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Community-Level Actions that Can Address Ocean Acidification

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Ocean acidification has led to detectable changes in seawater chemistry around the world, which are associated with reduced growth and survival of many species. Acute ocean acidification "events" in the Pacific Northwest United States have jeopardized the $270 million, 3200 jobs/year shellfish aquaculture industry in Washington State, and this has contributed to the state's broad-based, legislatively driven response to ocean acidification. Even though impacts from ocean acidification have yet to be felt in many locations, states, and regions are beginning to take action on the issue. In this paper, we present an array of actions that can be undertaken by communities or regions to address ocean acidification. The actions can be coupled, completed one at a time, or aligned with other environmental initiatives, and they can be tailored to the prevailing political or economic environment. We review which actions have been used by different U.S. states and identify common themes and popular choices. We close by suggesting combinations of conditions and clusters of activities that seem to promote rapid and sustained action. Cutting atmospheric carbon dioxide levels internationally is still the most comprehensive way to address ocean acidification, but this review shows that productive actions can still be taken at smaller scales to help marine resource-dependent communities adapt to existing ocean acidification and prepare for possible future impacts.

Keywords: ocean acidification, marine policy, CO_2 emissions, state legislation, national legislation, water quality

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INTRODUCTION

Often called a global problem with local impacts, ocean acidification refers to the progressive increase in seawater acidity (measured by a decrease in pH) and the decrease in carbonate ion levels that occur when seawater takes up atmospheric carbon dioxide (CO_2). Fossil fuel burning and land use changes have significantly increased emissions of CO_2 to the atmosphere in the last 200 years (Le Quere et al., 2009). The ocean, which naturally dissolves atmospheric CO_2 in surface waters via well-understood chemistry (Gattuso and Hansson, 2011), has taken up about 48% of the total CO_2 emitted by industrial activities (Sabine et al., 2004), and continues to take up about 26% of the CO_2 emitted annually (Le Quéré et al., 2013). This process has led to detectable increases in ocean acidity around the world (Orr, 2011). The changes in seawater chemistry associated with ocean acidification are associated with reduced growth and survival of many species (Gattuso and Hansson, 2011; Kroeker et al., 2013) and lack of predator avoidance of several finfish (Munday et al., 2009; Dixson et al., 2010, 2015; Cripps et al., 2011). Bivalve shellfish, including oysters, clams, and scallops, grow and calcify shells more slowly under ocean acidification (Kroeker et al., 2013), and are more likely to die at the larval stage due to energetic changes caused by ocean acidification (Waldbusser et al., 2013).

Acute ocean acidification "events" in the Pacific Northwest United States have jeopardized the $270 million, 3200 jobs/year shellfish aquaculture industry in Washington State (Washington State Blue Ribbon Panel on Ocean Acidification, 2012), but to date that state's shellfish industry has experienced the only well-documented socioeconomic impact that has been clearly attributed to ocean acidification. Model-based studies have estimated the potential costs of ocean acidification impacts to shellfish harvests in the US at $75–187 million a year (Cooley and Doney, 2009), global shellfish harvests at $6 billion a year (Narita et al., 2012), and coral reef impacts at $0–900 billion a year (Brander et al., 2009). Recent studies have begun exploring ocean acidification's threat to human communities with risk assessment frameworks (Cooley et al., 2012; Ekstrom et al., 2015; Mathis et al., 2015), which shed light not only on the areas at greater total risk, but also on the characteristics of the socioeconomic system that contribute to this risk.

Ocean acidification's impacts to marine ecosystems could indeed stretch well beyond marine harvests, because affected marine species provide a variety of ecosystem services (Cooley et al., 2009). Current discussions about ocean acidification's socioeconomic impacts focus primarily on marine harvests, coastline protection by coral reefs, and recreation or tourism opportunities supported by reef ecosystems or regional fisheries (Ekstrom et al., 2015; Gattuso et al., 2015). Nevertheless, ocean acidification is likely to enhance the biological effect of other global changes (temperature increase, deoxygenation; Przeslawski et al., 2015) that are occurring simultaneously (Gruber, 2011). The combined changes could ultimately have larger-scale impacts on human development and migration patterns (Cooley and Mathis, 2013).

Despite the rapid growth of scientific understanding of ocean acidification over the past decade, policy solutions to address its impacts on marine ecosystems and marine-dependent human communities are still few in number (Gattuso et al., 2015). This may be due to all of the factors outlined above: the lack of robust projections of the likely costs of ocean acidification's impacts to humans; the dual nature of ocean acidification, which results from global factors but has varying local effects; and the intangible nature of many of ocean acidification's expected impacts on planetary cycles, synergies with other stressors, and so on. This may also be due to the fact that impacts from ocean acidification have yet to be felt in many locations (Cooley et al., 2015). This in turn, creates a lack of knowledge, understanding, and concern among the general public, especially when compared to the suite of other stressors impacting the ocean and earth (Leiserowitz et al., 2010; Gelcich et al., 2014). Complicating matters is the fact that ocean acidification is a purely chemical process that has follow-on effects on human communities via marine biology, making it an interdisciplinary problem. Many current policies designed to address environmental issues are tailored to local-scale problems, or problems whose causes and effects are well defined, or problems that begin and end in the same environment. For example, current U.S. Environmental Protection Agency regulations that refer to aquatic pH are designed to respond to point source pollutants whose background levels are known, and whose lethality can be established (Kelly and Caldwell, 2013; Cooley et al., 2015). With a pollutant like CO_2, which is emitted everywhere and necessary for life at some concentrations, yet harmful at others, these qualifications cannot be set as easily as for other toxins.

