SWINOMISH CLIMATE CHANGE ADAPTATION STRATEGIES FOR SHELLFISH

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Swinomish Indian Tribal Community

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EXECUTIVE SUMMARY

Shellfish populations support globally-important fisheries, provide valuable ecosystem services, and sustain resource-dependent Indigenous communities. Yet shellfish populations are already facing myriad environmental changes that directly impact biological and ecological attributes of these species, which in turn affects recruitment into fisheries and the ability of shellfish to contribute to important ecosystem processes. Climate change (CC) and ocean acidification (OA) are two of the primary threats facing shellfish populations today, and as greenhouse gas emissions continue to rise, the likelihood will increase of significant shellfish loss and related damage to coastal communities. Native communities in particular will be disproportionately affected by these changes in shellfish populations, due to a strong sense of place embedded in Indigenous cultures and the fixed boundaries of reservations, which prevent traditional migration and delineate harvest areas. In recognition of the threats facing their people, many Indigenous communities are leading efforts to address climate impacts and identify strategies to reduce risk for natural and human systems.

The Swinomish Indian Tribal Community (SITC) is comprised of Coast Salish peoples originating from tribes and bands in the Skagit and Samish watersheds and surrounding coastal area and islands in Washington state. They are the People of the Salmon and have depended on coastal and upland resources, such as salmon, shellfish, cedar, and wild game, since time immemorial. Shellfish in particular play an important role in the Swinomish moral and cultural belief system and link an extensive network of values and practices. Consequently, when these traditional foods and their habitats are impaired, the overall health and wellbeing of the Tribe is negatively affected. Therefore in 2009, SITC conducted a vulnerability assessment and risk analysis to assess potential climate change impacts on the Reservation, and developed an adaptation action plan, which included community adaptation goals such as seeking off-Reservation harvest sites, restoration of shellfish populations, and maintenance of biodiversity, among others. There was also a short list of adaptation actions to address the community goals; however, they reflected the science at the time and were relatively broad for shellfish. Due to the importance of shellfish to SITC health and wellbeing, the Fisheries Department developed this shellfish-specific report based on new scientific research and included traditional harvest areas on and off the Reservation. The aim of CCASS is not a comprehensive literature review or exhaustive list of all possible actions, but a guide to direct further action and research for the Fisheries Department or other departments within the Tribe.

To identify adaptation strategies that reduce the vulnerability of SITC shellfish resources to current and expected climate change effects and strengthen the resilience of humans and nonhumans, we conducted an extensive literature review focusing on (1) climate change and ocean acidification impacts on shellfish and (2) mitigation and adaptation strategies from peer-reviewed publications, gray literature, tribal adaptations plans, regional vulnerability assessments, and input from Swinomish leaders and staff. We also adopted an ecosystem-level, nature-based approach in developing adaptation strategies that incorporate both Indigenous knowledge and western science.

Here, we present four broad and well-supported strategies, with goals that provide direction on how to implement each strategy and a list of adaptation actions specific to SITC to catalyze efforts and provide examples of local implementation. Shellfish remain under-researched, and the known impacts of CC and OA vary by species, life stage, and co-occurrence, with other confounding variables and stressors. Thus, some of the content addresses knowledge gaps that will better inform management decisions. Before

Swinomish or any agency implements a management action, we recommend the following systematic approach: (1) conduct or review findings of a vulnerability assessment and risk analysis specific to the action goal, (2) involve all affected parties in the decision-making process to ensure transparency and inclusivity, (3) employ a robust, transparent analysis to evaluate all feasible options to determine the optimal action, and (4) monitor the impacts to determine success and share lessons learned. Once established, these efforts should promote the availability of and access to tribally-important shellfish resources under changing ocean conditions for current and future generations.

Strategy 1: Healthy, intact ecosystems are more resilient to stressors than degraded ecosystems and can provide multiple co-benefits to human and nonhuman communities, including functioning habitat for shellfish species. We also know that **preserving intact ecosystems** is easier, more successful, and more cost-effective than active restoration, which cannot guarantee the return of baseline ecosystem functioning and services.

Goal 1.1: Protect intact critical transition zones (CTZ) and facilitate shoreward migration.

Intertidal marshes, coastal wetlands, beaches, and bluffs are all critical transition zones that link terrestrial and marine environments and provide myriad ecosystem services such as nutrient cycling, sediment trapping, carbon sequestration, and recreational sites for humans. Because the functioning within CTZs is dependent on the conditions of nearby ecosystems, areas upland and adjacent to CTZs should be conserved.

Suggested adaptation actions: (1.1.1) prioritize CTZs that conserve ecosystem connectivity, representation, and redundancy; (1.1.2) protect important juvenile Dungeness crab habitat by conserving intact tidal flats and adjacent tidal channels; (1.1.3) ensure inclusion of climate change projections when developing CTZ protection plans; (1.1.4) collect shellfish species abundance and habitat use data at various life stages to identify and prioritize critical habitat.

Goal 1.2: Protect seagrass beds and kelp forests.

Seagrass (which includes eelgrass) and kelp, collectively known as macrophytes, form dense aggregations and are among the world's most productive habitats that support diverse assemblages of nearshore species and provide a suite of ecosystem services and functions. Macrophytes are important primary producers that provide a critical food source for nearshore food webs and help mitigate the impacts of climate change by sequestering carbon, ameliorating OA conditions, and protecting shorelines from sea level rise.

Suggested adaptation actions: (1.2.1) protect existing eelgrass and kelp beds, (1.2.2) monitor kelp and eelgrass beds to identify conservation areas, (1.2.3) investigate local effects of kelp beds on seawater chemistry, and (1.2.4) research how certain environmental and ecological factors may influence kelp and eelgrass beds.

Goal 1.3: Protect climate and ocean acidification refugia.

Although anthropogenic climate change is predicted to occur at unprecedented rates, refugia may again play an important role in protecting particular organisms. For shellfish, the main parameter targeted for refugia is seawater chemistry via finding regions that may have higher capacity to protect calcifying organisms against ocean acidification.

Suggested adaptation actions: (1.3.1) encourage seaweed farming near tribally-important clam beaches and (1.3.2) identify operative refugia at various spatial and temporal scales for target species.

Strategy 2: Three primary drivers negatively affecting marine health are changes in land and sea use, direct exploitation of organisms, and pollution. These drivers encompass a wide range of stressors from coastal development and bottom trawling to road and agricultural runoff. The cumulative effect results in habitat destruction, loss of biodiversity, and impaired ecosystem functioning. Therefore, to enhance species, ecosystem, and community resilience to climate change, we must **reduce non-climate stressors**.

Goal 2.1: Reduce nutrient loading.

Inputs of nitrogen and phosphorous from upland sources can cause eutrophication in surface waters, which encourages algae blooms. As blooms subside, the decomposition of excessive plant and algae biomass lowers pH and can lead to hypoxic conditions, exacerbating OA and CC impacts on shellfish species.

Suggested adaptation actions: (2.1.1) increase monitoring of nutrients and harmful algal blooms in Whidbey Basin and northern Puget Sound, (2.1.2) enhance shellfish production (via appropriately-located commercial or conservation aquaculture projects) as a bioremediation technique in low dissolved oxygen and high nitrogen input areas, (2.1.3) encourage use of sustainable Indigenous and western farming and agricultural practices to reduce major sources of pollutants to the watershed.

Goal 2.2: Monitor toxic pollutants.

Coastal waters contain some of the highest levels of metals and pollutants, primarily from industrial discharges and urban and agricultural runoff. Additionally, ocean acidification can change water chemistry, making metals more abundant; because many shellfish are filter feeders, they can readily uptake metals, which can impact human health.

Suggested adaptation actions: (2.2.1) increase monitoring of toxic pollutants in Whidbey Basin and northern Puget Sound and (2.2.2) ensure oil spill response resources are sufficient to address spill risks, protocols are updated, and execution is efficient.

Goal 2.3: Promote sustainable harvest management practices.

To ensure long-term access to shellfish resources, fisheries must employ harvest management practices that promote robust shellfish populations under changing ocean conditions.

Suggested adaptation actions: (2.3.1) restore ancient Indigenous shellfish mariculture practices, (2.3.2) utilize best available science and fill research gaps to better inform sustainable harvest management policies, and (2.3.3) reduce fisheries-related mortality through research and outreach.

Strategy 3: The past 150+ years of development have fragmented and simplified the shoreline, impairing physical processes and resulting in loss of habitat and biota. Thus, restoration efforts should focus on **restoring physical, ecosystem-forming processes to promote landscape biodiversity and functioning**.

Goal 3.1: Restore hydrologic and geomorphic connectivity.

The degree of connectivity in the nearshore environment regulates the frequency, magnitude, and transfer of material, energy, and biota that support ecosystem structure and function. However, Salish Sea shorelines are highly fragmented and modified, which can lead to long-term impacts on shellfish habitat viability. Restoration of critical transition zones and geomorphic processes should aim to create nearshore regions that closely resemble nondegraded shellfish habitat.

Suggested adaptation actions: (3.1.1) restore sediment supply by removing hard armoring along erosional bluffs and beaches; (3.1.2) restore tidal flow and freshwater input in Skagit, Snohomish, and Stillaguamish river deltas; (3.1.3) conduct site-specific surface elevation studies to better understand sediment dynamics and restoration options; (3.1.4) enhance regulatory and permitting procedures to protect hydrologic and geomorphic processes; and (3.1.5) encourage soft armoring or living shoreline strategies.

Goal 3.2: Conserve the natural composition and configuration of ecosystems.

We must ensure that restoration areas are sited where the surrounding landscape (within drift cells and upland) can also support current and future ecosystems (e.g., a restored marsh may be able to regress naturally landward with sea level rise if the project is located adjacent to gently sloped shorelines).

Suggested adaptation actions: (3.2.1) prioritize protecting ecosystems that are rare, vulnerable, or have declined the most in size or quantity; and (3.2.2) identify key ecosystems that support vulnerable life stages or population sources.

Strategy 4: Ecosystems with high diversity are more resilient to climate events, disease, and invasion from exotic species. Therefore, to promote healthy, abundant shellfish resources under changing environmental conditions, conservation efforts should **protect and enhance native species and ecosystem biodiversity**.

Goal 4.1: Enhance presence and abundance of native ecosystem engineers.

Habitat-forming species, such as kelp, seagrass, salt marshes, and bivalves, are critical to the structure, productivity, and resilience of coastal ecosystems. Protecting ecosystem engineers (species that create or modify habitat, such as oysters), particularly in climate refugia locations, should be a conservation priority.

Suggested adaptation actions: (4.1.1) restore native Olympia oysters, (4.1.2) restore eelgrass and kelp beds by reducing non-climate-related stressors, (4.1.3) utilize conservation aquaculture to support sustainable restoration and stock enhancement efforts of native species, (4.1.4) encourage the collection of oyster shells for reuse in restoration projects, and (4.1.5) conduct genetics studies on native shellfish populations to identify appropriate augmentation strategies.

Goal 4.2: Monitor native and non-native species abundance and distribution.

There is evidence of intertidal species in the North Pacific expanding their range north, as well as an increase in abundance of warm-adapted species and decrease in cold-adapted species. Understanding where population shifts are occurring in the Salish Sea will inform conservation, restoration, and management efforts.

Suggested adaptation actions: (4.2.1) collect long-term biological datasets to track changes, (4.2.2) collect long-term abiotic datasets to track changes in habitat conditions and inform management practices, (4.2.3) monitor invasive species and impacts on local ecosystems, and (4.2.4) monitor disease in targeted species.

Goal 4.3: Reduce impacts of extreme weather events on important shellfish beds and nursery habitats.

Anthropogenic climate events (e.g., marine and atmospheric heat waves, freezing events, extreme heat waves) are causing mass mortalities and disease outbreaks among shellfish in the nearshore environment. Sea level rise will contribute to increased impacts of storm surge and other large wave events capable of inundating and eroding important intertidal shellfish beds and nursery habitats. Identifying effective temporary refuge techniques for target populations during these extreme events may reduce stress and the occurrence of rapid population decline.

Suggested adaptation actions: (4.3.1) research and identify effective techniques to provide temporary refuge for targeted shellfish populations during extreme weather events and (4.3.2) create a rapid response team to coordinate on-the-ground efforts to implement temporary refuge strategies.

ABBREVIATIONS

CCASS = Swinomish climate change adaptation strategies for shellfish
CTZ = Critical transition zones
DO = Dissolved oxygen
ENSO = El Niño-Southern Oscillation
GHG = Greenhouse gases: carbon dioxide, methane, nitrous oxide, ozone
HAB = Harmful algal bloom
OA = Ocean acidification
PDO = Pacific Decadal Oscillation
NPGO = North Pacific Gyre Oscillation
SITC = Swinomish Indian Tribal Community
SLR = Sea level rise
SST = Sea surface temperature
U&A = Usual and accustomed
WA DOE = Washington Department of Ecology

CLIMATE CHANGE ADAPTATION STRATEGIES FOR SHELLFISH

INTRODUCTION

Purpose

The purpose of the Swinomish Climate Change Adaptation Strategies for Shellfish (CCASS) report is to guide research and adaptation efforts of the Swinomish Indian Tribal Community's (SITC) Fisheries Department and other SITC departments. Once established, these efforts should promote the availability of and access to tribally-important shellfish resources under changing ocean conditions for current and future generations. The guiding concepts, strategies, goals, and actions presented in this report were derived from peer-reviewed scientific literature and technical reports on climate change (CC) impacts and adaptation strategies, as well as input from Swinomish tribal members, resource managers, and restoration practitioners.

Swinomish background

The Swinomish are Coast Salish peoples originating from tribes and bands in the Skagit and Samish watersheds and surrounding coastal area and islands in Washington state. They are the People of the Salmon and have depended on coastal and upland resources, such as salmon, shellfish, cedar, and wild game, since time immemorial. These Swinomish foods, or traditional foods, and the activities associated with them, including harvest, preparation, celebration, and sharing, are central to the Swinomish way of life. The Tribe is a federally recognized sovereign nation that retained treaty-protected fishing rights, including shellfishing, which extend over its treaty-time usual and accustomed fishing areas (U&A), both on and off its reservation. The heart of the much broader U&A area is shown in Figure 1.

