

The U.S. West Coast Shellfish Industry's Perception of and Response to Ocean Acidification

Understanding an ocean stakeholder



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Executive summary

Since the Industrial Revolution, humans have released dramatic amounts of carbon dioxide (CO₂) into the atmosphere. About one-third of the CO₂ in the atmosphere dissolves into the ocean, causing water chemistry to change, which in turn makes seawater more acidic by a process called ocean acidification (OA). As the CO₂ concentration in water increases, the pH decreases, making it harder for marine organisms to build shell. The acidity of surface ocean waters is increasing faster than it has in the past 800,000 years.

In the mid 2000s, the U.S. west coast oyster industry experienced several years of significant production failures.

An industry-led team of university and government scientists discovered a link between OA and poor oyster-seed production. A large portion of the U.S. west coast shellfish industry is supported by and dependent on the few shellfish hatcheries that produce seed. This multi-year production slowdown marked the first documented economic loss to any industry from rapidly increasing ocean acidity (Washington State Blue Ribbon Panel on OA, 2012). Significant economic losses to the industry spurred state- and regionally led initiatives to examine the current and potential impacts of OA.

The west coast shellfish industry has been nicknamed the aquatic “canary in the coal mine.” Changing ocean chemistry has impacted this group. Their announcements of alert show the wide range of implications OA will have for other ocean industries.

Currently, little is known about how the U.S. west coast shellfish industry perceives OA and how it envisions adaptation. To examine this industry’s perspectives, we conducted a regional (Washington, Oregon, and California) survey of the industry, covering oyster, mussel, clam, geoduck, and abalone producers. The Web-based survey contained 44 questions related to five general areas: experience,



Clam harvesting. (Photo: Pacific Coast Shellfish Growers Association)

understanding, concern, partnerships, and adaptability.

Summary of major findings

Although state lines determine regulations within the U.S. west coast shellfish industry, we found that stakeholder perspectives were not influenced by state boundaries. Our findings reflect all three states and all types of shellfish producers:

- Approximately half of the industry has personally experienced negative impacts from ocean acidification.
- The vast majority believes OA is happening globally, regionally, and locally.
- The shellfish industry's understanding of OA and concern for the problem is fairly advanced.
- Industry participants and OA researchers share comparable recognition of the timescales in which natural processes change nearshore water chemistry,

The west coast shellfish industry has been nicknamed the aquatic “canary in the coal mine.” Changing ocean chemistry has impacted this group. Their announcements of alert show the wide range of implications OA could have for other ocean industries.

highlighting coherence between the groups based on vastly different approaches and backgrounds.

- Greater than 80 percent of the shellfish industry noted that OA will have consequences today, approximately four times higher than the public's perception of the threat. The contrasting levels of concern for OA consequences between industry and the public appears to be driven by differences in economic investment in natural resources and perceived and realized impacts.
- The most useful information to inform shellfish business decisions is primarily obtained locally

and through straightforward resources. Tide charts are the most useful information source, followed by interactions with other shellfish operations and on-site measurements/observations.

- Measurements of water chemistry related to ocean acidification, such as pH, appear to be more useful to hatcheries than to growers.
- There is great potential for further partnership and data sharing between scientists and industry. However, barriers do exist and should be addressed.
- Participants from all three states expressed guarded optimism on adaptability to ocean acidification.

Introduction and context

People and cultures around the world have long shared a romantic and culinary obsession with shellfish. These valuable marine resources have a beloved history and culture along the west coast as a symbol of the region's heritage, natural environment, and connection between communities and their coastlines. Commercial harvesting took off in the early 1850s, and this venture proved enormously lucrative. This response prompted cultivation techniques to increase yields, and thus the expansion of the modern-day shellfish industry.

Who is the U.S. west coast shellfish industry?

Today, the U.S. west coast (Washington, Oregon, and California) shellfish industry is estimated to directly employ 3,200 people and annually contribute more than \$270 million to the region's economy. Washington leads per-state production of shellfish and accounts for 69 percent of domestic production of farmed bivalves. Growing sites throughout this region are coastal estuaries and bays, as well as the Puget Sound extending several hundred kilometers inland. Generally, members of this industry

do not work in conventional office settings; instead, they are spatially isolated along hundreds of miles of working tideland and estuarine coastlines.



Photo credits: OPB's 'The Oystermen'



The shellfish industry's rich history is rooted along the nearshore waters and estuaries of the U.S. west coast.



Shellfish aquaculture typically involves two distinct stages. First, hatcheries condition and spawn adult broodstock-selected parents. The subsequent larvae—early life offspring—are raised to their next life stage, growout to adulthood. This marks a transition from a free-swimming phase to the sessile life stage. Second, these developed “seed” are sold to growers, who farm the shellfish in an estuarine environment using a variety of methods until their crop reaches ideal market value for harvest. (Photos: Pacific Coast Shellfish Growers Association)

This industry predominantly cultivates Pacific oysters, introduced from Japan to replace the native and over-harvested Olympia oyster. Some Pacific oyster populations naturally reproduce in the warm waters of Dabob Bay and Willapa Bay, Washington. But otherwise, the coastal waters along the western Pacific shelf are too cold for natural spawning events. Inconsistent natural spawns initiated hatchery technology in the 1970s that revolutionized the shellfish industry by enabling larval cultivation. Now, many shellfish growers rely exclusively on hatcheries to provide sufficient “seed” for their businesses. But recently, hatcheries have been challenged to produce a reliable seed supply, because ocean chemistry is changing.

Between 2005 and 2009, two Pacific oyster hatcheries in the Pacific Northwest experienced a significant drop in larval oyster production, known as the “Oyster Seed Crisis,” in which mortalities reached approximately 80 percent. Production losses documented at the Whiskey Creek Hatchery in Netarts Bay, Oregon, were linked to the intensity and timing of estuarine water with low pH. The impact of these losses rippled throughout the industry, as many growers rely on seed from this single hatchery. In addition, natural sets of Pacific oysters in Willapa Bay were below commercially practical levels for six years, and historically this is the largest region for natural oyster production on the west coast.

Now, many shellfish growers rely exclusively on hatcheries to provide sufficient “seed” for their businesses. But recently, hatcheries have been challenged to produce a reliable seed supply, because ocean chemistry is changing.

What is ocean acidification (OA), and how is it impacting the marine environment?

Ocean acidification (OA) has received worldwide attention from researchers, media, and the public as an urgent environmental and economic issue. Increasing amounts of carbon dioxide (CO_2) in the atmosphere from fossil fuel combustion, land use change, and other human activities result in increased CO_2 being absorbed by the ocean (Figure 1). The combination of CO_2 with seawater makes the water more acidic (lower pH). Although the average surface ocean acidity has increased 30 percent since the Industrial Revolution (1750s), more notable is the fact that atmospheric CO_2 concentrations are increasing

at a faster rate than any occurrences in the past 50 million years. As CO_2 emissions increase in the atmosphere, ocean acidification will intensify.

