

SECTION 5

**CUMULATIVE
ECOSYSTEM
EFFECTS**

Whytecliff Park, West Vancouver, BC
Photo: Nick Pinkham



SECTION 5

CUMULATIVE EFFECTS CASE STUDIES

Pacific Herring in the Salish Sea

Salmon Marine Survival

Orcas, Southern Residents at Risk

PERSISTENT, CONTINUING, AND EMERGING IMPACTS

SUMMARY OF CUMULATIVE EFFECTS IN THE SALISH SEA

VIGNETTES

18: Bellingham Bay: Legacy Contaminants Under Repair

19: Invasive European Green Crab

20: Fraser River Estuary in Need of Urgent Intensive Care

The many impacts identified in this report caused by urbanization locally and climate change globally intersect and generate cumulative ecosystem impacts in the Salish Sea. Cumulative effects are defined as the collective impacts of past, present, and future human activities on the environment (Spaling & Smit 1993). There is great uncertainty in measuring and predicting cumulative effects, especially considering the unknown interactive effects of multiple stressors on ecological components (Figure 5.1; Murray et al. 2014). Stressors interact with each other and can be additive, non-additive, or can multiply (synergistic) or reduce effects (antagonistic) predicted from single stressors and combinations of stressors (Crain et al. 2008). Interactions can be direct or indirect and may be modulated by other unrelated factors. Additionally, non-linear responses can result in changing interactions in both time and space as thresholds or other inflection points are approached. For these reasons, understanding and describing cumulative effects in ecosystems is particularly challenging (Darling & Côté 2008), but nonetheless an important

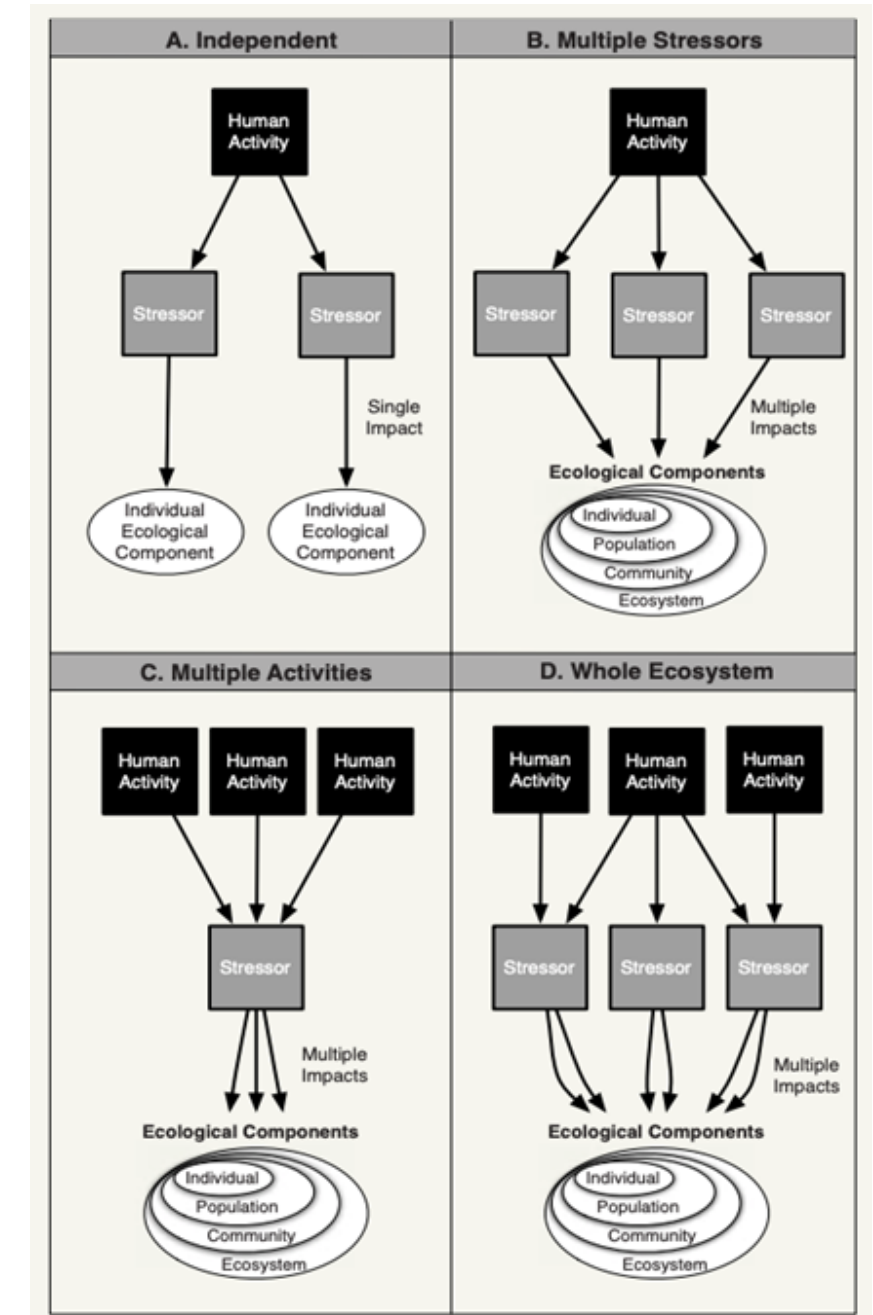


Figure 5.1. Theoretical framework of pathways by which independent and cumulative effects impact ecological components. A) human activities produce multiple stressors that impact ecological components, B) a single human activity produces multiple stressors that impact a suite of ecological components, C) multiple activities each produce a common stressor that has multiple impacts on a suite of ecological components or multiple impacts on a single ecological component over space or time, and D) accounting for the whole ecosystem, where multiple activities produce multiple stressors that have multiple impacts on a suite of ecological components. Stressors from activities can accumulate across space (local, regional, and global stressors) and time (past, present, and predicted future activities). Source: Clarke Murray et al. (2014)

consideration in science and management as ever more complex problems threaten our ecosystems.

In a laboratory, we may investigate the effects of temperature, dissolved oxygen, and ocean acidification on a species, but the complexities of the cumulative stressors in the environment, such as changing tides, weather conditions, contaminant concentration, productivity, and interactions among species, make the reality of identifying and understanding cumulative effects *in situ* much more challenging. The complex oceanography of the Salish Sea also means that effects are likely to vary from region to region, as oceanographic conditions change.

Cumulative effects studies—even those that are well planned and executed—are frequently limited in spatial and temporal scope. This makes understanding the interaction of legacy, continuing, and emerging stressors difficult to assess. Historical or legacy stressors have likely altered ecological components in the system, making the effects of the continuing disturbances more profound and rendering any habitat or organism less resilient to future impacts (Levin & Lubchenco 2008). For example, it's known and documented that previous overfishing exacerbates climate-induced temperature effects on fish population resilience (Free et al. 2019). This type of temporal evolution of ecosystem problems is a fundamental challenge in addressing cumulative effects, especially where decades of human impacts have critically altered organisms, biotopes, or ecosystem processes.

The interaction of global and local stressors is borne out on our coasts. One such intersection in the Salish Sea is the increased risk of coastal flooding due to climate change-induced sea level rise and urbanization. Rising sea levels are fundamentally altering our low-lying saltwater habitats by increasing inundation time, bringing

saltwater farther inland and flooding new areas (Nicholls et al. 2007). Increases in intensity of precipitation resulting from climate change will change hydrology and water delivery timing, bringing floodwaters to our coasts (Pacific Climate Impacts Consortium 2015). If you've visited a tropical city where rainfall during storms comes at rates of more than an inch per hour, you may know that the stormwater collection systems are typically built to handle these deluges. Here in the Pacific Northwest, the existing infrastructure is built to handle historically consistent amounts of input, not the rapidly increasing intensity of precipitation or sea level rise that are currently observed and predicted to increase with climate change (Raymond et al. 2013).

As time goes on, urbanization, sea level rise, and the increasing intensity of precipitation will further challenge shoreline armoring, roads, stormwater conveyance, sewage treatment facilities, bridges, and buildings along our shorelines. In addition, the intersection of increased flooding (driven by climate change) and increases in impervious surfaces (associated with land-use change) will combine to yield increased coastal flooding.

Additional sea level rise and flooding and will bring increased desire for shoreline armoring. But policy changes can result in more robust alternatives for long-term coastal ecosystem resilience (Kittinger & Ayers 2010). While most of the literature on cumulative effects in marine ecosystems is on the cumulative impacts of stressors (Korpinen & Andersen 2016), it should also be noted that cumulative impacts can be net positive when applied to restoration (Hall et al. 2018; Diefenderfer et al. 2021). While restoration can remediate some effects of urbanization, accounting for persistent changes resulting from global climate change presents an additional challenge and will require long-term solutions.

While this direct intersection of our two focal impacts—urbanization and climate change—is the most obvious illustration of cumulative impacts, there are many other manifestations of cumulative effects. There are also many approaches to evaluating cumulative effects: stressor or activity-based approaches (e.g., understanding the cumulative impacts of marine shipping; Transport Canada 2019), area-based approaches (e.g., Marine Spatial Planning; Foley et al. 2010; Collie et al. 2013; Washington Marine Spatial Plan 2021), and species-based approaches (Andersen et al. 2017; Fu et al. 2020). There is active research on how best to understand and manage cumulative effects in marine ecosystems and development of new methods (Hodgson & Halpern 2019).

