Title

Oregon Shellfish Farmers: Perceptions of Stressors, Adaptive Strategies, and Policy Linkages

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Abstract

In the United States, domestic oyster aquaculture production is insufficient to meet national demand, thus creating a reliance on international oyster imports for consumption. West coast shellfish farmers are threatened by climate change, including ocean acidification as well as socioeconomic challenges such as labor availability. To expand and enhance United States oyster production, and support domestic food security and livelihoods, a better understanding of the limitations that oyster farmers' experience, and corresponding pathways forward for adaptation is needed. Through semi-structured interviews conducted with commercial Oregon shellfish farmers, we assess the environmental, economic, social and regulatory stressors impacting oyster growing operations, and the corresponding adaptive strategies employed or envisioned by aquaculture farmers. We find farmers are most impacted by environmental stressors (nuisance species that interact with oysters or oyster habitat negatively), followed by regulatory and economic stressors (permitting and regulations and labor availability). Farmers perceived ocean acidification as a risk, but primarily at the oyster larva stage rather than the juvenile or adult grow-out stage. Examples of farmer-identified adaptive strategies included streamlining permitting and regulations, incentivizing employee retention, and having flexibility in culture type to avoid nuisance species and other environmental stressors. An increase in targeted outreach related to aquaculture policies and engagement with industry, scientists, managers, and policy-makers could facilitate policies that support these and other adaptive strategies.

1. Introduction

The marine aquaculture industry in the United States (US) is a valuable component of the economy, contributes to food security, and, when carefully managed can supplement wild-capture fisheries as a source of global food supply (Clavelle et al. 2019; Froehlich et al. 2022a; Knapp and Rubino 2016). Oysters lead domestic aquaculture by both value ($219 million) and production (42.3 million lbs/year) (NOAA 2022). Despite many opportunities for expansion in domestic marine aquaculture (Buck and Langan 2017; Kapetsky et al. 2013), oyster production in the US has stagnated since the 1950s relative to the rest of the world (Botta et al. 2020).

Challenges to oyster production worldwide include environmental stressors such as disease and parasites (Pernet et al. 2016), water quality (Webber et al. 2021), and climate change (Barton et al. 2015; Lemasson et al. 2017; Maulu et al. 2021; Raymond et al. 2022). In the US, slow growth in the oyster industry may also be attributed to social, economic and political stressors. These include the high cost of aquaculture operation (Chen et al. 2017; Hudson et al. 2012a; Hudson et al. 2012b), supply chain and marketing challenges (Love et al. 2020; Love et al. 2021; Rioux 2011), and state and federal regulatory frameworks, which can constrain existing aquaculture operations and/or future expansion of aquaculture (Engle and van Senten 2022; Froehlich et al. 2022a; Lester et al. 2022; Rubino 2022; van Senten et al. 2020). As a result, the scale of oyster production is limited and domestic production in the US is insufficient to meet national demand (Knapp and Rubino 2016).

To meet this gap in oyster supply, the US imports more oysters than any other country: annually an average of 12,101 metric tons of oysters between 2015 and 2019 (FAO 2022). Heavy reliance on international oyster production and international supply chains subjects the industry to increasing inflation (Agarwal and Kimball 2022; Auer et al. 2017), high fuel and energy consumption (Muir 2015), food quality and safety issues (King and Venturini 2005; Love et al. 2020; Love et al. 2021), and potentially unsustainable or unregulated oyster farming practices (Girard and Agúndez 2014; Liu et al. 2015; Liu and Su 2015). To address these and other issues, an Executive Order was signed in May 2020 to strengthen and expand domestic production of seafood (Executive Order No. 13921, 2020).

Increases in domestic production could support livelihoods and rural prosperity (Campbell et al. 2021; Knapp and Rubino 2016), facilitate ecosystem functions (e.g. water filtration and enhanced invertebrate and fish habitat; Barrett et al. 2022; Dumbauld et al. 2009; Michaelis et al. 2020, Petrolia et al. 2020), and enhance place-based and cultural relationships with oysters for human communities (Krause et al. 2019; Reeder-Myers et al. 2022). However, to effectively expand domestic oyster production and support the resilience of coastal communities, a better understanding of the impacts that stressors have on production, and the strategies shellfish farmers use to adapt to these stressors at a regional, state, and individual level is needed.

To date, research on adaptation to stressors in aquaculture has centered on climate change. A global review of aquaculture adaptations to climate change indicated that aquaculture farmers adapt at a variety of scales, but more support is needed at the community level, especially to support strategic aquaculture management techniques and access to funding to support or expand operations (Galappaththi et al. 2020; Ekstrom et al. 2015). Furthermore, existing studies on climate adaptation in aquaculture focus primarily on countries in the Global South where the needs and benefits of aquaculture directly relate to food and economic security (De Young et al. 2012; Froehlich et al. 2022b; Galappaththi et al. 2020). While it is of utmost importance to address climate change in aquaculture (FAO report; Stewart-Sinclair et al. 2020), an understanding of other stressors that are discrete from, and overlap with, climate change, is also necessary to support adaptive capacity in the oyster industry.

Ward et al. (2022) outlined a suite of biological and physical environmental stressors and their impacts on shellfish farmers in California, many of which are comparable to those faced by West coast farmers more broadly (e.g. marine disease which can cause mortality to cultured shellfish, ocean acidification which can reduce growth and survival and rainfall which can increase runoff and sedimentation). These environmental stressors can overlap in space and time, as well as with non-environmental stressors, leading to compounding impacts on operators that may result in a tipping point for shellfish operations. For example, if a shellfish operator is struggling to keep their operation in business due to a chronic stressor such as inflation, an acute event such as a mass mortality from hypoxia may lead to permanent closure of the operation. Understanding shellfish operators' perspective on both climatic and non-climatic stressors is one way to assess the impacts of multiple stressors on shellfish aquaculture.

In this study, we define adaptive capacity as: *'the ability of aquaculture farmers to respond to stressors, to take advantage of opportunities to adapt to these challenges, and to effectively respond to their consequences,'* modifying Ward et. al's (2022) definition to be inclusive of both environmental and non-environmental stressors. We focus on the following research questions: 1) What environmental, economic, social, and regulatory stressors affect shellfish operations? 2) What, if any, adaptive strategies do shellfish farmers employ (or plan to employ) to address these stressors? We answer these questions through semi-structured interviews with commercial shellfish farmers in the US state of Oregon and possible avenues towards increasing farmers ability to adapt, including policy changes.

2. Background/Case Study locations:

The Oregon shellfish industry is among the top 25% of states nationwide for commercial oyster production (USDA 2019). Between 2006 and 2019, median commercial oyster production in Oregon derived from state-solicited data was 41,036 bushels (range 3,136 to 104,349 bushels) (Froehlich et al. 2022a)[1]. Although overall oyster production trends in Oregon show a slight increase during this time period, production has been generally stable between 2008 and 2019 with the exception of a large peak in production in 2016 (104,349 bushels) (Froehlich et al. 2022a).

Indigenous people in Oregon, as in the rest of the US, were the earliest harvesters of oysters, with shell middens dating back to ≥6,000 years ago (Reeder-Meyer et al. 2022; Thompson et al. 2020). Native American tribes first harvested Olympia oysters (*Ostrea lurida*) in Oregon for nutritional and cultural sustenance (Robinson 1997). In the 1860s, colonial settlers began using mechanical implements known as dredges to harvest oysters in Oregon's bays, causing widespread depletion of Olympia oysters (Breese 1972). By the late 1800s, the Olympia oyster was cultivated in the Pacific Northwest, followed by the cultivation of imported Japanese oysters (Pacific oyster; *Crassostrea gigas* and Kumamoto oyster; *Crassostrea sikamea*) as well as the Eastern oyster (Crassostrea virginica) to combat the decline of wild oyster populations and supplement the growing American taste for oyster meat (Mackenzie 1996). Today, six areas (Coos Bay, South Slough, Tillamook Bay, Netarts Bay, Umpqua River and Triangle, and Yaquina Bay) are approved for commercial shellfish aquaculture by the Oregon Department of Agriculture (ODA; Figures 1 & 2). These bays range in size from 11.1 km^2 to 54 km^2 and commercial farming of Pacific, Kumamoto, and Olympia oysters within these bays provides major support for local economies, in addition to adjacent commercial logging and dairy industries.

