Section 11

How Will Climate Change Affect Marine Ecosystems in Puget Sound?

Coastal and marine ecosystems in Puget Sound are projected to experience continued increases in sea surface temperatures, sea level rise, and ocean acidification. These changes are expected to have implications throughout Puget Sound's marine food web affecting organisms at the bottom (e.g., phytoplankton and marine plants) and at the top (e.g., salmon and marine mammals) of the food chain. Increasing sea surface temperatures are projected to negatively affect salmon populations, increase the magnitude and frequency of harmful algal blooms, and may increase growth rates in eelgrass beds. Sea level rise is projected to increase the area of some coastal habitats (e.g., tidal flats and salt marshes), and decrease the area covered by other habitats (e.g., estuarine beach, tidal swamp). Ocean acidification will likely harm many estuarine species, especially shellfish and other organisms that form calcium-based shells. Efforts to address climate-related effects on marine ecosystems are increasing, particularly with respect to ocean acidification and ocean monitoring.

Climate Drivers of Change

CLIMATE DRIVERS ***Estuarine species and ecosystems in Puget Sound[A] are projected to face changes in sea level, sea surface temperature, and ocean acidification during the 21st century.***

- *Observations show a clear warming trend, and all scenarios project continued warming during this century*. Most scenarios project that this warming will be outside of the range of historical variations by mid-century (see Section 2).[1,2] Increasing air temperatures will likely cause sea surface temperatures to increase, leading to higher growth rates, increased risk of harmful algal blooms, and impaired health and habitat quality for certain species.

- *Nearly all scenarios project a rise in sea level.* Sea level rise is projected for all locations except Neah Bay, where a decline in sea level cannot be ruled out due to the rapid rates of uplift in that area (see Section 4).[3,4,5] Rising seas will inundate more land, altering the geographic area of many coastal habitats.

A Throughout this report, the term "Puget Sound" is used to describe the marine waters of Puget Sound and the Strait of Juan de Fuca, extending to its outlet near Neah Bay. The term "Puget Sound region" is used to describe the entire watershed, including all land areas that ultimately drain into the waters of Puget Sound (see "How to Read this Report").

- *Ocean water will become more acidic*[B] *as excess atmospheric carbon dioxide (CO_2) is absorbed by the oceans.*[6] Ocean acidification will make it more difficult for marine organisms to create shells and skeletons, potentially disrupting an important food source for many important fish species in Puget Sound and the northeast Pacific.[C,7]

Tidal Wetlands

TIDAL WETLANDS ***The area of tidal wetlands is projected to change during the 21st century.*** The actual changes (i.e., expansion or decline) will depend on wetland type, the rate of sea level rise, amount of sedimentation, and availability of landward buffers into which to migrate.

- *Sea level rise is projected to expand the area of some tidal wetlands but reduce the area of others.* An analysis of coastal areas in Puget Sound found that rising seas are projected to increase the area[D] of salt marsh by +260% (range: +49% to +4300%, depending on location), and result in +70 times more transitional marsh[E] (range: increasing by a factor of 16 to 378) by 2100, relative to 2000, for a mid-range sea level rise projection.[F,G,8] Sea level rise is also projected to change tidal flat area by +240%, on average (range: −81% to an increase from 0 to 236 acres), reduce estuarine beach area by −79% (range: −96% to −34%), reduce brackish marsh by −57% (range: −84% to −1%), change the area covered by tidal swamp by −77% (range: −97% to 0%), and change tidal freshwater marsh area by −24% (range: −85% to +3%).[8]

- *Sea level rise is projected to alter the composition of many existing coastal wetland areas.* By 2100, 52% of brackish marsh in Puget Sound, southwestern Washington, and northwest Oregon is projected to convert to tidal flat, salt marsh, and

---

B Although the acidity of the ocean is projected to increase, the ocean itself is not expected to become acidic (i.e., drop below pH 7.0). Global ocean pH has decreased from 8.2 to 8.1 (a 26% increase in hydrogen ion concentration, which is what determines a liquid's acidity) and is projected to fall to 7.8-7.9 by 2100. The term “ocean acidification” refers to this shift in pH towards the acidic end of the pH scale.

C Many marine organisms produce shells from the dissolved carbonate ions in seawater. As ocean waters become more acidic, the “aragonite saturation state” (the absolute carbonate ion concentration) decreases, making it more difficult to create and maintain “calcareous” (calcium carbonate) shells.

