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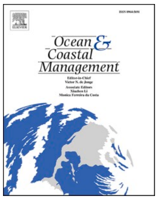

California shellfish farmers: Perceptions of changing ocean conditions and strategies for adaptive capacity

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ABSTRACT

Coastal communities along the U.S. West Coast experience a myriad of environmental stressors, including exposure to low pH waters exacerbated by ocean acidification (OA). This can result in ecological and social consequences, making necessary the exploration and support for locally relevant strategies to adapt to OA and other environmental changes. The shellfish aquaculture industry along the West Coast is particularly vulnerable to OA, given the negative effects of low pH on shellfish survival and growth. As such, the social-ecological system exemplified by this industry serves as an opportunity to identify and address strategies for local adaptation. Through interviews conducted with West Coast shellfish farm owners and managers (‘growers’), we investigate perceptions of OA and environmental change and identify specific strategies for adaptation. We find that growers are concerned about OA, among many other environmental stressors such as marine pathogens and water temperature. However, growers are often unable to attribute changes in shellfish survival or health to these environmental factors due to a lack of data and the resources and network required to acquire and interpret these data. From these interviews, we identify a list of adaptive strategies growers employ or would like to employ to improve their overall adaptive capacity to multiple stressors (environmental, economic, political), which together, allow farms to weather periods of OA-induced stress more effectively. Very few studies to date have identified specific adaptive strategies derived directly from the communities being impacted. This work therefore fills a gap in the literature on adaptive capacity by amplifying the voices of those on the front lines of climate change and identifying explicit pathways for adaptation.

1. Introduction

Coastal communities and resource users experience a wide range of environmental and livelihood stressors, including intense resource competition, urbanization, and environmental degradation that affect the resources upon which they rely. Climate change exacerbates these stressors and creates new pressures on coastal environments and the people whose livelihoods depend on them. The vast majority of academic work on climate change impacts has investigated biophysical assessments and responses to these environmental stressors, such as species migration in response to changing temperatures (Pinsky et al., 2013; Poloczanska et al., 2013), shifts in trophodynamic balance (Hoegh-Guldberg et al. 2014), genetic or evolutionary adaptation (Merilä and Hendry, 2014; Nascimento-Schulze et al., 2021), or effects on underlying biogeochemical mechanisms (Lahsen and Turnhout, 2021). While scholars have begun to explore the social, economic, and policy aspects of adaptation to these biophysical changes, much of this work remains primarily theoretical. In order to adapt to anticipated climate impacts, specific action must be taken at local, regional, national, and in many cases international levels that fosters adaptation (Ekstrom et al., 2015; Tittensor et al., 2019). An extensive literature covers frameworks, principles, and tools for adaptation assessment and planning, but few studies offer concrete suggestions for what these actions might look like to increase the adaptive capacity of human communities (Lindegren and Brander, 2018; Miller et al., 2018; Tittensor et al., 2019).

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One such system for which climate adaptation will be critical in coming years is marine aquaculture, especially shellfish aquaculture, given our understanding of climate change impacts (e.g., ocean acidification) on shellfish (Stewart-Sinclair et al., 2020). While several authors have explored the capacity of aquaculture systems to adapt to anticipated climate change (Clements and Chopin, 2017; Galappaththi et al., 2020; Greenhill et al., 2020), relatively little is known about how aquaculture operators, and the extended communities reliant on aquaculture operations, perceive and respond to ocean acidification (OA) and other environmental stressors, or about specific actions they have taken or needs they have to prepare for or mitigate environmental stressors. As such, shellfish aquaculture serves as an opportunity to conduct integrative research on social-ecological systems that improves our understanding of adaptive capacity in the face of current and future climate impacts.

The U.S. West Coast is home to a developing aquaculture industry that is poised to expand. In the state of California, new attention has gone toward aquaculture, with investment in aquaculture-related research and the development of a state-wide aquaculture plan (California Ocean Protection Council, 2020a; California Sea Grant, 2020). However, this region is uniquely exposed to climate change-induced stress via OA and other environmental stressors, which can be of particular concern for shellfish aquaculture (Feely et al., 2010, 2016; Hauri et al., 2009). Here, we explore California shellfish aquaculture operators' ("growers") perceptions of the impacts of climate and environmental change, in particular OA, and identify explicit strategies currently used, or being considered for use, by the industry to adapt to these changes. We focus on shellfish aquaculture in three focal regions of the state of California: Humboldt, Point Reyes, and the Central Coast. Specifically, we ask:

1) How do growers perceive OA and other environmental changes?
2) What strategies do growers employ (or would like to employ) in order to increase adaptive capacity to OA and other environmental changes?
3) What barriers and opportunities exist in implementing these strategies?

While definitions of adaptive capacity have varied across studies within the field (Siders, 2019; Smit and Wandel, 2006), we define adaptive capacity in the context of our study as: *the ability of aquaculture operators to adjust to challenges caused by OA and other environmental stressors, to take advantage of opportunities to adapt to these challenges, and to effectively respond to their consequences*. While identifying explicit adaptive strategies for shellfish aquaculture can lead to direct industry recommendations, these strategies can also fit into broad, theoretically defined domains of adaptive capacity that are applicable across geographies and communities. As such, this work can serve as a framework to explore vulnerable coastal communities' and industries' adaptive capacity and understand barriers to adaptation.

2. Background

Shellfish aquaculture (defined here as culture of bivalves and mollusks), and the facility operators and broader community that it engages, is one example of a coastal system impacted by climate stress. Shellfish are sensitive to changes in environmental conditions such as temperature (Gagnaire et al., 2006; Le Deuff et al., 1996; Martinez et al., 2018; Vilchis et al., 2005), carbonate chemistry (Kroeker et al., 2013), and numerous other factors such as nutrients, disease, and sediment (Soon and Zheng, 2020). In particular, the ongoing global reduction in ocean pH, termed OA, is negatively impacting shellfish through decreased growth and survival (Hauri et al., 2009; Kroeker et al., 2013). Along the U.S. West Coast (including California, Oregon, and Washington, hereafter 'West Coast'), there are more than 300 commercial shellfish farms and 5 private hatcheries (Pacific Shellfish Institute, 2013), resulting in an industry valued at over $270 million and accounting for roughly two-thirds of all oyster, mussel, and clam aquaculture sales in the U.S. (Mabardy et al., 2015; Pacific Shellfish Institute, 2013). While this industry has been expanding, mean seawater pH along this stretch of coastline has been declining, and the region is experiencing pH levels not expected in most other global ocean locales for decades (Feely et al., 2008; Hauri et al., 2009). This unique exposure to OA is driven in part by the natural changes in carbonate chemistry that occur with the region's seasonal coastal upwelling (Feely et al., 2009). As anthropogenic CO_2 emissions have reduced global ocean pH, these periods of upwelling-induced acidification have become more stressful to coastal organisms sensitive to OA, resulting in numerous ecological and economic impacts along the California coast (Fabry et al., 2008; Kroeker et al., 2013). Of particular interest, this phenomenon manifested itself in mass mortality of oyster seed along the coast of the Pacific Northwest in 2008, leading to intense economic losses for the hatcheries producing this seed and the grow-out farms that relied upon it (Mabardy et al., 2015). The finding that this seed mortality was largely attributed to OA brought attention to the West Coast shellfish industry as one of the earliest U.S. industries to experience direct climate change impacts (Barton et al., 2015; Kelly et al., 2014). This spurred interest for scientists, growers, managers, and policymakers to understand the impacts of OA on shellfish, and to find and facilitate avenues for adaptive capacity in the aquaculture industry (Clements and Chopin, 2017; Ekstrom et al., 2015; Keil et al., 2021).