The State of Oregon and the commercial shellfish industry support aquaculture expansion, yet major barriers exist (Ehrhart and Doerr 2022). Non-environmental barriers to aquaculture expansion include permitting and regulation, and workforce availability (Ehrhart and Doerr 2022). Oregon's shellfish industry is also particularly vulnerable to environmental impacts, including ocean acidification (Ekstrom et al. 2015, Hodgson et al. 2018), marine heatwaves (Raymond et al. 2022), and low dissolved oxygen, or hypoxia (Chan et al. 2019). Ocean

[1] Froehlich et al. (2022a) reports problematic discrepancies between state-solicited and federal (USDA and NOAA) estimates of aquaculture nationwide (and for Oregon discrepancies between 10 and 30%).

acidification (OA) poses a global threat to shellfish (Stewart-Sinclair et al., 2020). Shell-forming organisms, including oysters, are particularly negatively affected by low pH and low aragonite saturation state (e.g., Kroeker et al. 2010; Waldbusser et al. 2013). OA is also known to affect shellfish larval survival and has been implicated in shellfish larval mortality events at Oregon hatcheries (Barton et al. 2015; Mabardy et al. 2015). These severe hatchery mortality events in the mid-2000s were an early social and economic indicator of OA and spurred research in Oregon on understanding and mitigating OA impacts (e.g., Barton et al. 2015; Chan et al. 2019). Addressing OA concerns through regional and national research and action plans requires an integrated approach across scientists, policy-makers, and shellfish-dependent communities (Ekstrom et al. 2015; Chan et al. 2016; Whitefield et al. 2021). In 2017, the state legislature created the Oregon Coordinating Council on Ocean Acidification and Hypoxia (Senate Bill 1039) to direct research and recommend adaptation strategies. Furthermore, Oregon recently allocated funds to create a best management plan for shellfish aquaculture in Oregon (House Bill 3114 in 2021), which can aid aquaculture industry growth and success (Lester et al. 2022).

Figure 1. Map of approved Oregon aquaculture sites (black star) for oyster culture: Tillamook Bay, Netarts Bay, Yaquina Bay, Umpqua River and Triangle, Coos Bay, and South Slough.

The aquaculture industry in Oregon is regulated by ODA, the Oregon Department of Fish and Wildlife (ODFW), the Department of Environmental Quality (DEQ), the Department of State Lands (DSL), the Water Resources Department (WRD), the Department of Land Conservation and Development (DLCD), and the US Corps of Army Engineers (USCOAE). To pursue shellfish aquaculture in Oregon, a prospective farmer must schedule a pre-application meeting with ODA, DLCD, and ODFW to identify a leasing area, and submit an application packet for federal and state review, a shellfish plat lease map, an affidavit of public notice, and a plat filing fee (Figure 2a). If approved, the farmer provides a licensed survey of the lease area and plat boundary map to the USCOAW for a Nationwide Permit No. 48, Commercial Shellfish Mariculture Activities (contingent on a federal consistency review through the Oregon Coastal

Zone Management program at DLCD) (Figure 2a). If the federal land use permit is granted, and ODA approves the lease, the farmer must obtain a shellfish farmer license, a permit to transport shellfish, and a food safety license prior to selling shellfish products for human consumption (Figure 2b).

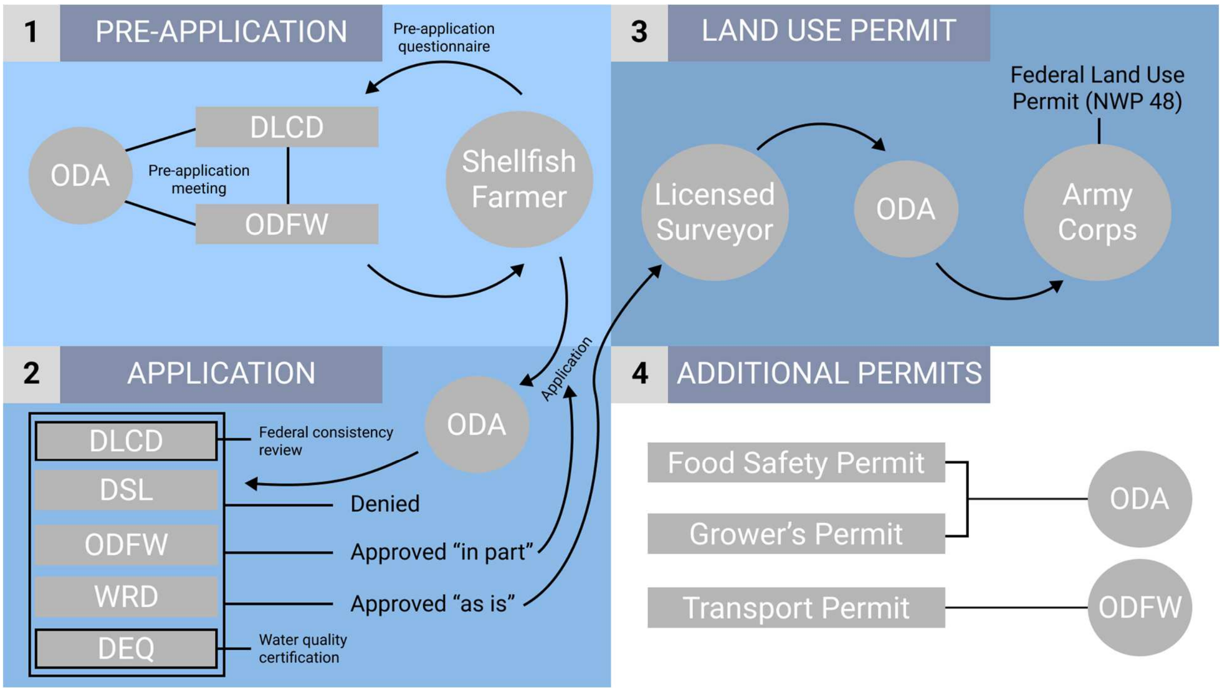

Figure 2a. Pre-application, application and permitting process. 1) A prospective farmer schedules a pre-application meeting with the Oregon Department of Agriculture (ODA), Department of Land Conservation and Development (DLCD), and Oregon Department of Fish and Wildlife (ODFW). 2) Post-meeting, the farmer submits an application to ODA, Department of State Lands (DSL), ODFW, Water Resources Department (WRD), and the Department of Environmental Quality (DEQ). 3) Upon approval, the farmer submits a licensed survey of the lease area and a plat boundary map to the United States Corps of Army Corps of Engineers (USCOAE) for a federal land use permit. 4) Additional permits are required by the state upon approval: a shellfish grower's permit and food safety permit (ODA) and a shellfish transport permit (ODFW).

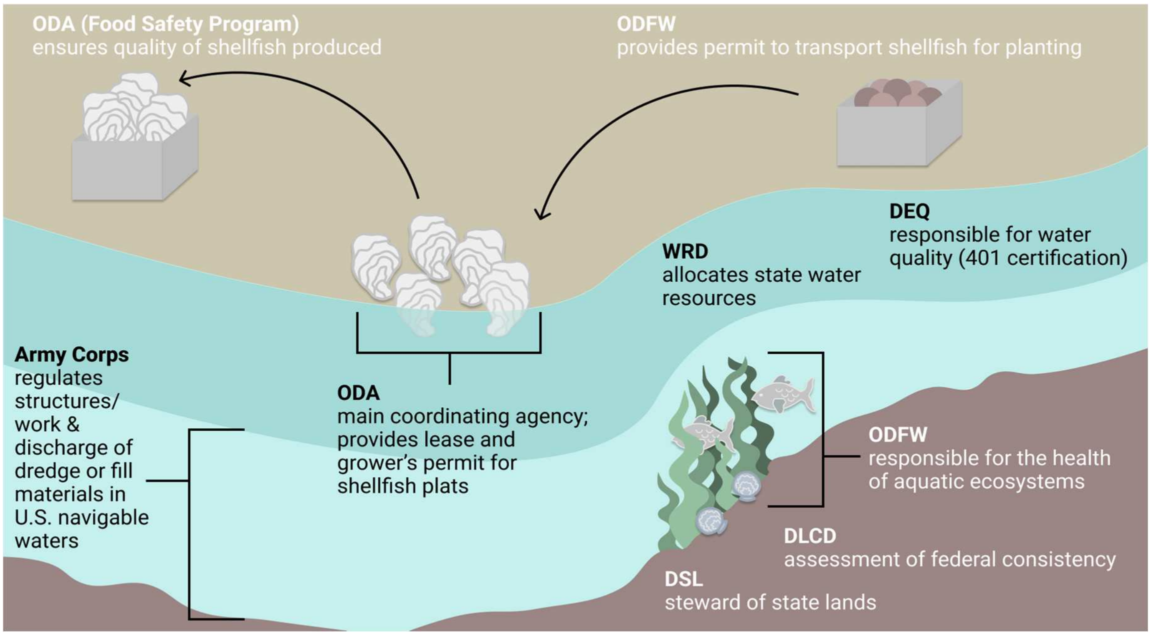

Figure 2b. State and federal agencies that regulate shellfish farming in the State of Oregon and a description of their roles: United States Corps of Army Corps of Engineers (USCOAE); Oregon Department of Agriculture (ODA); Water Resources Department (WRD); Department of Environmental Quality (DEQ); Oregon Department of Fish and Wildlife (ODFW); Department of State Lands (DSL); and the Department of Land Conservation and Development (DLCD).

3. Methods

3.1 Positionality: The author team included a team of six authors. AS, EW, SH, and LR are Oregon residents. KG, MW, AL are nonresidents but have multiple years of experience collaborating with coastal communities along the West coast.