Here we use a species-based approach and three case studies to highlight cumulative impacts of ecosystem change and response in three iconic Salish Sea species: herring (*Clupea pallasii*), salmon, and orcas. Each of the three taxa highlighted below is impacted in myriad ways by humans living in the Salish Sea region and, in the case of climate change, far beyond the region due to teleconnections across the globe (i.e., climate variability links between non-contiguous geographic regions). Examining the mechanisms of depletion and abundance helps highlight the ways in which human activities interact with ecological processes to impact these icons of the Salish Sea.



Emergency workers placing warning signs on flooded road
Photo: ML Harris, Adobe Stock

CASE STUDY:

PACIFIC HERRING IN THE SALISH SEA

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Background

Pacific Herring (*Clupea pallasii*; hereafter referred to as herring) are small, schooling, silver fish that play an important role in the food web of the Salish Sea. These forage fish transfer energy from plankton to predators, such as piscivorous fish (e.g., Chinook and coho salmon), seabirds, and marine mammals (Pikitch et al. 2012). Herring are also culturally and commercially important; they have been utilized by First Nation peoples in British Columbia and by Native American Tribes in Washington for food, social, and ceremonial purposes for thousands of years and harvested commercially since at least the early 1900s (Thornton 2015; Sandell et al. 2019). As is the case for many forage fish species, herring abundance is often highly variable from year to year and abundance trends may vary geographically. For example, Puget Sound's Cherry Point herring stock showed a 97% decrease in stock biomass since 1973 (Gustafson et al. 2006; SeaDoc 2018); whereas, Strait of Georgia's (SOG) aggregate migratory stock increased from 2010 to 2016, was comparatively stable, and, in 2020, was relatively high compared to historic levels (Fisheries and Oceans Canada 2021). Herring abundance and distribution can be affected by many factors, including climate change, environmental conditions, ecosystem productivity, fishing, and habitat changes. Understanding how these factors individually and cumulatively affect the abundance, recruitment, age structure, size, condition, and distribution of herring presents a challenge to the assessment of these species.

Life History

The aggregate stock of migratory SOG herring spend summers in feeding areas on continental shelf waters off the west coast of Vancouver Island before migrating to nearshore spawning areas in the SOG in winter (Taylor 1964). Herring in the southern Salish Sea (US waters) exhibit a mixture of life histories, with stocks in South Puget Sound exhibiting year-round residency while most northern stocks migrate to the ocean to feed during the summer. The migratory habits of a few stocks, such as Cherry Point and those in Hood Canal, are unclear, based on stable isotope and analyses of toxic chemicals (Sandell et al. 2019). Pacific Herring are generally zooplanktivores, consuming small, early-life history stages of copepods and switching to larger and later life history stages of copepods and euphausiids as they grow. In March-April each year, herring return to spawn in the same geographical region but not necessarily to the same spawning beach or bay. Herring spawn in nearshore areas where each female deposits 20,000-40,000 eggs on macrophytes, such as eelgrass, rockweed, kelps, and other algae, and males release sperm to fertilize the eggs (Haegle et al. 1981; Humphreys & Hourston 1978). Egg hatching time is temperature-dependent, but generally takes a couple of weeks (Alderdice & Hourston 1985). Young herring spend their first summer in nearshore areas (Haegle & Armstrong 1997; Emmett et al. 2004). Herring generally become sexually mature

between the ages of 2 to 3 and can live up to 15 years of age, but most live to less than 10 years of age (Cleary et al. 2017). Herring population abundance is determined largely by the annual recruitment of young fish to the adult spawning stock. Recruitment in turn is heavily influenced by survival during the early life history (Taylor 1964; Schweigert et al. 2009).

Indicators

In British Columbia, herring are managed as five major stocks (Strait of Georgia, SOG; West Coast of Vancouver Island, WCVI; Prince Rupert District, PRD; Haida Gwaii, HG; and Central

Coast, CC), and two minor stocks (Area 2W and Area 27) (Fisheries and Oceans Canada 2021; Figure 5.2). Fisheries and Oceans Canada (DFO) conducts annual scientific surveys for each of the five major herring stock areas. These scientific surveys, which include egg surveys and biological sampling, inform a yearly peer-reviewed scientific stock assessment with up-to-date advice on the status of all five major stocks. DFO also works with Indigenous communities and harvesters in the Strait of Georgia to better understand herring distribution, spawn dynamics and traditional harvest areas. In 2020, the stock assessment model was used to provide estimates of herring spawning biomass, an important indicator of

stock status (Fisheries and Oceans Canada 2021). Additionally, DFO reports annually on spawn distribution and biological indicators like weight-at-age.

Southern Salish Sea (SSS, including Puget Sound and Hood Canal) populations are managed individually, and the management focus is on maintaining viable populations at each spawning location (Siple & Francis 2016; Sandell et al. 2019; Figure 5.3). A minimum spawning biomass has been identified for each of the populations and status is determined by

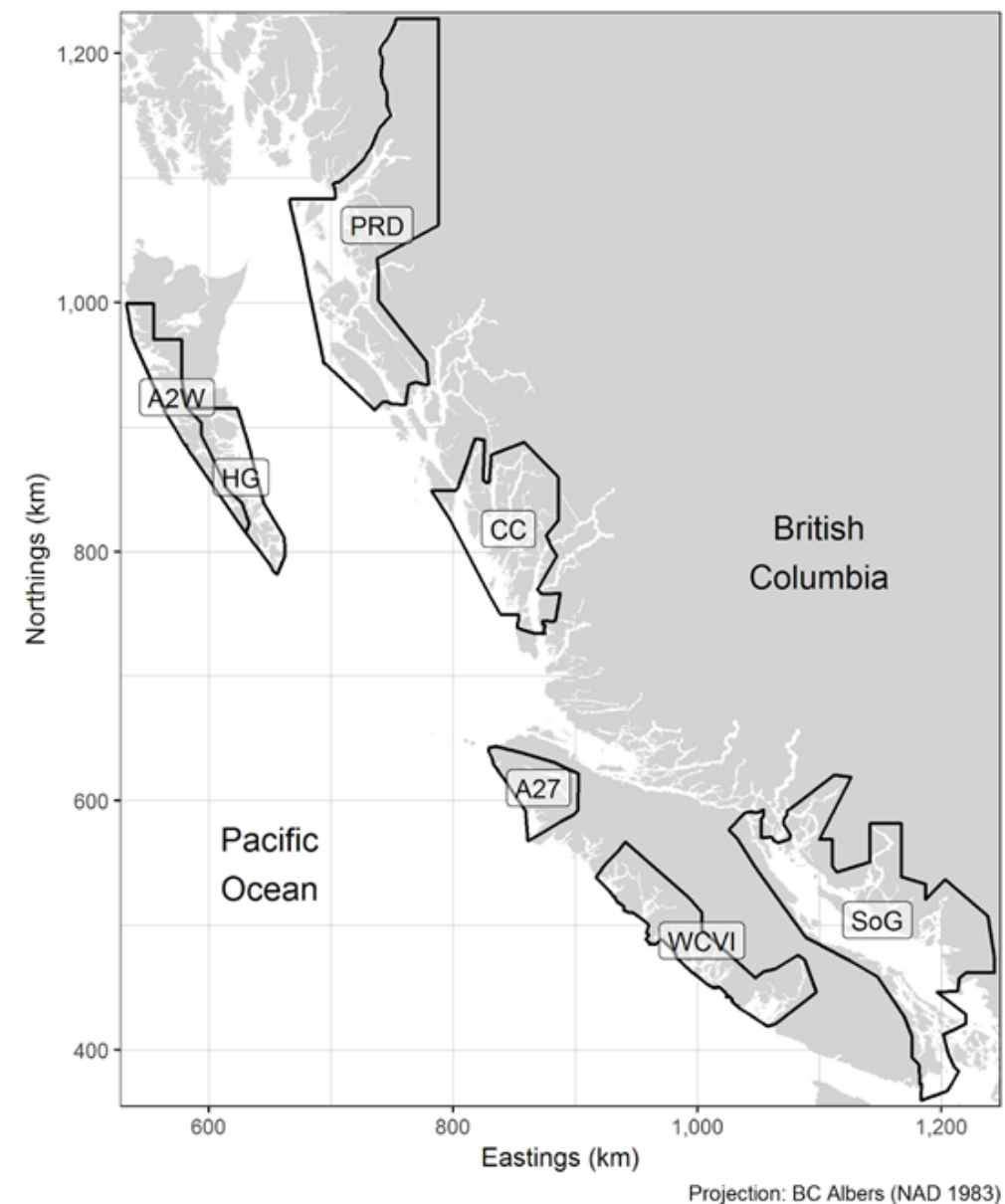


Figure 5.2. Boundaries for the Pacific Herring stock assessment regions (SARs) in British Columbia. The major SARs are Haida Gwaii (HG), Prince Rupert District (PRD), Central Coast (CC), Strait of Georgia (SoG), and West Coast of Vancouver Island (WCVI). The minor SARs are Area 27 (A27) and Area 2 West (A2W). Source: Fisheries and Oceans Canada (2019)

