SHELLFISH

INTRODUCTION

For thousands of years, the Port Gamble S'Klallam Tribe has depended upon shellfish as a source of food and as a resource for income, trade, and ceremonial purposes. In the 1855 Point No Point Treaty, the Tribe reserved the right to continue to harvest shellfish from usual and accustomed areas. A 1994 U.S. District Court decision established that Tribes have the right to take up to 50% of the harvestable shellfish—clams (including cockles and geoduck), oysters, crab, shrimp, sea urchins, and sea cucumber—on western Washington beaches and state-owned aquatic lands. Today, the Port Gamble S'Klallam Tribe still relies heavily on the harvest of clams, oysters, crab, and shrimp for subsistence and ceremonial purposes [1].

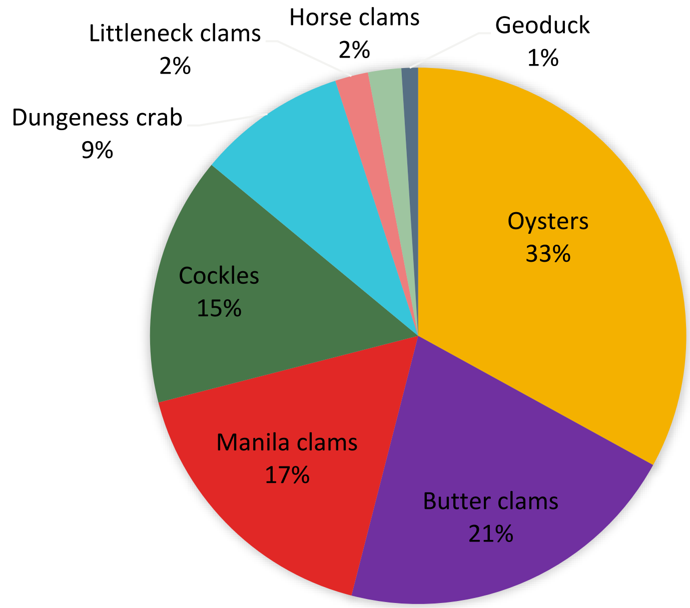
Even before the impacts of a warming climate became known, the Tribe already faced challenges in its shellfish harvests. The population of some wild shellfish species has been reduced through stressors such as habitat loss from development, pollution, eutrophication (often associated with nutrient pollution via runoff from urban and agricultural lands), and overfishing [2]. Climate change and ocean acidification now pose significant additional stress on top of these existing pressures.

IMPORTANCE OF SHELLFISH TO TRIBAL SUBSISTENCE, CULTURE, AND ECONOMY

Shellfish are a vital part of many Tribal members' diets. In 2014, the Tribe recorded a total of 192 members engaged in shellfish harvesting—most of whom harvested multiple species. This number is down from 2013, which saw 213 members engaged in shellfish harvests. Between 2005 and 2014, the most popularly harvested shellfish species among Port Gamble S'Klallam Tribal members was the Manila clam, followed by crab and oyster. Figure 1 shows the 2014 subsistence harvest by species.[1]

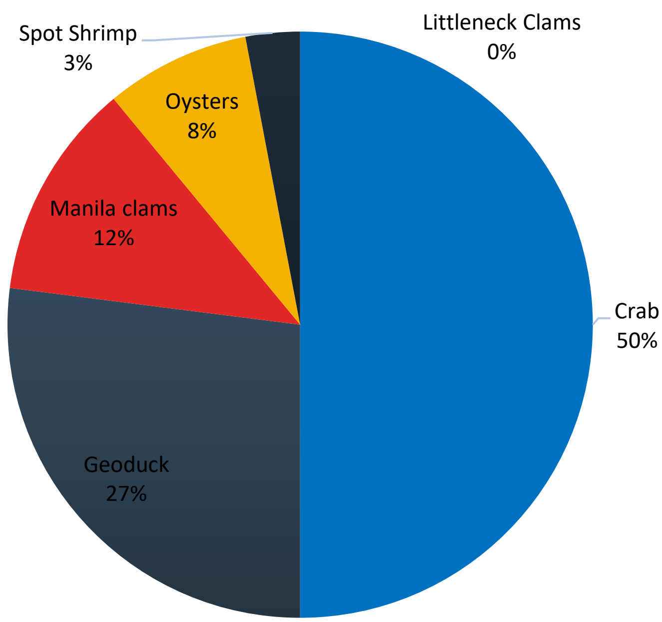
[1] It should be noted that these numbers are based on what is reported to the Tribe. 100% accurate subsistence numbers are not available given gaps in reporting from Tribal members.

