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Navigating ocean acidification in shellfish aquaculture: Stakeholder perspectives of developing strategies in the U.S. Pacific Region

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ABSTRACT

The marine shellfish aquaculture industry across the U.S. Pacific region faces escalating ocean acidification and its associated challenges. This study examines industry participant perceptions and experiences regarding ocean acidification, additional threats, and future research needs, finding a notable decrease in perceived concern regarding ocean acidification over the past decade. Through structured interviews, broad industry perspectives are explored regarding current practices and two specific ocean acidification adaptation strategies under development: parental priming and native species portfolio expansion. While parental priming garnered cautious support contingent on scientific validation, perceptions of native species expansion were polarized, driven by skepticism about regulatory barriers, economic viability, and scalability. Enhanced environmental monitoring emerged as the most widely supported adaptation measure, underscoring its importance in addressing multiple stressors in addition to ocean acidification. By considering industry and operation characteristics while examining potential decision-making biases, this study provides unique insights for co-producing relevant adaptation strategies. Additionally, the critical role of collaboration between stakeholders, researchers, and policymakers in fostering resilience is emphasized.

1. Introduction

Ocean acidification, resulting from the absorption of anthropogenically emitted atmospheric carbon dioxide, is causing a persistent decline in the pH levels of the global oceans and a concomitant decrease in the calcium carbonate saturation state (Caldeira and Wickett, 2003; Feely et al., 2008; Doney et al., 2009; Arroyo et al., 2022). This phenomenon particularly threatens shellfish as these changes reduce the availability of carbonate ions required for shell formation (Gazeau et al., 2007). Physiological impacts of ocean acidification on shellfish are broad and include impairments in growth, calcification, reproduction, and survival, especially during the vulnerable larval stage (Kroeker et al., 2010; Barton et al., 2012; Mos et al., 2020). Consequently, marine shellfish aquaculture, which not only bolsters economies and food security but also can sustainably augment wild-capture fisheries as a global food source (Knapp and Rubino, 2016; Clavelle et al., 2019; Froehlich et al., 2022), confronts a substantial and escalating threat (Stewart-Sinclair et al., 2020).

In response to this vulnerability, there is a growing body of research aimed at understanding and enhancing the adaptive capacity of aquaculture systems globally. There has been emphasis on the necessity for strategic management techniques and community-level support to facilitate adaptation in aquaculture, particularly in regions heavily reliant on this sector for food and economic security (Clements and Chopin, 2017; Galappaththi et al., 2020). The evaluation of ocean acidification and climate change adaptation strategies across scales has

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identified that tailoring actions to specific local needs has been underdeveloped (Ekstrom et al., 2015; Miller et al., 2017). There also remains a need for work considering concrete suggestions for what actions might look like to increase individual aquaculture operators' adaptive capacities (Ward et al., 2022; Green et al., 2023), while examining how adaptation strategies are selected in practice (Siders and Pierce, 2021).

The coastal waters of the Northeast Pacific are among the most variable when considering pH and carbonate chemistry dynamics, primarily due to coastal upwelling and inherently higher acidity levels (Feely et al., 2008, Feely et al., 2012; Cai et al., 2020). As such, the shellfish aquaculture industry along the U.S. West Coast has already encountered challenges due to ocean acidification, serving as a 'canary in the coal mine' for the broader sector (Barton et al., 2015). Between 2005 and 2009, two of the region's larger Pacific oyster hatcheries experienced larval mortalities reaching upwards of 80 %, likely attributed to reduced aragonite saturation state, which significantly restricting the seed supply (Barton et al., 2015; Washington State Blue Ribbon Panel on Ocean Acidification et al., 2012). Oyster seed, which are juvenile oysters cultivated in hatcheries before being transferred to farms for planting, are important for the industry since natural settlement is often inadequate to support commercial production.

Following the attribution of the mortalities to ocean acidification, a 2013 survey found that the West Coast shellfish industry perceived immediate consequences from ocean acidification at levels approximately four times higher than the public (Mabardy et al., 2015). Subsequent studies have documented the compounded challenges faced by shellfish growers in the region. In Oregon and California, ocean acidification and other environmental stressors, such as nuisance species, marine pathogens, and water temperature, intersect with non-environmental pressures like economic constraints and regulatory burdens, highlighting the need for tailored adaptive strategies (van Senten et al., 2020; Ward et al., 2022; Green et al., 2023). This compounding set of challenges underscores the necessity for a holistic approach to research that integrates the biological, physical, and socio-economic factors influencing the industry, thereby guiding actions that are both effective and contextually relevant.

By considering various shellfish growing operation types across the Pacific region (i.e., California, Oregon, Washington, Alaska and Hawaii), we seek to build upon state-specific studies and contextualize ocean acidification experiences, monitoring practices, and solicit industry feedback regarding additional ocean acidification research. While there are numerous approaches for ocean acidification adaptation such as pH buffering of incoming seawater at hatcheries, selective breeding, nutritional enhancement, and integrated multi-trophic aquaculture to name a few (Clements and Chopin, 2017; Melo et al., 2019; Hamilton et al., 2022), this study also aims to specifically explore two emerging potential ocean acidification adaptation approaches, parental priming and native species portfolio expansion, and to shed light on their viability. As research on these strategies is ongoing, it is essential to seek perspectives of those directly involved in commercial shellfish aquaculture as mutual learning among scientists and stakeholders is vital for co-producing relevant, actionable, and transferable knowledge (Lang et al., 2012; Plummer et al., 2022).

The first strategy we consider is leveraging parental priming techniques to enhance the resilience of shellfish offspring to ocean acidification. This approach does not rely on genetic modifications but instead uses environmental conditioning of the parental generation. Exposing broodstock to low pH conditions during gonadal maturation has been shown to yield offspring with faster growth rates and better overall fitness in adverse conditions, although the physiological mechanisms underlying these improvements remain incompletely understood and are the subject of ongoing research (Parker et al., 2012; Parker et al., 2015; Zhao et al., 2017; Zhao et al., 2018). Reflecting on accumulating evidence, Green et al. (2016) and Gavery and Roberts (2017) have proposed that the aquaculture industry might utilize the advantages of parental priming. They suggest intentionally subjecting broodstocks to brief environmental stressors to boost the resilience of the subsequent generations. By harnessing these parental carryover effects, the industry could produce shellfish stocks more robust against the impacts of ocean acidification.

The second strategy considered here is expanding species portfolios to include native species that might offer inherent resilience to ocean acidification. For example, the Olympia oyster (*Ostrea lurida*) and the geoduck clam (*Panopea generosa*) have demonstrated considerable resilience to low pH conditions, attributed to their unique physiological adaptations (Waldbusser et al., 2016; Putnam et al., 2017). Notably, conservation aquaculture strategies, such as those developed for Olympia oysters, highlight the species' potential for ecological restoration and economic viability, making them a promising candidate for diversification (Ridlon et al., 2021). Furthermore, Sunday et al. (2014) suggested species native to Washington's Puget Sound, as well as those from other regions experiencing significant pH variability, have evolved adaptive mechanisms to withstand the stresses associated with relatively low pH environments. The portfolio diversification approach advocates for a strategic shift towards cultivating native species, potentially offering a viable path for industry ocean acidification adaptation.

In the following manuscript, we aim to document perceptions, preferences, and potential barriers to the implementation of these developing ocean acidification adaptation strategies. In addition, we aim to document utilization and needs regarding environmental monitoring, as it is one of the most foundational ocean acidification adaptation strategies (Barton et al., 2015). By integrating stakeholder insights into research, we seek to inform solutions that are both scientifically sound and pragmatically viable in the face of changing environmental conditions (Phillipson et al., 2012; Adams et al., 2024). Guiding this work are the following research questions: 1) 15 years after the ocean acidification-induced hatchery shortages, what is the current experience with, and level of concern regarding, ocean acidification across the shellfish aquaculture industry? 2) What types of environmental monitoring are being conducted, what motivates these efforts, and what additional monitoring and ocean acidification research is considered necessary? 3) What are perceptions about parental priming related to ocean acidification adaptation? 4) What are perceptions of native species portfolio expansion as an ocean acidification adaptation strategy? Through structured interviews, this study seeks to explore these questions, providing context-specific stakeholder insights.