In this paper we present an array of actions that can be undertaken by communities or regions to address ocean acidification. The actions can be coupled, completed one at a time, or aligned with other environmental initiatives; this is happening in several locations. Even though reducing atmospheric CO_2 levels is ultimately the best and most complete solution for ocean acidification (Gattuso et al., 2015), productive actions can still be taken to help marine resource-dependent communities adapt to existing ocean acidification, prepare for possible future impacts, and mitigate acidification and synergistic stressors to decrease ocean acidification (Gattuso et al., 2015). Lack of agreement to decrease atmospheric global CO_2 levels is not a sufficient reason to delay taking action at local levels to strengthen marine ecosystems and prepare them for acidification, some level of which we know is inevitable (Frölicher and Joos, 2010). Here, we lay out actions that can be undertaken locally, regardless of the prevailing economic or political environment. Even though we focus on action taking place in the U.S., the actions we review could be undertaken anywhere in the world. We review which actions have been taken to date by different U.S. states and identify common themes and popular choices. We close by assessing which actions have yielded greatest progress and offer suggestions about effective ways forward for communities seeking to take action.

Why Act at the Community Level?

Even though global CO_2 reduction is widely agreed upon as the most effective solution for ocean acidification, action against ocean acidification is also effective at smaller spatial scales. For example, communities were galvanized to action very quickly in the Pacific Northwest United States (Barton et al., 2015), when ocean acidification jeopardized the existence of the region's lucrative and culturally iconic Pacific oyster aquaculture industry. Industry leaders quickly became activists in speaking out for action on this emerging issue (Kelly et al., 2014; Barton et al., 2015). The economic and cultural importance of the aquaculture industry forced decision makers to listen and respond.

Even in locations where ocean acidification is not occurring rapidly enough to cause measurable losses, citizen groups, and partnerships have yielded action. Shellfish industry groups are expressing concern about the issue (Pilaro Barrette and Rheault, 2015) and contributing to sustained action (Gledhill et al., 2015). At the same time, groups of scientists are teaming up with industries and local resource managers to express concern and advocate for action (Boehm et al., 2015). Statements from these groups, which often include personal anecdotes and locally tailored estimates of what unique cultural, ecological, or economic features could be lost can motivate action much more quickly than depersonalized

scientific information (Banikowski and Mehring, 1999; Center for Research on Environmental Decisions, 2009; Zak, 2014). By focusing on community scale impacts and solutions, a grassroots support base can provide the long-lasting foundation of support to encourage decision-makers to address ocean acidification.

A number of political analyses of the federal climate change legislation efforts in the United States often identify the lack of widespread local support for reducing carbon dioxide emissions as one significant reason for its failure (Skocpol, 2013). Local efforts to address climate change are multiplying, however, and local action is cited as a key component of comprehensive action (Center for Climate Energy Solutions, 2011). Not only does local action take concrete steps in reducing greenhouse gas emissions locally, but it also encourages broader action at regional and national levels (Center for Climate Energy Solutions, 2011). Local action can also offer co-benefits, such as employment in new sectors, money saved, and healthier communities. Just as with climate change, local action on ocean acidification can incite broader action and offer substantial benefits and co-benefits for coastal communities.

Because communities differ widely, both in terms of their priority concerns and their prevailing political and socioeconomic climates, an array of options to act on ocean acidification must be available. Not every state is able or willing to pass legislation strictly on ocean acidification. Not every community has an active and vocal industry that stands to lose directly from acidification. Action seems to occur most rapidly when scientific knowledge is well aligned with decision makers' questions, and there is enough cultural, economic, or scientific justification to devote resources to the issue (Cooley et al., 2015). In addition, some communities are willing to take precautionary action, whereas others are not. Simply from these characteristics, it seems a diverse array of actions exists to address ocean acidification. These actions respond to either decreasing the hazard or strengthening social-ecological systems to weather it, and undoubtedly a few options will be practical for every community. Adaptation options are best implemented in clusters, but every one helps protect human communities even more against harm from ocean acidification. To best protect human communities against global change including ocean acidification, both mitigation of atmospheric CO_2 and adaptation to its likely impacts are necessary (Gattuso et al., 2015).

As more local communities address ocean acidification, some have combined efforts with neighboring areas that share water bodies to create greater results. The symptoms of acidification throughout these areas are often similar, and made more manageable when the resources of these multiple communities can be leveraged together. On the North American Pacific coast, California, Oregon, Washington, and British Columbia have agreed to share information and combat ocean acidification by urging the American and Canadian governments to further research, model, and monitor their shared waters for ocean acidification through the Pacific Coast Collaborative (Pacific Coast Collaborative, 2013). While not a national effort, these neighboring jurisdictions have formed a larger regional effort that can potentially have a greater chance of reducing local impacts of ocean acidification; however, this regional effort is dependent on the state level work.

ACTION OPPORTUNITIES

Local governments and community actors have an array of options they can take to address ocean acidification (**Table 1**). Here we have compiled all the actions proposed or undertaken by state or regional expert panels, outreach and education specialists, scientific experts, and concerned coastal users. We have three sources for these actions: (1) the three state-convened ocean acidification commission reports; (2) reports and recommendations from workshops involving the shellfish industry and scientists; and a (3) literature review of public media, white papers, and research articles pertaining to activities related to ocean acidification.