The need to document and advance our understanding of adaptive capacity in aquaculture was recently outlined in Galappaththi et al. (2020). Their review of the global literature documented that the number of studies examining adaptive capacity within aquaculture social-ecological systems is limited but has increased in recent years. However, the majority of studies focused on shrimp or finfish aquaculture systems, and their adaptations to climate impacts such as extreme weather events (e.g., drought, flooding, heatwaves) throughout the Global South. Few of these studies were conducted within the Global North, and very few focused on bivalve aquaculture or the impacts of OA. This regional discrepancy is further supported by Siders (2019), who showed that almost half of the adaptive capacity work conducted by U.S. scholars has been conducted outside the U.S. Given the interdisciplinary interest in OA and shellfish, some scholars have begun to inform our understanding of adaptive capacity within shellfish aquaculture social-ecological systems (Clements and Chopin, 2017; Cross et al., 2019; Mariojouls and Prou, 2015). Mabardy et al. (2015), for example, surveyed West Coast shellfish growers, demonstrating that compared to the general public, growers in the region have an advanced knowledge of and concern for OA, and that they were cautiously hopeful that they would be able to adapt to OA and other anticipated environmental changes. While unsurprising given the direct linkage between OA and aquaculture, this heightened knowledge and sense of concern acts as an indicator for the shellfish aquaculture community's need and willingness to adapt, as awareness is a primary factor in building adaptive capacity in social-ecological systems (Marshall et al., 2013). However, no explicit adaptive strategies were identified, leaving ambiguity about the specific opportunities and challenges for aquaculture adaptive capacity. Subsequently, several studies investigating adaptive capacity in shellfisheries have suggested possible adaptive strategies (Clements and Chopin, 2017; Ekstrom et al., 2015; Greenhill et al., 2020). Yet these studies still lack a direct assessment or enumeration of specific strategies; none are directly informed by responses from the impacted community (i.e., shellfish growers), none are specific to the West Coast region, and only one is specific to shellfish aquaculture (Greenhill et al., 2020). These studies additionally note the need for specific, community-derived strategies, as Ekstrom et al. (2015) state: "rather than create and apply a nationwide solution, decision-makers and other stakeholders will have to work with fishing and aquaculture communities to develop tailored locally and socially relevant strategies". These foundational studies provide an opportunity for the work herein to explore the unique vulnerability and adaptive capacity of shellfish aquaculture in the West Coast region. This work can serve as a model for future research by identifying adaptive strategies empirically derived from impacted communities.

2.1. *Regional context*

Shellfish aquaculture is steeped in historical and cultural significance along the California coast, with the first commercial oyster fishery established in San Francisco in the 1850s, and indigenous harvest taking place for thousands of years prior (Braje, 2016; Braje et al., 2012; California Department of Fish and Game, 2008; Shaw, 1997). While San Francisco shellfish operations were halted due to water quality issues, commercial shellfish aquaculture now takes place in coastal communities across the state of California from San Diego Bay in the south to Humboldt Bay in the north (Northern Economics, Inc., 2013). Currently, California hosts 19 operations growing shellfish commercially, a small number compared to the more than 300 operations along the contiguous West Coast. In 2018, shellfish aquaculture in California reported an annual revenue of $15.3 million, down from its peak in 2011–2014, with oyster production being the dominant shellfish industry (California Department of Fish and Wildlife, 2020; Northern Economics, Inc., 2013). Very few new operations have been permitted in California in recent decades. Rather, the vast majority of farms in California are small, privately-owned businesses, which have operated for many years. This lower number of farms relative to other U.S. coastal states and lack of aquaculture expansion in California may be due to numerous factors, including challenges associated with lack of public acceptance and the high relative regulatory costs to operate or start an operation. For example, van Senten et al. (2020) reports an average regulatory cost of $125,072 per farm hectare in California, compared to $55,662/ha in Washington and $2628/ha in Oregon.

In this study, we focus on three geographic regions across the state of California – Humboldt Bay, Point Reyes (Bodega Bay and Tomales Bay), and the Central Coast (Monterey Bay to Santa Barbara) (Fig. 1). In Humboldt Bay, four primary shellfish are grown: Pacific oysters, Kumamoto oysters, Manila clams, and mussels, with the majority of California's oysters produced from this region (an estimated 70%) (Richmond et al., 2018). In the Point Reyes region, shellfish grow-out began with oysters in the early 1900s, and remains an active industry in the area, second only to Humboldt Bay in the State's shellfish production (University of California Cooperative Extension, 2017). One bay in the region, Drake's Estero, previously produced roughly 40% of California's oysters until its full closure in 2014. However, culture of oysters, mussels, and clams continues in Tomales Bay and to a lesser extent the neighboring Bodega Harbor, with Tomales Bay producing $5.4 million in shellfish in 2017 (University of California Cooperative Extension, 2017). California's central coast also has a long history of producing, harvesting, and selling shellfish. Morro Bay is currently one of the leading oyster-producing regions in California (Lisa Wise Consulting, 2015), with aquaculture operations engaged in producing shellfish from seed to market-size products. In addition to culture of oysters, mussels, and clams, the central coast produces much of the state's cultured abalone, with both land and ocean-based operations present along the coastline.

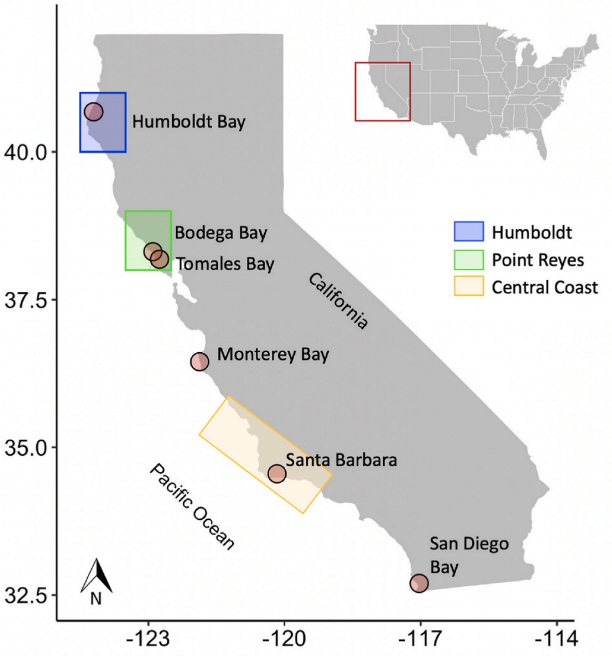

Fig. 1. Interviews were conducted with growers in the Humboldt Bay, Point Reyes, and Central Coast regions. Each circle represents a distinct bay or geographic location where operations were located (i.e., operations located within the same bay are represented by a single point). Circles indicate bays referenced in text, not specific locations where sampling occurred.