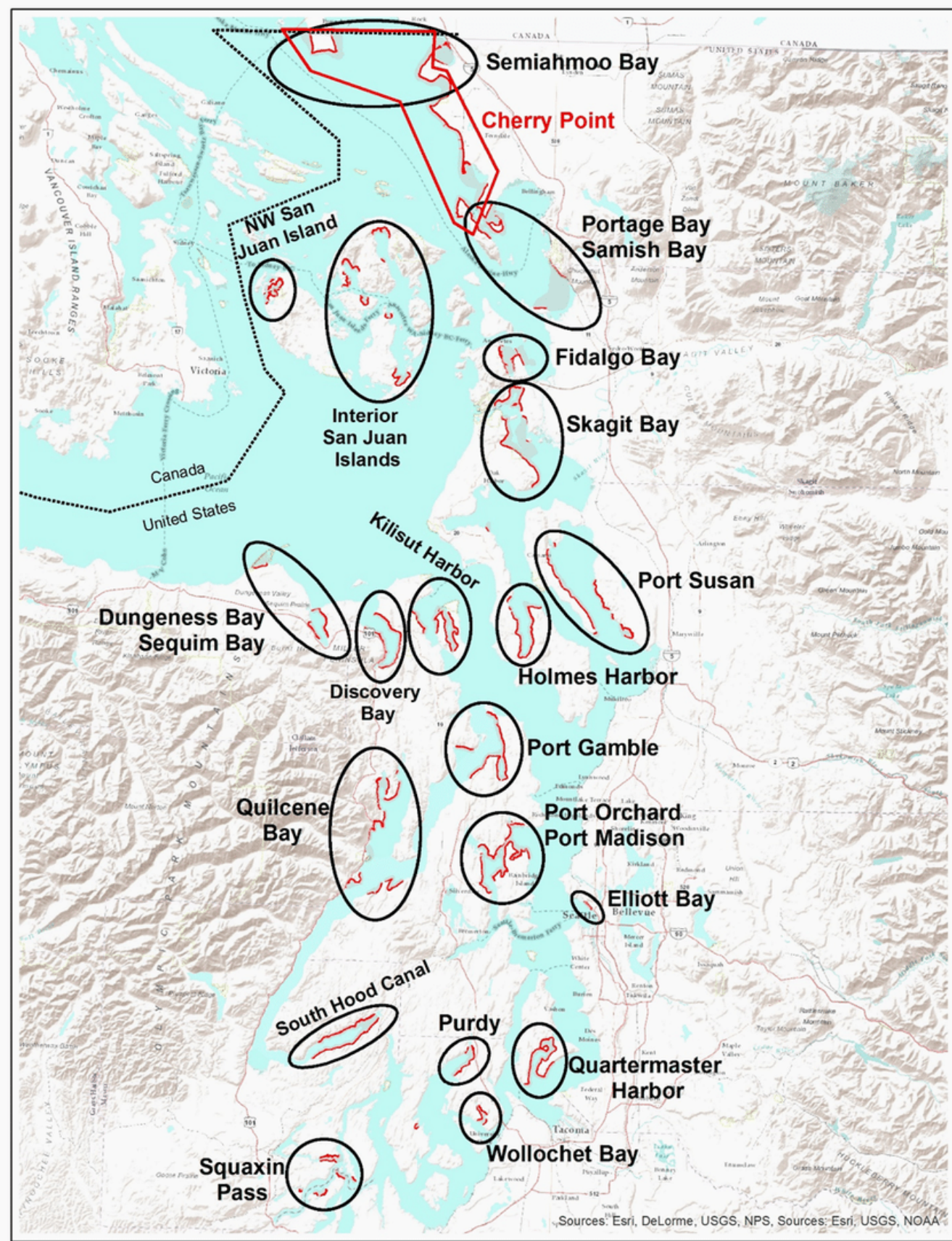


Figure 5.3. Known spawning stocks of Pacific herring in United States waters of the Salish Sea as of 2018. Source: SeaDoc Society (2018)

annual monitoring. Annual monitoring generates spawning biomass estimates derived from acoustic-trawl surveys (discontinued in 2009 due to budget restraints) and egg deposition surveys.

Status and Trends

In British Columbia, the overall biomass of herring is much greater than that of Puget Sound/SSS (SeaDoc Society 2018). DFO's stock assessment model estimate of herring spawn biomass in the Strait of Georgia region showed a strong increasing trend from 2010-2016, after which it was comparatively stable until 2020, when biomass was relatively high compared to historic levels (Fisheries and Oceans Canada 2021; Figure 5.4). For at least the past 15-years, herring spawning has been concentrated in

northern areas of the Strait of Georgia, primarily from Nanaimo to Comox. The weight-at-age of SOG herring declined from the 1980s to 2010, with an increase in recent years. This general pattern in weight-at-age has been observed in all major herring stocks of British Columbia.

As in British Columbia, the weight-at-age of SSS herring declined from the 1980s to 2012 (Stick et al. 2012); due to the cessation of acoustic trawl surveys, weight-at-age estimates are no longer available. In the SSS, overall herring biomass declined 23% from 2018 to 2019, largely due to declines in Hood Canal stocks (mainly Quilcene Bay), which had comprised over 50% of the total beginning in 2015 (Figure 5.5). The 2019 total was 9% lower than the five-year average, and six stocks had no spawn detected in that year,

although the Quilcene Bay and Port Orchard-Port Madison (PO-PM) stocks increased in biomass. 2020 brought dramatic changes, with record highs recorded at Quilcene Bay, PO-PM, and Purdy (in south Puget Sound); the total was the highest recorded since 1980 (18,559 tonnes, compared to a ten-year average of ~9,250 tonnes), even though surveys were curtailed due to the pandemic (making the total a known underestimate). However, most stocks continued to spawn at low levels, reflecting the overall

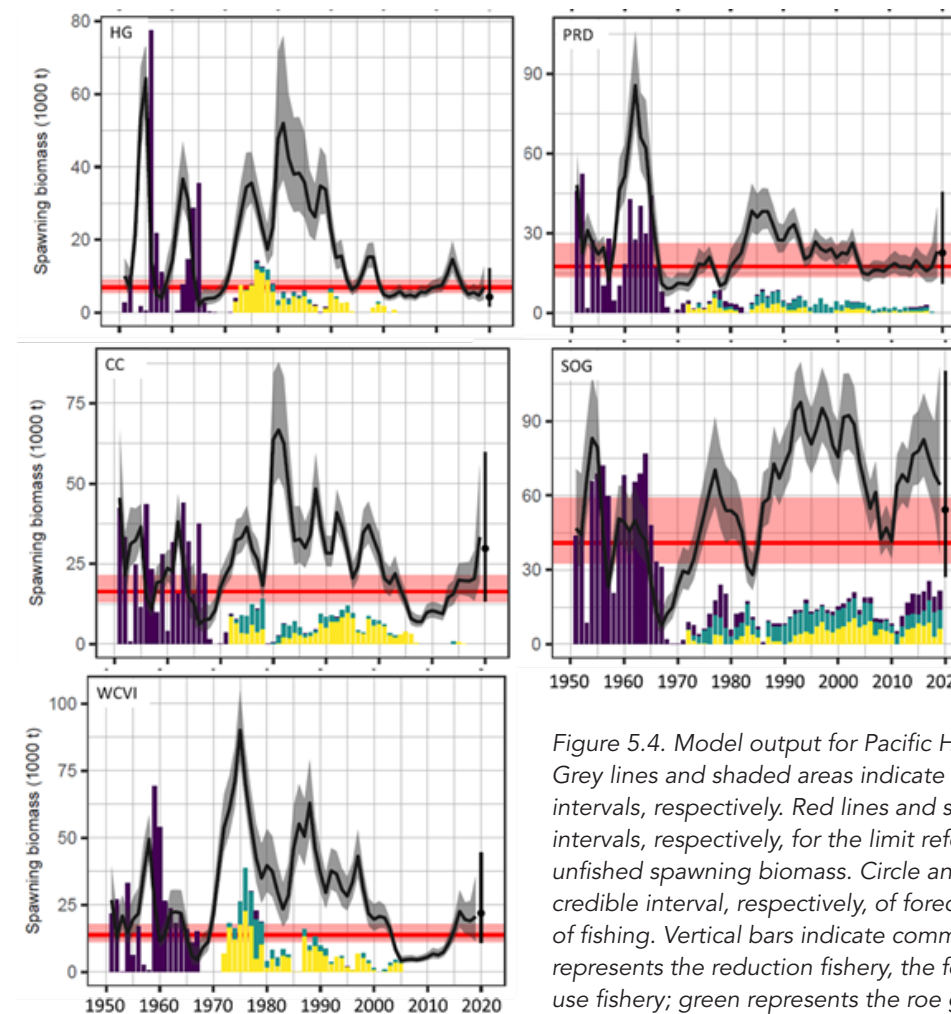


Figure 5.4. Model output for Pacific Herring in the major stock assessment regions. Grey lines and shaded areas indicate spawning biomass medians and 90% credible intervals, respectively. Red lines and shading indicate medians and 90% confidence intervals, respectively, for the limit reference point 0.3SBO, where SBO is estimated unfished spawning biomass. Circle and vertical line indicate the median and 90% credible interval, respectively, of forecast spawning biomass in 2021 in the absence of fishing. Vertical bars indicate commercial catch, excluding spawn-on-kelp; purple represents the reduction fishery, the food and bait fishery, as well as the special use fishery; green represents the roe gillnet fishery; and yellow represents the roe seine fishery. Source: Adapted from Figures 6-8, 10, and 11 in Fisheries and Oceans Canada (2021)