The three individual public reports issued by the Washington State, Maine, and Maryland ocean acidification commissions (Washington State Blue Ribbon Panel on Ocean Acidification, 2012; Maryland Department of Natural Resources, 2015; State of Maine 126th Legislature, Sec, 2015) all provided a number of recommended actions to address ocean acidification. Public marine science workshops and meetings focused on ocean chemistry such as the NOAA-sponsored Coastal Acidification Networks or industry events such as the Pacific Coast Shellfish Growers Association (PCSGA) and East Coast Shellfish Growers Association (ECSGA) meetings also proposed or implemented actions. Finally, internet searches for research papers, public events, educational outreach, and technical literature, news reports, and op-ed articles regarding ocean acidification yielded the remainder of proposed and implemented actions found to address acidification. Some actions that incidentally address ocean acidification may already be underway to address other issues, such as water quality, urban planning, coastal or fishery management, and marine industry engagement. Although the mechanisms for implementing these actions vary, the end results of any of these actions can provide short- or long-term gains on ocean acidification. The actions can be grouped into five major categories (**Table 1**), which are explored below.

A major distinction dividing the actions listed in **Table 1** is whether or not they result from formal legislative action (right vs. left sides of table). State actions are divided into two different categories: non-legislative (N) and legislative (L). A legislative action can be a piece of legislation, such as a bill or an executive order, or anything that is a direct consequence, like a panel convened at the order of the state governor. Non-legislative are events that do not directly result in or relate to government action, such as a science convening workshop hosted by a university. The actions listed that require legislative approval are typically more difficult to enact due to the larger number of individuals needed for approval; however, formally legislated actions often have greater ongoing support and impact than other actions. It is possible, but not necessary, to enact actions from the left column (non-legislative actions)

TABLE 1 | Actions that can be taken to address ocean acidification, divided into five major categories (top to bottom), and separated into non-legislative (left column) and legislative (right column) options.

	Non-legislative options	Legislative options
Education/outreach	Write and publish op-eds Hold conversations aided by fact sheets, videos Partner with informal educators to teach the public Identify and convene specialists and/or industry representatives to share information within or across industry and regions Facilitate conversations with equivalent policymakers from elsewhere	Proclaim that ocean acidification is a relevant issue Create a public-private partnership with industry to participate in data collecting Create or direct a state commission to create, track and publicize information about local acidification Direct funds to formal and informal ocean acidification education programs and teacher training Include ocean acidification in state education curriculum/learning standards
Assess and address knowledge gaps	Organize letters to decision-makers requesting research and monitoring Hold multi-stakeholder convening to ID state of science, knowledge gaps, risk to industry, optimal next steps Coordinate local research activities to address ocean acidification Broaden local monitoring (leverage IOOS and other networks) Determine baseline economic conditions of threatened industries Write a report capturing this information and include recommendations	Create or direct a state commission to identify state of science, knowledge gaps, optimal next steps Request formally to fund local research, monitoring, and coordination. Create budget mechanisms, RFPs (state entities) Write ocean acidification into existing ocean initiatives and environmental policy (research/laws/observation systems)
Support industry/jobs	Educate industry groups about specific adaptation/ mitigation steps for businesses Create a future proofing/ business survival plan: Support coastal business growth in uncertain environment (insurance, cooperation, relocation) Partner with businesses to protect themselves from ocean acidification	Fund survival planning/implementation via Sea Grant, grants, loans, tax credits, workshops, gear switching, diversifying seed sources (e.g., away from a single hatchery) Revise permit requirements: future proofing plans; data collecting requirements
Manage for resilience	Restore oyster reefs/sea grass beds Design fishery stock assessments to alert managers of changes Conduct coastal management/restoration pilot projects (with NGOs, state agencies, researchers) Practice smart growth and land use that seek win-win development opportunities* Participate in National Estuary Program and National Estuarine Research Reserve System*	Manage fisheries by including climate change and ocean acidification in planning and harvest decisions Increase photosynthesizing submerged aquatic vegetation e.g., eelgrass, kelp forests, and mangrove forests Broadly legislate consideration of climate impacts and other environmental threats Allow and fund coastal ecosystem restoration
Cut ocean acidification	Leverage CWA 319(h) funds to implement best practices, permanent improvements* Enforce existing water quality (WQ) regulations* Enhance wastewater treatment at public works* Voluntarily cut CO_2 emissions directly/indirectly (greener power, waste reduction, recycling, etc.)	Reduce nutrient runoff from point/nonpoint sources Enhance wastewater treatment at public works* Strengthen WQ regulations (point sources, limits, designated uses, wastewater treatment, etc.) to limit sources of coastal acidification (both air- and waterborne)* Include ocean acidification into Environmental review under State NEPA equivalents* Mandate CO_2 emissions cuts (fuel taxes, cap and trade, etc.)

Non-legislative options can be carried out legislatively, but legislative options cannot generally be carried out non-legislatively.
**See* *Kelly and Caldwell (2013)*.

using legislation, but actions from the right column (legislative actions) cannot generally be accomplished non-legislatively. Even though this study refers to U.S. state legislative actions, any subnational governmental entity, such as a town or province, could also take these sorts of legislative actions. One of the most common legislative actions that has been undertaken in multiple locations is the formal convening of a state study panel charged with assessing the state of knowledge on local ocean acidification and recommending further actions to take on ocean acidification.

Education and Outreach

Education and outreach actions (**Table 1**, top group) comprise varying types of communications designed to inform audiences about ocean acidification. These are the simplest actions which any leader can use to start action on ocean acidification. The challenges associated with this group of actions are to keep information updated, as new research is constantly being published, and to make the information relevant to listeners. Although education and outreach do not immediately reduce acidification, these actions can create initial awareness and concern that build coalitions of people willing to take additional actions. Outreach materials may be as simple as a short video explaining the problem or a two-page summary (e.g., Washington State Sea Grant, 2014) that can be used to support one-on-one conversations, or they may be as formal as lesson plans implemented in K-12 classrooms.