3. 2 Interviews and Pre-Interview Survey

We worked with state and academic extension agencies to acquire a list of approved shellfish aquaculture operations in the state of Oregon. We contacted every operator on the list (a total of 20 ODA approved operations) via phone, email, text or social media to explain the project and invite farmers to participate in a semi-structured interview. We purposefully chose to interview only the owner(s) or manager(s) of the operation based on their ability to make organizational-level decisions about the shellfish operations. Prior to interviews, shellfish farmers were invited by the university team to participate in a web-based survey to solicit information about farm operations (species and life stages cultured, culture techniques, presence and type of environmental monitoring, years of operation and lease size, and production/income generated from farm operations.)

The interview protocol was adapted from Ward et al. (2022) and included questions related to 1) background and history of shellfish operations; 2) environmental, economic, social, and political stressors that farmers perceive as negatively impacting operations; 3) current or future adaptive strategies to address these stressors; 4) factors that facilitate or constrain adaptation; and 5) perceptions of the current management structure for shellfish aquaculture policy and/or ideas for improving policies related to adaptive capacity. We were particularly interested in farmers' perception of environmental stressors and adaptive strategies related to OA; however, interviewees were first asked generally about environmental changes and stressors, and then prompted specifically about OA.

Between March and May 2022, fifteen interviews were conducted by the lead author with commercial shellfish farmers located on the Oregon coast, except for three interviews accompanied by one other author. Interviews were recorded with participant permission. Of the farmers interviewed, eight responded to the web-based survey; for the remaining seven farmers, the web-based survey questions were gleaned from interview data and follow-up questions with individual farmers by the lead author. Interviews were conducted via phone, Zoom, or in-person, depending on the comfort and availability of the interview participant. All interviews were conducted with the owner of the operation, with the exception of one location in which the manager was interviewed. In most cases, we conducted interviews with a single owner, with the exception of one husband and wife team that were interviewed together.

3.3 Analysis

Interviews conducted via Zoom were transcribed using the automatic Zoom transcription service and manually corrected by the lead author; interviews conducted by phone or in-person were recorded with a handheld audio recorder and transcribed by a professional transcription service. NVivo Software (QSR International 2011) was used to code transcribed interviews. The lead author coded interviews deductively using a codebook that included codes for the presence of environmental stressors and adaptive strategies adapted from Ward et al. (2022). Additional codes were added inductively by the lead author, based on emerging themes from interview responses, for the presence of economic, social, and regulatory stressors as well as additional codes for environmental stressors and adaptive strategies. Codes and sections of coded interviews were reviewed with other authors to refine and calibrate codes (Bernard 2000; Patton 2002; Tracy 2019).

Following Ward et al. 2022, only direct stressors were coded, rather than indirect stressors (e.g., if shellfish disease was mentioned, it was coded as such, rather than coding for potential drivers of shellfish disease such as harmful algal blooms unless explicitly mentioned by the interviewee). If multiple stressors were described in a sentence, these were coded individually. Individual codes for stressors were associated with an aquaculture operation if the interviewee described that stressor at least once during the interview. Likewise, we coded adaptive strategies into 16 of the 18 categories developed by Ward et al. (2022), under three broad themes: policy and networking, farm management, and science (Table 3). We inductively added two categories under the farm management theme that were unique to Oregon: Ecosystem Stewardship and Intentional & Proactive Farm Management and Planning. We coded more detailed strategies within these categories; if an interview respondent described any of the detailed strategies within the category, he or she was documented as reporting for the broader adaptive strategy category.

Results from interview coding were also triangulated with notes from participant observation (Flick et al. 2004), and visits by the lead author to shellfish operations throughout the state. The study design and interview protocol were reviewed and approved by the Institutional Review Boards at San Diego State University (Protocol #HS-2020-0208). All participants gave informed consent to participate in the research.

4. Results

4. 1 Shellfish operation background and history

All farmers performed aquaculture activities in the allowed areas for aquaculture in Oregon; exact locations are not disclosed to ensure anonymity of interviewees. Oyster farmers had many years of experience with oyster aquaculture (average 24.9 years; range 1 year to 60 years). Interviews were an average duration of 41 minutes, range 26-64 minutes.

Operations ranged in size from 1–13 full-time employees (some operations hired additional seasonal employees), with lease sizes between 22 and 1747 acres, and annual production between hundreds and hundreds of thousands of bushels[2]. All farms cultivated Pacific oyster, with Kumamoto and Olympia oysters as a secondary species; clams, and mussels were also cultivated in some locations. Operation types included in-water grow out of adult oysters, in-water nurseries (either land-based in tanks, or in a bay or estuary) or hatcheries.

4.2 Stressors negatively impacting growing operations:

Farmers reported 24 stressors that negatively impacted operations; these were categorized into four broad categories: Environmental, Economic, Social, and Regulatory (Table 1).

[2] Based on a conversion of 100 oysters per bushel (Oregon Department of Agriculture, personal communication).

Table 1. Stressor category (Environmental, Economic, Social, or Regulatory) and detailed stressors as reported by farmers in interviews. N is the number of farmers that mentioned a stressor one or more times; % is the percentage of farmers reporting out of n=15.

Environmental		N	%
	Nuisance species	11	79
	Ocean acidification	8	53
	Pollution	6	40
	Rainfall	6	40
	Hypoxia	6	40
	Air temperature	5	33
	Disease	3	27
	Hydrodynamics	2	13
	Water temperature	2	13
	Sedimentation	1	7
	Wind	1	7
Economic		14	93
	Labor	10	67
	Cost of supplies/fuel	8	53
	Cost of/demand for larvae	6	40
	Marketing and shipping costs	6	40
	Insurance cost	1	7
	Pathology cost	1	7
	Real estate and rental cost	1	7
Social		6	40
	COVID-19 Pandemic	4	27
	Physical nature of job	5	33

Regulatory		8	53
	Licensing and permits	10	67
	Water quality regulations	2	13

Environmental:

Environmental stressors most frequently reported included predators or other nuisance species. Some species directly predated on oysters (birds, green crabs, red rock crabs, oyster drills, sea stars), others had visible impacts of oyster products (e.g., mud blister worms that affected the appearance of oysters), while other species visibly damaged aquaculture infrastructure (e.g., harbor seals). While some farmers considered predators a mild nuisance, "*Maybe the green crab is stealing some of the oysters, but not a lot. We see maybe one oyster here and there [dead],*" in other cases, farmers described green crab predation as a cause of significant mortality. These farmers described making gear modifications to prevent green crab from accessing oysters and causing mortality (e.g., a suspended bag system versus on-bottom culture).

Habitat-impacting species such as burrowing shrimp infauna (e.g., ghost shrimp) or eelgrass affected habitat where oysters grow. Species that caused habitat impacts were reported by only a third of farmers. Yet, of the environmental stressors reported, this caused some of the larger impacts to oyster farmers in terms of loss of viable oyster grounds:

[Ghost shrimp] build burrows . . . they destroy the substrate underneath the oyster bed. . . that ground turns into a soft and soupy mess. The oysters will sink and suffocate in that mud much faster than you can maintain the oysters on that bed. We've lost hundreds and hundreds of farmable ground to ghost shrimp."

One farmer described losing "*50% of the farm ground. . . to ghost shrimp in the last four years.*" Other farmers described eelgrass, rather than shrimp, as a habitat problem for oyster growing:

"My problem with oyster farming is the eelgrass. There's too much of it. I know everybody wants it for habitat, but it's horrible now. It didn't used to be this thick. Now, I can't even hardly see the bottom .. . the grass grows so tall that it'll lay on top on the low tide and sinks [the oysters]."

Eelgrass, which also provides important ecosystem functions and is protected by NOAA as essential fish habitat, was not universally perceived as a stressor (NMFS, 2007). Some farmers explained that oysters were positive for eelgrass: "Y*ou will not see beds of eelgrass like you will within the oyster beds. You know where we usually have oyster grow, we'll have prolific growth of eelgrass."*

Although weather and climate-related stressors were not measured quantitatively, farmers described their perceptions of these trends, such as warming air temperature and wind. Warming air temperatures in the form of hot sunny days can cause thermal stress for the oysters and increase the potential for human disease, (e.g., *Vibrio cholera*) which concerned farmers, as described by this shellfish operator:

"Warming is not going to affect the oysters negatively as far as growing. It will affect them negatively as far as harvesting. . . . So as the water gets warmer, we get more Vibrio in the water, so there is more of a potential for food contamination."

Meanwhile, farmers described how wind events during low tides increased water turbidity and minimized oysters' ability to feed or caused sediments to cover oysters and increase mortality. Heavy rainfall can also cause pollutant runoff that affects water quality. Oyster harvest is prohibited when harmful bacteria (e.g. fecal coliform bacteria) exceed a threshold level under state water quality regulations, which was reported as a stressor by farmers. However, some farmers described less rainfall in the past year, which has benefitted them through fewer harvest closures, however, a lack of rain has led to different problems. One farmer described how she relies on *"big freshets* [freshwater inputs from rainfall] *to kill off a lot of those species that grow on the oysters . . . like sponges and tunicates."*

Farmers described hypoxia as a stressor, referencing acute hypoxia events that occasionally caused a large mortality event:

"It didn't seem to matter where [the oysters] were. There was about three months, they just all opened up. Somebody said they quit feeding for some reason, and they starved to death. Another person said it was low oxygen. . . at least half [to] probably two-thirds of all my seller product [died]. It was all market-size."