D Baseline habitat coverage areas were based on National Weather Inventory (NWI) photo dates, ranging between 1972 and 2000. The NWI photo date serves as the starting point for a SLAMM simulation.

E “Transitional marsh” refers to an intertidal shrub marsh: regularly flooded by tides, but not fully converted into a saltmarsh. In contrast with the sea grasses typical of salt marshes, transitional marshes are usually populated by broad-leaved deciduous trees.

F The large increase in area covered by transitional marshes is a consequence of the relatively small amount of area occupied by this habitat historically (only 138 acres in the entire study domain) and by the conversion of dry land to wetland as a result of sea level rise.

G Results are for based on a projected 27 in. (69 cm, about the middle of the range projected for 2100, relative to 1980-1999) increase in global sea level. The Sea Level Affecting Marshes Model (SLAMM 5.0) was applied to 10 sites within Puget Sound. The numbers in the text give the total change across all of Puget Sound, plus the range among the 10 sites.

transitional scrub-shrub, while 2% of undeveloped dry land is projected to be inundated, eroded, and converted to wetland or other coastal land cover.[G,8]

- *Projected changes in the timing and magnitude of peak and low streamflows could alter sediment delivery to tidal wetlands.* Adequate sediment delivery and sedimentation is vital for tidal wetlands, which can persist if increases in surface elevation proceed at a rate comparable to sea level rise.[9] Although sediment supplied from rivers is projected to increase, it is not known what proportion of sediments will be deposited in estuaries in the future, nor whether this increase might be sufficient to keep pace with sea level rise (see Section 5).

Eelgrass

EELGRASS ***Eelgrass may be resilient to climate change, and the area of eelgrass may expand in the short-term due to warming and sea level rise.*** Eelgrass beds are a key Puget Sound ecosystem, providing food and shelter for a wide variety of estuarine life, including salmon and crabs. Eelgrass area may expand with warming and sea level rise if thermal thresholds are not exceeded and its expansion is not limited by migration barriers. Eelgrass is generally resilient to, and has recovered from, disturbances such as disease and climate anomalies.[H,10]

- *Eelgrass growth rates may increase with warming, provided that thermal thresholds are not exceeded.* As sea surface temperature increases, eelgrass growth may increase up to a threshold temperature of about 77°F, as long as water clarity does not decline.[I,11,12] For instance, the highest observed summer growth rates for eelgrass in Sequim Bay tend to correspond with the warm sea surface temperatures associated with El Niño climatic conditions.[J,11] Once sea surface temperatures exceed the optimal range for eelgrass, growth may begin to decline.

- *Eelgrass area may increase with sea level rise as long as landward migration is not blocked.* For instance, eelgrass productivity and spatial area are projected to increase in Padilla Bay under moderate rates of sea level rise through the 21st century.[K,13] In Padilla Bay, eelgrass area is projected to increase because there is a landward buffer of mudflat into which the eelgrass is projected to migrate. However, under high sea level rise scenarios, eelgrass in Padilla Bay is projected to reach the limit of this buffer and the total area is expected to begin to decline as it is submerged.[13]

H Summarized from the literature.

I Based on laboratory experiments that measured dissolved oxygen changes in glass jars filled with sea water and three to four 3.94 inch-long (10 cm) eelgrass leaf sections at various temperatures.

J Based on the Oceanic Niño Index (ONI), which is defined by sea surface temperature anomalies from a long-term average in the Niño 3.4 region.

K Based on IPCC 2007 AR4 low, mid, and high greenhouse gas scenarios and a mid and high sea level rise scenario from Rahmstorf (2007) based on IPPC 2001. Eelgrass changes were modeled using a Spatial Relative Elevation Model.

Salmon

SALMON **_Pacific salmon populations are likely to be affected by changes in the temperature and salinity of ocean waters, ocean acidification, and upwelling._** Climate change effects are different depending on the life stage (adult, juvenile) and time spent in the ocean. Climate change is also expected to significantly affect Pacific salmon in their freshwater life history stages (see Section 10).

