be in a position to spur such actions. For example, the New England Ocean Action Network is a partnership among 17 different regional and national NGO, industry, university, and ocean-user representatives that supports the development of comprehensive regional ocean planning.

(3) Continue developing a coordinated network of monitoring stations to map the vulnerability of coastal areas to OA and to extend monitoring to near-shore systems relevant to management jurisdictions. Extensive spatial and temporal monitoring to establish baselines in coastal pH variability and to identify hotspots of biogeochemical stressors directly informs appropriate management actions and policy trade-offs. Long-term monitoring systems, such as those being deployed in the CCS, the Pacific Northwest, the Gulf of Maine, and the Gulf of Alaska as part of the US Integrated Ocean Observing System (IOOS), can take advantage of the latest advances of *in situ* measurement technology to identify hotspots and provide real-time information to users in need. For example, the Whiskey Creek Shellfish Hatchery,

at Netarts Bay, in Oregon, is already taking advantage of the IOOS monitoring (e.g., *http://io.aibs.org/ioos*).

The NOAA Ocean Acidification Program has also established a monitoring program at the regional scale. Beyond these efforts, coastal marine labs can be leveraged to extend monitoring to near-shore environments, where stations will be more sensitive to coastal sources of enhanced local OA. Some marine labs are already undertaking monitoring efforts, and others are poised to do so. In order to make better use of these invaluable data sources, information sharing can be streamlined within the scientific community, building on data portals such as C-CAN, which recently published a set of core principles for near-shore acidification monitoring (McLaughlin et al. 2013). Finally, nascent efforts to develop key ecosystem indicators of ecological health as part of an adaptive management strategy could include geochemical indicators (such as pH and the aragonite saturation state) designed as metrics to directly assess the variability and state of the coastal carbonate system to inform OA management efforts.

(4) Launch public education programs around OA and its causes to foster public awareness and stakeholder engagement. Public literacy of OA can increase the demand for science-based decisionmaking and can accelerate regional responses to OA impacts. Examples of efforts to bridge science and public understanding include the NOAA Ocean Data Education Project, which is intended to effectively share data from IOOS with policymakers and the public and to integrate OA into K–12 curricula. NGOs such as the Ocean Conservancy have launched efforts to communicate OA through multimedia to reach both the public and policymakers with messages from ocean users and industry representatives affected by OA. Narratives that describe OA's biological, ecosystemic, and socioeconomic impacts, as well as the multiple drivers of pH change from lawn fertilizers to automobile emissions, can motivate collective environmental action and effective policymaking when those narratives are grounded in quantitative monitoring data (Kelly RP et al. 2013). State and federal agencies; science, advocacy, and policy NGOs; and industry can look for ways to share these narratives to strengthen mechanisms for public engagement.

(5) Coordinate domestic research and communication efforts with international programs to leverage investments in OA research, increase international collaboration, and standardize global monitoring. Significant steps have been taken internationally to streamline and communicate OA research. State and federal OA programs can work to integrate domestic research with these international collaborative scientific efforts in order to promote knowledge sharing about experiences with enhanced coastal OA from North America to Europe and Asia. For example, NOAA's leadership within the International Ocean Carbon Coordination Project allows for direct collaboration of that project with monitoring efforts under NOAA's Ocean Acidification Program.

(6) Integrate the threat of OA into existing and new climate-change programs and state-level coastal programs under the Coastal Zone Management Act of 1972 (CZMA). States are increasingly preparing their coastal zones for the impacts of climate change, including sea-level rise. However, no state has incorporated OA into its state-level coastal zone management plan under the CZMA. Preparing for OA might feature prominently within these plans, given the leverage that these management plans have to secure federal funding and state agency capacity. There is also room for OA to be a focus within federal climate change programs, such as the Interagency Climate Change Adaptation Task Force. Within the Environmental Protection Agency's (EPA) current draft of its Climate Change Adaptation Plan, OA is the only climate change impact that is designated as "certain" among those listed, but it is not featured as an action item within the identified priority areas, and the EPA's 2014 US Climate Action Report makes only a brief mention of OA. Moreover, despite the fact that the EPA's National Water Program has identified OA as an issue for strategic action, no federal policy action has yet been recommended. OA is one among many climate change impacts, but sufficient science now exists, as was reviewed above, to graduate OA from an issue that is merely described to one that is included as an action item on federal and state planning agendas.

