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David J. Wrathall

The purpose of this study was to understand the vulnerability and adaptive capacity of shellfish stakeholders in the Pacific Northwest who are adapting to ocean acidification (OA). This study developed a geovisualization tool of existing environmental data for assessing species-specific risk profiles to OA (based on their exposure and sensitivity), and then created a decision tree of adaptation options reported by interviews conducted with shellfish stakeholders for identifying pathways to successful adaptation (based on their adaptive capacity and the barriers to their adaptation). Results from the geovisualization showed that OA risk is greatest in the northern Pacific Northwest, where a faster rate of change in OA exposure intersects with relatively greater social reliance on shellfish. Interviews showed that OA has led to substantial shortages of seed. Despite adaptation investments at hatcheries succeeding to improve overall seed production, industry consolidation has constrained access to seed for the smallest stakeholders. Adaptation investments prioritized in at-risk areas should account for uneven impacts and specific barriers that affect stakeholders engaged in shellfish production at multiple life stages. To facilitate discussions with stakeholders in local adaptation planning efforts, future work may benefit from pairing an adaptation pathway decision tree and the geovisualization tool developed here.

Keywords: *ocean acidification, vulnerability, adaptation pathways, risk, geovisualization, stakeholder interviews, barriers to adaptation*

Vulnerability and Adaptation of Pacific Northwest Shellfisheries to Ocean Acidification

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Brian Gardiner Katz

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Dean of the College of Earth, Ocean, and Atmospheric Sciences

Dean of the Graduate School

I understand that my thesis will become part of the permanent collection of Oregon State University libraries. My signature below authorizes release of my thesis to any reader upon request.

Brian Gardiner Katz, Author

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CONTRIBUTION OF AUTHORS

Jessamyn A. Johnson and George G. Waldbusser compiled the biological response data that were incorporated into the design of the geovisualization tool presented in Chapter 2. Jessamyn also obtained the oceanographic model data used in the geovisualization tool. David J. Wrathall secured funding for the project and assisted in conducting stakeholder interviews at four of six watershed groups presented in Chapter 3. David M. Kling, Bobbi Hudson, and Thamanna Vasan each supported stakeholder interviews conducted in one watershed group, and Thamanna also video recorded additional stakeholder interviews at the Pacific Coast Shellfish Growers Association conference in September 2019.

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1. CONCEPTUALIZING THE VULNERABILITY OF PACIFIC NORTHWEST SHELLFISHERIES TO OCEAN ACIDIFICATION

1.1. Background

In a time of climate change and social transformation, hazards like ocean acidification (OA) pose a risk to key resources that societies rely on, including shellfish species. On the Pacific Northwest coastline, shellfish stakeholders are already experiencing the impacts of OA, a climate-driven hazard caused by the ocean's absorption of accelerating carbon emissions. Social vulnerability to ocean acidification is conceptualized here as the potential for livelihood or food security consequences to arise, in the absence of adaptation, from the spatiotemporal intersection of exposure to OA –or where and when OA may impact growth of valued shellfish species– and sensitivity to OA –how susceptible shellfish stakeholders may be to such impacts (Capon et al., 2013; Ekstrom et al., 2015; Hare et al., 2016; Johnson & Welch, 2016; Wabnitz et al., 2018).

This study distinguishes between risk, defined as the potential for impacts, and social vulnerability, defined as the propensity to be adversely impacted (IPCC, 2014). In this context, shellfish stakeholders are considered at-risk populations, and their behavioral changes to adjust to OA are considered adaptations. If they are to avoid adverse consequences from OA, it is essential they reduce their vulnerability and implement adaptation strategies. The first step to avoiding negative outcomes is assessing the specific vulnerability of culturally and economically important shellfish species.

The two overall objectives of this research are: 1) to assess the vulnerability of Pacific Northwest shellfisheries facing OA risk; and 2) to evaluate adaptation pathways that might enable them to successfully avoid adverse outcomes. To assess vulnerability, this research used geovisualization to quantify risk and stakeholder interviews to answer the question: **How vulnerable are PNW shellfisheries to OA impacts on shellfish species at different life stages?** To evaluate the various possible adaptation pathways, this research used stakeholder interviews to answer the question: **How feasible are adaptation pathways for PNW shellfisheries to navigate OA impacts on shellfish species at different life stages?** Consequently, this research was divided into two separate studies (Fig. 1-1).

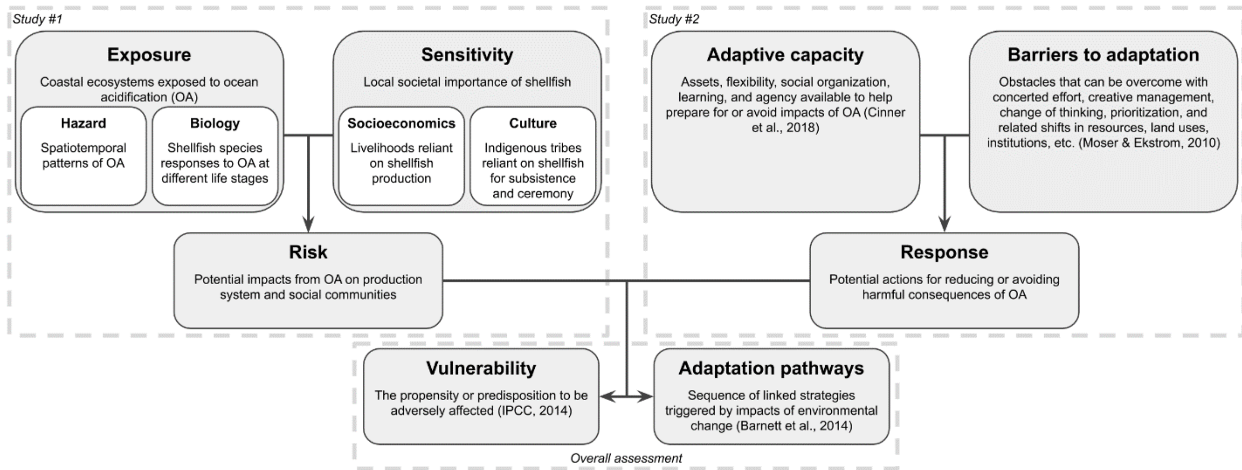

Fig. 1-1 | Conceptual framework of this study. The first study of this research investigated exposure and sensitivity of Pacific Northwest shellfisheries to ocean acidification in order to assess risk. The second study of this research investigated adaptive capacity and barriers to adaptation in order to assess response potential. Together, these studies help to assess social vulnerability and adaptation pathways. Conceptual model components were adapted from Ekstrom et al., 2015 and Jamshidi et al., 2019.

Four species of shellfish are particularly important culturally and economically in the PNW, and thus have good candidates to study social vulnerability and adaptation to ocean acidification: *Crassostrea gigas* (Pacific oysters), *Ostrea lurida* (Olympia oysters), *Mytilus galloprovincialis* (Mediterranean mussels), and *Mytilus californianus* (California mussels). Culturally, shellfish are valued by Indigenous peoples of the PNW for subsistence and ceremonies. Economically, shellfish are valued by working people for livelihoods and production. Aside from their social value, these species have been studied at multiple life stages (larvae, juvenile/adult) for growth responses to changes in carbonate chemistry, of which the most impactful variable to shell-forming bivalves is calcium carbonate saturation state — a metric for how stable or easy it is to make shell material (Waldbusser et al., 2013; Waldbusser et al., 2014; Waldbusser et al., 2015; Gimenez et al., 2018). When saturation state is too low, shells can dissolve or become more difficult to produce, resulting in reduced growth of some shellfish species (Waldbusser et al., 2015).

To successfully adapt to OA, shellfish-reliant stakeholders must therefore consider where, when, and how growing shellfish at different life stages may be impacted by low-saturation state extremes — i.e. carbonate weather extremes — as well as long-term reductions in saturation state baselines — i.e. carbonate climate change (Waldbusser & Salisbury, 2014).

The resource system that produces the shellfish species noted above comprises hatcheries, nurseries, growers (Barton et al., 2015; Mabardy et al., 2015), processors, distributors, retailers, port towns, Indigenous tribes (Lepofsky & Caldwell, 2013), and importantly, estuaries and intertidal habitats (Bendell, 2014), where oceanic conditions interface watershed-driven processes to amplify acidification near coasts (Feely et al., 2008; Feely et al., 2010; Feely et al., 2016; Pilcher et al., 2019; Rheuban et al., 2019). The reason for explicitly defining the resource unit and resource system in this study is to bound the focal system and minimize complexities associated with including additional resource units or types of actors (Johnson et al., 2019).

The period of study was 1995-2050 because this range corresponded with model projections used for assessing exposure to ocean acidification in the California Current (Hauri et al., 2013). The Hauri model only accounts for OA in the open ocean, and we lack models of OA in most estuaries; however, a study on how these interact found that the rates of change in many estuaries may be more rapid than ocean projections (Pacella et al., 2018). The study area was the U.S. Pacific Northwest, home to Indigenous peoples reliant on shellfish for millennia (Groesbeck et al., 2014; Deur et al., 2015; Smith et al., 2019; Cox et al., 2020), and a shellfish industry affected by some of the earliest documented impacts of ocean acidification in the mid-to-late 2000’s (Barton et al., 2015).

During the mid-to-late 2000’s, successive years of increasing exposure to OA exacerbated by seasonal upwelling (Feely et al., 2008) resulted in seed supply shortages at several key hatcheries across the PNW, such as the Whiskey Creek Shellfish Hatchery in Netarts Bay, Oregon (Fig. 1-2). When larval production failures at hatcheries coincided with sizeable losses in natural recruitment, shellfish growers’ demand for seed could not be met. The resulting “seed crisis” (Mabardy et al., 2015) left growers scrambling to meet production, escalating fears that OA could irreversibly impact the PNW shellfish industry, valued at $270 million annually, and which provided over 3,000 family wage jobs in rural communities (Barton et al., 2015). After the seed crisis triggered legislative actions and a science-industry partnership, investments in buffering and water treatment systems were made at some hatcheries, but not all. Although buffering and water treatment systems have the potential to help hatcheries once installed, they often require time and effort to monitor and maintain.

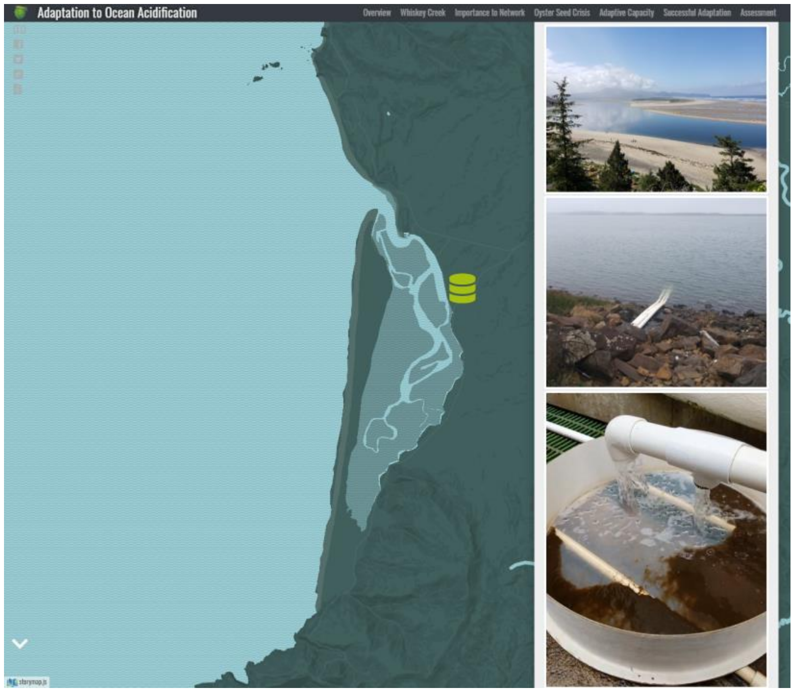

Fig. 1-2 | Location of Whiskey Creek Shellfish Hatchery in Netarts, OR. Netarts Bay is not fed by any rivers, so the attribution of ocean acidification extremes to impacts on seed production at Whiskey Creek Shellfish Hatchery signaled that OA risk in Netarts Bay was primarily driven by seasonal upwelling of acidified deep water saturated in CO_2 from global carbon emissions rather than from local amplifying factors that contribute to OA.

The problem with producing seed amid OA extremes was that larval shellfish were exhibiting negative growth responses (Barton et al., 2012) and decreased survival rates (Gimenez et al., 2018) in natural, untreated water. The adaptation investments made in response to the seed crisis have succeeded in restoring and improving the livelihoods of select hatcheries which benefited from new technologies, such as the Whiskey Creek Shellfish Hatchery (Fig. 1-3). The seed crisis revealed how the key bottleneck for the network of PNW shellfish stakeholders to successfully adapt to OA was reliable seed supply. While these technologies enabled certain hatcheries to automatically buffer intake water to maintain production of larvae amidst variable OA extremes, key gaps remain in understanding how the seed crisis and responsive adaptation strategies affected the livelihoods of other shellfish stakeholders across the PNW who did not have access to adaptation support (Althor et al., 2018; Pelling & Garschagen, 2019; Grecksch & Klöck, 2020). What is clear from this case study is that the industry was able to identify and respond to OA risk, but with uneven success. It provides support for the notion that when stakeholders are experts of their own risk, they may feel optimistic in their ability to adapt (Mabardy et al., 2015), and when empowered to diagnose problems and introduce solutions, at least some stakeholders can successfully adjust to changes. This case also justifies the creation of vulnerability assessment tools that are more broadly accessible.

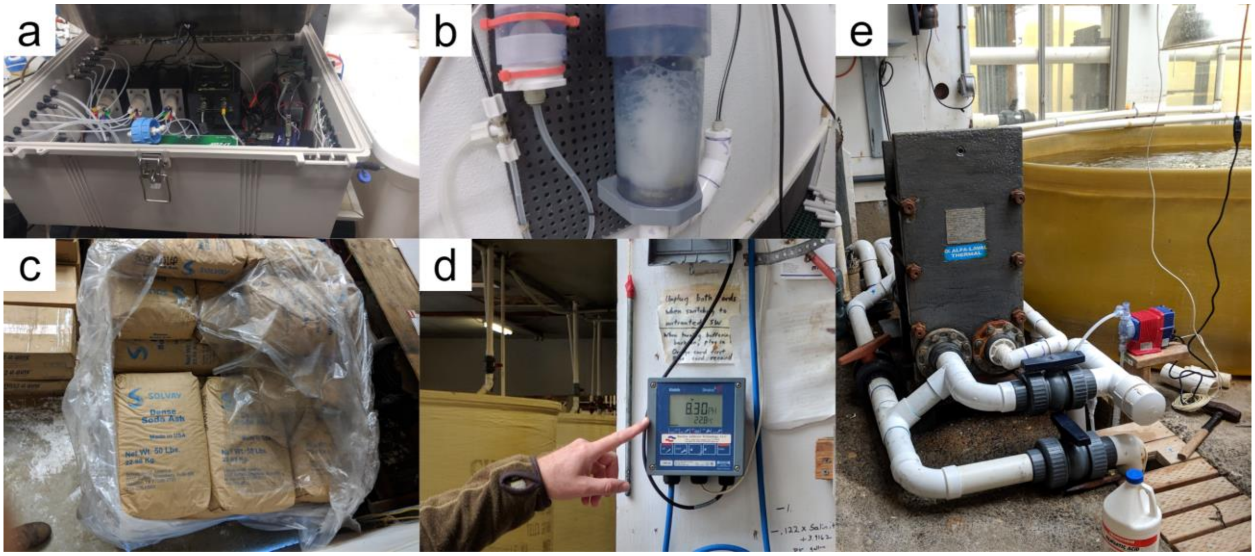

Fig. 1-3 | Adaptation investments made at Whiskey Creek Shellfish Hatchery in Netarts, OR following larval production failures attributed to ocean acidification in the mid-to-late 2000's. a–e, Adaptation investments: real-time monitoring of carbonate chemistry through multiple sensors linked to a computer (a), sensor for measuring dissolved CO2 in hatchery intake water, also known as the Burke-O-Lator (b), bags of dense soda ash used for buffering hatchery water (c), pH controller for setting desired pH of intake water (d), and pump for hatchery intake water is autonomously buffered to desired pH based on real-time observations of carbonate chemistry (e). This system has allowed select hatcheries to maximize larval shellfish (i.e. seed) production amidst extremes in ocean acidification. A story map on this case study is accessible online at https://briangkatz.github.io/oa/adaptation.

Taking a step back to the industry level, oyster and mussel growing firms in Washington state have begun closing up shop, or "opting out" of shellfish, at an increasing rate ever since the seed crisis (Fig. 1-4). Although new certifications of shellfish firms have been increasing over the years, the number of firms opting out has been increasing at a faster rate, with a noticeable increase in opt-outs occurring between 2013 and 2014, about five years after the "seed crisis", or about one or two crop rotations. Washington state is where the Pacific Northwest shellfish industry is most concentrated (Mabardy et al., 2015), so a net decrease in the number of firms certified in shellfish over time may signal that impacts and capacity for adaptation to the seed crisis were unevenly distributed across the range of different stakeholders (Althor et al., 2018; Gecksch & Klöck, 2020). Although adaptation policies or investments may achieve a specific goal, such as avoiding or recovering from impacts in the short term, long-term adaptation plans or responses that do not explicitly include equity aspects are likely to produce inequitable outcomes that may exacerbate social or environmental inequalities (Sovacool, 2018; Pelling & Garschagen, 2019; Fülöp & Stanley-Jones, 2020).

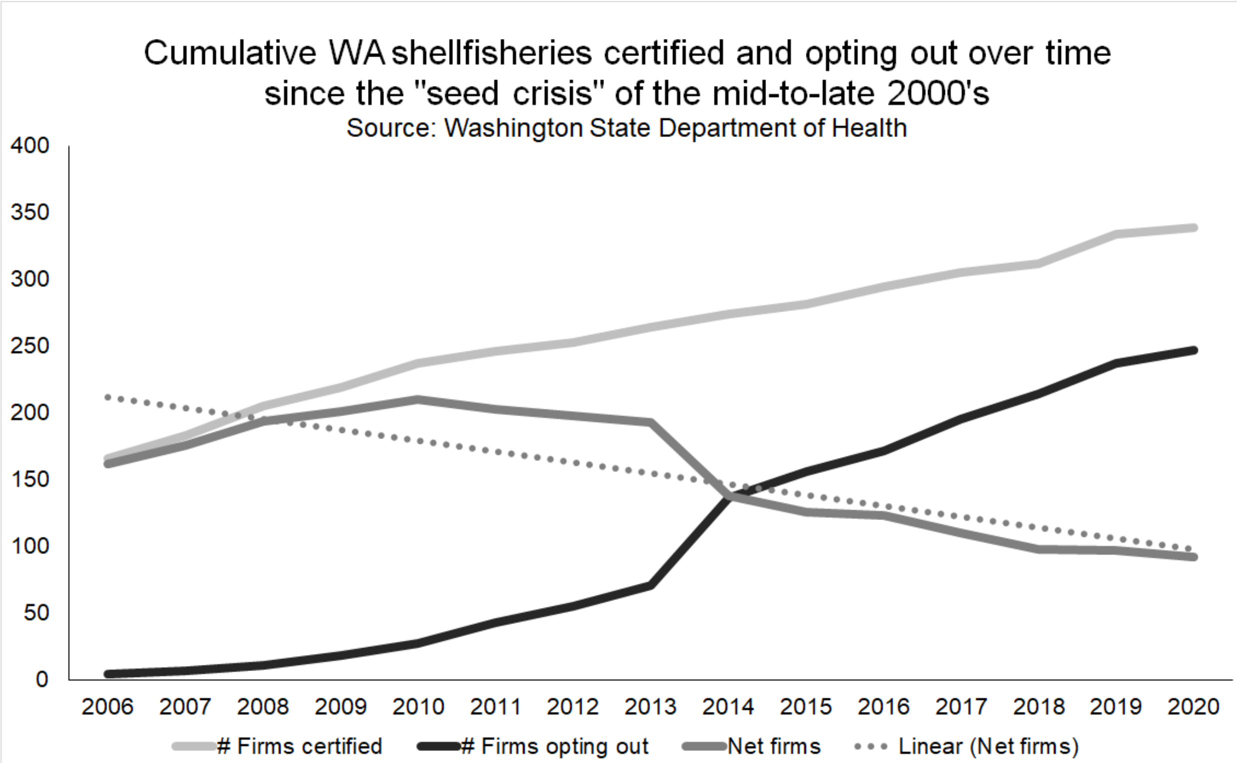

Fig. 1-4 | Shellfish firms in Washington state have begun opting out since the "seed crisis". Industry-level data on shellfish firms in Washington state was analyzed using a cumulative sum function on acreage per firm.

To understand the potential for uneven impacts, what is needed now are specific information tools that map how OA risk varies spatially and temporally with periods of shellfish use, particularly linking the exposure to the organismal sensitivity. Additionally, to identify and support long-term pathways to adaptation, more information is needed to characterize the adaptive capacity of stakeholders, and to identify limits and barriers to adaptation where inequities are evident.

1.2. A framework for vulnerability assessment

The frameworks used to assess vulnerability, risk, and adaptation to hazards have been modified and improved over time using a variety of approaches, including resilience (Merrill et al., 2018), network (Legras et al., 2019), multi-model (Hollowed et al., 2020), and social-ecological approaches (Yaella, 2020). The general aim of these approaches is to inform adaptation decision making by identifying at-risk places and populations, identifying the factors that might produce risk, and outlining scenarios in which these might come together at specific times and places (Ekstrom et al., 2015; Olsen et al., 2018; Hansen et al., 2019). Such diagnosis of risk provides a foundation for action that might be taken. Where such frameworks perennially struggle is devising approaches that include at-risk populations (Hardy & Hauer, 2018) to assess their own risk to climate hazards (Probst et al., 2019), or to present assessments in meaningful terms on how environmental changes might impact reliance on natural resources (Traore et al., 2017).

There is a need to couple increases in knowledge on interactions between biological and social-ecological dimensions of climate hazards with practical stakeholder uses for informed decision-making (Sippel et al., 2015; Fogarty et al., 2019) and multi-stakeholder engagement (Olsen et al., 2014; Reed et al., 2019). Furthermore, there is a need for climate-related research that informs environmental management to be cross-media – i.e. having multi-media elements coupled with publications – and cross-scale (Elliot et al., 2019), in explicit consideration of social dimensions of change, and focused on designing solutions to the specific risks climate change compounds on the environment and society (Weaver & Miller, 2019).

Human-centered assessments of vulnerability to climate impacts often produce vulnerability scores, such as a Social Vulnerability Index (SVI) (Pandey & Bardsley, 2015; Colburn et al., 2016; Weis et al., 2016; Nguyen et al., 2017), but few assessments explicitly prioritize follow-up work to ensure vulnerable communities participate in the development of sustainable adaptation options (Aswani et al., 2019). The need for place-based perspectives is essential for assessing the social outcomes and ecological impacts of proposed adaptation strategies (de Schutter et al., 2019).

The other problem with general vulnerability assessments is that they fail to show very specific relationships that pose risk (Crossman et al., 2012; Jones & Cheung, 2017; Sharma & Ravindranath, 2019; Albouy et al., 2020) — such as the vulnerability of stakeholders reliant on shellfish species that respond in discrete ways to changing OA conditions (Ekstrom et al., 2015). What is needed now are stakeholder-centered assessments that are tailored to the ways that specific species will respond to OA conditions (Pecl et al., 2014; Busch & McElhany, 2016; Koenigstein et al., 2016; Gaisberger et al., 2017; Marshall et al., 2017), and which piece together disparate datasets to quantitatively assess coastal health from a human-centric perspective (Burgass et al., 2019).

To build adaptive capacity to the impacts of climate change in vulnerable communities, Cinner et al., 2018 proposed five domains to be explored in vulnerability assessments in order to identify actionable adaptation investments: 1) assets that people can draw upon in times of need; 2) flexibility to change strategies; 3) social organization that fosters collective action; 4) learning ability to recognize and respond to change; and 5) agency to determine whether to change or not. This framework for building adaptive capacity was chosen for this study because it aligns with the overall goal of adaptation planning to produce equitable outcomes for communities at both the individual and collective levels. This study investigates the context of specific equity challenges within these domains of adaptive capacity in order to identify baseline risk, patterns of impact, and opportunities for local adaptation pathways.

1.3. Objectives

As noted above in the Background section, the two overall objectives of this research are: 1) to assess the vulnerability of Pacific Northwest shellfisheries facing OA risk; and 2) to evaluate adaptation pathways that might enable them to successfully avoid adverse outcomes. To assess vulnerability, this research used geovisualization to quantify risk and stakeholder interviews to answer the question: **How vulnerable are PNW shellfisheries to OA impacts on shellfish species at different life stages?** To evaluate the various possible adaptation pathways, this research used stakeholder interviews to answer the question: **How feasible are adaptation pathways for PNW shellfisheries to navigate OA impacts on shellfish species at different life stages?** Consequently, this research was divided into two separate studies (Fig. 1-1).

The objective of the first study was to assess risk of PNW shellfisheries to OA by geovisualizing spatiotemporal patterns of exposure and sensitivity to OA impacts on shellfish species at different life stages. This study developed a geovisualization tool and validated it in the field to answer the question: What are the different shellfish-reliant communities' current and future risk profiles to OA impacts in the PNW? The way that risk is characterized in this study is through projected impacts on species growth and societal reliance on shellfish for economic or cultural value. This study found that shellfish-reliant communities' current and future risk profiles to OA impacts in the Pacific Northwest vary across locations, and with a noticeable difference between north and south. The risk profile of the south is characterized by: a more intense baseline OA climate; more frequent and intense OA extremes; and social reliance on shellfish that is relatively more cultural than socioeconomic. The risk profile of the north is characterized by: a greater rate of change in OA climate and extremes; and greater social reliance on shellfish, both socioeconomically and culturally. These findings have implications for adaptation in local populations sensitive to OA impacts on shellfish species at different life stages.

The objective of the second study was to identify the adaptation triggers that prompted actions (Barnett et al., 2014) by interviewing stakeholders reliant on shellfish at different life stages across coastal watersheds with differential risk profiles to OA. To achieve this objective, this study conducted mixed-methods interviews with shellfish-reliant stakeholders to answer the question: Considering the range of options for adaptation to OA, what are the barriers preventing successful adaptation at key production stages? Adaptive capacity varies among stakeholders affected by OA impacts on shellfish species at different life stages, so we expect the barriers to develop and implement adaptation strategies to also be different among them. This study found that for stakeholders that could adapt to ocean acidification, the most difficult barriers to overcome at key production stages were operational costs, seed access problems, industry consolidation, employment problems, and insufficient management of water quality. It is likely to be easier for larger firms to navigate around barriers to adaptation than the smallest stakeholders, who may be most constrained by options available to them due to their lack of expandable resources to invest in new technologies, or due to restrictions requiring legislative intervention. These findings have implications for the adaptation potential of local populations sensitive to OA impacts on shellfish species at different life stages.

Results of these two studies include: 1) a novel geovisualization tool for assessing social vulnerability of shellfish stakeholders to OA in the PNW, developed through a synthesis of biological and social-ecological data, and 2) a fieldwork-informed decision tree for identifying potential adaptation pathways of stakeholders to OA in the PNW. Overall, this research contributes knowledge on OA impacts happening currently as well as projected in the future, and on feasible adaptation pathways to successfully adapt to OA. Together, these two chapters help advance the understanding of vulnerability and adaptation pathways for PNW shellfisheries facing increasing risk of OA over time.

2. RISK ASSESSMENT OF PACIFIC NORTHWEST SHELLFISHERIES TO OCEAN ACIDIFICATION

Abstract

Ocean acidification (OA) is a challenging problem for communities that are reliant on shellfish because OA reduces the growth of economically and culturally important species at different life stages. This goal of this study is to assess the risk of Pacific Northwest (PNW) shellfisheries to OA in order to inform decisions on how and where to invest in adaptation strategies to OA with respect to the patterns of exposure and sensitivity to OA, defined as where, when, and how potential problems to local societal reliance on shellfish may emerge from projected impacts of OA on species growth at different life stages. This paper examines the hypothesis that the most at-risk shellfisheries are located in places where OA exposure is projected to impact species growth the most over time, and especially where social reliance on shellfish is greatest. To assess current and future OA risks, a geovisualization tool was developed for mapping shellfish reliance using published data on modeled OA and associated biological responses of four shellfish species at different life stages: *C. gigas*, *O. lurida*, *M. galloprovincialis*, and *M. californianus*. Spatiotemporal patterns of exposure and sensitivity to OA were overlaid and visually analyzed for regional and sub-regional differences. Results indicate that baseline OA is greater and OA hotspots are more intense in the south PNW (e.g. Northern California and Southern Oregon), while both the rate of change in OA is faster and social sensitivity to OA is more acute in the north PNW (e.g. Washington and Northern Oregon). These results have implications for the different adaptation strategies that may will be necessary to counter risk. Persistent extremes in the south may mean that stakeholders there face high, but steady risks to shellfish growth, but in the north, faster rates of change and greater social sensitivity may mean that risk of adverse outcomes are higher. Moreover, due to fast rates of change in the north, adaptation strategies may only work for a limited time before OA conditions worsen even further, necessitating new strategies.

2.1. Introduction

2.1.1. Exposure to ocean acidification

The ocean is acidifying from the uptake of carbon dioxide, a process due to accelerating anthropogenic emissions, a problem for populations reliant on shell-forming species susceptible to declining pH and carbonate ion concentrations (IPCC, 2014). Ocean acidification (OA) is especially intense in coastal waters due to the interaction of local factors that have the potential to amplify OA and produce severe biological impacts (Feely et al., 2016). Factors that can intensify OA nearshore may include upwelling of CO_2-rich water (Feely et al., 2008), urbanization efflux (Feely et al., 2010), nutrient loading (Rheuban et al., 2019), net ecosystem heterotrophy (Pacella et al., 2018; Van Dam et al., 2018; Shadwick et al., 2019), and freshwater runoff (Pilcher et al., 2019).