Ocean acidification makes it harder for coral, phytoplankton, shellfish, and other marine organisms to build their shells and skeletal structures (Figure 2). Shellfish larvae are especially sensitive to acidified waters during critical, early life-stage development. Ocean acidification is happening quickly, and this rapid pace of change gives marine ecosystems and coastal stakeholders less time to adapt.

The U.S. west coast marine ecosystem is recognized as an “OA hotspot” because it is experiencing corrosive conditions that are higher than global averages of sea-surface acidification. This is likely due to

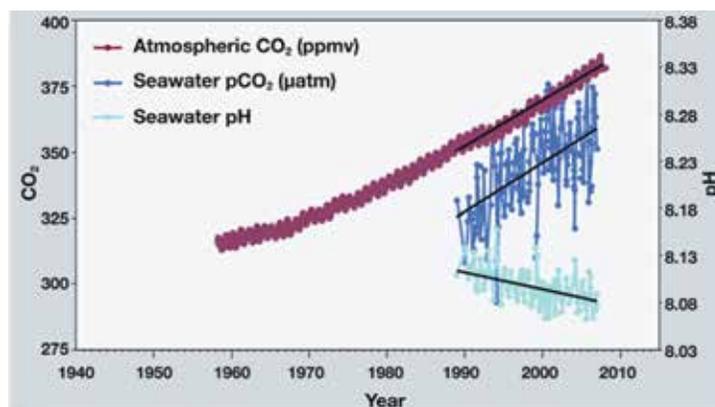


Figure 1.—Relationship between (1) rising CO_2 concentrations in the atmosphere in Hawaii, (2) rising CO_2 levels from nearby surface ocean water, and (3) decreasing pH of surface ocean water. (Courtesy of NOAA/Modified after R.A. Feely, *Bulletin of the American Meteorological Society*, July 2008)

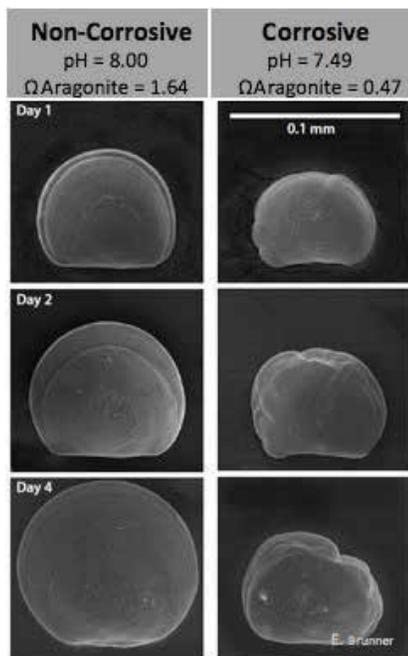


Figure 2.—Pacific oyster larvae with normal growth in non-corrosive water (left panel) and shell deformity in corrosive water (right panel) during first four days of life. These larvae were grown in naturally occurring waters of Puget Sound, within the Taylor Shellfish Hatchery. (Photo: Brunner, Waldbusser)

the fact that northern winds during summer months cause natural upwelling (Figure 3), and urbanized areas, particularly in Puget Sound, discharge stormwater and nutrients into estuarine waters, leading to an increase in acidification (Figure 4).

Why does OA matter to the U.S. west coast shellfish industry?

Understanding the complex nature of coastal ecosystems is essential when evaluating adaptation and mitigation strategies for acidification impacts,

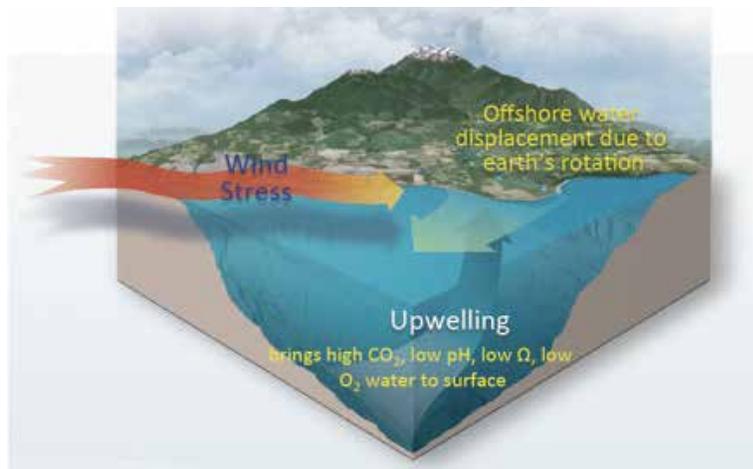


Figure 3.—Upwelling replaces surface ocean water with deep, cold, salty, nutrient-rich, and acidified water to nearshore ecosystems.

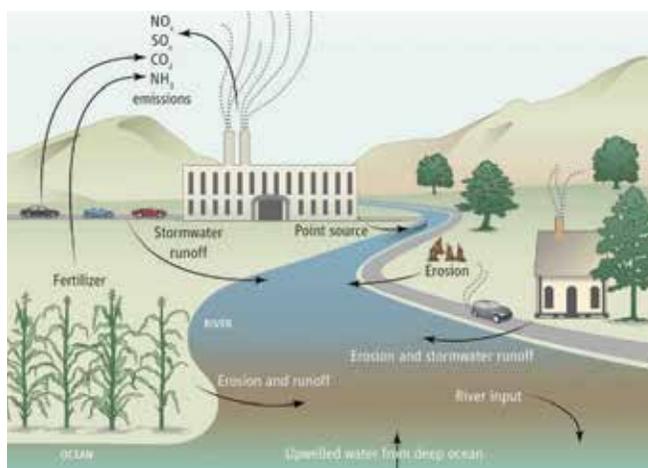


Figure 4.—Local sources of pollution and river input amplify the condition of ocean acidification in the nearshore waters. (Kelly et al., 2011)

and thus will require a combination of research and experiential insights from the shellfish industry. Recently, limited seed supply from hatcheries and unreliable natural sets had economic impacts on the industry shown by 22 percent decline of oyster production (13 percent reduction in gross sales). This reduced level of productivity prompted the Pacific Coast Shellfish Growers Association to identify seed scarcity as a top priority

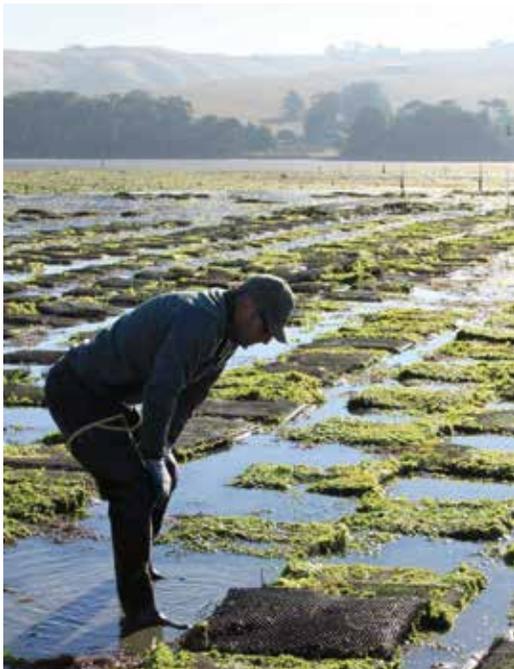
in 2009. In 2013, Oregon oyster growers identified seed availability and OA as their greatest concern. Management of marine resources has recently shifted toward integrated approaches that incorporate stakeholder insight with the implementation of coastal policy.