Figure 1. PGST 2014 subsistence shellfish harvest.



In addition to subsistence, shellfish harvests are an important source of income for Port Gamble S'Klallam Tribal members. Statewide, the economic value of commercial shellfish is approximately $270 million [3]. For the Port Gamble S'Klallam Tribe, the most economically important shellfish species are Dungeness crab, geoduck, Manila clams, oysters, littleneck clams, and spot shrimp. Figure 2 shows the 2014 commercial shellfish harvest by species.

Figure 2. PGST 2014 commercial shellfish harvest.



Climate change effects such as warming water and air temperatures, sea level rise, more extreme weather events, and the associated issue of ocean acidification (particularly eutrophication-induced local acidification) have the potential for direct impacts on shellfish populations, habitat, and harvesting opportunities for the Port Gamble S'Klallam Tribe. These and other changes consistent with what is expected with climate change have already been observed throughout Western Washington and the Puget Sound region—including on the Tribe's reservation and usual and accustomed areas—and are predicted to become even more severe over the coming decades due to rising greenhouse gases [4]. This chapter details the impacts that climate change is projected to have on shellfish in the Puget Sound region, including harmful algal blooms, ocean acidification, hypoxia, and habitat loss or change. Table 1 lists the optimal temperature, salinity, and pH ranges for those shellfish species important to PGST.

RESEARCH NEED: What are some potential benefits of warmer water temperatures to shellfish in Puget Sound?

Table 1. Optimal temperature, salinity, and pH ranges for shellfish species that are ecologically and economically important to PGST [5, 6, 7, 8, 9, 10, 11, 12, 13, 14].

Species	Temperature	Salinity	pH
Pacific oyster	50 – 85°F	10 – 30 ppt.	8.0 – 9.0
Olympia oyster	56 – 65°F	15 – 35 ppt.	8.0 – 9.0
Cockles	50 – 69°F	20 – 30 ppt.	6.5 – 8.5
Geoduck	43 – 61°F	27.5 – 32.5 ppt.	6.8 – 8.5
Manila clam	53 – 64°F	20 – 30 ppt.	6.5 – 8.5
Butter clam	---	---	---
Littleneck clam	50 – 59°F	27 – 32 ppt.	---
Horse clam	40 – 64.4°F	27 – 33 ppt.	---
Dungeness crab	53 – 60°F for mating. 48 – 60°F for egg brooding. 50 – 57°F for larvae. 50 – 60°F for adults.	25 – 30 ppt.	7.1 – 8.0
Shrimp	45 – 54°F	25.2 – 30.8 ppt.	7.6 – 8.1

WATER TEMPERATURE INCREASES

Temperature is an important factor influencing the physiology and development of shellfish species, as their body temperature and metabolism fluctuates with temperature variations [15]. Warming water temperatures will likely result in changing rates of growth, development, and productivity for shellfish; spatial shifts of marine life, increases in the number of hypoxic zones, and an increase in harmful algal blooms that can threaten human health will also occur [16].

Warmer water temperatures may provide certain benefits to some shellfish species. According to the Washington Department of Fish and Wildlife (WDFW), Pacific oysters, specifically, are most likely to have a successful spawning period when water temperatures reach 65°F [17]. As a result, warmer water temperatures could generate a longer spawning period for Pacific oysters and similar species.[2] A 2016 study by Valdez and Ruesink found that Pacific oyster recruitment in Hood Canal increased between 1942 and 1992, and correlated with increasing average July/August temperatures over the same timeframe [18]. However, studies on the response of Pacific oysters to extreme heat shocks of 98°F show that oysters, especially post-spawning oysters, have limited adaptability to extreme temperatures, often resulting in mortality [19]. Extensive research has been conducted around summer mortality of juvenile oysters as well, showing mortality can occur at temperatures of 64°F [20]. This suggests that any benefits of warmer temperatures to the Pacific oyster are restricted to a certain temperature range, and will end once temperatures become too high. Research is needed to determine if there are any potential benefits of a warming climate for the other shellfish species important to the Tribe.

RESEARCH NEED: Is it possible for shellfish species important to the Tribe to become acclimated to warm water and see reduced levels of toxicity that would otherwise be caused by HABs?

