Science-based Recommendations to Support the Adaptive Capacity of Shellfish Growers to Environmental Change on the U.S. West Coast

KEY MESSAGES

- Shellfish growers are concerned about ocean acidification and hypoxia (OAH), in addition to several other environmental stressors and socioeconomic challenges (e.g. permitting)
- They're not able to detect or monitor ocean acidification (OA), and we lack the monitoring data to pinpoint when and where OA may be impacting farms, making them particularly vulnerable to OA
- Growers identified several adaptive strategies that may help them respond and adapt to OA
- There are existing policies and active efforts by state and federal governments to support these adaptive strategies through policy action, but there are additional opportunities to further support grower's adaptive capacity.
- Given the diversity of stressors and grower challenges, a multi-stressor approach is needed to comprehensively support grower adaptive capacity: Strategy 1 (OA-focused) and Strategy 2 (non OA-focused)
- Understanding the impact of land-sea connections on coastal and ocean OA, especially with increasing atmospheric river activity, will improve forecasting abilities and potentially help develop mitigation measures.
- There is a need to advance the development of techniques or methods for increasing resiliency of stocks, such as shellfish hardening, via research and collaboration among growers, researchers, agencies, and Tribes.
- More thorough coordination and collaboration between and within regulatory agencies, scientists, Tribes, industry, and policymakers could lead to less siloed efforts and more data and lesson sharing.

U.S. West Coast coastal communities, including shellfish growers who are reliant on economically important species, have experienced adverse impacts from ocean acidification (OA) and other environmental stressors.[1] With global carbon emissions and associated warming expected to accelerate in the future, these marine environments are expected to experience even more change and impacts from OA and other climate stressors.

To date, there has been considerable scientific research and monitoring on OA to better understand its prevalence and the potential vulnerability of marine life and ecosystems.[2] State and federal governments have supported these efforts through investments via legislative and

[1] Barton et al. 2015 https://doi.org/10.5670/oceanog.2015.38
[2] Doney et al. 2020 https://doi.org/10.1146/annurev-environ-012320-083019

executive actions. State governments, including Oregon and California, have additionally developed statewide OA action plans to promote partnerships between industry, academia, and agencies to support shellfish grower resilience and adaptation. Despite this progress, there is a need to better understand all potential sources of vulnerability (i.e. environmental, economic, social, policy) to inform timely strategies to respond and adapt to OA.

THE APPROACH

A scientific team of experts conducted a multidisciplinary effort to understand the vulnerability and adaptive capacity of shellfish growers in California and Oregon to OA and broader environmental change. Specifically, the team:

- Conducted geospatial analyses to assess the environmental vulnerability of shellfish growers to a range of environmental stressors;
- Surveyed shellfish growers to understand their perceptions of environmental change and potential adaptive strategies to respond to OA;
- Reviewed and evaluated existing state and federal policies to determine how these policies may support grower adaptive capacity; and
- Identified actionable science and policy recommendations - in partnership with policymakers, shellfish growers, and scientific experts - to support the adaptive capacity of shellfish growers to environmental change.

As part of this effort, the project team also hosted a one day workshop to identify opportunities and actionable recommendations to advance adaptive capacity in West Coast shellfish aquaculture. Participants at the workshop included agency staff, aquaculture industry practitioners, and scientists. Presenters shared recent research on coastal vulnerability to OA and environmental stresses, industry perspectives and social vulnerabilities, and insights from policy and management. Discussions on recommendations and efforts moving forward followed presentations.

PERCEPTIONS OF ENVIRONMENTAL CHANGE & ADAPTIVE STRATEGIES

Following surveys of 11 shellfish farms in California[3] and 15 farms in Oregon[4], the team found that shellfish growers were concerned about 17 environmental stressors, including both physical (e.g. OA, rainfall, temperature) and biological (e.g. disease, nuisance species, eelgrass) factors. Importantly, growers were aware of and concerned about OA, but could not always detect its impacts, making them potentially more vulnerable to OA than other stressors. Additionally, growers shared sentiments about permitting and economic challenges that could

[3] Ward et al. https://www.sciencedirect.com/science/article/pii/S0964569122001302
[4] Green et al. https://www.sciencedirect.com/science/article/abs/pii/S0964569122004513

serve as hindrances to operations and adaptive capacity. This suggests growers may perceive other socioeconomic challenges as equally concerning as OA and other environmental stressors.