OA was reported by roughly half of farmers as a stressor, but it was described primarily as a hatchery problem:

"In the hatchery, it's all early stage, when they're smaller than 130 microns . . . [At a] smaller size, [the oysters] have a harder time form[ing] the shell. The older oysters that the farmers are involved with are hardier and less susceptible to change or to the product. . . I haven't seen much effect on the commercial size oysters."

Other farmers didn't view OA a concern for their individual operations or were not able to differentiate OA from other direct or indirect causes of mortality, "*I don't know anything about ocean acidification,"* indicating either a lack of awareness about OA or a lack of being able to discern any impact. Even if farmers were concerned about OA, they still had uncertainty about what actions to take going forward to mitigate or adapt to OA impacts on shellfish.

Table 2. Perceptions of ocean acidification (OA) as reported by Oregon farmers (n=15). N is the number of farmers reporting in a category, % is the percentage of farmers reporting out of n=15.

Perception of ocean acidification	N	%
Hatchery/young life stage problem, unsure about other stages	6	40
Is not a problem	4	27
Unsure if it is a problem	3	20
Is a problem	2	13

Economic:

The most frequent economic stressors reported included labor costs, for example, keeping and maintaining employees, the cost of supplies and fuel, marketing and shipping costs, and the cost of and the availability of larvae from hatcheries at certain times in the past or present.

These stressors, especially the challenge in finding and maintaining employees affected oyster farmers' ability to run their day-to-day operations, as one farmer commented:

"An oyster farm on the West Coast pays anywhere from $14 to $18 an hour [for an entry-level position]. The average nationwide for construction job, which would be on a set schedule and isn't near as physical as being an oyster farmer, [pays] anywhere from $22–$25 an hour. That can be difficult [to compete with]."

Recent economic inflation, conflated by the COVID-19 pandemic[3] have increased the cost of supplies needed for oyster farming and for fuel needed to operate boats for harvesting oysters. As one farmer explained,

"The rising cost in goods, and then inflation, fuel prices, cost of insurance, all of those things that contribute to an operation of any business are big factors. As prices rise, we don't have a good plan besides for us to follow suit. If fuel goes up, then the price of the oysters is going to go up because it costs more to farm them."

In addition to these described increases in fuel and supply cost, farmers struggled to obtain certain supplies due to supply chain issues, such as plastic containers to store harvested oysters.

Lack of funding was described by many farmers, particularly the ability to get loans to buy gear or invest in new culture techniques, buy oyster seed, or have capital to expand shellfish aquaculture leased ground. Several farmers described how the oyster industry was unfairly restricted from funding compared to other analogous industries, explained by this farmer:

"There's not a lot of grants available for oyster farmers . . . funding an oyster farm is near impossible and talking to other farmers [about] when they got any funding, it took them five to eight years. Whereas if I want to open a restaurant, I could find funding faster. [The banks] look at [oysters] like a wild species as opposed to a farm. A potato farmer can get a loan, but an aquaculture farmer can't."

These economic stressors impacted farmers' business plans, ability to maintain their business, and restricted opportunities for expanding their operation.

Social

The most frequent social stressor reported was the COVID-19 pandemic, which caused farmers to lose business or make decisions about turning away customers that refused to wear a face mask inside the retail store:

[3] The onset of the COVID-19 pandemic in 2020, which was still ongoing during these interviews affected and continues to affect many aspects of society, including impacting businesses (van Senten et al. 2020; Fairlie and Fossen 2021), delaying supply chains (Mangano et al. 2022) and increasing inflation (Banerjee et al. 2020).

"The pandemic has been difficult to navigate. . . People are not wanting to be cooperative and protect others. . . . we have an aging population, especially on the coast. . . The majority of my customers are older people. They appreciate that I'm continuing to require masks to come into the store."

Other farmers described changing from retail to wholesale operations, and how employee sick days during the pandemic caused hardship through loss of labor. Others talked about the physical nature of the labor needed to work in the oyster aquaculture industry as a challenge, particularly as they grew older.

Regulatory

Farmers described regulations as a stressor in two categories: 1) permitting and regulations that affected the ability to initiate and maintain daily operations, e.g., permitting complexity and timelines, or ability to culture new species, and 2) overarching federal policies related to water quality, e.g., the Clean Water Act. In the first category, one farmer gave an example of the long timeline and complex process needed to permit a new gear type:

"We are at the final stage of getting our permits approved by all the third parties involved. There is like 30 third parties involved from the Tribe to Coos County to the Army Port of Engineers, to Fish and Wildlife. . . we're just waiting for the permit to come in the mail now after two years."

Even farmers who were satisfied with their current permitting of culture techniques described fears about uses on existing leases being restricted by the state:

"I would say that the thing that you worry about the most is how you can use your shellfish farm. You never know what new regulation might come along that might make it a little bit tougher. In Oregon, we are pretty lucky in the fact that once your lease is established through the state, it's pretty defined as to what you can do and what you can't do. But [with a] a growing population, you always have that outside third-party stress that you must worry about."

In the second category, farmers described how pollution run-off, particularly from the dairy industry, could cause harvest closures that ranged from an inconvenience to a severe limitation on their business:

"When we were in full operation, we had 40 employees, and we were shipping about 100 gallons a year of oysters to Safeway, southern California, and Oregon. When the dairy industry [began to] pollute the bay . . . [we] had 100 days [of] closures a year sometimes. . . When it rains, and the government says that [the rain] washes the manure off the farmland, it pollutes the bay, and they close the bay. That happens during Christmas, New Year's, Valentine's Day, Easter. . . The big buyers like Safeway were counting on us because they had big specials for the holiday. And if we couldn't fill the orders, they would simply look for another seller. And we would lose those big markets, which we did."

This operator described having to reduce sales of oysters, and as a result, staff, over time due to the increasing water quality issues in the bay where they were permitted to operate.

Thus, permitting and regulations, whether a current or anticipated problem, was a stressor for many farmers, manifesting as either a direct burden in restricting culture techniques, lease expansion, or harvesting due to water quality, or indirectly due to the time needed or stress incurred through permit applications or litigation of water quality regulations.

4. 3 Adaptive strategies

We coded 18 types of adaptive strategies that farmers are currently using, or that they would like to employ in the future. These strategies were organized into three broad themes (policy and networking, farm management, and science (*a priori* Ward et al. 2022) (Figure 3; Table 3). See Table 3 for more details on each theme, including further categorization, detailed strategies, and exemplar quotes.

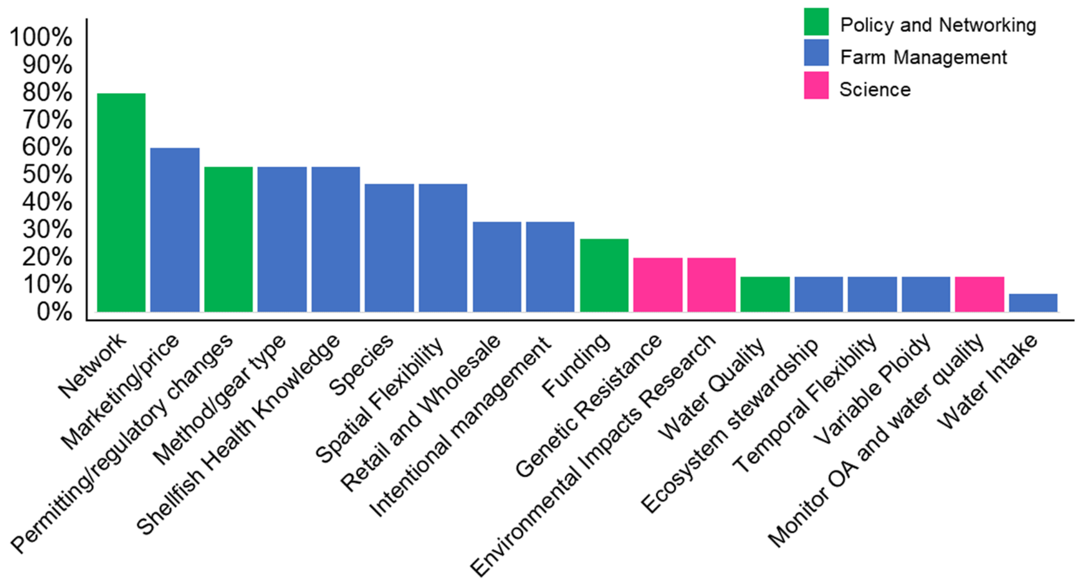

Figure 3. Categories of adaptive strategies (policy and networking (green), farm management (blue), and science (pink), and percentages (%) of farmers reporting the use of a current strategy or desire to employ a future strategy in each category.