Assess and Address Knowledge Gaps

The next suite of options in the table, assessing and addressing knowledge gaps (**Table 1**, second group), include actions that contribute to a more localized and specific understanding of ocean acidification and its impacts. These activities generally require more time, energy, and experts to produce useful results than the outreach and education category. Scientific assessments are generally best carried out by local marine resource users, marine managers, and scientists who are familiar with the local environment and ocean acidification. Although any group convened to explore local ocean acidification knowledge and needs does not necessarily need to be legislatively created, having a formal mandate may bolster this group by funding research and meetings and by creating harder deadlines that make the effort a higher priority. Examples of scientific assessments that have been completed by state groups include the Washington State Blue Ribbon Panel on Ocean Acidification Report (2012), Maryland Ocean Acidification Task Force Report (Maryland Department of Natural Resources, 2015), and the Maine Ocean Acidification Commission report (State of Maine 126th Legislature Sec, 2015).

Support Marine Industries and Jobs

Another category of actions that can be taken to address ocean acidification include supporting marine industries and jobs that could be affected (**Table 1**, third group). From the Pacific Northwest example described above and detailed in Barton et al. (2015), it is clear that industry and job impacts of ocean acidification could be sector- and region-specific, sudden, and potentially quite severe. Forecasting acute ocean acidification events for specific locations, however, is in its infancy (New ocean forecast could help predict fish habitat six months in advance, 2013). At this time, supporting industries despite limited knowledge about ocean acidification's effects on marine resources and dependent human communities currently depends on flexible precautionary planning enlightened by simple vulnerability-type assessments (e.g., Ekstrom et al., 2015). Nevertheless, knowledge exchanges among businesses that have been affected and those that have not can increase preparedness, as can development of informal or formal plans for an uncertain future (Capson and Guinotte, 2014).

Manage for Resilience

Managing marine resources for resilience (**Table 1**, fourth group) is another category of actions that can help address ocean acidification. This category includes restoration activities and plans that account for multiple stressors, such as hypoxia, nutrient runoff, and temperature change, which chemically enhance ocean acidification (Cai et al., 2011) or synergistically challenge marine organisms (Poertner, 2010; Gobler et al., 2014). In some locations, actions may even already be under way to address other issues (e.g., hypoxia, nutrient runoff) that coincidentally enhance the resilience of marine resources at risk from ocean acidification. This is true in the Chesapeake Bay, which has a long history of tracking and addressing nutrient pollution (U.S. Department of the Interior, U.S. Geological Survey, 1999). However, understanding the interaction of multiple stressors on particular marine resources are still yet topics of active research (Przeslawski et al., 2015). A very complicated set of considerations and solutions will likely be required to build resilience to ocean acidification comprehensively for key marine resources. For the most part, this has not been done yet. For this group of actions addressing ocean acidification, there is a marked increase in the number of individuals who need to be involved compared to the previous sections. In addition, non-legislative actions are likely to be weaker than legislative options, which can help set stronger, more attainable goals by setting clear standards, definitions, and enforcement.

Directly Cut Ocean Acidification

Actions that directly cut ocean acidification make up the final cluster of options presented here (**Table 1**, last group). This cluster may be the most challenging to implement because of the level of scientific certainty and political will required, but many actions listed in the other sections of **Table 1** can pave the way for these by enhancing knowledge and creating coalitions of engaged stakeholders. Many of the actions mentioned and explained by Kelly and Caldwell (2013) appear in this grouping, but most actions have not been attempted at the local or regional level for the purpose of addressing ocean acidification. Even when significant regional industries stand to lose substantial revenues due to ocean acidification, building wider public awareness, and concern over this vulnerability to stimulate action remains a challenge (Frisch et al., 2015). As a result, this ocean chemistry change has not yet become a significant impetus for actions in this category. Alone, these actions may be insufficient, because they are primarily focused on delaying or reducing (but not completely eliminating) the hazard of acidification. Knowledge of the efficacy of each action will be necessary to prioritize them, but it also represents another hurdle in determining which specific action to focus on and implement. Even with local actions to cut acidification, such as reducing nutrient pollution from land-based sources or local carbon dioxide emissions, global carbon emissions that continue unchecked will still drive local ocean acidification and need to be addressed. However, this paper focuses only on assessing and recommending local-scale actions against ocean acidification.

CASE STUDIES

States that have completed more than one or two actions addressing ocean acidification and have a sustained effort under way targeting the issue are discussed as case studies below. State actions were identified through a combination of efforts, including targeted searches for "ocean acidification" in state legislation (through search engines such as Legiscan.com), and analysis of reports and products generated by state-based commissions on ocean acidification. The data collection process for this was similar to that used to create **Table 1**. Key states were identified by searching for language concerning ocean acidification within legislation (e.g., searching for terms and phrases such as "ocean acidification," "coastal acidification," and "seawater" near "acidification"), and also by searching through publicly available meeting reports from workshops regarding ocean acidification and scientific publications related to ocean acidification. Once active states were identified, more exhaustive research was done to understand the history of ocean acidification within policy, science, industry, and education sectors in each active state.

Washington and Maine

The two states that have taken the most formal action on ocean acidification to date, Washington and Maine, have completed both legislative and non-legislative actions to address ocean acidification that fall into all five groups outlined in **Table 1** (**Figure 1**). These states both depend heavily on shellfish resources (2013 shellfish species landings for Washington: $265,004,696; for Maine: $407,418,013; NOAA Fisheries Statistics Division, 2015) for income and cultural identity, but they have contrasting cultural and political environments. Several similarities can be found in the ways each state has approached addressing ocean acidification despite other unique elements.