2. Background

With shell middens dating back over 6000 years, indigenous people along what is now the U.S. West Coast have long harvested Olympia oysters and other native species for both cultural and nutritional sustenance (Groth and Rumrill, 2009; Reeder-Myers et al., 2022). As colonial settlers surged to the region driven by the California Gold Rush in the mid 1800's, a large-scale commercial shellfish industry developed around oyster harvesting, expanding north from San Francisco, California to Willapa bay, formerly Shoalwater bay, and the Puget Sound in Washington.

Following the subsequent overharvesting and a collapse of the Olympia oysters, species from Japan (Pacific oyster; *Crassostrea gigas* and Kumamoto oyster; *Crassostrea sikamea*) and from the U.S. East Coast (Eastern oyster; *Crassostrea virginica*) were imported to combat the decline of wild oyster populations and supply growing demand in the early 1900's (MacKenzie, 1996). In addition to oysters, the region's shellfish aquaculture industry now also includes the production of native geoduck clams (*Panopea generosa*); non-native Manila clams (*Venerupis philippinarum*), Blue mussels (*Mytilus edulis*), and Mediterranean mussels (*Mytilus galloprovincialis*); and, to a lesser extent, several other species. These species are predominantly farmed in intertidal zones utilizing a range of aquaculture methods, from lower effort beach seeding and harvesting to more involved practices that require specialized equipment and infrastructure.

The fast-growing Pacific oysters came to dominate the industry by the early 1900's, comprising over 80 % of the total annual shellfish production by live weight (Barton et al., 2015). While the U.S. Pacific region of Washington, Oregon, California, Hawaii, and Alaska represented 38 % of the national aquaculture value in 2020 (NMFS, 2024), most shellfish are produced in Washington (Pacific Coast Shellfish Growers Association, 2011). Yet across the region, the impact of Pacific coast shellfish aquaculture extends far beyond direct sales, playing a pivotal role in local and state economies. According to Northern Economics (2013), the shellfish industry directly and indirectly supports over 2700 jobs, with each dollar spent by producers generating approximately 1.8 times its value in economic activity in Washington and nearly double in California.

In the late 1970's, commercial hatcheries were established to supply growers with larvae, with a few largely dominating the market (Barton et al., 2015). In response to the ocean acidification-induced hatchery shortages between 2005 and 2009, collaborative efforts by industry members, academic institutions, managers, and the Pacific Coast Shellfish Growers Association (PCSGA) led to increased environmental monitoring, adjusted production cycles, and the implementation of large-scale pH buffering systems that add sodium carbonate to incoming seawater in hatcheries to mitigate the effects of ocean acidification (Barton et al., 2015). Other firms responded by opening hatcheries in Hawaii and other locations that are less directly impacted by ocean acidification (Barton et al., 2015). This experience has not only highlighted the effectiveness of collaborative efforts but also prepared the industry to work proactively with researchers and regulators in assessing and implementing new ocean acidification adaptation strategies. Regardless, both ocean acidification related and unrelated challenges remain. Oyster production in the U.S. has stagnated since the 1950s and remains insufficient to meet national demand, with the scale of domestic production lagging behind global outputs despite opportunities for expansion (Kapetsky et al., 2013; Knapp and Rubino, 2016; Botta et al., 2020).

3. Methods and materials

3.1. Interviews

From August 2023 to April 2024, we conducted structured interviews with commercial shellfish industry participants. To establish a list of contacts, we collaborated with academic extension agencies and nonprofit organizations, while also conducting web searches. Additionally, we attended the 2023 PCSGA Conference and 2024 Washington Sea Grant Shellfish Growers Conference to solicit contacts in-person. This final list included 99 unique operation contacts from Washington, 19 from Oregon, 10 from California, 5 from Alaska, and 2 from Hawaii. Comparing this final list with prior surveys from the region, which were compiled from state agencies and shellfish organizations to construct near-comprehensive industry-wide databases, we find that our list represents approximately 25–40 % of the total universe of establishments (Adams et al., 2011; Mabardy et al., 2015; van Senten et al., 2020). For every contact, an initial personalized email was sent to explain the project and invite participation. A second and final email was then sent as a follow-up. This approach was guided by methodologies outlined by Dillman (2006).

Responses were typed to record the interviews, with follow-up questions and clarifications on questions requiring elaboration. Interview questions were structured and presented within six categories: (1) ocean acidification impacts; (2) environmental monitoring; (3) species portfolio; (4) seed acquisition; (5) environmental priming; and (6) general/demographics, and were pre-tested with shellfish aquaculture experts. To avoid constraining responses, open-ended questions were used rather than providing predefined definitions of potential ocean acidification impacts. Within the general/demographic questions, we asked about the respondent's operation types, specifically if their business included a hatchery component (land-based hatchery producing free-swimming larvae through settlement), a nursery component (shellfish seed/juveniles maintained in land- or field-based systems prior to growout), and a growout component (where shellfish are deployed into the field to grow until harvest). The study design and interview protocol were reviewed and approved by the Institutional Review Board at the University of Washington (#STUDY00017917) and all participants provided informed consent at the start of the interviews, following an explanation of confidentiality practices.

3.2. Analysis

Survey data were explored by calculating percentages for response distributions and through non-parametric analyses that focus on data ranks. Future concern about ocean acidification impacts over the next 5–10 years, measured on a Likert scale (4-point scale: Not concerned to Very concerned), was treated as a continuous variable (Carifio and Perla, 2007). The relationship between continuous variables such as operation scale, years in the industry, generations in the industry, and future concern about ocean acidification were assessed using Spearman's correlation. To compare the distributions of continuous variables across different binary categories, Mann-Whitney U tests were applied, which compare the ranks of the data between groups. These binary variables were created to reflect positive perceptions regarding parental priming and native species ocean acidification adaptation strategies, industry experience throughout the ocean acidification-induced hatchery shortages (i.e. > 20 years of experience), ocean acidification impact, and operation type. Businesses included hatcheries, nurseries, or grow-out operations; therefore, responses were used to create three distinct dummy variables for each operation type. Additionally, Fisher's Exact Tests were used to explore associations between categorical variables, such as perceived ocean acidification impact, operation type, and adaptation strategy perceptions as either positive or negative. Open-ended responses were thematically categorized to reflect average group perspectives (Bernard et al., 2010). Although this study is primarily qualitative, these statistical analyses were applied in an exploratory manner to identify patterns and relationships within the data. Given the sample size, statistical power is limited, and results should be interpreted with caution and serve to complement the qualitative findings by highlighting preliminary trends rather than providing conclusive evidence.

4. Results

Of the 35 total interviews, 4 were conducted as video calls, while the rest occurred over the phone for a 26 % response rate of the 135 identified and contacted shellfish aquaculture operations. Owners were the largest group of respondents (48 %), with field managers (11 %) followed by hatchery managers (8 %) making up the next largest groups. The median age for respondents was 46. Among them, 83 % represented a growout component in their operation, 51 % represented a nursery component, and 40 % represented a hatchery component. These components are not mutually exclusive: 11 % of respondents were involved solely in hatchery operations, 37 % solely in growout, and none solely in nursery. Additionally, 6 % of respondents were involved in both hatchery and growout, while 23 % were involved in all three components. Hatchery and nursery only operations made up 6 % of responses while nursery and growout only operations made up the remaining 23 %.

While operations with hatcheries tended to be larger, this difference approached $p \leq 0.05$ but did not reach statistical significance ($p = 0.06$). We likewise observed no statistically significant differences across the other operation types and operation scales, though all results again should be interpreted cautiously due to power limitations. Years in the industry, respondent age, and the number of generations represented within the operation also showed no significant differences across operation types. However, there was a positive correlation between respondent age and industry experience (rho =.38, $p = 0.02$).