(7) Enforce existing regulatory measures to regulate water quality that affect enhanced coastal OA. In addition to incorporating OA as a priority action item within existing coastal plans, states could leverage existing coastal regulatory authorities to mitigate coastal acidification sources, terrestrial runoff, and effluents, including nitrogen, phosphorus, and organic matter (i.e., biological oxygen demand) inputs, that likely affect ocean pH on smaller spatial scales than do atmospheric drivers. Where these local inputs, such as sewer overflows and residential nutrient loading, contribute substantially to OA, existing legal mandates provide ample opportunity for local jurisdictions to intervene by virtue of land-use planning, zoning, environmental impact analysis, and water quality laws (Kelly RP et al. 2011). Legal scaffolding on which local authorities may stand include the following:

The Clean Water Act affirms the authority of states to address non-point-source runoff associated with coastal OA, although agricultural runoff has proved politically challenging for local and state authorities to regulate in a significant way. In locations with substantial eutrophication problems, mitigating coastal OA may depend significantly on those jurisdictions' ability and willingness to curb agricultural runoff.

Estuarine and coastal nitrogen-loading standards could be developed under the Total Maximum Daily Load Program as is mandated by the Clean Water Act. Currently, load limits are included for inland waters, but as groups working in Casco Bay, in Maine, have highlighted, once the water becomes salty, nitrogen standards are no longer developed, despite the significant contribution of coastal nutrient loading on OA enhancement. Where it is applicable, state agencies can consult the EPA for guidance on listing coastal waters as *impaired* for pH or for nitrogen pollutants that induce coastal eutrophication.

Preventing the destruction of coastal wetland and mangrove habitats helps preserve the ecosystem services those habitats provide. Such services include reducing coastal nutrient and sediment loading to coastal habitats—such as threatened coral reefs—and could mitigate indirect OA drivers. The Clean Water Act and the CZMA have provisions useful for implementing these protections, and some state laws (such as the California Coastal Act) also provide significant leverage for wetland protection.

(8) Account for proposed actions' acidifying impacts when conducting environmental impact assessments under the National Environmental Policy Act (NEPA) or under state-level equivalents. NEPA requires that any major federal action undergo an assessment of the action's environmental impacts; state equivalents function in much the same way. Such assessments could (and should) include the impact of the action on coastal carbonate chemistry, as well as indirect effects on coast-dependent industries that are compromised by OA. Research should include quantification of the impacts of coastal development on carbonate chemistry in near-shore waters. Such research can also help assess the cumulative impacts of human activities that affect coastal ocean pH.

(9) Consider and incorporate information about species' genetic diversity and location planning for marine protected areas. Designers of marine protected areas can aim to encompass habitats that will be resilient in the face of OA and key populations that will be the hardest hit. For commercially important wild and cultured marine species, the emerging scientific literature suggests that management actions that conserve genetic diversity; that include local, potentially low-pH adapted populations; and that promote the ability for dispersal among populations could promote the evolutionary adaptation potential of species in a lower-pH world.

Conclusions

Managing a changed ocean requires that we understand the mix of policy options that the multiscale drivers and ecological effects of changing coastal pH demands. Many proactive steps do not require new national legislation or new international accords on CO_2 emissions to come to fruition. The recent scientific findings that we have reviewed here underscore an important policy lesson: Local or regional management options, such as those outlined above, provide crucial opportunities for engagement. The shift from a focus on global, CO_2-dominated OA toward a more nuanced understanding of the different direct and indirect contributors to coastal pH change has helped spur subnational jurisdictions to action. Nevertheless, we stress that any small-scale policy action takes place in the context of ever-rising concentrations of atmospheric CO_2 and that any ultimate solution to OA will demand far-reaching and international efforts to stabilize carbon emissions.

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