Following substantial scientific research progress in Washington, Maine, and across the country and world, increased education and outreach activities in these states preceded formal legislative processes to assess the state of the science and recommend next steps. For instance, Washington began education and outreach activities around 2011 (Washington State Sea Grant, 2015), and by the end of 2013 had completed actions in each of the five groups from **Table 1**. In 2013, a session convened by Island Institute, Sustainable Fisheries Partnership, and Maine Sea Grant at the Maine Fishermen's Forum jump-started the public discussion by convening shellfish industry representatives, scientists, and environmental nonprofit organization representatives to inform attendees about ocean acidification. Maine after this education-and-outreach oriented beginning, a joint resolution was adopted identifying acidification as a threat to its coastal economies and way of life in June 2013 [Maine Senate Paper (SP) 599. "Joint Resolution Recognizing Ocean Acidification as a Threat to Maine's Coastal Economy Communities Way of Life" (2013)]. These efforts created a foundation for the legislatively convened commission to further local acidification impacts in 2014 [Maine Legislative Document (LD) 1602. "Resolve (2014), Establishing the Commission To Study the Effects of Coastal and Ocean Acidification and Its Existing and Potential Effects on Species That Are Commercially Harvested and Grown along the Maine Coast," 2014]. In both states, legislative actions were led by passionate, concerned lawmakers: in Washington, by then-Governor Christine Gregoire, and in Maine, by Rep. Mick Devin and Sen. Chris Johnson. Ideas and best practices were shared freely among state legislators and their staffs; for example, Jay Manning (Gregoire's Chief of Staff, 2009–2011) and Brad Warren (Sustainable Fisheries Partnership) spoke by videoconference at the January 2014 state-of-the-science meeting in Augusta, ME to share lessons learned from the WA state process. Later, Manning and Devin appeared on a panel in November 2014 at Restore America's Estuaries Conference (Devin, 2014), while the panels were still active, to share their experiences and success stories about working on these panels. Within the U.S., Washington State's actions have set a precedent that many other states have borrowed from. Generally, states begin with education and outreach by knowledgeable scientists or resource managers, moving to legislatively convening a study panel charged with developing formal recommendations, and then to implementing actions from all five action categories laid out in **Table 1**.

Despite Maine's apparent emulation of the Washington process, there are some key differences that have affected the ways in which action on ocean acidification has occurred in these states. Maine's governor during this period, along with the state legislature, was not receptive to environmental legislation. The political environment was hostile to ocean acidification as an environmental issue. In contrast, Washington's governors (Gregoire, followed by Jay Inslee) were supportive of environmental legislation and were part of a more politically friendly environment for ocean acidification. Moreover, Maine had not seen measurable shellfish industry losses due to ocean acidification before dialogue began in the state about the issue. One Maine grower reported slower oyster seed growth events after rain events by February 2013, raising concern that pH alteration of coastal waters by rain was a local enhancer of acidification. But, unlike Washington, conclusive evidence was lacking that ocean acidification was already on Maine's shores. In contrast, concerned groups in Washington included major industries such as large shellfish hatcheries, which employed hundreds to thousands of people, and researchers at internationally renowned science centers such as NOAA's Pacific Marine Environmental Laboratory. Together, these groups emphasized the urgency of the situation and urged Gov. Gregoire to act. She wrote an executive order to create the Blue Ribbon Panel to study the issue and recommend next steps. This created an open conversation within Washington about ocean acidification science as well as its potential to cause economic losses. In Maine, two key groups led action on ocean acidification. Rep. Devin, also a marine biologist, was concerned about the possible consequences of ocean acidification for Maine, given the research results being published worldwide and the economic concerns coming out of the Pacific Northwest. He conducted education and outreach one-on-one within the Maine State Legislature (Devin, 2014) as well as initiated a bill to create a Maine ocean acidification commission. At the same time, the Maine lobster industry publicly raised its concerns that