To exercise these treaty rights and support the health and wellbeing of SITC, community members must be able to access abundant natural resources that persist in and support a healthy environment (NWIFC 2011). Shellfish in particular play an important role in the Swinomish moral and cultural belief system. In addition to providing a reliable, high-protein food source, shellfish are cultural keystone species that link an extensive network of values and practices (Garibaldi & Turner 2004). For example, clam harvests provide educational opportunities where elders can share teachings with youth that honor and reinforce community values and traditional practices (Donatuto et al. 2011, 2014, 2020). Clams, oysters, and crab are also a large component of the subsistence-based economy, which relies on functioning community relationships that are strengthened during ceremonies and gatherings to ensure nutritious foods are shared among tribal members and, in particular, elders (Usher et al. 2003, Donatuto et al. 2011). Additionally, shellfish comprise a substantial portion of the SITC market-based economy. Tribal members harvest crab, shrimp, intertidal clams, geoducks, sea urchins, sea cucumbers, and oysters, among other species, throughout their traditional fishing grounds, and are active participants in the local and global seafood market. Thus, shellfish provide cultural, physical, and economic sustenance. Consequently, when these traditional foods and their habitats are impaired, the overall health and wellbeing of the Tribe is negatively affected (Figure 2; Turner et al. 2008, Donatuto et al. 2011).

Shellfish ecosystem services

Shellfish also provide a number of ecosystem services that contribute to the functioning and resilience of marine ecosystems (Gazeau et al. 2013, Rullens et al. 2019). For example, shelled mollusks act as biofilters removing particles and pollutants from the water column, provide habitat structure and stabilize shorelines, and support nutrient and carbon cycling. Shellfish are also a food source for other organisms, like other shellfish species and native salmonids, and link benthic and pelagic systems (Gutiérrez et al. 2003, Newell 2004, Smaal et al. 2019). Additionally, many shellfish species, including crab and sea cucumbers, are detritivores and deposit feeders that provide nutrient decomposition and cycling, and mix sediment particles via bioturbation (reviewed in Prather et al. 2013). Although the capacity of shellfish to deliver these ecosystem services depends on various factors (e.g., individual species traits, population density, habitat quality, ecosystem connectivity), these marine invertebrates stabilize the food web, enhance biodiversity,

SWINOMISH INDIAN TRIBAL COMMUNITY

The Swinomish Indian Tribal Community makes no claim as to the completeness, accuracy, or content of any data contained herein. This map is not intended to reflect the exterior boundaries of the Swinomish Indian Reservation. No part of this document may be reproduced without prior permission of the Swinomish Indian Tribal Community. Greiner_map_JB_Edits.aprx, jtully, 2/22/2024.

Figure 1. The Swinomish Indian Tribal Community is a federally recognized sovereign nation that retained treaty-protected fishing rights, including shellfishing, that extend over its treaty-time usual and accustomed fishing areas (U&As), both on and off its reservation. The heart of the much broader U&A area is shown in this map.

improve water quality, promote productivity and resiliency in coastal ecosystems, and benefit human health and wellbeing (Doney et al. 2012, Parker et al. 2013, Gazeau et al. 2013). Consequently, tribes, government agencies, nonprofit organizations, and local residents are working to protect and restore native shellfish populations (State of Washington 2016, PSP 2018).

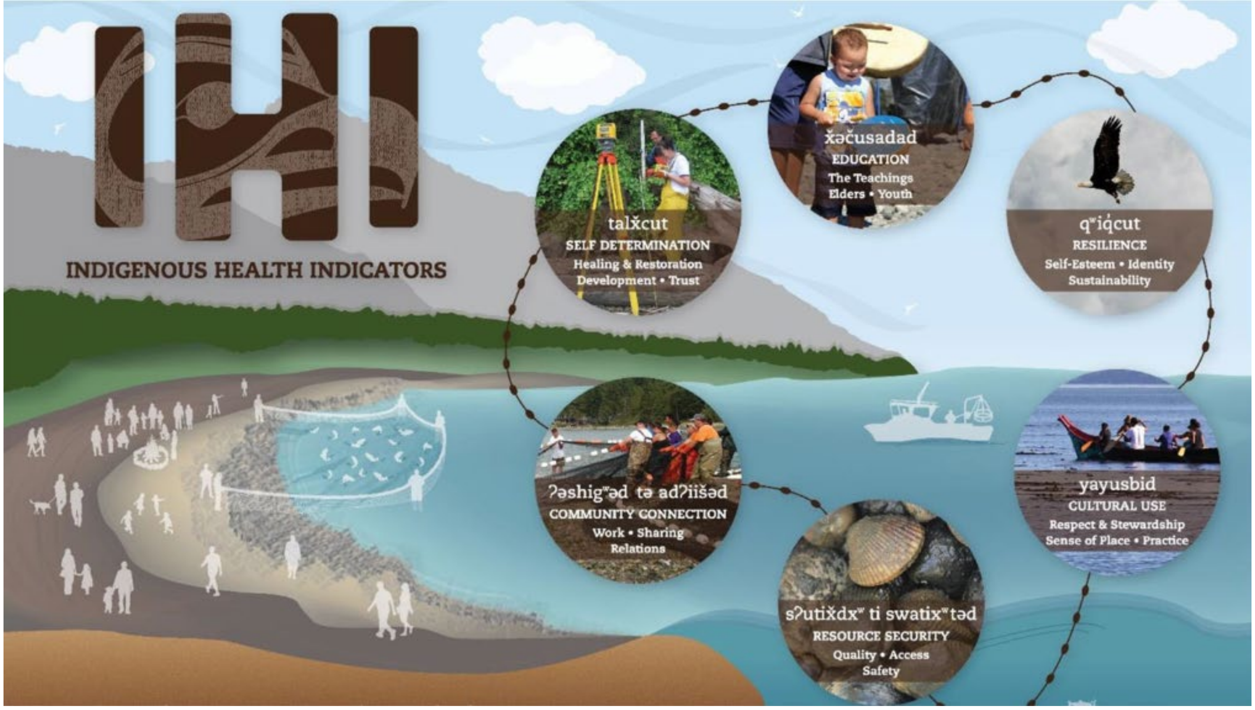

Figure 2. Swinomish Indigenous Health Indicators are community-scale, non-physical aspects of health identified by the community, which are integral to health and wellbeing and reflect deep connections between humans, the local environment, and spirituality (Donatuto et al. 2020).

Climate change & ocean acidification

Globally, there has been a decline in shellfish populations due to myriad factors, including overfishing, pollution, and habitat loss (Beck et al. 2009, Staudt et al. 2013, NWIFC 2016a). This report focuses on two primary threats facing shellfish populations: climate change and ocean acidification. Climate change, caused by the anthropogenic release of greenhouse gases (GHG) into the atmosphere, is altering the climate system and ocean conditions at an unprecedented rate, threatening human well-being and planetary health (Caldeira & Wickett 2003). Since the mid-1800s, fossil fuel combustion, deforestation, and intensive agriculture have increased the concentration of carbon dioxide (CO_2) in the atmosphere by 40%. This sharp uptake of energy by Earth's climate system is resulting in long-lasting and irreversible changes in the environment (IPCC 2014). For example, compared to the preindustrial period, global temperature has increased over 1.1° C, and in the last century, sea surface temperatures (SST) have increased 0.7° C, the majority of the world's glaciers have shrunk significantly, and sea level has risen 0.2 m (Vaughan et al. 2013, Huang et al. 2015, IPCC 2023a). These global changes are triggering feedback loops and domino effects that further alter physical and geochemical parameters (Hoegh-Guldberg & Bruno 2010). Cascading impacts can be observed in the warming of the upper ocean, accelerating the melting of sea ice and driving more intense storms while also increasing stratification in the water column, altering circulation and nutrient availability, and decreasing oxygen concentrations (Gruber 2011, Doney et al. 2012, IPCC 2014).

While the majority of anthropogenic CO_2 emissions remain in the atmosphere, approximately 30% of emissions have been absorbed into the ocean and are altering the carbonate chemistry of seawater. This phenomenon, called ocean acidification (OA), is the result of a series of chemical reactions that ultimately decrease seawater pH; reduce the availability of calcium carbonate minerals used to build and maintain shell, skeletons, and exoskeletons; and increase the occurrence of conditions that dissolve shell (Orr et al. 2005, Andersson & Mackenzie 2011). Since the Industrial Revolution, ocean pH has already decreased by 0.1, which is equivalent to a 26% increase in acidity, and is predicted to decline another 0.3-0.4 units by the end of the century (Feely et al. 2004, Sabine et al. 2004, Orr et al. 2005). Alterations in carbonate chemistry may affect metabolism and behavior in marine fishes and invertebrates (Briffa et al. 2012, Kroeker et al. 2013, Munday et al. 2013). However, calcifying organisms will be most impacted due to their characteristically low capacity to regulate acid-base disturbances and need to balance biomineralization with other physiological processes (Lannig et al. 2010, Parker et al. 2013, Gazeau et al. 2013). Dissolution in calcifying plankton is already being observed in current ocean conditions along the west coast of the U.S. Many of these species are now exhibiting decreased growth and survival (McLaskey et al. 2016, Bednaršek et al. 2020). Impacts at lower trophic levels can propagate up through the food web and affect fish catches and food security (Cheung et al. 2018). Scientific findings to date suggest that biological responses to OA vary among taxa, species, and life stage, making it difficult to predict impacts at the organismal, population, and ecosystem level (Doney et al. 2020). Geologic records indicate that, although changes in carbonate chemistry may appear small, they are occurring at an unprecedented rate and magnitude (Hoegh-Guldberg & Bruno 2010, Ciais & Sabine 2013). Moreover, OA, SST warming, and deoxygenation are all occurring simultaneously and resulting in synergistic effects on marine life (Pörtner & Peck 2010, Gruber 2011, Bopp et al. 2013).

In general, it is well known that these global environmental changes can directly influence biological processes (e.g., metabolism, respiration) and life history characteristics (e.g., development, reproduction) of organisms. This in turn will affect ecological attributes (e.g., larval dispersal, population connectivity, local adaptation) and ecosystem processes (e.g., nutrient cycling, community dynamics) (Hoegh-Guldberg & Bruno 2010, Pörtner & Peck 2010, Byrne & Przeslawski 2013). Impacts from CC are already being observed at this larger scale in shifting geographic ranges, species abundances, and predator-prey interactions, as well as substantial losses in biodiversity (Scavia et al. 2002, Mawdsley et al. 2009, Poloczanska et al. 2016). In the marine environment, alterations in primary productivity and biodiversity are compounded by impacts from other human activities (e.g., pollution, over harvesting, and land use changes) that impede the ability of organisms to respond to CC (Campbell et al. 2009). The combination of all these threats is expected to reduce fisheries productivity and other essential ecosystem services that support resiliency in coastal systems and communities (Boström et al. 2011, IPCC 2014, Barange et al. 2018).

Indigenous communities & climate-related change

As greenhouse gas emissions continue to rise, the likelihood of severe, pervasive, and irreversible impacts on ecosystems and communities, especially those dependent on agricultural or coastal livelihoods, will increase (Holsman et al. 2018, IPCC 2018, 2023a). Native communities in particular will be disproportionately affected due to a strong sense of place embedded in Indigenous cultures and traditional knowledge, as well as the fixed boundaries of reservations and U&As, which prevent traditional migration and delineate harvest areas (NWIFC 2016b, IPBES 2019). As CC alters habitat for tribally-important species in traditional territories, it will impact treaty rights, food sovereignty, and cultural identity (Dussias 2010, Voggesser et al. 2013, NWIFC 2016b). Communities in Alaska and Washington are already grappling with displacement due to increased erosion, inundation from sea level rise (SLR), and increased storm surge. Moreover, rising seawater temperatures and changes in ocean chemistry are predicted to exacerbate existing health issues in Indigenous communities by contaminating food and water resources with pollutants and increasing exposure to waterborne and food-borne pathogens and toxins. The effects of CC also occur in the context of colonialism and oppression, which have affected economic resources and the adaptive capacity of Indigenous communities (Norton-Smith et al. 2016, IPCC 2023a). Nevertheless, Indigenous communities are extremely resilient, with a long history of adaptive resource management. They are leading efforts to address climate impacts and identify strategies to reduce risk for natural and human systems (Norton-Smith et al. 2016). Importantly, many treaty tribes in the Puget Sound region have conducted their own CC analyses and are at the forefront of CC research (NWIFC 2016b).

For SITC, the Tribal Senate launched a Climate Change Initiative in 2008 to assess potential CC impacts on the Reservation and determine appropriate actions to protect community residents and resources. This Initiative led to a two-year study with the University of Washington's Climate Impacts Group and the Skagit River System Cooperative to identify potential climate impacts on the Reservation, as well as to conduct a vulnerability assessment and risk analysis. The work culminated in the release of an Impact Assessment Technical Report (2009) and the Climate Adaptation Action Plan (2010). These landmark documents outlined findings from the analyses and goals to address CC impacts based on the best available science and community input. A general assessment on shellfish populations on the Reservation determined that the potential impacts and level of estimated risk (vulnerability x probability) included (1) increasing inundation of tidelands (medium-high), (2) weakened viability due to habitat changes (medium-high), and (3) potential loss of harvest sites and opportunities due to impacts to shellfish populations and habitat (high) (SITC 2009). Five community adaptation goals were then identified to address those impacts (SITC 2010):

1. Fishery and shellfish resources and habitat of the Reservation should be restored and enhanced, maintaining traditional livelihood based upon these resources.
2. Seek off-Reservation sites for shellfish harvest/cultivation.
3. Preserve ability to fully exercise treaty rights and cultural practices and to improve physical and spiritual health.
4. Reestablish natural diversity in harvestable clam populations.
5. Biotic productivity and species diversity within the coastal zone should be maintained and enhanced.

Due to a paucity of scientific understanding on CC and OA impacts on shellfish species at the time these documents were published, potential shellfish adaptation strategies suggested in the Action Plan were broad and primarily noted the need for more research. However, the impact of reduced shellfish availability to community health and wellbeing was clearly stated, and the need to increase the internal capacity of the SITC Fisheries Department in order to ensure shellfish resources are available for future generations, even under changing ocean conditions, was emphasized.