- *Increasing sea surface temperatures may cause a small decline in Pacific salmon survival.* A +1.8°F increase in sea surface temperature (similar to the warming projected for the northeast Pacific by the 2040s, see Section 7), could result in a −1% to −4% decline in the survival of salmon species ranging from northern California to southeast Alaska.[L,14] Warm phases of the Pacific Decadal Oscillation (PDO, see Section 6), which are associated with warmer-than-usual Washington coastal ocean waters, tend to be associated with low Coho salmon fisheries landings[M] in Washington, Oregon, and California. Although not focused solely in Puget Sound, one study found that the percent change in average catch of southeast Alaskan pink salmon[N] declined by −37.2% in 1947, the start of a cool phase (negative) PDO (see Section 6), and increased by +242.2% in 1977, the start of a warm phase (positive) PDO.[15] Among other environmental factors, Chinook salmon return rates to the Skagit River are lower when sea surface temperatures are above normal in the 3rd year of ocean residency;[O] the opposite is true when sea surface temperatures are below normal.[P,16]

- *Stronger upwelling is associated with increased salmon productivity.* Although it is not known how upwelling may change with warming (see Section 6), changes in upwelling associated with PDO cycles are known to significantly affect salmon populations.[15] A study evaluating the effect of coastal upwelling on the growth of juvenile Coho salmon (*Oncorhynchus kisutch*) off the coast of Washington and Oregon found that earlier summer upwelling was associated with higher rates of survival between 1981 and 1985.[17] A similar study found increased Coho salmon survival during strong upwelling years.[18]

- *Ocean acidification could directly affect salmon via lower growth rates, altered olfactory preferences, and a reduced anti-predator response.* Juvenile pink salmon begin migration to the ocean shortly after hatching, and are the smallest salmon

---

[L] A lagged model of survival was developed for two salmon stocks included in the analysis: the Columbia Upriver Brights and the Oregon Coastal, to evaluate if survival was related to local conditions. This model uses ENSO conditions in the tropical Pacific between May and June to predict PDO conditions for the following June, and then links PDO conditions to local sea surface temperatures which could potentially affect Chinook salmon survival in the short-term.

[M] Fisheries "landings" refers to the total weight of fish that are caught and brought on land.

[N] Mean catch levels were estimated from intervention models fitted to the data and incorporating a 1-yr lag for the pink salmon stock.

[O] Chinook salmon spend an average of three to four years in the ocean.

[P] Sea surface temperature and sea level pressure from COADS data between 48-57°N and 122-137°W from October to the following September for coastal and inland passage areas. The upwelling mean index was taken from four coastal sites in Washington and British Columbia.

species arriving in saltwater.[19,20] Small body size at the time of ocean arrival increases the vulnerability of this species to the effects of ocean acidification. One laboratory experiment found that projected increases in ocean acidity could reduce early seawater survival in pink salmon by reducing metabolic rate,[Q] growth, and appetite. Additionally, increases in CO_2 concentration may impair the sense of smell in pink salmon, limiting their ability to detect and avoid predators.[21]

- *Ocean acidification could indirectly affect salmon via changes in food availability, but the effects are projected to be minimal.* One study, using a model of the Puget Sound food web, found that the majority of impacts on fisheries stemmed from direct effects of ocean acidification, primarily by inhibiting the formation of calciferous shells. The effects on salmon populations were found to be minimal because these species can rely on alternative sources of food that are not directly affected by acidification.[22]

Estuarine Primary Productivity[R]

PRIMARY PRODUCTIVITY ***Estuarine primary productivity may be affected by changes in nutrient inputs, carbon dioxide levels, and sea surface temperature.*** Primary producers in Puget Sound include phytoplankton, macroalgae, kelps, seagrasses, and wetland plants. Climate-related effects on primary productivity remain uncertain.

- *Increases in marine carbon dioxide levels may increase growth and productivity of estuarine eelgrass and bull kelp*. In laboratory experiments, elevated carbon dioxide levels resulted in increased growth and productivity for eelgrass and bull kelp at carbon dioxide concentrations up to 2.5 times higher than ambient levels, after which productivity began to decline.[S,23]