HARMFUL ALGAL BLOOMS

Harmful algal blooms (HABs) can cause a range of environmental effects and are expected to increase in scope and frequency under future climate regimes that project continued warming [21]. Some HABs produce toxins that can accumulate in filter-feeding shellfish. These toxins can then be passed through the food chain, leading to a variety of illnesses or even death when consumed by humans. Some research suggests that these toxins can also have certain physiological and behavioral impacts on marine invertebrates, such as reduced filtration capacity or inability for some mussels to create byssus threads [22, 23]. Additionally, the decomposition of algal blooms, toxic or non-toxic, can lead to decreases in dissolved oxygen with varying implications for shellfish and other marine life [24]. Information on the other impacts of HABs can be found in the Harmful Algal Blooms chapter.

Shellfish Poisoning

The most common human health risk associated with HABs is paralytic shellfish poisoning (PSP) [25]. PSP is spread to humans who eat filter-feeding shellfish that have accumulated toxins produced by the algae [26]. Although the accumulated toxins in shellfish are not thought to harm the health of the shellfish, these toxins can have varying health impacts on humans and animals that consume them. In Puget Sound, *Alexandrium catenella* is most often associated with the creation of these toxins, collectively referred to as paralytic shellfish toxins (PSTs) [21].

PSP is signified by a number of physiological responses that can begin nearly immediately after consumption of contaminated shellfish [26]. PSP reactions usually include tingling around the mouth that progresses to a numbness that spreads through the face and neck [27]. More severe symptoms include incoherent speech, loss of coordination of limbs, general weakness, muscular paralysis, and even death [28]. Up to 75% of victims in severe cases who do not receive supportive treatment die within twelve hours [27].

PSP is not the only type of shellfish poisoning present in the Puget Sound region. Other biotoxin-induced poisonings include diarrhetic shellfish poisoning (DSP), from toxins also attributed to HABs, have been recorded in South Puget Sound and Sequim Bay, where three people were treated for DSP after eating

[2] This does not assume that Pacific oysters will indeed spawn more, only that the period in which Pacific oysters can spawn is likely to increase with warmer waters. This does not account for how other climate impacts may affect Pacific oyster reproduction.

toxic mussels harvested there [29]. These toxins have been found in Hood Canal as well [30]. Much like PSP, DSP is caused by consuming shellfish that have accumulated toxins from HABs, in this case those consisting of the dinoflagellate *Dinophysis* [31]. Symptoms of DSP include acute gastrointestinal distress, such as nausea, abdominal pain, and vomiting, which can last up to 72 hours with supportive treatment [32]. Clams and oysters, which accounted for 20% of PGST's commercial shellfish harvest and 75% of the subsistence harvest in 2014, are among the most common transvectors of PSP and DSP.

Phytoplankton blooms also carry the threat of causing amnesic shellfish poisoning (ASP) in humans. ASP is caused by consuming shellfish that have accumulated domoic acid, a biotoxin produced by the diatom *Pseudo-nitzschia* [33]. As with PSP and DSP, the species of shellfish commonly found in Puget Sound are often transvectors of ASP. According to a 2004 study by Jeffery et al., domoic acid has been observed to accumulate in a broad range of invertebrates, including cockles, crabs, and clams [33]. Each of these species are important to the subsistence and economic vitality of the Port Gamble S'Klallam Tribe. The Washington State Department of Health reported that ASP is characterized by both gastrointestinal and, in severe cases, neurological issues including permanent short-term memory loss, seizures, and possibly death [34]. Diatom blooms responsible for the creation of domoic acid are thought to be increasing in frequency and toxicity world-wide [35], and studies indicate that this growth is triggered by climate change-related impacts such as increasing sea surface temperatures and altered weather patterns [36].

When HAB conditions for shellfish toxins are monitored, dangerous recorded levels can lead to closures of shellfish beds and beaches. This can disrupt commercial and subsistence harvesting activities and result in varying degrees of economic losses, health concerns, and the unavailability of shellfish for subsistence and ceremonial uses. For example, closures have occurred in various waterways in Puget Sound as a result of domoic acid found in commercial shellfish with accumulated levels of the toxin above the regulated limit of 20 ppm [37]. In June 2015, nearly all of the recreational shellfish beaches along Hood Canal were closed or under advisory because of toxins [38]. A study by Moore et al. published in 2009 examined closures occurring in Puget Sound from 1993 to 2007 and found that closures were often preceded by periods of warm air and water temperatures, and low streamflow [26]. These conditions correlated specifically with higher levels of PSTs in Puget Sound during that timeframe, and climate projections indicate that such conditions will become more common [26]. However, a study conducted in 2015 by Farrell et al. showed that some species of shellfish, when acclimated to warmer water temperatures (71°F and warmer), were significantly less toxic after being exposed to PSTs [39].