Content & scope

This report builds upon SITC's climate work by expanding the spatial scope to encompass the Tribe's U&A and focusing specifically on shellfish resources. Since 2010, there has been a substantial increase in the number of scientific studies examining CC impacts on shellfish species, and the capability of computer modeling to predict climate impacts at finer scales has improved. Furthermore, the list of potential adaptation strategies targeting shellfish has grown. Although many uncertainties and gaps in knowledge remain, enough is known to take action. Moreover, as time passes and GHG emissions continue, the opportunity and effectiveness of adaptation actions decreases and the cost of action increases (Maxwell et al. 2015, IPCC 2018, 2023a). The aim of the CCASS is to address the shellfish-specific community goals outlined in the Action Plan. However, the content herein supports SITC goals for other sectors in the Climate Adaptation Action Plan as well as the Tribe's mission and Tribal Code. The CCASS is not a comprehensive literature review or exhaustive list of all possible actions; instead it is a guide to direct further action and research.

METHODS

Study area

The Salish Sea is a large fjord-like estuary that straddles the U.S.–Canada political border and encompasses the Strait of Georgia, the Strait of Juan de Fuca, and Puget Sound. The waters are influenced seasonally by the Pacific Ocean; freshwater outflow predominantly from the Fraser, Skagit, Stillaguamish, and Snohomish rivers; semi-diurnal tides; and wind stress. In Puget Sound, circulation can be characterized as a stratified two-layer system with an inflow of nutrient- and CO_2-rich saline water in the lower layer and outflow of fresher water in the surface layer (Moore et al. 2008, Banas et al. 2015). The system experiences relatively rapid flushing, however, the complex bathymetry of the Sound creates interconnected sub-basins with unique local oceanographic processes like tidal mixing and river runoff, which result in different circulation and residence times (Sutherland et al. 2011, Khangaonkar et al. 2011, MacCready et al. 2021). Subsequently, the water parameters in Puget Sound vary spatially by sub-basin and water depth, and temporally at daily, seasonal, and interannual scales (Babson et al. 2006, Feely et al. 2010, Khangaonkar et al. 2018). Biological processes (e.g., photosynthesis and respiration) also influence local water properties and can be amplified by human activity like eutrophication, which results in hypoxic, low pH conditions (Feely et al. 2010, Mohamedali et al. 2011, Roberts et al. 2014). In general, Puget Sound SST ranges from 6.6-19.3° C, 7.77-8.25 pH, and residence time of 139-157 days (Babson et al. 2006, Moore et al. 2008, Feely et al. 2010, MacCready et al. 2021).

Puget Sound also has an extensive land-water interface containing rocky shoreline, beaches, embayments, and deltas. These dynamic landforms are linked by geomorphic processes that historically created and maintained habitat for diverse flora and fauna (Shipman 2008). Recent human modifications on the shore have disrupted these natural processes by installing tidal barriers, armoring, and artificial shoreforms, which has simplified and shortened the shoreline. In addition to habitat loss and shoreline development, this highly altered system also experiences pollution, alteration of freshwater flows, and overfishing, which threaten the biologically-diverse estuarine system (Fresh et al. 2011, Simenstad et al. 2011).

The Swinomish traditional territory for shellfish harvest is located in the center of the Salish Sea, predominantly in the San Juan Islands, the Strait of Georgia, and Whidbey and Admiralty Inlet (or North Central Puget Sound) sub-basins. Specifically, the area consists of the southern section of the Strait of Georgia, the San Juan Islands, the northern inland waters of Bellingham and Samish Bay, the eastern section of the Strait of Juan de Fuca, and the majority of Whidbey Basin and Admiralty Inlet (Figure 1).

Approach

To generate the strategies, goals, and actions in this report, we conducted an extensive literature review that focused on: (1) climate change and ocean acidification impacts on shellfish and (2) mitigation and adaptation strategies. Documents that we reviewed included peer-reviewed literature and agency 'gray' literature, including adaptation strategies from other treaty tribes, Northwest Indian Fisheries Commission's Tribal Habitat Strategy, Washington State's Integrated Climate Response Strategy, Washington State's Ocean Acidification Blue Ribbon Panel, Puget Sound Nearshore Ecosystem Restoration Project technical reports, and regional climate vulnerability assessments, among others.

Information regarding CC impacts, historical changes observed on shellfish resources, and potential adaptation strategies were also gathered during conversations with SITC's former Fisheries Manager, members of the Swinomish Fish and Game Commission, members of the SITC Fisheries Climate Change Program, SITC tribal members and staff, and restoration researchers and practitioners.

For our purposes, we use "shellfish" as a fisheries management term, referring to animals taxonomically identified as mollusks, crustaceans, and echinoderms (e.g., oysters, clams, crab, urchins, etc.).

RESULTS & DISCUSSION

Projected CC and OA impacts on study area

Under the IPCC's RCP 8.5 scenario, in which greenhouse gas emissions continue unabated, the North Pacific Ocean is predicted to experience high warming and acidification rates, a large decrease in subsurface oxygen, and a mixed response to net primary productivity due to changes in SST, upwelling, circulation, and ocean biogeochemistry. Specifically, models predict a minimum increase of 4° C in SST, a 0.12 decline in pH (~30% increase in acidity), an upward migration of calcite and aragonite saturation horizons, a -50 mmol m-3 in O_2 (i.e., decrease in dissolved oxygen), and continued acceleration in the rate of global mean sea level rise SLR (Feely et al. 2012, Bopp et al. 2013, Holsman et al. 2018).

In the Salish Sea, the global increase in atmospheric CO_2 and local eutrophication are the main drivers influencing estuarine conditions (reviewed in Bednaršek et al. 2021). The changes on the coast will coincide with alterations to freshwater input as air temperature is projected to increase an additional 2.2 °C by the midcentury. Rising air temperature will continue to reduce snowpack, melt glaciers, and increase precipitation, which will change the timing and magnitude of peak flows. There are approximately 400 glaciers in the Skagit headwaters alone that support late spring/early summer discharge (Lee & Hamlet 2011). River flow impacts salinity, which is a main driver for water circulation, influencing mixing and stratification and subsequently water properties, nutrient availability, and biological productivity (Khangaonkar et al. 2011, Mauger 2015). A decline in salinity, due to freshwater inputs or heavy rain events, is also associated with reduced pH and may exacerbate acidification. Compared to the coast, inland waters have a low buffering capacity to changes in pH (Ringwood & Keppler 2002, Feely et al. 2010, Fassbender et al. 2018). Air temperature also drives water temperature, therefore, the warming SST trends are expected to continue. Over the past century, SST on the coast and in Puget Sound have risen 0.5-1 °C and 0.4-0.9 °C, respectively. This will likely increase the occurrence of favorable growth conditions for harmful algal bloom species like *Alexandrium catenella*, resulting in an earlier and longer harmful algal bloom (HAB) season (Mauger 2015). Sea level is also expected to rise due to the thermal expansion of warmer ocean waters, melting land-based glaciers and ice caps, and melting of the Antarctic and Greenland ice sheets. However, the extent of change depends on global SLR and regional factors such as ocean currents, wind patterns, vertical land movement, and climate patterns such as El Niño-Southern Oscillation (ENSO). Most areas in Puget Sound will likely experience SLR by 2100, with a 50% probability relative sea levels will rise 0.61 m in the study area. Potential impacts from SLR include higher frequency and severity of flooding associated with high tides and storm surge, increased reach and energy of waves influencing sediment mobility, increased salinity of groundwater and porewater, and alteration of nearshore habitat (Mauger 2015, Miller et al. 2018, Raymond et al. 2018). In general, large river estuaries and human-modified shoreforms are projected to be less resilient to increased wave energy and SLR than barrier, sediment source, and rocky beaches (Beamer et al. 2020). Furthermore, a study conducted by Grossman et al. (2018) quantified biological communities along the western shoreline of the SITC Reservation in 2017 and utilized some of these data, combined with projections of SLR, to highlight site-specific habitat vulnerability of clams (Grossman et al., in prep). Interestingly, one of the most important shellfish beds for the Tribe is projected to face high levels of habitat loss, while another region may prove to be more resilient in the face of storm surge and SLR. These results highlight the differences in how shorelines and shellfish may respond to CC and SLR and emphasize the need for site-specific adaptation plans.

Projected CC and OA impacts on shellfish species

Predicting the direct impacts of CC and OA on mollusks, echinoderms, and crustaceans remains a complex endeavor, as physiological tolerances to key environmental factors varies by species and life-stage (see Table 1) (Melzner et al. 2009, Hale et al. 2011, Gazeau et al. 2013). In general, marine invertebrates are ectotherms and poor osmoregulators with limited capacity to adapt to environmental stressors, which can have additive, synergistic, or antagonistic effects that influence overall fitness (Pörtner 2008, Parker et al. 2013, Byrne & Przeslawski 2013). Changes in seawater temperature alone can alter metabolic and respiration rates, which impact calcification, growth, and development (Orr et al. 2005, Kroeker et al. 2013, Somero et al. 2016). If SST remains below physiological thresholds, an increase in SST can mitigate some impacts from OA. However, a recent habitat vulnerability model found that a 2° C in SST will likely lead to an increase in suboptimal and lethal nearshore habitat conditions for shellfish larvae, like Dungeness crab, in the Salish Sea (Gazeau et al. 2013, Beamer et al. 2020). Even suboptimal conditions can result in delayed development or reduced growth in early-life history stages and may have significant impacts on

Table 1: Generalized threshold relationships for specific physical environmental parameters for selected shellfish species utilizing nearshore habitats in the study area. ND = no known data source or thresholds not well understood relative to our predictive models, SST = sea surface temperature. From Beamer et al. (2020).

Species		**Life stage**	**Salinity**	**SST (^{0}C)**	**Dissolved oxygen**	**pH**	**References**
Metacarcinus magister	Dungeness crab	Larvae	Optimal 25-30	Megalopae only: Optimal 10-14; Optimal < 15-21; Extremely stressful > 22	High	Suboptimal < 7.1	(Reed 1969, Pauley et al. 1986, Sulkin & McKeen 1989, 1999, Holsman et al. 2003, Curtis & McGaw 2008, 2012, Rasmuson 2013, Miller 2015)
		Juveniles (instars)	ND	High mortality > 22	High	ND	
		Adults	Optimal 25-33, Suboptimal 16-24, Intolerable < 16	Optimal 7-15, Suboptimal 16-20, Extremely stressful > 20	High	ND	
Panopea generosa	Geoduck	Larvae	27-32	Optimal 6-16	High	ND	(Goodwin & Pease 1989)
		Juveniles	Saline	ND	High	ND	
		Adults	Optimal > 25; Tolerant 5-35	Spawn < 16	High	ND	
Leukoma staminea	Native littleneck clam	Larvae	Optimal 27-32	Optimal 10-15	High	ND	(Strathmann 1987)
		Juveniles	Saline	ND	High	ND	
		Adults	Optimal 24-31; Tolerant 20	Optimal 12-18	High	ND	
Saxidomus gigantea	Butter clam	Larvae	Optimal 20-29	Optimal 15	High	ND	(Quayle & Bourne 1972, Hiebert 2015a)
		Juveniles	Slow growth 5-15	ND	High	ND	
		Adults		Stressful < 5 and > 25	High	ND	
Clinocardium nuttallii	Cockle	Larvae	ND	Optimal 10-22; Lethal > 26	High	ND	(Gallucci & Gallucci 1982, Strathmann 1987, Liu et al. 2010)
		Juveniles	ND	ND	High	ND	
		Adults	ND	Lethal > 26	High	ND	

Table 1 continued.

Species		Life stage	Salinity	SST (^{0}C)	Dissolved oxygen	pH	References
Tresus sp.	Horse clam	Larvae	Optimal 27-29	Lethal > 20	High	ND	(Bourne & Smith 1972, Strathmann 1987, Harbo 1997, Coan et al. 2000, Hiebert 2015b)
		Juveniles	ND	ND	High	ND	
		Adults	ND	ND	High	ND	
Ruditapes philippinarum	Manila clam	Larvae	Optimal > 10	> 14	High	ND	(Bardach et al. 1974, Numaguchi 1998)
		Juveniles	ND	ND	High	ND	
		Adults	Optimal 24-32	Optimal 13-21; Spawn > 14	High	ND	
Ostrea lurida	Olympia oyster	Larvae	No growth or development ≤ 15	Vulnerable to high SST	High	Reduced shell growth, metamorphosis 7.8	(Strathmann 1987, Hettinger et al. 2012, 2013, Rippington 2015, Cheng et al. 2015, Barber et al. 2016, Gray & Langdon 2017, Hollarsmith et al. 2019)
		Juveniles	High mortality < 10 when exposed ≥ 5 days	Vulnerable to high SST	High	Reduced shell growth < 8.0	
		Adults	Feeding ceases < 10; Feeding effects 10-20; Optimum > 25	Brood > 10.5; Decreased survival > 14	High	ND	

recruitment and abundance of adult populations (Parker et al. 2010, Doney et al. 2012, Hettinger et al. 2012). Juvenile benthic invertebrates already experience high mortality rates (Gosselin & Qian 1997, Hunt & Scheibling 1997). These early-life history stages may act even more as a bottleneck under changing ocean conditions, as current research suggests planktonic and early benthic juvenile stages are most sensitive to stressors (Dupont et al. 2008, Pörtner 2010, Kroeker et al. 2013). Studies have shown abnormal and reduced shell development, elevated respiration rates, and behavior changes (e.g., reduced burrowing, delayed feeding) due to OA impacts on different carbonate chemistry variables (Talmage & Gobler 2010, Waldbusser et al. 2015, Clements & Hunt 2017). Although some species are able to produce shell under low pH conditions, it is an energetically costly process and can impair other biological functions, reduce thermal tolerance limits, and impact survival in later life stages (Lannig et al. 2010, Hettinger et al. 2012).

Additionally, shellfish utilize a variety of habitat types to complete their life cycle. Many species are broadcast spawners and complete fertilization, embryonic, and larval pelagic early-life history stages, then settle in benthic habitat for juvenile and adult stages where some remain sessile and others migrate. This exposes them to a range of conditions that vary spatially and temporally (Parker et al. 2013, Byrne & Przeslawski 2013). Ultimately, the level of stress on marine organisms will depend on the timing, duration, magnitude, and frequency of exposure to co-occurring variables, including temperature, pCO_2, dissolved oxygen (DO), and salinity (Pörtner 2008, Reum et al. 2014, Cheng et al. 2015). Efforts to expand CC and OA impacts to the population and/or ecosystem level is even more complicated, as there are fewer studies that focus on species' ability to acclimate or adapt and incorporate factors like predator-prey interactions and food availability. Furthermore, the studies that have investigated acclimatization or adaptation tend to be very species-specific, and while their results are certainly needed and helpful in understanding local impacts to this region, much more research is needed (e.g., Sunday et al. 2011, Gazeau et al. 2013, Kelly & Hofmann 2013, Kelly et al. 2013).