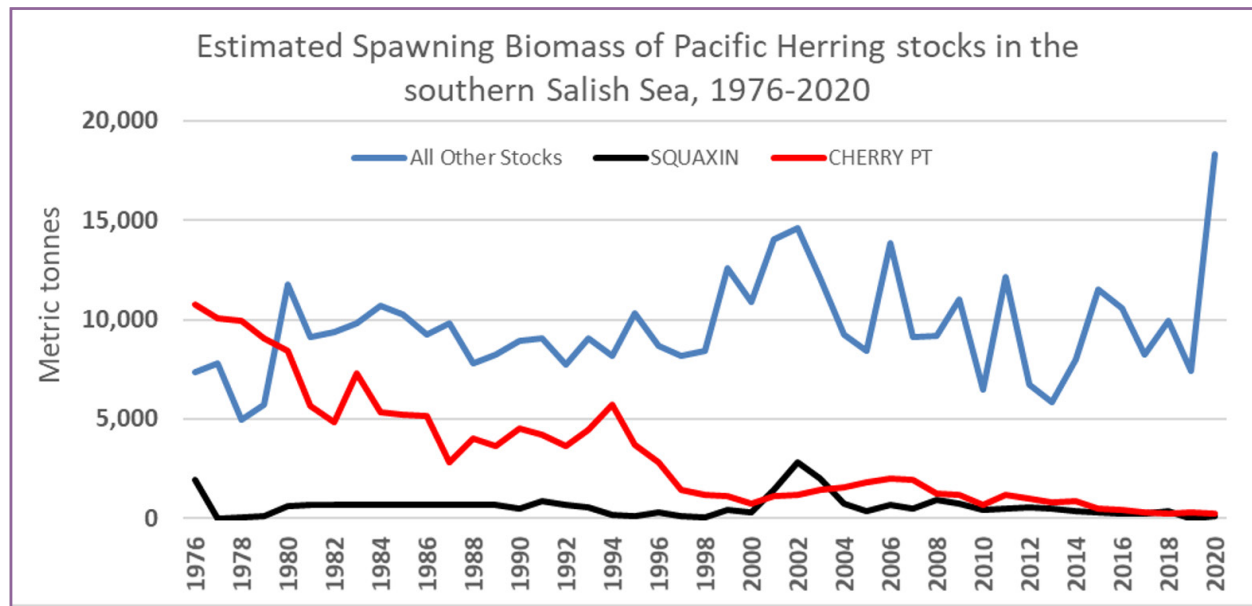
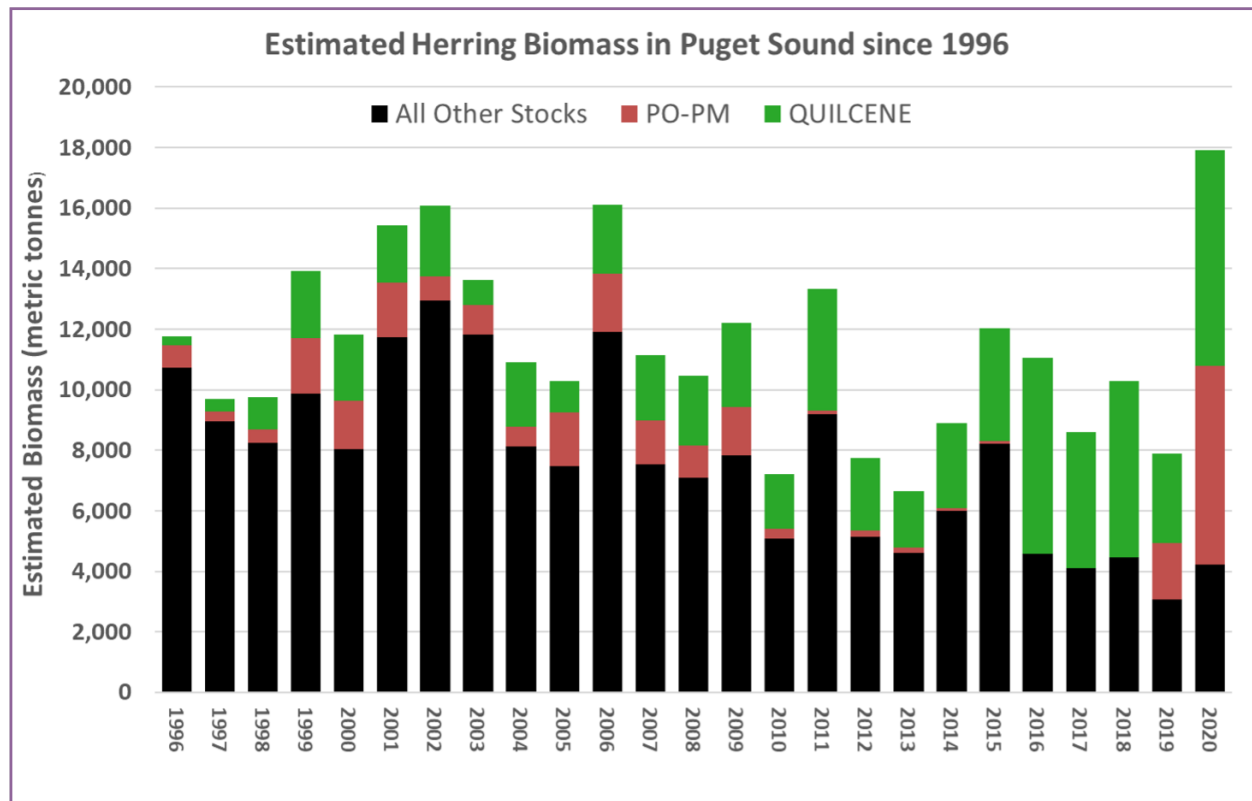


Figure 5.5. Estimated herring stock biomass estimates for the Southern Salish Sea. Source: Adapted from Sandell et al. (2020)

shift from widely dispersed spawning to the dominance of a few stocks in the biomass estimate (Figure 5.5) Forage fish populations are notorious for having extreme annual variations in population abundance and recruitment, but the increase seen in 2020 is striking. The most likely explanation is that, during the anomalously warm “Blob” years (~2014-17), when surface waters in the Northeast Pacific Ocean were much warmer than average, surface waters in the SSS were also higher and we had more sunlight than normal in the region. This led to increased phytoplankton blooms and zooplankton biomass that created a larger food supply for larval fish. Research by Dr. Julie Keister’s lab at the University of Washington showed the increases in zooplankton abundance were particularly large in the Main Basin of Puget Sound (which includes the PO-PM/Bainbridge Island area) and Hood Canal (Quilcene Bay). As a result, there may have been “jackpot recruitment” years for herring in 2016-17 due to increased zooplankton abundance. Herring return to spawn at age 2-3, so this may explain the abundance of spawning fish in 2020, although it does not explain why only a few stocks had such high recruitment.

The Cherry Point stock, which is genetically unique, increased 16% from 2018-19 and dropped slightly in 2020 (poor survey coverage due to the pandemic) but remains at critical levels in comparison to its historical run size—once the largest in the SSS.

Factors Causing Trends

Herring abundance, distribution, and weight-at-age can be affected by multiple factors, such as climate change, environmental conditions, system productivity, fishing, and habitat changes. These factors act at local, regional, and ocean-basin spatial scales and during different life history stages of herring. For example, local- or regional-scale toxic contaminants from legacy

pollution sites and stormwater runoff may be affecting central and South Puget Sound populations (West et al. 2008; West et al. 2014; see also Encyclopedia of Puget Sound (2021) for more about stormwater). The observed trends in herring weight-at-age in all British Columbia stock areas suggest that ocean-basin-scale factors may also be influencing herring population trends. When and where multiple pressures (i.e., cumulative effects) act on different life history stages of herring complicates our understanding of herring population dynamics.

It is thought that early life history stages (egg to juveniles) are the most critical in determining herring abundance and condition (Sinclair & Tremblay 1984; Shelton et al. 2014). Bottom-up processes (prey-driven) are the main factors affecting interannual variability in juvenile herring abundance and condition in the SOG (Boldt et al. 2018). Bottom-up factors include zooplankton prey availability, herring spawn biomass, temperatures, and the date when most herring spawn relative to the spring bloom date. The timing or match-mismatch between herring and their prey appears to be important in determining abundance of age-0 herring in the fall (Schweigert et al. 2013; Boldt et al. 2018). There is some evidence that top-down (predator-driven; e.g., juvenile coho and Chinook Salmon) processes may also affect age-0 herring condition (but not age-0 herring abundance).

Herring recruitment and survival has also been linked to water temperatures (Tester 1948; Ware 1991) and bottom-up control of production (Schweigert et al. 2013), prey availability, and competition with other fish (Godefroid et al. 2019). Changes in ocean conditions, such as temperature or currents, could affect the amount and types of prey available. For example, a northerly current direction could result in the presence of California Current waters off the west coast of Vancouver Island where SOG herring

feed in the summer; the California Current waters bring zooplankton species that have a lower energetic value, creating poorer feeding conditions for herring (Mackas et al. 2004; Schweigert et al. 2010).