The U.S. Pacific Northwest (PNW) has been recognized as an OA frontline, where sometime between 2006-2050, deep offshore water is expected to exceed a threshold for near-permanent undersaturation with respect to aragonite (Ωar), the mineral form of calcium carbonate which larval bivalve species use for shell-building (Hauri et al., 2013; Ekstrom et al., 2015; Waldbusser et al., 2015). During the mid-to-late 2000's, successive years of periodic exposure to low-aragonite saturation seawater led to a "seed crisis", in which seed supply shortages triggered responsive adaptation via federal, state, and industry investments in the PNW shellfish industry valued at $270 million annually (Barton et al., 2015; Mabardy et al., 2015). Although the seed crisis was primarily attributed to amplified OA from seasonal upwelling on the coastal shelf (Feely et al., 2008; Harris et al., 2013; Hauri et al., 2013), the relative importance of amplifying factors likely varied across geographies to produce differential impacts on shellfisheries. For example, in the Strait of Georgia, incoming upwelled "acidified" water from the outer coast has been shown to increase local pH due to higher carbon content and lower pH present in this subregion of the Salish Sea (Ianson et al., 2016). Such interactions — between globally-driven OA from upwelling and locally-driven OA from natural and land use factors — result in highly variable exposure to OA extremes in both space and time (Pacella et al., 2018). Consequently, spatiotemporal variability of OA exposure in the PNW may force shell-forming organisms to rapidly adjust to conditions that are both chemically challenging and out of phase from historical conditions (Hauri et al., 2013; Hales et al., 2017).

Seasonal extremes of low-aragonite saturation in coastal waters that are corrosive to shellfish ($\Omega ar < 1$) will typically occur between spring and autumn on the coastal shelf of the PNW (Hauri et al., 2013; Harris et al., 2013), but in the Salish Sea, spring and summer tend to be the only non-corrosive ($\Omega ar > 1$) seasons (Evans et al., 2019). Knowledge on local areas' spatiotemporal patterns of exposure to OA extremes may allow shellfisheries to pinpoint specific windows of time with favorable aragonite saturation conditions, but upper-bound CO_2 emissions trajectories suggest that these favorable windows may have already closed in some parts of the

Salish Sea (Pacella et al., 2018), and are expected to close by 2040 even in places like Alaska (Evans et al., 2015). Therefore, it is important for shellfisheries to have the ability to access knowledge on current and future spatiotemporal patterns of exposure to low-aragonite extremes to better understand their local risk to OA impacts, and to guide appropriate adaptation strategies around local patterns of exposure to OA.

2.1.2. Bio-physiological responses of shellfish species to OA

The impact of carbonate chemistry on the physiological responses of shell-forming mollusk species is important to evaluate risk and adaptation strategies of PNW shellfisheries to OA. Shellfish species such as *Crassostrea gigas* (Pacific oysters) (Gazeau et al., 2007; Barton et al., 2012; Waldbusser et al., 2013; Waldbusser et al., 2014; Brunner et al., 2016; Frieder et al., 2016), *Ostrea lurida* (Olympia oysters) (Waldbusser et al., 2016), *Mytilus galloprovincialis* (Mediterranean mussels) (Waldbusser et al., 2014), and *Mytilus californianus* (California mussels) (Waldbusser et al., 2015; Gray et al., 2017) have been studied at multiple life stages (larvae, juvenile/adult) for growth responses (Timmins-Schiffman, 2014; Waldbusser et al., 2014) as well as decreased survival rates (Barton et al., 2012; Gimenez et al., 2018) resulting from controlled exposure to extremes in carbonate chemistry variables, of which the most impactful to shell-forming bivalves are aragonite saturation state (Waldbusser et al., 2015), pH (Huo et al., 2019), and pCO_2 (White et al., 2013).

There is active research on the primary agent of OA, in which some studies focus on the impacts of pH (Busch & McElhany, 2016), while others focus on aragonite saturation state (Waldbusser et al., 2015). Choosing one sole indicator to study the impact of OA on calcification may lead to discrepancies in real-world environments subject to the influence of multiple factors that may influence species responses (Fassbender et al., 2016). There are multiple natural and anthropogenic processes in the coastal environment that may contribute to synergistic or antagonistic effects on habitat suitability for successful shellfish growth (Waldbusser & Salisbury, 2014), but in general, saturation state is a good indicator for capturing the changes that are occurring in the entire carbonate system (Waldbusser et al., 2015). Shellfish species may respond to a low-aragonite (OA) stressor as a function of: how far removed changes are relative to optimal physiological ranges and tolerance limits at different life stages; the average magnitude of the OA stressor over the production cycle; rate of change in OA stressor; variability, frequency, duration, and magnitude of OA extremes; epigenetic expression, genetic strain, and variation within and between populations; health and nutrition; and simultaneous stressor occurrence (Reid et al., 2019a).

Physiological responses of species to multiple stressors can also include changes in metabolism and behavior, as well as the ability to build calcium carbonate structures (Somero et al., 2016). Indirect interactions in the intertidal ecosystem can mediate the effects of OA on individual taxa, and research in other regions has suggested that species-level responses to OA may be even stronger in both positive and negative directions than community or ecosystem responses to OA (Havenhand et al., 2019). For example, experimental transplants of a marine intertidal mussel (*Perumytilus purpuratus*) into river-influenced habitats showed increased growth, calcification rates and decreased metabolic rates compared to organisms grown in non-river-influenced habitats, suggesting that enhanced food supply from freshwater discharge may offset shell dissolution in more acidic environments through additional contributions of metabolic carbon for shell composition (Pérez et al., 2016). Similar evidence from Greenland found that high food supply from freshwater discharge allowed *Mytilus* mussels to cope with low aragonite saturation state conditions, suggesting that shell-dissolution resistance may be possible through provision of sufficient food (Duarte et al., 2020). Food limitations were found to drive growth responses of *C. gigas* and especially *O. lurida* at up-estuary sites in Washington state, but predation pressure was a greater risk to survival at mid- and low-estuary sites, suggesting that effects are mediated by local environmental conditions as well as species type (Lowe et al., 2019).

Species responses to OA at different life stages have risk and adaptation implications for shellfisheries. Protecting early life stages from hostile environments has been suggested as a focal conservation action (Halley & Mantua, 2018); however, later life stages may also require protection from hostile environments because evidence suggests that negative effects of OA on early shell development may carry-over to later life stages in species such as *O. lurida* (Hettinger et al., 2012), and may be compounded trans-generationally (Griffith & Gobler, 2017). Treatment systems to control carbonate chemistry conditions have already been installed at some shellfish hatcheries in the PNW in response to the seed crisis (Barton et al., 2015). In environments that are difficult to treat, such as commercial leases in tidal flats, other management strategies may include selective breeding for more resilient species to withstand future exposure to OA (Fitzer et al., 2019), or buffering sediments with shell material (Green et al., 2009; Green et al., 2013). Management strategies are likely to vary by species and life stage, and across places and people;

therefore, the first step in designing place-based adaptation plans for shellfisheries is to understand how local patterns of current and future exposure to OA affect shellfish species at different life stages.

2.1.3. Socioeconomic-ecological impacts of OA

Socioeconomic and ecological impacts of OA from decreases in aragonite at high latitudes (e.g. PNW) are expected to greatly increase over time as atmospheric CO2 continues to increase from around 400 ppm presently to about 650 ppm projected by 2070 under emissions scenario RCP8.5 (Good et al., 2018). Impacts from increasing acidification may degrade biogenic habitats, including both coral and shellfish reefs, which are important to millions of people for coastal protection, fisheries, and aquaculture (Hall-Spencer et al., 2019). To complement knowledge on OA's impacts to the supply of ecosystem services, research has highlighted the importance of considering impacts to access and quality of ecosystem services as well (Singh, G. et al., 2020). For example, a study on the impacts of OA on Atlantic Canadian fisheries found that New Brunswick and Nova Scotia may be socially insulated from declines in resource accessibility while Prince Edward Island, Newfoundland, and Labrador may be more socially vulnerable to potential losses in supply despite minor differences in access, in part due to weaker adaptive capacity related to education and unemployment (Wilson et al., 2020).

Models of impacts on marine ecosystems may integrate both ecological and socioeconomic indicators for a range of uses, including: testing feasible management strategies (Tam et al., 2019), comparing management success across regions (Link & Marshak, 2019), analyzing scenarios to guide adaptive management decisions (Lozano-Montes, 2020), and evaluating tradeoffs among management actions, societal choices, and species (Olsen et al., 2018). Multispecies models that predict declines in community-level catches, spawning stock biomass, and mean body mass may be dominated by structural uncertainty, yet information produced by such models may help to inform and prioritize research and management strategies around both species and objective (Reum et al., 2020). In some cases, models have predicted habitat reassemblages driven by species responses to ocean change, showing the potential for spatial shifts in biodiversity and ecosystem functioning (Oliver et al., 2018). Range shifts stimulated by species responses to OA could also include toxic microalga that disrupt food webs, such as *Vicicitus globosus*, indicating a potential for some range expansions to cause harm to unprepared or poorly monitored areas (Riebesell et al., 2018). Most global OA models predict a worsening situation with long-term, gradual declines in both pH and aragonite saturation state; however, some OA impact scenarios that are better off unvalidated, such as fallout from regional nuclear conflict, present cases where pH may temporarily increase while aragonite saturation state continues to decrease, showing the potential for declining aragonite saturation state to exacerbate shell dissolution despite short-term increases in pH (Lovenduski et al., 2020). Such a scenario highlights the danger of regional actions in the short-term having potentially far-reaching effects on global ocean carbonate chemistry (Lovenduski et al., 2020). Evidence suggests that shifts in Earth's ecosystems can occur over ‘human timescales' of years and decades, implying that the collapse of large vulnerable ecosystems, such as Pacific Northwest shellfish beds, may take only a few decades once triggered (Cooper et al., 2020).

Economic analyses modelling climate change impacts have described impacts on labor productivity and agriculture as the largest negative economic consequences projected (Dellink & Chateau, 2019). Diverse sectors may benefit from proactive adaptation measures that reduce economic loss and damage from climate impacts (Martinich & Crimmins, 2019). In the shellfish sector, stakeholders may be incentivized to reduce the impacts of OA on shellfish species they rely on for their livelihood. For example, consumers wish to pay on average 52% less for mussels showing evidence of OA, such as color loss, but are willing to pay more to avoid such negative changes in appearance (Martin et al., 2019). An economic assessment of the impact of OA on shellfish production in Europe found that the overall annual impact may be over 1 billion USD by 2100, but that the spatial distribution of impacts may be uneven, disproportionately impacting places with the largest production today (Narita & Rehdanz, 2017). Disproportionate economic impacts may arise in places with high production of shellfish but limited income diversification options. For example, a survey on the economic impacts of harmful algal bloom (HAB) events showed that stakeholders with greater income dependence on shellfish reported higher overall income losses, underscoring the importance of income diversification during protracted harvest closures (Moore et al., 2020). Research suggests that a better understanding of the economic impacts of OA across a range of species, timescales, and spatial scales could inform decisions on where, when, or how to maintain or enhance economic services obtained from marine environments in the future (Falkenberg & Tubb, 2017).

Shellfish stakeholders may be at risk not only to ocean acidification impacts but also to poverty-environment traps, in which geographically isolated communities heavily reliant on natural resources may experience eroded assets from the impacts of climate change, thus marginalizing incomes, exacerbating vulnerability, and making outmigration from impacted areas more costly (Barbier & Hochard, 2018). By elevating the need for increased production to offset eroded assets, ocean acidification risk may thus reduce time available for stakeholders to perform other tasks like seeing healthcare providers or maintaining social networks. In this context, OA risk may also compound health and social risks which have clear negative effects on livelihood capitals (Su et al., 2018). As climate risks intensify, the compounding effect of global food trade market liberalization on geographically-confined, developing areas is expected to result in higher uncertainty of production and supply, affecting the stability of food security for vulnerable populations (Ho et al., 2018).

The most noticeable OA impact for shellfisheries is seed supply shortages, a problem that has already created far-reaching effects on shellfish-reliant communities across the Pacific Northwest. In the mid-to-late 2000's, at the Whiskey Creek Shellfish Hatchery, low-aragonite saturation seawater caused unprecedented larval mortalities, resulting in production failures and a serious threat to seed supply for the regional shellfish industry that supports $270 million in economic activity and over 3,000 family wage jobs in rural areas (Barton et al., 2015). Initially, the mortality events of the seed crisis were attributed incorrectly to pathogenic blooms of *Vibrio tubiashii* (Barton et al., 2015), for *Vibrio* bacteria grow and persist in relative abundance under hatchery conditions compared to their natural abundance in bay water (Gradoville et al., 2018). The seed crisis triggered responsive adaptation investments and a partnership between industry, scientists, and policy makers that led to continuous monitoring of carbonate chemistry at the Whiskey Creek Shellfish Hatchery (Barton et al., 2015). Monitoring data and biological experiments at the hatchery revealed that larval mortalities during the seed crisis coincided with successive years of exposure to low-aragonite saturation state conditions, attributed to amplified OA from seasonal upwelling on the coastal shelf (Feely et al., 2008; Harris et al., 2013; Hauri et al., 2013; Barton et al., 2015). Whiskey Creek Shellfish Hatchery was not the only location that experienced production failures from OA during the seed crisis, and the relative contribution of local amplifying factors and social contexts likely varied across geographies to produce differential impacts on shellfisheries.

Adaptation strategies implemented in response to the seed crisis have been heralded as successful in restoring production and livelihoods across the Pacific Northwest; however, key challenges remain in expanding the capacity of hatcheries, the monitoring of carbonate chemistry in coastal waters, and the understanding of biological responses (Barton et al., 2015). Further gaps remain in understanding how the seed crisis and responsive adaptation strategies affected stakeholder livelihoods, as well as how social vulnerability to OA may be understood given stakeholders' current and future exposure to ocean acidification, social reliance on shellfish species responsive to OA at different life stages, and capacity for adaptation strategies to be implemented.

2.1.4. Assessing risk and vulnerability to OA

Spatially-explicit assessments of vulnerability can help identify prioritized adaptation opportunities in at-risk communities by highlighting differences in geographic attributes related to hazard exposure, social sensitivity to impacts, and adaptive capacity to reduce or avoid harmful consequences (Ekstrom et al., 2015; Mathis et al., 2015). For example, a vulnerability assessment of U.S. shellfisheries to ocean acidification found that the Pacific Northwest region is highly exposed to OA, reaching a threshold for low-aragonite saturation state relatively sooner than other regions, but with relatively high adaptive capacity, the PNW region may be somewhat buffered to impacts from OA (Ekstrom et al., 2015). In contrast, the Gulf Coast region is projected to reach the low-aragonite saturation state threshold towards the end of the 21st century, but prevalent local amplifying factors, relatively high reliance on shellfish, and low adaptive capacity means that the Gulf Coast region may be more vulnerable to impacts from OA, which could arrive sooner than forecasted due to the influence of amplifying factors on local coastal acidification (Ekstrom et al., 2015). Whereas prioritized adaptation in a region like the Pacific Northwest may involve strategies to cope with rapidly intensifying exposure to OA, adaptation strategies in a region like the Gulf Coast may instead focus on reducing the impact of local amplifying factors or reducing social vulnerability through livelihood diversification or capacity-building investments (Ekstrom et al., 2015).

Temporally-explicit assessments of risk may use trade-off models for assessing vulnerability to climate hazards by quantifying current and future risk as projected changes to the value of ecosystem services under different scenarios (Sajjad et al., 2018). Assessing how differences in risk may change over time can serve as a useful first step in prioritizing further analyses to investigate contextual details in vulnerable places (Gaichas et al., 2018). Understanding how the timing of OA impacts interact with social, economic, and natural components that contribute to OA risk can facilitate development of adaptation pathways optimized to local contextual factors (Barnett et al., 2014; Mathis et al., 2015). Incorporating multiple interactions, time scales, and sources of variation may reveal deeper insights into contextual trade-offs relevant to local structure and function of ecosystems sensitive to climate perturbations (Trifonova & Kelble, 2019).

Species-explicit assessments of risk may integrate species responses to climate stressors in order to project changes in biomass or revenues for a number of valued species (Marshall et al., 2017). Multidisciplinary approaches that frame hazard risk through the lens of social reliance on species responsive to the hazard aim to evaluate locations by provision of ecosystem services, and to assess effects of socioeconomic factors and management decisions on the condition of ecosystems (Rendon et al., 2019). When conducting risk assessments, considering several uncertainties, and testing different indicators for determining vulnerability, may help to characterize the relative importance of environmental and biological variables for projecting impacts on species across locations (Spencer et al., 2019). Investigating impacts and interactions of multiple drivers and stressors on a social-ecological system through a hotspot approach may help to identify appropriate entry points and stakeholder groups for adaptation planning or policy interventions (Khan & Cundill, 2019). In order to understand appropriate adaptation strategies for shellfish stakeholders facing OA risk in the Pacific Northwest, first it is necessary to understand spatiotemporal patterns of exposure and sensitivity to OA, specific to species at different life stages.

Here, this study presents a novel contribution in assessing risk of shellfisheries to ocean acidification across space, time, species, and life stages through the development of an interactive web-based geovisualization tool. Decision-making tools designed in collaboration with multiple stakeholder groups for the purposes of communicating climate risks and informing adaptation strategies have proven effective in advancing theory on vulnerability to include practical implications for sustainable management of natural resources (West et al., 2018). Geovisualization has the potential to broaden applications and end-users of time series data by fostering immersive learning or research experiences through an interactive, shareable tool (Benway et al., 2019). The geovisualization tool developed in this study responds to calls in the literature for more effective translation of linkages between the climate system, the marine ecosystem, and societal needs of stakeholder groups at the frontlines of ocean acidification impacts (Bograd et al., 2019; Hurd et al., 2018). Although threats of ocean acidification are increasing, so is the technology to capture, process, and contextualize data to be delivered as knowledge (Buck et al., 2019).

2.1.5. Goal

The goal of this study was to assess risk of PNW shellfisheries to OA by geovisualizing spatiotemporal patterns of exposure and sensitivity to potential impacts from OA on shellfish production and social communities reliant on shellfish species at different life stages. To achieve this aim, this study developed a geovisualization tool to answer the question: **What are different shellfish-reliant communities' current and future risk profiles to OA impacts in the PNW?** The way that risk is characterized in this study is through the intersection of exposure and sensitivity, conceptualized as where, when, and how potential problems to local societal reliance on shellfish may emerge from projected impacts of OA on species growth at different life stages (Fig. 2-1). It is hypothesized that the most at-risk places are where OA exposure is projected to impact species growth the most on average or over time, and especially where social reliance on shellfish is greatest, either socioeconomically or culturally.

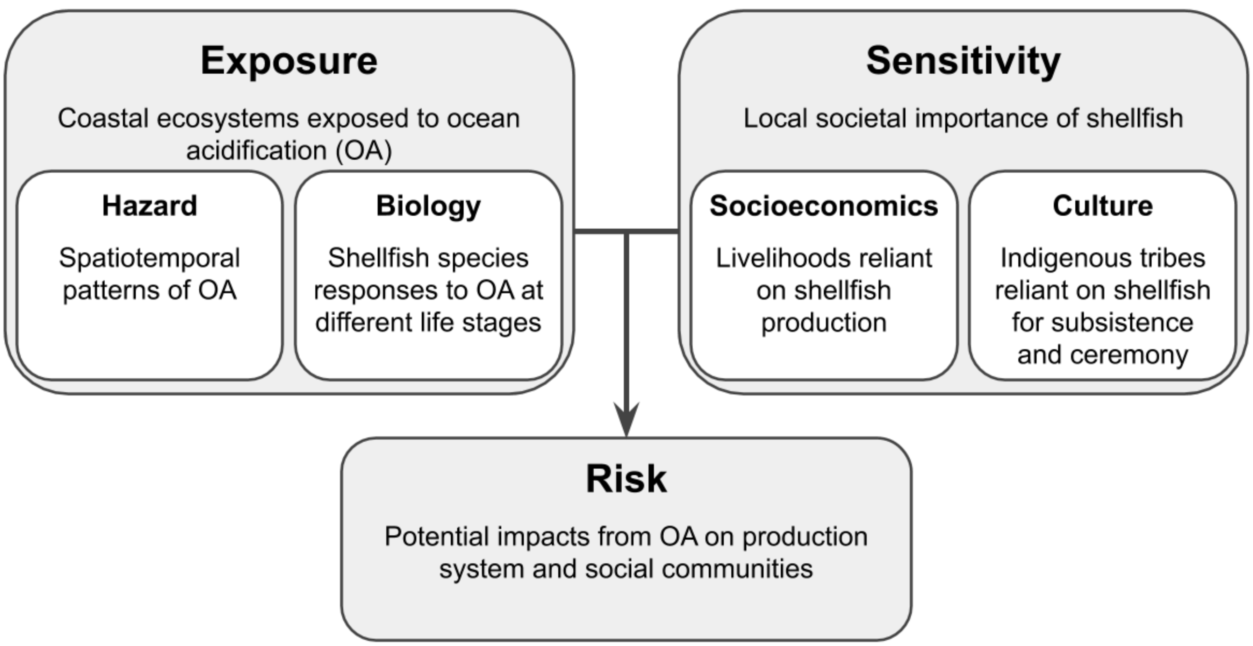

Fig. 2-1 | Conceptual framework structuring the risk assessment of Pacific Northwest shellfisheries to ocean acidification. Conceptual model components were adapted from Ekstrom et al., 2015 and Jamshidi et al., 2019.

2.2. Methods

Three major steps were involved to answer the research question. First, geospatial and biological data were collected and preprocessed for mapping. Second, a geovisualization tool was developed. Lastly, the geovisualization tool was visually analyzed to assess risk profiles to OA.

Data were collated from existing sources on exposure and sensitivity to OA using four types of risk dimensions: hazard, biology, socioeconomics, and culture (Table 2-1). Data preprocessing and analyses were performed in order to generate indicators for eventual geovisualization of each risk dimension. Indicators were joined by location into a common spatial landscape feature that formed the basis for analysis and geovisualization: watersheds in the U.S. with intertidal influence in two Pacific Northwest marine ecoregions — Oregon, Washington, Vancouver Coast and Shelf, and Puget Trough/Georgia Basin (Hoekstra et al., 2010; USGS, 2020). This scale was chosen because watersheds at the hydrologic unit code-8 (HUC8) level, also known as subbasins, are the cataloging units used by the EPA and USGS for managing watershed health of medium-sized rivers, and spatial patterns of OA exposure revealed by this study may therefore help to inform priority areas for watershed management changes aimed at minimizing risk of coastal acidification.

In order to geovisualize OA exposure in terms of the hazard itself, this study used a pre-existing model of ocean acidification in the California Current which included upwelling dynamics (Hauri et al., 2013). This model included variables for aragonite saturation state, pH, pCO2, salinity, and temperature, but this study chose to focus only on aragonite saturation state as the common currency for exposure to OA because aragonite saturation state: covaries with the others, allows for a complete description of the inorganic carbon system, and facilitates the clearest link between OA extremes and bioenergetic impacts on shellfish species (McLaughlin et al., 2015; Waldbusser et al., 2015). Hazard data was analyzed by calculating metrics for baseline carbonate climate and change in carbonate climate, using thirty-year averages of aragonite saturation state at the beginning (1995-2025) and end (2020-2050) of the OA model time series (Hauri et al., 2013). Additionally, hazard data was analyzed at annual timescales for the frequency and intensity of OA extremes by using an aragonite saturation state threshold of $\Omega ar \leq 1.4$. This cutoff for OA extremes was chosen because undersaturated water below this threshold corresponds with stressful conditions for shellfish (Barton et al., 2012; Waldbusser et al., 2015). Once calculated, hazard metrics were attributed to point features representing the 5 km resolution of the OA model used because vector points are more rapidly visualized with web mapping libraries than are raster images (Jenny et al., 2016). Using QGIS, those points were summarized within watershed polygons to calculate mean values for baseline OA climate and change in OA climate estimated for each watershed (Hauri et al., 2013; USGS, 2020).

In order to geovisualize OA exposure in terms of expected impacts on specific shellfish species, biological response data were compiled from a range of scientific studies that measured biocalcification or approximated it via growth (Appendix G Table G-1). Studies were identified on four species: *C. gigas*, *O. lurida*, *M. galloprovincialis*, and *M. californianus*. Biological data were stratified by larval and juvenile/adult responses, controlled for data quality across studies, standardized to make various response variables comparable, and ultimately fit to a curve to develop functional relationships. These studies reported larval shell length in response to carbonate chemistry. The number of studies found per species and life stage was quite variable. For example, there were no response studies for juvenile/adult *M. californianus*, whereas larval *C. gigas* had 11 studies that had usable data for growth, providing ~60 total data points. For juvenile and adult *C. gigas*, there were 3 studies using either alkalinity anomaly or buoyant weight to determine shell growth, with a total of 24 data points. In *O. lurida* the coverage was far less extensive, with only a handful of studies. Larval *O. lurida* had 3 studies with 40 data points, and juvenile/adults had 1 study with 5 data points. For larval *M. californianus* there were 3 studies with 32 data points, and no studies to date on juvenile or adults. And finally, for *M. galloprovincialis*, larvae had 3 studies with 16 data points, and juvenile/adults had 7 studies with 28 data points. In order to standardize and make the various data sets comparable, a functional response (linear or nonlinear) was fit to each response as a function of saturation state. With this fit, the response was computed at an aragonite saturation state of 2.5, roughly the estimated median coastal water values for the mid-coast of Oregon during pre-industrial times (Harris et al., 2013). This value was compared with each response at each treatment level for a given study, as a percentage change, to generate a response curve for each species and life stage across all respective studies.

In order to geovisualize OA sensitivity in terms of human livelihoods reliant on shellfish in the Pacific Northwest, socioeconomic data on certified shellfish shippers were collected from a combination of federal and state agencies in Washington, Oregon, and California (CDPH, 2020; ODA, 2020; U.S. FDA, 2020; WA DOH, 2020). Socioeconomic data on shellfish shippers included: shellfish farms, shellstock shippers, shucker packers, distributors, retail seafood markets, and tribal communities. Socioeconomic data were analyzed by calculating a metric for shellfish livelihoods as the number of certified shellfish shippers per watershed, normalized by population. The Count Points in Polygon plugin in QGIS was used to estimate shippers per watershed, and then population was estimated and matched to the same scale of watersheds by using the Zonal

Statistics plugin in QGIS to sum pixel values of a gridded population dataset for the year 2020 at approximately 1 km resolution (SEDAC, 2020). Watershed layers for baseline OA climate, change in OA climate, and socioeconomic sensitivity indicators were mapped in QGIS using five classes based on Natural Breaks in order to identify breakpoints in the data for assigning color symbology. The reason Natural Breaks were used to classify breakpoints, rather than Standard Deviation, was because Natural Breaks minimize differences between data values in the same class and maximize the differences between classes (Slocum, 2009).

In order to geovisualize OA sensitivity in terms of cultural reliance on shellfish in the PNW, data were collected on the locations of First Nations tribes with federally recognized reservations in the Columbia and Klamath watersheds which flow into PNW marine ecoregions. Cultural sensitivity to OA was represented by point centroids of present-day reservation boundaries (United States Census Bureau, 2019) in order to clearly identify where tribes are located in relation to spatial patterns of OA exposure and socioeconomic sensitivity. The reason tribes were mapped using point centroids, and not polygons or watersheds like the OA exposure and socioeconomic sensitivity analyses, was because geographic boundaries recognized today with respect to tribes may be arbitrary or undermine tribes' ancestral territories where shellfish reliance may have occurred over millennia. For added context, photos were collected directly from the websites of tribes, wherever available, and were joined to the point centroids of reservations to create a map layer of photo clusters which could be overlayed with the watershed layers showing OA exposure and socioeconomic sensitivity.

Table 2-1 | Indicators of exposure and sensitivity to ocean acidification, and the criterion for each used in this study. Aragonite saturation state = Ωar.

Risk Component	Dimension	Indicator(s)	Description	Scale for visualization	Data	Data type	Processing
Exposure							
	Hazard	Baseline carbonate climate	Mean Ωar from 1995 to 2050	Watersheds (HUC8)	Model of ocean acidification in the California Current between 1995-2050 at monthly temporal resolution and 5 km spatial resolution (Hauri et al., 2013); Watershed boundaries at the HUC8 scale (USGS, 2020).	Raster (5 km) Point Polygon	A Python script was written to parse a time series for Ωar from a collection of NetCDF raster images. The resulting text file contained coordinate locations, timestamps, and Ωar values for every pixel and time step of the OA model used. From this time series, two point layers were generated, one for baseline and change in climate, and one for hotspots (described below).
		Change in carbonate climate	Change in mean Ωar from 1995 to 2050	Watersheds (HUC8)			The first point layer contained one point per pixel in the study area, and to this layer, fields were created and calculated for mean baseline climate and mean change in climate. Using QGIS, these point metrics were summarized within watershed polygons to estimate mean exposure metrics for watersheds.
		Extreme carbonate weather	Frequency and intensity of modeled OA hotspots stressful to shellfish, where: Frequency = # months per year below Ωar ≤ 1.4 Intensity = mean Ωar per year	Points (5 km)			The second point layer was generated using a Python script. For every instance in the OA time series where and when Ωar ≤ 1.4 was projected, a separate data frame was created to summarize OA hotspots by year. For every location projected with an OA hotspot between 1995-2050, metrics for frequency and intensity were calculated as the number of months per year Ωar ≤ 1.4, and the mean Ωar of hotspots per year.