Shellfish growers identified a total of 20 adaptive strategies to respond to environmental change (Table 1). These strategies were categorized as (1) **Science** (i.e., filling key knowledge gaps through scientific research or monitoring), (2) **Farm Management** (i.e., implementing new or desired farm practices), and (3) **Policy & Networking** (i.e., regulatory changes and information sharing). Overall, shellfish growers most frequently suggested changing or clarifying the permitting and regulatory landscapes as a need for adaptation. The identification of these strategies serve as a catalyst for future discussions on a range of potential interventions that could facilitate shellfish grower adaptive capacity.

Table 1. Adaptive strategies identified by shellfish growers in CA and OR across each category.

SCIENCE	FARM MANAGEMENT	POLICY & NETWORKING
● Improve knowledge on shellfish health ● Develop broodstock with genetic resistance to environmental stressors ● Monitor OA & water quality ● Research new methods, gear types, species ● Study benefits and disadvantages of co-culturing shellfish with other species	● Increase spatial & temporal flexibility for growing products in response to environmental changes ● Increase/change method/gear types used ● Alter water intake to accommodate environmental change ● Diversify customer base via retail and wholesale businesses ● Change marketing/prices to account for shifts in cost ● Culture multiple species to diversify product line ● Culture multiple lifecycle stages in-house to avoid reliance on outside providers ● Outplant different oyster types (diploid v. triploid) to diversify stock ● Implement intentional & proactive farm management and planning ● Educate about and steward natural resources related to shellfish aquaculture	● Consider changes in water quality response & regulation ● Network within and outside the aquaculture sector ● Provide funding for implementing adaptive capacity measures ● Consider permitting, licensing, & regulatory changes

SPATIAL & TEMPORAL PATTERNS OF ENVIRONMENTAL CHANGE

To determine whether shellfish farms in California and Oregon may be environmentally vulnerable to OA and other climate stressors, the research team conducted a large data synthesis to compile publicly available oceanographic data across the U.S. West Coast[5]. At the time of the publication of this work, this synthesis included 13.7 million observations from 66 sources that spanned the years of 1949 to 2020 (the publicly available data has since increased to over 17 million observations). The research team found that observations were more common in nearshore, near-surface environments and there was a peak in spatial coverage of monitoring in 2015. This temporal trend is especially true for OA-related observations, where there have been significantly more measurements of pH, TA, DIC, or pCO2 after 2006, but declines since 2015. This is in contrast to temperature and salinity, which have been more consistently measured for several decades.

Furthermore, this synthesis illuminated that there is a lack of continuous, high-resolution OA monitoring in most bays, estuaries, and inlets where shellfish farms are typically located (Figure 1). Without the data and resources to track OA, it is challenging to understand the degree to which shellfish farms are environmentally vulnerable, or to identify when and how certain adaptation measures might be most helpful. An investment in consistent monitoring for OA, and especially in bays and estuaries, is needed to address this challenge.