The response rates for the invitations sent were as follows: 30 % from California, 25 % from Washington, 10 % from Oregon, 40 % from Alaska, and 50 % from Hawaii. Tribally managed operations represented 11 % of respondents, with an additional 5 % of operations being non-tribal but operating under agreements with tribes. Washington made up 71 % of survey respondents, followed by California (8 %), Oregon and Alaska (5 %) respectively, and Hawaii at (2 %). While respondents from Washington as the majority generally reflects the general distribution of the industry (Adams et al., 2011), we did have lower representation from Oregon and California than previous surveys of the industry that omitted Alaska and Hawaii (Mabardy et al., 2015).

Across the respondents, 86 % received information regarding ocean acidification from conferences, 71 % from industry publications, 62 % from NGOs, 57 % from government agencies, and 29 % from the news. Those not receiving conference-based information often attributed this to not being members of industry groups like PCSGA. Additionally, 71 % of respondents also said they received ocean acidification information from other sources such as social media, scientific literature, academic collaborations, and general networking within the small community of the industry. Respondents also mentioned specific institutions like the National Oceanic and Atmospheric Administration, “Sea Grant”, “Woods Hole”, and Oregon State University as valuable sources of information.

4.1. Ocean Acidification Experience, Concerns, and Additional Threats

When considering whether respondents’ operations had been negatively affected by ocean acidification, 54 % reported experiencing negative effects, 32 % reported no effects, and 14 % were unsure. Comparing these results with those of Mabardy et al. (2015), a similar survey conducted a decade earlier, we find consistency in the proportion of participants reporting negative ocean acidification impacts at close to 50 %. Yet our study found a higher percentage of respondents (31 %) reporting no perceived direct impacts compared to 18 % in Mabardy et al. (2015), suggesting a shift in perceptions from unsure to no impact within the industry. For those solely involved in growout operations, 46 % reported experiencing effects. Among operations that combined nursery and growout without a hatchery, 38 % reported experiencing effects, while half of operations with all three components reported impacts. In contrast, all respondents operating exclusively as hatcheries, as well as those combining hatchery and nursery components, reported experiencing having been negatively affected.

Among those affected by ocean acidification, responses varied across different operational components. For respondents engaged solely in growout, 17 % reported implementing pH monitoring. In contrast, for respondents involved only in hatchery operations, 75 % indicated they had either increased hatchery capacity, implemented pH monitoring and buffering, or began selective breeding, with 40 % implementing at least two of the responses and 30 % implementing all three. Among operations combining hatchery and nursery components, all respondents reported using pH monitoring and buffering. For those involved in hatchery, nursery, and growout collectively, 25 % implemented increasing capacity, 75 % used pH monitoring and buffering, and none used selective breeding. Of operations with only nursery and growout components, 33 % engaged in pH monitoring. Across operations with any hatchery component, 79 % conducted pH buffering.

Notably, respondents who reported no direct impacts still recognized the potential for indirect effects. For example, one shellfish farmer who said they had not been impacted went on to state, “Anyone who produces the seed is challenged, not every provider is successful. This could be ocean acidification related.” This type of perception indicates a broad, subtle influence of ocean acidification across the industry. Nevertheless, some respondents expressed skepticism about the direct impact of ocean acidification on their operations. One grower remarked, "ocean acidification is where the funding is, but the real challenge for farmers lies in survivorship—getting shellfish to market size before they die." Another noted, "We have aggressively invested in hatchery and nursery operations, yet we’ve observed a steady decline in survival," suggesting issues beyond ocean acidification are influencing survival rates. These insights underscore a complex interplay of factors, where ocean acidification is one of many potential compounding environmental stressors with one hatchery manager noting, “2023 was a horrendous year. Hatcheries were plagued with problems that were very multifaceted.”

Using Mann-Whitney U tests with ocean acidification impact as a binary variable, we observed no significant differences between groups in terms of industry experience, operation scale, respondent age, or generations represented by each operation. When considering operation type binary variables and ocean acidification impact using Fisher’s Exact tests, we observed no significant differences between groups. Furthermore, Spearman rank correlations revealed no significant relationship between future concern about ocean acidification (defined as concern over the next 5–10 years) and respondent age, scale of operation, generational representation within the operation, or type of operation component. However, a Mann-Whitney *U* test found that those who had been impacted by ocean acidification in the past were more likely to express concern about future impacts ($p = 0.03$). Across respondents, 22 % were very concerned, another 22 % were concerned, 48 % were somewhat concerned, and 5 % were not concerned regarding future impacts. When comparing this distribution with that of concern regarding the impacts of ocean acidification from 2013 across the region’s shellfish industry (Mabardy et al., 2015), we see a shift from most respondents being in the higher levels of concern categories to the somewhat concerned category (Fig. 1).

Those not concerned attributed their lack of worry to effective current adaptation strategies during the larval phase in hatcheries, with one noting, "No because we haven’t seen any at our location; it is a creeper situation, but more like 20 years from now maybe." Respondents who are very concerned cited the unpredictability and potential compounding effects of multiple stressors. One respondent emphasized, "ocean acidification is the enemy on the hill; while immediate issues like summer mortality are more pressing, ocean acidification’s profound implications, especially alongside climate change stressors and our efforts to breed climate-resistant oysters, cannot be overlooked." Those merely concerned are wary of the long-term effects and the gradual escalation of ocean acidification’s impacts, expressing dependency concerns: "We are at the mercy of the seed suppliers, and while we mitigate the initial stages, the broader ecological changes are daunting.” The somewhat concerned group acknowledges the issue but remains optimistic about the industry’s ability to adapt. "From my perspective, it’s a water chemistry issue first; we’re monitoring and adapting, though it’s not our primary concern just yet," said one respondent, reflecting a proactive yet measured approach to future developments. Additionally, specific rather than regional physical location influenced levels of concern, with one somewhat concerned grower stating: “Where we are located is in a deep area with low oxygen and low upwelling. I think it is going to take some time for us to be impacted directly.”

A recurring theme among all groups was the uncertainty about the rate of environmental change and its specific effects. "It’s always a concern, but it depends on how fast it rises. We’ve set larvae and noticed that smaller seeds have higher mortality—whether it’s due to pH or just the nature of the beast, we’re still figuring it out," an interviewee remarked concerning ocean acidification. Among respondents who purchased seed, the expected loss to field mortality averaged 27 % across various species, although many noted the interannual variability made estimating this loss difficult. Another grower commented: "The last eight years have shown accelerated changes, not just from ocean acidification but also from weather patterns affecting our operations. We’re adapting, but it’s tough."

Within the broader spectrum of threats facing the industry, we found ocean acidification is generally considered a mid-level concern (Fig. 2).