Table 2-1 (Continued) | Indicators of exposure and sensitivity to ocean acidification, and the criterion for each used in this study.

Risk Component	Dimension	Indicator(s)	Description	Scale for visualization	Data	Data type	Processing
	Biology	Organismal responses to OA at the larval life stage Organismal responses to OA at the juvenile/adult life stage	Shellfish species % growth under variable Ωar compared to pre-industrial Ωar	Flexible to many scales depending on OA hotspot points shown on map	Meta-analysis of documented species responses to aragonite saturation state at different life stages, represented in terms of percent growth from pre-industrial for *C. gigas*, *O.lurida*, *M. galloprovincialis*, and *M. californianus* (Appendix G Table G-1).	Equations	A spreadsheet was created to calculate species growth responses between $0.1 \leq \Omega ar \leq 3.0$, and these values were used to create an interactive line graph on the geovisualization tool.
Sensitivity							
	Socioeconomics	Certified shellfish shippers	Interstate and state certified shellfish shippers (normalized by watershed population)	Watersheds (HUC8)	CDPH, 2020; ODA, 2020; SEDAC, 2020; U.S. FDA, 2020; USGS, 2020; WA DOH, 2020	PDF Raster Polygon	A Python script was written to parse shipper data from PDFs into a spreadsheet. Point locations of shippers were geocoded and counted within watershed polygons. Zonal statistics were performed in QGIS using a gridded population dataset to estimate watershed population. Shipper counts were normalized per watershed by dividing the number of shippers by the estimated population.
	Culture	First Nations tribes	Federally recognized tribal reservations in the Columbia and Klamath watersheds	Points (photo clusters)	U.S. Census Bureau, 2019	Polygon	Reservation boundaries were converted to point centroids using the Centroids plugin in QGIS. Photo URLs were joined to point coordinates in JSON format using a Python script.

The second step to answer the research question was to develop a geovisualization tool for mapping data collected on exposure and sensitivity indicators (Fig. 2-2). An interactive map was created using Leaflet.js, an open-source JavaScript library for web cartography, so that code could be freely accessed by others to replicate or expand upon this work in the future. Once the OA exposure and sensitivity indicators were processed as described in the previous step, these data layers were added to the Leaflet map and programmed to be toggled on or off using a layer control icon in the upper right corner of the map. Adjacent to the map, graphs were added using three JavaScript libraries for creating interactive figures: D3.js, DC.js, and crossfilter.js. Four graphs were created in total, including: a line graph and time window slider showing the count of modeled OA hotspots by year, a line graph showing the species response curves compiled in the previous step, and two bar graphs showing intensities and frequencies of OA hotspots. These data-driven graphs were synchronized with the map to dynamically update with recalculated metrics whenever users interact with the map by panning around, zooming in or out, or selecting a time range of interest. Interactions with the panel of graphs were also programmed to filter OA hotspots visible on the map whenever users select a time range of interest, or one or more breakpoints in the bar chart graphs. The geovisualization tool also features story maps which pair narrative with scientific data, for research suggests that combining narrative with scientific data can lead to useful tools for addressing environmental degradation through policy interventions (Kelly et al., 2014).

Feedback on the geovisualization tool was collected from potential end-users at every stage of the development process via workshops, discussions, and interviews with resource managers, scientists, and stakeholders representing both socioeconomic and cultural reliance on shellfish. Iterative stakeholder engagement is important in the development of effective data products for identifying specific user needs, designing products around specific requirements and styles of interaction, and following up to ensure products stay relevant (Iwamoto et al., 2019). The web-based nature of the geovisualization tool allowed for demonstrations to be performed with stakeholders by using only a mobile phone wherever network coverage or Wi-Fi was present, and this flexibility was useful in maximizing stakeholder engagement with the tool in a variety of environments, including tidal flats in the middle of an estuary. Although a standardized survey and analysis of stakeholder engagement with the tool would have bolstered the results of this study, they were not within the scope of this study. Nevertheless, critiques received by stakeholders did help inform adjustments in the design of the geovisualization tool.

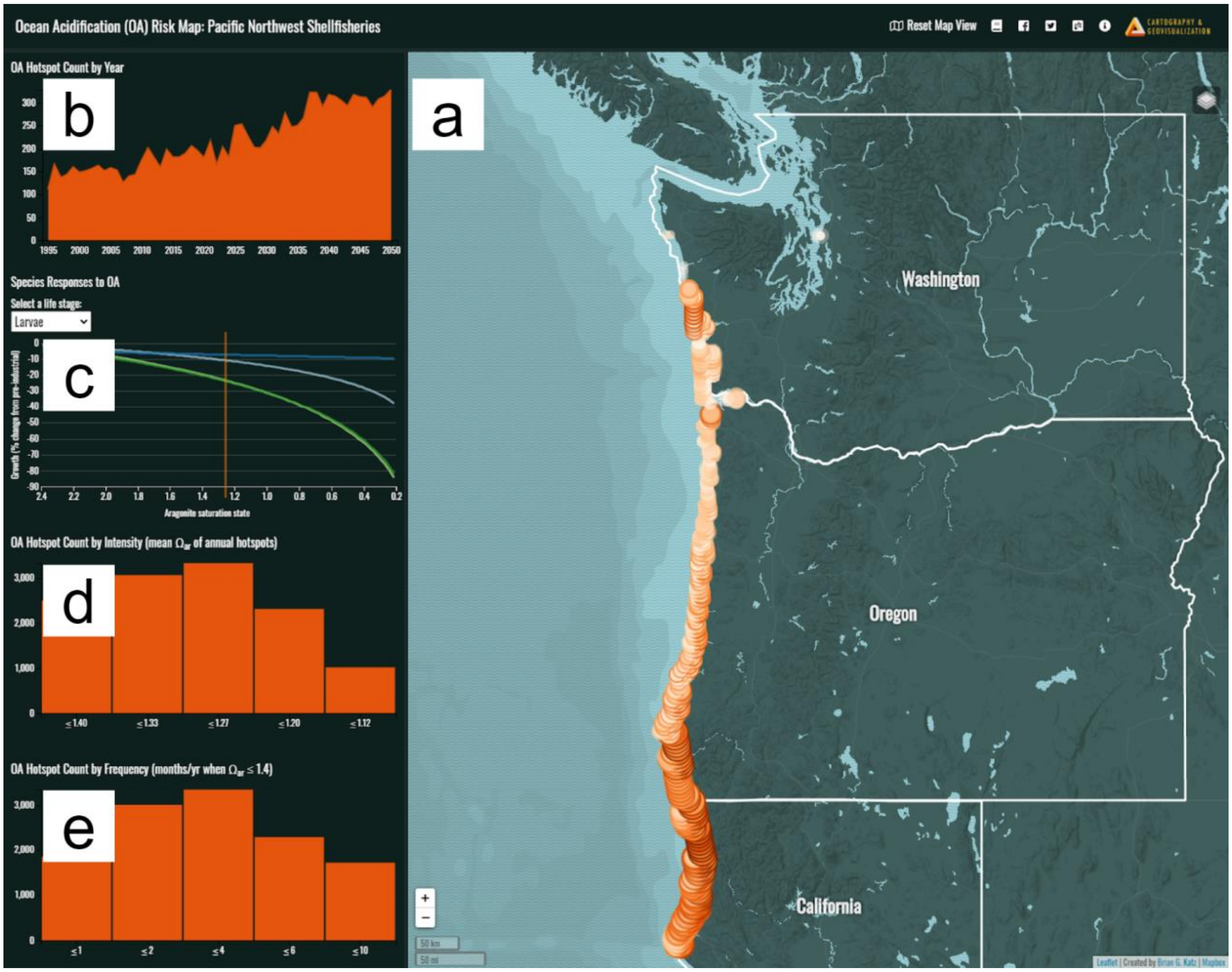

Fig. 2-2 | Interface of the geovisualization tool. a–e, Components of geovisualization: map (a), line graph and time window slider (b), species response curves (c), intensity bar graph (d), and frequency bar graph (e). Projected hotspots of OA are represented with orange circles where aragonite saturation state (Ωar) ≤ 1.4 between 1995-2050 (Hauri et al., 2013). Dynamic graphs (b–e) are synchronized with the map (a) to summarize spatially-explicit OA hotspots by: year (count of 5 km2 hotspots/yr, i.e. magnitude) (b), impact on species responses at different life stages (% growth from pre-industrial for larval and juvenile/adult *C. gigas*, *O. lurida*, *M. galloprovincialis*, and *M. californianus* when exposed to the calculated mean Ωar of hotspots filtered in view) (c), intensity (mean Ωar of annual hotspots) (d), and frequency (months/yr when Ωar ≤ 1.4) (e). The top graph (b) acts as an interactive "time window slider" that filters OA hotspots shown on the map when users click and drag the graph to specify a selected time range. The bottom two graphs (d–e) also filter OA hotspots shown on the map when users click one or more breaks in the data, i.e. bars in the graph. The species response graph (c) can be toggled between larval and juvenile/adult life stages, and map layers can be toggled by a layer control icon in the upper right corner of the map (a). The flexible design and interactivity of the tool allows for a multitude of geovisual analytics to be performed across spatial, temporal, and biological parameters specified by map users. Data sources listed in Table 2-1. Geovisualization available at https://briangkatz.github.io/oa/vulnerability/pnw.

The final step to answer the research question was to visually assess spatial patterns revealed by the geovisualization tool. To reveal exposure patterns, map layers were toggled between baseline OA climate and change in OA climate. Additionally, the map was panned to different spatial scales to see how species life stages are projected to respond to variable patterns of OA exposure projected at different spatial or temporal scales. To reveal social sensitivity patterns, a spatial overlay was performed, in which the photo cluster layer for cultural sensitivity was visualized on top of the map layer showing socioeconomic sensitivity to OA. The purpose of visualizing social sensitivity this way was to identify opportunities for local adaptation planning around the relative ratio of low-to-high socioeconomic and cultural reliance on shellfish exhibited by different geographic regions.

2.3. Results

Findings suggest that shellfish-reliant communities' current and future risk profiles to OA impacts in the Pacific Northwest vary across locations, and with a noticeable difference between north and south. The risk profile of the south is characterized by a more intense baseline OA climate, more frequent and intense OA extremes, and social reliance on shellfish that may be relatively more cultural than socioeconomic. The risk profile of the north is characterized by a greater rate of change in OA climate and extremes, and greater social reliance on shellfish, both socioeconomically and culturally. These findings have implications for adaptation in local populations sensitive to OA impacts on shellfish species at different life stages.

Screenshots of the geovisualization interface are shown in Fig. 2-3, comparing risk of PNW shellfisheries to OA across three spatial scales (WA, OR, CA) and three patterns of exposure and sensitivity relevant to stakeholders reliant on shellfish species at larval or juvenile/adult life stages. Baseline OA climate and OA hotspots are most intense in southern watersheds, while both rate of change in OA climate and social sensitivity to OA are more prominent in northern watersheds. Persistent extremes in the south mean that stakeholders there face greater risk of OA impacts on shellfish growth, and hatcheries reliant on larval shellfish may be especially impacted if intake water is not buffered. Faster rates of change and greater social sensitivity in the north mean that stakeholders there face greater risk of adaptation strategies working for only a limited time before OA conditions worsen even further, necessitating new strategies.

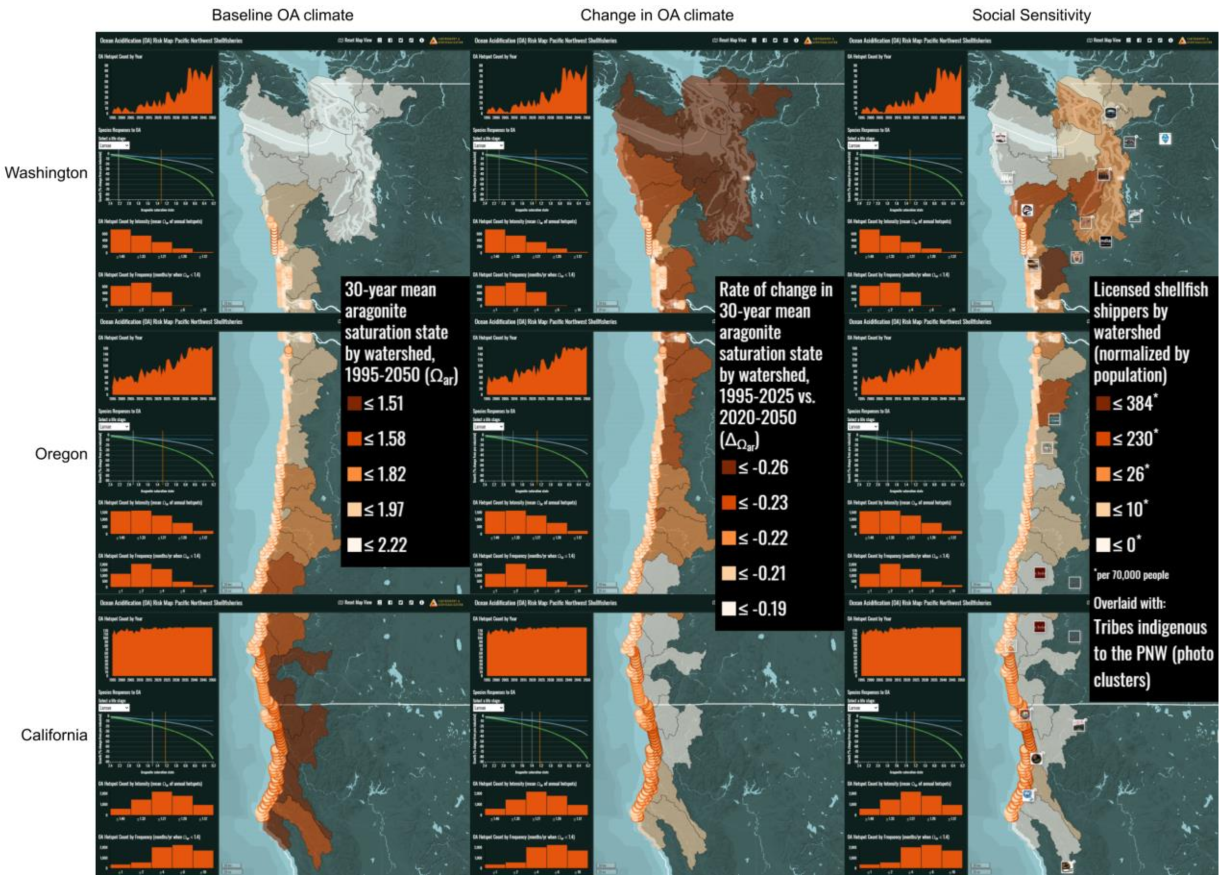

Fig. 2-3 | Screenshots of the geovisualization tool, providing visual comparison of PNW shellfisheries' risk to OA across three spatial scales and patterns of exposure and sensitivity relevant to stakeholders reliant on shellfish species at different life stages. Rows from top to bottom show results for different states: Washington (top), Oregon (center), and California (bottom). Columns from left to right show results for different patterns of risk: baseline exposure (left), change in exposure (center), and social sensitivity (right). Differences in risk to OA may necessitate different adaptation strategies; for example, the South must adapt to persistent OA extremes while the North must adapt to a faster rate of change in OA.

2.3.1. Exposure

On average, between 1995-2050, growth decline is projected to be greater in the south for all species and life stages (Table 2-2). Between life stages, juveniles/adults may be more impacted than larvae. Between species groups, mussels may be more impacted than oysters. Within species groups, Pacific oysters (*C. gigas*) are more impacted than Olympia oysters (*O. lurida*), especially at the juvenile/adult life stage. Mediterranean mussels (*M. galloprovincialis*) are impacted nearly the same as California mussels (*M. californianus*) at the larval life stage, with California mussels being slightly more impacted, but no data was available for California mussels at the juvenile/adult stage. These results imply that on average, shellfish stakeholders in the south face greater risk of consequences in terms of OA impacts on species growth, no matter which species or life stages are being relied on.

Table 2-2 | Estimated growth declines of shellfish species at larval (L) and juvenile/adult (JA) life stages from visualizing modeled OA exposure (Ωar) in three sub-regions of the Pacific Northwest between 1995-2050. Life-stage specific responses reported correspond with three types of exposure to OA shown in the geovisualization tool: mean Ωar climate, mean of hotspots Ωar ≤ 1.4, and change in mean Ωar climate between 1995-2050. Mean Ωar values were calculated as 30-year averages. Aragonite saturation state = Ωar.

Species		**Sub-region**	**Life stage-specific growth responses to OA (% change in growth from pre-industrial Ωar)**					
			Baseline Ωar		**Extremes (Ωar ≤ 1.4)**		**Change over time (ΔΩar)**	
Oysters			L	JA	L	JA	L	JA
	C. gigas	Washington	-2.1%	-9.2%	-10.0%	-34.3%	-1.8%	-7.2%
		Oregon	-4.4%	-17.7%	-10.3%	-34.9%	-1.8%	-6.4%
		California	-8.0%	-29.1%	-11.1%	-36.8%	-2.1%	-5.8%
	O. lurida	Washington	-5.0%	-1.1%	-7.0%	-4.7%	-0.5%	-1.0%
		Oregon	-5.7%	-2.3%	-7.1%	-4.8%	-0.5%	-0.9%
		California	-6.6%	-4.0%	-7.2%	-5.1%	-0.5%	-0.8%

Table 2-2 (Continued) | Estimated growth declines of shellfish species at larval (L) and juvenile/adult (JA) life stages from visualizing modeled OA exposure (Ωar) in three sub-regions of the Pacific Northwest between 1995-2050.

Species	**Sub-region**	**Life stage-specific growth responses to OA (% change in growth from pre-industrial Ωar)**					
		Baseline Ωar		**Extremes (Ωar ≤ 1.4)**		**Change over time**	
Mussels		L	JA	L	JA	L	JA
M. galloprovincialis	Washington	-3.8%	-5.3%	-21.9%	-20.8%	-4.0%	-3.4%
	Oregon	-9.0%	-9.7%	-22.4%	-21.2%	-4.1%	-3.5%
	California	-17.2%	-16.8%	-24.3%	-22.9%	-4.8%	-4.2%
*M. californianus**	Washington	-5.2%	–	-22.3%	–	-3.8%	–
	Oregon	-10.1%	–	-22.8%	–	-4.0%	–
	California	-17.9%	–	-24.6%	–	-4.6%	–

*Data was not available for *M. californianus* at the juvenile/adult life stage.

Over time, comparing 1995-2025 with 2020-2050, change in growth decline is projected to be greater in the south for all species at the larval stage, and for juvenile/adult *M. galloprovincialis*. Change in growth decline of all other species at the juvenile/adult life stage is greater in the north. Between life stages, juveniles/adults are more impacted than larvae. Between species groups, mussels are more impacted than oysters, especially in the south, while oysters are more impacted in the north. These results imply that over time, stakeholders reliant on larval shellfish (e.g. hatcheries) in the south face greater difficulty in successfully producing larvae in untreated water due to more extreme OA conditions in the south. Additionally, stakeholders reliant on juvenile/adult shellfish (e.g. nurseries and farms) in the north face increasingly longer production times to grow juvenile shellfish to planting size and to grow adult shellfish to harvest size due to faster rates of change in OA in the north.

2.3.2. Sensitivity

Results of geovisualization showed that socioeconomic sensitivity is greatest in the north, with most certified shellfish shippers per capita present in Washington state and the northern Oregon coast. Cultural sensitivity appears to be predominantly split between the presence of First Nations tribes in the north (i.e. Washington state) and the south (i.e. southern Oregon coast and Northern California). These results imply that adaptation planning efforts may seek to prioritize both economic and non-economic values in the north and south while adaptation planning in the central region of the Pacific Northwest may benefit from prioritization of economic values. However, this study cautions that relatively fewer tribes in the central Pacific Northwest may be indicative of historical oppression of indigenous populations, so future studies should aim to better understand adaptation requirements of First Nations people in the central PNW before assuming that economic values should be prioritized.

2.3.3. Combined Risk

Overall, the OA risk profile of Washington state may present the most challenging adaptation problem not only because OA conditions are projected to change most rapidly there, but also because of the relatively high societal importance of shellfish for both socioeconomic and cultural purposes. The projected decline in aragonite saturation state over a 30-year period in Washington state suggests that stakeholders reliant on larval mussel species could adapt by switching species to oysters (*C. gigas* or *O. lurida*) before 2050 in part because of relatively better growth of oysters in less saturated conditions (Fig. 2-4, a). In Oregon, a switch from *C. gigas* to

O. lurida larvae may occur after 2050, or when aragonite saturation state conditions are projected to average around Ωar = 1.7 (Fig. 2-4, b). However, Oregon appears to exhibit higher socioeconomic reliance on shellfish than cultural reliance, so shellfisheries could be slower to switch to *O. lurida* over *C. gigas* because the shellfish industry favors the larger size and overall faster growth of *C. gigas* from spawn to harvest. In Northern California, OA exposure is already intense enough at present to perhaps merit a switch from *C. gigas* to *O. lurida* larvae. Relatively high cultural reliance on shellfish in Northern California could indicate that such adaptation efforts to promote native *O. lurida* restoration and habitat enhancement might be supported by local Indigenous tribes. Switching from *C. gigas to O. lurida* in Northern California could perhaps create a win-win for economic users as well, if the investment to switch species today pays off in later decades in a more intensified OA climate where the impact of OA on larval growth becomes more noticeable between species (Fig. 2-4, c). Switching to *O. lurida* may be especially advantageous for the south because *O. lurida* shows very little negative response to OA (Waldbusser et al., 2016). These results provide insight into regional and local risk profiles to OA, but further work with communities on the ground would be needed in order to validate these patterns and to assess how current and future impacts may influence adaptation decisions and feasibility amidst the compounding influence of OA on local contexts, including social, economic, institutional, legislative, and technological factors.

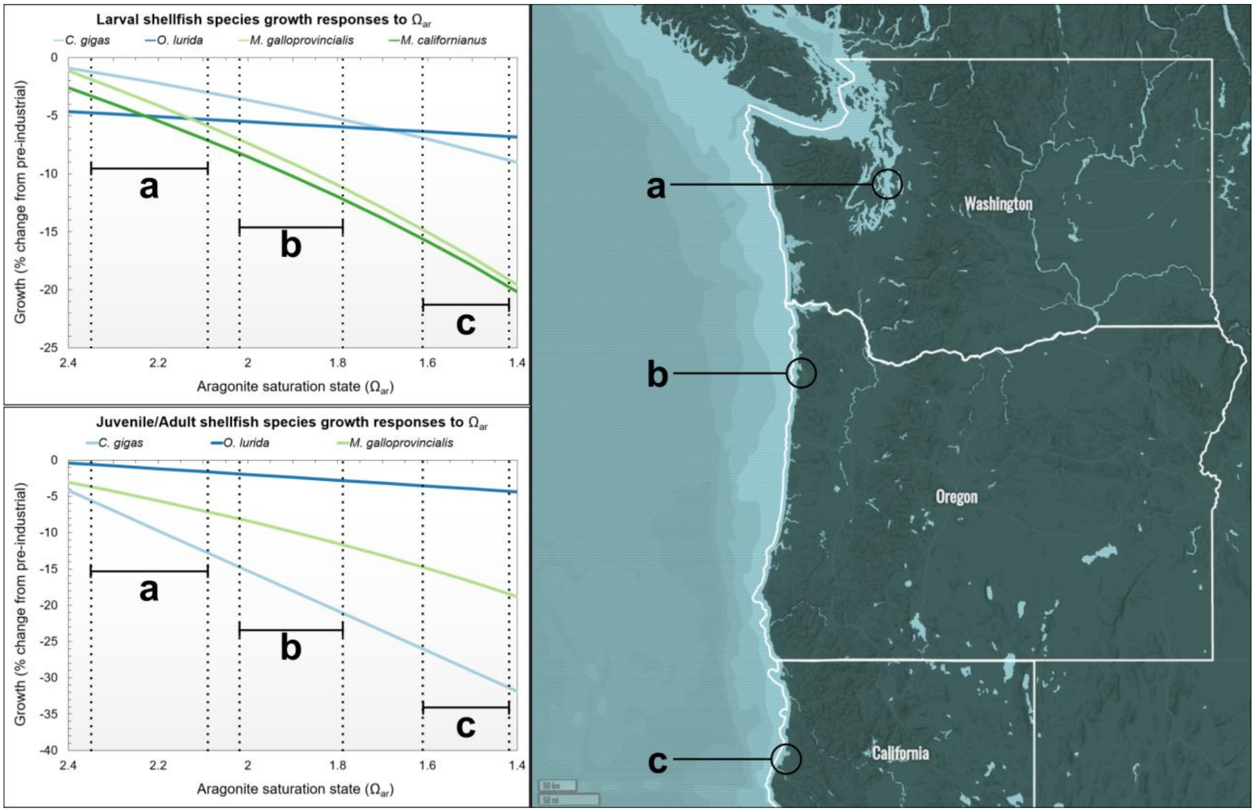

Fig. 2-4 | Projected impacts on shellfish species at different life stages across three locations in the PNW between 1995-2050. a–c, Dashed lines indicate projected changes in OA climate (Δ 30-year mean Ωar) for representative watersheds in PNW states: Washington (a), Oregon (b), California (c).

2.3.4. Robustness of analysis

This geovisualization of projected OA hotspots and associated species responses in a computationally-efficient web interface allows for rapid assessments of spatiotemporal risk. However, size limitations for hosting, filtering, and rendering data on the web meant that the data and information communicated by the geovisualization tool had to be reduced and simplified. Although this simplification allows the geovisualization tool to supplement or enhance communication and understanding of complex problems to wide audiences, the tool cannot fully replace knowledge generated from computationally demanding impact models (Monier et al., 2018).

Although the model used in this study was the best model to represent OA exposure in coastal environments of the Pacific Northwest due to its inclusion of the upwelling effect present in the California Current, it is still very difficult to model OA exposure on a regional scale with specific relevance for local intertidal zones where shellfish actually reside. Estuarine environments are dynamic, as conditions may be impacted locally by multiple factors, both natural (e.g. wind, waves, tides) and human-driven (e.g. excess nutrient loading, sedimentation, industrial pollution). Not accounting for other environmental variables besides aragonite saturation state in the geovisualization may have under- or over- estimated OA hotspot intensities; for example, variations in temperature and salinity can mask the expression of OA (Salisbury & Jönsson, 2018). Therefore, OA projections and corresponding species responses reported in this study represent only a relative snapshot of how conditions may vary across the region but should not be used as definitive predictions for how local OA conditions and shellfish growth might actually change over time.

A limitation of the social sensitivity analysis was that the spatial overlay for cultural sensitivity included point centroids for reservation land, but this does not clearly show tribes with land in multiple watersheds, nor does it recognize historical territories of First Nations people. Additionally, there are some First Nations populations who are not represented on the map at all due to insufficient data on federally unrecognized tribes. Another limitation was that the socioeconomic sensitivity map layer does not clearly account for shellfish-reliant populations who harvest shellfish for subsistence and not for economic production, nor does it account for the number of people employed either full-time or seasonally by certified shellfish shipper firms. This analysis and geovisualization would be more robust if data were included on unrecognized tribes, subsistence reliance on shellfish, and employment by shellfish producers. Furthermore, differences in social contexts across geographies may also influence shellfisheries' risk to OA, and it is unknown how social contexts may change over time. Findings of this study can only speak to relative risk, not predictions.

2.4. Discussion

For shellfisheries in the Pacific Northwest facing OA risk, the rate of change in extremes presents a different adaptation problem than the magnitude of extremes. Starting with low-aragonite baselines means adjusting to some intensification of extremes, but the more challenging problem may be the rate of change in extremes (Pacella et al., 2018) because a shellfishery might pass through multiple thresholds only a few years after adapting. This underscores the need for rapid and flexible responses to impacts (Miller et al., 2018). Knowing the baseline OA climate and how fast conditions are projected to change for a location may facilitate adaptation planning with stakeholders around adapting to local patterns of exposure.

At a global level, decreasing OA risk over time may only be possible through reduced fossil fuel emissions and uptake of carbon dioxide from the atmosphere. Without drastic changes in societal reliance on carbon emissions, adaptation to OA may become increasingly difficult and expensive, especially in places where the rate of change in OA is high. At a local level, decreasing OA risk may be possible through improvements in watershed stewardship aimed at reducing local OA amplification. However, the successful implementation of watershed management plans may ultimately depend on local contexts and how communities wish to prioritize values around reliance on shellfish and other watershed industries.

The methods presented in this paper may be applied in future studies using alternative models of ocean acidification at various spatial and temporal scales, or by incorporating alternative species responses to ocean acidification at different life stages. An expected outcome of sharing the open-source code used for the geovisualization in this study is to expedite training and capacity building of researchers looking to implement similar visualization tools for decision makers in other global initiatives (Bax et al., 2019). By building on the geovisualization framework presented in this study, future research may couple data on downscaled climate projections with data from the large and growing network of observational monitoring systems to improve understanding of regional processes, and to share findings open-source (Barth et al., 2019). The geovisualization developed in this study is accessible online at https://briangkatz.github.io/oa/vulnerability/pnw/.

3. ADAPTIVE CAPACITY OF PACIFIC NORTHWEST SHELLFISHERIES TO OCEAN ACIDIFICATION

Abstract

To inform decisions about how and where to invest in adaptation to OA, this study aims to identify OA triggers at other shellfish life stages that prompt adaptive actions. Specifically, it investigates what adaptation measures can be taken at key production stages, and what barriers to adaptation prevent successful adaptation. Interviews were conducted with shellfish-reliant stakeholders across the Pacific Northwest. Interviewees were classified into watershed groups and asked to identify problems at each shellfish life stage groups (larvae, juvenile, adult). Themes coded from interviews were used to identify barriers and develop an adaptation pathway for stakeholders reliant on shellfish at all life stages. Results indicate that despite improvements in seed production, the combination of OA and industry consolidation is leading to seed access problems, a notable barrier reported by shellfish producers; and suggest that adaptation investments should make explicit efforts to ensure benefits are distributed equitably across affected stakeholders in order to avoid lifting barriers for some while exacerbating barriers for others.