Collectively, California's shellfish aquaculture provides substantial contributions to the state economy, meeting the demand for seafood in the U.S., and addresses the need for domestically produced seafood. Although increases in aquaculture output have been slower in California than in other U.S. states, new shellfish operations are being considered and will likely lead to growth of this industry in coming years.

3. Methods

3.1. *Interviews*

We conducted semi-structured interviews with the owners and/or primary managers of aquaculture operations in the three focal regions, with three to four interviews conducted per region. To select the regions and interviewees in each region, we first developed a list of all current California shellfish operations through a web search and consultations with relevant coastal resource management representatives including state and federal agency staff and representatives working for or with existing California shellfish farms. This list was confirmed and verified by experts including local and academic extension staff in order to ensure that all operations were included with the owner or primary manager of each operation represented. Given the distinct characteristics of Northern California bays suitable for shellfish aquaculture, operations were concentrated in several growing regions. Specifically, the Humboldt and Point Reyes regions held a large number of operations and were a clear choice for focused interviews. The additional operations were more dispersed and can be described as a "Central Coast" region, ranging from Monterey Bay to Santa Barbara.

Interviews were designed to address the outlined research questions, using guides from past fisheries work in the region as an underlying framework (M. Poe, personal communication, September 25, 2019). Our guide was pre-tested with shellfish aquaculture experts to ensure the questions were clear and relevant. Interview prompts covered basic information about the history of each grower's operation, their perceptions of environmental change, and possible adaptive strategies, including opportunities for and barriers to adaptation. Although we were particularly interested in assessing perceptions of OA, interviewees were first prompted by a broad question: "Can you speak to any environmental changes you've noticed in this area, related to the marine environment?“. Interviewees were allowed to elaborate on their responses to this question before being additionally prompted with questions regarding whether they believed they could discern any changes specifically due to OA. All interviews were conducted, recorded, and transcribed via Zoom in 2020. Zoom transcriptions were automatically generated, and the audio of each recorded interview was re-played to manually correct and generate the final transcripts for analysis.

3.2. Analysis

Interviews were coded for themes using the software Atlas.ti, with analyses performed in R (Atlas.ti, 2021; R Core Team, 2018). Based on the interviews, we generated a first set of codes to analyze interviewees' perceptions of environmental change. Interview transcriptions were reviewed to generate a comprehensive list of environmental factors that interviewees observed to be changing or believed were impacting their operations. An observation of change could include 'long-term' change, such as climate change-induced ocean warming, or any other type of environmental change (e.g., 'we've had more rainfall in the last few years'). This initial list was then reviewed and refined to develop an environmental factor codebook of 17 unique types of change observations. Importantly, no code was assigned when the absence of change in an environmental factor was noted (e.g., 'I cannot perceive any changes in pH' or 'I don't think low pH negatively impacts my operation'). These codes were applied throughout the interviews, regardless of whether growers were prompted to speak about environmental change, or if they initiated the comment independently. Although many environmental factors are linked through their co-occurrence, we only coded for the explicit environmental factor mentioned. For example, shellfish marine disease can be linked to algal blooms, rainfall, and its related factors including salinity and run-off driven pollution (Esteves et al., 2015; Gray et al., 2022). Nonetheless, each of these environmental impacts were coded separately if mentioned given they may not always be linked or co-occur. If two separate factors were mentioned in a single sentence, both codes were applied. After applying the environmental factor codes across all interview transcriptions, these were thematically grouped into two broader categories ('physical factors' and 'biological factors').

Using a similar process to that used in the environmental factor codebook development, a second set of codes was then developed to include all adaptive strategies identified by growers. We first created a comprehensive list of all adaptive strategies mentioned by growers, including any strategies they had previously taken, were currently taking, would like to take, or had noticed others taking. After generating this list of strategies from interviews, we reviewed the list for themes and refined the list to develop an adaptive strategy codebook. Specifically, we identified 18 total adaptive strategies, which were each given a unique code to label each instance when a strategy was mentioned by a grower during an interview. These strategies were then grouped into three broader thematic categories ('policy and networking', 'farm management', and 'science'). After coding was completed, all data analysis and figure development were conducted in R.

4. Findings

4.1. California's regional aquaculture landscape

Interviews were requested with representatives from 13 shellfish operations across all of these regions combined, out of the 19 total operations in the state. We received 11 responses, resulting in a sample size that represents over half the operations in the state (Table 1). All interviews were conducted in 2020 with representatives whose farms were currently operating, with the exception of one interview with an operator whose farm shut down in 2020. Oysters were the most common species cultured by those we interviewed, and were the primary species grown by 8 out of the 11 farms.

Table 1
Summary of the eleven farms interviewed within 3 regions in California, the species each farm cultures, and the type of operation. For 'operation type', all hatcheries are land-based, 'in-water nursery' denotes the rearing of seed or juveniles *in-situ* prior to growout of adults such as with Floating Upweller Systems ('FLUPSYs'), in-water growout denotes *in-situ* culture of shellfish to market size, and 'land-based culture' denotes culture to market size occurring entirely within land-based facilities (e.g., abalone farms).

Farm ID	Species harvested	Operation type
Farm 1	Oysters, mussels, clams	Hatchery + in-water nursery
Farm 2	Oysters, mussels, clams, scallops	In-water growout
Farm 3	Oysters	In-water nursery + in-water growout
Farm 4	Oysters, mussels, clams	In-water growout
Farm 5	Oysters, mussels, clams	In-water nursery + in-water growout
Farm 6	Oysters, mussels, clams	In-water nursery + in-water growout
Farm 7	Oysters	In-water growout
Farm 8	Abalone, urchin, algae	Hatchery + land-based culture
Farm 9	Mussels	In-water growout
Farm 10	Oysters, clams	In-water nursery + in-water growout
Farm 11	Abalone	Hatchery + land-based culture

4.2. Perceptions of environmental change and impacts

Growers cited numerous physical and biological factors relating to environmental change and environmental impacts to shellfish operations (Table 2). Across all interviews, marine disease and pathogens were frequently mentioned as environmental impacts (Fig. 2). This was often mentioned in general terms, for example, "*There was a huge virus or something all up and down the West Coast of America. It took out so many oysters, some farms lost 90 percent of their oyster crop, and when you're waiting a year for something to be able to harvest it, that's a huge loss*". However, in other cases, specific diseases or pathogens were mentioned, which included Norovirus, Paralytic Shellfish Poisoning (PSP), Vibrio, *E. coli*, and Herpesvirus. Rainfall and algal blooms were also mentioned in numerous interviews, often due to the association these factors have with marine disease and pathogens. Similarly, pollution when referred to as a term for run-off, is also known to introduce pathogens into coastal waterways (e.g., Thickman and Gobler, 2017). However, these linkages did not always exist – at times pollution was mentioned more generally and was therefore counted as its own factor. For example, one grower states "*The bay is cleaner on a macro level but on the micro pollution level, I think it's as dirty as its ever been*". Given marine disease, algal blooms, rainfall, and associated pollution can all lead to shellfish mortality, temporary closure of operations, public health crises, and subsequent economic losses to farms (Gray et al., 2022; Ralston et al., 2011; Trainer et al., 2020), it is unsurprising that these factors were at the forefront of growers' minds when discussing environmental change and impacts.