Guiding concepts

Need for mitigation and adaptation measures

It is not surprising that we are already observing ecological impacts due to CC and OA. Geological records from the past millions of years indicate that ecosystem shifts and species extinctions have occurred at natural global CC rates much lower than the current rate of anthropogenic CC (Caldeira & Wickett 2003, IPBES 2019, IPCC 2023a). Even though the cessation of emissions will still result in irreversible changes to critically important ecosystems, reducing the rate and magnitude of change will increase opportunities for organisms and coastal communities to adapt to changing ocean conditions and prevent positive feedback loops from amplifying the concentration of CO_2 and other GHG in the atmosphere [e.g., thawing of permafrost, Amazon rainforest switching from a carbon sink to a carbon source, melting of Greenland ice sheet (IPCC 2018)]. For example, limiting global warming to a 1.5 ºC increase instead of 2 ºC could reduce the number of people exposed to climate-related risks and poverty by several hundred million by 2050 and reduce the loss in global annual catch in marine fisheries by 1.5 million tonnes (IPCC 2018). Therefore, aggressive mitigation measures must be enacted immediately to significantly reduce anthropogenic CO_2 emissions and reach net zero by 2050 (Hoegh-Guldberg & Bruno 2010, IPCC 2018). Although this will require stricter measures than those agreed upon under the Paris Climate Agreement and necessitate far-reaching transitions in energy, land use, urban planning, infrastructure, agriculture, and human behavior (e.g., less resource-intensive diets and reduced consumption per capita), there is a wide range of mitigation options that already exist and would provide immediate benefits to human health and wellbeing (IPCC 2018, Gattuso et al. 2018). Moreover, reallocating funds that support fossil fuel subsidies, harmful agricultural practices, and over extraction of resources to energy efficiency, conservation agriculture, and ecosystem restoration can simultaneously reduce GHG emissions, improve air and water quality, and promote biodiversity and ecosystem services (Campbell et al. 2009, IPBES 2019, IPCC 2023a).

Although global collective action can more effectively address the climate problem, local adaptation efforts are easier to implement than global measures and can provide co-benefits to the environment and coastal communities (Barange et al. 2018, Gattuso et al. 2018). In the marine environment, adaptation actions typically focus on reducing non-climatic drivers such as pollution, overexploitation, and coastal development that affect the health of the environment and degrade ecosystem processes. Addressing these drivers locally helps reduce the exposure and sensitivity of species and ecosystems to climate-related impacts and can reduce disaster risk, food and water insecurity, and poverty in coastal communities, which in turn reduces resource exploitation and improves ecosystem resiliency (Halpern et al. 2015, IPCC 2018). Immediate implementation of no-regret measures that simultaneously address multiple indirect and direct drivers can provide early benefits, slow impacts on biodiversity and ecosystem loss, and improve adaptive capacity in coastal communities (Rau et al. 2012, Ekstrom et al. 2015, IPBES 2019). Because trade-offs and conflicts with other human needs and interests can undermine adaptation efforts, it is important to integrate natural and social science with traditional and local knowledge, account for socio-economic and gender inequality, promote education, and partner with local communities to identify societal and environmental needs and prioritize solutions (Ekstrom et al. 2015, Maxwell et al. 2015, Norton-Smith et al. 2016). Coordinating practices within watersheds and promoting integrated land management can also enhance the effectiveness and success of adaptation strategies and ensure efforts are complementary (Barange et al. 2018, Gattuso et al. 2018, IPBES 2019). Most importantly, while some adaptation measures can reduce climate-related drivers locally, efforts cannot address global climate impacts and are futile if the underlying cause, GHG emissions, are not significantly reduced. Furthermore, delay in both mitigation and adaptation efforts will increase costs, reduce flexibility in future response options, and diminish the feasibility and effectiveness of actions as GHG emissions continue to rise and CC impacts and risks intensify (Rau et al. 2012, Gattuso et al. 2015, IPCC 2023a).

Ecosystem-level approach

In the scientific literature, there is a strong focus on enhancing ecosystem resiliency so natural biological and geologic processes can allow systems to adapt to change and provide sufficient habitat to facilitate species adaptation (Scavia et al. 2002, reviewed in Campbell et al. 2009). This directs management to address CC at the ecosystem scale and requires the recognition of dynamic relationships between process, structure, and function. In the coastal environment, geomorphic processes create and maintain landforms, the composition and configuration of which influence the flow of material, energy, and biota, and therefore the overall functioning and delivery of ecosystem goods and services. Moreover, applying an ecosystem approach in a landscape ecology framework can place CC efforts in the appropriate context and allow change in landforms to be analyzed across multiple spatial and temporal scales (Boström et al. 2011). In addition to supporting ecosystem and species adaptation, improving ecosystem resiliency can enhance the delivery of particular adaptation services that benefit human adaptation and provide opportunities for biodiversity conservation. If necessary, additional protection for certain vulnerable or important species can be achieved by combining a species and ecosystem approach (LaRoe 1993, Franklin 1993). Ecosystem-based management also acknowledges the dependence of economic and social wellbeing on ecological sustainability, applies the precautionary principle, and promotes adaptive management, which is especially important due to system complexities and uncertainties (ICES 2005, Boesch 2006, Barange et al. 2018). For fisheries management in particular, addressing CC at an ecosystem level is a critical property for adaptation and resilience building because it allows multiple climate- and non-climate-related stressors to be evaluated, as well as the local ecosystem processes that modulate impacts on habitat and organisms (Barange et al. 2018, Lowe et al. 2019).

Utilize nature-based solutions

A prominent approach reported in climate adaptation documents is the ecosystem-based approach, or nature-based solutions, where the capacity of nature is used to buffer adverse impacts from CC on coastal communities and infrastructure. Healthy ecosystems (e.g., wetlands, oyster reefs, seagrass beds) can provide protective services that reduce the risk of erosion and flooding from increased tidal surge and SLR as well as benefits to carbon storage and sequestration, food security, sustainable water management, and livelihood diversification (Doney et al. 2012, Munang et al. 2013, IPBES 2019). When ecosystem services are properly valued and incorporated into cost-benefit analyses, the use of nature-based solutions is often more cost effective than hard-engineering infrastructure, which requires expensive maintenance, impacts biological and geomorphic processes, and operates on short time scales (Perkins et al. 2015, IPCC 2023a). For example, restoring wetlands in New Orleans for coastal protection has been estimated at $6 USD per square meter plus $14.3 USD million for freshwater diversion. Conversely, armoring levees cost $21-28 per square meter plus $17.6 million to heighten dykes, floodwalls, and dams, an approach which ultimately exacerbated flooding during Hurricane Katrina by locking flood waters in residential areas (Jones et al. 2012). Coastal structures can also interfere with tide, wave, and current parameters, altering sediment transport, nutrient cycling, and nearshore habitat characteristics and connectivity (e.g., Dethier et al. 2016). These changes can result in shifts in community assemblages, simplify trophic structure, and fundamentally change ecosystems while degrading their adaptiveness (Jones et al. 2012, Perkins et al. 2015). Although maladaptation can occur in nature-based solutions as well (e.g., introducing non-native species), appropriate application and robust planning in the restoration and conservation of ecosystems can avoid negative impacts and address a range of adaptation needs for species, systems, and humans (Maxwell et al. 2015). For example, several communities in the tropics are restoring mangroves to protect coastlines against erosion and wave damage, as well as to provide nursery habitat for fishes and promote sustainable fisheries (Maxwell et al. 2015).

Nature-based solutions can also be paired with soft and hard engineering. If hard infrastructure is deemed necessary, modifying seawalls to mimic pre-disturbance habitat by drilling pools and pits onto wall surfaces, or adding vegetation or habitat benches to rip-rap armoring, can increase community diversity and functional richness (Toft et al. 2013, Perkins et al. 2015). Additionally, management of hard infrastructure that maintains more natural hydrodynamic processes can provide coastal protection and reestablish ecosystem linkages. Jones et al. (2012) found that the seasonal opening of the Chinese Yangtze River sluice gates reversed issues of flooding, poor water quality, and habitat fragmentation by restoring connectivity between the Yangtze, major lakes, and associated wetlands. This more natural flow regime increased flood water retentions, water purification, and migration routes for spawning fishes as well as increased agricultural opportunities, incomes, and climate resilience in local communities (Jones et al. 2012). It is important to note that the effectiveness of nature-based solutions depends on the implementation of other mitigation and adaptation actions. Although risk of maladaptation and exposure to CC impacts in the long-term are lower using nature-based solutions than hard infrastructure, their ability to deliver benefits to human and nonhuman communities decreases as global warming and GHG emissions continue to rise (IPCC 2023a).

Incorporate Indigenous knowledge and priorities

Through experimentation and observation over millennia, Indigenous communities developed diverse portfolios of conservation and management strategies that promoted productive food systems and endured periods of environmental change and colonial expansion (Berkes et al. 2000, Folke 2006, Thornton et al. 2015). If integrated appropriately, Indigenous knowledge could strengthen conventional management strategies. In fact, many traditional methods are precursors to contemporary conservation and management approaches learned through adaptive management. They focus on maintaining ecosystem processes and function, and include resource rotation, management of landscape patchiness and multiple species, harvest restrictions, and protection of certain species or habitats that support specific life-history stages (reviewed in Jackley et al. 2016). Traditional management practices also accept that uncertainty and unpredictability are innate characteristics of ecosystems, allowing for flexibility and constant ingenuity directed by observations of the environment. These practices mimic natural processes occurring in the landscape and incorporate concepts of renewability and cycles of succession. This contrasts current resource management practices that focus on ecological stability and productivity yields, and are dependent on technologies that mask vulnerabilities and maintain business-as-usual strategies. Moreover, Indigenous knowledge and practices support a vibrant social-ecological system where the health of humans and nonhumans are interconnected. This is apparent in social mechanisms and governance protocols that promote sustainable management. Rules are created and enforced by resource users who have a rich base of ecological knowledge that reflects community values of reciprocity, respect, and humility (Berkes et al. 2000, Turner & Berkes 2006). Although there are challenges to successfully incorporate Indigenous knowledge and local values in adaptation practices, inclusion can increase the effectiveness and success of adaptation efforts (IPCC 2023a). Close collaboration between all resource managers and users can improve the identification of priority actions; creation of culturally appropriate, community-based strategies; and successful implementation (Norton-Smith et al. 2016, Reid 2016, Donatuto et al. 2020).

SHELLFISH ADAPTATION STRATEGIES

The strategies we have outlined in this report provide adaptation options that aim to reduce the vulnerability of SITC shellfish resources to current and expected CC effects and strengthen the resilience of human and nonhuman systems within the Tribe's U&A (IPCC 2014, Barange et al. 2018). It is clear that we must implement a combination of strategies (i.e., old, new, and still under development) to address the growing list of stressors degrading the integrity of the marine environment and undermining the services that humans depend on (Higgason & Brown 2009). As such, the following content integrates knowledge from multiple sources, disciplines, and time periods. Here we have presented four broad, well-supported **strategies** that reduce the impacts of CC on shellfish and promote opportunities for adaptation. Within each strategy, we have included **goals** that provide direction on how to implement the strategy. Lastly, **actions** specific to SITC are listed under each goal to catalyze efforts and provide examples of local implementation.

We recommend the following systematic approach before Swinomish or any agency implements a management action: (1) conduct or review findings of a vulnerability assessment and risk analysis, (2) involve all affected parties in the decision-making process to ensure transparency and inclusivity, and (3) employ a robust, transparent analysis to evaluate all feasible options to determine the optimal action. Criteria to consider in each analysis include climate- and non-climate-related factors, cost effectiveness, feasibility, benefits (especially proper valuation of ecosystem services), long-term effectiveness, and potential maladaptation (Gattuso et al. 2018). An optimal action would be examined within the larger context of the landscape and avoid further degradation, pollution, and exploitation of targeted and adjacent ecosystems and communities (Barange et al. 2018). Adaptation management should also be flexible and open to diverse strategies. Furthermore, we should orient goals within a range of acceptable outcomes and realistic timelines to cope with ecological succession, unexpected shocks, natural disasters, and changes in resource availability (Higgason & Brown 2009, Raymond et al. 2018, Barange et al. 2018). Adaptation projects should also incorporate monitoring so practitioners can assess the effectiveness of various actions and advance adaptation efforts (Goetz et al. 2004, Barange et al. 2018). Monitoring is a resource-intensive effort, but collaboration and strategic planning can reduce expenses and ensure that data is widely available to all interested parties.

Swinomish Shellfish Adaptation Strategy 1: Preserve intact ecosystems, especially those that support critical habitat or ecosystem services

Healthy, intact ecosystems are more resilient to stressors than degraded ecosystems and can provide multiple co-benefits to human and nonhuman communities, including functioning habitat for shellfish species. As a result, these places should be protected from anthropogenic threats and allowed to adapt naturally to environmental changes (reviewed in Greiner 2010, Munang et al. 2013, NWIFC 2019) (Figure 3). Additionally, addressing ecosystem resilience by protecting intact systems is easier, more successful, and more cost-effective than active restoration, which cannot guarantee the return of baseline ecosystem functioning and services (Roni et al. 2002, MEA 2005). Protecting natural processes that sustain a diverse landscape of shoreforms not only supports species, assemblages, and communities, but allows organisms access to different habitat types and an opportunity to utilize their full range of adaptive responses (Boström et al. 2011, Maxwell et al. 2015). Ecosystems can also be targeted to protect critical habitat for specific species or protect ecosystems that provide certain functions and services for human communities, like coastal protection, sequestration of carbon, water filtration, or opportunities for landward migration

(Campbell et al. 2009, Boström et al. 2011, Weatherdon et al. 2016). However, it is important that protected areas do not preclude tribal practices or access to traditionally important resources (Norton-Smith et al. 2016). In fact, as the original stewards and cultivators of the land and sea, the inclusion of appropriate place-based practices by native peoples may enhance conservation and climate adaptation efforts as well as support health and wellbeing within tribal communities (Augustine & Dearden 2014). When considering protection options such as land acquisitions, reserve development, marine and riparian buffer zones, setback lines for development, or rolling easements, it is essential to have all relevant parties, especially tribes, involved in the decision-making process (Scavia et al. 2002).