This suggests that future climate scenarios may favor the development of HABs, but some shellfish may be able to adapt to the increased water temperatures and maintain low levels of toxicity.[3] It also showcases the need for more advanced HAB monitoring technologies, in particular those that can conduct streamlined detection of harmful algae and provide early warnings of changing conditions. One such system is being developed by NOAA's Northwest Fisheries Science Center and is called the Environmental Sample Processor (ESP) [40]. ESP performs on-site, automatic water sampling to remotely detect toxins produced by harmful algae [40].

Hypoxia from HABs

HABs can also indirectly harm shellfish by increasing cases of hypoxia (when oxygen levels become too low to support marine life). In cases where HABs create excess organic matter that decomposes and causes reductions in dissolved oxygen levels, massive fish and shellfish kills can happen as a result [41]. More

[3] It should be noted that there are species-specific differences in biotoxin uptake rates and detoxification rates, including how biotoxins are stored within bivalves and any physiological or behavioral effects that happen as a result [105].

mobile invertebrates, like Dungeness crab, show particular sensitivity to hypoxic zones, having been shown to avoid hypoxic areas even if food is present [42].

Currently, relatively few cases of hypoxia directly related to high biomass HABs have been documented in the United States [2]. However, the apparent linkages between climate change, HABs, and stratification of coastal waters suggest that hypoxia could become more prevalent in the future. Together, the projected increases in hypoxic zones, if realized, would prove to have significant impacts on shellfish populations in Puget Sound, and consequently adverse economic impacts on those dependent on shellfish for their livelihoods.

For more information, see the chapter on Harmful Algal Blooms.

VIBRIO

The presence of naturally occurring *Vibrio spp.*, like PSP and DSP due to HABs, are associated with increasing water temperatures. *Vibrio spp.* are a type of marine bacteria that can cause vibriosis, a gastrointestinal illness usually contracted from exposure to seawater or consumption of raw or undercooked shellfish and other seafood [43]. *Vibrio parahaemolyticus and V. vulnificus* pose a significant variety of risks to humans in Washington State, including gastroenteritis, bullous lesions, and death [43]. As with other toxins, the detection of *Vibrio* in coastal habitats can force the closure of shellfish beds and beaches [44].

The State of Washington has enacted a control plan in an effort to prevent oysters contaminated with *Vibrio* from reaching consumers [45]. The plan applies to all oyster harvesters during the months of May through September, and places stringent requirements on harvesters to monitor water and internal oyster temperature and to abide by specific conveyance and cooling methods triggered by temperature thresholds [45]. Oyster harvesting is completely prohibited during July and August whenever water or oyster-tissue temperatures reach 70°F; prohibitions last for twenty-four hours, and are extended at twenty-four hour intervals until temperatures fall below 70°F [45].

A 2012 study done by Newton et al. showed that vibriosis cases have increased in the U.S. over the past decade [46]. From 1996 to 2010, Washington, along with seven other states, was categorized as "high incidence" for reported cases of vibriosis [46]. Increasing water temperatures over the same timeframe may provide an explanation: a study done by Won Kim et al. (2012) showed that *Vibrio* growth is highly dependent upon temperature, with growth occurring at water temperatures of 52°F and above [47]. According to water temperature tracking data produced by NOAA, average summer time water temperatures in Puget Sound range from 53 to 55°F [48].

Research done by Chae et al. in 2009 showed that temperature also affects shellfish depuration (the discharge of contaminants) for reducing *Vibrio*, where depuration capabilities are diminished in oysters at water temperatures above 59°F [49]. Because temperature projections for the Pacific Northwest show continued increases in temperature, *Vibrio* may develop at an accelerated speed and expand in geographic scope to more northern latitudes, as well as diminish the capacity of shellfish to depurate the bacteria once contaminated.

Temperature is not the only driver of *Vibrio* growth. Salinity is an important factor in creating favorable conditions for *Vibrio* growth as well, and may be influenced in nearshore zones and estuaries by sea level rise, freshwater input, and changing precipitation patterns [50].