Policy is beginning to address OA at national, state, and local levels and the shellfish industry can help guide the process forward by sharing their insight. However, there are limited studies that examine the perspective and experience of the collective U.S. west coast shellfish industry dealing with OA related obstacles, and how they envision adaptation.

Why we did the study, what we did, and who participated

Our study focused on commercial shellfish growers and hatcheries in Washington, Oregon, and California, since they support the base of the extended commercial industry and are closely affected by outcomes of OA. Our research objectives were to

- evaluate the shellfish industry's experience with OA impacts
- assess their self-reported understanding of OA
- evaluate how experience with OA impacts and understanding influence level of concern



Oyster grower at low tide. (Photo: Chris Botnick, NOAA)

- determine which data sources provide the most useful information to the industry
- explore the potential for partnership between the industry and researchers
- investigate how the industry perceives adaptation to OA.

We began our study by conducting informal, face-to-face interviews with shellfish stakeholders at the 2012 annual Pacific Coast Shellfish Growers Association Conference and Tradeshow. We probed the industry's willingness to participate in a research project and gauge their overall view of OA. These initial interactions revealed

stakeholders' preference for Internet communication and guided the decision to conduct an online survey.

Shellfish—oyster, clam, geoduck, mussel, and abalone—hatcheries and growers in Washington, Oregon, and California were targeted to participate. State agencies and shellfish organizations along the west coast helped compile a list of potential survey participants and promoted survey participation. In total, we built a list of 189 commercial shellfish stakeholders and contacted them via e-mail in mid-January 2013 with an invitation to participate in this study.

Contributing state agencies and shellfish organizations

- Washington, Oregon, and California Sea Grant
- Pacific Coast Shellfish Growers Association
- Pacific Shellfish Institute
- Washington Department of Health
- Oregon Department of Agriculture
- California Department of Fish and Wildlife
- California Aquaculture Association

The online survey contained 44 questions and took about 30 minutes to complete. The survey was pre-tested and revised based on the length and layout, the sequence of questions, and use of terminology. The survey was open for seven weeks and concluded at the end of March 2013.

A total of 86 questionnaires were collected; just about half of the industry responded (46 percent overall response rate). Ninety-six percent of respondents answered all 44 questions. The total response was 95 percent growers and 5 percent hatcheries, and most of the participants were owners and managers. Responses by state and shellfish product are summarized in Figure 5. The response to the survey generally reflects the distribution of the shellfish industry along the west coast.

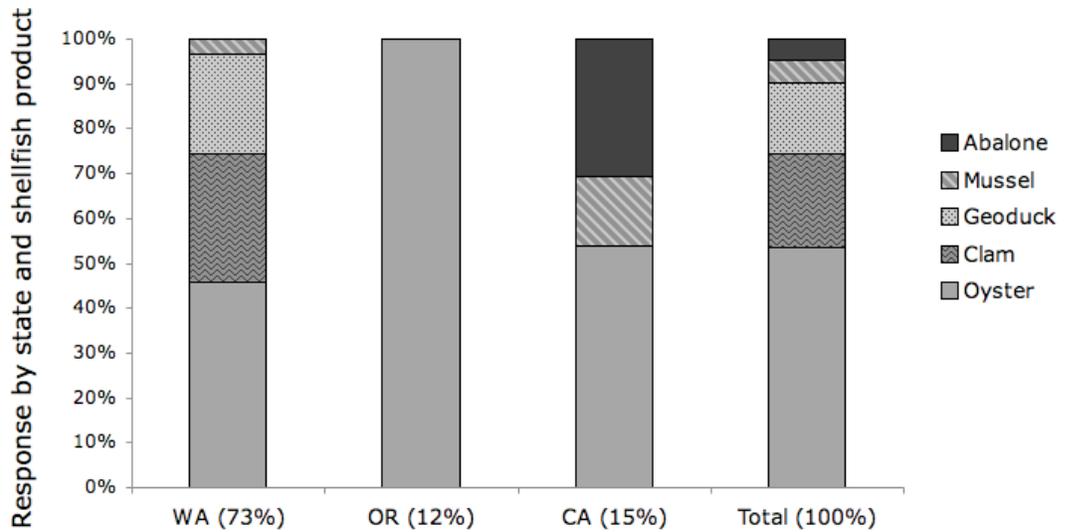


Figure 5.—Response percentages by state and overall, showing proportion of participants from each type of shellfish production. Most participants were oyster growers in Washington. All Oregon participants were exclusively oyster producers, and California was the only state with abalone producers.

The aquatic “canary in the coal mine”?

Is the industry experiencing OA impacts?

When asked whether they had heard the term “ocean acidification,” only six percent of survey participants had *never* heard this phrase. When navigated beyond this section of the survey and asked a follow-up question on the length of time since they first heard of OA, 11 percent indicated “0 to 2 years ago,” 47 percent “2–5 years ago,” 33 percent “5–10 years ago,” and 9 percent “more than 10 years ago.”

Over half (51 percent) of survey participants reported that they *had personally experienced* negative impacts from OA, and 31 percent indicated *not knowing*. When queried about the type of negative impact experienced, nearly all participants reported financial impact and almost 70 percent indicated an emotional impact:

Ocean acidification kills larvae—larvae are my business. This makes me sad and angry.

Seventy-one percent of participants knew a member of their industry who experienced negative impacts from OA. We examined personal experience with negative OA impacts among shellfish products. It appears oyster and clam producers are experiencing the most negative impact. Survival of out-planted geoduck seed in one

hatchery has markedly improved since implementation of a buffering program for hatchery waters; interestingly, this was noted after the survey was conducted and points to the many potential, present-day, sub-lethal acidification impacts of which we may be largely unaware.

I’ve been unable to buy sufficient oyster seed for my farming business because the suppliers are unable to produce enough.

Eighteen percent of participants reported *no* personal experience with OA impacts. Interestingly, geoduck participants represented the highest proportion of respondents (43 percent) who have *not* personally experienced negative impacts from OA.

What is the industry’s perceived understanding of OA?