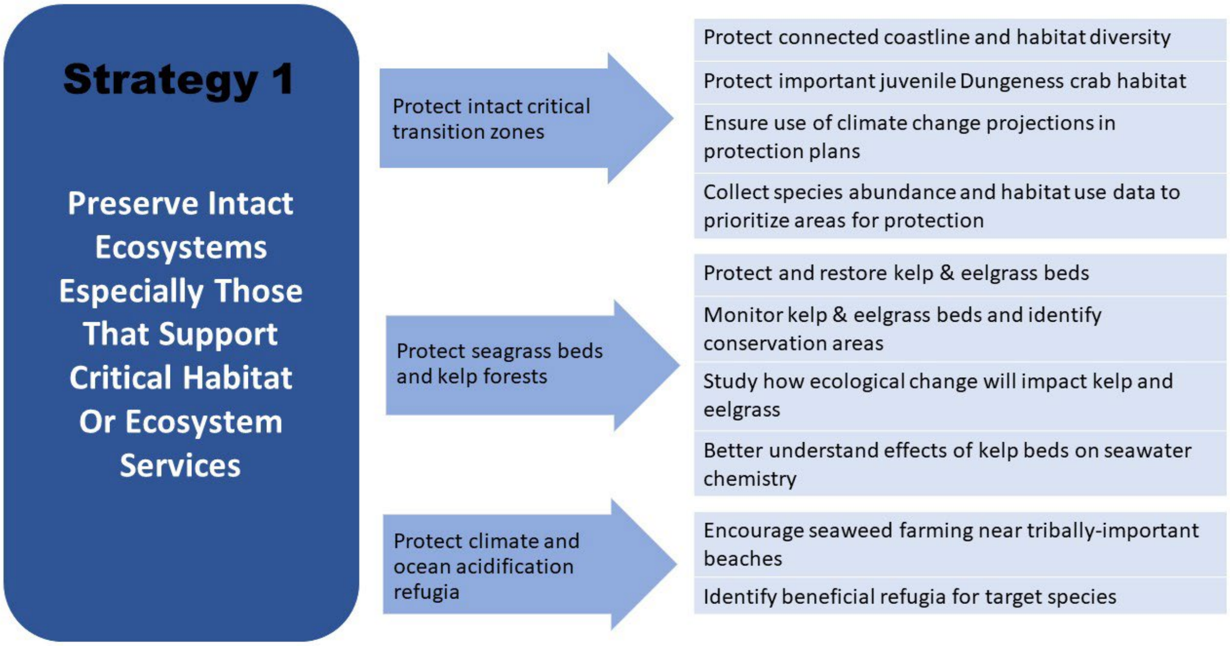

Figure 3: Swinomish Shellfish Adaptation Strategy 1, associated goals, and suggested adaptation actions.

Goal 1.1: Protect intact critical transition zones and facilitate shoreward migration.

Background: Critical transition zones (CTZ) (e.g., intertidal marshes, coastal wetlands, beaches, and bluffs) are ecosystems that link terrestrial and marine environments and influence the flow of material, energy, and organisms across the land-seascape (Ewel et al. 2001, Levin et al. 2001, Boström et al. 2011). Many life history stages (e.g., larval, juvenile, adult) of shellfish species utilize habitat in these transition zones, demonstrating their importance to the continued longevity of shellfish populations. They provide a multitude of ecosystem services, including essential habitat for invertebrates and fishes, nutrient cycling, decomposition, sediment trapping, carbon sequestration, flood mitigation, and recreational sites for humans (Ewel et al. 2001). Therefore, protecting CTZs and the surrounding ecosystems that support them should be a high priority as communities decide how to accommodate coastal populations, protect shellfish resources, and address impacts from CC (Boström et al. 2011, Jones et al. 2012, Cooley & Schoeman 2023). Because the functioning within CTZs is dependent on the conditions of nearby ecosystems, areas upland and adjacent to CTZs should also be conserved. When that is not possible, land managers should ensure development and land-use changes in the surrounding environment do not disrupt hydrologic and sediment regimes in CTZs. Efforts to protect natural processes may be more resilient to SLR if the protected area accounts for landward migration as nearshore habitat is impacted by inundation, coastal flooding, salinity, and erosion (Scavia et al. 2002, Raymond et al. 2018). Ideally, upland forests and forested wetlands should also be maintained and allotted space to migrate landward in order to maximize carbon sequestration in the land-seascape and limit carbon emissions from forest loss and decomposition (Warnell et al. 2022).

Action 1.1.1: Prioritize CTZs that conserve ecosystem connectivity, representation, and redundancy.
Alterations to the composition and configuration of ecosystems within the land-seascape can have profound consequences on ecosystem structure and functioning. Loss of critical habitat to land conversion and CC is especially concerning for marine invertebrates that utilize a variety of ecosystem types for different life history stages. Therefore, CTZs should be targeted to conserve ecosystem connectivity, representation, and redundancy. Ideally, the first ecosystems to target for conservation should be those that have declined the most in size or quantity, connect intact areas, or have substantial influence on the surrounding environment (e.g., bluffs that supply sediment to downdrift beaches) (Noss & Washington 1995, Johannessen & MacLennan 2007).

Action 1.1.2: Protect important juvenile Dungeness crab habitat by conserving intact tidal flats and adjacent tidal channels.
Juvenile Dungeness crab spend up to a year post-settlement rearing in complex intertidal habitats, such as mixed pebble beaches with algae or eelgrass beds, before migrating to the upper subtidal areas as subadults (+1 yr class) (McMillan et al. 1995). These subadult crab tidally migrate from subtidal estuarine side channels to intertidal areas, particularly targeting unvegetated tidal flats, where they forage and meet the majority of their dietary needs (Holsman et al. 2003, 2006, Lewis et al. 2020). Therefore, to promote a productive fishery, it is important to protect these food-rich intertidal areas and tide flats and ensure that juvenile crab can access them from functioning subtidal channels (Lewis et al. 2020). This includes ensuring that upland areas support the landward migration of intertidal beaches and estuarine channels. We also suggest limiting anthropogenic activities that alter sedimentation processes (e.g., dredging) and degrade water quality.

Additional action items include: (1.1.3) ensure inclusion of CC projections when developing protection plans for CTZs, and (1.1.4) collect abundance and habitat use data for invertebrate species at various life stages to identify and prioritize protection of critical habitat that promotes healthy populations and sustainable harvest management.

Goal 1.2: Protect seagrass beds and kelp forests.
Background: Protecting seagrass and kelp beds is a “no regrets” win-win for human and nonhuman coastal communities. Seagrass (which includes eelgrass) and kelp, collectively known as macrophytes, form dense aggregations and are among the world’s most productive habitats that support diverse assemblages of nearshore species and provide a suite of ecosystem services and functions (Peterson et al. 1984, Mumford 2007, Calloway et al. 2020). For example, seagrass and kelp beds are considered essential fish habitat, providing nursery, foraging, and migration habitat for invertebrates (e.g., crab, shrimp, sea cucumbers, and urchins) and fishes, including threatened Chinook salmon, endangered rockfish, and forage fish (Beck et al. 2001). Macrophytes are also important primary producers that provide a critical food source for nearshore food webs and improve water quality. Additionally, macrophytes can help mitigate the impacts of CC by sequestering carbon, ameliorating OA conditions, and protecting shorelines from SLR and increased storm surge, although their degree of effectiveness depends on the species and site conditions (Nielsen et al. 2018, Cyronak et al. 2018, Prentice et al. 2020) . The direct effects of CC and OA on macrophytes are also mixed and species-specific and may result in changes in abundance and composition that alter their ability to provide certain ecosystem services to the surrounding environment and community (reviewed in Haigh et al. 2015). Therefore, it is important to ensure currently functioning macrophyte beds are allowed to adapt to environmental changes unimpeded by additional stressors.

Action 1.2.1: Identify eelgrass and kelp beds to protect and restore.
Healthy macrophyte beds should be identified and protected to conserve the many ecosystem services and functions they provide. Stressors and site conditions impacting macrophyte health

should be assessed at specific sites. Proximity to critical shellfish habitat should be considered when prioritizing conservation areas due to the potential for multiple co-benefits. Although the predicted impacts on the health of macrophytes is mixed due to ocean warming and acidification (Kroeker et al. 2010, Koch et al. 2013), dense beds may provide critical refugia for calcifying organisms. Even fragmented kelp beds have been found to improve seawater chemistry (Murie & Bourdeau 2020). Macrophytes may also attenuate subtidal light stress and reduce heat and desiccation stress in the intertidal (Wahl et al. 2017, Falkenberg et al. 2021). Dense aggregations of macrophytes may also increase food availability for mollusks, crustaceans, and echinoderms, which can reduce sensitivity to OA (Parker et al. 2013, reviewed in Ramajo et al. 2016).

Action 1.2.2: Monitor kelp and seagrass beds to better understand trends and identify conservation areas.

Partner with Northwest Straits Commission, marine resources committees, and other entities to monitor the distribution and health of native canopy-forming and understory macrophytes (e.g., *Zostera marina, Nereocystis luetkeana, Macrocystis pyrifera*) and non-native species (*Z. japonica, Sargassum muticum*).

Additional action items are the following: (1.2.3) investigate local effects of kelp beds on seawater chemistry (Pfister et al. 2019), and (1.2.4) research how certain environmental and ecological factors may influence kelp and eelgrass beds.

Goal 1.3: Protect climate and ocean acidification refugia.

Background: In addition to global climate drivers, local biogeochemical and physical factors influence ocean conditions that vary spatially and temporally across the landscape and generate unique characteristics and microclimates (Wootton et al. 2008, Feely et al. 2010, Cai et al. 2011). Historically, some of these areas have provided refugia for species during extreme climate events, allowing them to persist locally where inhospitable conditions occurring regionally or globally were buffered or compensated (Morelli et al. 2016). Although anthropogenic CC is predicted to occur at unprecedented rates, refugia may again play an important role in protecting particular organisms. Recent research has found that some microclimates can reduce vulnerability to acidification and warming by modulating adaptation capacity (Kelly et al. 2013, Kapsenberg & Cyronak 2019). Thus, an emerging conservation goal is to identify and protect CC and OA refugia, especially for species that are culturally, ecologically, or economically important (Billé et al. 2013, Kavousi & Keppel 2018, McLaughlin et al. 2022). This can also be an effective approach for sessile or sedentary organisms that are not capable of finding advantageous microclimates on their own (Woodson et al. 2018). Refugia may not provide a long-term solution to CC, especially biologically derived refugia (e.g., macroalgae, seagrasses, saltmarsh). However, they can allow systems and organisms time to adapt while other actions are implemented (Morelli et al. 2016, Ban et al. 2016). In areas that do provide consistent refuge, enhancement or conservation efforts could be implemented to maximize species resilience long-term. Ideal refugia criteria to support targeted species/taxa include habitat that (Morelli et al. 2016, Kapsenberg & Cyronak 2019):

- alleviates stress on a physiologically and ecologically relevant timescale
- persists long enough to allow generations to survive
- is large enough to sustain a small population or metapopulation
- supports multiple ecosystem services and functions
- is managed at a larger scale to include natural processes that maintain the refugia, address overall ecosystem health, and account for variability in space and time

Action 1.3.1: Encourage seaweed farming near tribally important clam beaches.

In addition to protecting and restoring natural kelp and eelgrass beds (Goal 1.2), seaweed mariculture has the potential to mitigate OA impacts locally (Hendriks et al. 2015, Ricart et al. 2021). Therefore, when located in the appropriate locations, promoting the growth of seaweed near clam habitat could potentially support clam growth and survival. The magnitude of a CC and OA buffering effect is context and site specific. Factors to consider when identifying sites include: residence time of water body in the bed; species of kelp, seagrass, or eelgrass; proximity to other anthropogenic stressors; presence of competitive or predatory organisms (Falkenberg et al. 2021). In addition to providing ecological benefits to the local ecosystem, a successful operation could increase economic opportunities for fishers by creating jobs and providing economic and cultural benefits to local communities by sustaining or enhancing shellfish productivity.

Action 1.3.2: Identify operative refugia at various spatial and temporal scales for target species. In order to identify potential refugia, physical drivers for shellfish species abundance and local environmental conditions must be well understood. Therefore, it is important to conduct long-term environmental monitoring. Physical variation even at the scale of a kilometer or less may provide areas of refugia (Woodson et al. 2018). Additionally, combining climate and ecological niche models with knowledge of distribution shifts may extend the temporal effectiveness of refugia by identifying locations where habitat is likely to persist in the future (Morelli et al. 2016, Magel et al. 2022). For calcifying organisms, areas to target include those that have (1) sustained high mean pH that modulates exposure to harmful conditions and (2) characteristically high and variable CO_2 conditions that may enhance adaptive capacity via physiological plasticity, epigenetics, or genetics. Coastal areas that may support these mechanisms include: higher latitudes, upwelling zones, estuaries, tidepools, primary production hotspots, and active phytoremediation and alkalization management actions (reviewed in Kapsenberg & Cyronak 2019). For example, dense macrophyte beds can provide critical temporal refugia for calcifying organisms. These primary productivity hotspots exhibit a diurnal CO_2 cycle due to photosynthetic activity during daylight hours, which increases pH and aragonite saturation state inside the bed versus outside the bed (Unsworth et al. 2012, Hendriks et al. 2014, Ricart et al. 2021). They may also increase food availability for mollusks, crustaceans, and echinoderms, which can reduce sensitivity to OA, though their effectiveness as refugia is context and site specific (reviewed in Parker et al. 2013, Ramajo et al. 2016, Falkenberg et al. 2021). Studying survival and/or adaptation of shellfish in regions that have already faced extreme stressors, such as acute marine or atmospheric heatwaves, can also help pinpoint refugia. Indeed, Raymond et al. (2022a) note areas in the Salish Sea where certain conditions allowed intertidal shellfish to survive the record-setting heatwave of June 2021. When identifying refugia, it is essential to examine multiple parameters, such as pH, temperature, DO, and salinity, that can have additive, antagonistic, or synergistic impacts on organism fitness. A step-by-step workflow outlined by Morelli et al. (2016) can help identify, manage, and monitor refugia.