Policy and Networking

The most frequently described adaptive strategy for the policy and networking theme (80% of farmers) was *Networking*. Farmers gave specific examples of how it was important to communicate with other farmers to learn about the most effective techniques for farming. One farmer described the lack of compliance by surrounding dairy farmers with the Clean Water Act as a problem solvable only through litigation, *"there's no point in talking to policymakers, litigation is the only answer.'* Other farmers had a different perspective; they wanted agencies to consider additional testing (e.g., multiple depths within the water column) or more frequent water quality monitoring to liberalize harvesting restrictions during rain events (assuming water quality standards were met).

Another adaptive strategy within policy and networking was *Permitting and Licensing* (53% of farmers). Many farmers described the extensive time they devoted to licensing and permitting (e.g., shellfish growing license, food transport permit, permitting of new culture types), and that reducing paperwork and streamlining regulations would allow them to more rapidly take actions to adapt to stressors. Developing consistent criteria for permitting and regulations across the relevant agencies was another suggestion made to enhance farmers' capacity to adapt. For example, one farmer described the need for agencies to survey bays where shellfish are farmed over multiple time intervals, rather than basing restrictive regulations off a survey data collected during a single time interval. Other farmers discussed the need to design regulations to allow for increased *Spatial and Temporal Flexibility* (under *Farm Management*), such as the flexibility to use alternate areas within their lease when certain areas are seasonally restricted due to the presence of federally-protected eelgrass or migratory birds.

Farmers desired more frequent monitoring for *Water Quality Response* (13% of farmers) to provide more opportunity for harvesting oysters around rain events, or adding sampling of the oyster meat, rather than just the water column to determine safety for human consumption of oysters. One farmer posited that if the oyster flesh was safe for consumption, then harvesting should be permitted.

Farmers also described the need for potential adaptive strategies related to *Funding* (27% of farmers), for example, oyster aquaculture loans and funding opportunities for capital investment. One farmer suggested specific incentives to encourage aquaculture investment, such as an oystercoin cryptocurrency used to buy, sell, and exchange goods related to oyster aquaculture.

Farm Management

Adjusting *Marketing and Price* was the most frequently reported farm management strategy (60% of farmers). Specific *Marketing and Price* strategies included raising the price of oysters to counteract inflation, selling empty oyster shells to the City of Portland for filtering wastewater, advertising on social media, diversifying retail products, and modifying the ratio of wholesale/retail as needed during the pandemic.

Farmers invested time and money into various *Method and Gear* modifications, innovations, and culture techniques (53% of farmers). To combat supply chain issues and inflation, one farmer described exploring alternative (and less expensive) gear options. Some farmers described the benefits of off-bottom techniques as requiring less labor, reducing mortality rates, and resulting in better product. Meanwhile, other farmers were concerned that off-bottom systems would fail in soft sediments and predicted higher labor costs with this method. Other farmers maintained lower risk through continuing current culture techniques rather than expend time or capital experimenting with a new method. Farmers also described gear modifications to reduce oyster mortality from predators (e.g., changing to a suspended-bag system to protect oysters).

Farmers described a need for *Spatial Flexibility* (47% of farmers), such as having sufficient lease size and flexibility in culture type to move product to new areas if they encounter habitat problems and having flexibility in permitting to switch to different culture techniques, like off-bottom systems. Several farmers who relied on on-bottom culture described planting oysters farther apart in recent years to decrease mortality, potentially due to overcrowding in hypoxic conditions. Meanwhile some farmers described the opposite, having to plant oysters closer because they had lost ground due to burrowing shrimp, while another farmer did not have sufficient lease space to plant oysters farther apart.

Intentional & Proactive Farm Management (33% of farmers) and *Ecosystem Stewardship and Education* (13%) were categories mentioned by farmers expanded from the codebook used by Ward et al. (2022). *Intentional & Proactive Farm Management* included designing five- and ten-year grow out plans, providing supervisory training for employees, and creating a supportive, inclusive employee culture. *Ecosystem Stewardship* was described as respecting the environment, leaving no or minimal trace, supporting restoration of native oysters, and educating the public about the environmental stewardship benefits of oyster farming.

Science

Shellfish Health Knowledge was a suite of strategies listed by 53% of farmers. This adaptive category included understanding impacts to oysters at different life stages and monitoring and adjusting water chemistry as needed to reduce mortality. The importance of developing genetically resistant broodstock (*Genetic Resistance*; 20% of farmers) was documented under the Science theme. Some farmers mentioned the importance of working with Oregon State University's Molluscan Broodstock Program as beneficial for developing such broodstock. A total of 13% of farmers described needs such as mitigating potential OA effects through water quality monitoring on their own farm (*Monitor OA and WQ Response*). This included monitoring water in land-based tanks to optimize conditions for young oysters. One farmer talked about using certain apps, such as Oyster Tracker and Blue Trace®, to do this more efficiently.

Table 3. Adaptive themes, N (number of oyster farmers reporting any one of the specific strategies for this theme), % (percent of oyster farmers reporting this theme), description of categories within each theme (adapted from Ward et al. 2022 (themes with an asterisk are new categories or additions to categories from this work), exemplar quotes describe each strategy, and detailed strategies within each category.

Adaptive theme	**No.**	**%**	**Description**	**Exemplar Quote**	**Specific Strategies**
Policy and Networking					
Networking	12	80 %	Developing and leveraging networks of other farmers, managers, policymakers, and scientists to share information, build best practices, and communicate policy and scientific needs	*"We're doing really good [with our operations]. Thanks to [another farmer for sharing his] knowledge and experience on the oyster business. I combined [his] ideas and [mine]."*	Educate public and industry about OA risk; lobby for this in Washington DC
					Network with industry, DEQ, USCOAE s, ODFW, and ODA to survey/develop criteria for leasing new ground
					Communicate with other farmers (intra- and inter-state as well as international) and internal farm staff about best practices and gear innovations/culture techniques
					Join with other farmers in advocacy (e.g., approach legislature)
					Form co-operative with other farmers
					Develop good rapport with other farmers and

					non-competitive business plans
					Maintain good relationships with local community members
					Create business partnerships with other oyster farmers in the Oregon
					Develop partnerships with university scientists (e.g. OSU Molluscan Broodstock Program) to monitor carbonate chemistry and develop solutions to mitigate impacts on larval stages
					Maintain trust with ODA inspectors
					Pursue litigation to enforce compliance with Clean Water Act
					Join membership with industry group Pacific Coast Grower's Association & increase membership benefits (e.g., representation in Washington DC, group insurance benefits)
					Access environmental lawyers and consultants to have all the permits applications written correctly
Permitting and Licensing	8	53 %	Permitting new operations and simplifying or clarifying permit	*"I think that we should base more [farming regulations] on research and science*	Streamline and simplify inspections
					Reduce paperwork and time needed to

			changes for existing operations can reduce regulatory burdens, allowing for increased flexibility and allocation of resources towards other adaptive strategies	*aspects. . . In Tillamook Bay, we have a plat that says we cannot mechanically harvest or mechanically plant a certain plat. And that is due to the black brant population that's in this bay. But black brant are migratory, so they are only here for a small portion of the year, and in very, very small numbers . . . Maybe [instead] for three months out of the year, we are subject to not being able to do that there."*	expand operations, acquire new leases, or change culture technique/method
					Allow temporal flexibility in farming areas that are restricted due to eelgrass, migratory birds, or fishing rather than permanent closures
					Maintain affordable lease prices (State of Oregon)
					Restrict additional leases to not overcome shellfish carrying capacity of the bay
					Develop safe and economical means of mitigating burrowing shrimp infauna
					Create clear criteria for new leases suitable for oyster farming
					Base farming restrictions on best available science rather than public comment alone
					Reduce/avoid additional restrictions in the future that will make oyster farming more challenging
Funding*	4	27 %	Access to funding opportunities can serve numerous purposes including improved ability to attain permits or insurance, invest in	*"I think the biggest [need] is always cash. . . looking at the size of our farm compared to our potential. To get the gear on the 10 acres, it*	Access capital to purchase gear for new culturing techniques, invest in water quality or OA monitoring, expand farm lease size

			new gear, expand farm operations through new leases, conduct research, etc.	*is $800,000. That's before I put a seed in the water . . . . You are 12 to 14 months away before you can turn that into revenue. That is a lot of money to be putting out for any type of farm. But if we were a dairy farm, we could get that money in a heartbeat. We are [seeking loans]in a really professional manner and cannot get funding.”*	Access aquaculture loans to buy oyster seed/initiate business or maintain operations during economic recession
					Implement cryptocurrency such as oystercoin
Water Quality (WQ) response	2	13 %	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)	*“We've always wanted the state to sample, not the water, but the oysters because the oysters never have coliform in them, just the water column above them.”*	Invest in additional testing of oyster meat or seawater to liberalize oyster harvest after rainfall if oyster meat is safe for consumption rather than relying only on rainfall gauges as an automatic harvest closure
	Farm Management				
Marketing and Price	9	60 %	Changing marketing strategies or product prices (e.g., raising the price of shellfish) can help farmers keep pace with other costs of business up-keep, cost-of-living, market shifts, etc.	*“Last week I set up a side window where they can come and buy oysters if they don't want to wear a mask, but they can't come in and have access to my huge array of hot sauces and my beer cooler.”*	Access to better support for international export of oysters from federal government
					Advertise on social media to sell oysters
					Maximize net profit through quality oyster end-product; high price point and low labor cost
					Diversify retail products within retail storefront