There are a wide variety of herring predators, including Pacific Hake, Lingcod, Spiny Dogfish, Pacific Cod, Sablefish, Arrowtooth Flounder, Pacific Halibut, Steller Sea Lions, Northern Fur Seals, Harbour Seals, California Sea Lions, and Humpback Whales (Schweigert et al. 2010). As of 2010, off the WCVI, fish predator abundance had decreased in recent years, while the abundance of most marine mammal predators increased (Olesiuk et al. 1990; Jeffries et al. 2003; Olesiuk 2008). Research into predator consumption of herring indicated that a significant proportion of the herring population could be consumed annually by predation, although it was not clear if this could cause the observed estimates of natural mortality of WCVI herring (Schweigert et al. 2010). When examined both spatially and temporally, it was found that the summer distribution and abundance of herring off the WCVI (this includes SOG herring) may be driven by Pacific Hake abundance, zooplankton prey availability, and competition with Pacific Sardine (Godefroid et al. 2019).

Implication of Trends

Trends in herring biomass have implications for First Nations in British Columbia and Tribes in Washington, commercial and recreational fisheries, and the marine ecosystem and its predators. The SOG stock comprises more than 50% of the total herring biomass in British Columbia waters, and this stock has supported commercial fisheries in the SOG annually since the 1950s. Opportunities for commercial herring fisheries in the other four stock areas have been more variable over the same time period and have at times included full commercial closures due to low herring

abundances and/or restricted opportunities (e.g., for First Nations spawn-on-kelp harvest only).

The only commercial fishery for herring in the SSS is the sport-bait fishery (supplying herring for recreational salmon and groundfish fishers); no fishing is allowed north of Admiralty Strait to protect the Cherry Point stock. The sport bait fishery mostly targets 1+ to 2+ year old (juvenile) herring assumed to be an aggregate of stocks within the main basin. This fishery has a harvest guideline of less than 10% of the cumulative adult herring spawning biomass estimate of stocks that spawn in South/Central Puget Sound, Hood Canal, and the Whidbey Basin (Bargmann 1998), but usually only achieves 2% to 6% of the spawning biomass because of market conditions and processing/holding capacities (Sandell et al. 2019). Hood Canal has been closed to all commercial herring fishing since 2004 due to concerns about the impacts of low dissolved oxygen and elevated summer temperatures on fish health and abundance.

Trends in herring biomass have implications for herring predators, such as fish, marine mammals, and seabirds. Age-0 herring are an important part of juvenile Chinook and coho salmon diets (Beauchamp & Duffy 2011; Chamberlin et al. 2017). Herring may also represent up to 88% of Lingcod diet (Pearsall & Fargo 2007), 40% of Pacific Cod and Pacific Halibut diets (Ware & McFarlane 1986), and 35% to 45% of pinniped diets (Olesiuk et al. 1999; Lance et al. 2012; Olesiuk 2008). Depending on the level of diet specialization and ability to switch to alternate prey, herring abundance and condition may affect predators' growth and abundance.

Future Research

Northern Salish Sea

DFO is committed to a Precautionary Approach in the management of Pacific Herring, which includes establishing biological limit reference points (a fisheries management tool) and the use of harvest control rules. Harvest control rules define harvest rates, which are reduced to zero when herring spawning biomass is below a pre-defined low biomass level (Cleary et al. 2017). Recently, DFO has been using simulation models to test the ability of harvest control rules to meet conservation objectives by maintaining stocks above the limit reference point. These simulations are part of a coast-wide Management Strategy Evaluation (MSE) process, focused on establishing conservation objectives and renewing the management framework. The herring MSE process engages First Nations and the fishing industry in the development of objectives and management strategies for sustainable fisheries. Additionally, uncertainties in stock structure (i.e., existence of smaller sub-stocks) and climate change impacts can also be explored as "scenarios" or "hypotheses" within herring MSE.

Southern Salish Sea

Recognizing the many data gaps in our knowledge of forage fish, the Washington Department of Fish & Wildlife has also adopted a Precautionary Approach to the management of forage fish in Puget Sound and the SSS. The precautionary approach "utilizes caution when the agency is faced with a decision and a lack of information. The approach calls for reducing fishery or other activities if there is reason to believe that the activities will cause significant harm, even if such a link has not been established by clear scientific evidence. Treaty Indian tribes are not part of this policy and are not bound by it" (Bargmann 1998).

The Salish Sea Pacific Herring Assessment and Management Strategy Team identified several factors in 2018 that could potentially limit herring recovery. These include exploitation (fisheries), human population growth (with effects on water quality, nearshore light pollution, habitat loss, and nutrient enrichment, among others), toxics (including pollution from legacy sources, which continue to contribute toxics regardless of human population), vessel traffic/noise, Allee effects (positive correlation between population size or density and mean individual fitness), predation, competition, disease, climate change, and ocean acidification. One area that may be conducive to management action is jellyfish, which act as both competitors and predators of herring during various life stages. Recent reports suggest jellyfish are becoming more abundant in Puget Sound (Greene et al. 2015; see Vignette 17, Salish Sea Jellyfish), and resources should be directed to quantify jellyfish abundance and establish the timing of jellyfish blooms, which may be occurring earlier in the year as water temperatures warm. In Puget Sound, at least one proposal has been forwarded to initiate jellyfish fisheries for Asian markets, although concerns about bycatch have slowed progress on this front.

CASE STUDY:

SALMON MARINE SURVIVAL

Michael Schmidt, Long Live the Kings

Dr. Isobel Pearsall, Pacific Salmon Foundation

Iris Kemp, Long Live the Kings

Dr. Brian Riddell, Pacific Salmon Foundation

Our Northwest culture, economy, Tribal and First Nation title, rights, and treaty rights, orca whales, and the overall health of our ecosystem are at risk without thriving salmon populations. We have invested hundreds of millions of dollars in habitat restoration, significantly reduced harvest, and improved the way we manage hatcheries. Yet we are still struggling to recover salmon in the Salish Sea. This includes Puget Sound Chinook salmon and steelhead trout (both listed as threatened under the United States Endangered Species Act) Puget Sound coho salmon (which have declined substantially in abundance) and many populations of Chinook, coho, and steelhead in the Strait of Georgia basin that are listed as Species at Risk in Canada.

In 2013, the Pacific Salmon Foundation (PSF) and Long Live the Kings (LLTK) launched the Salish Sea Marine Survival Project (SSMSP): a US-Canada research collaboration to identify the primary factors affecting the survival of juvenile Chinook salmon, coho salmon, and steelhead trout in the Salish Sea marine environment (Salish Sea Marine Survival Project 2021). It was established in response to unique declining patterns in Salish Sea Chinook, coho, and steelhead production compared to the Washington and British Columbia coast (Zimmerman et al. 2015; Kendall et al. 2017; Ruff et al. 2017), ecological changes in the

Salish Sea, and the belief that once salmon leave the freshwater environment, their marine survival or overall survival in the saltwater to adulthood is largely determined by the early marine period (described as their critical period, *sensu* Beamish & Mahnken 2001).

From 2014 to 2018, a multidisciplinary international collaborative of over 60 federal, state, Tribal, nonprofit, academic, and private entities implemented a concurrent, coordinated research effort that encompassed numerous hypothesized impacts on Chinook, coho, and steelhead as they entered and transited the Salish Sea. The SSMSP operated under a single overarching research framework with shared hypotheses and aligned sampling and analyses strategies. Ultimately, over 90 studies were initiated and some of the research continues.

The project aimed to determine the extent to which early marine survival in the Salish Sea was limiting population recovery and whether it was driven by local factors or global processes, or more likely, some cumulative, synergistic combination thereof. Local impacts result in recommendations to improve the Salish Sea ecosystem, whereas globally driven impacts result in recommendations to adapt to our changing environment.

Survival Declines and the Critical Period

The Salish Sea appears to once have been a productive place for salmon compared to the coast. Chinook, coho and steelhead generally have declining trends in marine survival from the late 1970s to present, whereas northwest coastal and Columbia River populations generally began with lower marine survival and either show less of a decline or none at all over the same time period (Zimmerman et al. 2015; Kendall et al. 2017; Ruff et al. 2017). Chinook survival rates varied significantly by population within the Salish Sea, with Strait of Georgia populations exhibiting clearer declines in survival (Ruff et al. 2017). Coho salmon populations had similar survival declines throughout the Salish Sea (Zimmerman et al. 2015; Sobocinski et al. 2021). This is consistent with salmon distribution patterns in the Salish Sea that suggest different Chinook populations rear in specific areas of the Salish Sea, whereas coho are more widely distributed and mixed (C. Neville, Fisheries and Oceans Canada, personal communication). Like coho, steelhead marine survival and adult abundance declined among Salish Sea populations although the strength of synchrony in trends was slightly less (Kendall et al. 2017).