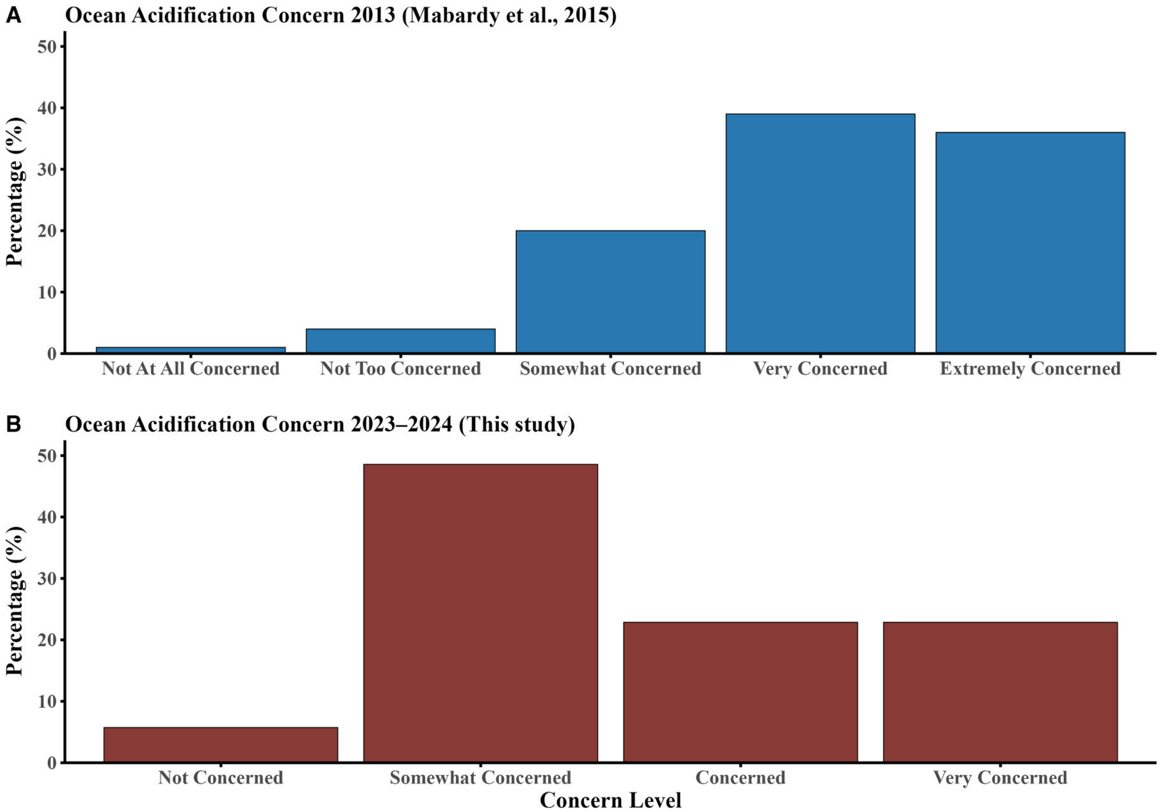

Fig. 1. Percentage of respondents reporting different levels of ocean acidification concern among U.S. Pacific shellfish aquaculture industry participants. Panel A displays 2013 general future concern levels from Mabardy et al. (2015). Panel B displays concern levels regarding the next 5–10 years from this study (2023–2024).

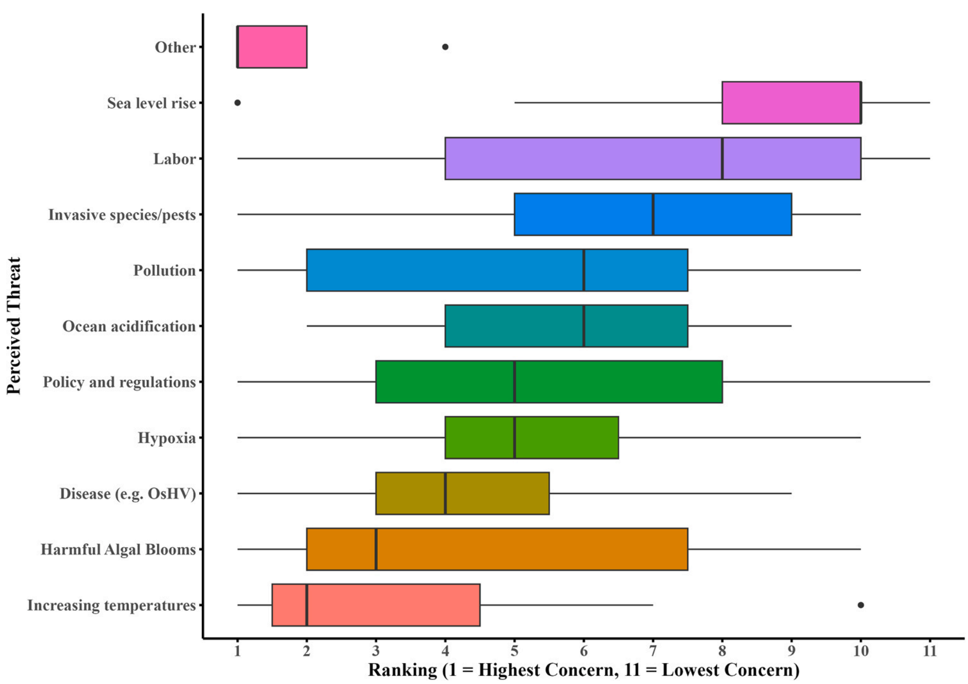

Fig. 2. Rankings of perceived threats to aquaculture operations reported by U.S. Pacific shellfish aquaculture industry participants. Each box represents the interquartile range (IQR) for a given threat, covering the middle 50 % of rankings from respondents. The line within each box indicates the median ranking, while the whiskers extend to the minimum and maximum values within 1.5 times the IQR from the lower and upper quartiles, respectively. Points outside the whiskers represent outliers.

Other threats, when specified, emerged as top concerns but were often specific to individual operations. These included diverse issues such as gear loss, algal drift, or the documented costly impact of sea lion predation (Nash et al., 2000), which one farm highlighted due to their reliance on exclusion gear. Others cited the increasing cost of materials and unexpected early spawning of crops. Additionally, environmental changes such as reduced snowpack and early melts were noted for impacting oyster mortality through starvation, especially detrimental early in the spawning season, with associated salinity changes also monitored as contributing factors. Social conflicts related to development were also mentioned, along with concerns about restrictive new regulations implemented without adequate understanding of the farming operations. Excluding these individualized responses, the predominant threats included increasing temperatures, harmful algal blooms (HABs), disease, and hypoxia. These were followed by issues related to policy and regulations, ocean acidification, pollution, invasive species, labor challenges, and sea level rise (Fig. 2).

In addition to contextualizing perceptions regarding the threat of ocean acidification, our inquiry allows for qualitative comparisons with the state-specific stressors documented from Oregon and California (Ward et al., 2022; Green et al., 2023). Across all respondents, we likewise find a diverse range of operation threats that fit within broader environmental, economic, social, and regulatory categories. However, the only non-regulatory social stressor identified during the interviews was conflicts around social licensing and a perceived increase in anti-aquaculture sentiment among rural landowners following the COVID-19 pandemic. As in Green et al. (2023), the industry participants we surveyed from Oregon similarly ranked nuisance species as a higher-level threat, while California respondents ranked environmental stressors like HABs, hypoxia, and disease as top stressors (Ward et al., 2022). When considering the threat rankings for Washington respondents, we find that environmental stressors such as increasing temperatures, HABs, and disease are top concerns, while pollution is generally considered a lower threat. In contrast, respondents from Oregon and California ranked pollution higher. This differing perception of pollution might in part be explained by an Oregon grower who noted that their farms, like those in California, are geographically contained within bays, which are being considered for wind energy development that would likely bring higher pollution levels and closures. They stated, “if a cruise ship goes by and pollutes our water I am shut down for weeks, imagine what a large shift in port traffic could mean.”

4.2. Monitoring and Research Needs

One of the earliest approaches for adapting to the impacts of ocean acidification is environmental monitoring, which allows managers to "pick their moments" to enhance larval production and survivability (Barton et al., 2015). Across the interviews, we find that monitoring remains important. Tracking temperature, salinity, and pH is ubiquitous across the operations with hatchery components. This monitoring is primarily conducted by the operations themselves, with only one operation acquiring pH from a public source instead of monitoring it with their own equipment.

In comparison, operations without hatchery components monitor less consistently, with temperature, HABs, and salinity receiving primary attention (Fig. 3). Of the public information sources, respondents mentioned several key resources, including Northwest Association of Networked Ocean Observing Systems’ buoys, various government websites, and the Harmful Algal Bloom network. Some operations hosted sensors from which they could calculate aragonite saturation state data. Research partnerships were also crucial, with some respondents relying heavily on these for daily operations.