					Select single seed for growing to reduce labor cost and profit margin
					Modify balance of retail vs wholesale during COVID-19 pandemic
					Sell empty oyster shells to City of Portland for filtering sewage wastewater for a profit
					Target specific size oysters for certain markets
					Diversify markets through flexibility, e.g., add oyster delivery service if customers request this
					Raise price of oysters to reflect inflation of other operation costs
					Combine deliveries when possible, to save fuel costs
					Accept food stamps for oyster purchase
Method and Gear	8	53 %	Employing multiple or new methods or gear types (or switching between them) can allow farmers to use the best-available and most suitable methods and technology to effectively grow their product.	*"I cannot say exactly what it is, but I believe it's-- sometimes, we have incidence of low oxygen, low DO. And I have seen cases where if you crowd the oysters, then you do have a higher rate of die-off than you would if the oysters were more spaced out and less dense."*	Invest in off-bottom culture because of the benefits of lower labor, higher quality end-product, and reduced oyster mortality
					Optimize gear direction and placement for local conditions (e.g., tidal exchanges and currents)

					Rotate oyster beds for better productivity
					Plant oysters farther apart to increase production (reduce density dependence or low dissolved oxygen stress)
					Plant oysters closer together (maximize space because losing ground to burrowing shrimp infauna)
					Innovate gear alternatives that are more affordable and last longer
					Avoid experimentation with new culture techniques because of time investment
					Transplant 1–2-year-old oysters that can handle soft sediment areas better than younger oysters
					Plant more oysters in the event of mortality because oyster seed is affordable
					Avoid moving oysters and using flip bag/tumbling methods to avoid stressing the oysters
					Use tipping line for oyster culture and twist oysters intro three-strand line (reduce labor, better product)

					Outplant oysters at a bigger size to reduce mortality
Spatial Flexibility	7	47 %	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.).	*"Oysters will grow better in a suspended culture because they cannot grow down in the mud. The only way they can grow is up. If you suspend them, you gain that [survivability]."*	Move to different ground within lease that does not have habitat impacts from burrowing shrimp or eelgrass
					Have flexibility to utilize multiple culture or gear types within lease
					Move to areas that are more optimal for growing because of water currents or channels
Species	7	47 %	Culturing numerous, additional, or alternative species diversifies farmers' products and can open new markets or help ensure product is available if one species does poorly or is more impacted by a mortality event & tailor culture species to environmental conditions available	*"[Oysters] get really covered with mussels and you can go out and harvest them widely and there are no regulations to where you harvest them. We said 'We have this tideland, let's just do a U-pick where people go pick those mussels.' But, we cannot figure out a way to do it. . . If we built any kind of structure for the mussels to grow, it gets classified as aquaculture, which then is not allowed in that location. If it's wild grown, then it's fine to harvest, because then they are just wild mussels, but then we can't put any structures where we are because then it's aquaculture…"*	Optimize certain species for local conditions (e.g. Kumamotos grow well in certain bays)
					Cultivate other species (clams, mussels) to diversify products if regulations allow

Intentional & proactive farm management and planning*	5	33 %	Farm management strategies that include long-term growing plans, economic frugality and operational efficiency, and an inclusive, supportive employee culture.	*"Listening to my crew, those that have done it, and what they see. . . I will come up with an idea and I'll throw it to them . . . I don't let it bother my ego if they kick it right back to me or look at me like I'm nuts. . . [then I ask], 'Okay, what do you think?' [and then] we come up with the best solution [through a] proactive management style."*	Create operational efficiency (e.g., use equipment rather than hire additional labor) Foster a supportive, inclusive employee culture (e.g., listen to employees, pay them well, encourage supervisory training)
Retail and Wholesale	5	33 %	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).	*"We have a lot of customers. . .we dominate the local market. We do the quality, we do the service, we have a competitive price, and we make all the customers happy. We are small, we're mobile, we keep changing things faster than the bigger company, that if we run out of oysters, we deliver to you right away. We deliver seven days a week."*	Diversify retail products (smoked oysters, etc.) Diversify merchandise (clothes, etc.) to retail shop products
Ecosystem stewardship and education*	2	13 %	A holistic approach to oyster growing that encourages ecosystem diversity, minimizes impact to the surrounding environment, and educates the public on the benefits of oyster growing and responsible stewardship practices	*[We are trying to] minimize all the [impacts] to Mother Nature. Because Mother Nature provides this unique environment for us to build this [oyster] species. And we need to respect that."*	Cultivate native Olympia oysters for ecosystem diversity Respect the environment that allows them to grow oysters Educate children on benefits of oyster farming for the environment

Temporal Flexibility	2	13 %	For in-bay culture, altering the timing of shellfish outplanting or harvesting around anticipated environmental stress events can allow farmers to avoid mortality and loss of product.	*"We [could] stop all farm activity besides harvesting [if there was a dieoff event forecasted]. Instead of just having these oysters die, regardless of age or size, we may be able to pull them off the beds. . . and produce some sort of a profit from it."*	Harvest additional oyster product after a rainfall closure to recover lost sales
					Forecast die off events and prioritize harvesting in advance of dieoff
					Outplant before eelgrass starts growing in the spring
					Have flexibility in regulations for using mechanical harvesting techniques at certain times of the year (when they will not impact other species) rather than hard closures
					Have temporal flexibility in regulations for when you can plant or use certain grounds rather than having them closed permanently
					Outplant oysters later in the spring to reduce juvenile mortality (water is warmer & there is more food)
Variable Ploidy	2	13 %	Having access to both triploid and diploid oysters can diversify farmers' products and help reduce risk of product loss due to possible differential environmental effects between the two.	*"In 2007, we had a tremendous mortality of triploid oysters. And after that, I just moved everything [to diploid.] [Now], 90% is diploid oysters. Only 10% is a triploid oyster."*	Use triploids in the summer months so that they will not spawn (and delay meat growth)
Water Intake	1	7%	For land-based culture, altering water upon intake into farms,	*"We treat our water to stay at an 8.2 Ph and infuse it with dissolved*	Alter water take to make conditions more favorable for larvae

			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.	*oxygen whether or not it needs it."*	
Science					
Shellfish Health Knowledge	8	53 %	Identifying drivers of shellfish mortality and health can allow farmers to recognize and respond to environmental conditions likely to lead to shellfish mortality.	*"We're trying to get a handle on lessening the mortality. There will always be some mortality with shipping [of larvae] but we are trying to lessen that . . .having . . . the tanks be ready and at right temperature as the stuff arrives via FedEx. [We try and avoid] all the things that happen that could make the larvae sitting in the refrigerator as opposed to in a tankful of bay water, with enough food."*	Monitor conditions carefully for oysters at sizes <12 mm due to higher mortality at this stage
					Develop humane and approved ways to mitigate ghost shrimp
					Monitor water quality to harvest adult oysters early before dieoff
					Identify oyster predators and remove/kill these species
Genetic Resistance	3	20 %	Developing shellfish broodstock that is genetically resistant to environmental stressors can yield a greater quality or quantity of product.	*"We're lucky enough to have the Molluscan Broodstock Program down at Oregon State. [Is there] going to become a point where you have to have specific families that you get your seed stock from because they're more resilient to changing ocean conditions?"*	Develop a disease-resistant (herpes-resistant) oyster seed
					Access to specific seed stock that will be more resilient to environmental conditions
					Access to seed stock with good gills, good meat contents.
Monitor OA and water	2	13 %	Improving water quality monitoring,	*"Our crew can log in on their phone when*	Adjust water for land-based tanks to

quality (WQ)			including carbonate chemistry data, can inform farmers of environmentally stressful conditions. This can allow for adaptive responses and lead to greater understanding of how water quality affects shellfish health and mortality.	*they've harvested, we can add everything from temperature to . . . when it goes into [and out of] the wet storage. . . We can have better controls on our product from the bay to customer, the oyster tracker gives us better control of our inventory. . . better control of mortality. . . how much larvae we received versus in 2 years from now, how much we are harvesting off of that bed. . . our true larvae to product count."*	optimize temperature, Ph and dissolved oxygen Improve monitoring (Oyster Tracker, Blue Trace®) to adjust water chemistry as needed to improve survival

5. Discussion

5.1 Adaptive responses and nature of stressors

We observed certain trends related to adaptive capacity and Oregon oyster farmers' ability to develop and implement strategies. For example, the cost of labor was frequently described as a stressor by farmers, but farmers with additional assets, that is, bigger operations that required a larger labor force, were more motivated to create (and had assets to fund) incentives to recruit and maintain employees. Meanwhile, smaller operations with fewer assets chose to delay, or avoid expanding their operations under the existing labor shortage. We also found that farmers described adaptive strategies related to knowledge acquisition, such as collaborating with scientists to learn about ocean conditions and selecting broodstock that were genetically resistant to disease. The absence of knowledge about, for instance, response to OA or other stressors may have contributed to knowledge gaps that delay adaptation. For example, in this study, farmers expressed concern about large oyster mortality events that destroyed marketable oysters but were uncertain as to what instigated these events and how to strategize adaptive responses. The ability (or lack thereof) of farmers to implement adaptive strategies may be linked to broader characteristics of adaptive capacity such as presence or absence of assets, social organization, flexibility, learning, or agency described in the adaptive capacity literature (Cinner et al. 2018; Whitney et al. 2017). Ward et al. (2022) found ties to these domains in California shellfish growers' such as the implementation of networking among growers to share information about farming (e.g., social organization) or flexibility in altering the species or gear used for culture. Green et al. (in prep) will assess the adaptive strategies of shellfish farmers in California and Oregon in the context of these theoretical domains of adaptive capacity.