The 'critical' aspect of the early marine phase for individuals may be to achieve a growth threshold or specific condition in their first summer at sea in order to survive the subsequent fall/winter period (Holtby et al. 1990; Tovey 1999; Beamish & Mahnken 200; Beamish et al. 2004; Tomaro et al. 2012). Alternatively, direct mortality during the early marine phase may signify the importance of the critical period in regulating survival. For steelhead, which migrate quickly through the Salish Sea to the open ocean, direct mortality as smolts in the Salish Sea appears more important (Moore et al. 2015; Moore and Berejikian 2017). For Chinook and coho, growth during the first summer in the Salish Sea is likely a greater

determinant of overall marine survival (Beamish et al. 2008; Duffy & Beauchamp 2011; Claiborne et al. 2020). That said, during this early marine phase there are signs of high juvenile Chinook and coho mortality due to seal predation (Chasco et al. 2017; Nelson et al. 2019b; Nelson in prep; Nelson in press) and little evidence that size-selective mortality is occurring on Chinook (Gamble et al. 2018; K. Pellett, Fisheries and Oceans Canada, personal communication). Work to collect additional data and assess relationships with first summer growth is ongoing.

Factors Affecting Marine Survival during the Salish Sea Critical Period

Numerous factors can affect salmon survival during this critical period. Broadly, the primary hypotheses of the SSMSP were:

1. Early marine survival is determined by bottom-up ecological processes: **weather, water conditions, and productivity that determine the food supply for salmon and result in variation in size and growth rate.** Salmon may also compete among themselves or with other fishes for food.
2. Early marine survival is determined by top-down ecological processes. **Predation is likely the direct cause of mortality**, but salmon may be affected by other biological factors (e.g., disease and contaminants), increasing their susceptibility to predation, directly killing them, or affecting their condition such that overall marine survival is reduced.
3. **Multiple factors interact and have cumulative effects** in determining early marine survival. These may be additive, synergistic, or dampening.

Humans have also influenced salmon productivity and marine survival through our impact on habitats and related losses of life history diversity in salmon.

Key Findings of the Project

Salish Sea-wide factors affecting food supply and predation are the most critical, whereas other impacts are significant at population or sub-basin levels. Findings of the SSMSPP clearly illustrated that changes in environmental conditions influence zooplankton (Keister & Herman 2019; Keister et al. 2019; Perry et al. 2021) and forage fish production (Chamberlin et al. 2017; Boldt et al. 2018; Duguid et al. 2021), which in turn, regulate salmon growth and survival (Duffy & Beauchamp 2011; Chamberlin et al. 2017; Keister & Herman 2019; Greene et al. 2020). Populations of harbor seals have increased concomitantly with declines in salmon marine survival (Jeffries et al. 2003; Nelson et al. 2019). Growing evidence suggests that direct predation is a significant contributor to steelhead mortality (Berejikian et al. 2016) and is likely contributing to increased mortality in coho and Chinook salmon as well (Chasco et al. 2017; Nelson et al. 2019; Nelson in prep; Nelson in press). Other contributing factors include contaminants (O'Neill et al. 2019, O'Neill et al. 2020) and disease (Stentiford et al. 2017; Mordecai et al. 2019), which for some populations are limiting growth and/or causing sub-lethal stress.

In all, empirical findings and modeling efforts suggest multiple interacting causes of declines in marine survival in the Salish Sea (Sobocinski et al. 2020; Sobocinski et al. 2021). There are substantial concerns about the role of climate change in both the Salish Sea and North Pacific Ocean and how changing conditions impact salmon, but the difficulties in isolating its impacts are considerable, especially in the inland waters where numerous other factors are at play.

A synthesis report titled *Factors limiting survival of juvenile Chinook salmon, coho salmon and steelhead in the Salish Sea: synthesis of findings of the Salish Sea Marine Survival Project* will be completed in 2021 (Pearsall et al., in prep). It will

present a synthesis of the findings to date and the perspectives of the lead scientists regarding the primary factors affecting survival and the next steps in research and management.

Potential Management Actions and Research Needs

In many cases, the suite of management actions chosen will be dependent upon species and populations targeted. All actions should be treated like experiments given the uncertainty around outcomes and should take an adaptive management approach (monitor, analyze, adjust). These actions include but are not limited to:

- Reduce damage to and restore estuary and nearshore (e.g., kelp and seagrass) habitat for salmon, Pacific herring, sand lance, and crab. Ensure that connectivity of marsh, eelgrass, and kelp habitats is accounted for. Support soft-shore initiatives.
- Recover, protect, and maintain diversity in herring populations. Better understand early year class dynamics.
- Support salmon life-history variability through habitat restoration, population management, and testing various hatchery rearing and release strategies. This may build resilience to variation in food supply and reduce the potential for density-dependent impacts including competition, disease, and predation.
- Investigate various approaches to reducing predation by seals including: facilitating passage at migration barriers where predation is an issue; obstructing or removing log booms and other seal haulouts; using predator deterrents; and, if necessary, performing experimental removals.
- Take targeted actions to reduce contaminant burdens in juvenile salmon and steelhead where those impacts are greatest (e.g., PBDEs affecting Chinook in the Snohomish estuary). Focus larger-scale remediation efforts on PCB hotspots to reduce impacts

"We must acknowledge that our salmon continue to decline because we are losing their habitat faster than it can be restored. We must reverse that trend."

Lorraine Loomis, NWIFC Chair, from State of our Watersheds Report 2020

Sockeye salmon in Adams River, BC
Photo: Yuri Choufour

to Chinook residing in Puget Sound. Also, assess contaminant inputs and impacts in the Strait of Georgia, prioritizing the lower portions of the Fraser River and its estuary.

- Optimize fish health in hatcheries, especially as increasing temperatures associated with climate change continue to be a concern. This includes disease management and smolt readiness.
- Protect and manage flows in freshwater to reduce predation-based mortality of outmigrating salmon smolts (e.g., under British Columbia's Water Sustainability Act 2014).
- Use newly compiled environmental data to improve adult return forecasting and harvest management, and new ecosystem models to broadly guide ecosystem recovery actions.

Uncertainties

We still have many questions about what is affecting salmon survival in the Salish Sea. In particular, we have substantial evidence that impacts to the food supply of Chinook and coho salmon are occurring but have yet to iron out the mechanistic relationships that explain how and why. This includes understanding the relative impact of climate variation on temperature, nutrients, winds, shifts in primary productivity (e.g., diatoms versus dinoflagellates), and conditions that affect light attenuation underwater. It also includes having a more refined understanding of salmon rearing locations, as SSMSMP results suggest that different rearing locations within the SOG may be associated with variation in survival. This information is critical for improving our ability to predict adult returns for fisheries management and recovery and for refining our recovery actions for resilient salmon and a resilient ecosystem.

To continue to integrate multiple environmental changes within the Salish Sea and assess impacts to salmon in a cumulative fashion, an ongoing effort within the SSMSMP is the development of

food web and end-to-end models that simulate full ecosystem processes from oceanography up through trophic dynamics and fisheries. These include an Ecopath with Ecosim model being developed by the University of British Columbia, and an Atlantis model led by NOAA and LLTK. End-to-end ecosystem models are increasingly being used to consider cumulative impacts, to evaluate fishery management options, and to evaluate impacts of nutrient loading, oil, and other contaminants. These models are now a core part of the toolbox for supporting ecosystem-based management of fisheries and marine resources. Due to the uncertainty in understanding complex natural systems with limited data, using multiple models to evaluate and inform policy choices and management decisions is an emerging best practice.

The quality of model outputs and other analyses of the impacts of ecosystem change are tied to the quality and quantity of data available. Therefore, we must continue to collect and improve upon the empirical data available. Specific monitoring recommendations derived from the SSMSMP, as well as several new and innovative assessment techniques are described in detail in the forthcoming paper titled, *Novel Assessment Techniques, Monitoring Recommendations, and New Tools for Ecosystem-Based Management Resulting from the Salish Sea Marine Survival Project* that will be available at www.marinesurvivalproject.com.

Community science was a novel part of British Columbia's endeavors to increase capacity to collect oceanographic data. The PSF Citizen Science Oceanography Program developed via the SSMSMP collects an unprecedented amount of oceanographic data at spatial and temporal scales not previously attainable, and at a fraction of the cost. Other groups of citizen scientists sample forage fish embryos and identify forage fish spawning habitat in collaboration with PSF, local Shore-keepers, World Wildlife Fund, and

Vancouver Island University. Plus, a new PSF-supported community science initiative through the University of Victoria was established to sample adult Chinook and coho diets in the Strait of Georgia to assess seasonal, regional, and inter-annual variability in herring and other forage fish availability.

An Achievement in Science and Transboundary Collaboration

The SSMSMP has already been extremely influential. Findings have already guided over 20% of recommended orca recovery actions put forth by the Washington State Governor's Southern Resident Orca Task Force and many actions in NOAA's Puget Sound Steelhead Recovery Plan. However, one of the greatest achievements from the SSMSMP has been the development of an integrated and broad community of researchers, across disciplines and borders. This network of professional and community scientists was necessary to undertake the most comprehensive study of the salmon's

Salish Sea marine ecosystem conducted to date. Strong transboundary collaboration among researchers—in government, academia, and nonprofits—was facilitated through program funding, annual workshops, and working groups. For more information regarding the approach, see the forthcoming affiliated paper, *The Salish Sea Marine Survival Project: how collaborative ecosystem research addressed a major impediment to salmon recovery* that will be available at www.marinesurvivalproject.com.