Swinomish Shellfish Adaptation Strategy 2: Reduce non-climate stressors

While there is no place on Earth that is not affected by humans, the majority of the population lives within 100 km of the coast, thereby amplifying anthropogenic impacts on marine resources (Halpern et al. 2008). Three primary drivers negatively affecting marine health are changes in land and sea use, direct exploitation of organisms, and pollution (IPBES 2019). These drivers encompass a wide range of stressors from coastal development and bottom trawling to road and agricultural runoff. The cumulative effect results in habitat destruction, loss of biodiversity, and impaired ecosystem functioning, and undermines the ability of natural and human systems to adapt to CC and OA (Scavia et al. 2002). Therefore, to enhance species, ecosystem, and community resilience to CC, non-climate stressors should be identified and reduced (Higgason & Brown 2009, Mawdsley et al. 2009, WABRPOA 2012) (Figure 4). Not only is this strategy uniquely practical for large-scale adaptation, but solutions are technologically ready and provide multiple benefits at the local scale for both human and nonhuman communities (Campbell et al. 2009, Gattuso et al. 2018).

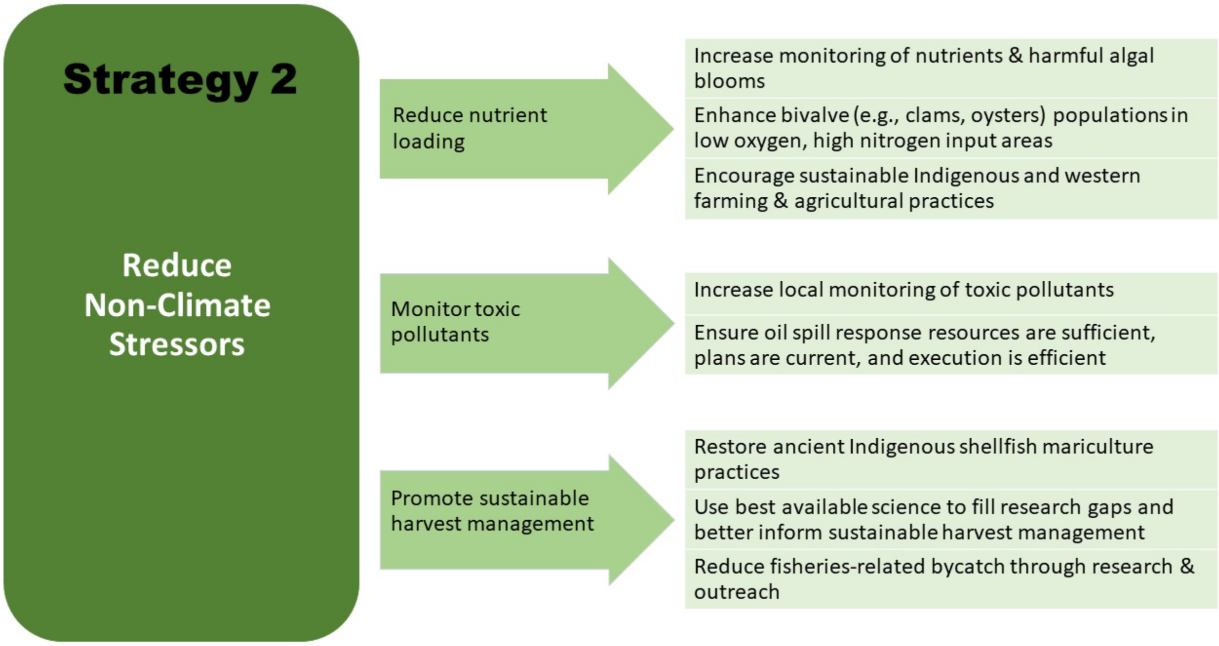

Figure 4: Swinomish Shellfish Adaptation Strategy 2, associated goals, and suggested adaptation actions.

Goal 2.1: Reduce nutrient loading.
Background: Inputs of nitrogen and phosphorous from upland sources (e.g., wastewater treatment facilities, stormwater outfalls, concentrated animal feedlots, septic systems, urban runoff, and residential lawns and gardens, etc.,) can cause eutrophication in surface waters, which encourages algal blooms. As blooms subside, the decomposition of excessive plant and algal biomass lowers pH and can lead to hypoxic conditions, exacerbating OA and CC impacts on shellfish species (Cai et al. 2011, Billé et al. 2013, Pelletier et al. 2017). In the Salish Sea, DO levels have been declining over the past 70 years with an increase in seasonal hypoxia events from spring and summer algal blooms that are in part due to nutrient inputs from human-related activities coupled with CC impacts (e.g., summer drought, reduced water circulation) (EPA 2021, Department of Ecology 2023). The frequency of hypoxic events is expected to increase due to rising SST, which may also increase the frequency of harmful algal blooms that produce paralytic shellfish toxins and domoic acid, impacting human health and harvest opportunities (Moore et al. 2015, McKibben et al. 2017). Increased nitrogen can also alter nutrient ratios and indirectly initiate a cascade of effects that may impact food availability, benthic-pelagic coupling, and composition of the benthic community (Krembs et al. 2014). Therefore, to benefit human and nonhuman communities, it is important that nutrient sources are identified and reduced or eliminated (WABRPOA 2012, Ekstrom et al. 2015, IPBES 2019). For example, installing nutrient reduction technology at municipal wastewater treatment plants can improve local DO conditions by offsetting both the current nitrogen in effluent and the expected increase due to rising populations in the region (Roberts et al. 2014, Ahmed et al. 2019). Action in Whidbey Basin can be especially effective where the carbonate chemistry is sensitive to anthropogenic nutrient loadings and the waters are classified as impaired by the Washington Department of Ecology (WA DOE) due to low DO (Pelletier et al. 2017).

Action 2.1.1: Increase monitoring of nutrients and HABs in Whidbey Basin and northern Puget Sound.
Current nutrient and HABs monitoring in northern Puget Sound is insufficient to assess water conditions at a biologically meaningful scale that can inform shellfish management, conservation,

and restoration efforts. Within Whidbey Basin, San Juan Islands, and Admiralty Inlet, there are several nutrient and pollutant sources that can exacerbate already-low DO and pH conditions. The rivers in Whidbey Basin contribute 56% of the river nitrogen load into Puget Sound, and projected population growth in Anacortes, Bellingham, Mount Vernon, Oak Harbor, and Everett will increase wastewater treatment plant dissolved inorganic nitrogen contributions to the region (Mohamedali et al. 2011, Roberts et al. 2014). Biotoxin events are already reducing opportunities for shellfish harvest and cultural practices (Berdalet et al. 2015, NWIFC 2016a, Hintz 2020). Therefore, a more robust fine-scale monitoring network could provide a better understanding of local conditions, trends, and anomalies as well as an early warning system for HAB events. Partnering with monitoring programs, like SoundToxins, Mussel Watch, and PSEMP, could effectively and efficiently bolster efforts and require minimal additional resources.

Action 2.1.2: Employ bioremediation techniques in low DO, high nitrogen input areas.
Bivalves are effective filter feeders capable of alleviating eutrophication factors like excess nitrogen from local waters, especially in smaller, shallow bays. With proper siting and implementation, shellfish production can be targeted at strategic locations to help offset anthropogenic nutrient sources and augment wastewater treatment facilities (Filippini et al. 2023). For example, in Oakland Bay, WA, shellfish aquaculture/production removed 11.7 metric tons of nitrogen from the water, providing an estimated $25,000 to $815,000 in benefits to water quality (Burke 2009).

Action 2.1.3: Encourage use of sustainable Indigenous and western farming and agricultural practices.
Ancient Indigenous agricultural practices like root and forest gardening provide examples of sustainable, ecosystem-based food production (Thornton et al. 2015, Jackley et al. 2016). Appropriate restoration and application of these practices led by native communities can provide a multitude of benefits to the environment as well as community health and wellbeing. Additionally, working with farmers, researchers, policy makers, and financial institutions to support more sustainable agricultural practices and improve major sources of pollutants (e.g., drainage and irrigation systems) can potentially benefit farmers while reducing nutrient inputs into the watershed (IPCC 2018, Barange et al. 2018, IPBES 2019).

Goal 2.2: Monitor toxic pollutants.
Background: Coastal waters contain some of the highest levels of metals and pollutants, primarily from industrial discharges and urban and agricultural runoff (IPBES 2019). Infaunal filter-feeders, like clams, can uptake metals via burrowing in the surface sediment and feeding in the overlying water (López et al. 2010). Ocean acidification impacts on water-column and sediment geochemistry can increase the abundance of metals (e.g., copper, zinc, lead) available for biota to absorb, compound direct physiological stress on organisms (e.g., maintaining intracellular pH balances), and may result in sub-lethal and lethal effects on shellfish (Ringwood & Keppler 2002, López et al. 2010, Clements & Hunt 2017). Warmer SSTs also increase the bioaccumulation and toxicity of certain contaminants in shellfish and can impact human health (Barange et al. 2018, IPBES 2019). For example, the formation of methylmercury (MeHg), a neurotoxin, increases when SSTs rise, which can be especially threatening to Indigenous people who typically consume higher rates of shellfish than the general public (Donatuto et al. 2011, Dijkstra et al. 2013, Cozzetto et al. 2013). Additionally, organisms' risk of exposure to toxic chemicals is expected to increase as the number of tanker vessels carrying oil products is expected to increase in the Salish Sea (Greene & Aschoff 2021). Crude oil and other hazardous chemicals, such as ethanol, ammonia, and sulfuric acid, are also transported by rail and can result in sub-lethal or lethal effects on marine biota (WA DOE 2020). Historically, sediment quality studies in northern Puget Sound, including waters around the Swinomish Reservation, have reported significant chemistry or toxicity results as well as differences in infaunal assemblages in toxic and nontoxic sediments (see Donatuto et al. 2011).

Action 2.2.1: Increase monitoring of toxic pollutants in Whidbey Basin and northern Puget Sound.
Collaborate with partners like WA DOE's Marine Monitoring Unit to ensure robust surveying at tribally important harvest locations, especially areas located near pollution sources such as oil refineries, railroads, and superfund sites.

Action 2.2.2: Ensure oil spill response resources are sufficient to address spill risks, protocols are up to date, and execution is efficient.
Rapid containment and recovery of crude oil before it becomes viscous and sinks is key to reducing ecological impacts from rail or tanker vessel spills (WA DOE 2020, Greene & Aschoff 2021). Therefore, it is important to ensure Swinomish and other agency oil spill response resources are sufficient to quickly address spills and prevent impacts to critical habitat and shellfish resources both on and off the Reservation. Specifically, Swinomish Marine Oil Spill Standard Operating Procedures should be updated to include: (1) shellfish priority areas; (2) increased spill avoidance and response training with the Swinomish Port Authority, tribal staff, and the fishing fleet; and (3) coordination with other agencies (i.e., WA DOE) and tribes to maximize response efficiency and update tribal geographic response plans.

Goal 2.3: Promote sustainable harvest management practices.
Background: To ensure that future generations have access to abundant shellfish resources under changing ocean conditions, fisheries must employ scientifically supported harvest management practices that promote robust shellfish populations and prevent stock collapse (Perry et al. 2002, Worm et al. 2006, Miller et al. 2010, Barange et al. 2010). Overfishing continues to be one of the main human impacts on marine ecosystems, undermining the ability of individual species to adapt to CC and maintain ecosystem functioning (Barange et al. 2018, Gattuso et al. 2018, IPBES 2019). Similar to global trends, there are signs of overexploitation (e.g., reduced catch per unit effort and lower abundance at index sites) in marine invertebrate fisheries in Puget Sound (Anderson et al. 2011, Carson et al. 2016). Unfortunately, harvest management options to promote stock recovery and prevent future overexploitation are limited by lack of basic fishery biology of the targeted species (Carson et al. 2016, Mueller 2016, Buckner et al. 2022). Recent closures in northeastern Pacific Ocean Dungeness, red king, and snow crab fisheries also highlight the need to integrate harvest impact, environmental variability, and adaptive management (Scavia et al. 2002). Integrating these variables with harvest impact is of particular importance, as sudden and nonlinear changes are more likely to occur in the marine environment as CC impacts intensify and compound other anthropogenic impacts (Hoegh-Guldberg & Bruno 2010, Rogers-Bennett et al. 2019, IPCC 2023a). New management strategies or indicators may be necessary to account for environmental threats to stock health and productivity like mass mortality or HAB events (Rogers-Bennett et al. 2019). When implemented appropriately, sustainable harvest management can also be an effective action at the local scale that supports resiliency in human and nonhuman coastal communities (Gattuso et al. 2018). Additionally, Indigenous communities have a long history of sustainably managing resources using a variety of technologies. The application of place-based knowledge by native communities should be encouraged to increase fishery yields in a manner that promotes biodiversity and restores the complex socio-ecological systems that supported human and nonhuman communities for millennia (Serra-Diaz & Franklin 2019, Toniello et al. 2019, Reeder-Myers et al. 2022).

Action 2.3.1: Restore ancient Indigenous shellfish mariculture practices.
Indigenous communities maintained a resilient marine food system using a number of ecosystem-based mariculture practices developed over centuries of observation and adaptive management. As active managers and stewards of the nearshore environment, communities created and enhanced habitat of various coastal resources that increased productivity and supported sustainable harvest (Turner & Berkes 2006, Deur et al. 2015, Jackley et al. 2016, Toniello et al. 2019). For example, clam gardening, or sea gardening, applied a variety of habitat enhancing techniques to maximize

intertidal clam productivity in a manner that provided habitat for other flora and fauna, and increased biodiversity in the surrounding environment (Groesbeck et al. 2014, Jackley et al. 2016, Salter 2018). Active tending associated with the gardens included selectively harvesting larger clams to reduce density-dependent growth and returning shell to the beach, which encourages clam settlement and growth, and may improve future conditions for calcifying organisms as oceans acidify (Deur et al. 2015, Lepofsky et al. 2015). Applying ancient Indigenous practices, like clam gardening, in modern times simultaneously promotes a more holistic, socio-ecological approach to resource management than contemporary practices, addresses food security and tribal treaty rights, and supports communities disproportionately impacted by CC (Lynn et al. 2013, IPBES 2019).

Action 2.3.2: Utilize best available science and fill research gaps to better inform sustainable harvest management policies.