In many cases, growers immediately responded with observations of species population changes after being prompted for observations of environmental change. For example, "*Species diversity has probably declined. Although there have been some new species that have arrived like the Atlantic crab.*" At times these observations were linked to shellfish operations, such as with oyster drills or fouling organisms on culture equipment (e.g., Fitridge et al., 2012; Padilla et al., 2011), whereas at other times (as with the Atlantic crab), explicit impacts to operations were not discussed. Arguably, the high prevalence of responses about species populations is illustrative of farmers' likelihood to report on easily observable changes (in this case, measured by visual observations overtime).

Eelgrass was counted separately from other species due to the fact that its federal protections and common co-location with shellfish can introduce additional management challenges for growers (e.g., Ferriss et al., 2019), leading to unique commentary by growers. Specifically, California upholds a policy of "no net loss" of eelgrass or eelgrass function, given its federal protections under the Magnuson-Stevens Fishery and Conservation Management Act (National Marine Fisheries Service, West Coast Region, 2014). As a result of these protections, growers indicated concern that if eelgrass meadows expand into or near in-bay shellfish aquaculture equipment, they might be liable for environmental damages due to unintentional impacts to eelgrass through harvest activities or equipment, or they might be forced to move gear, adversely impacting their operations. At the same time however, existing research finds that eelgrass can modify environmental conditions to enhance shellfish growth, survival, or health (for example, through OA amelioration or disease prevalence reduction) (Reusch et al., 2021;

Table 2
Environmental factors identified by growers, with descriptions of how each factor may affect shellfish or shellfish operations.

Environmental Factor	Description
Biological Factors	
Disease/pathogens	Many marine diseases and pathogens can impact shellfish health and survival. Their increased prevalence could increase temporary closures of shellfish operations and increase mortality of cultured shellfish (Burge et al., 2021; Ralston et al., 2011).
Species population changes	Shifts in species populations occur within waterways occupied by shellfish culture, having varying levels of impacts on shellfish. For example, oyster drill populations and fouling communities can directly affect shellfish and shellfish harvest, while other species populations such as birds or invasive green crabs may shift, but impact operations less directly, if at all (Padilla et al., 2011).
Eelgrass	Eelgrass can grow in and around shellfish culture, yet is protected by state and federal regulations, introducing co-management challenges (Ferriss et al., 2019; National Marine Fisheries Service, West Coast Region, 2014). The two can also interact both positively and negatively through a variety of complex environmental interactions (e.g., Donaher et al., 2021; Fales et al., 2020; Ricart et al., 2021).
Algal blooms	Algal blooms, which can be linked to other factors such as marine disease and water temperature, may cause mortality in shellfish or lead to temporary closure to operations for co-occurring public health concerns (e.g., Lassudrie et al., 2020; Pitcher et al., 2019).
Kelp	Wild kelp serves as a primary food source to support cultured abalone. Abalone farms can therefore be impacted by declines in kelp populations or nutritional quality, which can be associated with ENSO cycles and other environmental factors (Kübler et al., 2021; Searcy-Bernal et al., 2010).
Physical Factors	
Carbonate chemistry	Shifts in carbonate chemistry (e.g., pH, pCO$_2$, Ω_{arag}, DIC) can reduce shellfish calcification, growth, and survival (Avignon et al., 2020; Kroeker et al., 2013). This can occur episodically via co-occurring changes in factors such as rainfall or upwelling, or over long-term scales from emissions-induced ocean acidification (Feely et al., 2016; Hollarsmith et al., 2020).
Rainfall	Episodic rainfall events can have a variety of impacts to shellfish such as increasing run-off, sedimentation, blooms, and marine pathogens or altering seawater carbonate chemistry and salinity (e.g., Fleury et al., 2020; Hollarsmith et al., 2020).
Water temperature	Increasing water temperatures can impact shellfish through a variety of mechanisms, for example, by altering marine pathogen populations (Green et al., 2019) or shellfish metabolic, spawning, and mortality rates (Abe, 2021; Kavousi et al., 2022; Li et al., 2007).
Cloud cover	Cloud cover (or reduced fog levels) can be of particular importance to shellfish grown in the intertidal or shallow water. The associated increased surface irradiance, particularly when coinciding with midday low tides, can lead to increased shellfish desiccation and thermal stress (e.g., Wethey et al., 2011).
Pollution	Pollution, referring to either macro- (e.g., marine debris) or micro-pollution (e.g., run-off induced impacts to water quality), can have varying impacts on shellfish through a variety of mechanisms, and co-occur with other factors such as rainfall, pathogens, or blooms (Baechler et al., 2020; Webber et al., 2021).
Wind	Changes in wind speed and direction can affect the strength and duration of coastal upwelling, impacting numerous factors such as carbonate chemistry, dissolved oxygen, water temperature, and kelp cover, all of which can subsequently impact shellfish (Bakun, 1973; Jacox et al., 2018; Feely et al., 2016).
Air temperature	Increased air temperatures, much like decreased cloud cover, can be particularly impactful to intertidal shellfish through increased desiccation and thermal stress (e.g., Jenewein and Gosselin, 2013; Hui et al., 2020).
Dissolved oxygen	Reduced seawater dissolved oxygen, which can co-occur with upwelling, run-off, blooms or other factors, can adversely impact shellfish in many ways, manifesting in increased mortality or reduced growth (e.g., Donaher et al., 2021; Lenihan and Peterson, 1998).
Sediment	Sediment changes can be induced by rainfall events or altered hydrodynamics. Such changes can be impactful to shellfish by increasing turbidity, or for on-bottom culture in particular, whereby scouring, burial, or depth alterations can directly affect shellfish and culture equipment (e.g., Poirier et al., 2021).
Hydrodynamics	Changes in hydrodynamics such as currents and waves can impact shellfish through a variety of mechanisms, such as nutrient and sediment deposition (Campbell and Hall, 2019; Poirier et al., 2021).
ENSO	During times of positive ENSO (El Nino Southern Oscillation) cycles, associated impacts such as warm water, reduced kelp populations, and many other factors can impact shellfish (Galanis et al., 2020; Green et al., 2019; Kübler et al., 2021).
Sea level rise	Sea level rise is of particular importance for farms in bays and estuaries when considering how the culture locations and total suitable area for shellfish culture within their permitted lease areas may change in the future.

Ricart et al., 2021a; 2021b), while shellfish may simultaneously benefit eelgrass, leading to their beneficial co-location (Groner et al., 2018). For instance, one grower states, "*[Eelgrass] is thriving all around our oyster farm. So, I kind of hope that the eelgrass is good for the water quality, and I think it is*". Thus, the management of shellfish aquaculture and eelgrass is complex and the two can be tightly linked.

Water temperature was also frequently noted, and in some cases, growers reported that water temperatures were becoming warmer: "*I would keep seawater temperature data every day for a while back out to the 80s, and I would say there's definitely an increase in average seawater temperature,*" while others detected change but were unsure if it was indicative of a long-term trend – "*The water has seemed warmer over the last five years, but is that just a five-year run of water?*" The impacts of increased water temperature on shellfish can be direct or indirect by interacting with or amplifying other environmental factors (e.g., Jones et al., 2019; Lannig et al., 2010). For instance, research suggests that impacts from marine disease may become more prevalent due to increasing water temperatures (Harvell et al., 2002; Petton et al., 2021), a phenomenon several growers alluded to or expressed concern for and discussed in more detail below.