Harmful Algal Blooms

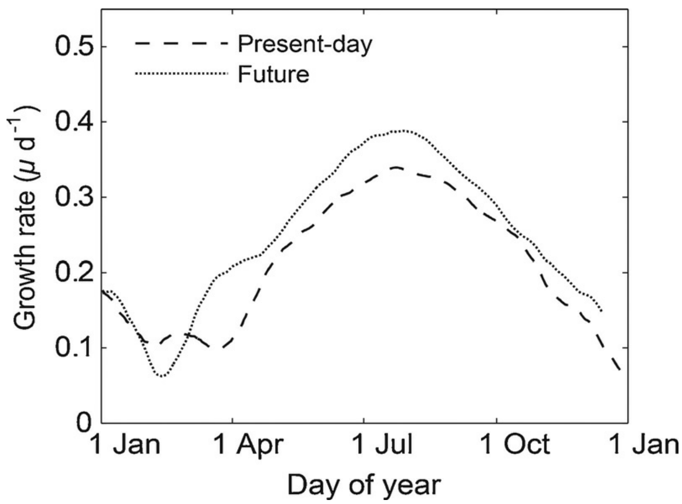
HARMFUL ALGAL BLOOMS ***Climate change may increase the magnitude and frequency of harmful algal blooms (HABs).*** Often called "red tides," HABs are a public health concern due to the toxins subsequently found in shellfish, and also have negative consequences for ecosystems. Climate change is projected to increase growth rates of harmful algal species,[24] and increasing sea surface temperature is projected to expand the "window of opportunity" when such blooms can occur.[25] In addition, ocean acidification may increase the toxicity of some harmful algal blooms (see Section 7 for more details).[26]

Q "Metabolic Rate" refers to the level of energy expenditure in a specific period of time.

R "Primary Productivity" refers to the total rate of biological production (growth, reproduction, etc.) in an ecosystem.

S 28 to 30 eelgrass shoots were collected from Sequim, Washington, planted in plastic pots, and placed in 130 L tanks filled with seawater. Sea water was then enriched with CO_2 at levels 1x, 1.25x, 1.75x, and 2.0x ambient CO_2 levels. Plants were grown for 10 and 7 days in two different trials.

Figure 11-1. Longer season of elevated risk for Harmful Algal Blooms in Puget Sound. Daily mean growth rates of *Alexandrium* are higher in the future, and the growth rates begin to increase about 30 days earlier in spring as a result of increasing sea surface temperatures. When *Alexandrium* growth rates are high enough HABs can form, so higher growth rates earlier and later in the year could lead to a longer HAB season. The plot shows the daily mean growth rate of *Alexandrium* for present day (1988, dashed-line) and under future conditions projected (2047, dotted-line). The projection is based on a single global climate model (CCSM3) and a moderate (A1B) greenhouse gas scenario. Growth rate is averaged over the Puget Sound Basin and both lines are smoothed with a 31-day running mean. *Figure source: Moore et al. 2015.*[T,24] *Reproduced with permission.*



Ocean Acidification

OCEAN ACIDIFICATION ***Ocean acidification will likely harm many estuarine species, especially shellfish and other organisms that form calcium-based shells.*** Ocean acidification is projected to increase the frequency, magnitude, and duration of periods of harmful pH conditions in Puget Sound (see Section 7). Limited field studies have been conducted on the impacts of ocean acidification on estuarine species in Puget Sound; however, experimental studies in the region and throughout the world have demonstrated potential effects of increased ocean acidification.

- *Ocean acidification is projected to reduce shell formation and increase shell dissolution.* Ocean acidification makes it more difficult for calcifying organisms (e.g., oysters, clams, mussels, pteropods, and crabs) to produce and maintain their shells and skeletons.[7,27] For instance, the shell formation of larval stages of calcifying invertebrates may take more energy to produce.[U,7] One experiment showed that shell dissolution of the pteropod *Limacina helicina* occurred under acidity levels that occasionally occur in Puget Sound and are projected to occur more frequently in the future (Figure 11-2).[V,28] Globally, ocean acidification is projected to result in a −40%

T Reprinted from Harmful Algae, 10(5), Moore, S.K., Manuta, N.J., Salathé Jr., E. P. Past trends and future scenarios for environmental conditions favoring the accumulation of paralytic shellfish toxins in Puget Sound shellfish, 521-529, 2011, with permission from Elsevier.

U Saturation state is the absolute carbonate ion concentration, while pH is the ratio of dissolved CO_2 concentration to carbonate ions.