SPECIES DISTRIBUTION

Warmer waters have the potential to affect species distribution as warm-water species' habitat range is expanded and cold-water species' habitat range is diminished [51]. The most dramatic impacts will be felt in northern latitudes, where water bodies are characterized by historically cooler seawater. One observed example of the redistribution of species resulting from warming water temperatures in Puget Sound is the growth of dinoflagellates, specifically *Alexandrium*, since the late 1950s [52]. Burrowing shrimp are also thought to be becoming more prevalent in this region, particularly in Willapa Bay [53]. The burrowing activity of these shrimps disrupts the sediment within intertidal zones used for oyster harvesting, and can result in the smothering and subsequent loss of oyster beds [54]. The increased occurrence of burrowing shrimp reported by shellfish harvesters could be linked to warmer-than-average water temperatures, which are favorable by some species of burrowing shrimps [55]. Some shellfish harvesters also attribute the prohibited use of the pesticide imidacloprid to recent infestations [53].

RESEARCH NEED: What are the potential distributional effects on specific Puget Sound shellfish species due to warmer waters?

Warmer water temperatures may dramatically impact the physiology of marine life. Warming water temperatures affect many species' metabolism, growth, and reproduction, which can lead to further alterations in their geographic distribution [56]. Numerous studies point to the relationship between climate change and the distribution of particular species [57, 58]. Still, it is difficult to project the potential distributional effects on specific Puget Sound shellfish species, given the limited species-specific research on this topic and the potential for additive stresses from multiple environmental variables.

Invasive Species

There is potential for warming water temperatures to facilitate the introduction of nonnative, invasive species to Puget Sound shellfish habitats. One such example is the increasing prevalence of invasive tunicates in Hood Canal and across Puget Sound [59]. Invasive tunicates are a fouling organism, meaning they have the ability to attach to the surface of material immersed in water. They also have a wide tolerance to environmental variables, long breeding periods, and exhibit rapid growth [60]. These facts suggest that future attributes of Puget Sound described in climate projections (increasing water temperature and rates of salinity) may allow for invasive tunicate population expansion.

According to Cordell et al. (2013), invasive tunicates are currently presenting challenges for shellfish harvesters in Puget Sound given their tendency to appear on man-made structures used during harvesting operations, like floating docks or aquaculture facilities [61]. Additionally, invasive tunicates can impede shellfish harvesting because they have the ability to "overgrow" other fouling organisms like oysters and clams, suffocating them [61]. Figure 3 shows invasive tunicates found on mussels in Puget Sound.

Figure 3. Tunicates attached to mussels in Puget Sound [62].

Other invasive species of concern that have been recorded in Western Washington include the New Zealand mud snail and European green crab [63], as well as the Japanese oyster drill [64]. Varnish clams have been growing in number around Washington State for the past ten years, and can be harvested recreationally [65]. More research needs to be done to determine any potential ecological impacts [65].

New Zealand mud snails can survive in a variety of water temperatures and salinity, suggesting that the species will be able to adapt easily to the warmer waters predicted in climate projections for Puget Sound. While it is unclear how damaging these mud snails are to the physiological health of native shellfish, they do present a potential threat to habitat as it is very difficult to eradicate the mud snails once they have been established without causing further damage to the water body [66].

European green crabs prey on small oysters and clams, and have recently been found in Westcott Bay (San Juan Island) [67]. They can tolerate varying rates of salinity and temperatures from 32 to 90°F, meaning that they can continue to thrive even as other species are stressed by warming waters [68]. Additionally, green crabs pose threats to commercial shellfish harvests of clams, oysters, and mussels in Puget Sound, where estimated future losses vary from 3% to 64% depending on green crab population densities [69].

Another prominent example of the impact invasive species may have on shellfish populations is the Japanese oyster drill (*Ocinebrellus inoratus*). These snails feed on shellfish after "drilling" a small hole in the outer shell of a mollusk in order to insert their radula and extract the soft tissue (thereby killing the animal) [64]. Recent efforts (2013) between Washington tribes and the USDA have begun to address the threat these snails pose to shellfish harvests [64]. Oyster drills are most common in areas with low freshwater input (higher salinities) and higher temperatures [70]. They are often attracted to naturally-formed Pacific oyster reefs—given the protection from predators and abundant food source [71]. Oyster drill management typically includes manual removal of adult drills and egg capsules, but complete removal of drills from oyster beds has proven difficult—leading to the closure of some oyster beds due to extensive predation [71].