Unlike local finfisheries such as salmon, shellfisheries in Washington are data limited, and the information needed for a conventional stock assessment (e.g., surveys, biological parameters, etc.) is lacking. These data limitations in turn undermine the ability of harvest comanagers to ensure stable stocks and long-term fishing opportunities (Anderson et al. 2011, Carson et al. 2016, Buckner et al. 2022). For example, much of the biological data required to estimate population abundance and appropriate harvest rates is not collected for shellfish species, including Dungeness crab, species of pandalid shrimp, sea urchins, and sea cucumbers (Wainwright & Armstrong 1993, NMFS 2001, Carson et al. 2016, Buckner et al. 2022). Ideally, abundance and biological data is collected using statistically designed, fishery-independent surveys at the appropriate spatial and temporal scales to account for biological population structure, stock heterogeneity, and climate-induced variability (Orensanz et al. 1998, Scavia et al. 2002, Buckner et al. 2022). There is also limited understanding on the current environmental conditions shellfish species experience throughout their habitat range as well as the impacts of CC (e.g., warming SST, OA, hypoxia, heatwaves) on a species or ecosystem-wide scale (Rogers-Bennett et al. 2019). Pairing biotic and abiotic factors is important to assess sublethal and lethal effects that influence individual fitness, mortality, and recruitment into fisheries. Additionally, incorporating economic, social, and other environmental variables will help predict changes in fisheries and support more robust harvest management policies, including habitat conservation efforts (Essington et al. 2017, Holsman et al. 2018, Sobocinski et al. 2022). Therefore, shellfish comanagers as well as academic institutions and other agencies and organizations should work collectively to address data gaps and support the development, implementation, and enforcement of adaptive, climate-ready management practices.

Action 2.3.3: Reduce fisheries-related mortality through research and outreach.

Research, policies, and public outreach should address loss due to derelict gear, detrimental handling of organisms, and poaching. In part due to the lack of biological parameter and species abundance data, there is limited understanding on fishing impacts and management strategies on shellfish species within the Salish Sea. Potential research areas that can improve harvest management include identifying ecological drivers of crab molting so managers can time fishery closures with shell condition, or evaluating impacts of one-sex harvest on population genetics to assess the sustainability of 3-S crab management strategies (Buckner et al. 2022). In addition to removing derelict pots, increasing outreach to crabbers on the importance of biodegradable cotton escape cord can help reduce loss of harvestable crab populations from ghost fishing and lost pots. Collaboration with other tribes, agencies, and organizations (e.g., Northwest Straits Foundation's crab pot removal program) can streamline resources and increase public awareness.

Swinomish Shellfish Adaptation Strategy 3: Restore physical, ecosystem-forming processes to promote landscape biodiversity and functioning

The nearshore is a highly integrated environment, strongly mediated by physicochemical and other environmental factors (e.g., river flow, sediment resuspension, circulation) which support shoreform structure and ecosystem functioning (Goetz et al. 2004, Greiner 2010, Raymond et al. 2018). Unfortunately, +150 years of development has fragmented and simplified the shoreline, impairing physical processes and resulting in loss of habitat and biota (Fresh et al. 2011, Cereghino et al. 2012, NWIFC 2016a). In order to restore self-sustaining ecosystem functions, including habitat for fauna, restoration efforts should focus on physical, ecosystem-forming processes that enhance landscape connectivity and complexity. This is especially important to promote life-history diversity (Goetz et al. 2004, Boström et al. 2011, Barange et al. 2018) (Figure 5). Shellfish, in particular, include many multi-habitat species that carry out their life cycle over several types of ecosystems. Improving the integrity of the shoreline by addressing degradation from human development will not only provide short-term functioning habitat for biota but also enhance climate resiliency of habitat in the long-term. Emergent wetlands, shellfish reefs, subtidal kelp, submerged aquatic vegetation, and intertidal habitat are among the most vulnerable habitat types to climate change. A more resilient nearshore can also provide co-benefits for coastal communities like flood protection and carbon sequestration (Farr et al. 2021). Sites where minimal actions could lead to greater recovery of ecosystem processes may be more cost and risk friendly, however, habitat in developed areas should not be neglected (Cereghino et al. 2012).

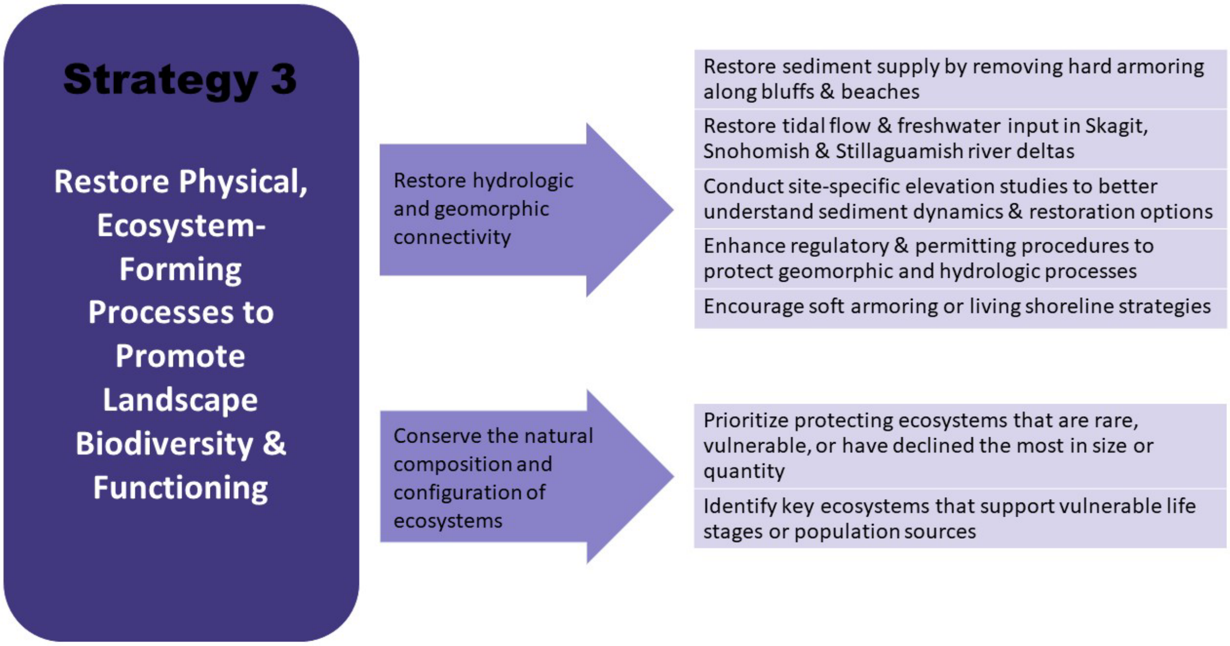

Figure 5: Swinomish Shellfish Adaptation Strategy 3, associated goals, and suggested adaptation actions.

Goal 3.1: Restore hydrologic and geomorphic connectivity.

Background: The degree of connectivity in the nearshore regulates the frequency, magnitude, and transfer of material, energy, and biota that support ecosystem structure and function. For example, in Puget Sound, beach building sediment primarily comes from bluff erosion and is distributed by longshore transport (Keuler 1988, Shipman et al. 2010). However, as of 2006, only 31% of the shoreline was unmodified (Fresh et al. 2011). In Whidbey Basin, Cereghino et al. (2012) found a large proportion of beaches had moderately high levels of degradation based on factors of sediment supply, nearshore impervious surfaces, and parcel density. Reduced sediment input can have long-term cumulative effects that influence habitat viability for invertebrates and fishes within a drift cell (Johannessen & MacLennan 2007, Dethier et al. 2016). Restoring geomorphic and hydrologic processes in drift cells and critical transition zones can result in a nearshore structure that more closely resembles the environment biota adapted to (Goetz et al. 2004). Therefore, to promote ecological processes, projects restoring connectivity should be given high priority (Lambeck & Hobbs 2002, Gaydos et al. 2008).

> *Action 3.1.1: Restore sediment supply by removing hard armoring along erosional bluffs and beaches.*
> The restoration of sediment supply will likely result in the recovery of other processes that support ecosystem structure and function such as sediment transport, tidal channel formation and maintenance (Cereghino et al. 2012). When the removal of hard armoring is not possible, the employment of living shoreline or nature-based technology should be considered. While these two technologies are not as likely to restore sediment supply, their application may enhance ecosystem functioning. Actions to restore sediment supply and tidal flow can also help restore barrier embayments co-located in the same drift cell (Clancy et al. 2009).

> *Action 3.1.2: Restore tidal flow and freshwater input in Skagit, Snohomish, and Stillaguamish river deltas.*
> Historically, the Skagit and Snohomish deltas accounted for ~70% of all delta tidal wetlands but are now moderately degraded due to agricultural use, impervious surfaces, and shoreline modifications. However, there is high potential to return lost ecosystem services and functioning, especially in oligohaline and freshwater wetlands. Removing dikes and berms is an effective way to restore tidal flow processes which support other physical and ecological processes critical for the restoration of delta ecosystem services (Hood 2004, Clancy et al. 2009, Simenstad et al. 2011). Additionally, watershed barriers that obstruct river sediment supply should be removed to allow tidal marshes and wetlands to keep pace with SLR. When that is not possible, delta resiliency will depend on local land use and landward migration (Cereghino et al. 2012).

> Additional actions include: (3.1.3) conduct site-specific surface elevation studies to better understand sediment dynamics and restoration options; (3.1.4) enhance regulatory and permitting procedures to protect hydrologic and geomorphic processes; (3.1.5) encourage soft armoring or living shoreline strategies where appropriate.

Goal 3.2: Conserve the natural composition and configuration of ecosystems.
Background: Conserving ecosystem representation and redundancy can allow the continued evolution of shoreforms as well as support species persistence, especially for species that utilize a variety of habitat types to complete complex life stages (Noss et al. 1994, Farina 2000). When evaluating specific sites for restoration or protection, it is important to make sure the surrounding landscape, including the drift cell and upland area, can support long-term project objectives, including persistent short- and long-term CC impacts like SLR (Mawdsley et al. 2009, Raymond et al. 2018). For example, a restored marsh may be able to regress naturally landward as sea levels rise if the project is located adjacent to gently sloped shorelines rather than steep shorelines (FitzGerald & Hughes 2019).

> *Action 3.2.1: Prioritize protecting ecosystems that are rare, vulnerable, or have declined the most in size or quantity.*
> To maintain biodiversity and ecosystem functioning, the presence of ecological components essential to the integrity of the landscape should be restored and protected. Loss or fragmentation of rare ecosystems may threaten regional ecological functioning (Dale et al. 2000, Roberts et al. 2003). In Puget Sound, pocket estuaries (bodies of water located behind spits or barrier beaches) and pocket beaches (beaches at the base of rocky bluffs where sediments are only derived locally) are two examples of ecologically-important rare habitat (Beamer et al. 2003, 2020). In addition to rarity, ecosystems that have experienced the greatest loss or are most vulnerable to future impacts should be targeted for protection. For example, Beamer et al. (2020) demonstrate that large river

estuaries, which comprise a significant amount of coastal habitat in our study's region (>34 wet area hectares), are the least resilient to wave and SLR threats.

Additional action: (3.2.2) Identify key ecosystems that support vulnerable shellfish life stages or population sources.

Swinomish Shellfish Adaptation Strategy 4: Protect and enhance native species and ecosystem biodiversity

Since the signing of the Point Elliot Treaty in 1855, traditional hunting and fishing grounds have been drastically changed by European settlement and development that continues to this day. Habitat loss, pollution, and overexploitation are resulting in a rapid decline in biodiversity, undermining ecosystem functioning and threatening livelihoods and food security (Tilman et al. 2014, NWIFC 2016b, IPBES 2019). Biodiversity and species composition are significant factors that drive ecosystem processes and influence ecosystem stability, productivity, and nutrient dynamics. Ecosystems with high diversity are also more resilient to climate events, disease, and invasion from exotic species (Tilman 1999, Campbell et al. 2009, Isbell et al. 2015). Therefore, to promote healthy, abundant shellfish resources under changing environmental conditions, conservation efforts should prioritize the preservation and restoration of nearshore biodiversity (Worm et al. 2006) (Figure 6). Enhancing biodiversity can also provide other benefits, including protective services to coastal communities and carbon sequestration. Although climate-related impacts will alter the abundance and distribution of certain species and taxa, in particular echinoderms and mollusks, addressing overall biodiversity supports CC adaptation and disaster risk reduction (Hale et al. 2011, IPCC 2014, Poulain & Wabbes 2018).

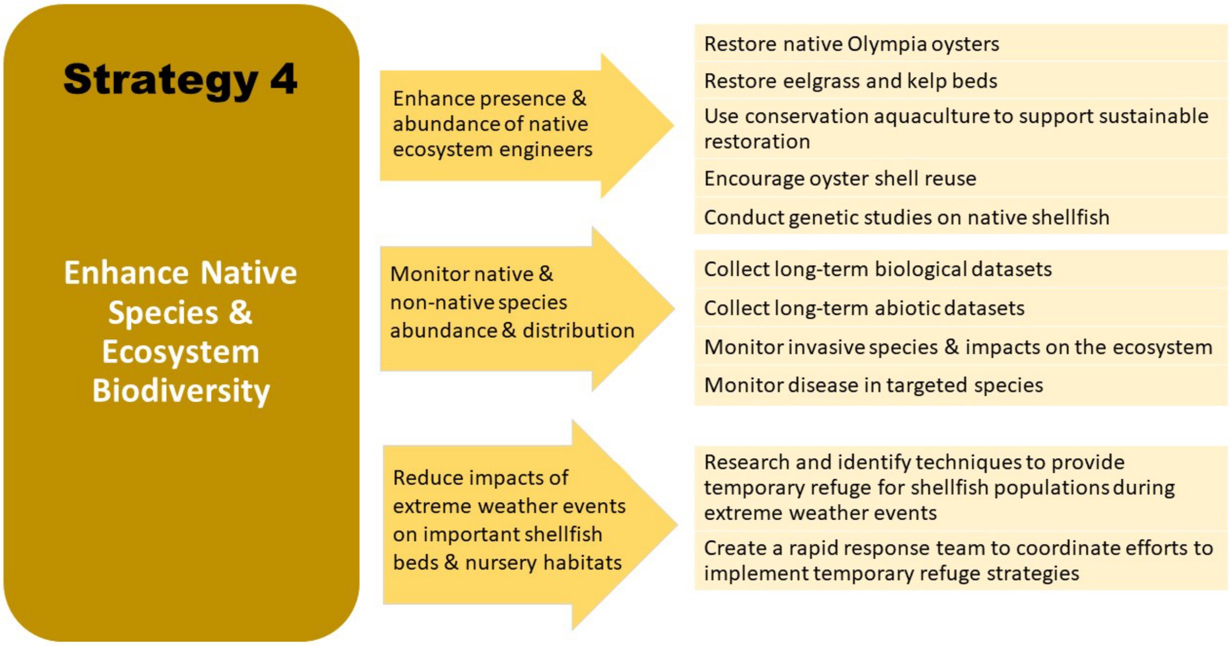

Figure 6: Swinomish Shellfish Adaptation Strategy 4, associated goals, and suggested adaptation actions.