3.1. Introduction

To successfully navigate the negative impacts of climate change, such as the impacts of OA on shellfisheries, adaptation measures will be necessary, and as impacts worsen and accumulate over time, decision makers will have to plan for the succession of multiple measures that will be necessary – adaptation pathways (Wise et al., 2014; Eisenhauer, 2016; Bloemen et al., 2017; Dias et al., 2020). Adaptation pathways are a sequence of strategies, each triggered by specific moments of environmental change that result in locally-important social impacts (Barnett et al., 2014; Eisenhauer, 2016; Dias et al., 2020). These adaptation triggers and strategies are identified proactively, and co-developed by diverse stakeholder groups, with the aim to build consensus around low-risk, low-cost decisions to preserve options for future generations (Barnett et al., 2014; Dias et al., 2020). Adaptation options are plentiful for stakeholders in aquaculture, and may include changes in management, biotechnology investments, or even relocation (Reid et al., 2019b). Although adaptation options may exist, implementing them may not be technologically or financially feasible for all stakeholders (Geyer et al., 2015; Singh, C. et al., 2020). Feasibility may be a more important factor than desirability when it comes to adaptive decision-making (Deng et al., 2017). Evaluating the barriers that prevent adaptation actions is important in the development of adaptation pathways so that stakeholders may manage their expectations on the feasibility and sustainability of adaptation strategies under future climate scenarios (Friedman et al., 2020; Singh, C. et al., 2020). At every decision point along an adaptation pathway, multiple trade-offs must be considered across sectors prior to implementation of strategy changes (Hansen et al., 2019; Wiréhn et al., 2020). In order to identify place-based adaptation priorities and levers for action, it is important to understand how local communities are affected by climate change impacts in the context of other economic and political factors that have influenced the local environment (Groulx, 2017), social and institutional dynamics (Rocle et al., 2020), and the available resources that form the basis for adaptive action (Cinner et al., 2018). To avoid exacerbating inequalities, successful adaptation plans must respond to communities' historically embedded contexts across social, cultural, and political domains, and engage with changes in both ecological and social systems (Ensor et al., 2018). The risk is that uneven access and allocation in adaptation action can accelerate inequality (Chen et al., 2018; Pelling & Garschagen, 2019; Grecksch & Klöck, 2020).

3.1.1. Limits and barriers to adaptation

The Intergovernmental Panel on Climate Change (IPCC), in their fifth assessment report, distinguished between limits to adaptation as "points at which an actor's objectives or system's needs cannot be secured from intolerable risks through adaptive actions", and barriers to adaptation as "factors that make it harder to plan and implement adaptation actions or that constrain options" (IPCC, 2014). These concepts are relevant to the formation and navigation of adaptation pathways because limits represent immutable factors that must be considered in planning and decision making processes, and barriers represent mutable opportunities that can be overcome, avoided, or reduced by individual or collective action with concerted effort, creative management, changed ways of thinking, political will, and reprioritization of resources, land uses and institutions (Moser & Ekstrom, 2010). Studies on barriers to adaptation in specific communities have identified several families of barriers, including: social (Matasci et al., 2014; Hinkel et al., 2018), economic/financial (Hinkel et al., 2018; Clissold et al., 2020), institutional (Matasci et al., 2014; Stuart & Schewe, 2016), legislative/political (Matasci et al., 2014; Serrao-Neumann et al., 2014), and technological barriers (Matasci et al., 2014; Barnett et al., 2015). In addition to the identification and classification of barriers, research has called for actor-centric approaches that provide meaningful frameworks to help explain and overcome barriers (Eisenack et al., 2014). Furthermore, identifying interdependencies of barriers has been suggested to help inform well-designed interventions that simultaneously address multiple related barriers (Eisenack et al., 2014).

3.1.2. Shellfisheries in the Pacific Northwest

This study focuses on adaptation pathways for Pacific Northwest shellfisheries facing ocean acidification (OA) impacts on four shellfish species at larval and juvenile/adult life stages: *Crassostrea gigas* (Pacific oysters), *Ostrea lurida* (Olympia oysters), *Mytilus galloprovincialis* (Mediterranean mussels), and *Mytilus califonianus* (California mussels). For decades, the PNW has been recognized as an OA frontline with deep ocean water presently approaching a threshold for near-permanent undersaturation with respect to aragonite, the mineral form of calcium carbonate which bivalve species use for shell-building (Hauri et al., 2013; Barton et al., 2015; Ekstrom et al., 2015; Waldbusser et al., 2015). As such, federal and state agencies have directed adaptation efforts towards shellfish aquaculture, with the recognition that the policy environment, capacity-building, and adaptation planning efforts can improve the social-ecological benefits of shellfish aquaculture in the region (Theuerkauf et al., 2019).

3.2. Adaptation pathways in shellfisheries

In the mid-to-late 2000's, the region experienced a now-classic case of adaptation to OA at the Whiskey Creek Shellfish Hatchery in Netarts Bay, Oregon, where extremes in seawater chemistry caused unprecedented larval mortalities. The resulting production failures represented a serious threat to seed supply for the regional shellfish industry that supports $270 million in economic activity and over 3,000 family wage jobs in rural areas (Barton et al., 2015). Initially, the mortality events of the seed crisis were attributed incorrectly to pathogenic blooms of *Vibrio tubiashii* (Barton et al., 2015), for *Vibrio* bacteria grow and persist in relative abundance under hatchery conditions compared to their natural abundance in bay water (Gradoville et al., 2018).

The seed crisis triggered a series of responsive adaptation investments on continuous water monitoring of carbonate chemistry at the Whiskey Creek Shellfish Hatchery, and fomented a partnership between industry, scientists, and policy makers (Barton et al., 2015). Monitoring data and biological experiments at the hatchery revealed that larval mortalities during the seed crisis corresponded with successive years of exposure to low-aragonite saturation state extremes, attributed to amplified OA from seasonal upwelling on the coastal shelf (Feely et al., 2008; Harris et al., 2013; Hauri et al., 2013; Barton et al., 2015). Whiskey Creek Shellfish Hatchery was not the only location that experienced production failures from OA during the seed crisis, and the relative contribution of local amplifying factors and social contexts likely varied across geographies to produce differential impacts on shellfisheries.

Adaptation strategies implemented in response to the seed crisis have been heralded as successful in restoring production and livelihoods across the Pacific Northwest; however, key challenges remain in expanding capacity of hatcheries, monitoring carbonate chemistry of coastal waters, and improving understanding of biological responses (Barton et al., 2015). Further gaps remain in understanding how the seed crisis and responsive adaptation strategies affected stakeholder livelihoods, and how social vulnerability to OA may be understood given stakeholders' current and future exposure to ocean acidification, social reliance on shellfish species responsive to OA at different life stages, and capacity for adaptation strategies to be implemented.

3.2.1. Adaptation planning

In the decade following the seed crisis, the states of Washington, Oregon, and California have all designed action plans aimed at reducing and preparing for impacts from ocean acidification. These plans recommend strategic actions and opportunities for prioritized investments to address OA, such as: monitoring, open access information tools, knowledge sharing, stakeholder engagement, reduction of land-based factors contributing to OA, native shellfish and seagrass restoration, and support for installing and maintaining technologies in at-risk locations (Washington State Blue Ribbon Panel on Ocean Acidification, 2012; California Ocean Protection Council & California Ocean Science Trust, 2018; Oregon Coordinating Council on Ocean Acidification Hypoxia, 2019). "Knowledge-to-Action Pipelines" have been formed in recent years to build up evidence, mutual trust, and consistent communication practices on ocean acidification across scaled networks of stakeholders (Cross et al., 2019). Ideally, networks in a knowledge-to-action pipeline coordinate to produce actions that reduce future impacts from OA on coastal communities, and to narrow the gap between scientific research and actionable decision-maker support products; however, obstructions exist in the scalability and prioritization of action plans developed by knowledge-to-action pipelines due to differences in local context and difficulty in balancing multiple stakeholder priorities (Cross et al., 2019). While these plans have the potential to enhance social capital by increasing participation of and fostering collaboration between stakeholders, there also exists the possibility that adaptation plans may inadvertently undermine social capital through shifts in power structures and resource access (Hagedoorn et al., 2019). Additionally, the evaluation of adaptation plans implemented to address ocean acidification impacts should account for potential feedback processes on both natural and human systems (Brousselle & McDavid, 2020).

3.2.2. Stakeholder perspectives on adaptation

Although scientific capacity for risk assessments in the Pacific Northwest is relatively high, resources are unevenly distributed across the region and some vulnerable communities are insufficiently studied. Decision-makers are therefore left with inadequate access to existing knowledge from vulnerable stakeholders, perhaps as a result of insufficient networking and exchange between experts due to cultural, political or language barriers (Cramer et al., 2018). Understanding how shellfish stakeholders themselves perceive the resource, OA-related issues, and changes in resource availability, forms the basis for developing potential management options or adaptation strategies that will have the support and buy-in from local communities (Bulengela et al., 2020). Even if public perceptions are in favor of generally implementing adaptation strategies, a barrier to implementation of a specific strategy for shellfish stakeholders, such as the expansion of species beyond their native ranges, may be encountered through social controversy around what risks really matter to the public (Hagerman & Kozak, 2018).

Forward-thinking assessments of vulnerability and adaptation planning should account for likely changes in the future when engaging stakeholders to ensure that results are rooted in local realities (Cochrane et al., 2019). A values-driven assessment can meaningfully engage community members and effectively add their knowledge and values into the adaptation planning process, ensuring that community members and others are working toward common goals, and establishing agreement around intended outcomes/results (Campbell & Trousdale, 2020). If place-based populations face difficulty in identifying and formulating common outcomes during adaptation planning because of differences in human needs at the individual level, then those populations may become vulnerable to dominant or new industrial interests in the place-based resource system (de Schutter et al., 2019).

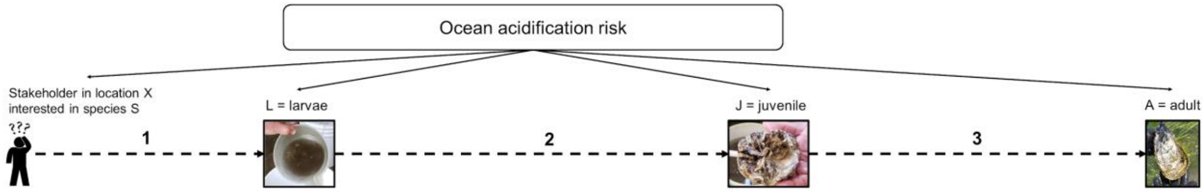

Fig. 3-1 | Conceptualization of a shellfish stakeholder considering the process to produce larvae, juvenile, and adult shellfish amidst ocean acidification risk. Multiple pathways could be taken by a person who is interested in acquiring larvae (1), juvenile (2), or adult (3) life stages of shellfish for purposes such as livelihoods, subsistence, ceremonies, or habitat enhancement. Ocean acidification risk can be a compounding influence on social, economic, demographic, political, and environmental drivers which affect human decision-making (Black et al., 2011). Decisions made for each life stage may also see variable outcome success due to the compounding effect of ocean acidification risk on shellfish growth rates (Appendix G Table G-1).

3.3. Methods

The goal of this study was to identify the adaptation triggers that prompt actions (Barnett et al., 2014) by interviewing stakeholders reliant on shellfish at different life stages across coastal watersheds with differential risk profiles to OA. To achieve this goal, this study conducted mixed-methods interviews with shellfish-reliant stakeholders to answer the question: **Considering the range of options for adaptation to OA, what are the barriers preventing successful adaptation at key production stages?** Adaptive capacity varies among stakeholders affected by OA impacts on shellfish species at different life stages, so we expect the barriers to develop and implement adaptation strategies to also be different among them (Fig. 3-2).

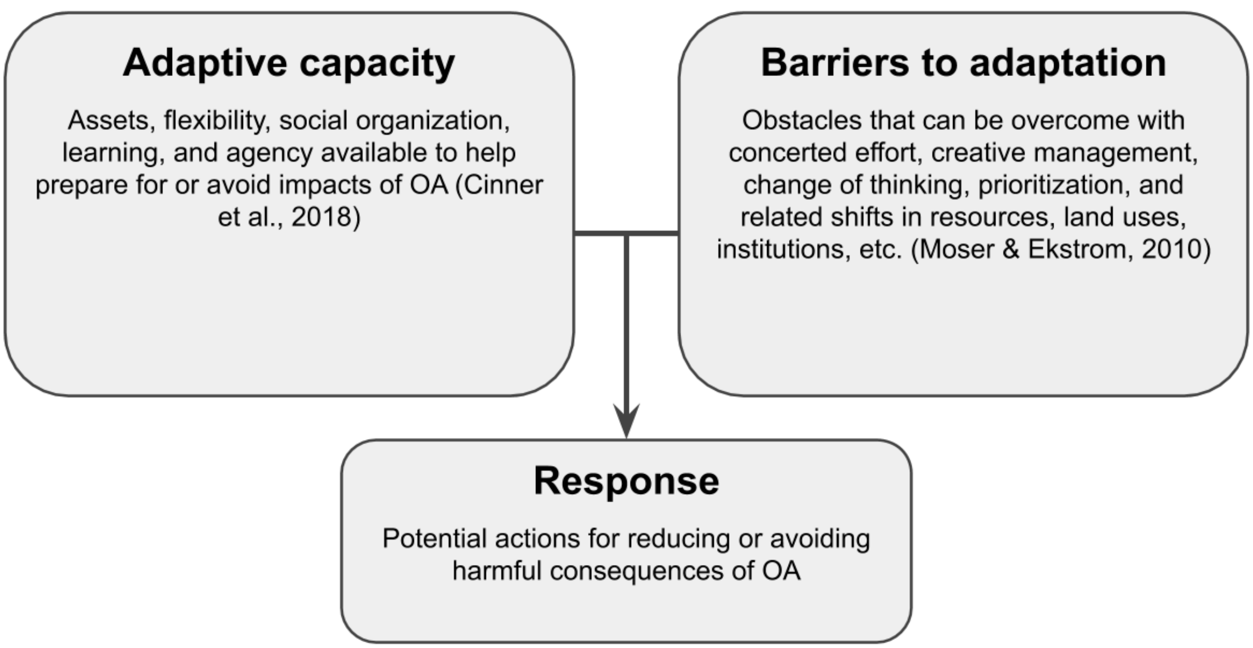

Fig. 3-2 | Conceptual framework for this assessment of adaptive capacity and barriers to adaptation. Conceptual model components were adapted from Ekstrom et al., 2015 and Jamshidi et al., 2019.

3.3.1. Sampling and recruitment

To answer the research question, this study modified frameworks for exploring different types of barriers to adaptation, and where they slow adaptation (Matasci et al., 2014) from an actor-centric perspective (Eisenack et al., 2014), by conducting interviews with stakeholders reliant on different life stages of shellfish. Sites for fieldwork were selected by using the geovisualization tool developed in Chapter 2 to identify watersheds with differential risk profiles to OA (Fig. 2-3). The scale of watersheds was chosen to facilitate place-based discussions on relevant social-ecological contexts that could inform adaptation efforts to overcome barriers at the local level (de Schutter et al., 2019).

Fieldwork resulted in a total of 46 interviews, conducted over two rounds of four trips each to six watershed groups across the Pacific Northwest between Jan-Apr 2019 and Jun-Aug 2019, respectively (Table 3-1). A list of potential contacts was gathered from data on licensed shellfish shippers in Washington (U.S. FDA, 2020; WA DOH, 2020), Oregon (ODA, 2020; U.S. FDA, 2020), and California (CDPH, 2020; U.S. FDA, 2020). Recruitment of participants was done through a combination of emails, phone calls, text messages, and in-person site visits, using the following recruitment script:

> "Hi [Name],
>
> My name is Brian, and I'm a graduate student researcher studying Geography at Oregon State University. I study the human dimensions of climate change, and I'm currently working on a research project focusing on Pacific Northwest shellfisheries' risk and adaptation to ocean acidification. Please see attached flyer (Appendix B) and explanation of research (Appendix C).
>
> I'm reaching out to see if you and about three others would be interested in participating in a mapping exercise and small group discussion around ocean acidification (OA) risk factors in the [Watershed name] watershed. Basically, I'll be asking folks to individually mark X's on maps where OA risk factors such as harmful algal blooms (HABs) have been observed to impact shellfisheries in the [Watershed name] watershed (e.g. [Bay(s) included in watershed]), and then collectively the small group of participants will discuss possible explanations for the patterns that emerge around each risk factor, in addition to barriers to adaptation when problems have arisen before.

Participation would take between one to two hours, and I'll be staying in [Town] between [Dates of visit]. Please let me know if one of those days works for you, and I'd be happy to schedule a time. If you know anyone knowledgeable on watershed dynamics in [Bay(s) included in watershed], feel free to bring them along. Incentives for participating include your choice of: 1) one Oregon State University hooded sweatshirt, or 2) one meal (excluding alcohol) – each valued up to $30. You may reach me at [phone #] (text/call) if you have any questions or would like to participate.

Thank you for your consideration,

Brian Katz [email and phone #]"

Table 3-1 | Watersheds visited for stakeholder interviews.

Watershed(s)	**State**	***n***	**Population†**	**# Shellfish licenses‡**
Strait of Georgia-Nooksack*	Washington	5	906,863	35
Hood Canal	Washington	8	50,165	165
Puget Sound	Washington	10	1,662,292	427
Willapa Bay	Washington	9	19,675	108
Wilson-Trask-Nestucca	Oregon	10	19,727	15
Mad-Redwood	California	4	96,371	5

* Responses from the Strait of Georgia and Nooksack watersheds were combined in this analysis.
† Population per watershed calculated from a Zonal Statistics sum of gridded population estimates (SEDAC, 2020; USGS, 2020)
‡ # Shellfish licenses = interstate licenses + in-state only licenses (WA DOH, 2020; ODA, 2020; CPDH, 2020; U.S. FDA, 2020)

The researcher found that shellfish stakeholders were particularly elusive to contact, especially during the spring and summer when they were limited in time. For example, there were limited responses in recruiting for small group spatialized interviews held at major towns, and this led to a change in course in recruitment. By the second round of fieldwork trips conducted in the summer, the researcher was doing the work of traveling to the stakeholders themselves to conduct interviews rather than relying on a group of stakeholders to collectively take off time to travel away from their place of work to participate in research activities. The results of this change were positively received for the most part, with a notable number of stakeholders reporting that scientists and policymakers do not often meet them where they are to see what they do in person. Overall, the in-person experiences with stakeholders helped facilitate a more actor-centric understanding of risk, barriers, limits, and adaptation options reported by individual and collective human experiences (Eisenack et al., 2014).

3.3.2. Survey methods

The initial goal for fieldwork was to use the geovisualization tool developed in this study for engaging stakeholders in focus group discussions on validating risk and identifying barriers to adaptation associated with local patterns of OA exposure and sensitivity. Fieldwork began before the geovisualization tool was functional for focus group activities. Therefore, it was decided that stakeholder feedback on the tool would be collected in fieldwork, but that the tool would not be used in mapping exercises as initially designed. Alternatively, fieldwork activities were split between small group spatialized interviews and semi-structured expert interviews.

For the small group spatialized interviews (Appendix D), participants were asked to mark X's on a series of maps where reported OA risk factors may have caused problems for shellfisheries in the past; additionally, a timeline of months on each map was marked by participants to show both the range of months (circled) and peak month (indicated by a triangle) when the OA risk factor is or has been potentially problematic for shellfisheries (Appendix D, Fig. D-1). For each X marked by participants, two scores were reported on a three point scale (low=1; medium=2; high=3), representing the intensity and frequency of impacts on shellfisheries (i.e. how many stakeholders the problem affected, and how often the problem affected stakeholders). After participants were finished mapping the locations and likely timeline of each OA risk factor, group discussions would follow each map to provide contextual descriptions of how problems for shellfisheries manifest from each risk factor. Altogether, the data collected from these small group spatialized interviews included information on where, when, and how problems related to OA may be amplified by risk factors present in watersheds where shellfish are grown. Stakeholder feedback on the mapping exercises was not always well-received due to sensitivities associated with mapping problems related to other watershed actors. To alleviate stakeholder concerns, emphasis was placed back on the discussion over the mapping itself. As a result, this study chose to report primarily qualitative data collected in the small group spatialized interviews rather than reporting geospatial data collected with mixed success across participants.

For the semi-structured expert interviews (Appendix E), participants were asked open-ended questions on the most impactful problems which affect human reliance on shellfish in their local watershed, and which may trigger adaptation responses, or switching strategies. Participants were then asked about perceived barriers which may prevent adaptation in problematic trigger moments, and to discuss potential opportunities to overcome barriers through concerted efforts (Moser & Ekstrom, 2010). Participants were given the prompt, “Barriers are any type of challenge or constraint to economic or cultural reliance on shellfish that prevents adaptation but can be overcome.” Then participants were asked, “What sort of barriers would you imagine? Are they limited to specific places? How important are these barriers to overcome if we’re going to successfully adapt (i.e. high importance, medium importance, low importance)?” Examples of barriers prompted included: regulations or zoning, exclusive contracts and market relations, capital to acquire existing technology, training to implement existing technology, traditional practices, and traditional reliance (i.e. cultural reliance). On feasible adaptation pathways, participants were asked, “When problems have arisen in the past, what sources of adaptive capacity were available to help reduce or avoid harmful consequences?” Examples of adaptive capacity prompted included: assets, flexibility, social organization, learning, and agency (Cinner et al., 2018). Additionally, participants were asked about perceived limits which cannot be overcome through actions. And finally, participants were asked to describe what actions or adaptation options they could take at the larvae, juvenile, and adult life stages to successfully adapt to ocean acidification over time, given the barriers and limits to adaptation previously described.

3.3.2. Coding and analysis methods

Fieldwork notes from discussions and interviews were collected in a spreadsheet. Transcriptions and notes from each interaction with stakeholders were reviewed one by one, and running lists of themes identified on barriers, limits, and adaptation options were compiled into a codebook used for identifying themes in subsequent interview notes (Appendix A, Table A-1). Depending on similarity, some coded themes were refined or combined after reviewing all the interview notes at least five times using the codebook. Barriers to adaptation were classified as social, economic/financial, institutional, legislative/political, or technological. Limits to adaptation were classified as related to temperature, acidification, and sea level. Adaptation options were classified as related to the larval, juvenile, or adult life stages.

Frequencies were calculated as the mean reporting average of participants mentioning each barrier, limit, and adaptation option by summing the number of stakeholder responses mentioning each theme by the total number of stakeholder responses. This was done to calculate overall frequencies among all participants, as well as frequencies per watershed group.

Finally, adaptation options coded from interviews were used to create a human-centric adaptation pathway to ocean acidification, represented as a series of decision-making moments, organized around each life stage along the production cycle: larvae, juvenile, and adult (Fig. 3-1). Frequencies calculated from reported adaptation options were used to create weighted arrows in Figs. 3-4—3-6, showing the estimated mean likelihood of stakeholders choosing each pathway. In this conceptualization of adaptation pathways, ocean acidification risk may influence decision-making processes as adaptation options are weighed out by people. Additionally, ocean acidification risk may impact organismal growth rates at each step. Taken together, OA risk represents a driver for both decisions of shellfish stakeholders and outcomes of species growth at each life stage in the production cycle. OA risk may influence — but not necessarily cause — how a person chooses between pathways, and how species life stages grow as a result of the decisions made by shellfish stakeholders. The purpose for using an actor-centric approach was to highlight the range of adaptation options available to stakeholders at each stage of the shellfish production process, and to highlight the particular points along the pathway where limits and barriers to adaptation may constrain the feasibility of certain decisions, in order to inform more effective adaptation efforts to overcome barriers (Eisenack et al., 2014).

3.4. Results

This study found that for shellfish stakeholders adapting to ocean acidification in the Pacific Northwest, the most difficult barriers to overcome at key production stages are operational costs, access to seed, industry consolidation, employment problems, and insufficient management of water quality (Table 3-2). While stakeholders with the most assets may be able to navigate around barriers to adaptation more flexibly than smaller stakeholders, the smallest stakeholders may be most constrained in their available options due to lack of resources to invest in new technologies, or due to the presence of barriers that cannot be overcome without legislative intervention. Insufficient seed production was the first trigger for legislative action on OA, in which technological barriers were lifted at select shellfish hatcheries that received support for monitoring, buffering, and scientific research. In spite of improved seed production resulting from adaptation to the first trigger, this study asserts that the second trigger for legislative action on OA in the PNW may now be around the challenge of natural recruitment, the demand for seed, and insufficient access to seed. These findings have implications for adaptation in local populations sensitive to OA impacts on shellfish species at different life stages. If steps are not taken to resolve these uneven adaptation triggers and responses, it is reasonable to expect that OA will contribute to a consolidation of an increasing share of shellfish production by a smaller number of industry actors. A shellfish stakeholder in the Hood Canal watershed explained:

> "[The biggest actors] want people to not sustain anymore. That's the tragedy. They're trying to put small businesses out. Everything will be [only a few large businesses] one day."

The following sections 3.4.1.—3.4.2. will discuss barriers and limits to adaptation identified from interviews. Afterwards, sections 3.4.3.—3.4.6. provide detail on the most frequent adaptation options that stakeholders reported for each life stage in the shellfish production cycle. Decision trees are used in Figs. 3-6—3-9 to highlight how adaptation barriers and limits may affect the feasibility of choices, and the success of outcomes, for stakeholders navigating ocean acidification risk.

3.4.1. Barriers to adaptation

Interviews revealed a total of twenty-two barriers to adaptation which were categorized as social, economic/financial, institutional, legislative/political, or technological barriers (Table 3-2). The most impactful barriers reported, with respect to ocean acidification risk, and for which policy interventions should prioritize, were access to seed and industry consolidation. As OA degrades self-sufficiency of seed production through impacts to natural recruitment and species growth, shellfish stakeholders are increasingly constrained into having to purchase seed from few hatcheries, and access to seed becomes a problem when hatcheries prefer to keep surplus seed in-house for their own growing operations. To overcome these barriers, policymakers could support the development of cooperative hatcheries. The implication of a cooperative hatchery is that ownership of seed produced could be allocated equitably across multiple stakeholder groups who buy in, including — but not limited to — shellfish producers, tribes, academics, resource managers, and non-profit organizations. However, it is unlikely that a "one-size-fits-all" solution exists for overcoming shellfisheries' barriers to adaptation to OA. It is important to note that adaptation strategies appropriate for one watershed may not be appropriate for another due to differences in the contextual factors relating to how stakeholders reported barriers across different places (Fig. 3-3).

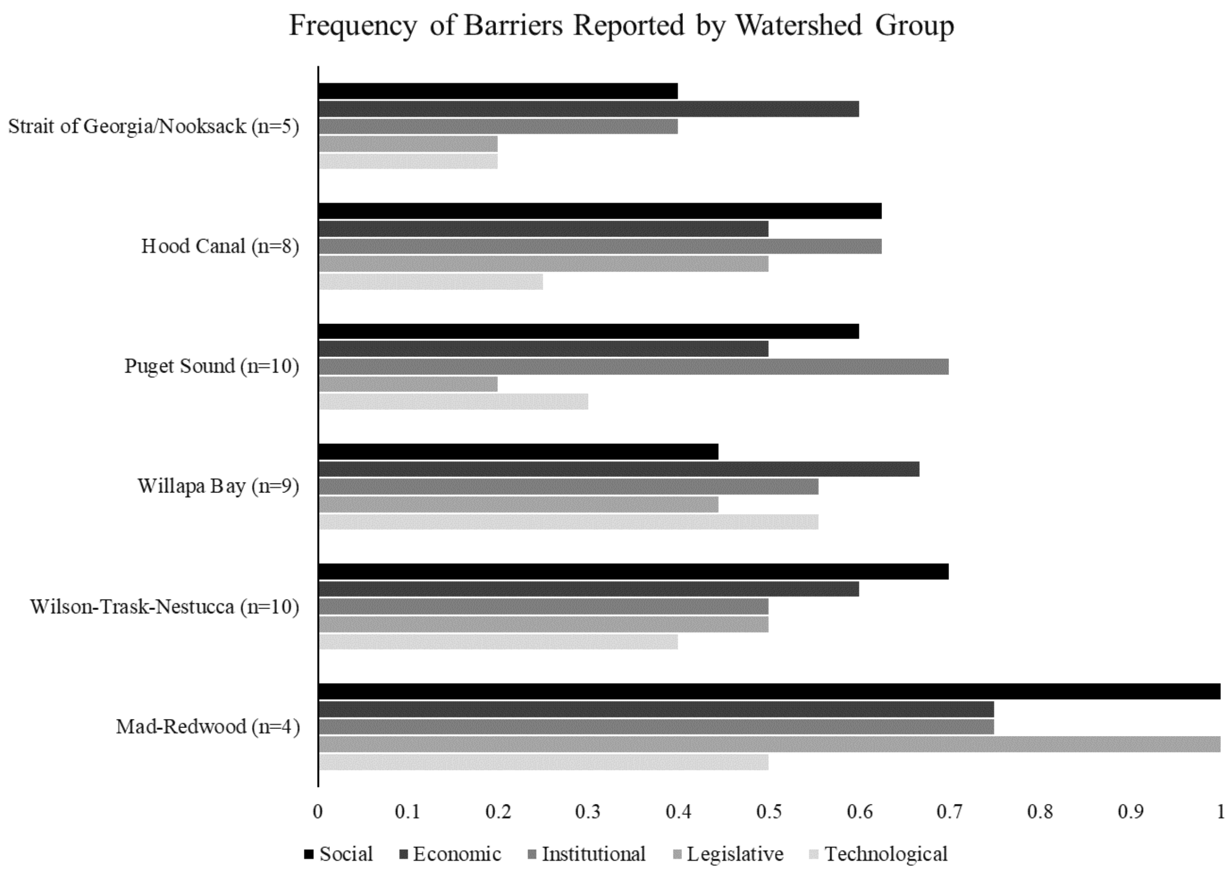

Fig. 3-3 | Categories of barriers to adaptation reported in stakeholder interviews by watershed group. Semi-structured interviews were performed with stakeholders across six coastal watershed groups of the Pacific Northwest (n=46).