In summary, the Salish Sea Marine Survival Project has made a significant contribution to our understanding of Pacific salmon and coalesced an active research and management community in the process. Our findings support the implementation of a number of management actions for the benefit of Chinook and coho salmon and steelhead trout and the other species and for the benefit of Tribes, First Nations, and other people who depend on and value Pacific salmon.

Anemone nestled between rocks on the seafloor
Photo: Kathryn Sobocinski



CASE STUDY:

ORCAS, SOUTHERN RESIDENTS AT RISK

Lynda V. Mapes

The Salish Sea is home to three ecotypes of orcas: the northern and Southern Residents, Bigg's or transient killer whales, and offshores. Of these, the southern resident orcas that visit Puget Sound are at grave risk of extinction. Their small population size and social structure also puts them at risk for a catastrophic event, such as an oil spill that could impact the entire population (National Oceanic and Atmospheric Administration 2016). The southern resident killer whales are struggling for survival and are listed as a Species in the Spotlight by NOAA as one of the ten most endangered animals the agency protects. There are only 74 Southern Residents in the population (Center for Whale Research n.d.). Yet in Canadian waters, the northern resident killer whale population has grown at a mean annual rate of 2.2% since 1973 and in 2019 contained a minimum of 310 individuals (Towers et al. 2020).

The reasons why southern resident killer whales are at risk of extinction are multifold and intertwined with the cumulative effects of environmental harm wrought by 150 years of development since European settlement. Development has profoundly altered and harmed the resources the Southern Residents need to survive, especially abundant, quality salmon that is readily available to them year-round.

The Southern Residents are challenged by at least three main threats: scarce food, pollutants, and marine noise (Lacy et al. 2017). Chinook salmon, the primary food they hunt for today are increasingly scarce. In particular, Chinook salmon

are the most sought species by resident killer whales and also are the species most in decline throughout the Southern Residents' foraging range (Hanson et al. 2021). While they eat chum and coho, Chinook salmon are the most sought because of their larger size, year-round presence in coastal waters, and caloric reward for the hunting effort (Ford et al. 2010). Pollutants in the fish they eat are taken up in their bodies and stored in their fat (Mongillo et al. 2016). That means when the orcas are hungry, toxics in their fat are released. These toxics harm their ability to reproduce and to fight disease. Orcas too often also are forced to hunt in a fog of noise (Noren et al. 2009; Williams et al. 2014). Females are the most affected in their foraging by anthropogenic noise, raising further risk for recovery of the species (Holt et al. 2021).

Not a day, and scarcely an hour, goes by when Haro Strait, in the middle of their critical summer habitat, is not busy with bulk cargo carriers, container ships, oil tankers, ferries, fishing vessels, military vessels, and recreational boaters of all kinds including kayakers and commercial whale watch tours (Figure 5.6).

In this clash of maritime cultures, the disturbance and noise caused by boats and vessels masks the natural sounds orcas need to hear in order to hunt using echolocation. Noise and disturbance by boats—even non-motorized vessels, such as kayaks—reduces the areas, and hours in which orcas can hunt effectively to feed their families (Holt 2008; Holt et al. 2019; Williams et al. 2019). One of the biggest determinants in vessel noise

is speed: the faster a boat, the louder it will be underwater. Additionally, the closer a ship is, the louder it will be. About 85% of vessel noise is created by a ship's propeller (Hildebrand 2009). The rest is created by propulsion machinery including the engine and by water flowing over the ship's hull. Large vessels create lower frequency noise that can travel hundreds of miles underwater in the open waters of the eastern North Pacific (Veirs et al. 2016). Underwater noise from ships and other vessel traffic interferes with the ability of whales to communicate and forage because they overlap with the sound frequencies whales' need to hear (Erbe et al. 2019). This forces orcas to increase the volume (one decibel for each decibel of noise) or length of their calls (Holt et al. 2008). That comes at a cost of energy required for sound production, and increased stress levels.

Scientists have also learned orcas forage less in the presence of vessels (Lusseau et al. 2009). A noisier environment also decreases the distance at which orcas can detect prey, forcing them to work harder to find food (Williams et al. 2014).

When people displace orcas from their primary feeding areas with noise and disturbance, orcas suffer. Where the Southern Residents have, over many thousands of years, learned to use the rock canyon along the west side of San Juan Island, Washington like a fish funnel to hunt Chinook salmon returning to the Fraser River, humans have in just the last century created an echo chamber of industrial noise (Williams et al. 2014). Williams et al. (2014) found that critical habitats for both northern and southern resident killer whales (Robson Bight and Haro Strait, respectively) were the noisiest in the frequency bands that killer whales use for social communication.

These areas are poised to become much noisier given major proposed developments including expanded port facilities at the Fraser River Delta

and increased tanker traffic serving increased capacity planned for the Trans Mountain Pipeline at Burnaby, BC. The Canadian National Energy Board found in its reconsideration of the project that it would likely result in significant adverse effects to the southern resident killer whale. While project-related marine vessel traffic would be a small fraction of the total cumulative effects of noise in the Salish Sea, any further increase is damaging (National Energy Board of Canada 2019). The project was subsequently nationalized and is proceeding. It will bring a seven-fold increase in tanker traffic to the inlet, and an attendant risk of oil spills of bitumen oil for shipments overseas.

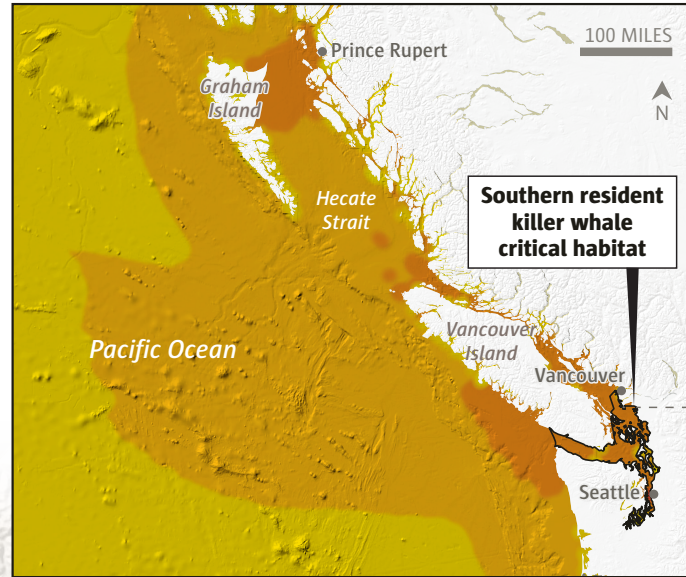
The Southern Residents eat only fish, primarily salmon. Research has confirmed that in winter, as much as half the Southern Residents' diet is coho and chum salmon, steelhead, and some lingcod, skate, or flatfish (Ford & Ellis 2006; O'Neill et al. 2014; Ford et al. 2016; Hanson et al. 2021). What these predators need the most, however, is Chinook salmon. To stay healthy, an adult orca must catch about eighteen to twenty-five salmon every day, or up to 300 pounds, depending on the age and condition of the orca (Lacy et al. 2017). Prey intake for lactating females, an energy expensive activity, is 42% higher, making adequate salmon availability a crucial aspect to southern resident recovery (Williams et al. 2011).

Food specialization in fish, especially chinook salmon, is a culturally-transmitted behavior among resident orcas that is deeply embedded and passed generation to generation. But it has become a risk for the Southern Residents as salmon runs, especially Chinook salmon runs, have declined throughout their foraging range (Ford & Ellis 2014). Of 396 populations of Chinook salmon that used to be available throughout the orcas' foraging range, today 159 are locally extinct, leaving gaps in the calendar year in which the orcas' preferred prey is no longer available. Chum also are depleted, with 23 of 112 populations extirpated and many others reduced in numbers.

THE SOUTHERN RESIDENTS' NOISY HOME

The endangered southern resident orcas that visit Puget Sound confront the noisiest waters in their critical habitat, including the west side of San Juan Island, the Fraser River Delta and the Strait of Juan de Fuca. Noise is caused by vessel traffic, especially commercial shipping.

Their habitat in all of the Salish Sea has underwater noise levels that would be out of compliance with noise-pollution limits that are recommended by the European Union.