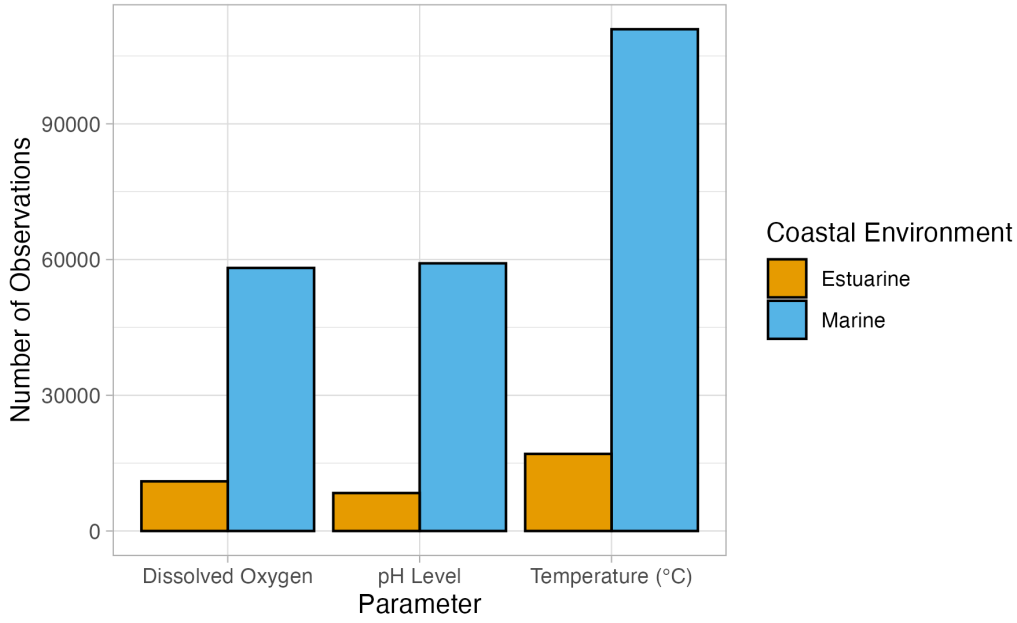

Figure 1. Comparison observations of dissolved oxygen (DO), pH, and temperature (temp) between estuarine and marine environments (both nearshore and offshore) in state waters. Observations are averaged by day, location, depth, and project. Data from Kennedy et al. 2024.

[5] Kennedy et al. 2024 https://essd.copernicus.org/articles/16/219/2024/essd-16-219-2024-discussion.html

ALIGNMENT WITH EXISTING STATE & FEDERAL POLICIES

A review of existing written state and federal OA policies (e.g. legislation, executive orders, actions, etc.) found that there are several existing policies that could support the adaptive strategies identified by growers.[6] Some of these policies are actively supporting grower adaptive capacity through investments for research and monitoring, addressing barriers to farm management (e.g. permitting), and promoting networking and information sharing (Table 2). Table 2, below, includes a subset of policies identified through this assessment that currently align with the adaptive strategies. A full list of all policies can be found in Wolters et al. 2025.

Table 2. A subset of existing state and federal policies that align with and support grower-identified adaptive strategies. CA = California, OR = Oregon, Fed = Federal.

Guiding Document	Potential Adaptive Capacity Alignment
Science	
2016 Ocean Protection Council: Ocean Acidification and Hypoxia (A.B. 2139) Amended (CA)	Develop an Ocean Acidification and Hypoxia task force to address OA science and monitoring
2022 Inflation Reduction Act (Fed)	Allocated $14 million to research OA and mitigation of impacts on coastal economies and communities
Farm Management	
2018 State of California Ocean Acidification Action Plan 5.1.4 (CA)	Provide "extension-type" of technical support that could accelerate OA into operations of shellfish communities.
2018 OAH Report Action Steps 3.1, 3.3 (OR)	Research on maintaining shellfish farm resiliency through co-production/growth of submerged aquatic vegetation (SAV), develop best management practices (BMPs)
Policy & Networking	
EO 13921 (2020) Section 6(i) (Fed)	Establishes NOAA as the lead agency for federal permits of shellfish aquaculture

[6] Wolters et al. 2025, manuscript available upon request

Guiding Document	Potential Adaptive Capacity Alignment
Fish and Game Code §15502 et seq. (CA)	Established an aquacultural coordinator within the California Department of Fish and Wildlife; created the Aquaculture Development Committee (ADC) to assist with aquaculture opportunities and barriers
2019 OAH Action Plan Theme 4 – Step 4.2.2 (OR)	OAH Council convenes "State of OAH" workshops for communities on OAH science, impacts, and solutions with policymakers as well as communities and at-risk industries

Within these existing policies, there are likely additional opportunities to support grower adaptive capacity beyond what is currently being done. For example, Wolters et al. 2025 suggests that there are opportunities to expand programs like the Emergency Assistance for Livestock, Honey Bees and Farm-raised Fish Program (ELAP) and the Noninsured Crop Disaster Assistance Program (NAP) to address chronic OA impacts. Along with potential expansion of existing programs, authors suggest that renewal of legislation pertaining to OA would bolster shellfish grower adaptive capacity. Taking advantage of the renewal of the Farm Bill, which provides insurance for all life stages of shellfish, would increase financial security for national shellfish aquaculture.