The following text highlights notable barriers for each category, offers opportunities to overcome them, and discusses implications of doing so for equitable adaptation planning. After introducing each barrier category, contextual similarities and differences between watershed groups visited are discussed.

Table 3-2 | Self-reported barriers to adaptation identified from stakeholder interviews (n=46). *Mean reporting across all participants.

Category	Barrier	Frequency*	Exemplary quotes
Social		61%	
	Insufficient long-term employees	37%	“It's easier to offer peace work to guys at a parking lot on the weekend to do extra work tasks quicker than some employees who would rather take off work early and hang out at the bar instead.”
	Insufficient communication, trust between shellfisheries and public, academia, government, and/or NGO's	35%	“People don’t listen to 99% of climate science because scientists aren’t aware of other people.” “A lot of people aren’t interested in science if it affects what they think or do, or their livelihoods.”
	Climate denialism, or a refusal to accept the possibility of anthropogenic impacts on the environment or shellfish	26%	“God has made this Earth and made it bulletproof. Whatever we do now doesn’t make an impact.”
	Conflicting claims between property owners	22%	“The challenge is educating private tideland owners who come in from all over the country. [New homeowners] are used to tidelands being independent elsewhere, but here you're sharing resources.”
	Place connection	22%	“My mental medicine is that I can watch the tide go out here and not say a word. It’s very healing.”
	Poaching	13%	"Someone stole $40,000 worth of oysters from me when I was out for a while due to a medical issue."
Economic/Financial		59%	
	Operational costs: financial, time, permitting, emissions, employee benefits, etc.	48%	“Every month I pay $20,000 and get back $10,000, so I lose every month. I am both the owner and an employee, and I do not have medical insurance.”
	Access to seed	41%	"Seed producers will prioritize their own company’s supply first, and they will only sell surplus seed they have to individuals or farms who are not on their blacklist. Seed availability is provided to those who are either playing nicest with the seed producers or are paying the biggest bucks to get their names higher up on the lists."
	Insufficient transparency on appropriation of funds by government or NGO's	22%	“I’m not a member of the shellfish grower’s association because aside from a class or conference, where does the money go?”
	Insufficient livelihood diversification options	15%	“We're all stuck in shellfish. There are not many other natural resource alternatives.”

Table 3-2 (Continued) | Self-reported barriers to adaptation identified from stakeholder interviews (n=46). *Mean reporting across all participants.

Category	Barrier	Frequency*	Exemplary quotes
Institutional		59%	
	Industry consolidation	39%	"[One company] has three seats on the board for the shellfish grower's association, and a lot of people think companies should only have one member on boards."
	Resistance to change by powerful industries or actors with lobbying influence in local politics	37%	"There's no way you're going to change the cow situation [here]. You got that big building over there that belongs to shareholders. No, you're not going to change that. Not going to happen. Too much money."
	Profits are prioritized over sustainability or living wages	30%	"My grandpa told me the difference between an oyster haver and farmer is that the haver whines about how to get rich while the farmer figures out how to do things the best way."
Legislative/Political		43%	
	Insufficient watershed co-management on nutrient inputs and factors that affect water quality (i.e. insufficient rules or rule enforcement)	30%	"Our water quality used to be looked at more heavily 20 years ago."
	Unclear regulatory overlap between local, county, state, federal, and tribal governments (i.e. unclear authority)	22%	"I operate in [four counties], and they all have different regulations. Imagine if you were going to a bunch of different churches all saying different things. Whose voice really matters?"
	Eelgrass limitations	22%	"[Agencies] are setting rules on eelgrass impacts, but for me it's a crazy thing that we're not supposed to grow in a certain place or proximity to eelgrass that's growing and evolving. There's a lot more eelgrass now than there was a long time ago when I started [growing shellfish] in my area. We're putting out structures in the bay which affects flow and currents across mud flats. If mud flats are barren [without structures] and eelgrass is present, the impact of wind and wave action would be so much more on eelgrass. But if structures act as barriers, eelgrass may survive in or around oyster areas where it normally may not."
	Poor management of species that prey on or outcompete shellfish	20%	"Ghost shrimp are the highest priority because they reduce feed. Ghost shrimp can wipe you out." "We still need a place to grow oysters, but shrimp take out habitat and food."
	Harvest restrictions	11%	"Ceremonially, if there's a funeral, someone has to go do it. People are put to work to go harvest. It's important to feed people for the event. If they know a closure is there, they might propose something different, but most people don't listen. Last summer, we were harvesting for an event, but closures were widespread in the region during that time."

Table 3-2 (Continued) | Self-reported barriers to adaptation identified from stakeholder interviews (n=46). *Mean reporting across all participants.

Category	Barrier	Frequency*	Exemplary quotes
Technological		37%	
	Insufficient information on sources of biotoxins and harmful algal blooms (HABs)	33%	"The information we've been pondering about is the amount of river flow in winter time. We take samples that show we may have X amount of fecal coliform, but we haven't been able to come up with flow times volume to determine which creeks are putting in more water [and biotoxins] than others."
	Insufficient monitoring for carbonate chemistry or biological impacts	11%	"We wouldn't be able to see growth responses here because we're not monitoring to that level of sophistication."
	Insufficient selection for OA-resistant or set-improving genes	11%	"We're looking at genetics for fast-growing shellfish, but we're not looking at OA-resistance."
	Insufficient locational accuracy of geospatial data on plat boundaries	7%	"Some employees use an app on their phones to track plat production, but the problem is that tidal ground moves and changes. Sometimes their app tells them their boundaries are actually within someone else's."

The most frequently reported categories of barriers to adaptation across all stakeholders were social and economic/financial barriers. This is supported by findings from similar studies on barriers to climate change adaptation in other sectors, such as tourism (Matasci et al., 2014) and coastal development (Hinkel et al., 2018), in which both cases argue that social and economic/financial barriers are most critical for legislative action to prioritize, especially in poorer and rural areas. The two most reported social and economic/financial barriers were insufficient long-term employees and operational costs, and these have clear interdependencies. Some of the smallest stakeholders cannot afford to pay many employees, and this creates an amplifying effect of increasing operational costs in terms of time spent completing day-to-day tasks over time spent completing permits or investing in new adaptation strategies. To overcome these barriers, policymakers could invest in technical college programs on shellfish aquaculture, or award scientific grants for shellfish stakeholders to partner with scientists. Investing in technical support could result in a “win-win” scenario, in which shellfish stakeholders receive additional support for day-to-day operations, while scientists receive opportunities to complete their research. This strategy may create new job opportunities, and could complement plans to develop cooperative hatcheries in local communities; however, the smallest stakeholders with the least representation must be given equal opportunities to participate, which could mean adaptation financing is needed if buy in is too costly.

Social barriers were reported most frequently in the Mad-Redwood, Wilson-Trask-Nestucca, and Hood Canal watersheds, but there were some differences in the specific barriers reported between these places. For example, participants in the Mad-Redwood watershed reported recurrent issues with finding and retaining long-term employees. One stakeholder in the Mad-Redwood watershed explained:

> “It’s hard to compete for employees in the fall when people would rather go up in the hills, trim bud, and hang out, making way more money for the cannabis industry.”

Another stakeholder in the Mad-Redwood watershed explained:

> “We used to employ a lot of ethnic labor. In the last seven or eight years, the Hispanic workforce cannot get work permits anymore. Ten or fifteen years ago, [migrants] could still obtain work permits even though it was a pain in the butt. Now, there's NO opportunity for someone here illegally to obtain a green card.”

In contrast, participants in the Hood Canal watershed reported frequent property disputes on tidelands. One stakeholder in the Hood Canal watershed explained:

> "A visitor comes up from [somewhere with public beaches], visiting a relative. They have got kids and dogs, and they think they have a right to be on the beach. Then someone like me comes out saying this is private property. I own down to low tide. You can't just go down and dig for clams here. Folks don't understand the definition of private anymore."

Furthermore, participants in the Wilson-Trask-Nestucca watershed reported connection to place and climate change denial as relevant social barriers to adaptation in their watershed. Reflecting on their place connection, one stakeholder in the Wilson-Trask-Nestucca watershed explained:

> "[Being out in the bay]…my office is more beautiful than anyone. In December, at sunrise, the water is like glass."

Showing a sense of refusal to accept climate change impacts on shellfish, another stakeholder in the Wilson-Trask-Nestucca watershed explained:

> "I've heard that in 50 years, there's not going to be an oyster. And I don't buy it. I think [oysters] are going to be around forever."

Economic barriers were most frequently reported in the Mad-Redwood, Willapa Bay, Wilson-Trask-Nestucca, and Strait of Georgia-Nooksack watersheds. While all these watersheds reported operational costs as frequent economic barriers to adaptation, there were some contextual differences in how costs were reported as problematic. Some stakeholders reported difficulties in affording the time off to invest in new strategies. One stakeholder in the Mad-Redwood watershed explained:

> "It costs $1,200 to apply for a boat captain's license. If you're doing 10% margin, you have to sell $12,000 worth of oysters to afford it. At $0.50/oyster, that's 24,000 oysters you have to sell. That's like a whole month of production. Plus, you have to take a seven-day course in the Bay Area. So that's five days lost in one week, and two days lost the next week just to take the course and test. You end up losing one of your 52 weeks out of the year, so it costs you a lot. It all adds up."

Other participants in the Willapa Bay watershed reported cost-distance problems which may limit harvest opportunities on state-owned lands for stakeholders located too far away to make economically feasible trips. One stakeholder in the Willapa Bay watershed explained:

> "Folks have to pay $2-$3 per bushel to bid for harvesting rights on state land...not leasing – BIDDING. State land owned by Fish & Wildlife is bid for near Nemah, Naselle, and the Willapa National Wildlife Refuge, but these bidding areas are not feasible for guys in the North bay to get to. It would be a 13-hour boat day from Bay Center to Nemah, but the guys in Nahcotta did well because they were closer to those bidding areas."

In other cases, costs can add up for the assets necessary for shellfish hatcheries to adapt to ocean acidification. One stakeholder in the Wilson-Trask-Nestucca watershed explained:

> "At first, I thought, 'Oh, I'm going to buffer this tank. I'm going to work on this one over here, and buffer these buckets, and see what the difference is.' Meanwhile, we lost another $100,000...Money was going away while we were trying different strategies."

Another notable economic barrier that came up frequently among stakeholders, and especially by those in the Wilson-Trask-Nestucca and Willapa Bay watersheds was access to seed. In some cases, access to seed was reported as a problem at specific moments when it was needed. One stakeholder in the Wilson-Trask-Nestucca watershed explained:

> "There have been times when we couldn't buy seed from [our seed producer] because it wouldn't be ready for another few months."

In other cases, access to seed was reported as a problem related to loss of natural recruitment, which can result in increased costs for seed when compounded by production problems at hatcheries. One stakeholder in the Willapa Bay watershed explained:

> "In 2007 and 2008, [hatcheries] experienced larvae failures, but the natural recruitment in Willapa Bay was still fine. Now there are high costs for seed since recruitment is way down. Seed costs me $5,000 today vs. $400 back in the day."

Overcoming the barrier of access to seed may require more hatcheries to open over time, but permitting costs are reportedly slowing the process to open new hatcheries in some places. One stakeholder from the Strait of Georgia-Nooksack watershed explained:

> "There's too little seed to go around, so opening hatcheries in more locations seems like the best way to go. I've been trying to open a hatchery in [the North Puget Sound], but I'm still waiting on permitting delays."

The next most frequently reported barriers to adaptation across all stakeholders were institutional and legislative/political barriers. The two most reported institutional and legislative/political barriers reported were industry consolidation, and insufficient watershed co-management on nutrient inputs and factors that affect water quality. While it is possible that the former could be overcome by legislative action to remove the influence of lobby money in government, the latter could possibly be overcome by establishing total maximum daily load (TMDL) rules for water quality indicators relevant to OA, and then following up to monitor and enforce those standards when exceeded by point sources (Lewis et al., 2019). Until the rate of change in human systems and governance actions to address OA can keep pace with the rate of change in exposure to OA, there will likely be substantial consequences on ecosystem services and human well-being (Jagers et al., 2019). This need for rapid transformation underscores the importance of limiting the influence of lobbying money in politics which may otherwise continue to delay adaptation action. The development of watershed management plans to address OA may also present opportunities for bringing together watershed industries, actors, and shellfisheries to discuss synergies, sustainability, and community values to be prioritized in action plans. Indeed, there may be potential for coexistence of shellfish production with other urban and industrial land uses (Fernández, et al., 2016).

Institutional barriers were reported most frequently in the Mad-Redwood, Puget Sound, and Hood Canal watersheds. Across all these watersheds, industry consolidation was the most frequently reported institutional barrier, and especially in the Puget Sound and Hood Canal watersheds. One stakeholder in the Puget Sound watershed explained:

> “Starting in the 1990's, what was once a small, modest-sized farm…started purchasing huge swaths of land, and in Washington state, when you purchase waterfront land, you also own the tidal land down to the low tide mark. They started with a big land purchase in [one bay], where they bought out a facility with one of the oldest leases in the state's history of farming shellfish. Then about a decade later, they started buying up a lot of land in [another bay].”

Industry consolidation may be putting up additional barriers for stakeholders who cannot afford to keep up with industrial demands, and who cannot afford to expand their growing areas as easily as larger companies. One stakeholder in the Hood Canal watershed explained:

> “If I had a million bucks, I’d buy up property and push everyone out…Small independent growers are being pushed out because of the industrial presence.”

Stakeholders in the Mad-Redwood watershed reported the theme of industry consolidation within the context of the expanding cannabis industry, but the principles may apply to the shellfish industry as well. One stakeholder in the Mad-Redwood watershed explained:

> "The free-market system is putting the thumb on small growers. [Big companies] keep growing more and more and more…and keep choking [small growers] out."

Legislative barriers were reported most frequently in the Mad-Redwood, Wilson-Trask-Nestucca, and Hood Canal watersheds. Across all these watersheds, water quality management was a commonly reported legislative barrier. One stakeholder in the Mad-Redwood watershed explained:

> "California doesn't do [water quality] testing very often, so it's like voodoo to them. California struggles to follow the lead of the FDA. California thinks [water quality] is not as big of a problem … [agencies say] they're 'overworked'. This issue would benefit not just the shellfish industry, but also other recreational harvest users and overall ecological function."

This need for additional water quality testing was shared in the Wilson-Trask-Nestucca watershed. One stakeholder in the Wilson-Trask-Nestucca watershed explained:

> "In order to harvest or approve new ground, the water quality has to be monitored. ODA is taking monthly water samples to make sure it is safe, but in Oregon, we lease the land from the state because it's public coast. There would have to be processes to open up the estuary, and to start testing and make water quality monitored."

Accountability issues around water quality management was also reported as a notable barrier to adaptation in the Hood Canal watershed. One stakeholder in the Hood Canal watershed explained:

> "The Department of Ecology has a Clean Water Act, so I go upriver and take a picture [of cattle] to show the Dept of Ecology. Why can't I go up with a drone and provide them a picture? … [The land] looked like scorched earth from cow waste … Ever since post-agricultural models, they have holding tanks now, and it's like a jungle down there because of the nitrogen."

There were also some contextual differences in the other legislative barriers reported across these watersheds. For example, in the Mad-Redwood watershed, stakeholders reported problems with eelgrass restrictions. One stakeholder in the Mad-Redwood watershed explained:

> "Eelgrass is not a limited resource here, but saltwater marsh is. 99% [of saltwater marsh] is eliminated despite species' dependence, but 99% of regulatory time is spent dealing with eelgrass, and not the areas of the bay that actually need work."

In the Wilson-Trask-Nestucca watershed, stakeholders reported problems with insufficient management of other species which prey on shellfish, outcompete shellfish for food, or make certain growing methods more difficult. One such species of concern reported by stakeholders was ghost shrimp (*Neotrypaea californiensis*). One stakeholder in the Wilson-Trask-Nestucca watershed explained:

> "Ghost shrimp are a problem not just to oyster farmers because of their manipulating methods around ghost shrimp, but also because the shrimp are decimating eelgrass ground."

However, levels of concern over ghost shrimp varied among stakeholders. Another stakeholder in the Wilson-Trask-Nestucca watershed explained:

> "We have more problems with the shrimp than anything. But the thing is it's our best growing site...because [shrimp] pump things out of the ground, and that makes food for the oysters. It grows beautiful oysters. Willapa Bay had a big problem with [shrimp]. We can't spray our grounds [like Willapa Bay]. It's a tradeoff because the ground gets muddy and things can sink…there's some shrimp ground you can't even walk across."

In the Hood Canal watershed, stakeholders reported unclear authority from regulatory overlaps across three counties and five tribal governments. One stakeholder in the Hood Canal watershed explained:

> "Each state and county has its own rules on what they allow and don't allow. The Boldt Decision of the 1970s ruled that…half of the marine resources in areas where treaty tribes are present need to be comanaged…[including] shellfish…The State of Washington did a disservice to the population by selling off tidelands when [the state] was established. 90% of tidelands are privately owned, and so because treaty rights are established, the tribes are the only ones who can play that role as managers of the water bodies. That puts things into an odd place for others."

The least frequently reported barriers to adaptation across all stakeholders were technological barriers. This finding suggests that stakeholders may perceive technological barriers to be the easiest to overcome through creative solutions, or that they do not perceive to lack the technical know-how to adapt (Matasci et al., 2014; Mabardy et al., 2015). The two most reported technological barriers reported were insufficient information on sources of biotoxins and harmful algal blooms (HABs), and insufficient monitoring for carbonate chemistry or biological impacts. Not enough rivers and creeks which flow into estuaries are monitored for biotoxins, let alone carbonate chemistry parameters such as pH or aragonite saturation state, and not enough hatcheries and nurseries are monitoring for those variables either. Investments in monitoring technologies may help to overcome these barriers, such as YSI water quality sensors (Herrmann et al., 2020), or the Burke-O-Lator instrument which has helped hatcheries monitor and buffer against OA (Barton et al., 2015). Equitable adaptation planning should account for where there are monitoring gaps, and especially where there are vulnerable populations who rely heavily on shellfish for livelihoods or subsistence, in order to increase adaptive capacity where sensitivity to impacts is greatest (Ekstrom et al., 2015).

Technological barriers were reported most frequently in the Willapa Bay, Mad-Redwood, and Wilson-Trask-Nestucca watersheds. Across all these watersheds, the most reported technological barrier was insufficient information on the sources of biotoxins and harmful algal blooms. In some cases, problems may arise from unknown, nonpoint sources. One stakeholder in the Willapa Bay watershed explained:

> "Lately, there has been an unusual type of algae that, at certain times of the year, with the sunlight, it just explodes. I don't know where it comes from, but you can see it all over … I've had [the algae] smother my oysters and kill them."

Better monitoring of the multiple factors which may impact shellfisheries could help overcome these knowledge gaps. One stakeholder in the Mad-Redwood watershed explained:

> "We have mortalities, and we don't know what they are from. We are all adapting to that by trial and error. Data is incredibly important to have because then you can look back [at the data] … and coordinate your losses."

In other cases, problems were reported from point sources, but because monitoring data is not collected for specific inputs which could amplify problems, sustainable management of watershed practices can be difficult. Overcoming this technological barrier may be especially difficult in places where, for example, powerful watershed actors do not want their nutrient inputs monitored. One stakeholder in the Wilson-Trask-Nestucca watershed explained:

> "In 1995, a surprising event occurred at the Tillamook Bay National Estuary Project's first Management Committee meeting devoted to "Water Quality". This surprise event set the tone for the next five years of the Project: When this 7 hour water quality meeting was nearly over and dairy waste, as a pollutant, had not been mentioned, I brought it up. When I did…a Management Committee member, said: 'We don't know that! It could be seagulls, seals, elk, deer - or cat and dog runoff!'…[The Committee member] was furious…sitting with his friends, all dairy representatives. The Management Committee was 95% government agents, unable and unwilling to say anything, but the point had been made. The tone was set, and that tone…remains to this day: We do not talk about dairy waste, manure management, agricultural runoff, etc."

Overall, planning to overcome barriers will likely need to be done with respect to differences in local contexts and priorities of stakeholder groups, as highlighted above. Furthermore, the finding that access to seed and industry consolidation were frequently reported barriers to adaptation could signal that past adaptation investments, such as automatic buffering at hatcheries, may not have done enough to ensure equitable outcomes for stakeholders across the shellfish industry. These findings support past research which argues careful attention should be made on equity in adaptation planning (Fülöp & Stanley-Jones, 2020) to ensure that lifting barriers does not facilitate colonial objectives that exacerbate power inequalities and marginalize vulnerable populations (Biermann et al., 2016; Clissold et al., 2020; Ober & Sakdapolrak, 2020).

3.4.6. Limits to adaptation

Interviews revealed a total of four limits to adaptation which were categorized as related to temperature, acidification, or sea level (Table 3-3). These limits are associated with climate impacts that are locked in and expected to worsen in coming decades under present-day high-emissions trajectories represented in the Representative Concentration Pathway (RCP) 8.5 scenario (Hartin et al., 2016; Good et al., 2018; Wabnitz et al., 2018; Wilson et al., 2020), so it becomes imperative that shellfish stakeholders are able to navigate around these limits with minimal obstructions from barriers to adaptation. To successfully adapt to OA, policy interventions should prioritize actions to make alternative options more accessible to stakeholders navigating limits to adaptation at each life stage in the shellfish production cycle. The implication of a responsive policy environment (Barnett et al., 2014; Vij et al., 2017) is that some limits, such as slow growth of shellfish species, may be indirectly overcome by increasing adaptive capacity of stakeholders (Cinner et al., 2018) or by lifting barriers to adaptation (Moser & Ekstrom, 2010), as was the case with hatcheries that improved larvae production amidst OA extremes after receiving legislative support to begin buffering intake water (Barton et al., 2015).

Table 3-3 | Self-reported limits to adaptation identified from stakeholder interviews (n=46). *Mean reporting across all participants.

Category	Limit	Frequency*	Exemplary quotes
Temperature		35%	
	Temperature extremes	35%	"In summer, temperatures go up to 90 degrees, and you can almost predict a die-off at that point. They're cooking out there. Over the last five summers, we've had three record years of temperature, both air and water. Our former all-time high was 100 degrees, but we've had 103 and 101 over the last five years."
Acidification		22%	
	Slow growth of shellfish	15%	"We've been having problems in our nursery with an on-land flow-through upwelling system. There's food in the water, but seed is just not growing to size fast enough."
	Loss of natural recruitment	15%	"A decade ago, the natural sets growers typically collected failed seven years in a row. If you look back through history, natural sets in the bay have always been sporadic...a few good years, a few bad years...but seven bad years was the longest ever experienced."
Sea Level		7%	
	Loss of tidal grounds	7%	"A narrow strip of intertidal land leading to shellfish beds used to be accessible like a road when exposed at low tide, but this area has been eroding away, and now it's nearly impassable. Waves have also crashed over the top there. Those shellfish beds are at risk of erosion from these additive stresses."

The most frequent limit to adaptation reported by stakeholders was temperature extremes. To overcome temperature extremes at the adult life stage, stakeholders may need to incorporate alternative growing methods that keep shellfish submerged in water during the lowest tides, such as shellfish rafts (Newell & Richardson, 2014; Li et al., 2018; George et al., 2019) or "shellfish garden terracing", a technique used by Indigenous peoples in the Pacific Northwest for millennia (Smith et al., 2019; Toniello et al., 2019), in which artificial dikes are constructed on intertidal ground so that tides can sweep in but cannot entirely sweep out. While these strategies may have implications for reducing harm to adult shellfish from temperature extremes, there are compounding stresses in the estuarine environment (O'Brien et al., 2019), such as acidification (Range et al., 2014; Gaylord et al., 2015), that may also affect outcome success from switching strategies. Therefore, it may be most appropriate for adaptation planning to account for multiple, interacting stressors that can impact shellfisheries (Waldbusser & Salisbury, 2014; Crotty et al., 2017).

The next most frequent limits to adaptation reported by stakeholders were two limits related to acidification: slow growth of shellfish species, and loss of natural recruitment. To overcome slow growth of shellfish at the larval and juvenile stages, hatcheries and nurseries may need to switch adaptation strategies towards on-land seed production with buffering capabilities to combat adverse species responses to OA. The installation and maintenance of community hatcheries with buffering may also help stakeholders overcome loss of natural recruitment by increasing seed production in diverse locations where reliance on natural sets is no longer feasible. The implication of investing in cooperatively-owned hatcheries instead of investing in specific firms is that doing so may allow the smallest stakeholders to secure access to seed, so long as adaptation planning focuses on equitable outcomes (Pelling & Garschagen, 2019; Fülöp & Stanley-Jones, 2020; Grecksch & Klöck, 2020).

The least frequent limit to adaptation reported was related to sea level rise and coastal erosion: loss of tidal ground. Loss of tidal ground can create problems for shellfish stakeholders by limiting access to or reducing productivity of growing areas. Communities adapting to sea level rise and coastal erosion have used engineering solutions such as dikes to protect coastlines (Hinkel et al., 2018; Dedekorkut-Howes et al., 2020), and it's possible there may be synergies between dike construction and shellfish garden terracing, which could simultaneously meet goals for hazard mitigation and adaptation (Meissner et al., 2020). However, implementing this type of win-win scenario may depend on the ability of adaptation planners to balance the interests of shellfish stakeholders and local communities with competing interests by powerful actors with other imagined futures (Tilt & Cerveny, 2016). This implies that multiple adaptation trade-offs must be considered at the local level, and that equity should be prioritized throughout the planning process.

Switching adaptation strategies to navigate limits to adaptation would likely require considerable investments in order to assist the poorest stakeholders who alone could not afford to invest time or resources into permitting new dikes or on-land hatcheries and nurseries. Legislative action may help to increase adaptive capacity or lift barriers for shellfish stakeholders, but to avoid uneven outcomes, these actions must consider equity. The implication for equitable adaptation is that even the most vulnerable stakeholders may be empowered with opportunities to sustain their reliance on shellfish amidst intensifying OA, and not only those who capitalize on OA limits and barriers compounding problems for marginalized populations.

3.4.3. Larvae life stage adaptation pathways

The most cost-effective action a shellfish stakeholder can take at the larval stage is catch natural sets (Fig. 3-4, L1). A shellfish stakeholder in the Willapa Bay watershed explained:

> "We get natural sets every year to some degree, but you have to put material out to catch it. That can be expensive if nothing catches, but if sets do stay, you can get a lot."

During warmer months, oysters may spawn in estuaries on their own. For years, shellfish growers would catch larvae from natural spawning events by placing bags of cultch in the estuary and growing whatever stuck. Due to changing OA conditions, few locations today still support natural sets where larvae attach to hard surfaces on their own in the intertidal zone. This limit to adaptation means that most shellfish growers cannot rely on natural sets as their only method for acquiring larvae (Fig. 3-4, L1). One shellfish stakeholder in the Puget Sound watershed explained:

> "A decade ago, the natural sets growers typically collected failed seven years in a row. If you look back through history, natural sets in the bay have always been sporadic...a few good years, a few bad years...but seven bad years was the longest ever experienced."