V Shell dissolution was measured after one week of exposure to sea water with saturation state $\Omega_a \approx 1.59$, $\Omega_a \approx 1.17$, $\Omega_a \approx 0.56$, and $\Omega_a \approx 0.28$ under starvation conditions. Shell dissolution was determined based on transparency/opaqueness, transparency/brownness, scarred structures, corrosion, and number of perforations.

reduction in the rate at which molluscs (e.g., mussels and oysters) form shells, a −17% decline in mollusc growth, and a −34% decline in mollusc survival by the end of the century.[W,29]

- *Ocean acidification is projected to reduce the effectiveness of other marine biomaterials*. For instance, ocean acidification is projected to weaken and reduce the extensibility (i.e., capability of being extended) of the filaments that attach mussels to hard substrates.[X,30] Mussels require strong, extensible filaments to remain secure during disturbances, such as from storms and waves.

- *Fish and other organisms that depend on shelled organisms may decline if they are unable to switch to alternate food sources.* Ocean acidification impacts on shellfish and plankton are projected to result in a −10% to −18% decline in the abundance of commercially important groundfish on the U.S. west coast by 2028 (relative to 2009), including English sole, arrowtooth flounder, and yellowtail rockfish, owing to the loss of shelled prey items from their diet.[31] However, predators may be able to switch food sources and avoid the effects of ocean acidification.[Y,32]

- *Increasing water temperatures may modulate the responses of shelled organisms to ocean acidification.* One study evaluating the effect of ocean acidification and water temperature on shell growth in the blue mussel (*Mytilus galloprovincialis*) found these effects to be tightly coupled. The study found that while waters with a high

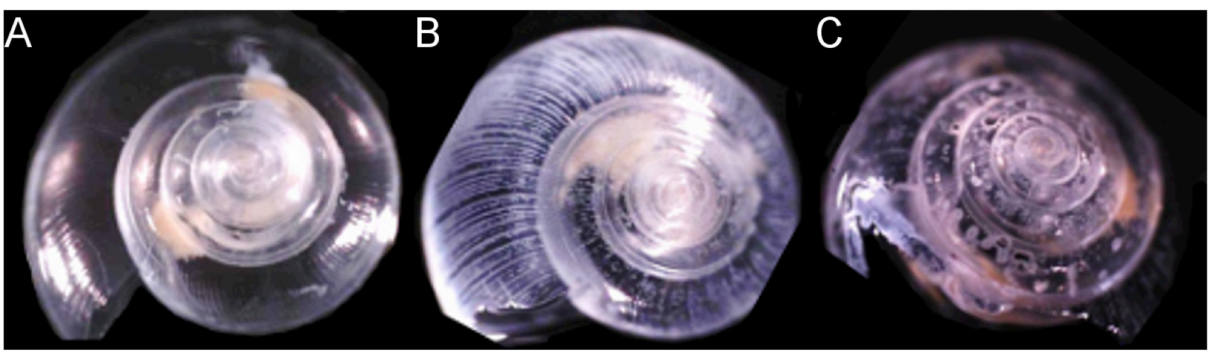


Figure 11-2. Ocean acidification is projected to reduce shell formation and increase shell dissolution in pteropods. Pictures of pteropod (sea snail) shells in aragonite saturation state levels of (A) 1.59 (current summer suface conditions), (B) 0.56 (current surface conditions during upwelling), and (C) 0.28 (projected future surface conditions during upwelling) showing corrosion and shell perforations. Pteropods are an important prey species in the Puget Sound marine food web. *Figure Source Busch et al. 2014*.[28]

W Based on a meta-analysis of many different studies: Results were included from any research that measured a biological response to a decline in pH (increase in acidity) of –0.5 or less. By 2100 (relative to 1986-2005), ocean acidification is projected to result in a decline in pH of –0.14 to –0.32 (see Section 7).

X Individual byssal threads of *Mytilus trossulus* (1.57-1.97 inches shell length) broke at lower forces as water ρCO_2 ranged from 300-15,000 µatm in flow-through experimental chambers with sea water at controlled pH measurements.

Y The food web model used was developed for the central basin of Puget Sound using the Ecopath with Ecosim software version 5.1.

CO_2 concentration[Z] reduced mussel growth at 57.2 °F, the reduced growth effect tapered with warming up to 68 °F. This study demonstrates how a moderate level of sea surface warming can offset some of the negative effects of ocean acidification for shelled organisms.[33]

Species-Specific Responses

SPECIES-SPECIFIC RESPONSES ***Some estuarine species may benefit from climate change, while others will not.*** Particular changes are dependent on species-specific responses to the interaction of physical and biological processes. Additional research is needed to quantify the impacts on a wider variety of species and climate scenarios.