It should be noted that invasive species are often spread by means that are unrelated to climate change (e.g., recreational boats or commercial ships). However, once an invasive species has established itself in the new environment, the lack of natural predators and the potential for increasingly beneficial conditions created by climate change could allow for rapid population growth.

RESEARCH NEED: Are there specific traits that make an organism more resilient to ocean acidification, and can the development of these traits be predicted?

OCEAN ACIDIFICATION

Ocean acidification—a direct consequence of increased atmospheric carbon dioxide—carries the potential to severely impact shellfish populations in Puget Sound as pH levels lower. Current measurements of dissolved carbon dioxide in Puget Sound, as published in the *Blue Ribbon Panel Report on Ocean Acidification*, indicate that local water bodies, including Hood Canal, have been at corrosive levels for many calcifying organisms since recording began in 2008 [72]. Higher levels of dissolved carbon dioxide are likely to threaten some shellfish populations by diminishing their ability to form shells [72]. According to a 2009 study by Ries et al., the most negatively impacted species include clams and oysters [73]. However, the researchers found that calcification by other species, such as crabs and shrimp, was not impacted by the rates of dissolved carbon dioxide that proved problematic for other types of shellfish [73]. Crabs, in particular, appear more resilient to ocean acidification by their ability to regulate pH as they are building their shells [73]. There is a large and emerging literature on the effects of ocean acidification on marine organisms generally, as impacts are likely to be severe and long-lasting.

For more information on ocean acidification trends and projections, see the Observed and Projected Climate Changes chapter.

IMPACTS ON SHELL CALCIFICATION

The increase in hydrogen changes in carbonate chemistry associated with ocean acidification inhibits the calcification process for some shellfish species [74]. Increased levels of hydrogen reduce the amount of calcium carbonate available for organisms with calcium-based shells, thereby impacting shellfish throughout their entire life cycle [75]. Higher levels of acidification driven by anthropogenic carbon emissions have been projected to develop within decades, a much faster rate than previously thought [76]. These projections are based on current global emissions rates, which have been replicated in both laboratory and field studies that found such emissions create pH conditions in seawater capable of dissolving the shells of calcifying pteropods [76].

The impact of ocean acidification on shell calcification has already been observed in the Pacific Northwest. A study conducted in 2012 by Barton et al. attributed Pacific oyster declines and impacts on larval development to poor water quality from natural upwelling of deep ocean water with lower pH levels, which gave researchers a glimpse of the types of impacts expected from increased acidification in the future [77]. The specific vulnerability of larvae to acidification is echoed in a study by Waldbusser et al. in 2013, which found that bivalve larvae are most heavily impacted by acidification during early developmental and shell formation stages, namely due to excess energy used to regulate their internal chemistry [78].

Additionally, research done on Olympia oysters showed that temporary exposure to seawater with elevated levels of dissolved CO_2 can have lasting developmental impacts, even after the oysters are transported to less acidic waters [79]. This suggests that even temporary instances of lowered pH (e.g., during natural upwelling) can have cascading effects on development throughout an organism's life span and on the general population dynamics of impacted species. However, Olympia oysters have been observed brooding their larvae, which in turn helps larvae begin the calcification process before being exposed to lower pH levels [80].

RESEARCH NEED: Will increased erosion lead to the increased use of emergency HPAs in the Tribe's primary traditional use area?

Finally, a study by O'Donnell et al. (2013) found that ocean acidification has the potential to impede the development of byssal threads used to anchor mussels to rocks and other substrates, even though these are non-calcified biomaterial [81], suggesting that elevated levels of dissolved carbon dioxide can have impacts on shellfish biology beyond shell calcification.

Some research has shown that shellfish may have the potential to adapt to the increased acidity of seawater. In 2013, Pespeni et al. found the genes that control biomineralization in calcifying organisms can evolve when exposed to acidic conditions over long periods of time (50 days, post-fertilization) to ensure calcification [82]. Similarly, selectively bred larvae spawned from adult oysters after they were exposed to acidic conditions showed signs of more resilience to elevated carbon dioxide levels than wild larvae [83]. However, it is unclear if these genetic evolutions can be repeated in organisms impacted by multiple environmental stressors, such as those in Puget Sound. In any case, ocean acidification's effect on shell calcification carries the potential to disrupt entire marine ecosystems: changes in population size, dynamics, and community structure of bivalve and crustacean species could lead to species extinctions [84].