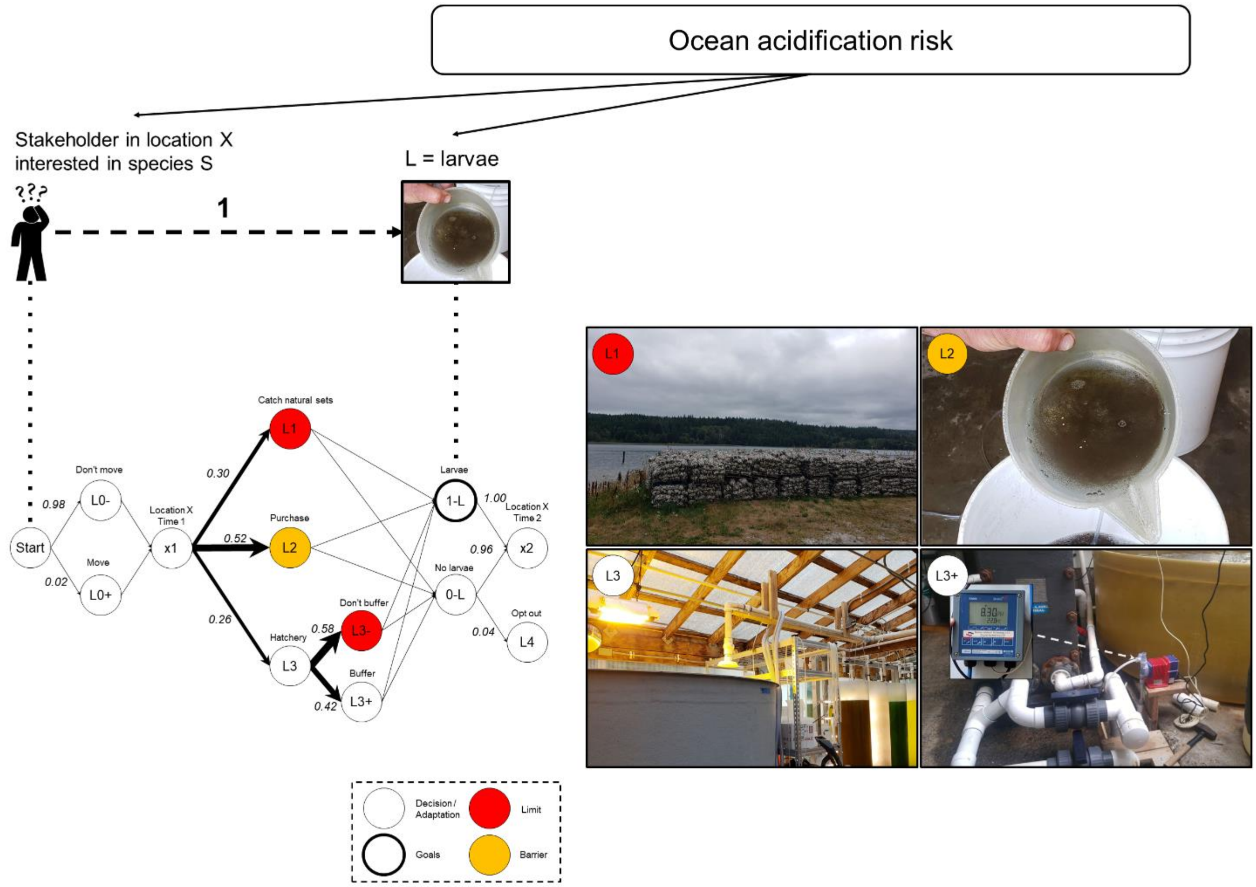

Fig. 3-4 | Adaptation pathways for stakeholders reliant on larval shellfish. L0–L4, Larval life stage stakeholder adaptation options: catch natural sets (L1); purchase larvae (L2); produce larvae in on-land hatchery (L3); produce larvae in on-land hatchery with buffering (L3+); diversify locations for larvae (L0+); or opt out of reliance on larval shellfish (L4). Red circles indicate reported limits to adaptation, the loss of natural recruitment (L1) and slow species growth in unbuffered water (L3-). The orange circle indicates a reported barrier to adaptation, access to seed when attempting to purchase from few seed producers (L2). Bold arrows are weighted by the frequency of stakeholders that reported deciding on each pathway. Stakeholders reported any combination of pathways that they have decided on before.

The next most cost-effective thing a shellfish stakeholder can do is purchase larvae from hatcheries with sufficient supply (Fig. 3-4, L2). One shellfish stakeholder in the Wilson-Trask-Nestucca watershed explained:

> "I try to get larvae all before February, and preferably before the end of May, so it can grow. Larvae were hard to get during the OA crisis, but in the last few years, it's very available."

Buying larvae from other producers allows shellfish stakeholders to perform their own sets to make their own seed; however, larvae set in estuaries today are not guaranteed to attach successfully, a limit to adaptation. What requires increasing investment from shellfish stakeholders at the larval stage is to produce larvae by investing in a hatchery (Fig. 3-4, L3), and then a hatchery with buffering and water treatment systems (Fig. 3-4, L3+). On-land hatcheries are becoming more common since demand for larvae frequently exceeds supply. These hatcheries pump water from estuaries into an indoor environment controlled for temperature and nutrients, allowing larvae to be spawned and to develop for long enough to grow their "foot", which is what larvae use to set onto hard substrates in the transition from larvae to juveniles. However, the costs to open and operate hatcheries are expensive. One shellfish stakeholder in the Wilson-Trask-Nestucca watershed explained:

> "It's tough to put in a new hatchery. Most farms don't want to own hatcheries because that's a totally different game. It'd be nice to have, but it's not the same."

Extreme adaptation measures at the larval stage would include diversifying locations (Fig. 3-4, L0+), or quitting the shellfish business, i.e. "opting out of reliance on larval shellfish" (Fig. 3-4, L4). Diversifying locations means a hatchery may close in one place and open in another, and if there are fewer hatcheries in a particular place, then there may be less larvae available for other local stakeholders to buy. One shellfish stakeholder in the Willapa Bay watershed explained:

> "I chose not to continue the hatchery because the water in this bay was just too unpredictable, and I didn't have the money to open a half million dollar hatchery with a water treatment system. I might have been able to treat the water at some times of the year, but not year-round."

There is an industry-level need for more hatcheries, so if there are fewer hatcheries open over time, then that is a problem. One shellfish stakeholder from the Strait of Georgia-Nooksack watershed explained:

> "Opening as many hatcheries as possible seems like the best way forward to adapt to OA. By diversifying hatchery locations, when problems happen in one bay, it might be possible to still obtain seed from another bay."

Loss of natural recruitment from intensifying OA may decrease the availability of naturally-occurring larvae over time, i.e. a limit to adaptation. Limited installation and maintenance of hatchery treatment systems means that only some firms can treat and buffer water year-round to successfully produce larvae amidst OA extremes, i.e. a barrier to adaptation. This barrier can be overcome with directed investments to install and maintain buffering technology at hatcheries in diverse locations.

3.4.4. Juvenile life stage adaptation pathways

The most cost-effective action a shellfish stakeholder can take at the juvenile stage is to set and nurse larvae into seed in an estuary (Fig. 3-5, J1 & J3). The problem with this option is that it potentially exposes larvae and juveniles to extremes in OA, in which either of two limits to adaptation may be encountered: loss of natural recruitment and slow growth of shellfish species. This means the first OA challenge is timing when to set larvae in favorable conditions for recruitment, and the second OA challenge is getting spat — larvae that successfully attached — to grow quickly enough to be planted at a later stage. To overcome these challenges with increasing investment, some seed producers use a floating upweller system, i.e. FLUPSY (Fig. 3-5, J3+), a structure that stays in the estuary with a water wheel that turns to distribute nutrients and oxygen to growing juveniles. Under ideal conditions, a FLUPSY may help shellfish stakeholders maximize their recovery rate, or the fraction of viable juvenile seed produced from setting a certain amount of larvae. However, since a FLUPSY is directly in water that's not buffered, ocean acidification risk increases the likelihood that FLUPSY nurseries may still be exposed to OA extremes which can limit recruitment and growth. For that reason, shellfish stakeholders using a FLUPSY in two locations with differential exposure to OA may see drastic differences in production. One shellfish stakeholder in the Willapa Bay watershed explained:

> "With our new FLUPSY out here, we get 85-90% recovery after we set and nurse seed to planting size. Other bays are seeing a lot lower, between about 50-60% recovery."

The next most cost-effective action a shellfish stakeholder can take is purchase seed from somebody else (Fig. 3-5, J2). If obtaining larvae is not possible, shellfish stakeholders may buy pre-set seed from producers with available surplus. It costs less to buy smaller seed around 2380-microns in size compared to larger seed, but before seed can be planted into the estuaries to be grown into adults, seed must be nursed to about the size of a fingernail — between a quarter-inch to half-inch size. This means that although smaller seed is bought at a more cost-effective rate at the time of purchase, the process of nursing smaller seed into the desired size for planting may become more costly as expenses add up for heating and feeding juveniles in nursing tanks. There is also the risk that OA extremes could slow juvenile growth rates during this critical nursing period, thus prolonging the process and reducing the amount of seed ready for planting when it is needed. One shellfish stakeholder in the Puget Sound watershed explained:

"I've had issues getting enough seed in the past, and now the seed I do get is so small I've had to build my own nursery upweller. I have to wait for a certain size of seed to be planted in order for it to stay put and not float away."

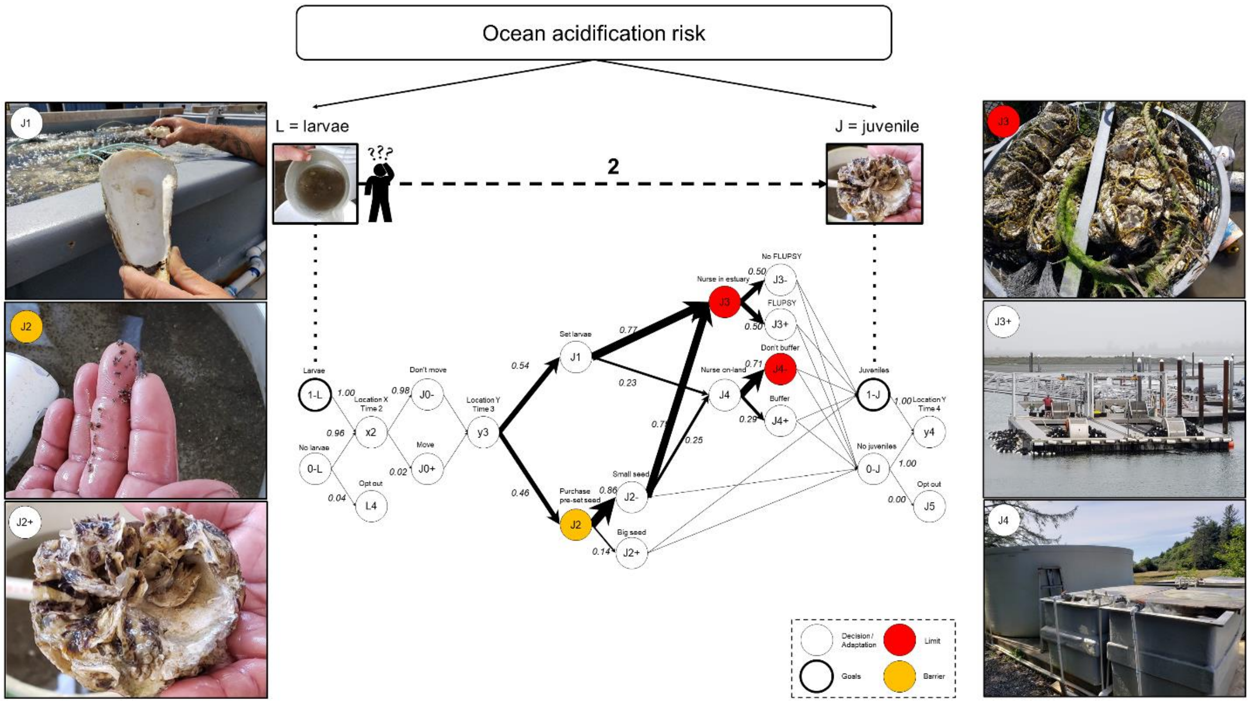

Fig. 3-5 | Adaptation pathways for stakeholders reliant on juvenile shellfish. J0–J5, Juvenile life stage stakeholder adaptation options: set larvae (J1); purchase pre-set seed (J2); purchase large pre-set seed (J2+); nurse seed in estuary (J3); nurse seed in estuary with floating upweller system, i.e. FLUPSY (J3+); nurse seed in on-land nursery (J4); nurse seed in on-land nursery with buffering (J4+); diversify locations for juveniles (J0+); or opt out of reliance on juvenile shellfish (J5). Red circles identify a reported limit to adaptation, slow growth of shellfish species in unbuffered water (J3 and J4-). The orange circle identifies a reported barrier to adaptation, access to seed when attempting to purchase from few seed producers (J2). Bold arrows are weighted by the frequency of stakeholders that reported deciding on each pathway. Stakeholders reported any combination of pathways that they have decided on before.

Buying larger seed that is already grown to sufficient size for planting into the estuaries enables shellfish stakeholders to bypass the entire nursing process if purchasing funds and seed supply are readily available (Fig. 3-5, J2+). If shellfish stakeholders need to plant seed but are unable to invest in infrastructure to support nursing juveniles (e.g. setting tanks, pumps, buffer, FLUPSY, etc.), then purchasing larger seed may be their only option to continue growing crops of shellfish. The problem is that large seed is much more expensive than small seed, and some shellfish stakeholders may not be able to afford it. One shellfish stakeholder in the Willapa Bay watershed explained:

"It costs $10,000-$12,000 per one million 2380-micron [small] seed, and it costs $26,000 per one million ¼-½ inch [large] seed."

The next most cost-effective action a shellfish stakeholder can take at the juvenile stage is to invest in an on-land nursery (Fig. 3-5, J4) that uses setting tanks filled with water pumped in from the estuary for seeding bags of cultch with larvae and nursing spat into juveniles. To promote growth, setting tanks are kept warm, and juveniles are fed a nutrient-rich diet consisting of a variety of beneficial algae species. Although temperature and nutrients are critical for nurseries to maintain suitable living conditions for juvenile shellfish, it is also important for nurseries to maintain other variables such as carbonate chemistry and oxygen saturation. One shellfish stakeholder in the Hood Canal watershed explained:

> "We've been having problems in our nursery after larvae leave the hatchery tanks and move to the nursery flowthrough upwellers. The juveniles aren't growing fast enough to size even though there's food in the water, and we don't know why."

What requires increasing investment is for hatcheries to buffer intake water for setting tanks so that extremes in carbonate chemistry may be controlled for to reduce or eliminate harm to juvenile shellfish being nursed (Fig. 3-5, J4+). The problem is only a few hatcheries and nurseries have treatment systems in place for controlling carbonate chemistry. The technology to automatically buffer intake water is new to the past decade, and many stakeholders impacted by the seed crisis have not had the resources to invest in anything else beyond their current production models. One shellfish stakeholder in the Willapa Bay watershed explained:

> "Our setting tanks contain millions of dollars worth of product, yet we have a hard time taking care of basic needs for the nursery because we aren't investing in new techniques. I'm starting to question if going into the oyster business was a good idea."

Extreme adaptation measures at the juvenile stage would include diversifying locations (Fig. 3-5, J0+), or opting out of reliance on juvenile shellfish (Fig. 3-5, J5). On relocating a nursery, one shellfish stakeholder in the Willapa Bay watershed explained:

> "A few years ago, we moved our nursery closer to the ocean because we started experiencing freshwater issues and were seeing too many mortalities in the setting tanks. Now we have to heat and feed more since water in the new location is colder and has less food."

If a shellfish stakeholder cannot successfully grow or purchase juveniles (Fig. 3-5, 0-J), then they may be left in a position to opt out of reliance on shellfish altogether because they will have no opportunities to grow shellfish on their own without seed. This is why seed availability is critical for continued reliance on shellfish, and why the seed crisis of the mid-to-late 2000's exposed seed shortages as the most important bottleneck determining if shellfisheries may continue or must opt out of their reliance on shellfish. On opting out of the juvenile life stage, a shellfish stakeholder in the Willapa Bay watershed explained:

> "Seed has always been a vulnerability for shellfish farms. You have to have it to farm the stuff, or else you're at risk of going out of business."

Fewer seed producers is leading to less seed available to others, and that's a barrier to adaptation. One shellfish stakeholder in the Strait of Georgia-Nooksack watershed explained:

> "Two years ago, I called a producer for seed and was told, 'We'll put you on the list' with no follow up. I had to strike a deal with a different producer, but the deal took six months to finalize so I lost out on production for an entire season."

Producers of seed will often supply nurseries and farms affiliated with their own firms before choosing to sell surplus seed to non-affiliated firms. One shellfish stakeholder in the Puget Sound watershed explained:

> "Seed producers will prioritize their own company's supply first, and they will only sell surplus seed they have to individuals or farms who are not on their blacklist. Seed availability is provided to those who are either playing nicest with the seed producers or are paying the biggest bucks to get their names higher up on the lists."

3.4.5. Adult life stage adaptation pathways

The most cost-effective action a shellfish stakeholder can take at the adult stage is harvest natural sets (Fig. 3-6, A1). In select locations where natural sets are supported, shellfish will grow into adults on hard surfaces and may be harvested by hand or chipped off their attachments using the back of a hammer. In Oregon and California, oysters may only be harvested by those with commercial licenses; however, Washington state conditionally allows for harvesting of oysters and clams at some state parks, so long as beach biotoxin levels are tested to be safe. Recreational harvests of shellfish in Oregon and California primarily include mussels (*M. californianus*) and clams. Due to harvest limits on open beaches, shellfish stakeholders couldn't support commercial livelihoods by only harvesting natural sets. One shellfish stakeholder in the Hood Canal watershed explained:

> "It's hard to try and live off of natural recruitment. Natural recruitment played a big role in the development of the shellfish industry."

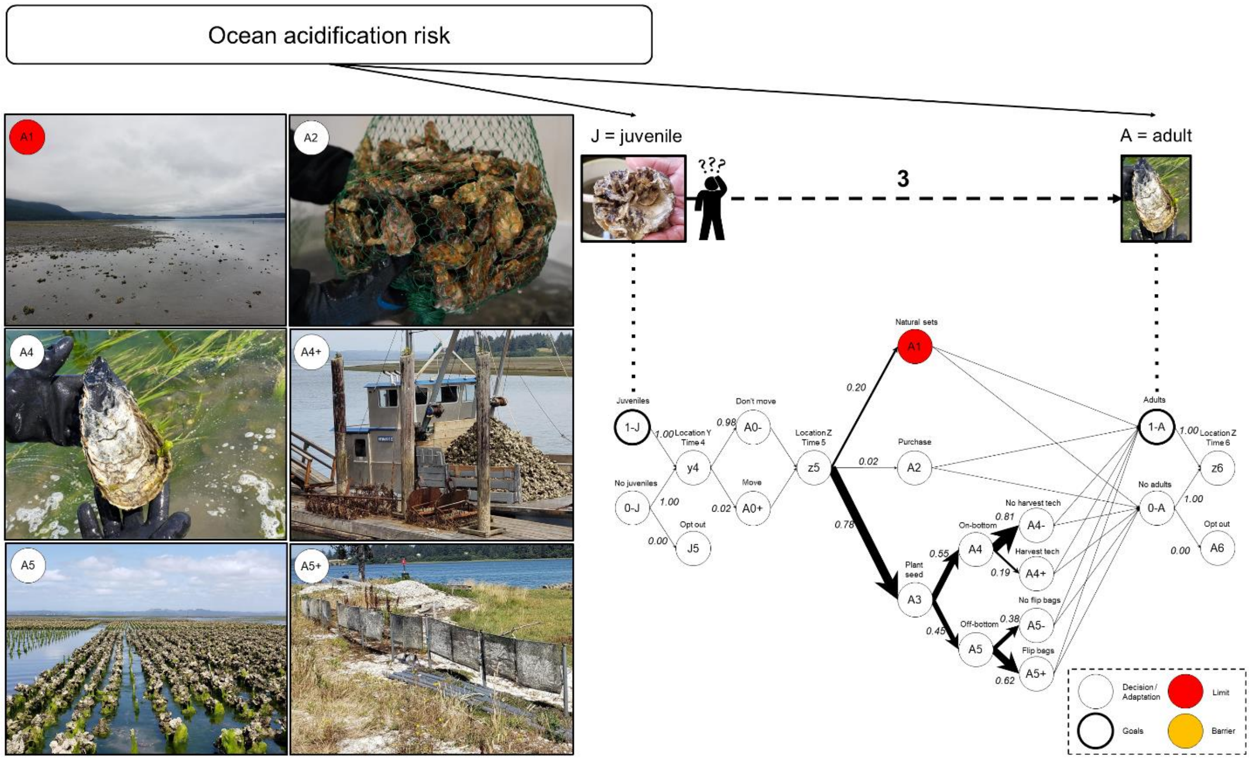

Fig. 3-6 | Adaptation pathways for stakeholders reliant on adult shellfish. A0–A6, Adult life stage stakeholder adaptation options: harvest natural sets (A1); purchase wholesale adult shellfish (A2); plant seed (A3) either on-bottom (A4) or off-bottom (A5) using efficient harvest technology (A4+) or flip bags (A5+); diversify locations for adult shellfish (A0+); or opt out of reliance on adult shellfish (A6). The red circle identifies a reported limit to adaptation, the loss of recruitment at the larval stage, which reduces harvest opportunities for natural sets at the adult stage (A1). Bold arrows are weighted by the frequency of stakeholders that reported deciding on each pathway. Stakeholders reported any combination of pathways that they have decided on before.

However, for stakeholders harvesting shellfish strictly for subsistence, recreational harvests at open beaches may suffice only temporarily as ocean acidification continues to erode shellfish growth. One shellfish stakeholder in the Puget Sound watershed explained:

> "Some of the oysters we were harvesting were so brittle they actually shattered in my hand."

The next most cost-effective action a shellfish stakeholder can take is purchase adult shellfish from somebody else (Fig. 3-6, A2). Stakeholders may buy shellfish from another location at wholesale market rates to cushion impacts on production, or to supplement production. One shellfish stakeholder in the Mad-Redwood watershed explained:

> "I pull wholesale product from somebody else to fill around half my retail markets, so when I'm in production, I can capture a big margin, but if I lose production because my product dries up, or if I have a huge farm mortality, then I can still get something out of the product I bought from somewhere else."

Buying shellfish at wholesale rates may only be economically practical for stakeholders who are diversified with a retail operation, but opening a retail operation may present a barrier to adaptation for those who are unable to afford the initial investments or time to apply for licenses, permitting, and certifications.

What requires increasing investment at the adult stage is to plant seed (Fig. 3-6, A3) in order to grow and harvest shellfish using techniques such as on-bottom (Fig. 3-6, A4) or off-bottom (Fig. 3-6, A5). On-bottom involves fattening juvenile shellfish into adults by either placing bags of seeded cultch directly onto tidal flats, or by separating and scattering around larger juveniles that cluster together. Once market size is reached, shellfish grown on-bottom are typically harvested by hand (Fig. 3-6, A4-), or with efficient harvesting technology such as dredges or tractors (Fig. 3-6, A4+). In contrast to natural sets which need to be chipped off of hard surfaces when harvested, on-bottom harvests may simply be picked up by hand since the chipping off process already occurred when human intervention separated juveniles from clusters to spread out on-bottom. One shellfish stakeholder in the Wilson-Trask-Nestucca watershed explained:

> "Not all plat ground quality is equal. You have to improvise, adapt, and change growing methods because the ground changes a little bit year after year."

Efficient harvesting technology may also allow shellfish stakeholders to maximize yield in times suitable for harvesting. When the tides are right for harvesting, shellfish stakeholders have a narrow window of time to get out to tidal flats and harvest adults. Consider a scenario where OA extremes are measured or forecasted for a number of days, and a given shellfish stakeholder can only harvest so many adults from their entire crop per tide; if a large number of adults remain unharvested after the stakeholder's best efforts, then persistent OA exposure may increase the likelihood of impacts to the adult shellfish that remain in the water. Should technology for efficient harvesting be paired with technology for monitoring or forecasting OA, then perhaps shellfish stakeholders could recover more of their crop than they would otherwise from prolonged exposure to OA. One shellfish stakeholder in the Strait of Georgia-Nooksack watershed explained:

> "I use a weather app on my phone to track the height of the river when there are heavy rains forecasted. The key is to harvest as many oysters as you can before big rain events when closures become possible."

Off-bottom, or "long-line", shellfish aquaculture involves intertwining shells into long lines of rope, fastening those ropes onto stakes hammered into tidal flats, and then seeding the intertwined shells with juveniles. Long lines ready to harvest are cut at low tide and attached to buoys, where a barge with a crane boom picks them up at high tide. Clusters grown undisturbed on long lines over time become relatively larger and irregular in shape, so this growing method is commonly used to produce shellfish destined for the wholesale market. One shellfish stakeholder in the Willapa Bay watershed explained:

> "There were a few 'ropers' in the past, but mainly because there was no dredge to harvest. Once a couple people got boats to cultivate and dredge, most everyone got rid of ropes."

With flip bag aquaculture, shellfish are grown and harvested in bags fastened onto ropes strung across tidal flats and attached to buoys so shellfish in the flip bags naturally tumble as the tide sweeps in and out. This frequent tumbling induces shorter but deeper growth of shellfish compared to undisturbed clusters, resulting in a shape favorable for the half-shell market. Bags are frequently checked on so that shellfish may be harvested as soon as they reach the desired size. One shellfish stakeholder in the Willapa Bay watershed explained:

> "Flip bags and zip ties are cheap in financial terms, but they're very labor intensive. Plus we're messing with plastic that must be picked up."

Extreme adaptation measures at the adult stage would include diversifying locations (Fig. 3-6, A0+), or opting out of reliance on adult shellfish (Fig. 3-6, A6). Stakeholders may decide to move to another location to grow or harvest shellfish if their current location has either: no shellfish to harvest, conditions not suitable for shellfish, or tidal flats not approved for shellfish growing. Drivers for migration may also include social, economic, demographic, political, or environmental factors, in addition to the compounding influence of OA on these drivers (Black et al., 2011). In the case of shellfisheries in the Pacific Northwest, stakeholders may prefer some locations over others due to presence of existing networks, access to markets, low-density urbanization, favorable political climates, better growing conditions for shellfish, or perceived risk of harm from ocean acidification. This is where adaptive capacity becomes important for a given shellfish stakeholders' ability to move if they want to. Migration is costly and often only feasible for people exhibiting relatively high adaptive capacity — assets, flexibility, organization, learning, and agency (Cinner et al., 2018). Thus, there exists a possibility that some shellfish stakeholders may fall into poverty traps where their assets (i.e. shellfish) are eroded over time from increasing exposure to OA, and they may not have enough adaptive capacity to move anywhere else (Black et al., 2013). While immobility traps assume that communities would want to move away, this may not hold true across all contexts, especially where place connection is reported as a social barrier to adaptation. For example, increases in climate activism by Indigenous communities may indicate that the global climate agenda is not doing enough to address subordination of Indigenous peoples and the marginalization of their desires to stay put in culturally important places over outmigration as adaptation (Suliman et al., 2019). Opting out of reliance on adult shellfish may occur if not enough adult shellfish are available to harvest for a given shellfish stakeholder in location X, or at least until harvest opportunities open up again. This option may become more likely as ocean acidification continues to intensify over time. One shellfish stakeholder in the Willapa Bay watershed explained:

> "If 100% yield is processed into one bushel, or one gallon of oysters, then you should quit harvesting whenever you're under 70% yield because it's not worth it."

Changing locations or production strategies works mostly for larger firms that already have multiple locations or the staffing and time to go through permitting processes. Bigger firms can use favorability of locations to their advantage, whereas smaller firms with less acreage may be locked into areas where shellfish grow slower or are exposed longer to potential mortality risks. One shellfish stakeholder in the Willapa Bay watershed explained:

> "A few years ago, growing oysters to harvest size took three years; now, it takes three and a half to four years. If oysters are growing slower, then you're jammed up because you don't have beds open to replant, and you're not able to move things as fast."

A key barrier to adaptation is a complex permitting process, involving multiple overlapping agencies, which can make it difficult for smaller firms to move or diversify locations by acquiring acreage in different places. One shellfish stakeholder in the Puget Sound watershed explained:

> "There's a suite of permits to deal with that are not particularly flexible if shellfish farms need to change locations, species, or culture gear. Adaptation to change is not easy because the overlap between permitting agencies is especially challenging to navigate, and it makes some changes impossible to make."

3.4.6. Overall adaptation pathways for all life stages

An integrated adaptation pathway for all life stages, with a focus on a worst-case scenario pathway where multiple limits and barriers to adaptation are encountered, is shown in Fig. 3-7. Key problems that were identified by stakeholders include loss of natural recruitment (Fig. 3-7, L1 and A1), access to seed (Fig. 3-7, L2 and J2), and slow growth in unbuffered water (Fig. 3-7, L3-, J3, and J4-). First in the scenario presented in Fig. 3-7, a stakeholder may encounter loss of natural recruitment when trying to acquire larvae (L1). Without larvae, the stakeholder may attempt to purchase pre-set seed, but then they encounter problems accessing seed from large seed producers (J2). Without juvenile seed, the stakeholder has nothing to plant, so their only option for obtaining adult shellfish self-sufficiently — i.e. without purchasing from others — is to harvest natural sets from a limited number of locations that still support natural sets (A1). Without adult shellfish, the stakeholder may decide to opt out of shellfish reliance altogether (A6). At that point, the stakeholder may seek to diversify their livelihood or food sources in a departure from reliance on shellfish growth and production.

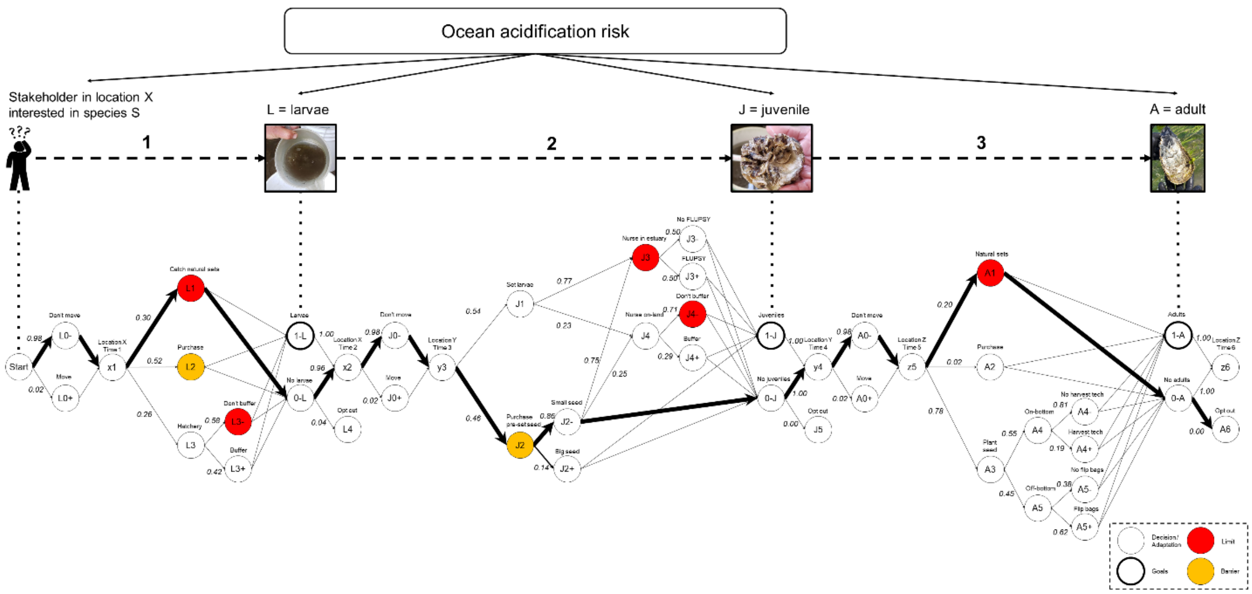

Fig. 3-7 | Overall adaptation pathways of PNW shellfisheries to ocean acidification. Bold arrows highlight a scenario of a "climate change loser's" adaptation pathway, in which a shellfish-reliant stakeholder encounters numerous limits and barriers to adaptation while navigating the shellfish production cycle amidst ocean acidification risk, and is ultimately left without any shellfish to harvest.