- *Dungeness crab populations in Hood Canal may increase or decrease under future climate change.* Increases in sea surface temperatures are projected to increase juvenile survival, leading to increases in Dungeness crab population size.[AA,34] However, other factors, such as ocean acidification and decreases in dissolved oxygen (see Section 7), may counterbalance the positive influence of sea surface temperature. Sea level rise could also reduce the area of estuarine and nearshore habitats, potentially leading to declines in the Dungeness crab fishery.[35] More research is needed to clarify potential responses of Dungeness crabs to climate change.

- *Salmon are a vital food source for southern resident killer whales* (*Orcinus orca*). If salmon populations decline, this could negatively affect Orcas.[36] To date, very little research has examined the effects of climate change on whale populations in Puget Sound.

Climate Risk Reduction Efforts

CLIMATE RISK REDUCTION ***Various communities, government agencies, tribes, and organizations are planning for the effects of climate change on estuarine species and ecosystems in Puget Sound.***

- *The Washington Ocean Acidification Center* works with scientific researchers, policymakers, industry, and other stakeholders to provide a scientific basis for strategies and policies to address the effects of ocean acidification. The Center is hosted at the University of Washington and was established in 2013 by the Washington State Legislature based on a recommendation from the Blue Ribbon

---

Z 1200 µatm $CO_{2(atm)}$

AA Based on linked watershed-marine models that estimate the influence of land use and climate change on watershed discharge, nutrients, marine water quality, and population available for harvest. Climate change impacts for 2035-2045 from five global climate models under the moderate (A1B), high (A2), and low (B1) greenhouse gas scenarios compared to 2005-2007.

Panel on Ocean Acidification. http://environment.uw.edu/research/major-initiatives/ocean-acidification/washington-ocean-acidification-center/

- *The Swinomish Climate Change Initiative* was a two year project to identify vulnerability of the Swinomish Indian Tribal Community to climate change impacts and prioritize planning areas in order to create an action plan. The Initiative was based on the 2007 Proclamation of the Swinomish Indian Senate to respond to climate change challenges. An Impact Assessment Technical Report[37] and a Climate Adaptation Action Plan[38] were published from the Initiative. Coastal impacts included inundation from sea level rise and storm surges. http://www.swinomish-nsn.gov/climate_change/climate_main.html

- *The Swinomish Tribe is studying how coastal climate change will affect traditional foods, cultural sites, and tribal community health and well-being.* This project, funded by an EPA grant awarded 2014, will develop a model showing projected coastal erosions due to sea level rise, storm surge, and wave energy on the shores of the Swinomish Reservation through 2100. Additionally, the Tribe will map the vulnerability of Swinomish coastal ecosystem habitats of first foods[BB] and culturally significant sites; create educational and outreach tools for Swinomish community members and coastal Salish communities; and assess research results and develop adaptive strategies. http://1.usa.gov/1Wm3HdR

- *The Washington State Integrative Climate Change Response Strategy[39]* developed a framework to aid decision-makers in state, tribal, and local governments, public and private organizations, and businesses prepare for climate change impacts on natural resources and economy. Climate change effects on marine species and ecosystems included sea level rise and ocean acidification. Adaptation strategies included restoring tidal wetlands and replacing hard shoreline armoring with green or soft alternatives.

- *The Jamestown S'Klallam Tribe Climate Vulnerability Assessment and Adaptation Plan[40]* identified climate change impacts on tribal resources and developed adaptation strategies for each resource. The Adaptation Plan identified sea level rise, coastal flooding, and ocean acidification as key threats. Resource areas of high priority included salmon, clams, oysters, and shellfish biotoxins. Strategies for reducing stressors on salmon resources included habitat restoration and the reduction of stressors such as urbanization and pollution.

[BB] "First foods" includes salmon, wild game, roots, berries, and clean water.

1 Vose, R.S. et al., 2014. Improved historical temperature and precipitation time series for US climate divisions. *Journal of Applied Meteorology and Climatology*, *53*(5), 1232-1251.

2 Mote, P. W. et al., 2013. Climate: Variability and Change in the Past and the Future. Chapter 2, 25-40, in M.M. Dalton, P.W. Mote, and A.K. Snover (eds.) *Climate Change in the Northwest: Implications for Our Landscapes, Waters, and Communities*, Washington D.C.: Island Press.