Carbonate chemistry factors were also mentioned by many growers, but unlike all other environmental factors depicted in Fig. 2, growers were specifically prompted for whether they thought they had experienced OA-derived changes or impacts, making it challenging to evaluate grower perceptions of the relative significance of OA compared to other factors mentioned. Although most growers suspected and were concerned about changes in seawater carbonate chemistry or OA-induced impacts, they also cited the inability to detect this change or attribute impacts specifically to OA. Some growers observed carbonate chemistry-derived changes or impacts to their operations, but they did not always connect these observations to OA or global acidification trends. For example, one grower observed direct linkages between carbonate chemistry and rainfall, stating, "*we had a really heavy rainfall winter and there [were] extremely low* pH *levels that year that coincided with the heavy rainfall which also pushed the* pH *down, and we had a lot of extremely slow growth that year on our north lease.*" Another grower did note measured carbonate chemistry change, stating "*there's one research buoy that does take the* pH *levels and it was dramatic. I mean, our growth dropped in half,*" but again, this was not specifically attributed to broader OA trends. Rather, the majority of growers stated that they were unable to attribute observed changes to OA. As one interviewee stated, "*We are not currently using any kind of instrument or observations to look for acidification because*

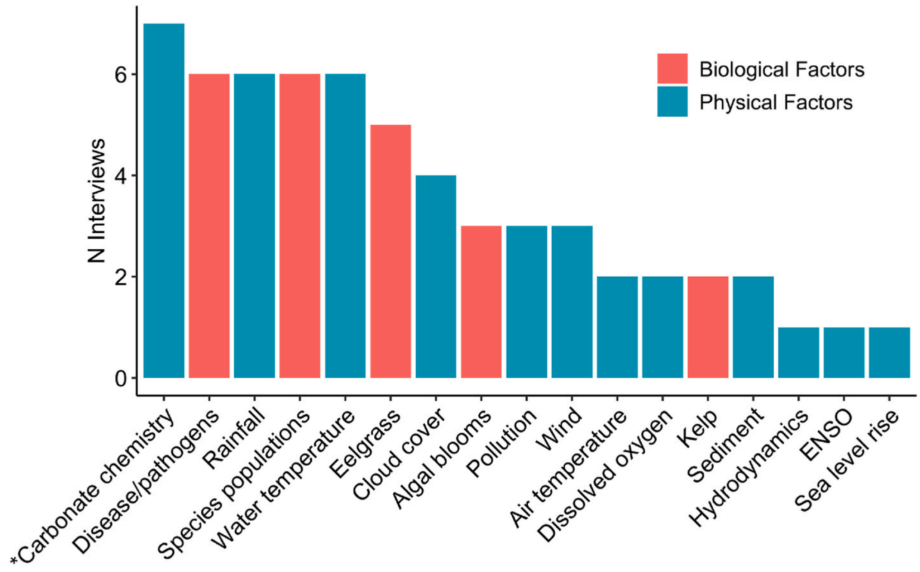

Fig. 2. Commonly observed environmental changes and impacts mentioned in interviews with aquaculture operators (n = 11). 'Species populations' refers to species population changes. Full descriptions of each environmental factor are listed in Table 2. The '*' denotes that questions regarding carbonate chemistry were specifically prompted during the interviews when discussing OA, so these counts may not be directly comparable to the other listed physical and biological factors.

number one, we don't know how to do that." In some cases, an inability to directly measure and observe changes in ocean chemistry led to uncertainty or skepticism that OA was impacting them at all (e.g., "*I don't have any indication of acidification on my farm*"), a phenomenon that has also been seen in other marine resource users' perceptions of environmental change (Donkersloot, 2012; Greenhill et al., 2020; Maltby et al., 2021; Nursey-Bray et al., 2012).

4.3. Adaptive capacity strategies

Given the myriad of stressors and impacts growers experience, interviewees identified a variety of potential associated adaptive strategies (Table 3) to ensure their operations survive change from both OA and broader environmental, social, economic, or regulatory challenges. The specific strategies discussed by growers can be described by three overarching categories, 1) adapting regulatory policies and networking with external partners, 2) flexible strategies for farm management, and 3) drawing on scientific research and expertise (Table 3).

4.3.1. Policy and networking

The most frequently discussed strategies fell within the policy and networking category, with permitting/regulatory changes and network development/reliance being the most commonly discussed adaptive strategies (Fig. 3). When permitting and regulations were discussed, this typically came in the form of commentary that difficult, expensive, and time-consuming permitting processes inhibited overall ability to adapt or remain resilient to change, a challenge that has been described previously regarding aquaculture in both California and the United States more broadly (Knapp and Rubino, 2016; van Senten et al., 2020). For example, one grower described,

> *"All the coordination amongst the different agencies, it's been consuming a considerable amount of time. And so, that is what I would call a significant obstacle … Here we are in 2020 still talking about the same thing we've been talking about for almost our entire time. It's just been increasing in cost and increasing in time and increasing in complexity over the years … What it means is that for people at an entry level, the bar is very, very high. So, if we're talking about the need to increase aquaculture or the ability to increase aquaculture, it's not happening, period."*

These sentiments were expressed almost ubiquitously by other interviewees, with all growers commenting on the time and money spent on permitting and regulation, for example, "*the regulations have gotten tighter*", "*it takes so long, it's so expensive, and it's such a black box. There's no programmatic approach to projects*". There were few mentions of specific permitting/regulatory solutions to facilitate adaptive capacity. Rather, growers mentioned that the current permitting/regulatory landscape inhibited adaptive capacity and generally expressed a desire for improved permits and regulations in the form of greater clarity, reduced costs, or faster timelines.

In some cases, growers pointed towards less cumbersome permitting examples from other states, noting that "*in other states this barrier to entry is just nonexistent … They've streamlined the process and so, you look up at Washington or East Coast states, you know, they're exploding with oyster farms because they've made it super easy*." One specific strategy mentioned was the potential for pre-permits to be granted for larger areas of coastal space, whereby individual growers sub-leasing parcels within this space would face a simplified permitting process given a previously acquired overarching permit (see California Sea Grant, 2015 and Humboldt Bay Harbor, Recreation, & Conservation District, 2020).

Networking was described as an adaptive strategy by way of building connections and sharing information to improve operational efficiency, institutional knowledge, or business success more generally across the industry, a strategy that has been similarly identified across other communities impacted by environmental change (Barnes et al., 2016; Bierbaum et al., 2013; Cross et al., 2019; Keil et al., 2021). Growers interviewed here valued connections with many different stakeholder groups, including scientists, policymakers, regulators, other growers, and local community members. Some growers remarked that good relationships with regulatory agencies could ease their ability to make adaptive changes:

> "*We work really closely with some of these agencies that are giving us the green light or red light, whether we can harvest or not and they're really key. Having people that are available and knowledgeable … you know they're able to change the regulations based on need and make them more workable and more reasonable.*"

Connections with scientists facilitated the translation of scientific findings and knowledge of ocean conditions to grower audiences. For instance, given growers' aforementioned uncertainty about ocean conditions, when prompted about observations of change one interviewee noted "*I just kind of rely on things I hear from different biologists.*" Such connections also formed the foundation for many direct scientist-grower

Table 3
Adaptive capacity strategies identified by growers. Strategies apply to both in-bay and land-based culture unless otherwise specified.