“Understanding” is a measure of knowledge and demonstrates the importance and relevance of a topic. We consider understanding to be a combination of knowledge from experience, intuition, tradition, science, etc. Later we discuss from where the industry obtains information to inform its understanding and its business decisions regarding shellfish production. Figure 6 displays how

“Ocean acidification kills larvae—larvae are my business. This makes me sad and angry.”

“I’ve been unable to buy sufficient oyster seed for my farming business because the suppliers are unable to produce enough.”

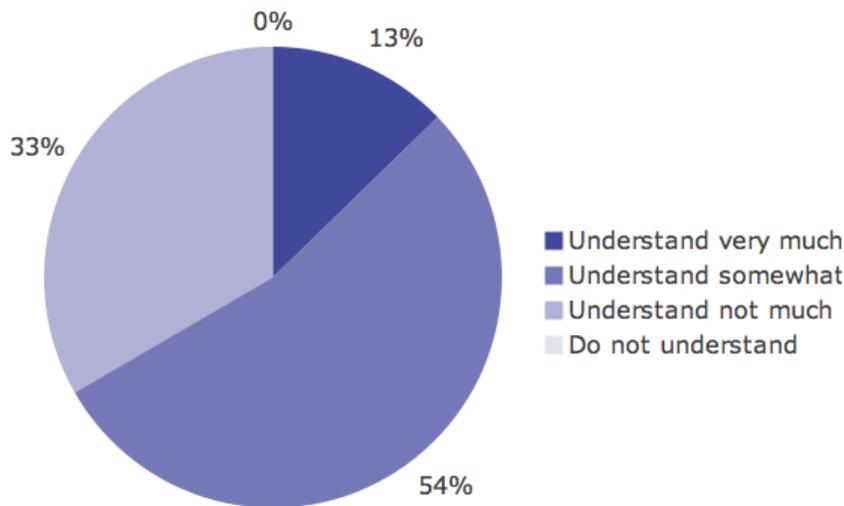


Figure 6.—Participants’ perceived level of understanding OA.

participants reported their perceived level of understanding of OA. The shellfish industry’s understanding of OA is fairly advanced, and most participants *somewhat understand* OA; zero participants reported *no understanding*. Overall, the vast majority (more than 80 percent) of participants believe that OA is happening in the global ocean, along the U.S. west coast, and at their local site of business. “We are becoming aware of the issue and its potential impact on our business, so we need to learn more about this issue as research is being done on it.”

While the industry as a whole demonstrates an advanced understanding of OA, we wanted to examine overlap and discrepancies in OA understanding between shellfish stakeholders and researchers. We conducted a post-hoc survey of 10 researchers with academic work relating to OA at Oregon State University, in Corvallis, Oregon. Both groups answered identical

questions about the timescales for marine processes to effect a change in nearshore water chemistry.

Generally, OA researchers and the shellfish industry agreed that

- ocean currents and atmospheric CO₂ absorbed by the ocean change the acidity of seawater over longer timescales
- upwelling and rivers delivering freshwater change the acidity of seawater over intermediate timescales
- photosynthesis and respiration change the acidity of seawater over shorter timescales

The general agreement between the industry and researchers is compelling, as comparable recognition of OA information can improve communication between the shellfish industry and researchers. This further demonstrates how experiential and academic knowledge are both valuable contributors to understanding OA, and may align.

What is driving the industry’s level of concern about OA?

Concern is a measure of awareness, the acknowledgment of a problem, and the potential for collective action. Participants indicated their level of concern about the problem of OA: 36 percent were *extremely concerned*, 39 percent were *very concerned*, 20 percent were *somewhat concerned*, 4 percent were *not too concerned*, and 1 percent was *not at all concerned*.

Of participants who personally experienced negative impacts from OA, 93 percent were *extremely to very concerned* about the problem. However, 64 percent of respondents who had not personally experienced negative impacts from OA were still *extremely to very concerned* about the problem. Fifty-four percent of participants who did not know whether they personally experienced negative impacts from OA were still *extremely to very concerned* about the problem (Figure 7).

All participants who reported understanding OA very much also felt extremely to very concerned about the problem of OA. Seventy-nine percent of respondents who understand OA somewhat also feel extremely to very concerned about the problem of OA. Furthermore, 63 percent of respondents who understand OA not much still feel extremely to very concerned about the problem of OA. Overall, 77 percent of participants were extremely to very concerned about OA, regardless of their level of understanding. Results indicate that a participant’s level of concern for the

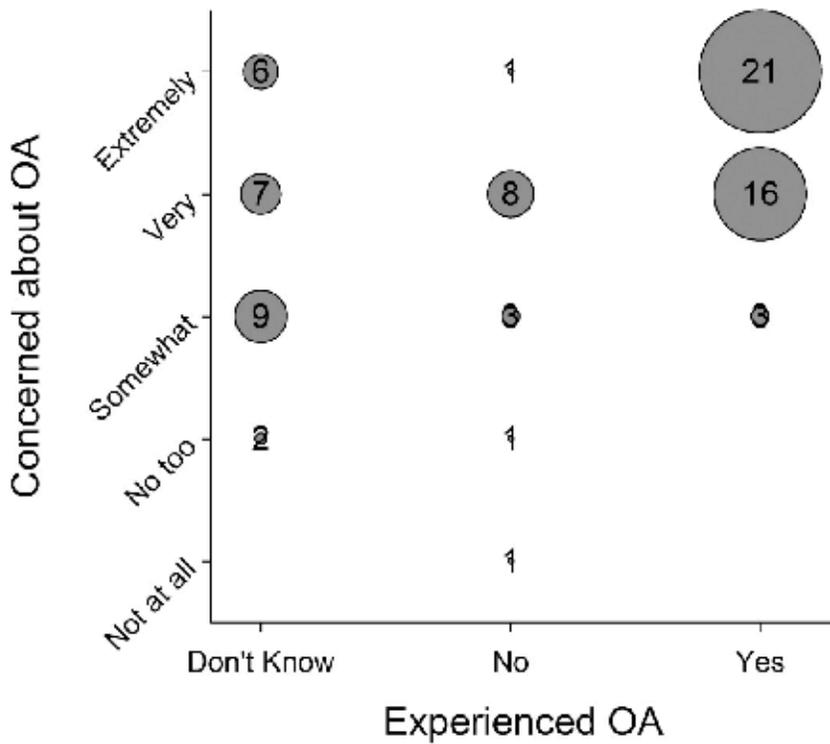


Figure 7.—This plot shows the connection between experience with OA and level of concern by the numbers of participants falling within each category. The larger bubbles indicate more participants (with actual numbers noted within the bubble) who share the same perspective, while smaller bubbles indicate fewer participants who share the same perspective. The majority of respondents (n=21) have experienced OA and are extremely concerned about the problem.