Findings from Wolters et al. 2025 also suggest that while some existing policies and programs support adaptive capacity, there is room to build more robust alignment between grower adaptation strategies and state and federal policies. Opportunities exist to support and advance adaptive strategies without policy action or change, from within existing policies, and potential with new policies (e.g., renewal of the Agriculture Improvement Act of 2018 to improve crop insurance for shellfish growers). However, not all adaptive strategies require an associated policy, as some adaptive strategies take place outside of the policy realm (e.g., networking and information sharing). Collaboration and consultation with agency staff are essential to develop actionable recommendations that will advance these adaptive strategies.

SCIENCE & POLICY RECOMMENDATIONS

This research suggests a multi-stressor approach, one that addresses both OA and the myriad of other environmental stressors and socioeconomic challenges, will be needed to support shellfish growers' adaptive capacity. In doing so, such an approach will not only reduce shellfish grower vulnerability to OA, but it will also address other potential barriers to adaptation.

Following deliberations between scientific experts, state and federal agency staff, and shellfish growers, a list of actionable science and policy recommendations were identified and organized

across two broad strategies for advancing adaptive strategies that directly relate to OA (Strategy 1) and those that do not directly relate, or indirectly related, to OA (Strategy 2). It is important to recognize that while Strategy 2 does not address OA directly, reducing one stressor's impacts (e.g. permitting) can allow growers to proactively allocate resources towards responding to other stressors (i.e. OA) in order to improve overall resilience. Thus, identifying growers' strategies to enhance their overall adaptive capacity can also help build capacity for adaptation to OA.

Strategy 1: Advance adaptive strategies that directly or indirectly address shellfish grower vulnerability and adaptive capacity to OA.

- **Conduct community-specific OA research to inform solutions:** scientific data needs to be tailored to shellfish farms (e.g. time, location, type of data) to adequately inform selection of adaptive strategies most relevant to those communities.
- **Invest in estuarine environmental monitoring and research:** There is an urgent need to ensure there is sufficient environmental monitoring to detect OA and other climate and broader environmental impacts near shellfish farms (in estuaries, bays, inlets); need for coordination between scientists & farmers to determine where those monitoring needs are; also need improved models and remote sensing approaches.
- **Ensure scientific data is accessible and delivered to shellfish growers:** Farmer's ability to respond to OA is contingent on updated real-time information about OA at their farms; additionally need the data infrastructure (e.g. repository, IOOSes website) to house data where it is most accessible.
- **Continue to advance existing OA policies that support adaptive strategies:** state and federal efforts have been vital in addressing OA and we need to continue this work; E.G. continued funding for implementation of state OA action plans.

Strategy 2: Advance adaptive strategies that improve community resilience of shellfish growers to the full range of other environmental stressors and socioeconomic challenges.

- **Invest in research to inform the efficacy of innovative adaptive strategies:** E.G. developing broodstocks with genetic resistance to environmental stressors
- **Develop new or expand existing programs to improve financial security**: explore creating an aquaculture disaster relief fund or insurance program.
- **Conduct outreach and engagement with shellfish growers to better understand perceptions of risk:** Literature has highlighted concerns about a focus on other socioeconomic factors and conditions can create cognitive barriers towards adaptation; additionally growers would like more info on ocean science and potential impacts on their farms; there's an opportunity to deliver science on the range of stressors to

farmers so they can better inform us about their perceptions of risk and what stressors they may be experiencing; this info would in turn guide management and science.

- **Explore and assess how existing policies not directly related to OA may support adaptive strategies:** Wolters et al. 2025 policy analysis looked at policies related to OA, but there may be other non-OA policies that could support adaptive strategies. We need to be lookin at these policies for additional policy opportunities.
- **Continue to explore and identify opportunities for addressing permitting challenges:** Reduced permitting timelines and costs of permitting; more farm and product flexibility
- **Explore the need for developing a community- or aquaculture-resilience policy:** state agencies (e.g. OPC, FGC) are currently or have had conversations to develop a climate-ready fisheries policy; is there a need to do the same for aquaculture where the goal would be to bring in align multiple policy initiatives and actions across sectors to advance aquaculture resilience and adaptive capacity?