Strategy	Description
Policy and Networking	
Permitting/regulatory changes	Permitting new operations and simplifying or clarifying permit changes for existing operations can reduce regulatory burdens, allowing for increased flexibility and allocation of resources towards other adaptive strategies
Network	Developing and leveraging networks of other growers, managers, policymakers, and scientists to share information, build best practices, and communicate policy and scientific needs
Funding	Access to funding opportunities can serve numerous purposes including improved ability to attain permits or insurance, conduct research, etc.
Water quality (WQ) response	A timely WQ regulatory response to allow operations to open more quickly after a WQ-induced closure and avoid economic losses (i.e., monitoring conditions for improvement and allowing a prompt reopening if criteria are met)
Farm Management	
Spatial flexibility	For in-bay culture, growing in multiple locations and moving product within leased areas can allow real-time responses to environmental stressors (e.g., moving away from a run-off source, out of the intertidal, towards the mouth of the bay, etc.).
Species	Culturing numerous, additional, or alternative species diversifies growers' products and can open up new markets or help ensure product is available if one species does poorly or is more impacted by a mortality event.
Multiple lifecycle stages	Having multiple life cycle stages and size classes (broodstock, small seed, small adults, and large adults) in-house can reduce reliance on outside operations. Self-operated hatcheries can reduce negative impacts of regional seed shortages. Smaller shellfish are often sold to restaurants, while larger sold direct retail - having both can provide market diversification and flexibility.
Method/gear type	Employing multiple or new methods or gear types (or switching between them) can allow growers to use the best-available and most suitable methods and technology to effectively grow their product.
Retail and wholesale	Having both a retail and wholesale business can allow diversification of customers and sales. Wholesale typically allows access to restaurant markets, while retail is direct to customers. Having both can make operations more resilient if for example, the restaurant industry suffers (as was the case during the COVID-19 outbreak).
Marketing/price	Changing marketing strategies or product prices (e.g., raising the price of shellfish) can help growers keep pace with other costs of business up-keep, cost-of-living, market shifts, etc.
Water intake	For land-based culture, altering water upon intake into farms, turning pumps off at strategic times, or altering the location of the intake can allow manipulation of water quality and/or carbonate chemistry towards more favorable conditions for culture.
Temporal flexibility	For in-bay culture, altering the timing of shellfish outplanting or harvesting around anticipated environmental stress events can allow growers to avoid mortality and loss of product.
Variable ploidy	Having access to both triploid and diploid oysters can diversify growers' products and help reduce risk of product loss due to possible differential environmental effects between the two.
Science	
Shellfish health knowledge	Identifying drivers of shellfish mortality and health can allow growers to recognize and respond to environmental conditions likely to lead to shellfish mortality.
Genetic resistance	Developing shellfish broodstock that is genetically resistant to environmental stressors can yield a greater quality or quantity of product.
Monitor OA and water quality (WQ)	Improving water quality monitoring, including carbonate chemistry data, can inform growers of environmentally stressful conditions. This can allow for adaptive responses and lead to greater understanding of how water quality affects shellfish health and mortality.
Environmental impacts research	Advancing research on the environmental impacts of new methods, species, or gear types can serve as proof-of-concept studies, ultimately leading to easier permit approvals when growers seek to make such changes.
Polyculture	Exploring and researching the benefits of co-culturing shellfish with other species may be a highly sustainable way for operations to expand, with possible OA amelioration benefits from co-culture with algae/marine plants.

partnerships, opening doors for research and monitoring studies that fill scientific knowledge gaps and simultaneously inform grower operations. Nearly all growers noted value in the efforts to facilitate broad networking opportunities such as conferences and meetings. For example, when speaking of the Pacific Coast Shellfish Growers Association meeting, one grower mentioned "*it is a really helpful conference to see what all this data has shown and all the adaptations that everybody has made that kind of aid with that and how everybody can work together to kind of help with OA or help with bacteria problems or anything that's going on with the industry.*" Yet despite acknowledging the value in network connections, growers also stated the challenge in finding time to invest in these efforts. For instance, one grower stated, "*I think those [meetings and conferences] would be great, but I'm too busy just trying to do the day-to-day things on my farm.*"

4.3.2. Farm management

Growers mentioned a number of practical strategies surrounding the operations and management of shellfish farms that can facilitate adaptive capacity. Often, this came in the form of strategies allowing increased flexibility in the species or life stage cultured, or in the methods or location of the culture. Culturing numerous or additional species and life-stages provided a type of insurance – akin to the 'portfolio effect' applied in both ecological and economic fields (Markowitz, 1952; Schindler et al., 2015). In this way, growers' businesses could maintain income and operations if one species (e.g., *C. gigas* over *C. virginica*) or life-stage (e.g., small adults versus large adults) fared more poorly than the other due to mortality events, market shifts, or other factors. Some growers identified this as a strategy that was likely to become more necessary in the future, to diversify their products and ensure a stable income under variable ocean conditions. For instance, one grower stated, "*I'm very interested in growing different varieties of Pacific oyster such as Kumamoto or maybe a hybrid or ones that are more adapted to warmer water.*" Other growers noted that they are already employing this 'species shift' strategy when times become difficult. For instance, some choose to harvest and sell mussels growing naturally on culture gear for additional revenue or during years of poor oyster success: "*We have mussels that are native that are clinging to our ropes. And we're going to go ahead and harvest those this year. We don't usually, but we're desperate.*"

Growers also expressed a desire to alter or expand culture methods, equipment, or location to generate greater flexibility in operations. The specifics of these strategies varied widely between growers, depending on numerous factors including the location (land-based vs. in-bay), species, or life stages being cultured. Some oyster growers with in-bay operations noted variable success between areas within their leases or between seasons of product outplanting, that could be capitalized on if well understood. One grower stated, "*we tried to avoid planting juveniles in the summertime and just planted the fall through spring and we were able to survive that big outbreak of herpes virus then by doing that.*" For land-based