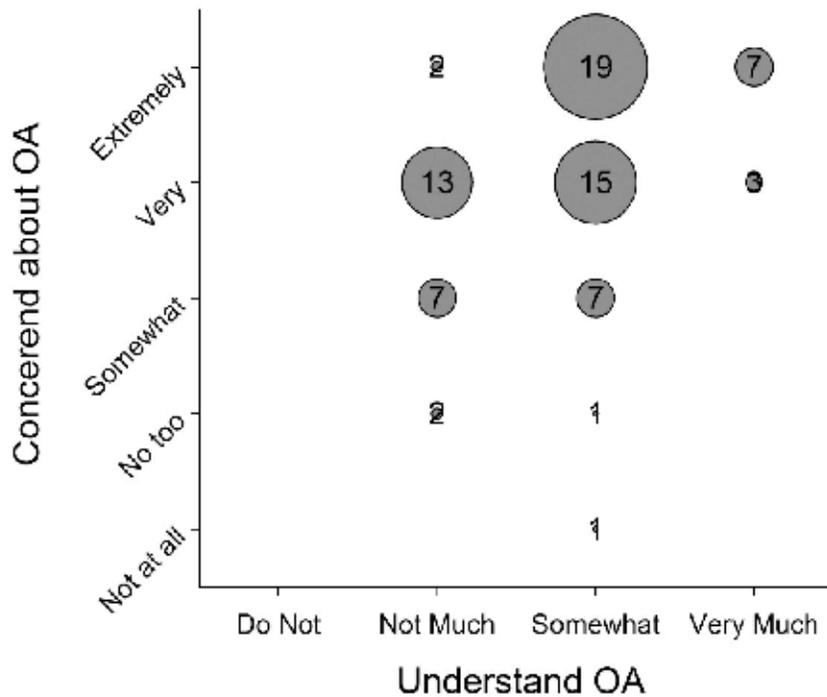


Figure 8.—This plot shows the connection between understanding OA and level of concern, with the same format as above. The larger bubbles indicate more participants who share the same perspective, while smaller bubbles indicate fewer participants who share the same perspective. The majority of respondents (n=19) somewhat understand OA and are extremely concerned about the problem.

problem is not entirely reflected by understanding OA, and, as previously noted, negative experiences with economic losses may be a greater contributor to one’s level of concern:

I may not understand the data but I believe it and feel concerned about it.

Participants acknowledged OA and felt concerned about the problem through their beliefs, experiences with negative OA impacts, and economic losses.

How do the shellfish industry and the public view present and future OA consequences?

It is interesting to compare the public’s response regarding the consequences of OA to those of the shellfish industry. To look at this, we asked three identical questions that had been answered by a representative sampling of the U.S. public in research conducted by the Ocean Conservancy and Edge Research. A Comparison of responses shows the shellfish industry recognizes OA consequences for (1) people today, (2) people in my lifetime, and (3) future generations, to a far greater extent than the public (Figure 9).

Although the public viewed fewer consequences from OA at present, they recognized that consequences from OA would increase in future scenarios. The contrasts in these responses on perceived OA consequences between the public and the shellfish industry are likely driven by differences of economic investment in natural resources, as is shown in other industries. Previous research regarding how the public processes information about complex issues found that

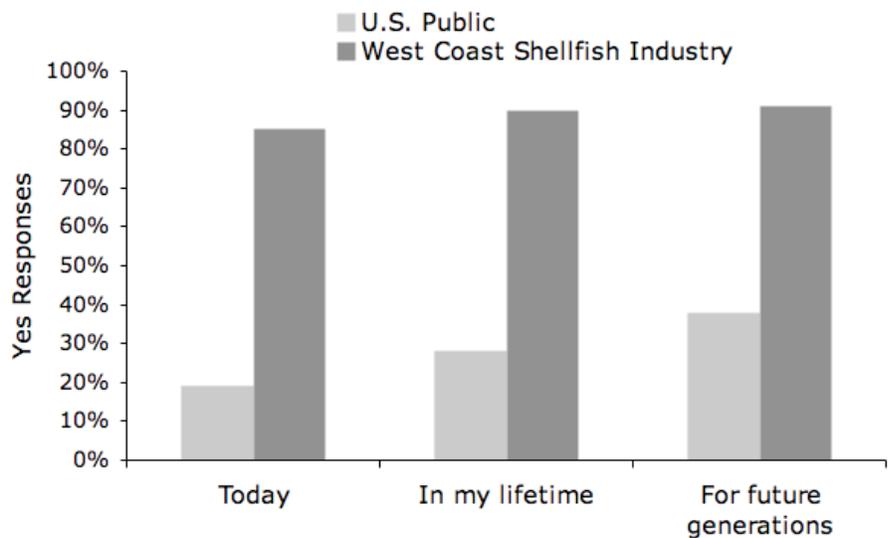


Figure 9.—The shellfish industry recognizes OA consequences for “today,” “in my lifetime,” and for “future generations,” to a far greater extent than does the U.S. public.

individuals generally use information that is most easily assessable but not necessarily relevant. While the shellfish industry is a key stakeholder group with a highly developed recognition of OA as an environmental and economic hazard, the public’s level of concern about the severity of OA may increase substantially only after personally experiencing food security issues.

Which data sources provide the most useful information?

Investigating the usefulness of information sources can provide insight on communication preferences. Participants indicated how useful a variety of data sources are to inform their business decisions. Overall, information is primarily obtained locally and through straightforward resources. Eighty-three percent of participants agreed that tide charts are the most useful information source, and interactions with other shellfish operations and measurements from

on-site observations are the second- and third-most-useful information sources (Figure 10).

Regional information is being shared across state boundaries, as participants reported using both the NANOOS (Northwest Association of Networked Ocean Observing System) and CeNCOOS (Central and Northern California Ocean Observing System) online platforms. A survey respondent noted, “We have a small operation and I did not know that the information was available through so many sources,” indicating that the survey raised awareness.