When asked about the reasons for monitoring, many emphasized its critical nature for operational success, stating that it is essential for

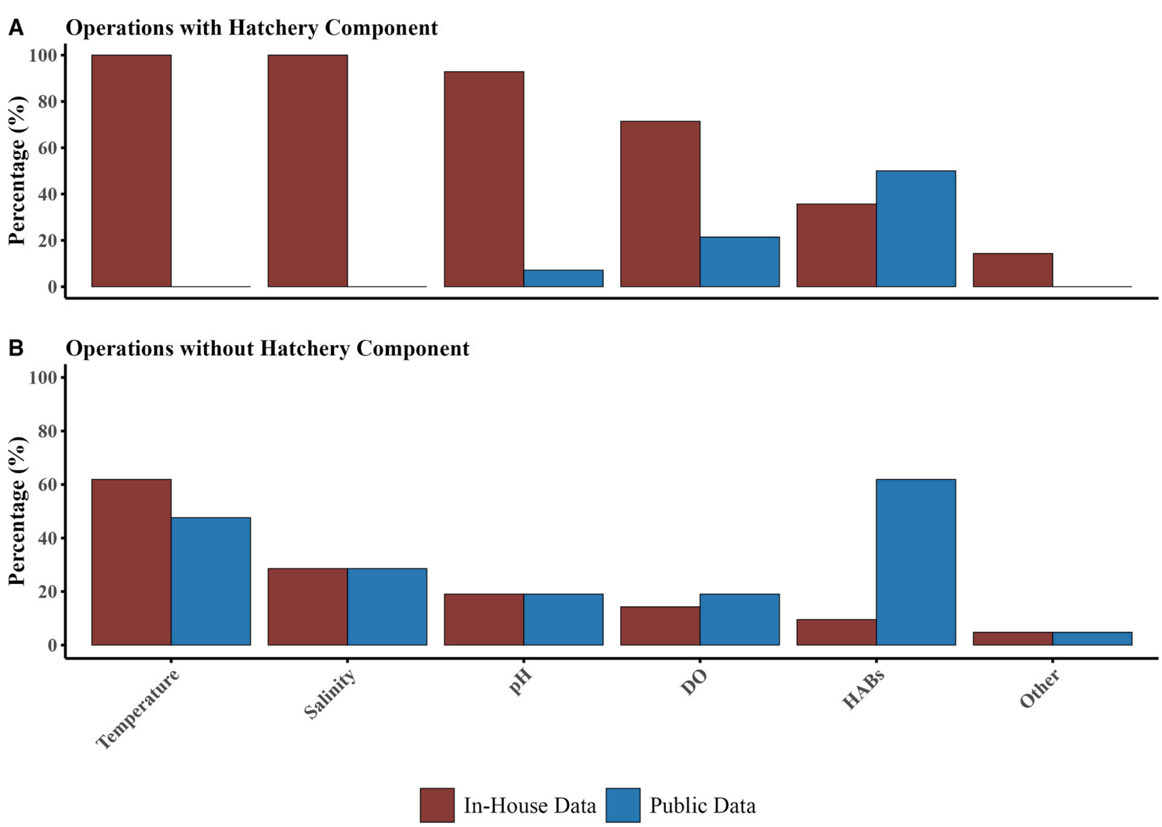

Fig. 3. Percentage of U.S. Pacific shellfish aquaculture industry participants reporting the use of environmental monitoring data sources. Panel A shows responses from operations with hatchery components, while Panel B shows responses from operations without hatchery components. Participants reported monitoring various environmental conditions using either in-house or public data sources.

understanding the environmental conditions that affect larval growth and overall hatchery operations. For instance, respondents mentioned the importance of monitoring to "reduce the black box for water coming into the hatchery" and the need to "understand what is happening and why." Safety and regulatory requirements also play a significant role in monitoring practices to ensure human safety and comply with health codes and departmental regulations. Respondents also indicated that monitoring is often driven by business needs and husbandry practices. For example, periodic monitoring helps track operational performance and respond to significant environmental issues. Some respondents mentioned using monitoring data to make informed decisions about planting and other activities, while others pointed out that monitoring helps them log and understand growth patterns.

Increased monitoring research and implementation by government, academic, and nonprofit organizations were suggested by 83 % of respondents, with some expressing the need to revive, maintain, and improve existing monitoring systems, such as buoys, which they perceived as previously more available and instrumental in tracking water conditions. Analysis across operation components, scale, and generations revealed no significant differences in the desire for additional monitoring. However, a Mann-Whitney *U* test indicated that younger respondents were less likely to want additional monitoring capacities.

Respondents expressed interest in tracking the parameters of aragonite saturation state, dissolved oxygen, and temperature more accurately, especially since many public data sources do not well reflect the intertidal and nearshore environments utilized for aquaculture. Several respondents highlighted the need for better in-house tracking of pH and dissolved carbon dioxide. Enhanced plankton monitoring, including specific types and their growth rates, was mentioned for understanding food availability and animal health impacts. Improved monitoring of aragonite saturation state was also suggested for understanding shell formation and overall health, while precise data on dissolved oxygen and temperature would be ideal for managing growth conditions. More reliable HAB monitoring was mentioned as needed to predict and mitigate potential impacts. Tracking pollutants and bacteria was also deemed important by several respondents. Furthermore, a desire for more long-term funding to support continuous monitoring efforts was highlighted.

Besides monitoring, reducing carbon emissions and deploying carbon capture techniques was suggested as a useful area for future research by 66 % of respondents, followed by breeding for ocean acidification resistance (57 %), and researching new ocean acidification-tolerant species (57 %). There is also interest in understanding the impact of environmental changes and human activities on pH levels in specific locations, such as Willapa Bay, Washington and exploring environmentally viable farming practices that could mitigate these impacts. Husbandry techniques, such as developing thicker oyster shells at an earlier stage, were mentioned as important areas for research. Furthermore, respondents highlighted the need for comprehensive modeling of ocean acidification impacts on different species to forecast future conditions and inform proactive strategies, which aligns with recent bioeconomic modeling efforts to assess the possible effects of ocean acidification on bivalve aquaculture while considering biological, appearance, and market complexities (Duarte et al., 2022).

4.3. Parental Priming Perceptions related to Ocean Acidification Adaptation

Among hatchery respondents, there was varied opinion regarding the adoption of parental priming; however, a majority indicated willingness to adopt the practice if supported by scientific literature (Table 1). Specifically, while only 7 % would implement the technique immediately, another 64 % would consider it after reviewing supportive literature, and an additional 7 % would prefer waiting to observe its effectiveness in other operations first with one hatchery manager stating "I don't jump immediately, we do trial stuff, like when we were trying Eastern oysters." Despite priming potentially being viewed as radical since hatcheries work to shelter their animals, a couple respondents mentioned they experimented with heat stressing broodstock, suggesting this type of approach would not be uniquely novel.

Table 1
Responses from U.S. Pacific shellfish aquaculture operations with hatchery components regarding willingness to implement parental priming.

Response	Count	Percentage (%)
Yes, immediately	1	7
Yes, but after other growers try it	1	7
Yes, but after reviewing literature supporting the practice	9	64
No	3	21

Conversely, the 21 % of respondents who were opposed cited concerns about broodstock stress and the financial burden of setting up new protocols under current production systems. They emphasized that minimizing stress on broodstock was a priority and that the cost implications of integrating parental priming could be significant. Capturing the severity of potential financial burdens, one hatchery manager stated, "Having a hatchery is difficult. Hatcheries don't make money, they make animals. Every year we get closer to not losing money. It costs 99 cents to make the dollar." Of the hatcheries that would adopt the practice, 72 % would implement it in both broodstock and larvae while 27 % said only in broodstock, with one hatchery manager mentioning that this would be species specific: "Larvae die in ocean acidification conditions. This would be a nightmare; geoduck in particular would be horrible."

Like hatchery respondents' cautious views on adopting parental priming, operations without a hatchery component, which therefore all included a growing component, demonstrated a guarded but notable openness to paying more for primed seed, primarily contingent upon empirical validation. The slight majority (53 %) indicated a willingness to pay more for primed seed after accessing supporting data, paralleling the 64 % of hatchery respondents who would consider parental priming after reviewing supporting literature (Table 2). Additionally, 17 % of growers would start with a test plot, while 7 % would wait to observe success in other operations before adopting the practice.