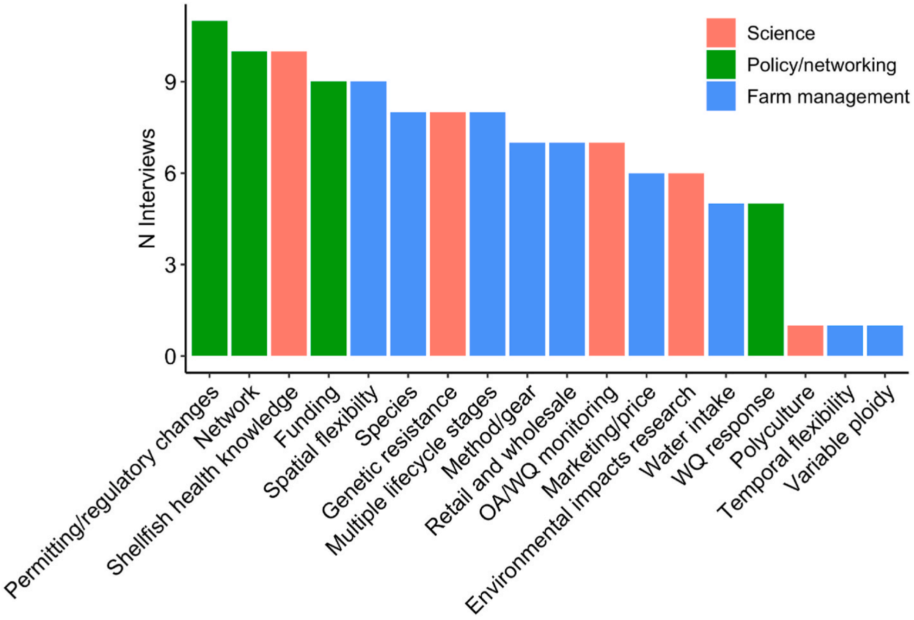

Fig. 3. Total number (N) of aquaculture operators who mentioned each identified adaptive strategy during interviews. Descriptions of each strategy are detailed in Table 2. WQ = Water Quality, OA = Ocean Acidification.

operations (adult abalone or oyster hatcheries), changes to the culture system such as adding fans or depuration systems could help growers adapt to changes in temperature or water quality, respectively, acknowledging costs come with these modifications. Strategic method and gear placement strategies are employed by in-bay operators as well. For example, to respond to environmental changes, growers noted they might move shellfish racks around existing lease areas to avoid mortality events: "*you could potentially move [oysters] around the bay, and we've done that a little bit in relation to summer mortality*." When responding to carbon chemistry-derived stress, in-bay operators were not as well positioned to adapt as land-based operations. For land-based hatcheries in particular, given the adverse impacts of low pH on larval and juvenile shellfish (Hauri et al., 2009; Kroeker et al., 2013), growers can alter seawater pH upon farm intake or strategically turn water pumps off during times of low pH to ensure suitable conditions in tanks. Although this strategy is key for OA adaptation in West Coast shellfish aquaculture (Barton et al., 2015), once shellfish enter bay waters, growers' ability to control carbonate chemistry is greatly reduced.

Implementing these changes in farm operations comes with regulatory challenges, intersecting directly with strategies operators cited relating to policy and networking. For example, regulatory barriers may exist if a grower seeks to move product away from areas where rainfall may lead to temporary closure due to public health concerns, or to avoid areas where eelgrass presence may impact operations. One grower stated, "*you can't just say, oh, this is the best place to grow and I'm going to start growing them here. You have to get permits obviously, and so it's very restrictive*." Specifically, once an individual permit has been granted, the permit only applies to that single applicant (it cannot be generalized to other growers in the same bay), and it generally only applies to the specific methods, location, species, and gear stated in the permit, prohibiting flexibility without costly permit amendments.

4.3.3. Science

The need to better understand drivers of shellfish health and mortality was mentioned in all but one of the interviews (Fig. 3). Mortality events can be severe, and periodically lead to loss of the majority of shellfish in some lease areas or hatcheries (Gray et al., 2022; King et al., 2021; Soon and Zheng, 2020). In some cases, growers estimated mortality of 90% of their in-bay oysters, and published literature about West Coast hatcheries cites events leading to mortality of over 75% of larvae, causing considerable economic damage (Barton et al., 2015; Mabardy et al., 2015). Scientific literature about the causes of such mortality events along the West Coast is sparse, but recent research points towards marine pathogens, harmful algae, warm water, and other interacting environmental factors as likely drivers of in-bay mortality events (Bill et al., 2016; Green et al., 2019; King et al., 2021), with low pH as an additional noteworthy stressor for land-based hatcheries (Barton et al., 2015). High uncertainty remains though around the mechanisms by which these factors lead to mortality events (Go et al., 2017; Gray et al., 2022) and how impacts and outcomes may vary by species (Soon and Zheng, 2020). In response to mortality caused by disease, warm water, OA, and broad environmental change, many growers mentioned development of genetically resistant shellfish strains as an avenue to improve adaptive capacity (e.g., Nascimento-Schulze et al., 2021), with comments similar to one grower's sentiments of hoping to "*breed animals that can adapt to changing conditions. So essentially what I need is money for a local hatchery and a geneticist that's breeding a better animal, basically engineering against the harms of ocean acidification*."

A lack of monitoring and site-specific data goes hand-in-hand with these scientific knowledge gaps and makes it extremely difficult for growers to predict and respond to mortality events. Given the demands of business operations, no interviewed growers mentioned targeted plans to measure or monitor shellfish mortality and co-occurring environmental factors. As one grower explained,

> *"There are these mortality events that happen in oyster culture that are usually not clear why they happen, but they often happen in the summertime and they might be related to warm water and spawning events. And so, I worry that that's getting worse. And we just had a big die off in June of this year [2020] where we lost about half of our year-old oysters, and I have no idea what caused it or why."*

The time, cost, and technical skill sets required to conduct such monitoring are major barriers in facilitating growers' adaptive responses. As a result, the aforementioned networking strategies became increasingly valuable to connect growers to this scientific information. Indeed, the existing examples of these partnerships exemplify their value in helping growers understand and respond to environmental change (Barton et al., 2015).

5. Discussion

5.1. Facilitating adaptive strategies

Interviews with growers revealed numerous environmental and other stressors affecting California's shellfish industry and identified multiple strategies available to facilitate the industry's ability to adapt to these stressors. Adaptive strategies were often directly linked, in that reduction of one stressor could allow growers to allocate resources towards implementation of a strategy targeting other stressors. In particular, growers' ability to implement a given adaptive strategy could often be facilitated by a modified permitting process. Indeed, the most frequently cited approach for adaptation was modified or expedited permitting and regulatory processes, as obtaining permits and complying with regulations are necessary precursors to making changes in most farm management practices, and permitting challenges acted as a barrier to slow or prohibit the implementation of such strategies. For example, strategies such as the cultivation of additional species or the adjustment of gear or gear placement were challenged by the ability to get permits to implement these approaches, particularly on the time frames needed to keep pace with environmental change. Similarly, adaptive strategies relating to networking and scientific partnerships require a significant investment of growers' time, much of which is currently devoted to navigating complex or opaque permitting and regulatory processes.

These high regulatory burdens in California are largely due to the fact that growers must remain compliant with numerous environmental policies, in particular, the California Environmental Quality Act and the California Coastal Act (e.g., California Coastal Commission, 2020). As a result, growers must navigate multiple permitting processes that require approval from multiple different agencies including the California Department of Fish and Wildlife, Fish and Game Commission, California Coastal Commission, California State Water Resource Control Board, California Department of Public Health, U.S. Army Corps of Engineers, among others (Bernadett, 2013). Efforts to improve and clarify permitting and regulations are essential to supporting growers' adaptive capacity, an approach that may become increasingly important as pressure from climate change-induced environmental change increases. For example, promoting and supporting programmatic permitting approaches is a promising avenue identified by both the interviewed growers and other key actors in California's aquaculture landscape (California Sea Grant, 2015; Humboldt Bay Harbor, Recreation, & Conservation District, 2020). Such an approach could allow a larger entity with more available resources to navigate the costly permitting process, thereby reducing burdens on small, individual farms and allowing these farms to invest in other adaptive strategies. Additional avenues to reduce permitting and regulatory barriers could also be supported, such as investment in training and education for farm operators and permit writers and regulators or in improving permit processing timelines and clarity (e.g., California Coastal Commission, 2020). These efforts could clarify regulatory processes for operators and keep permit writers and regulators up to date on emerging farm practices and adaptive strategies (Osmundsen et al., 2017). Making these changes, while simultaneously balancing the diverse interests of coastal stakeholders and California's environmental protection standards, could facilitate adaptation and sustainable production of shellfish in the state and its accompanying co-benefits.