There were differences based on the roles respondents played in the industry. For example, hatcheries are interested in collecting and monitoring pH data, while growers are paying less attention to this environmental measure. Differences may stem from the ability of hatcheries to control and manipulate water conditions. Hatchery environments have the potential to provide refuge to larvae by monitoring pH and buffering seawater with

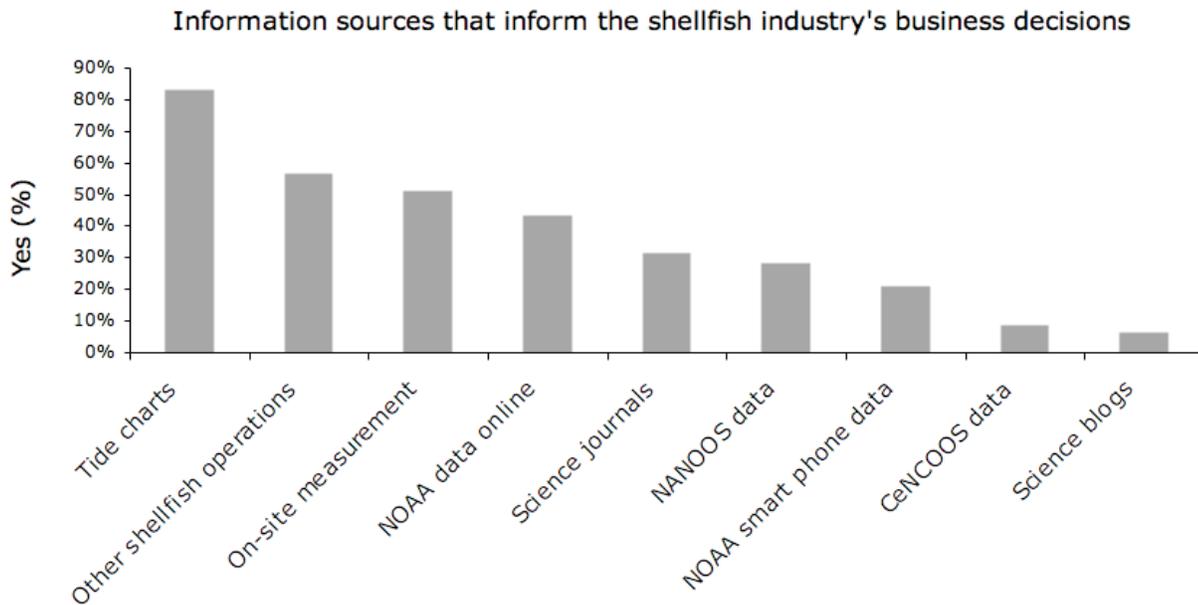


Figure 10.—Information sources used to inform business decisions of the shellfish industry in order of decreasing usefulness.

sodium carbonate. Measuring water chemistry can also reveal “windows of opportunity” when conditions are favorable, based on tides, daily photosynthesis, and nightly respiration cycles.

Grower respondents tended to share an attitude that their business operates at the whim of “Mother Nature,” implying that water conditions are outside their control. However, it is worth investigating whether pH measurements are also not used because this site-specific data is just not available. The following quotes taken from the narrative data support both scenarios:

Just because we don't measure some of these parameters doesn't mean we are not interested. We are limited in our equipment and budget.

I call this [ocean acidification] dealing with mother nature... I cannot change what comes at me from the world.

How can the shellfish industry and scientists work together when dealing with OA?

It is widely recognized that scientists can learn from stakeholders, and stakeholders can learn from scientists, when addressing questions to support shellfish production (breeding programs and triploid oysters). Recent researcher and hatchery collaborations have shown that current, high-CO₂ conditions are negatively impacting bivalve larvae, and research findings prompted hatcheries to selectively pump tank water with higher pH to allow more continuous operation.

Survey participants reported on the usefulness of university-based research and their willingness to share data. Sixty-three percent thought university-based research was *usually* to *extremely* useful, and 90 percent were *somewhat* to *very* willing to share data (Figure 11). Willingness to work with scientists demonstrates the

industry's respect for the intention and value of research. Further, the majority of participants agreed that the shellfish industry and science are the groups tasked with the highest priority for addressing OA. Acknowledgment of joint responsibility to address OA shows great potential for collaborative partnerships.

However, participants who generally maintained a positive attitude toward research and the sharing of data also shed some light on barriers that may potentially obstruct partnerships between industry and scientists:

My trust in many of the researchers is fading. An increasing percentage seems more concerned and focused on perpetuating their income and personal agenda than in solving problems so the shellfish industry can remain functional.

So called scientists who are just industry and grant hacks are too numerous. Researchers are

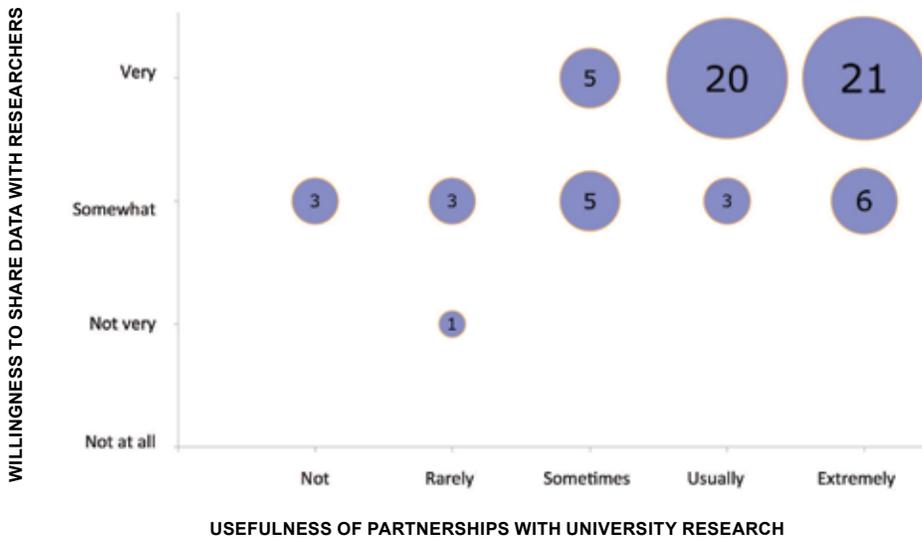


Figure 11.—This plot shows the connection between the usefulness of university partnerships and willingness to share data. The larger bubbles indicate more participants who share the same perspective, while smaller bubbles indicate fewer participants who share the same perspective. The majority of respondents (n=21) think that university partnerships are extremely useful and are very willing to share data.

the worst and normally start out with the answer already decided. It is obvious and needs to be fixed before we can go any farther.

Don't dismiss or dodge questions from people who are questioning OA.

I don't think that scientists that study this stuff would assert with certainty impacts from OA.

While it wasn't a primary research objective, we were interested in participants' feedback on this study. Although some participants expressed disappointment with the wording of survey questions and felt that this attempt to explore the needs of the industry was insufficient, others expressed gratitude for the opportunity to express their insight:

...Felt like I was providing data for some study to support theory

and not find out what the real problems ocean acidification is having on my business and the shellfish industry.

Thanks for putting this survey together! There is clearly a lot of work ahead in quantifying effects, communicating to policy, and monitoring.... The big question is how do we live with what is coming in these pH changes...

Thank you for the survey. I want to learn more about my location and look forward to participating in any way possible.

Thank you for undertaking the survey and disseminating results. OA is one of the top threats, environmental or otherwise, to continued health of our businesses and crops.

Overall, 80 percent of respondents indicated they were interested in being

contacted to receive a summary report of survey findings. It could be interpreted that this research with the shellfish industry fostered a sense of stakeholder ownership and partnership.