The pattern of cautious optimism contingent on proven effectiveness reflects a broader industry trend towards evidence-based practices. One grower commented, "If it is just priming for ocean acidification then I would say no to paying more, there needs to be proof on the beds with overall survivability." These responses largely track with the finding that price was only cited by 5 % of respondents that buy seed as the key factor in seed purchasing decisions, with 34 % of respondents mentioning business relationships as the key factor, 34 % mentioning availability, and 17 % mentioning previous performance. Yet, 23 % of growers were not willing to pay more for primed seed, echoing the 21 % of hatchery respondents wary of the practice. These parallels highlight an approach of balancing innovation with practical and financial feasibility. Of the growers who would pay more, 73 % would still consider paying higher prices for primed seed if survivability increased at the cost of slower growth.

Using a Fisher's Exact test, we did not observe a significant difference between groups regarding perceived direct impacts of ocean acidification and willingness to pay more for primed seed, or for hatchery

Table 2
Willingness of U.S. Pacific growers to pay more for parental priming of seed.

Response	Count	Percentage (%)
Yes, immediately	0	0
Yes, starting with a test plot	5	17
Yes, but after other growers try it	2	7
Yes, but after reviewing data supporting the practice	16	53
No	7	23

operations' willingness to adopt priming. Similarly, Mann-Whitney U tests with a binary variable for positive responses to priming indicated that industry experience, operation scale, respondent age, and the number of generations involved were not significantly associated, again noting these results may be affected by the study's limited statistical power. To explore whether respondents with over 20 years of experience in the industry were more likely to view priming across hatchery implementation and willingness to pay more, we conducted a Fisher's Exact test with a positive perception binary variable, finding there was no significant difference between the groups ($p = 0.2$; Fig. 4). However, this result should be interpreted cautiously, as the limited power increases the likelihood of a type II error.

The stacked bars reflect responses from participants with less than 20 years and 20 or more years of industry experience. Positive responses included willingness to implement priming in hatchery operations or willingness to pay more for primed seed. Fisher's exact test results are shown, with no significant relationship found.

4.4. Perceptions of Native Species Portfolio Diversification as an Ocean Acidification Adaptation Strategy

When prompted about the influence of worsening ocean acidification on the willingness to adopt new native species, opinions varied: 37 % considered it not important, while 63 % deemed it important to critically important (Table 3). Subsequently, when asked whether culturing native species with greater resilience to ocean acidification is a viable adaptation strategy for the broader shellfish industry, 51 % of respondents said no, 43 % said yes, and 6 % were unsure.

This disagreement contrasted with respondents' general and near complete willingness (91 %) to consider integrating new species, either native or nonnative, to their operations. When asked specifically about their willingness to add native species, 69 % already cultivated native species, with an additional 6 % actively adding new native species to their operations for the first time. Of the remaining respondents, 66 % were "somewhat willing," to "very willing" to do so. While Olympia oysters, geoducks, and native clams were the primary native shellfish species identified by respondents when considering this question, kelp was also mentioned especially for perceived and documented ocean acidification mitigating co-culturing benefits (Clements and Chopin, 2017; Fernández et al., 2019; Hamilton et al., 2022). Among the operations, there was a mean of 3 different species across portfolios with counts and percentages displayed in Table 4.

No significant association was found between respondents' ocean acidification experiences or levels of future concern and whether worsening ocean acidification was considered somewhat to critically important in their individual decision to add native species to their portfolio. Similarly, no association was observed between these factors and respondents' perceptions of the broader viability of this adaptation strategy across the industry. Generational involvement and respondent age were not significantly associated with either personal or industry-

Table 3
Importance of worsening ocean acidification on willingness to add new native species to individual portfolios for U.S. Pacific shellfish aquaculture participants.

Response	Count	Percentage (%)
Critically important	8	23
Very important	6	17
Important	6	17
Somewhat important	2	6
Not important	13	37

Table 4
Shellfish species, origin status (introduced or native), counts, and percentages represented in respondent portfolios.

Species	Category	Count	Percentage (%)
Pacific Oysters	Introduced	31	89
Manila Clam	Introduced	21	60
Olympia Oyster	Native	18	51
Kumomoto Oyster	Introduced	12	34
Geoduck	Native	11	31
Eastern Oyster	Introduced	5	14
Littleneck Clams	Native	4	11
Blue Mussels	Introduced	2	6
Mediterranean Mussels	Introduced	2	6
European Flat Oyster	Introduced	2	6
Varnish Clam	Introduced	2	6

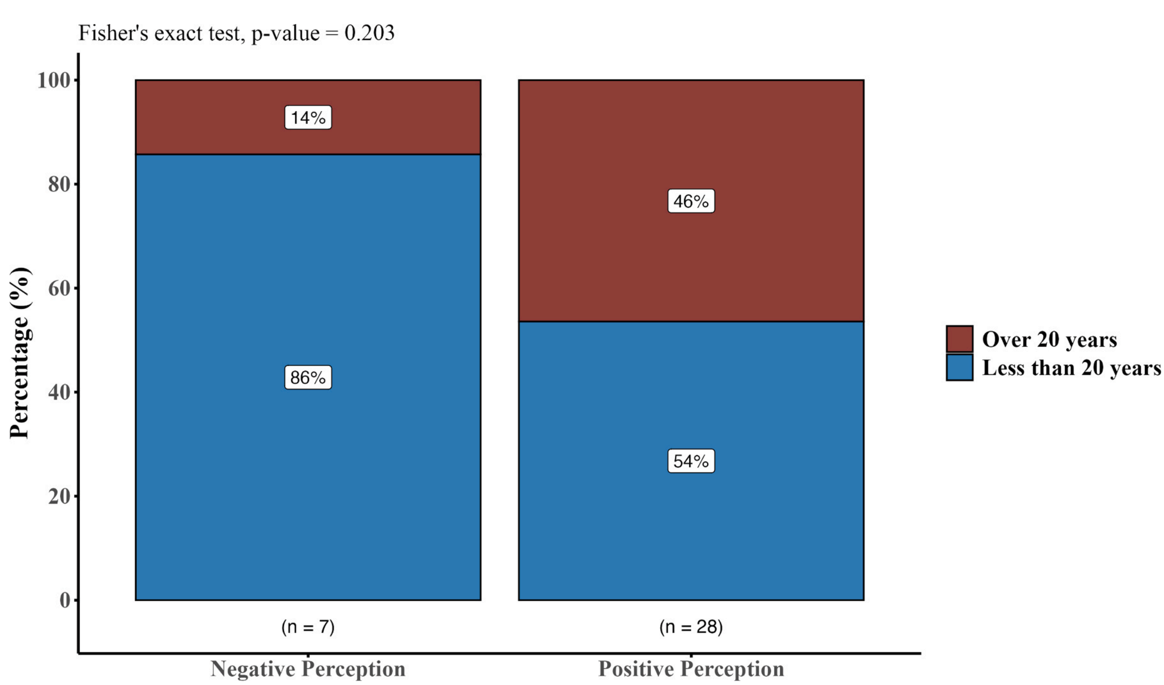

Fig. 4. Percentage of U.S. Pacific aquaculture industry participants reporting positive perceptions of parental priming as an ocean acidification adaptation strategy, by industry experience.

level viability perceptions. Contradictorily, the importance of worsening ocean acidification on personal decisions to add native species was also not significantly associated with beliefs about the strategies' broader viability. However, a significant ($p < 0.05$) positive association was found between an optimistic perception of industry-wide native species portfolio diversification and whether operations contained a growout component and the scale of operations from a Fisher's Exact and Mann-Whitney *U* test respectively. With a Fisher's Exact Test, we also found respondents with over 20 years of experience in the industry were more likely to view worsening ocean acidification as somewhat to critically important in their individual decision to add native species to their portfolio ($p = 0.03$; Fig. 5), however, it was not found to influence the perception of the strategy's broader viability.