3 (NRC) National Research Council. 2012. *Sea-Level Rise for the Coasts of California, Oregon, and Washington: Past, Present, and Future.* Committee on Sea Level Rise in California, Oregon, Washington. Board on Earth Sciences Resources Ocean Studies Board Division on Earth Life Studies The National Academies Press.

4 Petersen, S. et al. 2015. *Climate Change Preparedness Plan for the North Olympic Peninsula*. A Project of the North Olympic Peninsula Resource Conservation & Development Council and the Washington Department of Commerce, funded by the Environmental Protection Agency. Available: www.noprcd.org

5 Reeder, W.S. et al., 2013. Coasts: Complex changes affecting the Northwest's diverse shorelines. Chapter 4, 67-109. In M.M. Dalton, P.W. Mote, and A.K. Snover (eds.) *Climate Change in the Northwest: Implications for Our Landscapes, Waters, and Communities*, Washington D.C.: Island Press.

6 Feely, R.A. et al., 2012. *Scientific Summary of Ocean Acidification in Washington State Marine Waters*. NOAA OAR Special Report, 172 pp.

7 Waldbusser, G.G. et al., 2014. Saturation-state sensitivity of marine bivalve larvae to ocean acidification. *Nature Climate Change,* 5, 273-280.

8 Glick, P. et al., 2007. Sea-level rise and coastal habitats in the Pacific Northwest: An analysis for Puget Sound, Southern Washington, and Northwestern Oregon. National Wildlife Federation, Reston, VA.

9 Reed, D.J. 1995. The response of coastal marshes to sea-level rise Survival or submergence? *Earth Surface Processes and Landforms,* 20, 38-48.

10 Thom, R.M. et al., 2012. Restoring resiliency: case studies from Pacific Northwest eelgrass ecosystems. *Estuaries and Coasts,* 35, 78-91

11 Thom, R. et al. 2014. Climate-linked mechanisms driving spatial and temporal variation in eelgrass (*Zostera marina L.*) growth and assemblage structure in Pacific Northwest estuaries, U.S.A. *In*: Huang, W. and Hagen S.C. (eds.), Climate change impacts on surface water systems. *Journal of Coastal Research* SI 68:1-11.

12 Thom, R.M. et al., 2008. Light requirements for growth and survival of eelgrass (*Zostera marina* L.) in Pacific northwest (USA) estuaries. *Estuaries and Coasts,* 31, 969-980.

13 Kairis, P.A. and Rybczyk, J.M. 2010. Sea level rise and eelgrass (*Zostera marina*) production: A spatially explicit relative elevation model for Padilla Bay, WA. *Ecological Modeling,* 221, 1005-1016.

14 Sharma, R. et al., 2013. Relating spatial and temporal scales of climate and ocean variability to survival of Pacific Northwest Chinook salmon (*Oncorhynchus tshawytscha*). *Fisheries Oceanography,* 22(1), 14-31.

15 Mantua, N.J. et al. 1997. A Pacific interdecadal climate oscillation with impacts on salmon production. *Bulletin of the American Meteorological Society,* 78(6), 1069-1079.

16 Greene, C.M. et al., 2005. Effects of environmental conditions during stream, estuary, and ocean residency on Chinook salmon return rates in the Skagit River, Washington. *Transactions of the American Fisheries Society,* 134, 1562-1581.

17 Fisher, J. P., and Pearcy, W. G. 1988. Growth of juvenile Coho salmon (*Oncorhynchus kisutch*) off Oregon and Washington, USA, in years of differing coastal upwelling. *Canadian Journal of Fisheries and Aquatic Sciences*, 45, 1036-1044.

18 Nickelson, T.E. 1986. Influence of upwelling, ocean temperature, and smolt abundance on marine survival of Coho salmon (*Oncorhynchus kisutch*) in the Oregon production area. *Canadian Journal of Fisheries and Aquatic Sciences*, 43(3), 527-535.

19 Grant, A. et al., 2009. Growth and ionoregulatory ontogeny of wild and hatchery-raised juvenile pink salmon (*Oncorhynchus gorbuscha*). *Can. J. Zool.*, 87, 221–228.

20 Heard, W. R. 1991. *Pacific Salmon Life Histories* (eds Groot, C. and Margolis, L.). 319–377 (UBC Press).

21 Ou, M. et al., 2015. Responses of pink salmon to CO_2-induced aquatic acidification. *Nature Climate Change,* 5, 950-955.