SEA LEVEL RISE

IMPACTS ON SHELLFISH HARVESTING AND HABITAT

Sea level rise has the potential to change the Puget Sound region's coastal landscapes, thereby causing habitat loss and associated impacts on shellfish populations and harvesting activities. Species that live in intertidal areas and/or depend on estuaries as nurseries—including littleneck clams, geoduck clams, Olympia oysters, butter clams, and Dungeness crab—are at risk due to habitat damage associated with higher sea levels. Due to differences in tectonic activity and subsidence rates, sea level rise projections vary even within Washington State (see Observed and Projected Climate Changes chapter), and habitat losses will not be equally distributed.

Shellfish habitat loss in the Puget Sound region

In the Pacific Northwest as a whole, it has been estimated that an increase in sea level of 27 inches would equate to the loss of nearly 65% of estuarine beach and 44% of tidal flats [85].

In a study focused on the upper Hood Canal and Kitsap Peninsula, including Port Gamble, more than half of beach land is predicted to be lost and converted to tidal flats by 2050 because of sea level rise [85]. A 2014 study by Solomon et al. showcased the effects of sea level rise on intertidal zones and the cascading impacts on oyster populations, and ultimately concluded that oyster reef survival is dependent upon the habitat's ability to move inland to maintain optimal submersion rates as sea levels rise [86]. A study by Rodriguez et al. 2014 supported that conclusion [87], but also found that intertidal oyster reef accretion kept pace with, or even benefitted from, sea level rise in modeling scenarios when reef accretion was not otherwise impeded [88]. This suggests that some human activities (e.g., shoreline armoring) would likely restrict the natural inland migration of shellfish habitat. A 2013 study by Peterson found that more pronounced long-term ecological impacts of sea level rise will be experienced where human-built dikes alter tidal influence on floodplains [89]. Remote sensing and simulations generated similar results, indicating that sea level rise will lead to significant losses of shellfish habitat around Puget Sound unless small dikes enclosing marshes are allowed to deteriorate [90]. Dikes and similar types of developments are currently found in approximately 86% of natural shoreline segments in Puget Sound [91].

Changes in habitat composition can greatly impact the Tribe's ability to harvest shellfish when these changes result in the reduction of shellfish populations or restrict access to traditional harvest areas, namely intertidal substrates. For example, in a presentation by Dewey and Cheney it was estimated that a sea level rise of approximately 6 inches in Washington State could reduce harvest time by 13% compared to the current number of harvest days due to increased water coverage; this number jumps to 31% with 12 inches of sea level rise [87]. Furthermore, the impacts of sea level rise are happening simultaneously with other impacts that affect shellfish habitat, which suggests that the estimated loss of habitat and resulting effects on shellfish could potentially be more pronounced.

Population Dynamics and Composition

It is also important to consider the effects of changing shellfish distribution, competition, and predation as sea level rises. Because sea level rise combined with nearshore development reduces the availability of intertidal habitat, shellfish species may be required to compete for limited space and may become more vulnerable to predators [92].

In a study by Ferriss et al. 2015, the primary areas used for harvesting geoduck clams in central Puget Sound produced significantly smaller yields than other shellfish-producing regions in the state, while accounting for 27% of the Tribe's commercial harvest in 2014 [93]. Even though geoduck clams represent a small portion of the overall commercial shellfish harvest in the area, they are a significant economic driver for the Tribe and may be more vulnerable to sea level rise given their low population numbers.

EXTREME EVENTS

Extreme climatic events in the form of extended drought and heavier rain events can have varying impacts on shellfish and shellfish habitat. Generally, these events have been shown to alter the delivery of nutrients and sediments, the physical-chemical properties of estuaries, and ecosystem functionality [94]. Human activities, particularly those that influence the transport of sediment from watersheds, will exacerbate the impacts of these natural events [95].

HEAVY PRECIPITATION AND EROSION

Reduced Salinity

Many climate change projections forecast an increase in extreme rainfall events, which could result in localized flooding and high-flow events for rivers [96]. A 2008 study showed that such events reduced the salinity of estuaries [96]. Reduced salinity in estuaries that provided habitat for shellfish resulted in a correlated reduction in hemocyte cells, which are used to maintain the immune system of invertebrates [96]. This suggests that flooding and high-flow events could have a severe impact on shellfish species' health depending on the duration and amount of precipitation in the event.