Goal 4.1: Enhance presence and abundance of native ecosystem engineers.

Background: Habitat-forming species, such as kelp, eelgrass, salt marsh grasses, and native oysters, are critical to the structure, productivity, and resilience of coastal ecosystems. In addition to providing species-specific ecosystem services, they provide physical structure that supports settlement and refuge for other estuarine species. Biogenic habitats (i.e., habitat created by living species whom are often referred to as foundational species or ecosystem engineers) are also important to connectivity in the seascape, influencing the integrity of adjacent ecosystems and the larger nearshore environment (as reviewed in Hoegh-Guldberg & Bruno 2010, Boström et al. 2011, Clements & Hunt 2017). Unfortunately, due to a number of compounding stressors, including overharvesting, watershed development, and CC, total global loss estimates of these biogenic habitats is an average of 30%; oyster reefs may be over 85% loss (Beck et al. 2011). In order to maximize effectiveness and support nearshore biodiversity, ecosystem engineers should be a conservation priority. Because these foundational species are susceptible to CC and OA, conservation efforts should target climate-refugia locations (Pörtner et al. 2022, Raymond et al. 2022a, b). As stewards that sustainably managed these resources for centuries, it is important tribes maintain a key role in restoring the native species along with other agencies and organizations (Ridlon et al. 2021a, Reeder-Myers et al. 2022).

Action 4.1.1: Restore native Olympia oysters.

Prior to European settlement, *Ostrea lurida,* Washington's only native oyster, was widely distributed in Washington state waters, with dense assemblages in bays and inlets (Cook et al. 1998, Blake & zu Ermgassen 2015). They played a key role ecologically in the nearshore, as well as culturally and economically for native communities (Reeder-Myers et al. 2022). However, overfishing by European settlers, habitat loss, and pollution decimated the population. Currently, they are considered functionally extinct, with less than 5% of the historic population in existence (circa 1850, Blake & Bradbury 2012). Although the impacts of CC and OA on *O. lurida* are mixed, the native species may be more tolerant to environmental changes than non-native oyster species in the Salish Sea (Hettinger et al. 2013, Waldbusser et al. 2016, Lawlor & Arellano 2020). Restoration efforts are working to biologically conserve *O. lurida* and its associated habitat and ecosystem services, including local water filtration, coastal protection, and support for other tribally important species, like Dungeness crab (Blake & Bradbury 2012, zu Ermgassen et al. 2013, Dumbauld et al. 2021, McArdle et al. 2022).

Action 4.1.2: Restore eelgrass and kelp beds by reducing non-climate-related stressors.

Due to their innumerable benefits, eelgrass and kelp beds are considered priority marine habitats by several federal and state agencies. Most importantly, tribes in Washington reaffirmed a fundamental right to protect critical fish habitat from environmental degradation in Puget Sound, which includes macrophyte habitat (Calloway et al. 2020). There are additional calls to protect and restore kelp and eelgrass beds in the Puget Sound Kelp Conservation and Restoration Plan, Washington State Blue Ribbon Panel on OA, and West Coast OA and Hypoxia Science Panel (Chan et al. 2016). However, despite these federal and state protections, recent trends in Puget Sound suggest that both kelp and eelgrass beds are declining as a result of local and global factors (Gaeckle et al. 2011, Berry et al. 2021). At a global scale, warming sea temperatures can reduce kelp reproductive success, increase the occurrence of eelgrass wasting disease, and increase vulnerability to other stressors (Groner et al. 2021). While efforts to reduce global ocean warming are limited to reducing GHG emissions, there are a number of local actions identified in regional plans that can reduce non-climate-related factors (Mumford 2007, Calloway et al. 2020). For example, reducing or eliminating shoreline development activities that impair water quality and alter natural shoreline processes in or near kelp or eelgrass beds (e.g., overwater structures, shoreline armoring, outfalls, and dredging) can have positive effects on bed health.

Action 4.1.3: Utilize conservation aquaculture to support sustainable restoration and stock enhancement efforts of native species.

Conservation aquaculture is the cultivation of aquatic species for management and protection, and can be an effective tool to enhance wild populations in an ecologically responsible manner (Washington Marine Resources Advisory Council 2017, Froehlich et al. 2017, Barange et al. 2018). For example, the production of *Ostrea lurida* seed has helped address limited recruitment at certain restoration sites (Wasson et al. 2020). Identifying appropriate techniques depends on a variety of criteria, including the targeted species' life-history, conservation needs and objectives, environmental conditions, and resource capacity, as well as a thorough evaluation of risks and rewards. To assess genetic and ecological risks of hatchery-raised stocks on wild populations and promote genetic diversity and fitness, additional research, such as population structure, may be necessary (Lowell 2021, Ridlon et al. 2021a, Dimond et al. 2022). Spatial analyses that consider socio-ecological factors are also essential to identify locations where conservation aquaculture efforts are most likely to succeed (Ridlon et al. 2021b).

Additional actions include: (4.1.4) encourage oyster shell recycling (the collection of shell from commercial aquaculture operations for use in restoration projects) and (4.1.5) conduct genetics studies on native shellfish populations to identify appropriate augmentation strategies for future use in conservation aquaculture.

Goal 4.2: Monitor native and non-native species abundance and distribution.

Background: Physiological responses to CC are already being observed at the population level, as abundance and geographic distribution in some marine species has changed due to extreme events and changing ocean conditions (Doney et al. 2012, IPBES 2019, IPCC 2023a). There is evidence of intertidal species in the northeast Pacific tracking local climate velocities and expanding their range north (Barry et al. 1995). Furthermore, scientists have recorded an increase in abundance of warm-adapted species and a decrease in cold-adapted species (e.g., Barry et al. 1995, Poloczanska et al. 2016). Species are also expected to migrate vertically to avoid plumes of water that are warmer, more acidic, hypoxic, or too low in salinity (Somero et al. 2016, Holsman et al. 2018). The frequency of climate-related events is predicted to increase, reducing the opportunity for community structure and function to recover, particularly when habitat-forming species are significantly impacted or events occur during certain life history stages (Shanks et al. 2019, IPCC 2023b). Therefore, it is important to understand where population shifts are occurring to inform conservation, restoration, and management efforts.

Action 4.2.1: Collect long-term biological datasets to track changes.

Continue conducting long-term studies like clam biomass surveys and biological inventories on intertidal communities to monitor population and community changes over time. Recruitment and settlement surveys should also be conducted on targeted species to elucidate biological and physical drivers that influence population dynamics, and impacts from and responses to CC and OA (Roegner et al. 2007, Gaitán-Espitia et al. 2017, Greiner et al. 2018). Long-term data collection helps scientists build better predictive models (e.g., ecological niche models), which, coupled with ecological forecasting, can help identify potential future habitat and inform resource management and conservation efforts (Helmuth et al. 2006, Giron-Nava et al. 2017, Harvey et al. 2020).

Action 4.2.2: Collect long-term abiotic datasets to track changes in habitat conditions and inform management practices.

To support local adaptation efforts, research should continue to address knowledge gaps related to abiotic data in order to improve regional oceanographic, climate, and biological models. Currently, projections at finer scales relevant to practitioners and managers are interpolated and may not accurately report local variability, especially in areas with uniquely complex oceanographic properties like SITC's U&A, where there is valuable shellfish habitat. To better understand and predict habitat conditions, improve modeling capabilities, and identify appropriate management actions, monitoring efforts should be augmented (Rau et al. 2012). We suggest implementing a long-term water property/oceanographic monitoring program in northern Whidbey Basin in order to provide data to inform oceanographic models like the Salish Sea Model (Khangaonkar 2023) or Live Ocean (MacCready 2021), and to better understand the preferences and needs of local biota.

This effort will improve predictive capacity of future change and understanding of human impacts on local conditions (Gonski et al. 2021).

Action 4.2.3: Monitor invasive species and impacts on local ecosystems.
The spread and establishment of invasive species, typically as a result of human activity, may be facilitated by CC and further exacerbate stress on community composition, structure, and function (Campbell et al. 2009, Doney et al. 2012, Serra-Diaz & Franklin 2019). For example, during the spread of the European green crab (*Carcinus maenas*) on the coast of the western Atlantic, researchers noted local depletion of softshell clams due to intense predation and loss of eelgrass beds from digging and burrowing behavior (Garbary et al. 2014, Tan & Beal 2015). In the Salish Sea, the abundance and distribution of green crab is increasing due to the absence of controlling factors from its home range (e.g., parasites and pathogens) and because warmer water conditions promote rapid growth and development. Although the high diversity of native crabs may be slowing the spread, green crab may impact bivalve, Dungeness crab, flatfish, and eelgrass abundance if established, resulting in ecological, cultural, and commercial impacts on local communities (as reviewed in Bizzarro 2009, Grason et al. 2018, Howard et al. 2019). As communities become dominated by non-native species and biodiversity decreases, ecosystems may be less resistant to perturbations even if non-native species provide key ecosystem functions (e.g., McDowell et al. 2017). Therefore, it is important to track the distribution of invasive species, like green crab, as well as assess the impacts on local ecosystems to inform management and conservation efforts. These types of datasets can be collected in conjunction with Action 4.2.1.

Action 4.2.4: Monitor disease in targeted species.
Marine organisms, mollusks and echinoderms in particular, are susceptible to disease, especially during/post climate events, when immune systems are weakened due to thermal stress (Harvell et al. 1999, Burge et al. 2014, Cooley & Schoeman 2023). Disease outbreaks in sea urchins, sea stars, and eelgrass associated with marine heatwaves and warmer oceans have resulted in significant decreases in the abundance of foundational species, resulting in ecological phase shifts and reduced biodiversity (Hoegh-Guldberg & Bruno 2010, but see Menge et al. 2016, Harvell & Lamb 2020). In addition to rising temperature, factors such as introduction of new species, decline in host abundance and diversity, eutrophication, and range shifts in pathogens and hosts can also accelerate disease transmission (Burge et al. 2014). Rapid identification and monitoring of disease outbreaks as well as determining environmental factors would considerably help disease prevention, management, and food safety (Harvell et al. 2004, IPCC 2022, Cooley & Schoeman 2023).

Goal 4.3: Reduce impacts of extreme weather events on important shellfish beds and nursery habitats.
Background: In addition to natural climate events (e.g., ENSO, PDO, NPGO) that influence shellfish population dynamics (e.g., Shanks 2013, Barber et al. 2019), there are anthropogenic climate events (e.g., marine and atmospheric heatwaves, freezing events, extreme wave events) that are causing mass mortalities and disease outbreaks in the nearshore (IPCC 2022, Raymond et al. 2022b, Hesketh & Harley 2022). Sea level rise will contribute to increased impacts of storm surge and other large wave events capable of inundating and eroding important intertidal shellfish beds and nursery habitats (Harris et al. 2011, Zhang et al. 2021). Identifying effective temporary refuge techniques for target populations during these extreme events may reduce stress and the occurrence of rapid declines in individual species abundance and distribution. These declines in turn can interrupt interactions with other species and have cascading effects on biodiversity, ecosystem functioning, and fisheries productivity (Walther et al. 2002, Poloczanska et al. 2016, IPCC 2023a). Reductions in abundance and access to shellfish resources disproportionately impact Indigenous communities that rely on subsistence and commercial fisheries within traditional territory (Norton-Smith et al. 2016, NWIFC 2016b, Holsman et al. 2018).

Action 4.3.1: Research and identify effective techniques to provide temporary refuge for targeted shellfish populations during extreme weather events.
Local beach conditions such as freshwater seeps, aspect, and proximity to shade may have mitigated thermal stress for some shellfish populations during an unprecedented atmospheric heatwave in 2021 that caused widespread massive shellfish mortality (Raymond et al. 2022b). Future research should examine the effectiveness of these environmental conditions as well as techniques to mimic the refuge-like conditions that may be applied to provide temporary relief to targeted populations on culturally and commercially important beaches during extreme weather events.

Action 4.3.2: Create a rapid response team to coordinate on-the-ground efforts to implement temporary refuge strategies.
Provide a group of interested individuals with the training and resources to efficiently execute techniques identified in action 4.3.1 to prevent significant mortality in targeted populations during extreme weather events. The technical members of the team would also, ideally, develop a plan for collecting data both before and after predicted extreme events so that managers could better learn about species' responses and be better prepared for future events.

Conclusion

Over the past 50 years, the global rate of change is unprecedented in geologic history and threatens human well-being and the health of the planet. The most effective way to sustain the ecosystem services that support a livable environment for humanity is to directly address the main driver and drastically reduce CO_2 emissions. At the local level, there are several feasible, low-cost adaptation actions to reduce CC and OA impacts that can be implemented immediately and provide co-benefits to coastal communities with minimal adverse effects (Rau et al. 2012, Doney et al. 2020, Pörtner et al. 2022). Those outlined in this report serve as an adaptive guide specifically to promote healthy, abundant shellfish resources for future generations of the Swinomish Indian Tribal Community. The Swinomish Fisheries Department is already working on several of the goals and actions presented. Additionally, there are effective mitigation and adaptation actions that support multiple CCASS strategies and goals simultaneously. For example, many policies and regulations already exist in various levels of government to protect critical habitat and species by addressing stressors like development and pollution; however, their implementation and enforcement is variable. Ensuring strict adherence to these policies and regulations could help prevent additional stressors from impacting species and ecosystem health and resiliency. Collaboration should also be emphasized to maximize limited resources among various entities with overlapping interests and jurisdictions in the Salish Sea. Integrated, inclusive, long-term planning across sectors can provide greater benefits and increase adaptation success (IPCC 2023a).

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Author contributions

Conceptualization: CG; Writing – Original Draft Research and Preparation: CG; Writing – Second Draft Preparation: CG, JB; Writing – Review & Editing: JB, CG; Visualization: CG, JB, LH; Project Administration: CG, JB; Funding Acquisition: CG.

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