OA & WEST COAST SHELLFISH AQUACULTURE WORKSHOP

The project team hosted an in-person workshop exploring the effects of OA on west coast shellfish aquaculture under a changing climate in October 2024. The goals of the workshop were to (1) share recent research along the West Coast to identify knowledge gaps and potential opportunities for support adaptive capacity of shellfish growers, (2) develop guidance and recommendations for research and policy around shellfish aquaculture resilience to OA and other stressors, and (3) determine next steps to progress common goals across agencies, organizations, and roles. Workshop participants included scientists and researchers, aquaculture industry practitioners, state and federal agency staff, and Tribal representation (see Appendix A for a list of workshop attendees). The workshop consisted of presentations on the existing knowledge of coastal vulnerability to OA and environmental stresses, social vulnerability and industry perspectives, and insights from policy and management of shellfish aquaculture and adaptive capacity. An open dialogue and discussion on identifying opportunities and actionable recommendations to advance adaptive capacity in West Coast shellfish aquaculture closed out the workshop.

Main Takeaways

- **Develop more thorough coordination and collaboration between and within regulatory agencies, scientists, Tribes, industry, and policymakers.** There have been efforts toward research-industry collaborations (e.g. California Current Acidification Network), however, agency engagement was less common or lacking. More cooperation between groups could create opportunities for data sharing, data accessibility, and shared learning. Internally within agencies, increasing connections and aligning goals between single-issue programs could begin to address the challenge of addressing multi-stressor issues. For example, more interaction between the NOAA OAP and Office of Aquaculture could lead to more effective outcomes.
- **Consider exploring streamlining permit pathways for aquaculture** via ideas such as programmatic CEQA evaluations and programmatic or general permits that would consolidate

similar projects and analyze environmental impacts in one process across permitting agencies. Many of these suggestions could potentially help alleviate the cost and effort of permitting for aquaculture industry applicants. Another streamlining approach might be to initiate collaborations between agencies and researchers to identify and fill the science knowledge gaps commonly encountered when evaluating environmental aquaculture projects, thus more rapidly securing the necessary data agencies need for CEQA analyses.

- **Advance development of techniques or methods for increasing resiliency of stocks**, such as shellfish hardening. Most experimentation cross-breeding, breeding thermal-tolerant genotypes, and priming of broodstock (known as transgenerational effects) has been largely restricted to lab studies. Developing these techniques and understanding the limitations and risks could increase resilience of species and the aquaculture community. Agencies, scientists, and farms could collaborate to expand *in situ* experimentation including sharing mortality and growth rate data and pairing with environmental data.
- **Expand scientific research on land-sea connections and multi-stressors to better understand vulnerability and impact of OAH.** With increasing extreme weather events (including marine heatwaves, atmospheric rivers, hypoxia, and HABs) activity with a changing climate, freshwater inputs to coastal and ocean systems are important to consider when predicting and mitigating impacts. Shellfish aquaculture resides in highly dynamic environments where a combination of stressors are having impacts and require a multistressor approach to better understand the risk factors and impacts to farms. Investing in both multi-stressor and land-sea connection research can help with forecasting and developing mitigation measures.

CONCLUSION

Enhancing the adaptive capacity of shellfish growers on the West Coast through a variety of strategies is critical for building resilience in the face of OA. By providing diverse strategies and recommendations, we have identified opportunities for scientists, policymakers, NGOs, and shellfish growers to collaborate and contribute to sustainable solutions. Achieving long-term resilience to OA will likely require partnerships that span multiple sectors and disciplines, emphasizing the importance of collective action. It is our hope that this research serves as a foundation for fostering such collaborations, driving forward a united effort to address the challenges posed by environmental change.

Appendix A

Participants in OA Workshop
October 24, 2024

Workshop Participants	
Kimi Rogers	California Fish and Game Commission
Alex Puritz	National Oceanic and Atmospheric Administration
Katie Cieri	California Ocean Protection Council
Randy Lovell	California Department of Fish and Wildlife
Kristy Kroeker	University of California Santa Cruz
Rachel Carlson	University of California Davis
Terry Sawyer	Hog Island Oyster Co.
Luke Gardener	California Sea Grant, San José State University
Brian Wall	Kashi Band of Pomo Indians
Charli Seyler	Ola Farms
Christina Frieder	Southern California Coastal Water Research Project
Henry Ruhl	Central & Northern California Ocean Observing System
Project Team / Organizers	
Melissa Ward	Windward Sciences
Anthony Rogers	Ocean Science Trust
Heidi Waite	Ocean Science Trust
Erin de Leon Sanchez	University of California Santa Barbara
Arielle Levine	San Diego State University
Jacqui Vogel	San Diego State University
Meghan Zulian	University of California Davis