The stacked bars reflect responses from participants with less than 20 years and 20 or more years of industry experience. Fisher's exact test results are shown, with a significant relationship found ($p < 0.05$).

Skepticism about the effectiveness and scalability of native species in combating ocean acidification was a recurrent theme. One respondent noted about co-culturing, "They did the math with kelp. They said the scale of the problem is too large. We are seeing the bullet but can't stop it." This skepticism was mirrored in concerns over economic viability given growth time comparisons, with another adding, "Switching to native species sounds nice and dandy, but the ability to do it without solving the other problems makes no sense. Native species take like 4–5 years to grow; it's got potential in the half-shell market, but in Willapa and Grays, we bottom culture shucked meats." Another grower noted the challenge regarding demand stating, "The problem is the demand for the Pacific [oyster] and manila [clam] is huge." Additionally, the robustness of native species raised some skepticism: "Olympia's are being outcompeted, and their populations are declining, if we can't resolve it then I don't think it will be useful."

In contrast, the cultural and historical significance of native species, particularly Olympia oysters, resonates strongly with some in the industry, illustrating a value that transcends economic considerations. As one grower shared, "I raise Olympia [oysters] as a passion. I love the flavor and the history, such a big part of the saltwater history of South Puget Sound. It's a labor of love." Still other growers contrastingly perceived native species as a favorable approach praising their ocean acidification resistance: "At my site we have generally acidic water, we see it in shell development as the juveniles get larger, not in the larval stage. We don't have great success with Pacific's here, maybe due to ocean acidification. We grow native species, maybe they are more placid." Some discussions also highlighted perceived benefits of introducing new strains of Pacific oysters, specifically Midoris, which have been touted as being able to reduce the impact of disease (Melo et al., 2021).

Across the varying perceptions of the strategies viability, regulatory barriers for introducing both native and nonnative new species was the primary top concern. This was followed by consumer preferences and then costs. A grower noted; "I don't know how feasible it would be when combining farmers, regulators, and the hatcheries." Additionally, a hatchery manager commented: "Any expansion the industry wants to make, the regulations will not allow it. There are nonnative options that could be good, but we are not allowed to import, I think in California you can but in Washington you cannot. We just are not allowed to breed native species; they want to keep the genetics as broad as possible." The potential for targeted government support was mentioned as a catalyst for broader adoption of native species, with one respondent advocating for dedicated grants: "I believe that any grants that come out of the government should have an allocated portion specific for native species."

5. Discussion

Collaboration to co-produce knowledge is important when addressing complex environmental challenges and fostering actionable solutions (Brandt et al., 2013; Plummer et al., 2022). As ocean acidification continues to threaten the U.S. Pacific marine shellfish industry, this study bridges knowledge gaps by documenting a range of associated industry experiences and perceptions, including how these have evolved over time. Additionally, we document perceived research needs in the region, examine the utilization of monitoring practices, and engage industry members on two emerging adaptation strategies: parental priming and native species portfolio expansion. By framing the development of adaptation strategies with industry participant perspectives, this work demonstrates how early-stage stakeholder engagement can provide

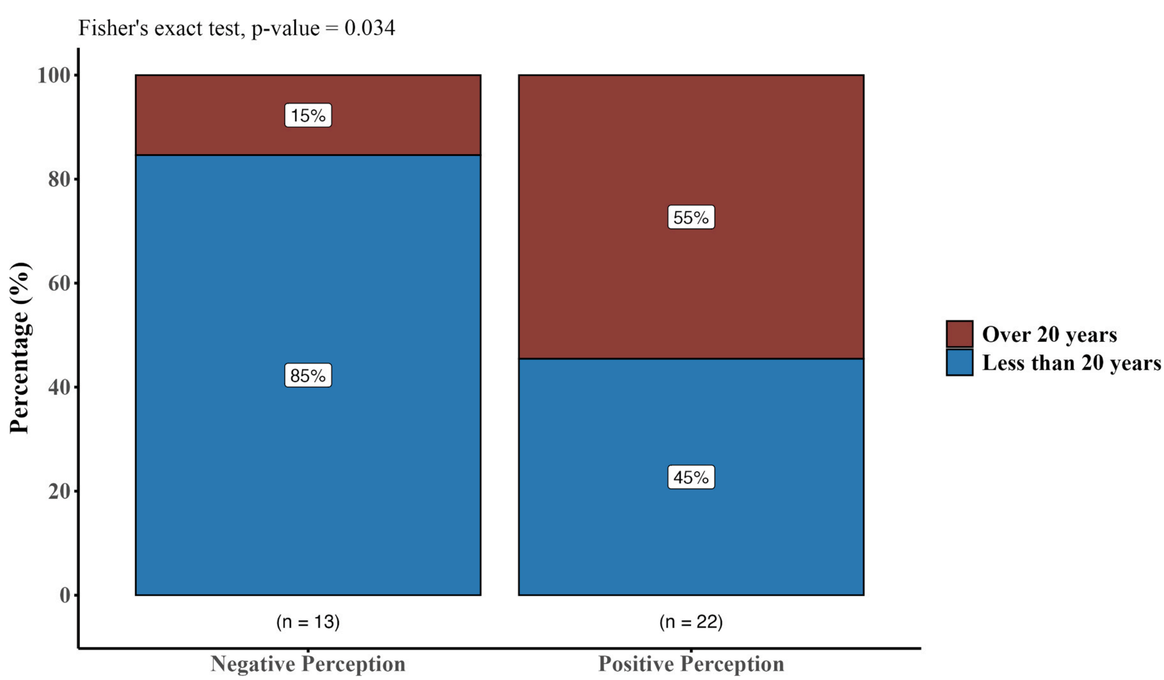

Fig. 5. Percentage of U.S. Pacific shellfish aquaculture industry participants indicating that worsening ocean acidification would influence their willingness to add new native species, by industry experience.

insights for future research processes and priorities (Phillipson et al., 2012).

Adaptation depends on how firms interpret external events and perceive their exposure and operational implications (Daft and Weick, 1984; Canevari-Luzardo et al., 2020). While around half of the industry participants we interviewed reported experiencing negative ocean acidification impacts, a recurrent theme was the difficulty in attributing experiences beyond supply chain disruptions and the need for pH buffering practices directly to ocean acidification. This uncertainty is consistent with broader climate change related challenges, where firms struggle to understand and attribute specific impacts to complex climate events due to their multifaceted and complex nature (Winn et al., 2011; Pinkse and Gasbarro, 2019). Furthermore, we regionally expand upon the findings from Ward et al. (2022), that California shellfish farmers largely perceived ocean acidification as an unknown and potential stress multiplier.

Although our sample size limits generalizability, we observe that industry experience, operation types, scale, generation, and respondent age, are not significantly related with the perception of ocean acidification impacts or related level of future concern. This suggests that despite ocean acidification being largely mitigated during the larval, hatchery life cycle stage (Barton et al., 2015), its impacts are perceived rather evenly distributed across the industry. Despite the proportion of respondents reporting direct ocean acidification impacts being relatively stable over the last decade, we find a shift with more respondents moving from being unsure to reporting no impact when compared with Mabardy et al. (2015). This aligns with more recent findings by Green et al. (2023), where 27 % of Oregon shellfish farmers did not perceive ocean acidification as a problem, while 13 % remained unsure. Additionally, we found future concern about ocean acidification has declined over the past decade, expanding upon similar decreased concern observed in Oregon (Green et al., 2023).