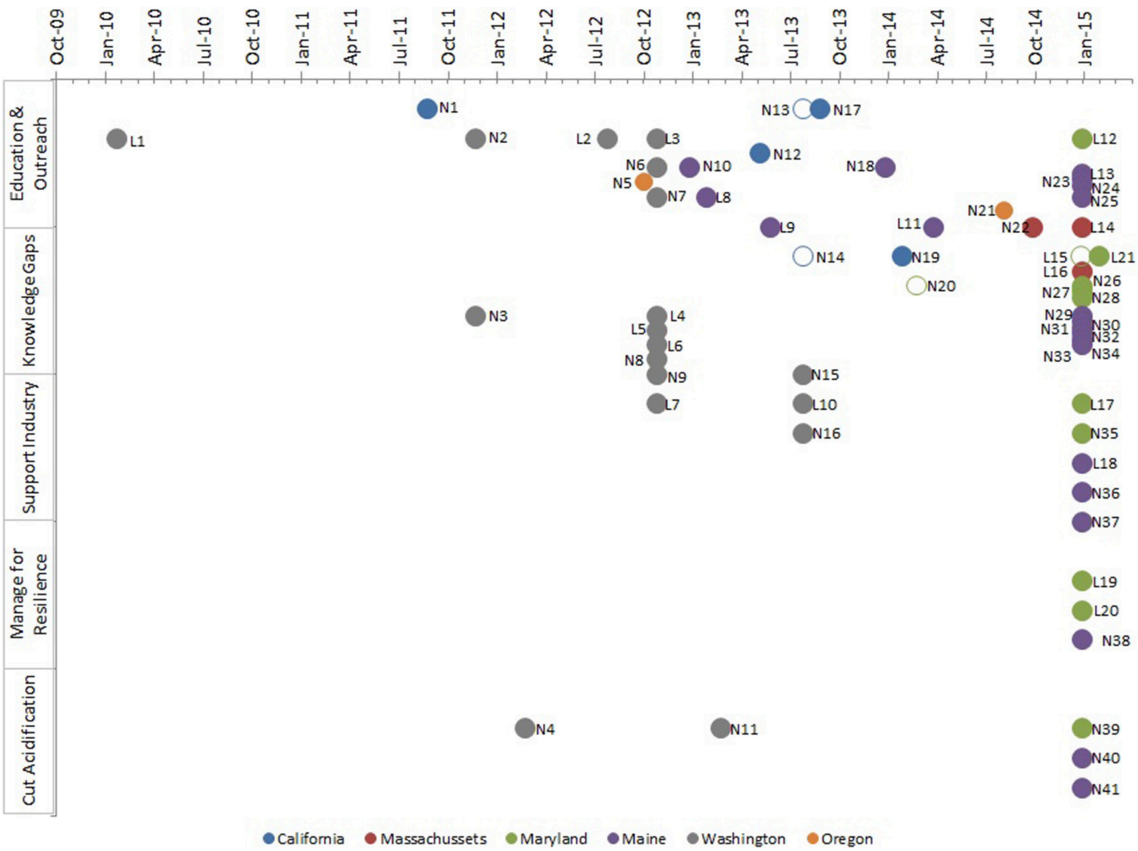

FIGURE 1 | Timeline schematic showing actions addressing ocean acidification undertaken by different U.S. states in the five categories of action shown in Table 1. Only states that have taken more than one action are included on the figure. Filled circles indicate completed actions, and open circles indicate actions under way. Annotations next to data points (e.g., N1) correspond to entries in Supplementary Table 1, which details the action. Annotations beginning with "N" indicate non-legislative actions; "L" indicates legislative actions or recommended legislative actions.

more ocean acidification knowledge was needed, given lobster's key economic role [$464,497,308/year; (Department of Marine Resources State of Maine, 2015)] for the state[1]. Ultimately, the industry's concern helped move Devin's bill through the governor's office.

A core difference between Maine and Washington's pursuit of action on ocean acidification was that Washington's process included environmental and industry concerns in equal measure, whereas Maine's process gained long-lasting momentum from industry concerns. The key difference driving this seems to be political: Maine's leadership was Republican whereas Washington's was Democratic. In a Republican-dominated (fiscally and socially conservative) political environment, the focus on jobs and potential economic consequences proved as effective to pass legislation on ocean acidification as the dual focus on science and economics was in a Democratic-dominated (fiscally and socially liberal) political environment. The environment may have contributed to the panels' working conditions, as well: Washington's state panel had approximately a year to work, whereas Maine only had 5 months and $3000 total from the state and nonprofit organizations. The different prioritization also affected follow-up actions that have occurred after convening the states' study panels. Washington has a large number of actions continuing in the "outreach/education" and "addressing knowledge gaps" action clusters (**Figure 1**), whereas Maine's efforts currently cluster in "supporting industry."

Other States

Several other states have also been taking action on ocean acidification, which has been colored by the political, scientific, and economic environments in each state. In January 2014, a Maryland Democratic state delegate sponsored an ocean acidification bill that provided for the creation of a state task force (**Figure 1**). Not long after, Maryland's scientific community and resource managers independently convened a preliminary workshop on the state of ocean acidification science in the state in March 2014. Then, the National Aquarium and other Maryland NGOs, as well as one Maryland shellfish hatchery, supported the Ocean Acidification Task Force bill through written and oral testimony. The bill passed and a task force was convened for 5

[1]Impacts of OA on American lobster are still not well understood. An early study suggested their shells grow thicker at 77 F, a temperature not ecologically appropriate for New England lobster (Ries et al., 2009), but a subsequent study showed delays in larval growth (Keppel et al., 2012).

months, with no budget (Michael, 2015), to evaluate the state of the science and make recommendations. Since that activity concluded, no subsequent actions have been taken on ocean acidification or to implement any activities recommended by the task force.

New England states have begun to take legislative and non-legislative action as well. In Massachusetts, a similar scientist-driven conference on ocean acidification was held in October 2014 that convened scientists, natural resource managers, state legislators, and NGO representatives. The conference explored the state of ocean acidification science as it related to MA's resources and other activities. Not only were connections identified between ocean acidification monitoring needs and existing environmental monitoring programs administered by the state (e.g., Coastal Zone Management), but the relevance of ocean acidification to MA's shellfish and finfish fisheries was underscored. Two state representatives (Timothy Madden and Benjamin Straus) introduced a bill (H716) to establish an ocean acidification commission legislatively to identify knowledge gaps and policy responses in January 2015, which has been in committee since. In New Hampshire, Representatives David Bordham, Robert Cushing and Senator Martha Fuller Clark introduced a similar bill to establish a state ocean acidification commission in January 2015 (HB 379), but the bill was tabled in March[2]. In Rhode Island, Representative John Edwards introduced a bill (2015-H 5320) to establish a state ocean acidification commission, and the bill is still in committee[3]. Meanwhile, in the Mid-Atlantic, New Jersey has hosted an education and outreach convening for stakeholders on ocean acidification[4].