Programs and funding that support networking opportunities amongst growers, scientists, policymakers, and managers can further contribute to adaptive capacity, given the described value of these networks by growers. Networking also links many of the identified strategies together; it provides the basis for growers to learn about the effective strategies available to them (e.g., farm management techniques, understanding environmental challenges) and can lead to reduced permitting timelines if relationships between growers and regulators are well-established. Networks from regional to global levels are already facilitated through consortia and initiatives such as the Pacific Coast Shellfish Growers Association, the Pacific Shellfish Institute, and the California and National Shellfish Initiatives. Similarly, national, regional, and state OA initiatives, policies, and action plans have identified developing partnerships between scientists, agency staff, and shellfish growers as key goals to facilitating effective responses to OA and environmental change (Chan et al., 2016; FOARAM Act, 2009; Oregon Coordinating Council on Ocean Acidification and Hypoxia, 2019; Whitely Binder, 2012). Efforts to connect growers and scientists, many of which are already supported and underway (e.g., California Ocean Protection Council, 2020a; California Sea Grant, 2020; Central and Northern California Ocean Observing System, 2022; National Oceanic and Atmospheric Administration, 2020), facilitate networking opportunities and partnerships that can improve growers' ability to detect and respond to OA by connecting them with scientific expertise and resources. Nonetheless, academic-private partnerships can at times be hamstrung by the temporary nature of academic grant cycles and personnel turnover. This may merit the exploration of other models to address, fund, and sustain growers' science-based adaptive strategies, such as formal agreements between growers and long-term monitoring programs (e.g., Central and Northern California Ocean Observing System, 2022) or private sector companies, as is more common in finfish and large-scale aquaculture operations in other global locales (e.g., ScootScience, 2022; SmartOysters, 2022; Umitron, 2022).

5.2. Implications for adaptive capacity

Although this study was specific to the U.S. West Coast shellfish aquaculture industry, its relevance and linkages to the broader field of adaptive capacity are readily evident. The described strategies, while tailored to this specific community, can be more broadly categorized into domains of adaptive capacity observed across communities and geographies. In one synthesis on the subject, Cinner et al. (2018) identifies five common domains of adaptive capacity: Assets, Flexibility, Social Organization, Learning, and Agency. By cross-examining these five domains and the grower-identified strategies, we see that they can be operationalized across all 18 of the strategies (Table 3). For instance, within the 'flexibility' domain, many of the described farm management strategies rely on a need for flexibility - such as the desire to alter the species or gear used for culture ('species' and 'method/gear type') or the ability to move equipment around their lease area ('spatial flexibility'). Similarly, growers identified numerous 'assets' needed to implement these strategies, for instance, access to the necessary equipment ('methods/gear') or facility types, such as a hatchery and a grow-out space ('multiple life cycle stages'). The 'social organization' domain is evident in the growers' reliance on and desire to improve their networks to gain information and share data. Strategies falling within the 'learning' domain are clear in the identified scientific gaps, such as the desire for more information on the drivers of shellfish mortality or on OA conditions. Lastly, 'agency' is defined in Cinner et al. (2018) as the ability for people 'to have free choice in responding to environmental change'. Within the grower strategies, a lack of agency was clearly identified in the growers' sentiments that regulations and permitting prevented implementation of many of the identified adaptive strategies, in particular the farm management strategies. Many of these strategies can also fall under multiple domains. For example, altering the chemistry of a land-based farm's incoming water ('water intake' strategy) inherently relies on flexibility in farm management, and requires that growers evaluate when stressful conditions are occurring ('learning' domain) and have the equipment to respond ('assets' domain). By viewing these strategies through a broader lens of adaptive capacity, we see that despite their high level of specificity, comparisons can be drawn to numerous other communities. For example, previous work shows the need for flexibility in many fishing communities, whereby fishermen with larger vessels or wider or more diverse species or fishing grounds were demonstrably more resilient than those with smaller vessels or fishing grounds (Anderson et al., 2017; Sievanen, 2014; Stoll et al., 2017; Young et al., 2019). Similarly, within the organization and learning domains, previous work shows that agricultural communities have an increased ability to adapt when they are well networked and able to share, generate, and process information on climate change (Silici et al., 2021; Takahashi et al., 2016). A more thorough operationalization of these domains of AC based on the strategies mentioned by growers would require more responses, but through these examples, we see that the identified strategies for shellfish aquaculture have broadly applicable underlying domains and characteristics. Thus, governance and management approaches aiming to support adaptation can and should support such characteristics, recognizing their value and prevalence across communities and industries.

6. Conclusions

California shellfish farmers directly observe and experience numerous environmental changes, some of which are more easily observed or measured. While most growers expressed concern for changing ocean conditions, it was often challenging for growers to make direct links between outcomes to their operations and changes that could not be easily observed or measured. In particular, linking impacts or outcomes to OA posed challenges in their ability to implement direct responses. Rather, OA was perceived more as an unknown and potential stress multiplier, and growers instead identified (and in many cases are implementing) a number of strategies that could help them adapt to changes resulting from environmental, economic, or political stressors. Some strategies directly targeted OA (e.g., improving pH monitoring or developing OA-resistant broodstock), but the broad range of strategies supported adaptation to multiple diverse stressors to facilitate increased farm resilience. Facilitating adaptive capacity requires a coordinated approach that recognizes the interconnected nature of stressors and associated strategies, whereby reducing one type of stressor may allow growers to proactively allocate resources towards implementation of adaptive strategies relating to other stressors in order to improve overall resilience.

By evaluating aquaculture operator-identified adaptive strategies and key challenges to their implementation, this work makes evident the need for improved policies, coordination, and scientific advances within the shellfish aquaculture industry and associated agencies. Future work will build off this research to identify what characteristics affect or drive adaptive capacity, further informing management decisions that support resilience to OA and environmental change in the West Coast shellfish industry. Additional work will explore the policies that might be leveraged to facilitate adaptation while maintaining the existing priorities and environmental protection standards of coastal stakeholders and rights holders. Future work could also identify and investigate strategies other than those discussed by growers here, such as disaster relief funds or insurance, to further explore available adaptation avenues and identify areas where collaboration between agencies, industry, and academic partners might aid in their implementation. With calls for increased domestic seafood and shellfish aquaculture production, research on the social-ecological systems behind them must be considered in tandem in order to ensure the sustainable adaptation of these growing industries and communities.

Author Contributions

MW led original draft preparation, investigation, and formal analysis. AS led project conceptualization, funding acquisition, and contributed to investigation and manuscript review and editing. AL contributed to project conceptualization, funding support, supervision, and manuscript review and editing. EW contributed to investigation and manuscript review and editing.

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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