Resolving differences between stakeholders and researchers is critical and requires enhanced risk communication (Advani and Satterfield, 2024). While ocean acidification received substantial focus following the hatchery shortages, the decline in future concern that we observe may reflect how industry and research needs have evolved and expanded. For instance, growers face diseases like Ostreid herpesvirus-1 (Fuhrmann et al., 2018) and the persistent challenge of summer mortality, which is linked to multiple environmental stressors (Samain, 2011; Advani and Satterfield, 2024). We find these associated concerns are considered more threatening to operation success despite some regional variation, with increasing temperatures, HABs, disease, and hypoxia generally perceived as more pressing than ocean acidification. This shift in perceived threat may be partly influenced by recent extreme events such as the 2021 Pacific Northwest heatwave, which resulted in widespread intertidal mortality and underscored the vulnerability of shellfish operations to acute temperature stress (Raymond et al., 2022). Although ocean acidification as a mid-level concern was consistent with findings from prior regional studies, our observation that policy and regulations were not identified as the top perceived threat aligns with Green et al. (2023) but stands in contrast to van Senten et al. (2020). As such, our survey provides additional evidence of evolving industry priorities and highlights the importance of a holistic, multiple stressor focused approach in developing relevant adaptation strategies.

Regarding research needs, enhancing monitoring capabilities was considered important by more respondents than parental priming and native species portfolio expansion, likely due to its use in addressing multiple stressors in addition to ocean acidification. Monitoring was noted as supporting operational success, regulatory compliance, business needs, and husbandry practices by helping operators understand environmental conditions, ensure human safety, and make informed decisions about planting and growth. Despite existing infrastructure, most respondents expressed a need for enhanced capacities, specifically in near-shore environments. The consistent mention of reliance on public information sources underscores the importance of accessible, reliable data. Furthermore, information sharing and participation in research partnerships were largely regarded as widespread.

The industry's collaborative culture, along with the market structure and dynamics between hatcheries and growers can offer insights when considering implementation pathways across adaptive strategies. Specifically, the few large hatchery operations primarily support their own associated grow-out businesses, leveraging economies of scale. In contrast, many small growers depend on these hatcheries for seed. The importance of business relationships and seed availability over price in grower sourcing decisions suggests relational contracting, where trust and reliability are valued to ensure consistent supply, with informal agreements sustained by the value of future relationships (Baker et al., 2002). This structure might partially explain why larger operations were more likely to view native species as a viable ocean acidification adaptation strategy at the industry scale. Their greater resources and established practices may enable them to invest in and sustain such initiatives, in contrast to smaller operations that might face more constraints.

When considering responses to parental priming as an adaptation strategy for ocean acidification, we primarily find a cautious interest among industry participants, with decision-making heavily influenced by empirical evidence and practical considerations, underscoring the importance of effective engagement for successful climate change-driven planning (Khatibi et al., 2021). We find that in hatcheries, while immediate adoption of parental priming would be minimal, a substantial majority are open to the practice after reviewing supportive scientific literature. This indicates a strong preference for evidence-based approaches, reflecting an industry trend towards cautious innovation (Byron et al., 2011). However, concerns about broodstock stress and financial burdens are notable barriers. These respondents prioritize minimizing stress on broodstock and highlight the potential cost implications of integrating new protocols, suggesting that any widespread adoption of parental priming will need to address these concerns directly. Similarly, growers show a guarded willingness to pay more for primed seed, contingent on empirical validation. The majority indicate readiness to invest in primed seed following access to supporting data while prioritizing survivability over growth.

Of the obstacles to incorporating new both native and nonnative species into respondents' portfolios, regulatory barriers were mentioned as the most significant, aligning with the industry's documented high regulatory burden (van Senten et al., 2020). This supports calls for modified or expedited permitting processes to facilitate adaptive strategies (van Senten et al., 2020; Ward et al., 2022), echoing the wider recognition of the need for more adaptive and flexible regulatory frameworks to avoid stifling innovation in aquaculture (Osmundsen et al., 2017; Abate et al., 2018). In fact, substantial delays in West Coast shellfish permitting have been found to create 'perverse incentives,' akin to moral hazards, where more environmentally friendly and efficient practices are foregone due to permitting delays (van Senten et al., 2020). If permitting for native species remains restrictive due to these regulatory burdens, there is a risk of not only losing potentially more resilient portfolios but also foregoing associated environmental benefits (Ridlon et al., 2021).

Beyond regulatory barriers, there is noted skepticism about the robustness of native species that will need to be empirically addressed for wider scale adoption of this adaptation strategy. Specifically, native species have been viewed as inferior and outcompeted. Concerns about economic viability, particularly growth times and market fit, were prominent throughout our interviews. Despite these perceptions, some growers raise native species due to their cultural and historical significance, recognizing these non-pecuniary considerations as important factors influencing their decisions. This mirrors findings from the region's commercial fishing industry, where some individuals are willing to forgo higher income for the satisfaction and identity derived from their profession (Holland et al., 2020).

These mixed perceptions underscore the need to examine both structural barriers and psychological biases that may hinder broader adoption of the strategies explored here, as well as others such as selective breeding, nutritional enhancement, and integrated multi-trophic aquaculture (Clements and Chopin, 2017; Melo et al., 2019; Hamilton et al., 2022). This is evident in how we find a high level of disagreement regarding native species portfolio expansion as an ocean acidification adaptation strategy, with just under half of the participants believing it is widely viable. Then in slight contrast, over half of respondents ranked worsening ocean acidification as having importance for their decision to adopt new native species. This contradiction between an individual's behavior and perception of the broader viability of the strategy may reflect a comparative pessimism bias (Menon et al., 2009), where individuals view their success with native species as an exception, attributing it to personal perseverance rather than structural opportunities.

Furthermore, adaptation uptake can also benefit from considering the role of heuristics (Siders and Pierce, 2021). While heuristics simplify decision-making under uncertainty, they can also introduce judgment-shaping biases (Tversky and Kahneman, 1974). For instance, we observe that respondents with over 20 years of experience, having faced ocean acidification-related hatchery shortages in the 2000s, are more likely to view ocean acidification as a critical factor in the decision to adopt native species. This aligns with evidence that personal experience drives adaptation action (Sambrook et al., 2021) and suggests a potential recall bias (Zhao and Luo, 2021). In contrast, respondents with over 20 years of experience showed no significant difference in positive perspectives toward parental priming. While this approached significance, the smaller sample size limits interpretation, suggesting future research aimed at confirming the prevalence of heuristics might benefit from participation incentives, formalized snowball sampling techniques, or more flexible response methods such as traditional surveys by mail and online, although this would likely come at the expense of detailed qualitative data. These cognitive biases and the diversity of stakeholder perspectives highlight the complexity of adaptation decision-making, suggesting that future work may also benefit from decision-support approaches such as decision theory or fuzzy logic, which are particularly useful for structuring decisions under uncertainty, incorporating qualitative and subjective data, and supporting adaptive planning in complex socio-ecological systems (Gregory et al., 2012; Jones and Cheung, 2017).

6. Conclusion

This study highlights the multifaceted nature of ocean acidification impacts and adaptation strategies within the U.S. Pacific shellfish aquaculture industry. Enhanced monitoring capabilities emerged as a substantial need, supporting operational success, regulatory compliance, and informed decision-making. Despite the cautious interest in parental priming and the existing cultivation of native species, the industry faces significant regulatory and economic barriers that could potentially hinder the adoption of these strategies for adaptation. Furthermore, the perception of ocean acidification as one of several stressors, rather than the primary threat, underscores the need for a holistic approach to industry resilience and co-production research partnerships. Effective engagement, risk communication, and collaborative efforts between scientists and industry stakeholders are essential for developing adaptive strategies that address the dynamic challenges facing shellfish aquaculture.

Ethical Approval

This study was reviewed and approved by the Institutional Review Board at the University of Washington (#STUDY00017917) with all methods carried out in accordance with approved guidelines.

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CRediT authorship contribution statement

Lewis-Smith Connor: Writing – original draft, Visualization, Formal analysis, Data curation. **Norman Karma:** Writing – review & editing, Supervision, Methodology. **Root Larken:** Writing – review & editing, Conceptualization. **Crim Ryan:** Writing – review & editing, Resources, Conceptualization. **Roberts Steven:** Resources, Project administration. **Gavery Mackenzie:** Project administration, Funding acquisition, Conceptualization.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

The data that has been used is confidential.

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