Action on ocean acidification has also begun in Florida, although it is in its very earliest stages. Research on ocean acidification has been under way in Florida for years, particularly focused on its warm-water coral reef ecosystems, which are unique in North America. However, a comprehensive assessment of the state of ocean acidification science in Florida has not occurred yet via legislative or non-legislative pathways. Nevertheless, estimates exist of the value of tourism and recreational fishing in Florida that depend on healthy coral reef environments and iconic finfish. Saltwater recreational fishing supports 109,341 jobs, generates $13.1 billion in local sales, and $4.8 billion in local income (NOAA, 2014). Coral reef tourism is harder to evaluate, but it supports more than 70,000 jobs (Johns et al., 2001, 2004), generates about $60 billion in local sales, and $2.8 billion in local income [estimates from Johns et al. (2001, 2004), adjusted to 2014 dollars, and summed]. In 2015, at the writing of this paper, 13 House Representatives from Florida (eight Republicans, five Democrats) have cosigned the Coastal Communities Ocean Acidification Act (H.R. 2553) directing NOAA to conduct socioeconomic vulnerability assessments that will examine the potential job and economic impacts of ocean acidification on coastal human communities. Viewed through a human vulnerability and economic perspective, ocean acidification is compelling enough to incite action from lawmakers in Florida even though a vocal industry stakeholder group has not yet come forward to express concern on the issue. Florida may well be the first state willing to take precautionary action on ocean acidification that is motivated primarily by financial concerns.

Researchers and shellfish growers in West Coast states have been leaders on ocean acidification research and action for years. Formal legislative action in Washington has been accompanied by non-legislative action in California and Oregon. The California Current Acidification Network (C-CAN), including researchers, growers, and state environmental advocates from all West Coast states (WA, OR, CA), was one of the earliest self-organizing groups dedicated to education and outreach on ocean acidification, beginning its work in 2010. C-CAN members have also participated in activities to assess and address knowledge gaps, producing recommendations on best practices (McLaughlin et al., 2015) and educating researchers and growers in a one-on-one approach (California Current Acidification Network, 2010). C-CAN has not generally engaged in larger efforts to support (or secure support for) industry, manage for resilience, or directly cut acidification, which may be related to its origin as a self-organizing or "bottom up" organization populated by volunteers willing to speak out on the issue. Involvement of entities like state or regional resource management agencies that can implement more difficult tasks like supporting industry, managing for resilience, or cutting acidification from a top-down authoritative position may be necessary to complement and formalize this sort of action. Adding to West Coast momentum, Alaska Sea Grant helped convene a stakeholder workshop in December 2014 to educate citizens about this issue[5].

DISCUSSION: EMERGING THEMES

The actions listed in **Table 1** and the extent to which they have been carried out in different states (**Figure 1**) appear to follow a common trajectory, beginning with easier, low-investment early activities like education and outreach and knowledge gap assessment. Action seems to slow or even stall when larger coalitions of individuals are needed for approval (e.g., legislative bills), entities with top-down authority are needed as partners or implementers (e.g., to support industry, manage for resilience, or cut acidification), or broad partnerships are needed (e.g., for actions that will cut acidification altogether), which all require sustained efforts over a longer period of time. See, for example, in **Figure 1** how early actions in nearly every state focus on education and outreach or assessing knowledge gaps, while later actions span the full range of action categories. While this result may be somewhat inevitable, as individuals can always move more nimbly and strategically than groups, a recognition of the different types of action and their palatability in different situations is useful to allow the most effective solutions to be sought.

The contrasts between Washington and Maine (Section Washington and Maine; and Florida, to some extent) indicate the

[2]https://legiscan.com/NH/text/HB379/id/1074196.

[3]https://www.billtrack50.com/BillDetail/577860.

[4]http://njseagrant.org/ocean-acidification-stakeholder-workshop/.

[5]http://www.aoos.org/ocean-acidification-workshop/.

role of the political environment in affecting ocean acidification action. When the possible economic consequences of ocean acidification are highlighted, either by industry spokespeople or by lawmakers themselves, ocean acidification action seems to proceed more readily in politically conservative environments. Without linkages to human communities and local jobs or economies, ocean acidification may seem to be just another abstract environmental issue on which action can be delayed in favor of other more pressing concerns. To promote action on ocean acidification in a politically conservative environment, placing it in a cost-benefit context seems to provide an opportunity to compare it with other issues as well as to connect faces of local businesspeople with the issue. Stories help personalize these issues, greatly increasing their relevance and ability to be remembered for not only environmental activism (Kelly et al., 2014), but other fields involving behavioral change such as business marketing (Escalas, 2004), public health (Hinyard and Kreuter, 2007), and philanthropy (Maclean et al., 2013). Politically liberal environments like Washington and other West Coast states seem more receptive to taking initial action on emerging science and environmental concerns as part of a broader philosophy of environmental engagement (Hoffman, 2011). However, this does not necessarily lead to activities that span all categories of action shown in **Table 1**. Furthermore, there is no guarantee that actions taken by one state administration will be continued to the next. For example, Maryland experienced a regime change from a Democratic to Republican leadership just after the publication of its commission report, and a number of key state natural resource administrators were let go (Wheeler, 2015), leaving the implementation of its commission recommendations in an uncertain position.

Sustained legislative action seems to occur in locations where two out of three major stakeholder groups are activated on ocean acidification. In Washington, scientists and industry led the way, whereas in Maine, legislators and industry led. In Maryland and in Florida, scientists and legislators are leading the way (Section Other States). Some East Coast states (New Hampshire, New Jersey, Massachusetts, Rhode Island) have begun to propose bills, evaluate the state of the science, or reach out to stakeholders, but these efforts have not moved forward legislatively and neither have critical masses of two types of stakeholders emerged in each state. In New Hampshire, a bill was proposed to establish a commission on ocean acidification, but both the research and fishery communities are quite small in the state and the bill has not had many champions to add momentum. In New Jersey, a science convening has occurred, but neither the fishery nor legislative communities have become activated on the issue. Non-legislative actions can certainly be led by individual stakeholder groups, and the movement listed above in NH, NJ, and MA (Section Other States) contributes to building a coalition of interested people who may advocate for future, formally legislated actions. The effectiveness of non-legislative actions may be limited because of lack of dedicated or ongoing funding; progress can depend on the commitment of just a few individuals leveraging other resources.