Increased Sediment Loads and Erosion

Sea level rise will alter wave energy and distribution and result in increased shoreline erosion and an adjustment of the coastline [97]. A study by Allan and Komar found that deep-water wave heights off the coast of Washington are significantly greater during extreme events and cause changes in shoreline composition at faster-than-average rates [98]. These sudden alterations in beach profiles make Tribal beach seeding operations particularly difficult to plan given the unpredictability of extreme storms and threaten the loss of existing seed sets.

Heavy rainfall and subsequent flooding could potentially change sediment profiles along coastal areas as well. In 2014, Wong et al. used flood-modeling technology to demonstrate changes in fluvial processes during extreme flooding events and showed that such events can create dramatic geomorphological changes to river systems that may result in above-average sediment deposition [99]. Such events could mean quick changes in coastal habitat that give minimal time for slow-moving or stationary invertebrate species to adapt or respond. Past records of extreme floods, for example, show that high-volume deposition can result in rapid progradation of river mouths often followed by immediate post-flood recession of the "new" shoreline [100]. These circumstances could smother shellfish beds with remarkable quickness and unpredictability, leaving shellfish harvesters vulnerable to losses of shellfish product.

DROUGHT

As mentioned above, episodes of extreme rainfall can throw off the balance needed for stable shellfish habitats and population dynamics, particularly when it comes to salinity reductions. Research has also shown that similar effects on population dynamics can occur under drought conditions, when salinity rates in estuaries are elevated. In 2000, Attrill and Power found that even small increases in salinity brought on by reduced freshwater inflows under extended drought conditions can have dramatic effects on the composition of invertebrate species, often resulting in population decreases [101]. A 2012 study similarly concluded that large, harvestable oysters suffered more frequently from disease-related mortality under high-salinity drought conditions [102]. Together, the projections for increased drought, sea level rise, and extreme rainfall suggest that the composition of estuaries in Puget Sound is especially threatened by climate impacts.

RESEARCH NEED: How will future periods of drought in Washington State affect the growth of phytoplankton upon which shellfish feed?

Drought can also affect the growth and availability of phytoplankton that serve as the basis of the food chain for marine life, including shellfish. Wetz et al. 2011 found that low streamflow and increased stratification during drought conditions led to reduced levels of phytoplankton growth in estuaries and created hypoxic conditions with subsequent fish kills [94]. Research is needed to relate the influence drought has on phytoplankton growth with regional projections of future precipitation patterns in order to determine specific impacts on Puget Sound shellfish species. In theory, though, less freshwater inflow should lead to reduced phytoplankton activity [103].

LOOKING AHEAD

Recent research has found that bivalves tend to grow slower and live longer in northern latitudes than those found in southern, more tropical latitudes [104]. This could be the result of a warmer climate in southern latitudes allowing for higher metabolic rates, which leads to faster growth and shorter lifespans [104]. As Pacific Northwest temperatures continue to increase in the future, bivalve species in this region may experience faster growth and shorter lifespans. However, our interviews with regional experts suggested that these sorts of physiological changes are unlikely within the next 20 years.

Ocean acidification and warming water temperatures are likely the biggest threat to shellfish in the Puget Sound region. The impacts of acidification and warming water temperatures can have on shellfish and shellfish harvesting are presently being observed, which suggests that these impacts will only continue (with the potential to worsen). However, regardless of the specific impact affecting shellfish, it is possible that shellfish species will be able to adapt to future conditions.

> "We probably underestimate the ability of species to adapt. Many studies that show how shellfish are impacted by acidification basically just plop the shellfish into a bucket of water that's supposed to simulate what it's going to be like in 100 years. They don't account for species' ability to adapt over time."
>
> **Austin Paul, Subtidal Shellfish Manager, Point No Point Treaty Council**

That being said, the adaptability of species relied upon by Tribal members remains to be seen. It is possible that many Tribal members, particularly those who rely on subsistence harvest of shellfish, will see diminishing opportunities to retain shellfish as a reliable source of nutrition. While technological advances in aquaculture would help ensure shellfish remain a part of the Tribe's diet, the Tribe will need to be poised to take advantage of such innovations.

Of particular importance into the future will be the continued focus on monitoring environmental changes and correlating changes in shellfish species, especially population dynamics. This will help to ensure shellfisheries are managed with climate change in mind.

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