For a shellfish stakeholder adapting to OA, the risk of opting out is highest when there is no juvenile seed ready to plant when it is needed (Fig. 3-7, 0-J). One shellfish stakeholder in the Puget Sound watershed explained:

> "Since seed is so hard to get these days, I don't know how much longer I'll be able to keep doing this. Maybe about five more years, or one more crop rotation, but if seed continues to become harder to get when I need it, then I'll probably have to throw in the towel and retire."

The implications of OA on early life stages mean that shellfish stakeholders must have a reliable seed supply at critical planting times. Since natural recruitment is not feasible for acquiring seed due to OA risk increasing over time, it becomes imperative that shellfish stakeholders either foster connections with seed producers or are provisioned seed to ensure they do not lose access to seed by in-house producers or their preferred partners. This dynamic can place seed producers in a unique position of power, in which seed producers may prioritize seed supply to their own in-house farms while being selective about who else can have access to surplus seed. This is especially the case with increasing ocean acidification risk because stakeholders are no longer able to rely entirely on natural sets to self-sufficiency produce their own seed. One shellfish stakeholder in the Mad-Redwood watershed explained:

> “The big boys produce seed on their own, but they don't let out a lot to the little guys. They want to sell the adult product, but they don't want to sell the small stuff.”

Another shellfish stakeholder in the Hood Canal watershed explained:

> “There’s not many suppliers of seed, and if there’s not enough seed to go around, then some of the smaller guys are going to get shorted and lose out on business profitability in two or three years. Or if the seed they get is not robust or somehow compromised, then whatever they plant out there will get lower yields as well.”

The next highest risk of opting out is when there is not enough area to replant because slower species growth may jam up production (Fig. 3-7, A0). One shellfish stakeholder in the Mad-Redwood watershed explained:

> “The general trend is to keep selling smaller oysters to keep getting the turnover, but the tricky spot is knowing how long it’s going to take to get to market size. We're consistently suffering from permitting issues. There’s no new ground, and it can take up to five years for a new permit to be approved.”

The implications of OA on adult shellfish growing slower mean that shellfish stakeholders must have enough area or growing locations to replant to keep production going season after season. Since shellfish species are expected to take longer to grow to planting size or harvest size in untreated water due to OA risk increasing over time, shellfish stakeholders limited to fewer growing areas must find a way to move their juveniles and adults through the production cycle more efficiently to avoid prolonged exposure to problems that can reduce growth or increase mortality.

Considering additional or alternative locations may present problems for smaller firms with the least acreage who may have more difficulty navigating a complex permitting process with limited time or other employees. While the largest firms with the most time and resources can more easily become larger and more diversified in locations, the smallest firms may be becoming smaller and seeing a higher probability of closing up shop over time. This is evident at the industry level in Washington state, in which the rate of oyster and mussel growing firms closing up shop, or “opting out” of shellfish, has begun exceeding the rate of new firms opting in ever since the seed crisis (Fig. 3-8).

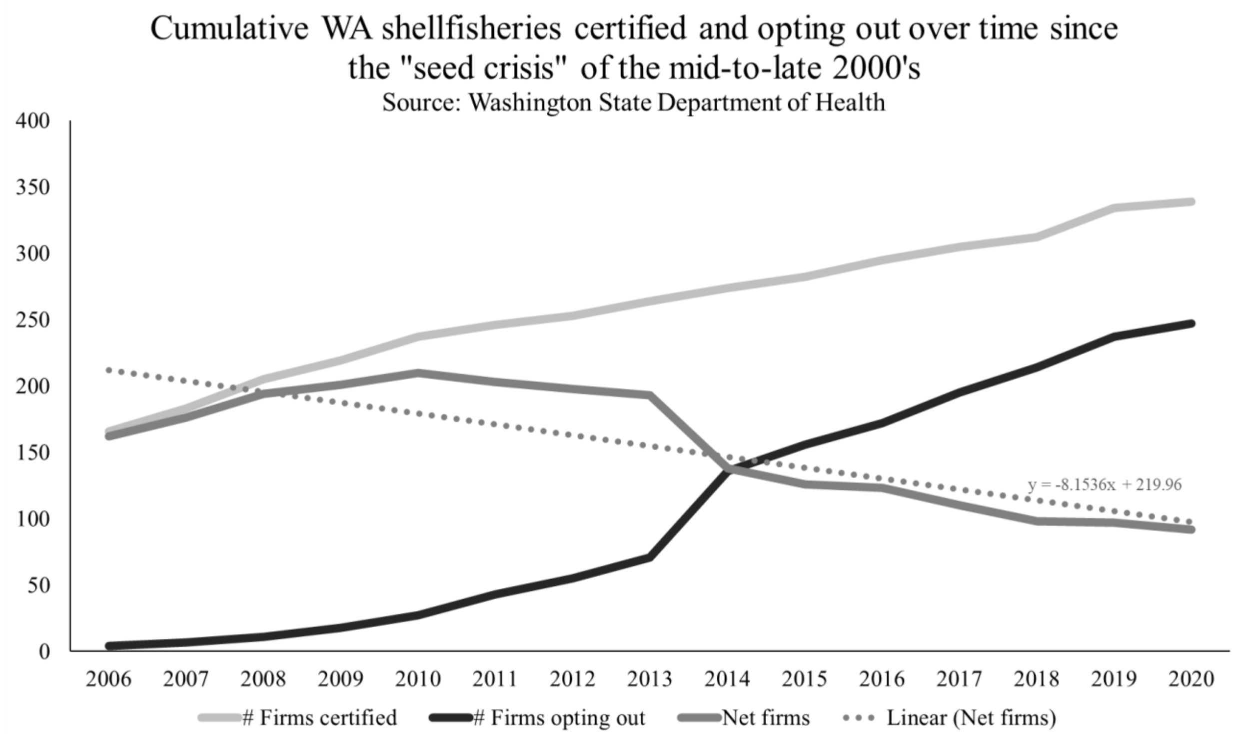

Fig. 3-8 | Shellfish firms in Washington state have begun opting out since the “seed crisis”. Industry-level data on shellfish firms in Washington state was analyzed using a cumulative sum function on acreage per firm. Firms switching from positive cumulative acreage to zero were classified as opt outs for a given year. Although new certifications of shellfish firms have been increasing over the years, the number of firms opting out has been increasing at a faster rate, with a noticeable increase in opt outs occurring between 2013 and 2014, about five years after the “seed crisis”, or about one or two crop rotations.

Although new certifications of shellfish firms have been increasing over the years, the number of firms opting out has been increasing at a faster rate, with a noticeable increase in opt outs occurring between 2013 and 2014, about five years after the “seed crisis”, or about one or two crop rotations. Washington state is where the Pacific Northwest shellfish industry is most concentrated (Mabardy et al., 2015), so a net decrease in the number of firms certified in shellfish there over time may signal that impacts and capacity for adaptation to the seed crisis were unevenly distributed across the range of different stakeholders (Althor et al., 2018; Grecksch & Klöck, 2020).

Overall, other factors could have been at play, but there is a rationale for the seed crisis having affected the likelihood of firms opting out of shellfish. Similar findings that industry consolidation and access to seed are barriers to adaptation have been reported in the agricultural sector, in which few seed producers have the power to limit choices of smaller stakeholders who rely on seed (Stuart & Schewe, 2016). The story of adaptation from the seed crisis cautions how responsive investments may inadvertently exacerbate power inequalities and industry consolidation if there are no explicit efforts made to ensure that benefits are distributed equitably across affected stakeholders.

3.4.7. Robustness of analysis

Although themes reported in this study were identified by at least three participants representing different firms, the information gathered from fieldwork was prone to subjective biases and experiences that may not hold true across all actors. The author did their best to identify themes from interviews, but the process of coding and interpreting interviews could have been influenced by the researcher's subjective biases. Preliminary chi-square statistics were run on reported barriers to adaptation coded from interviews (Appendix A), but these statistics still need inter-rater reliability scores that were not completed for this study. Industry-level data on firms opting out was only available from Washington state which has a certain type of vulnerability that may or may not be applicable to firms outside the state of Washington.

This analysis is most useful for hypothesis testing, and for proposing more robust tests of the themes presented. Although this study suggests some compelling findings, the aim was not to understand causation but to work out the process. This research attempted to interview stakeholders at the scale of local watersheds, but participants often reported contextual themes that involved changes in actors and agencies at multiple levels outside their communities. This supports the need for a multi-scalar lens over emphasis on a single scale like watersheds (Sovacool, 2018), for transboundary commons can defy arbitrary spatial resolutions to generate flexible geographies that re-"b/order" over time (Miller, 2020). While this study focused on the impact of OA on species growth, there was no consideration of the potential for OA to affect other relevant attributes that end users of shellfish species desire, such as shell appearance, a qualitative attribute which has been suggested to compound the impact of OA on market supply quantities (Oliva et al., 2019). Furthermore, research has argued that species-based narratives on climate change can shift attention away from the social environment, thereby refocusing adaptation efforts towards Earth science and systems ecology rather than prioritizing changes in the political economy or neoliberal agenda (Luisetti, 2019).

3.5. Discussion

Contrary to the hypothesis that PNW shellfisheries' adaptation to ocean acidification following the seed crisis succeeded in making seed more available to shellfish stakeholders, the results of this study indicate that access to seed may have been reduced. This surprising result underscores the need for adaptation pathway planning efforts to define how success is measured. If success is measured by production, then one could point to how the technological investments made at certain hatcheries have resulted in improved production of larvae year-round. However, this production metric overlooks the problem that access to seed continues to become harder for small shellfish stakeholders. Increased larvae production disproportionately helped hatcheries who were beneficiaries of adaptation investments following the seed crisis all while non-beneficiary farms were experiencing an eroded ability to collect seed self-sufficiently from natural sets because of intensified OA. As a result, select beneficiary hatcheries and their in-house farming operations have become the "seed haves" in a new era of climate change winners and losers, leaving the smallest stakeholders at-risk of opting out from being "seed have nots". These findings support calls in the literature for barriers to adaptation to be overcome through postcolonial approaches that address underlying power imbalances (Ober & Sakdapolrak, 2020).

The case of shellfisheries adaptation to ocean acidification in the Pacific Northwest shows how responsive investments may inadvertently exacerbate power inequalities and industry consolidation if there are no explicit efforts made to ensure that benefits are distributed equitably across affected stakeholders. The decision tree presented in this study may be useful for discussing adaptation as a value proposition with stakeholders in order to decide how and where to invest in adaptation with respect to what stakeholders decide is valued in their community. Adaptation pathways can be useful for highlighting the range of options available to stakeholders facing climate hazards, but only by critically examining barriers to adaptation can likelihoods be estimated for stakeholders to successfully adopt options for achieving desired outcomes and values.

To overcome the barrier of access to seed, large seed may need to be provisioned to shellfish stakeholders, or investments may need to be made in hatchery and nursery infrastructure across diversified locations, perhaps in the form of community co-op hatcheries and nurseries. The latter option would be most successful in an intensifying OA climate if further investments were made in buffering technology, as well as investments in sustainable power sources that do not exacerbate the OA problem through increased carbon emissions at hatchery or nursery sites. The development of community shellfish hatcheries and nurseries as an adaptation to ocean acidification may present an opportunity to promote sustainable seed supply to local stakeholders interested in subsistence, restoration, or economic activity. This idea is supported by research which suggests that government assistance can help facilitate the integration of small-scale producers into cooperative units that work together with larger, high-intensive producers in order to attain higher levels of both sustainability and overall production compared to disconnected, less intensive units (Nguyen et al., 2019).

For successful adaptation to take place, shellfish hatcheries and nurseries must find alternatives to fossil fuels for heating seawater so that the impacts of ocean acidification are not exacerbated through additional emissions. Additionally, adaptation planning efforts must explicitly address institutional inequalities that have made marginalized populations even more vulnerable to impacts from social, economic, political, health, and environmental factors, all of which are exacerbated by increasing risk of ocean acidification. Adaptation to OA should focus not only on restoring livelihoods after impacts are felt; adaptation to OA should focus on improving livelihoods towards equitable, sustainable stewardship of shellfish resources amidst inevitable changes in ocean chemistry.

4. OVERALL VULNERABILITY OF PACIFIC NORTHWEST SHELLFISHERIES TO OCEAN ACIDIFICATION

4.1. Evaluation of objectives

Vulnerability and adaptation pathways were assessed through two studies investigating risk and response potential of shellfish-reliant stakeholders facing OA impacts on shellfish species in the Pacific Northwest (Fig. 4-1). This research concludes that the most vulnerable shellfish-reliant stakeholders in the Pacific Northwest are those who cannot access seed at the larval or juvenile life stage because intensifying exposure to ocean acidification has led to a two-fold problem. First, OA limits species growth and natural recruitment, which affects self-sufficiency of seed production. This limit to adaptation has triggered a switch for many stakeholders, who, after multiple generations of reliance on natural recruitment, now must purchase nearly all their seed from a select number of producers with the technological assets to buffer water. Second, seed producers put up barriers to seed access by prioritizing seed supply to their own in-house growing operations and having the power to choose who else can access seed, and who cannot. Thus, the impact of OA on shell-forming species may be compounding industry consolidation in Pacific Northwest shellfisheries, in which social vulnerability is exacerbated for small stakeholders who cannot afford to successfully produce seed self-sufficiently, while, in contrast, the largest firms can profit through control of seed production. Adaptation pathways for the system of PNW shellfisheries to overcome and adapt successfully to OA will require policy interventions that address not only risk reduction and the technological problem of producing seed amidst OA, but also the social, economic, and institutional problems associated with powerful actors limiting access to seed for vulnerable stakeholders.

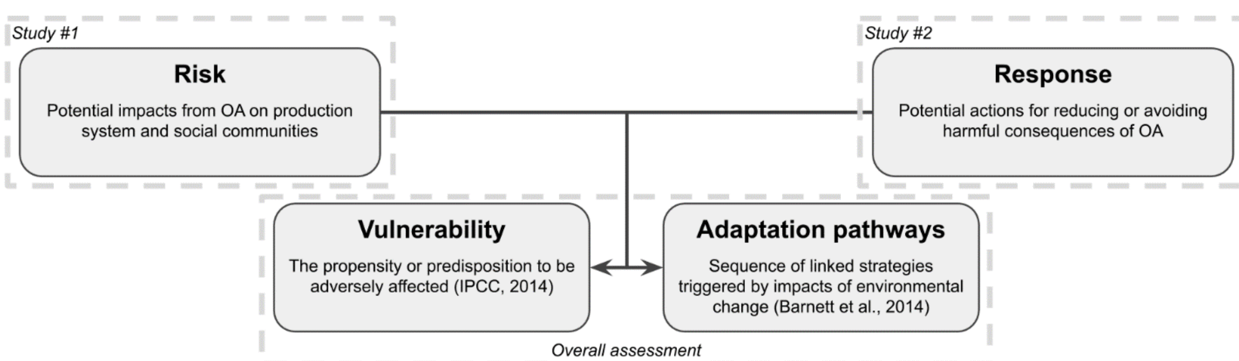

Fig. 4-1 | Conceptual framework of this assessment of vulnerability and adaptation pathways.

An understanding of risk profiles to OA can help inform adaptation strategies suited to local patterns of exposure and sensitivity. The first study in this research found that risk profiles to OA varied between the North, Central, and South sub-regions of the PNW.

In the North (i.e. Washington state, coast & sea), the rate of change in exposure to OA is expected to be greatest, implying that adaptation efforts may require multiple iterations and strategy reevaluations as conditions progressively worsen over time. Washington state is also where the greatest socioeconomic and cultural sensitivity to OA is, so it is imperative that legislative actions for adaptation pathways be carried out as quickly as possible with local stakeholders to plan sequences of adjustments specific to place-based risk profiles and other socially-relevant contextual factors.

In contrast, the South (i.e. Oregon, southern coast & California, northern coast) exhibits a higher propensity for exposure to OA extremes but a relatively slower rate of change in OA. This implies that adaptation in the South PNW may involve adjusting to an intensification of extremes by buffering water in the production of early life stages, or switching to more OA-resistant species, such as *O. lurida*. While socioeconomic sensitivity to OA is limited to select watersheds in the South, cultural sensitivity appears to be distributed more evenly, with Indigenous tribes present in more watersheds in the South than watersheds with shellfish shippers. This implies that adaptation efforts in the South may look to prioritize cultural reliance on shellfish, and when combined with the South's more extreme OA exposure pattern, this means species switches and restoration efforts associated with native *O. lurida* may be compatible adaptation strategies for the South.

The Central PNW (i.e. Oregon, northern & central coast) has an exposure pattern that is a mix of both OA extremes and a relatively fast rate of change in OA, but to slightly lesser extents than the North and South. Social sensitivity to OA in the Central PNW leans towards socioeconomic sensitivity over cultural sensitivity. While at first glance this may imply that adaptation efforts may look to focus on socioeconomic factors associated with shellfish reliance, adaptation planning efforts in the Central PNW should give equitable consideration to cultural sensitivity and Indigenous values in order to pay reparations for Oregon's history of marginalizing non-white populations, a potential explanatory factor for the low representation of tribes in this sub-region. Adaptation for shellfish-reliant stakeholders in the Central PNW may thus involve a diversity of strategies, including swift planning to implement local adaptation pathways, buffering, or switching species to *O. lurida*. This implies that the Central PNW may benefit over time from knowledge sharing with stakeholders in the North and South about successful adaptation strategies suitable to both OA extremes and a fast rate of change in OA.

An understanding of response potential to OA can help prioritize adaptation planning efforts where inequities exist in adaptive capacity and barriers to adaptation. The second study in this research found that the most opportunistic actions to increase adaptive capacity and lift barriers for shellfish-reliant stakeholders adapting to OA are investments in new hatcheries and nurseries in diversified locations, investments in the installation and maintenance of buffering technology at new or existing hatcheries and nurseries, and provisions to ensure access to seed for the smallest stakeholders. While larger firms may have more agency and assets to adapt to OA, smaller stakeholders may require adaptation financing from legislative action to avoid adverse consequences to shellfish species which could affect people's livelihoods or culture.

4.2. Scope and limitations

Overall, the scope of this research intended to visualize and contextualize how vulnerability and adaptation pathways are characterized for Pacific Northwest stakeholders reliant on specific life stages of shellfish responsive to OA. Specifically, this research intended to accomplish two aims. First, this research intended to develop a web-based geovisualization tool for communicating species-based risk to OA. This research did not intend to make predictions, only to assess relative risk based on what is known in the scientific literature about regional exposure to OA and associated species responses to OA. Second, this research intended to interview shellfish-reliant stakeholders for identifying pathways and barriers to OA adaptation. This research did not intend to make general claims about the adaptive capacity of regional shellfisheries or specific communities, nor did it intend to present all potential pathways or barriers based on subjective reporting by individual stakeholders or specific places. Instead, this research intended to focus specifically on pathways and barriers relevant to stakeholder reliance on specific life stages of shellfish responsive to OA.

Limitations in sampling included limited responses to emails and phone calls made to recruit stakeholders for focus group discussions and interviews. To overcome this, most sampling was done through in-person outreach and snowball sampling, in which contacted participants would identify other notable stakeholders to contact next. While snowball sampling was effective in scheduling interviews with individuals, it was difficult to bring together multiple stakeholders for group discussions.

Limitations in validity included not having a completed geovisualization tool ready by the time fieldwork began. To better validate the findings of this research, future applications are needed to explicitly use the tool in field interviews and group discussions. Additionally, fieldwork coding and frequency reporting of interview themes still need inter-rater reliability scores calculated to estimate agreement between the results identified by the researcher and those identified by others.

Limitations in methodology included refocusing the aim of interview discussions away from directed questions on local watershed risk factors and towards open-ended questions on barriers to adaptation. This was done because many stakeholders expressed concerns about targeting policy actions towards risks associated with specific watershed actors and their land use practices. To overcome confidentiality concerns, mapping data collected was not reported, and instead, qualitative data was emphasized. While qualitative data was useful in highlighting risks and barriers specific to watershed groups, spatialized data that could have bolstered the results were excluded. Future applications of a risk mapping exercise would look to bring together shellfish-reliant stakeholders with multiple other stakeholder groups who operate in watersheds where shellfish are grown so that problems can be discussed, validated, and overcome cooperatively across sectors and stakeholder groups.

The goal of this research was not to recommend the most suitable adaptation planning efforts needed for specific communities reliant on shellfish across the Pacific Northwest. Instead, by providing a geovisualization tool for assessing risk at flexible scales, and a stakeholder-informed adaptation pathway for identifying key barriers relevant to stakeholders reliant on specific life stages, the hope is that future adaptation planning with shellfish-reliant stakeholders at the local level can better identify and evaluate the most feasible adaptation pathways for their communities.

4.3. Contribution and future work

This regional assessment of vulnerability and adaptation pathways contributes an integrative view of adaptation requirements for PNW stakeholders reliant on shellfish at different life stages, but more work is needed to understand how local contexts and multi-stakeholder interactions may affect the effectiveness of legislative actions to address OA. Future research may benefit by using the geovisualization tool and adaptation pathway decision tree developed in this research to facilitate stakeholder engagement and planning processes. For example, future mapping exercises may consider collecting stories and associated point locations where stakeholders report factors related to exposure, sensitivity, adaptive capacity, and barriers to adaptation, and explicitly linking reported points to specific nodes along the adaptation pathway decision tree presented in this research. Incorporating these fieldwork-collected points into the geovisualization tool framework with interactive graphs could allow users to identify stakeholder-reported locations of differential vulnerability and barriers to adaptation to OA alongside projected impacts to species. Doing so may enable planning efforts to assess placed-based contextual factors to effectively direct adaptation investments.

4.4. Implications

Future efforts to adapt to OA should prioritize actions that either reduce risk or enhance response to OA. Reducing human reliance on shellfish is not a practical adaptation strategy, so reducing risk to OA means that exposure to OA must be limited. At a global level, slowing the intensification of OA exposure may only be possible through halting fossil fuel emissions and sequestering carbon from the atmosphere. At a local level, reducing OA exposure may be accomplished through more effective watershed management, particularly for managing land use factors that contribute to amplified OA in estuaries where shellfish are grown. Actions to enhance response to OA should be done with equity in mind, so that all stakeholders may have opportunities to respond and adapt to OA without being constrained by low adaptive capacity or multiple barriers to adaptation. With a coordinated, responsive policy environment, adaptation to OA may well be possible for shellfisheries, but to avoid uneven consequences to vulnerable stakeholders, planning efforts must concurrently address risk reduction with social and environmental justice.

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APPENDIX A: CODEBOOKS FOR IDENTIFYING FIELDWORK THEMES

Table A-1 | Codebook for identifying themes on barriers, limits, and adaptation options from stakeholder interviews.

Theme	**Code**	**Description**	**Barrier, Limit, or Adaptation**	**Category**
Insufficient long-term employees	LE	Participant describes difficulties in finding or retaining employment, or in lack of employee work ethic.	Barrier	Social
Insufficient communication, trust between shellfisheries and public, academia, government, and/or NGO's	LC	Participants describes a disconnect between groups in understanding, empathy, or relation to personal experiences.	Barrier	Social
Climate denialism, or a refusal to accept the possibility of anthropogenic impacts on the environment or shellfish	CD	Participant states a lack of concern for climate impacts, or states that juvenile/adult shellfish are not affected by OA.	Barrier	Social
Conflicting claims between property owners	P	Participant describes a conflict that occurs when tideland owners, homeowners, and/or shellfish stakeholders hold competing values on practices allowed on shared tidelands.	Barrier	Social
Place connection	PL	Participant describes a personal, cultural, or emotional tie to their location.	Barrier	Social
Poaching	PO	Participant describes illicit activity or theft of shellfish resources.	Barrier	Social
Operational costs: financial, time, permitting, emissions, employee benefits, etc.	OC	Participant describes difficulty in affording basic needs or new adaptations, due to limited assets, time, employees that can assist with permitting, or energy costs.	Barrier	Economic/Financial
Access to seed	SA	Participant describes difficulty in purchasing seed from producers, such as access denied, ignored contacts, insufficient surplus, or rising costs.	Barrier	Economic/Financial

Table A-1 (Continued) | Codebook for identifying themes on barriers, limits, and adaptation options from stakeholder interviews.

Theme	**Code**	**Description**	**Barrier, Limit, or Adaptation**	**Category**
Insufficient transparency on appropriation of funds by government or NGO's	AF	Participant describes a concern about the allocation of funds, in which either: the participant does not see a visible difference in their lives from money spent by institutions, or the participant does see self-described “improper” expenditures.	Barrier	Economic/Financial
Insufficient livelihood diversification options	LD	Participant describes a limited number of alternative livelihoods in their location that provide living wages or benefits.	Barrier	Economic/Financial
Industry consolidation	IC	Participant describes a dynamic where large companies continue to get larger while small companies are squeezed out, ignored, or absorbed by the large companies.	Barrier	Institutional
Resistance to change by powerful industries or actors with lobbying influence in local politics	RC	Participant describes a power dynamic where local politicians allow industries who pay lobby money to continue unsustainable or polluting practices.	Barrier	Institutional
Profits are prioritized over sustainability or living wages	PR	Participant describes how money, profits, and/or cheap but environmentally-harmful practices are normalized to the point where they take precedence over sustainability or employee benefits.	Barrier	Institutional
Insufficient watershed co-management on nutrient inputs and factors that affect water quality (i.e. insufficient rules or rule enforcement)	WQ	Participant describes poor management of water quality from insufficient accountability of watershed practices which, left unchecked, can create problems for shellfisheries.	Barrier	Legislative/Political
Unclear regulatory overlap between local, county, state, federal, and tribal governments (i.e. unclear authority)	R	Participant describes distinctions and mismatches in rules across governance institutions, whose regulations overlap in space and lead to reported confusion on what is allowed or not.	Barrier	Legislative/Political

Table A-1 (Continued) | Codebook for identifying themes on barriers, limits, and adaptation options from stakeholder interviews.

Theme	**Code**	**Description**	**Barrier, Limit, or Adaptation**	**Category**
Eelgrass limitations	EG	Participant describes difficulties associated with moving their shellfish growing practices around their plats due to regulations restricting operations on tidelands with eelgrass, which moves around in space and time.	Barrier	Legislative/Political
Poor management of species that prey on or outcompete shellfish	PD	Participant describes difficulties in growing shellfish in cohabitation with invasive, predative, and/or outcompeting species (e.g. Japanese drill snails, moon snails, or ghost shrimp) which are not actively managed.	Barrier	Legislative/Political
Harvest restrictions	HR	Participant cites widespread harvest closures which affect the timing and locations of available harvest opportunities.	Barrier	Legislative/Political
Insufficient information on sources of biotoxins and harmful algal blooms (HABs)	B	Participant describes uncertainties associated with identifying sources and/or contributing factors of biotoxins and/or HABs.	Barrier	Technological
Insufficient monitoring for carbonate chemistry or biological impacts	M	Participant describes how monitoring data for pH, saturation state, pCO2, and/or species responses to OA are not collected for their location.	Barrier	Technological
Insufficient selection for OA-resistant or set-improving genes	GM	Participant suggests that genetic selection for OA-resistant qualities is not yet complete and/or widely available.	Barrier	Technological
Insufficient locational accuracy of geospatial data on plat boundaries	LA	Participant describes an instance where GIS or GPS-based technologies do not accurately portray plat boundaries on ever-changing tidal grounds, sometimes leading others to inadvertently trespass.	Barrier	Technological

Table A-1 (Continued) | Codebook for identifying themes on barriers, limits, and adaptation options from stakeholder interviews.

Theme	**Code**	**Description**	**Barrier, Limit, or Adaptation**	**Category**
Temperature extremes	T	Participant describes an instance of a temperature extreme, either too hot or too cold, which led to shellfish mortalities.	Limit	Temperature
Slow growth of shellfish	SG	Participant describes an instance where shellfish grew slower-than-expected in untreated water (e.g. estuaries or on-land hatcheries/nurseries without buffering)	Limit	Acidification
Loss of natural recruitment	LNR	Participant describes an instance where natural sets failed to recruit for longer periods (e.g. successive years) than ever experienced, or an instance where natural sets have stopped recruiting indefinitely.	Limit	Acidification
Loss of tidal ground	LTG	Participant describes coastal erosion or increasingly greater-than-expected tides which reduce area of and/or access to intertidal grounds.	Limit	Sea Level
Diversify locations for larvae	L0+	Participant describes an instance where a hatchery moved to improve production of larvae, or cultch was moved to improve recruitment success of larvae.	Adaptation	Larvae life stage
Catch natural sets	L1	Participant describes a practice they conduct where bags of cultch are placed in estuaries to catch natural sets of larvae.	Adaptation	Larvae life stage
Purchase larvae	L2	Participant describes purchasing larvae from hatchery producers.	Adaptation	Larvae life stage
Produce larvae in on-land hatchery	L3	Participant describes a practice they conduct to produce larvae in an on-land hatchery.	Adaptation	Larvae life stage
Produce larvae in on-land hatchery without buffering	L3-	Participant describes a practice they conduct to produce larvae in an on-land hatchery without buffering.	Adaptation	Larvae life stage

Table A-1 (Continued) | Codebook for identifying themes on barriers, limits, and adaptation options from stakeholder interviews.