How does the industry feel about its ability to adapt to OA?

The ability to adapt to climate change is a topic of great interest in research these days, with many natural and social scientists studying vulnerability (sensitivity, susceptibility, and exposure), resilience (the ability to cope with change), and adaptive capacity (the ability to evolve). For this study, we consider adaptation as the capacity of the marine system to respond to a hazard such as OA while maintaining everyday “self-interest.” A recent study of commercial fishing captains revealed that their industry is adapting to environmental changes and variability of fish populations associated with climate change, despite low agreement (13 percent) that climate change is happening. Ultimately, industries that rely on marine resources will have to adopt practices to compensate for the changing ocean conditions happening today. The capacity of the shellfish industry to adapt to OA will be greatly enhanced if the industry recognizes this environmental hazard.

Survey participants reflected that most (52 percent) of the shellfish industry felt *somewhat* able to adapt to OA, while 29 percent reported *not knowing* their level of OA adaptation (Figure 12). Seven percent of participants felt *definitely* able to adapt, 9 percent were *not really* able to adapt, and 3

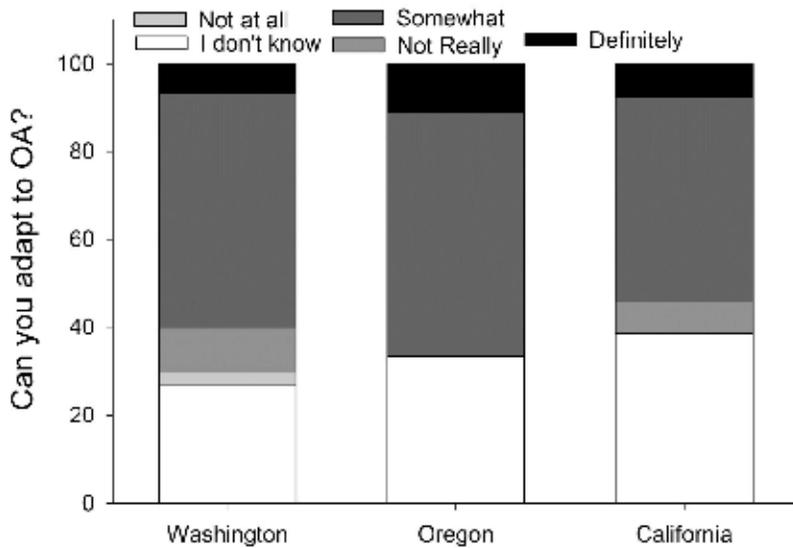


Figure 12.—The industry shows a guarded optimism regarding its adaptability to OA. There were no differences in perceived ability to adapt among states.

percent reported *not at all* able to adapt. Thirty-nine percent of the industry acknowledged that they have personally experienced negative impacts from OA and still felt *definitely* or *somewhat* able to adapt. While facing OA, the industry is working toward adaptation strategies that sustain the

shellfish resource and their businesses. Hatcheries have successfully adapted to OA in the short term, and this accomplishment may inspire confidence that adaptations can sustain shellfish resources. The data from the narrative portion of the survey reflected the perspective that

there is general agreement that “Short term we can adapt. Long term is unknown.” Figure 13 presents a model displaying the current (2013 – left panel) and future (2050 – right panel) pH trends for the U.S. west coast and marine ecosystem. Data from the narrative portion of the survey reflected the variety of perspectives related to the present and future:

I think in the long term we are screwed. Duh.

We’re on a pathway that will have numerous ugly outcomes in the future...

Ocean acidification has already happened and has already impacted our industry to the tune of tens of millions of dollars each year. The quicker we get this message across to the general public, the quicker we can get around to trying to salvage what’s left.

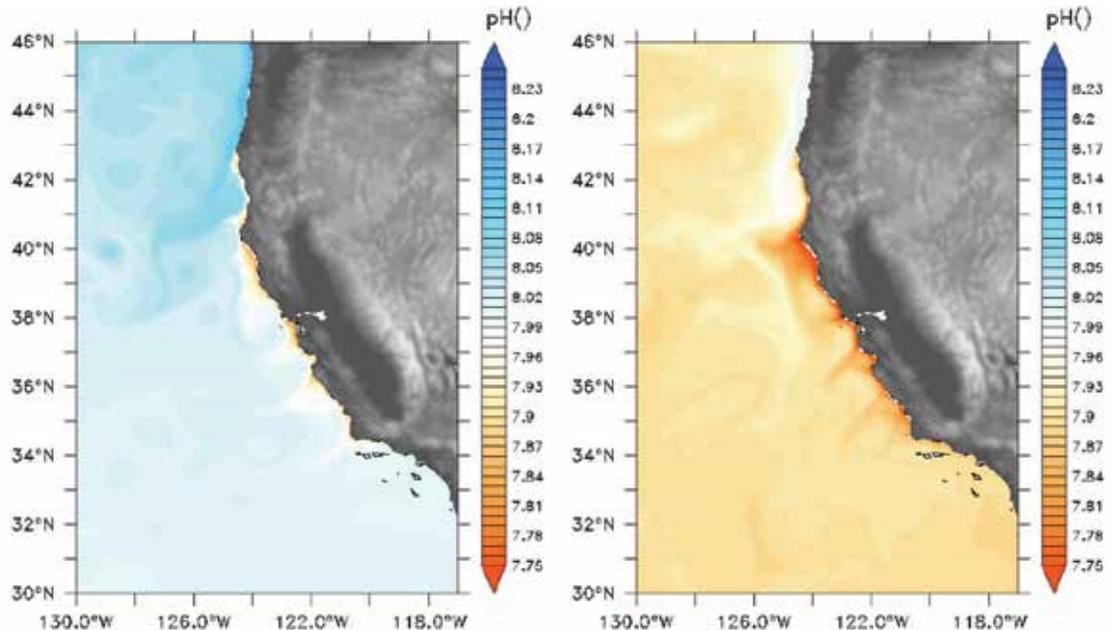


Figure 13.—Model shows current (2013 – left panel) and future (2050 – right panel) pH trends for the U.S. west coast and marine ecosystem. Lowest pH levels are shown along the coastlines. (Figure adapted from Gruber et al., 2012)

Conclusions

The U.S. west coast is home to ecologically and economically important shellfish. However, the intrusion of acidified water, and a projected increase in magnitude and frequency of these waters, poses a serious threat to shell-forming organisms and the associated commercial shellfish industry. Survey results show the shellfish industry experiencing OA impacts, learning about it and its consequences, and committing to adaptation.

This industry possesses unique characteristics that may promote innovative adaptations that sustain production in future climate-change scenarios. Shellfish hatcheries and

growers appear to share a collaborative mentality that fosters trusting relations. Perspectives on OA were not significantly different among states, demonstrating how communication and community are cultivated within this industry. This shellfish industry acknowledges the problem of OA, as they are presently encountering change and are feeling pressure to act.