The timescale and nature of a stressor can influence the development and implementation of adaptive response strategies (Green et al. 2021). We found shellfish farmers reported stressors that varied in scale, intensity, frequency, and associated impact on oyster production. For example, farmers reported some stressors at a high frequency (e.g., species that predate oysters such as green crabs or sea stars) and yet the effect of these species on production was minor and farmers rarely dedicated a specific response strategy to this problem. Other stressors, such as habitat-modifying organisms (e.g., burrowing shrimp) were reported by only one-third of farmers, but had significant impacts on operations, and triggered large-scale responses from farmers such as moving oyster beds or investing in off-bottom culture systems. At a regional scale, this information is relevant for managers and policy makers deciding how to prioritize research and instill flexibility in management to adapt to a suite of stressors. This may be especially important when farmers' responses to climate-related stressors are compounded by non-climate-related stressors, for example the COVID-19 pandemic overlapping with an acute hypoxia event.

5.2 The importance of flexibility

Flexible and equitable regulatory policies, combined with an individual's agency are theorized in the literature to aid in the ability to mobilize resources related to adaptation (Gupta et al. 2010; Cinner et al. 2018). This was exhibited in the strategies that Oregon farmers were currently employing versus strategies they envisioned for the future. Current strategies clustered around the ability and decision-making that individuals had over the day-to-day management of their operation, in other words, aspects of spatial or temporal flexibility in growing operations, choices in marketing and sales, species cultured, and communication with local farmers. These adaptive strategies were within an individual farmer's own control and could be implemented by him or her without relying on, or being restricted by, an outside governing agency. These strategies were based on farmers' practical and technical expertise in oyster aquaculture, networking with other farmers, for example, to learn about the cost, effectiveness, and implementation of new culture techniques. Meanwhile, future strategies discussed by farmers centered around streamlining permitting and regulations governed by external state and federal agencies, encouraging capital investment in aquaculture operations, or monitoring water conditions within the bay to forecast conditions that might cause oyster mortality. These strategies require flexible policies, and networking with partners outside the industry such as government officials, scientists, and investors, and ability to implement change within the current regulatory framework.

5.3 Diversification versus specialization in adaptation

Diversification has been widely shown in the literature to increase adaptive capacity in aquaculture and reduce risk to climate change (Galappaththi et al. 2020; Harvey et al 2016), while a lack of diversification is correlated with higher vulnerability in shellfish aquaculture (Stewart-Sinclair 2020). Specialization in livelihoods, meanwhile, can be maladaptive (sensu Barnett and O'Neil 2010). Ward et al. (2022) documented adaptive strategies for California farmers that included diversification, such as culturing multiple species in hopes that some species will be more resilient to warming water temperatures. In Oregon, we observed both diversification and specialization as adaptive strategies among farmers. Farmers with larger operations (e.g., many employees) also tended to be more diversified, for instance, selling to both wholesale and retail markets, as well as selling non-oyster products. We also, however, recognized a pattern in which specialization was adaptive, that is, farmers with small operations, (often a husband and wife team), used a single in-bay cultivation method (e.g., on-bottom or off-bottom), and sold solely to wholesale markets. Although these farmers had more specialized operations, they also minimized infrastructure and operation costs, and time invested in marketing, shipping, and advertising.

Whitney et al. (2017) describe the trade-offs individuals might consider between short- and long-term adaptive capacity. These oyster farmers with smaller, more specialized operations may have been making trade-offs in which they accepted a risk of higher potential product loss or reduced product quality to avoid costly off-bottom gear purchases even if that gear could better protect against predation or provide a higher quality market product. Similarly, Ward et al. (2018) describe how specialization can have positive effects on revenue for Alaskan salmon fishers, but at the cost of increased risk of environmental variability affecting a single-species fishery. Cochrane and Cafer (2017) further theorize livelihood diversification can be maladaptive, especially if individuals pursue additional jobs with lower economic return during times of increased vulnerability. Although we were not explicitly able to link increased diversification or specialization with economic return in this study, heterogeneity in the size of aquaculture operations and degree of specialization may be associated with adaptive capacity on a regional scale.

5.4 Perceptions of stressors

Coastal users' perception of, and experience with stressors can influence their perceived need for, and development of, adaptive strategies and long-term shellfish aquaculture success (McGreavy et al. 2018; Spence et al. 2018). An excellent example of this in our study is the perception of OA. In the laboratory, OA has been shown to affect oysters through reduced calcification and growth (Barton et al. 2015; Hettinger et al. 2013) and increased mortality (Barton et al. 2015), especially at the larval and juvenile stages. Farmers in our study perceived OA as a problem that affected oysters at the larval stage, or not at all. More specifically, farmers with hatcheries or land-based facilities developed water intake modification practices to mitigate the impact of acidified water, but farmers in our study who cultured in-bay juvenile or adult oysters did not describe any strategies related to OA. Our results differ from Mabardy et al. (2015), who found 75% of shellfish farmers on the West Coast had a high-level of concern about OA even if they had not been directly affected by OA. The lack of perception of OA risk among Oregon shellfish farmers may be related to the challenges in assessing the impacts of OA in dynamic, *in situ* estuarine environments and disentangling OA impacts from other environmental stressors (Doo et al. 2020; Ekstrom et al. 2015; Kroeker et al. 2017). Alternatively, the timing of our study could have influenced these results. Between 2006 and 2008, the impact of OA on oyster larvae at Oregon hatcheries was profound. However, these effects have been mitigated through monitoring and adjusting carbonate chemistry of the water tanks where eyed larvae are cultured (Barton et al. 2015), and other threats now seem more important. Additionally, the growth stages cultivated by most farmers in our study do not require the same attention to carbonate chemistry that hatcheries have had to employ. However, increasing effects of OA may render more visible (such as predation) to the oyster life stages cultured by farmers in the future (Kroeker and Sanford 2022).

Regardless, understanding the differences between published findings vs. shellfish farmers' perception of OA and other stressors on production at different life stages can better inform the urgency for funding, research, and policies that support adaptation strategies and action. An example of an avenue for translating farmers' observations and experiences to action are the Regional Coastal Acidification Networks (CANs), which exist around the United States to convene and inform stakeholders by OA and set and prioritize goals for mitigation and adaptation (Cross et al. 2019). In Oregon, the Oregon Sea Grant, Oregon State University and Newport, Oregon fishing community developed Scientist and Fishermen Exchange (SAFE) meetings to promote collaboration and scientific exchange of ocean and species observations between scientists and fishermen (Whitefield et al. 2021). A parallel partnership between shellfish farmers, scientists, and policy makers could likewise provide opportunities for information exchange, networking, and inspire policy-related action that could support adaptation in the shellfish aquaculture industry. Understanding perceptions of stressors can also be an avenue for networking or research beyond OA. We describe here the multiple resources (scientific, networking) dedicated to OA as a threat, however these resources could also be applied to concerns about hypoxia and nuisance species.

5.5 Comparisons with California

The comparable dataset collected in California (Ward et al. 2022) enables a unique, cross-region comparison between the industries, stressors, and responses between Oregon and California shellfish farming. Oregon and California shellfish farmers are subject to similar environmental stressors via the California Current and have annual production values of a similar magnitude (USDA 2019). We found that Oregon farmers experienced a similar diversity of stressors and used similar adaptive strategies to California farmers; however, there were key differences as well. For example, many of the nuisance species that Oregon farmers described (e.g., invasive green crabs, burrowing shrimp) were not mentioned by California farmers. Although these species are established in bays and estuaries in both states and documented to impact oysters and oyster habitat along the West coast (Feldman et al. 2000), it is possible that other stressors are more impactful, and were therefore more prevalent in California interviews. Likewise, a higher number of California farmers reported disease as a stressor than Oregon farmers. Given the increasing impacts of marine diseases on shellfish with increasing water temperatures (Harvell et al. 2002); the prevalence of this stressor among California farmers may be related to higher average sea temperatures in California than in Oregon. Although costs associated with permitting were significantly higher in California than Oregon (van Senten et al. 2019), regulations and permitting were described by farmers in both states as the most significant barrier to expansion and flexibility in aquaculture, indicating that the challenges associated with regulations and permitting persist beyond cost.