Theme	**Code**	**Description**	**Barrier, Limit, or Adaptation**	**Category**
Produce larvae in on-land hatchery with buffering	L3+	Participant describes a practice they conduct to produce larvae in an on-land hatchery with buffered water for protecting larvae from OA.	Adaptation	Larvae life stage
Opt out of reliance on larvae	L4	Participant describes an instance where they had previously caught, purchased, and/or produced larvae, but then decided to forego doing so, or closed shop at their hatchery.	Adaptation	Larvae life stage
Diversify locations for juveniles	J0+	Participant describes an instance where a nursery moved to improve production of juveniles.	Adaptation	Juvenile life stage
Set larvae	J1	Participant describes a practice they conduct to set larvae on cultch themselves (i.e. as opposed to natural sets).	Adaptation	Juvenile life stage
Purchase pre-set seed	J2	Participant describes purchasing pre-set juvenile seed from hatchery or nursery producers.	Adaptation	Juvenile life stage
Purchase small pre-set seed	J2-	Participant describes purchasing small pre-set juvenile seed from hatchery or nursery producers (e.g. 2380-micron size).	Adaptation	Juvenile life stage
Purchase large pre-set seed	J2+	Participant describes purchasing large pre-set juvenile seed from hatchery or nursery producers (e.g. ¼-½ inch size).	Adaptation	Juvenile life stage
Nurse seed in estuary	J3	Participant describes a practice they conduct to set larvae and nurse juvenile seed in an estuary.	Adaptation	Juvenile life stage
Nurse seed in estuary without a floating upweller system, i.e. FLUPSY	J3-	Participant describes a practice they conduct to set larvae and nurse juvenile seed in an estuary, but without using a FLUPSY.	Adaptation	Juvenile life stage
Nurse seed in estuary with floating upweller system, i.e. FLUPSY	J3+	Participant describes a practice they conduct to set larvae and nurse juvenile seed in an estuary, within a FLUPSY.	Adaptation	Juvenile life stage

Table A-1 (Continued) | Codebook for identifying themes on barriers, limits, and adaptation options from stakeholder interviews.

Theme	**Code**	**Description**	**Barrier, Limit, or Adaptation**	**Category**
Nurse seed in on-land nursery	J4	Participant describes a practice they conduct to set larvae and nurse juvenile seed in an on-land nursery.	Adaptation	Juvenile life stage
Nurse seed in on-land nursery without buffering	J4-	Participant describes a practice they conduct to set larvae and nurse juvenile seed in an on-land nursery without buffered water.	Adaptation	Juvenile life stage
Nurse seed in on-land nursery with buffering	J4+	Participant describes a practice they conduct to set larvae and nurse juvenile seed in an on-land nursery with buffered water for protecting larvae and juveniles from OA.	Adaptation	Juvenile life stage
Opt out of reliance on juvenile shellfish	J5	Participant describes an instance where they had previously set larvae, purchased juvenile seed, and/or produced juvenile seed, but then decided to forego doing so, or closed shop at their nursery.	Adaptation	Juvenile life stage
Diversify locations for adult shellfish	A0+	Participant describes an instance where a growing area moved to improve production of adult shellfish.	Adaptation	Adult life stage
Harvest natural sets	A1	Participant describes an instance where they harvested adult shellfish grown from natural sets.	Adaptation	Adult life stage
Purchase wholesale adult shellfish	A2	Participant describes a practice they conduct to purchase adult shellfish from other producers at wholesale rates.	Adaptation	Adult life stage
Plant seed	A3	Participant describes a practice they conduct to plant juvenile seed in a growing area produce adult shellfish.	Adaptation	Adult life stage
Grow adult shellfish on-bottom	A4	Participant describes a practice they conduct to grow adult shellfish on-bottom, either in bags or scattered on intertidal ground.	Adaptation	Adult life stage

Table A-1 (Continued) | Codebook for identifying themes on barriers, limits, and adaptation options from stakeholder interviews.

Theme	**Code**	**Description**	**Barrier, Limit, or Adaptation**	**Category**
Grow adult shellfish on-bottom without using efficient harvest technology	A4-	Participant describes a practice they conduct to grow adult shellfish scattered on-bottom, and to harvest them by hand.	Adaptation	Adult life stage
Grow adult shellfish on-bottom using efficient harvest technology	A4+	Participant describes a practice they conduct to grow adult shellfish scattered on-bottom, and to harvest them using high-efficiency technology (e.g. dredges or tractors).	Adaptation	Adult life stage
Grow adult shellfish off-bottom	A5	Participant describes a practice they conduct to grow adult shellfish off-bottom, strung from ropes either in clusters or bags.	Adaptation	Adult life stage
Grow adult shellfish off-bottom without using flip bags	A5-	Participant describes a practice they conduct to grow adult shellfish off-bottom, strung from ropes in clusters, without using bags.	Adaptation	Adult life stage
Grow adult shellfish off-bottom using flip bags	A5+	Participant describes a practice they conduct to grow adult shellfish off-bottom, strung from ropes using flip bags which tumble with tidal action.	Adaptation	Adult life stage
Opt out of reliance on adult shellfish	A6	Participant describes an instance where they had previously harvested natural sets, purchased adult shellfish, and/or produced adult shellfish, but then decided to forego doing so, or closed shop at their growing area.	Adaptation	Adult life stage

APPENDIX B: RECRUITMENT FLYER

Oregon State University | PACIFIC SHELLFISH INSTITUTE | NOAA

Dear Stakeholder in the vitality and health of shellfish in the Pacific Northwest!

We are seeking stakeholders who are involved in shellfish culture –the harvest, expansion, restoration, and availability of important bivalves in the Pacific Northwest— to participate in a research study. You were identified by the Pacific Shellfish Institute as having strong connections to the shellfish community and expert knowledge on shellfisheries' adaptive responses to ocean acidification (OA).

The purpose of this study is to identify responses taken by shellfish stakeholders to adapt to specific OA stresses in areas of variable vulnerability to OA.

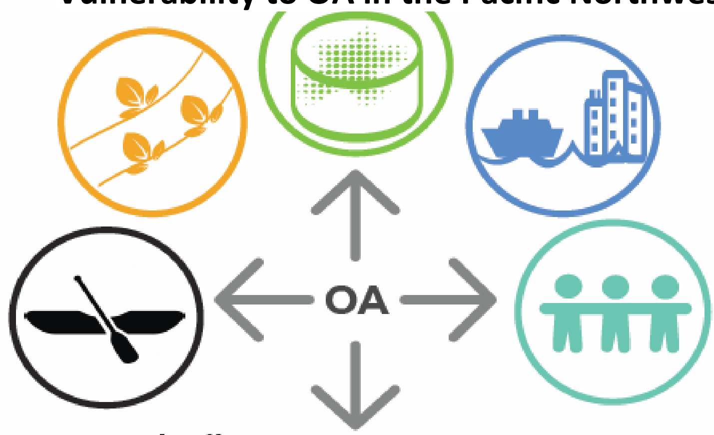
Participation in this study involves:

- A time commitment of 2 hours
- Participation in an interactive activity designed to identify OA-related threats

We understand that your time is limited! Our research team values your participation and will make every effort to ensure your experience will be beneficial to you. We will provide lunch and facilitate a mutual learning environment that we hope will be conducive to a shared understanding of OA impacts in our region, and a collaborative approach to responding to shellfish resources and affected communities.

We hope that your participation will provide a cooperative learning and networking opportunity. For more information about this study, please contact the principal investigator, Dr. David J. Wrathall (Oregon State University), by phone at [PI phone] or email at [PI email].

Vulnerability to OA in the Pacific Northwest



1. Coastal Tribes

Ocean acidification threatens the wild and commercial harvest of shellfish that are integral to the culture, identities and livelihoods of tribal communities.

2. Shellfish Growers

Shellfish aquaculture is valued at $270 M annually in the US Pacific Northwest. OA has already cost the industry $110M, jeopardizing more than 3,200 jobs.[1]

3. Shellfish Hatcheries

Pacific oyster seed shortages from '05 - '09 correlated with upwelled, CO2-enriched waters, causing nearly 80% larval mortality at hatcheries[2] and a 22% decline in production across the industry.[3]

4. Port Towns

Tourism from recreational shellfish harvesting brings in $27M annually in WA state alone, a critical driver of coastal and Puget Sound economies.[4]

5. Employees

The shellfish industry is often the leading employer in rural, coastal communities directly and indirectly supporting thousands of jobs in these regions.

1. Washington Shellfish Initiative white paper, December 2011
2. Washington State Blue Ribbon Panel Report on Ocean Acidification 2012
3. Pacific Coast Shellfish Growers Association, 2011
4. Washington Dept. of Fish and Wildlife (WDFW)

Thank you,

Bobbi Hudson, PSI Director
Principal Investigator

David Wrathall, OSU Professor
Principal Investigator

APPENDIX C: EXPLANATION OF RESEARCH

Vulnerability and adaptation to ocean acidification among Pacific Northwest mussel and oyster stakeholders

Project Title:	Vulnerability and adaptation to ocean acidification among Pacific Northwest mussel and oyster stakeholders
Principal Investigator:	David J. Wrathall
Student Researcher:	Brian G. Katz
Co-Investigator(s):	David M. Kling, George G. Waldbusser, and Bobbi Hudson
Sponsor:	NOAA
Version Date:	01/04/2019

Purpose: You are being asked to take part in a research study to evaluate shellfish stakeholders' responses to ocean acidification (OA) in the Pacific Northwest, and identify potential pathways for successful adaptation.

Activities: The study activities include focus group discussions and semi-structured interviews.

Time: Your participation in this study will last about two hours. The focus group activities will take about two hours. Candidates for a semi-structured interview will be identified during the FGDs, and will be invited to participate in an interview that will require approximately 1 and a half hours.

Risks: There are no foreseeable risks to participating in this study.

Benefit: Benefits of this study include increased awareness of OA, and OA adaptation alternatives.

Confidentiality: Other people may learn that you participated in this study. Unless specified, we will not attribute anything to your name.

Voluntary: Participation in this study is voluntary, and participants are free to skip questions that they would prefer not to answer. We will give you opportunities to withdraw any comments or data collected at any time.

Study contacts: If you have any questions about this research project, please contact: David J. Wrathall. If you have questions about your rights or welfare as a participant, please contact the Oregon State University Human Research Protection Program (HRPP) office, at (541) 737-8008 or by email at IRB@oregonstate.edu.

______________________________ ______________________________ ______________

Participant Name (please print) Signature Date

APPENDIX D: SMALL GROUP SPATIALIZED ACTIVITY

Vulnerability and adaptation to ocean acidification among Pacific Northwest mussel and oyster stakeholders

Name: ____

Agency/Sector: ____

Agenda:

11:00 A.M. – 11:10 A.M. Introduction & Instructions

11:10 A.M. – 11:45 A.M. Mapping Exercise Part I: Exposure & Sensitivity

11:45 A.M. – 12:15 P.M. Lunch

12:15 P.M. – 12:50 P.M. Mapping Exercise Part II: Adaptive Capacity

12:50 P.M. – 01:00 P.M. Wrap-up

Introduction & Instructions:

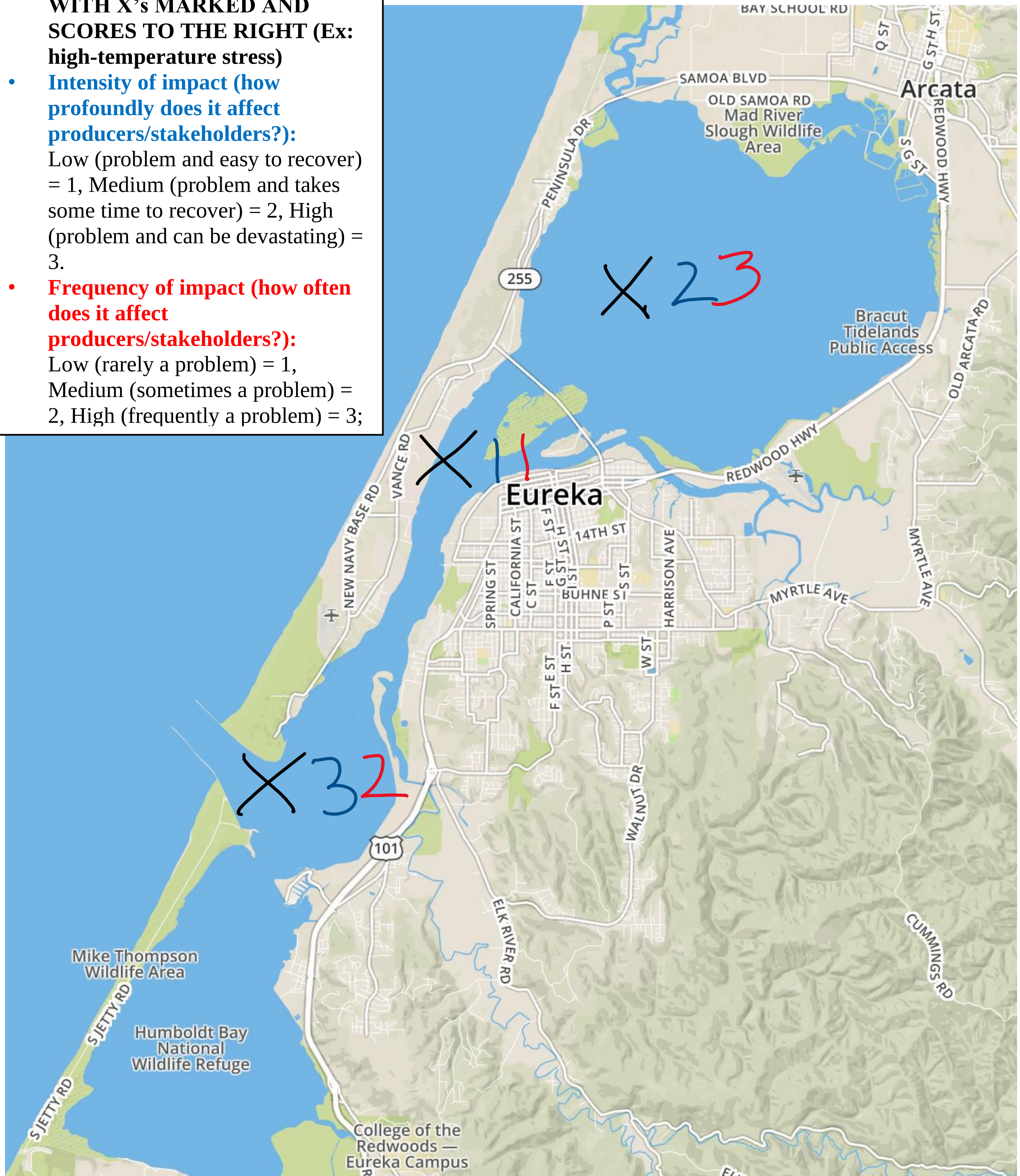
Thank you for joining us today. We will be performing a mapping exercise today to collect data relevant to ocean acidification in estuaries where shellfish are grown. This packet contains a series of maps that are each labeled with a factor that affects shellfish. For each map, we will ask you to perform the following tasks to the best of your knowledge:

1. Mark X's on the map in any place(s) where the factor is located.
2. To the right of each X you mark, write two numbers between one and three to represent low (1), medium (2), or high (3) scores for characteristics we will specify on each page.
3. On the timeline of months below each map, please circle the months when the factor occurs. Then place a triangle around the peak month when the factor occurs.

Please see the following page for a complete example (Fig. D-1). Once participants are finished with their individual answers for each map, we will ask everyone to pair up with one or two other participants. Those groups will briefly share individual answers with each other, and then each group will elect one person to enter all their points into the researchers' laptop computer. Once every group has entered their points in the computer, the combined locations marked from every group will be displayed on a projected screen. A brief group discussion on each factor will then commence, and researchers will record notes from the discussion.

Intro / MAP 0: EXAMPLE MAP WITH X's MARKED AND SCORES TO THE RIGHT (Ex: high-temperature stress)

- **Intensity of impact (how profoundly does it affect producers/stakeholders?):** Low (problem and easy to recover) = 1, Medium (problem and takes some time to recover) = 2, High (problem and can be devastating) = 3.
- **Frequency of impact (how often does it affect producers/stakeholders?):** Low (rarely a problem) = 1, Medium (sometimes a problem) = 2, High (frequently a problem) = 3;



Please circle the months below to indicate when this happens in a typical calendar year. Then place a triangle around the peak month when this happens.

Jan Feb Mar Apr May Jun Jul Aug Sep Oct Nov Dec

Fig. D-1 | Example map used to introduce small group spatialized interviews activity.

APPENDIX E: SEMI-STRUCTURED INTERVIEW PROTOCOL

Vulnerability and adaptation to ocean acidification among Pacific Northwest mussel and oyster stakeholders

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“Experts” with specific knowledge of shellfish reliance will be identified in FGDs and invited to participate in a semi-structured interview. Portions of these interviews will be video recorded for use in project materials and outputs. Interviews will all include a standard portion, determined by the results of the FGD. Informants will be asked to explain specific examples of OA vulnerability (i.e. exposure, sensitivity, and adaptive capacity), and provide spatiotemporal information on where these triggers have occurred or are likely to occur.

Following the standard portion, we will ask experts to participate in one of two semi-structured activities: 1) transect; and 2) community timeline. These will allow us to understand in greater detail community reliance on shellfish through time, and across space.

Expert Interview:

1. Explain what we did in the Focus Group Discussion

2. Comparison of our map and theirs, side by side:

> Exposure: “This is what you said, and this is what we said. Looking at similarities: why are they similar? (Are we right/wrong?) Looking at differences: why are they different? (Are we right/wrong?) Would you like to adjust your answers? How can we adjust our answers?”
>
> Sensitivity: “This is what you said, and this is what we said. Looking at similarities: why are they similar? (Are we right/wrong?) Looking at differences: why are they different? (Are we right/wrong?) Would you like to adjust your answers? How can we adjust our answers?”
>
> Adaptive Capacity: “This is what you said, and this is what we said. Looking at similarities: why are they similar? (Are we right/wrong?) Looking at differences: why are they different? (Are we right/wrong?) Would you like to adjust your answers? How can we adjust our answers?”

3. Barriers to adaptation:

“Barriers are any type of challenge or constraint to economic or cultural reliance on shellfish that prevents adaptation but can be overcome.”

Questions for participants about barriers:

--What sort of barriers would you imagine?
--Are they limited to specific places?
--How important are these barriers to overcome, if we’re going to successfully adapt (i.e. high importance, medium importance, low importance)?

PROMPTS
--regulations or zoning
--exclusive contracts, and market relations
--capital to acquire existing technology
--training to implement existing technology
--traditional practices
--traditional reliance (cultural reliance)

4. Specialized portion (two of each per site):

Transect: the expert will be asked to provide a tour of shellfish reliance in the local area, indicating points of special interest. Researchers will accompany the informant with a camera equipped with GPS.

Community timeline and contextual change: an expert of advanced age will be asked to describe the community’s history of reliance of shellfish with special emphasis on years in which specific challenges to stakeholders have occurred, and spaces where challenges have occurred.

APPENDIX F: CODE BANK OF COMPUTER PROGRAMMING SCRIPTS

All computer programming scripts used in this research, along with descriptions and instructions for use, are accessible open-source at: https://www. github.com/briangkatz/oa

APPENDIX G: STUDIES USED TO DERIVE SPECIES RESPONSE CURVES

Table G-1 | List of studies on biological impacts of OA on shellfish species growth at different life stages. Meta-analysis completed by Jessamyn A. Johnson and George G. Waldbusser of Oregon State University. TA = total alkalinity; Omg. Ar. = aragonite saturation state; DIC = dissolved inorganic carbon

Author	**Link to Paper**	**Species**	**Life Stage**	**Carbonate Variable (what was measured during experiment)**	**Biological response variable**	**System Fully Constrained /Partially Constrained**	**Parameters constrained**	**Notes**
Lannig et al., 2010	http://www.mdpi.com/1660-3397/8/8/2318	*C. gigas*	adult	pH, TA	Condition Index (tissue dry mass (g)/ shell dry mass (g)	Yes	TA, pH	Also contains info on metabolites and respiration
Gazeau et al., 2007	doi: 10.1029/2006GL028554	*C. gigas*	adult	pH	Calcification	Yes	pCO_2, Talk	
Timmins-Schiffman et al., 2014	http://www.biomedcentral.com/1471-2164/15/951	*C. gigas*	adult	CO_2	RGR (from buoyant weight wet), Microhardness, fracture toughness	Yes	pH, TA	was also heatshock mortality data that I did not extract
Bamber, 1990	https://doi.org/10.1016/0022-0981(90)90069-O	*C. gigas*	adult, juvenile, larvae	pH	Survivorship, Calcification	No		
Buckham et al., 2015	http://cedar.wwu.edu/wwuet/451/?utm_source=cedar.wwu.edu%2Fwwuet%2F451&utm_medium=PDF&utm_campaign=PDFCoverPages	*C. gigas*	larvae	CO_2	Growth Rate, Shell length, shell weight	Yes	pH, TA	
Kurihara et al., 2007	doi: 10.3354/ab00009	*C. gigas*	larvae	pH, TA	shell length(um), shell height(um), %normal, % lifestage, shell mineralization	Yes	TA, pH	
Gazeau et al., 2011	https://doi.org/10.1371/journal.pone.0023010	*C. gigas*	larvae	pH	Shell Area, Shell Length, % to D-hinge, Calcium Incorporation	Yes	pCO_2, TA	
Waldbusser et al., 2014	doi: 10.1038/nclimate2479	*C. gigas*	larvae	pCO_2, Omg. Ar.	shell length, prop. normal	Yes	pCO_2, DIC	
Barton et al., 2012	doi:10.4319/lo.2012.57.3.0698	*C. gigas*	larvae	Omg. Ar.	prop. normal, relative production, days until 120um shell nominal shell size, days from 120-150 um nominal shell size	Yes	pCO_2, DIC	

Table G-1 (Continued) | List of studies on biological impacts of OA on shellfish species growth at different life stages.								
Author	**Link to Paper**	**Species**	**Life Stage**	**Carbonate Variable (what was measured during experiment)**	**Biological response variable**	**System Fully Constrained /Partially Constrained**	**Parameters constrained**	**Notes**
Brunner et al., 2016	doi: 10.3354/meps11828	*C. gigas*	larvae	Omg. Ar.	shell length, weight, Lipid, calcification, Total C+N, Organic C+N	Yes	pCO_2, DIC	
Frieder et al., 2017	doi:10.1093/icesjms/fsw213	*C. gigas*	larvae	Omg. Ar.	Shell length (um), shell weight (ng), hrs to d-hinge, hrs to onset of calcification, calcification rate, calcium uptake, loss of 45Ca, O2 consumption, Protein synthesis	Yes	pCO_2, DIC (daily)	
Parker et al., 2010	doi: 10.1007/s00227-010-1508-3	*C. gigas*	larvae	pH	Shell length, Growth, % abnormal, % to D hinge	Yes	pCO_2, pH	
Timmins-Schiffman et al., 2012	doi: 10.1007/s00227-012-2055-x	*C. gigas*	larvae	CO_2	Shell Length, Shell Height, Prop. Calcified	Yes	pH, TA	
Barros et al., 2013	http://dx.doi.org/10.1016/j.jembe.2012.12.014	*C. gigas*	larvae	pH	Length, mortality, % abnormal veliger, hatching rate	No	pH	
Ross et al., 2011	doi: 10.3390/w3041005	*C.gigas*	larvae	pH	Shell growth, Shell Length, % embryo to d hinge	Yes	pCO_2, TA	
Gray et al., 2017	doi: 10.3354/meps11977	*M. californianus*	larvae	pCO_2, Omg. Ar.	% feeding, gut fullness, shell size, ingestion rate,	Yes	pCO_2, DIC	estimations of energy spent on shell, energy in food content ingested as well
Waldbusser et al., 2015	doi:10.1371/journal.pone.0128376	*M. californianus*	larvae	pCO_2, Omg. Ar.	shell length, prop. normal, initiation of feeding, respiration rate		pCO_2, DIC	

Table G-1 (Continued) | List of studies on biological impacts of OA on shellfish species growth at different life stages.

Author	**Link to Paper**	**Species**	**Life Stage**	**Carbonate Variable (what was measured during experiment)**	**Biological response variable**	**System Fully Constrained /Partially Constrained**	**Parameters constrained**	**Notes**
Frieder et al., 2014	doi: 10.1111/gcb.12485	*M. californianus*	larvae	pH, O_2	Shell length (um)	Yes	pH, TA (both discrete)	Did not include data that show means of the proportion of veligers in pH treatments as a percentage of veligers in stable ambient pH on day 2.
Gaylord et al., 2011	doi:10.1242/jeb.055939	*M. californianus*	larvae	CO_2	Projected Shell, Shell Thickness, Shell breakage, Tissue weight, Area/Mass	Yes	pH, TA (both discrete)	
Eads et al., 2016	doi: 10.3354/meps11944	*M. galloprovincialis*	adult	pH	Sperm motility	No	pH	
Freitas et al., 2017	http://dx.doi.org/10.1016/j.ecolind.2017.04.003	*M. galloprovincialis*	adult	pH	Glycogen, protein, lipid	Yes	pH, TA	TA only measured for pH 7.8, sal 28, pH 7.3 sal 28, ph 7.8, sal 14 and 35 not included because TA not measured
Gazeau et al., 2014	doi: 10.3389/fmars.2014.00062	*M. galloprovincialis*	adult	pH, Temp	mortality, shell length, fresh weight, shell weight, respiration, excretion, net calcification, haemolymph pH, extrapallial fluid pH, haemolymph pC)2, Extrapallial fluid PCO2	Yes	Every 2 months	

Table G-1 (Continued) | List of studies on biological impacts of OA on shellfish species growth at different life stages.

Author	**Link to Paper**	**Species**	**Life Stage**	**Carbonate Variable (what was measured during experiment)**	**Biological response variable**	**System Fully Constrained /Partially Constrained**	**Parameters constrained**	**Notes**
Michaelidis et al., 2005	http://www.int-res.com/articles/meps2005/293/m293p109.pdf	*M. galloprovincialis*	juvenile, adult	pH, pCO_2	Shell length, width and height (mm), shell length frequency, wet tissue weight (g), total body dry weight (g), shell dry weight (g), O2 consumption, Ammonia excretion, intracellular pH	Yes	pH, pCO2	
Fernández-Reiriz et al., 2012	doi: 10.3354/meps09660	*M. galloprovincialis*	juvenile	pH	AFDW (%), Consumption rate, ingestion rate	Yes	pH, TA	
Range et al., 2012	doi: 10.1016/j.jembe.2012.05.010	*M. galloprovincialis*	juvenile	pH	Growth Rate, Dry Tissue Weight, Condition Index, Ashed Shell, Ash free shell weight	Yes	pH, TA (TA discrete)	
Kroeker et al., 2014	http://journals.plos.org/plosone/article?id=10.1371/journal.pone.0100353	*M. galloprovincialis*	juvenile, adult	pH, TA	dry weight tissue and shell (g), change in volume (weight wet) mg/cm^3	Yes	pH, TA (discrete samples)	
Kurihara et al., 2008	doi: 10.3354/ab00109	*M. galloprovincialis*	larvae	CO_2	% at each stage (1-cell 2-cell 4-cell Morula Gastrula Trochophore D-larva Abnormal), % normal (at d-hinge), shell length (um), shell height (um)	Yes	pH, TA	
Frieder et al., 2014	doi: 10.1111/gcb.12485	*M. galloprovincialis*	larvae	pH, O_2	Shell length (um)	Yes	pH, TA (both discrete)	Did not include data that show means of the proportion of veligers in pH treatments as a percentage of veligers in stable ambient pH on day 2.

Table G-1 (Continued) | List of studies on biological impacts of OA on shellfish species growth at different life stages.								
Author	**Link to Paper**	**Species**	**Life Stage**	**Carbonate Variable (what was measured during experiment)**	**Biological response variable**	**System Fully Constrained /Partially Constrained**	**Parameters constrained**	**Notes**
Waldbusser et al., 2014	doi: 10.1038/nclimate2479	*M. galloprovincialis*	larvae	pCO_2, Omg. Ar.	shell length, prop. normal	Yes	pCO2, DIC	
Cole et al., 2016	doi: 10.1007/s00227-016-2880-4	*O. angasi*	larvae	CO_2, Temp, Food	Shell Length, Mortality, % abnormal	Yes	pH, TA	
Buckham et al., 2015	http://cedar.wwu.edu/wwuet/451/?utm_source=cedar.wwu.edu%2Fwwuet%2F451&utm_medium=PDF&utm_campaign=PDFCoverPages	*O. lurida*	larvae	CO_2	Growth Rate, Shell length, shell weight	Yes	pH, TA	
Hettinger et al., 2012	doi:10.1890/12-0567.1	*O. lurida*	larvae, juvenile	pH, TA	shell growth, shell area	Yes	pH, TA (discrete samples)	
Hettinger et al., 2013	doi: 10.1111/gcb.12307	*O. lurida*	larvae	pCO_2	Shell length (um), AFDW, % metamorphosis	yes	TA, DIC (discrete bottle samples + pH meter)	
Waldbusser et al., 2016	doi: 10.1002/lno.10348	*O. lurida*	larvae	pCO_2, Omg. Ar.	Shell length, prop. Normal	Yes	pCO2, DIC	