Continuing to document losses and returns from implemented adaptation strategies can improve managers' and scientists' ability to support these stakeholders. Maintenance and expansion of monitoring and research to quantify the magnitude of OA impacts on the shellfish industry ultimately should help justify the costs of implementing adaptation strategies. As shown, such strategies already have offset a large portion of the current oyster seed losses due to OA.

When relaying research to industry, the attention must focus on issues and aspects that are directly relevant to operations or profit. Also, science that is understood and applied is more likely to be incorporated, or at least considered. Since understanding is a combination of knowledge from experience, intuition, tradition, science, etc., the potential exists for collaborative research and data sharing between scientists and industry. Issues of lack of trust, frustration,



Clam bags in eelgrass. (Photo: Pacific Coast Shellfish Growers Association)

and uncertainty, however, need to be addressed. In a rapidly expanding and relatively new field of research, inconsistent and contradictory results may hinder the ability of the collective scientific community to deliver a clear message (Gattuso et al., 2013). But increasing interactions, in consort with making the scientific process unbiased and transparent, can help restore trust (Luhmann, 2000).

Scientists need to involve shellfish farmers to direct research so that it is relevant and useful. This would be a major shift in research ideology that would better serve the public.

...We would benefit from organized forums with facilitated information exchanges.

Monitoring and adaptation are rapidly evolving and we could benefit with some structured dialogue periodically.

Scientists at Oregon State University and University of Washington are among the leading experts in understanding OA and how marine organisms respond to acidification stress. Washington has designed a strategic action plan for responding to OA that focuses on reducing CO₂ emissions, runoff of nutrients, and pollution from local, land-based sources. In addition, they recognize the importance of filling knowledge gaps, building awareness among stakeholder groups, and promoting scientific collaboration. California and Oregon have developed shellfish initiatives to restore and expand shellfish resources.

Often described as the “canary” in an acidic “coal mine,” the west coast shellfish industry should have our attention; we must listen to their “voice” and consider its influence for future policy options. The perceptions of this industry can inform the acceptability and implementation of management and the ultimate effectiveness of different strategies to sustain commercial production. Inevitably, OA has happened and ocean acidity will worsen significantly in nearshore waters of the west coast in the coming years. Scientists, policy-makers, and stakeholders need to act quickly and work together to protect ecologically and economically valuable marine resources and coastal communities.

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Glossary of terms

Acidity—The concentration of hydrogen (H^+) ions in a solution.

Alkalinity—A measure of the maximum capacity of an aqueous solution to neutralize acids.

Aragonite—A specific crystalline form of the mineral calcium carbonate, found in mollusc shells (particularly the larval and juvenile forms) and coral skeletons. It dissolves more readily than calcite.

Benthic—In contact with the ocean bottom.

Bivalves—Belong to the taxonomic class Bivalvia; they are bivalves (two shells), molluscs that include mussels, clams, abalone, and oysters.

Calcifier—An organism that uses calcium carbonate to form shells, skeletons, carapaces, and other stiff structures; for example, molluscs, corals, crustaceans, and some algae.

Calcium carbonate—A mineral composed of calcium (Ca^{2+}) and carbonate ions (CO_3^{2-}). Marine calcifiers incorporate specific crystalline forms of $CaCO_3$ (e.g., calcite and aragonite) into their shells, skeletons, and other hard body parts.

Carbonate chemistry—The inorganic dissolved chemical species of the carbon system in a solution, including dissolved carbon dioxide

(CO_2 [aqueous]), carbonic acid (HCO_3^-), bicarbonate (H_2CO_3), and *carbonate ion* (CO_3^{2-}).

Estuary—A partially enclosed coastal body of water with one or more rivers or streams flowing into it, and with a free connection to the open sea. Estuaries are among the most diverse and biologically productive ecosystems on Earth.

Keystone species—A species upon which other species of a community depend, whose removal leads to reduced species diversity within the community.

Larvae—An immature, free-swimming life stage that is quite different from the adult form.

Ocean acidification—Reductions in the pH of seawater due primarily to the uptake of carbon dioxide from the atmosphere by the ocean, but can also be caused by other chemical additions or subtractions from the ocean.

PCO_2 —The partial pressure of CO_2 . Quantitative units used to describe pCO_2 are microatmospheres (μatm), which are a unit of atmospheric pressure equal to one-millionth of 1 atmosphere (atm).

pH—The term used to describe *acidity*; pH is the negative log of the hydrogen ion (H^+) concentration in an aqueous solution. Neutral pH is 7.0.

Solutions with pH values less than 7.0 are “acidic,” and those with pH values greater than 7.0 are “basic.”

ppm—“Parts per million”; often used to describe the relative abundance of dissolved chemical species or gases in water.

Photosynthesis—The process used by plants and other organisms to capture the sun’s energy to split water into hydrogen and oxygen. The hydrogen is combined with carbon dioxide (absorbed from air or water) to form sugar (glucose); oxygen is produced as a waste product.

Phytoplankton—Photosynthesizing microorganisms that inhabit the upper sunlit layer of the ocean. In terms of numbers, the most important groups of phytoplankton include the diatoms, cyanobacteria, and dinoflagellates.

Plankton—Organisms that drift in the ocean.

Point source—A single, identifiable source of pollution, such as a wastewater treatment plant.

Respiration—The metabolic conversion by organisms of nutrients into biochemical energy. Biological respiration consumes oxygen and generates CO₂ as a waste product.

Saturation state—The saturation state (Ω) of a mineral is a measure of the thermodynamic potential of that mineral to form or to dissolve. At Ω values greater than 1.0, precipitation of the mineral is thermodynamically stable.

Seed—A young shellfish, usually raised by a hatchery, suitable for transplant to a bed.

Setting; Settlement—The metamorphosis from the planktonic (free-swimming) larval form to the benthic adult form. When oysters set or settle, they are permanently attached to a hard substrate.

Spawning—Producing and releasing gametes (eggs or sperm). Males often spawn first, and the presence of sperm in the water is a stimulant to the females. Gametes are released into the water, where fertilization occurs.

Stakeholders—Individuals, groups, or organizations that can affect or may be affected by a process and/or its findings.

Substrate—A surface on which an organism grows or is attached.

Time series data—A sequence of observations that are ordered in time.

Tolerance—The ability of an organism to survive in certain physical conditions.

Upwelling—A process whereby winds push surface ocean waters away from shore, causing an upward movement of deeper waters to replace the surface water. The upwelled water is typically colder, saltier, and nutrient- and CO₂-rich, but oxygen poor. Along the U.S. west coast, the upwelling season is during summer months.

Glossary definitions were adapted from Washington State Blue Ribbon Panel on Ocean Acidification (2012) and Oyster Recovery Partnership (www.oysterrecovery.org).

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