The five clusters of actions laid out in **Table 1** (Section Action Opportunities) progress from "easier" (top) to "more difficult" (bottom), an order which is partly influenced not only by the number of people involved, but also by cost. Educating peers, proclaiming ocean acidification is a relevant issue, and evaluating knowledge and gaps are all low-investment actions. Undertaking steps that support industries, manage for resilience, or cut acidification directly are more costly. Implementing these steps also tends to be time consuming, making them more susceptible to changes in policy priorities and more likely to be undeveloped or unfinished. Supporting industry via more sophisticated actions like revising permit requirements, tax incentives or the like (**Table 1**) may need formal cost/benefit studies performed by impartial evaluators, newly developed insurance or tax structures that need offsetting elsewhere, or training for affected industries. All of these actions require allocation of dedicated funds and substantial staff time to evaluate. Likewise, managing for resilience requires economic support to underwrite restoration or development of new fisheries and coastal growth plans (again, perhaps using consultants or outside specialists). Cutting acidification directly requires funds for enforcement and infrastructure repair or growth. In addition to costing more, managing for resilience and cutting acidification directly may also require a philosophical shift toward precautionary planning that increases the health of today's coastal resources in preparation for whatever may come. Hence, we have ordered the clusters of actions from easier (informal, individual, cheap, immediate) to harder (formal, collective, expensive, precautionary) in **Table 1**.

With such an array of actions available on ocean acidification, ranging from easy and cheap to hard and expensive, what can be done to carry early actions forward into more sustained work? Certainly, a legislated commission seems to help with this, as Washington, Maine, and Maryland have the most diverse portfolios of completed actions (**Figure 1**), and they are the only states that have had official commissions. Even so, the actions that these states have taken in each category have not been utterly comprehensive. Washington's actions leave out managing for resilience entirely, whereas Maine and Maryland have completed a few actions in this category including calling for a comprehensive carbon reduction strategy and ocean acidification task force (Maryland, **Figure 1**, and Supplementary Material; Maryland Department of Natural Resources, 2015) and increase sustainable culture of macroalgae, which may mitigate ocean acidification somewhat (Maine, **Figure 1**, and Supplementary Material; State of Maine 126th Legislature, Sec, 2015). Previous work has shown the need for dialogue among coastal users, scientists, and policy makers in helping transform the flow of information about ocean acidification into a more decision-relevant context (Cooley et al., 2015). Until decision makers' (that is, both policy makers and coastal resource users) questions can help scope research and monitoring, information will be offered in a one-way, bottom-up mode that is less effective at motivating action by partners or in allied sectors or projects (Cooley et al., 2015). Activities specifically intended to bring together different stakeholder groups early on, to explore common needs, are likely to help jump-start the pursuit of actions further down **Table 1** that require coalitions, more funding, and perhaps a precautionary perspective.

CONCLUSIONS

Far from being powerless against global change, this review shows that communities actually have a diverse array of actions available to begin addressing ocean acidification. Taken from "easy" to "difficult," these actions can build momentum sequentially within a state or province. These state-based actions can then influence regional progress (such as via the Pacific Coast Collaborative), leading to impacts greater than those just associated with one community alone. In addition, these types of concrete, finite actions are also reasonable for communities to undertake, even with financial, political, or other limitations.

As may be true for other issues, we see that for ocean acidification, early actions focusing on education, outreach, and assessment build coalitions of citizens that can advocate for more difficult or expensive actions that address other aspects of ocean acidification. Formally legislated actions do tend to result in a more comprehensive array of actions addressing the concerns of many stakeholder groups, by creating a mandate, a timeline, and accountability, as seen in Washington, Maine, and Maryland. Nevertheless, non-legislative actions can channel momentum into positive progress even during times of political stagnation. These can suffer from lack of funding or resources, though, and require the committed involvement of leaders from multiple stakeholder groups (research, industry, and policymakers, for instance).

Actions analyzed here can be implemented in a wide variety of political and economic environments. They can be grouped into clusters that align with different priority interests of states or regions. For example, more environmentally focused communities may choose actions that manage coastal resources for resilience, whereas more fiscally oriented communities may choose actions that support local industries. Challenges do emerge, however, when progress needs to be sustained with more advanced activities that rely on groups of committed leaders, working together, with dedicated time and funds. We believe that progressing through actions from "easy to hard" (**Table 1**) helps build coalitions and identify knowledge gaps that contribute to building the political and collaborative will that later facilitates more difficult steps. In addition, open dialogue among stakeholders is needed to help prioritize information needs given a community's interests. A shared vision of needs and desired outcomes will help motivate action when obstacles arise.

All of these actions, no matter how small, count toward addressing ocean acidification. Instances such as the ones reviewed also show that this action must be custom-tailored for a region, given its priorities and concerns. In conclusion, taking action on ocean acidification is clearly feasible for communities of every size, and it is not simply the territory of international intergovernmental groups. Everyone can take a part in addressing ocean acidification, even in their home towns.

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SC, SM, and CO carried out the research, analysis, and wrote the paper. JR obtained funding support for the project and helped shape the scope and analysis of the paper.

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SUPPLEMENTARY MATERIAL

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