22 Busch, D. S et al., 2013. Potential impacts of ocean acidification on the Puget Sound food web. *Ices Journal of Marine Science*, 70, 823-833.

23 Thom, R.M. 1996. CO_2 – Enrichment effects on eelgrass (*Zostera marina* L.) and bull kelp (*Nereocystis luetkeana* (mert.) P & R.). *Water, Air, and Soil Pollution,* 88(3-4), 383-391.

24 Moore, S.K. et al., 2015. Present-day and future climate pathways affecting the harmful algal blooms species *Alexandrium catenella* in Puget Sound, WA, USA. *Harmful Algae,* 48, 1-11.

25 Moore, S.K. et al., 2011. Past trends and future scenarios for environmental conditions favoring the accumulation of paralytic shellfish toxins in Puget Sound shellfish. *Harmful Algae,* 10, 521-529.

26 Tatters, A.O. et al. 2012. High CO_2 and silicate limitation synergistically increase the toxicity of *Pseudo-nitzschia fraudulenta*. *PLoS ONE*, 7:e32116. doi: 10.1371/journal.pone.0032116.

27 Barton, A. et al., 2012. The Pacific oyster, *Crassostrea giga*, shows negative correlation to naturally elevation carbon dioxide levels: Implications for near-term ocean acidification effects. *Limnology and Oceanography,* 57(3), 698-710.

28 Busch, D.S. et al., 2014. Shell condition and survival of Puget Sound pteropods are impaired by ocean acidification conditions. *PLoS ONE,* 9(8),1-12.

29 Kroeker, K.J. et al., 2013. Impacts of ocean acidification on marine organisms: quantifying sensitivities and interaction with warming. *Global Change Biology,* 19, 1884-1896.

30 O'Donnell, M.J. et al., 2013. Mussel byssus attachment weakened by ocean acidification. *Nature Climate Change Letters,* 3, 587-590.

31 Kaplan, I.C. et al., 2010. Fishing catch shares in the face of global change: a framework for integrating cumulative impacts and single species management. *Canadian Journal of Fisheries and Aquatic Sciences,* 67, 1968-1982.

32 Busch, D.S. et al., 2013. Potential impacts of ocean acidification on the Puget Sound food web. *ICES Journal of Marine Science,* 70(4), 823-833.

33 Kroeker K.J. et al., 2014. The Role of Temperature in Determining Species' Vulnerability to Ocean Acidification: A Case Study Using *Mytilus galloprovincialis*. *PLoS ONE*, 9(7): e100353. doi:10.1371/journal.pone.0100353

34 Toft, J.E. et al., 2013. From mountains to sound: modeling the sensitivity of Dungeness crab and Pacific oyster to land-sea interactions in Hood Canal, WA. *ICES Journal of Marine Science*. doi: 10.1093/icesjms/fst072

35 McDonald, P.S. 2011. Climate Impacts on the Dungeness Crab Fishery: A Preliminary Assessment. Prepared for the "Assessing Vulnerability of West Coast Fisheries to a Changing Climate" workshop, May 25-26, 2011. Seattle, WA.

36 O'Neill, S.M. et al., 2014. Energy content of Pacific salmon as prey of northern and southern resident killer whales. *Endangered Species Research,* 25, 265-281.

37 Swinomish Indian Tribal Community. 2009. Swinomish Climate Change Initiative Impact Assessment Technical Report. Office of Planning and Community Development. La Conner, Washington.

38 Swinomish Indian Tribal Community. 2010. Swinomish Climate Change Initiative Climate Adaptation Action Plan. Office of Planning and Community Development. La Conner, Washington.

39 Adelsman, H. et al., 2012. Preparing for a changing climate: Washington State's integrated climate response strategy. Department of Ecology, Olympia. No. 12-01-004.

40 Jamestown S'Klallam Tribe. 2013. *Climate change vulnerability assessment and adaptation plan.* Petersen, S., and J. Bell (eds.) A collaboration of the Jamestown S'Klallam Tribe and Adaptation International.

41 Konrad, C.P., 2015, Geospatial assessment of ecological functions and flood-related risks on floodplains along major rivers in the Puget Sound Basin, Washington: U.S. Geological Survey Scientific Investigations Report 2015–5033, 28 p., http://dx.doi.org/10.3133/sir20155033