Farmers in both states relied heavily on networking to learn about practical techniques related to aquaculture and to create partnerships with scientists for improving broodstock, or funders for capital loans. Spatial flexibility was another important strategy described by farmers in both states. For example, farmers in both areas strategically moved gear within their lease area, but the drivers of this adaptive strategy differed in each state. Farmers in Oregon were primarily motivated to change grow out locations within their lease due to interactions with other species, such as habitat-modifying organisms like burrowing shrimp. Meanwhile, California farmers cited spatial flexibility as a response to variable water quality or to select for advantageous grow out conditions such as depth or nutrient availability.

In addition to these comparisons between California and Oregon, many lessons can be taken from other regions with larger aquaculture industries than California and Oregon. For example, Washington State has a long history of shellfish aquaculture, and efforts to tackle similar stressors such as species interactions, permitting needs, and others that can act as important examples to enhance adaptation in other regions. For instance, Washington Sea Grant has an ongoing Washington Coast Shellfish Aquaculture Study (https://wsg.washington.edu/community-outreach/aquaculture-outreach/coast-shellfish-study/) to understand and adaptively manage interactions between eelgrass, burrowing shrimp, and shellfish (NMFS, 2017). The Pacific Shellfish Institute provides permitting, surveying, and research assistance for sustainable shellfish production along the West coast; one recent project is assessing the causes of Pacific oyster summer mortality events which have had recent devastating ecological and economic impacts for market-size oysters in the Pacific Northwest (https://www.pacshell.org/triploid-oyster-health.asp). The Pacific Coast Shellfish Growers Association (PCSGA) represents shellfish farmers' interests along the West coast, and acts as a venue for knowledge exchange and policy leadership. Recent efforts include developing a 2021 list of research priorities to support the shellfish industry, such as better understanding the ecosystem services that shellfish farms provide (https://pcsga.org/research-priorities/). Understanding regional differences among states, as well as efforts to support shellfish research, management and policy both on the West coast and nationwide can help identify and strengthen gaps in adaptive capacity and support aquaculture growth, particularly with respect to improved flexibility in permitting, regulations and licensing.

5.6 Policy and regulations

While environmental stressors are most frequently cited in the literature on adaptive capacity in aquaculture, we found the existing state and federal regulatory framework in Oregon was a source of frustration and limitation for current farmers and may limit prospective farmers from initiating shellfish aquaculture (Ehrhart and Doerr 2022). Based on interviews with Oregon farmers in this study, and in line with Ward et al. (2022) and Van Senten et al. (2020), both regulatory barriers and high regulatory costs limit opportunities for aquaculture expansion. Van Senten et al. (2020) reports that the majority of regulatory costs for the Pacific shellfish industry are indirect costs of compliance (e.g., staff time, legal expenses, or management changes required for compliance) . Thus, finding ways to eliminate redundancies and streamline the current regulations for compliance and permitting offers one avenue to support the growing national demand for oyster production. Farmers in our study also saw a need for additional coordination among agencies when assessing criteria for new shellfish ground to be leased, which would streamline the permitting process for operators looking to expand their current lease or seek new leases. Another opportunity to provide additional economic support to indirectly encourage aquaculture expansion is to include oyster farmers in 'nutrient credit trading programs' such as the Maryland Nutrient Trading Program in the Chesapeake Bay region. In this program, farmers receive economic compensation for the removal of nutrients such as nitrogen and phosphorus that their oyster can provide that can be harmful in excess (Weber et al. 2018).

Our findings offer insights regarding how flexibility and stakeholder participation with respect to aquaculture regulations, licensing, and policies can support adaptation and expansion in conjunction with existing guidelines. Establishing opportunities for convening industry and agency staff could provide forums to share knowledge and communicate policy needs. Krause et al. (2015) describes a 'people-policy gap' in aquaculture, which can manifest through the exclusion of certain stakeholders from the decision-making process, but also through the lack of context-specific, socio-economic considerations in policy. Thus, when providing venues for communicating farmer needs with respect to flexible regulations and timely and cost-efficient permitting, farmer participation will depend on the accessibility of these meetings and that their input is considered in policy decisions (Singleton 2000). Like many industries, the social actors that represent agencies and directly interact with the industry play a key role in communication and trust-building (Luhmann 2018) and must be motivated to do so (Singleton 2000). One farmer described the importance of having '*government officials that he can work with'* in relation to the aquaculture permitting and inspection process with ODA. Building trust between industry members and key aquaculture personnel in agencies could facilitate communication and improve policy outcomes in Oregon.

Given the relatively small number of shellfish farmers in Oregon, outreach and communication need not be a monumental or expensive task. For instance, enabling policy-related feedback with farmers might include offering annual or biennial individual meetings with current farmers and shellfish coordinating agencies. Industry groups such as the PCSGA offer industry representation and policy leadership for West coast shellfish farmers. Included in the

PCSGA's 2021 research priorities are investigating ways to reduce the regulatory burdens that farmers face with respect to eelgrass habitat and forecasting of detrimental water quality events that impact the sale of shellfish (https://pcsga.org/wprs/wp-content/uploads/2021/06/2021_PCSGA_Research_Priorities.pdf). Increasing Oregon industry membership in PCSGA and clarifying their policy role could further facilitate policy discussions between farmers and policy makers. Oregon Sea Grant also plays a key role in outreach and communication in the aquaculture community, including the documentation of aquaculture policy needs and barriers to expansion (Ehrhart and Doerr 2022). Providing an avenue for farmers to implement new techniques on a more rapid timescale would allow scientists, managers, and industry to develop and experiment with innovative gear techniques to adapt to aquaculture challenges. Such a permit exists in the state of Maine and allows for commercial and scientific research to occur with an expedited timeline and few application requirements (Stoll et al. 2019; https://www.maine.gov/dmr/aquaculture/applications-and-forms).

5.7 Caveats and future directions

We documented a variety of stressors that Oregon shellfish farmers experience, which were qualitatively linked to shellfish production output. However, we did not inquire about the timescale of non-environmental stressors, thus farmers may have focused more on recent stressors that were prominent in their minds at the time of interviews, such as fuel prices and supply chain issues correlated with overseas conflict and the COVID-19 pandemic. Future directions for research could include linking stressors more quantitatively to production volume and value, and to broader domains of adaptive capacity (i.e., Cinner et al. 2018) to adaptive strategies (Green et al. in prep). Finally, farmers described permitting, licensing, and regulations as prominent limitations on shellfish aquaculture, however it would be advantageous to include perspectives of agency staff involved with these regulations to better understand what obstacles might exist to better meet farmers' needs. Wolters et al. (forthcoming) is analyzing policy alignment opportunities between strategies identified both in this paper, and by Ward et al. (2022) and OA policies at the state and federal level. This work will utilize discussions with key agency personnel to devise a series of policy recommendations to help facilitate farmer adaptation to OA.

6. Conclusion

An understanding of the stressors that impact oyster production and the adaptive strategies to combat those stressors is key to enhancing and maximizing the domestic production of oysters in the United States. Farmers' perceptions of environmental stressors in our study were linked to their direct experience. Thus, stressors that are more visibly tangible, e.g., burrowing shrimp and crabs, were correlated with current adaptation strategies. Although programs such as the national Integrated Ocean Observing System support publicly available ocean observation datasets for both California (https://www.cencoos.org/; https://sccoos.org/) and the Pacific Northwest (http://www.nanoos.org/) the scale of these datasets are often not at a resolution that an individual shellfish farmer can use to correlate with oyster mortality events . Furthering partnerships with research institutions to track these parameters *in situ* would help interpret oyster mortality events at various life stages, educate farmers, and better inform the need for adaptation strategies.

Although climate change is a real threat to shellfish aquaculture both in the United States and globally, our study clarifies that the presence of non-environmental threats must also be carefully considered in adaptation. The regulatory environment for aquaculture in Oregon is complex, yet the regulatory problems described by Oregon farmers are not unique (Lester et al. 2021; Rubino 2022). We offer additional insights to national and state-level recommendations for addressing these regulatory burdens, namely increased and meaningful outreach and public participation between industry, scientists, managers, and policymakers. Overall, Oregon oyster farmers desire aquaculture expansion and are optimistic about the future of oyster growing. Equipping farmers with the knowledge and capacity to apply a suite of adaptation strategies, access to sufficient funding to implement strategies, and a flexible regulatory framework will be important for enhancing and expanding existing aquaculture operations in Oregon and contributing to national oyster production.

Author Contributions

KG 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. MW, SH, and EW contributed to investigation and manuscript review and editing.

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