CUMULATIVE NOISE EXPOSURE FROM VESSEL TRAFFIC IN 2008

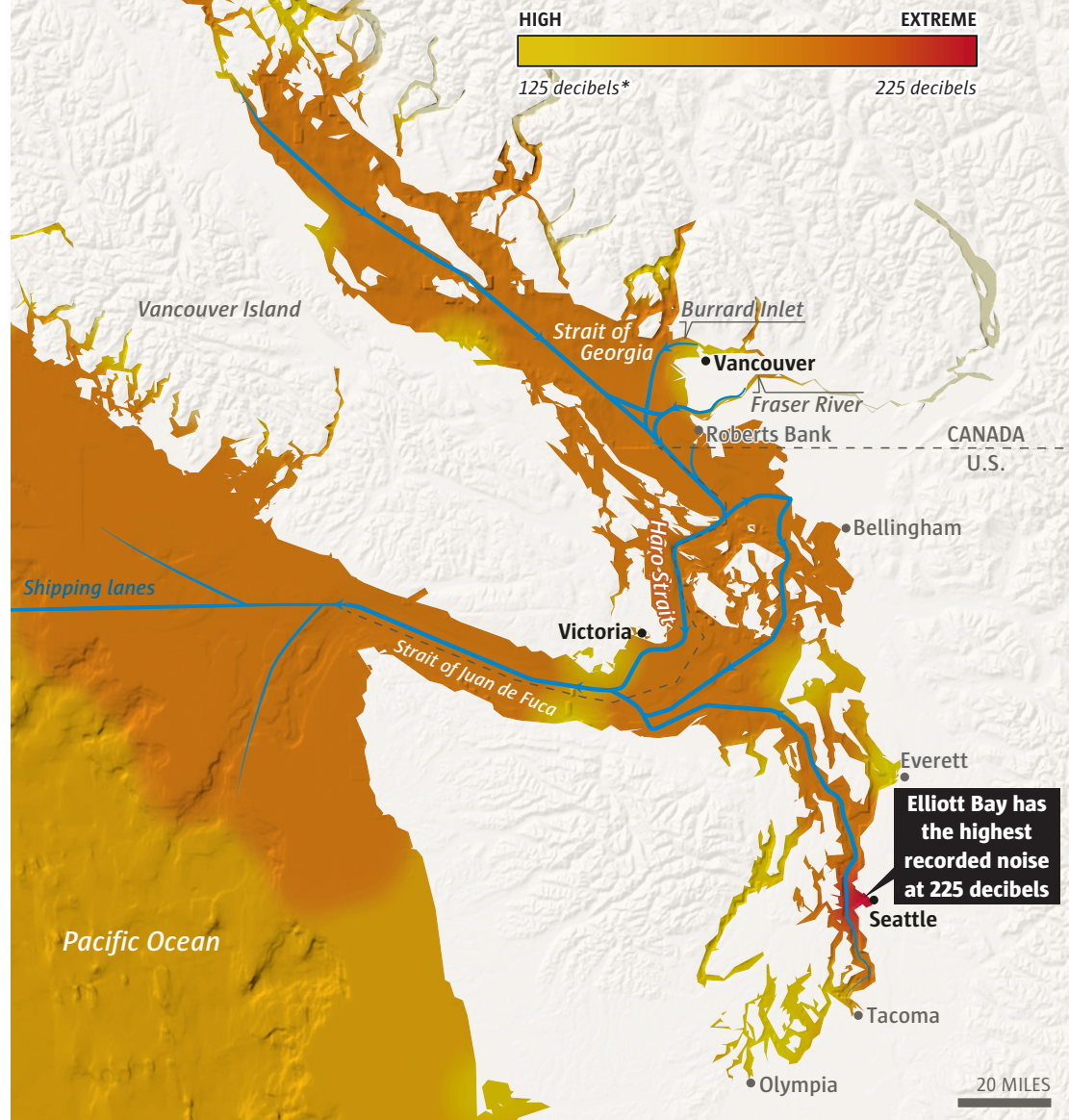
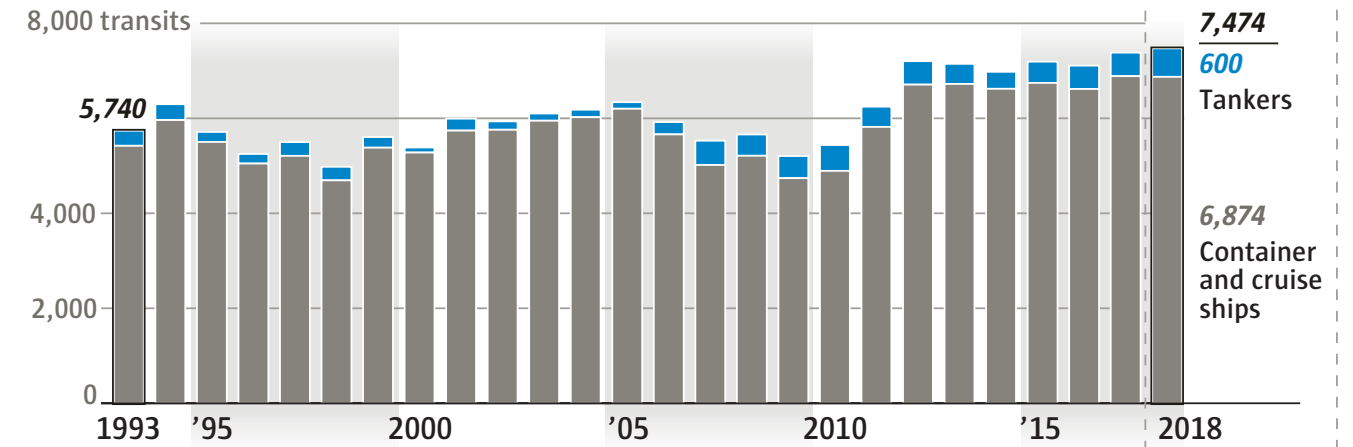


Figure 5.6. (Left and Right) Noise impacts on Southern Resident orcas in the Salish Sea. Source: Emily Eng and the Seattle Times

A BUSIER HARO STRAIT

Busier means noisier: More tankers, container ships and cruise ships bring more noise confronting endangered southern resident orcas in their core summer foraging habitat in Haro Strait.



*Calculated with a reference of one microPascal squared times one second

Sources: Erbe, Christine, et. al, "Mapping cumulative noise from shipping to inform marine spatial planning," *The Journal of the Acoustic Society of America*, Washington State Department of Ecology

With so much lost diversity and biomass, recovering the southern resident population will be more than a matter of recovering existing salmon stocks. In some cases, reintroduction from captive broods will be necessary, as has been done with winter-run Chinook salmon in tributaries of the Sacramento River (California Department of Fish and Wildlife 2018).

Northern resident killer whales benefit from a wider variety of fish and quieter, cleaner water. They also capture fish targeted by southern resident killer whales when those fish are in the range typically used by the Northern Residents and where the two populations overlap in the Salish Sea (Hanson et al 2021).

Climate change is raising the stakes (Crozier et al. 2019). Across the Northwest, climate change threatens Chinook salmon across their life cycle (Crozier et al. 2021). During the Blob marine heat wave (see discussion in Section 4), temperatures increased as much as 3.9°C

(7°F) above average in a mass of warm water that stretched from Alaska to California, and reached to a depth of more than 480 m (1,600 ft). The warm water depleted the ocean food web both in its abundance and nutritional value, killing uncounted millions of animals, from sea birds to marine mammals (Piatt et al. 2020).

Scientists are concerned that downturns in ocean conditions are becoming both more frequent and severe, giving salmon runs little chance to bounce back—another threat to orca survival. The marine heat wave that began in late 2013 reduced salmon returns to the Columbia and Snake Rivers to near record lows. Climate warming is expected to further reduce survival in the ocean because of sea surface warming, making improvements necessary at every life stage. Some salmon, such as Snake River spring and summer Chinook, will be nearly extinct by 2060 without interventions desperately needed to stave off extinction due to cumulative effects of

changes in their environment, including warming of sea surface temperatures predicted in the coming decades (Crozier et al. 2021).

From the Salish Sea to California's Central Valley and the Snake River, the Chinook runs scientists have documented as crucial to southern resident killer whales are among the most vulnerable to the effects of climate change, both at sea and in the tributaries to which these salmon return. Sustained temperatures above 20°C (68°F) increase rates of disease and mortality in salmon, a cold-water species. Low marine survival in the Salish Sea also continues to thwart recovery.

Meanwhile, degradation to the freshwater environment has also reduced salmon survival, including dams that have reduced and eliminated spawning habitat; development that has destroyed estuaries, wetlands, and side channel rearing areas; and a steep drop in nutrients in spawning streams to support productivity. Wild Puget Sound Chinook salmon overall have not improved in abundance since they were listed as a threatened species under the United States Endangered Species Act in 1999. Chinook salmon runs in the Columbia, Snake, and Sacramento rivers also remain at risk of extinction. In November 2018, the Committee on the Status of Endangered Wildlife in Canada (2018) determined 12 of 13 Fraser River Chinook stocks were in steep decline, too.

Chinook salmon throughout the Southern Residents' foraging range also have shrunk in size over the past 40 years (Ohlberger et al. 2018). The trend is remarkably widespread, affecting both wild and hatchery fish in the northern Pacific from California to western Alaska. The southern resident orcas are shrinking too, with documented smaller body size in younger whales tracking along with the decline in Chinook abundance (Groskreutz et al. 2019).

Today scientists are concerned about serial failures resulting from cumulative effects, in which orcas throughout their foraging range cannot reliably get enough to eat. That results in poor nutritional status, pregnancy failures, and lost calves. The Southern Residents were listed for protection under the United States Endangered Species Act in 2005 and in Canada under the Species at Risk Act in 2001. With long life spans, low reproductive rates, and only a small number of reproducing orcas in the population, the Southern Residents are even more vulnerable to extinction than their low population would indicate. There were two births to the Southern Residents in 2019 and another two in 2020, bringing the population to 74 animals. That is the second lowest number since counting began in 1974, with 71 Southern Residents. Prior to this time over 50 killer whales were removed from the population and placed in marine parks for exhibition, dramatically reducing the population abundance.

The cumulative impacts of stresses, including noise pollution, poor food supply, and contaminant burden, combined with changing ocean conditions (among other unknown or emerging concerns) continue to threaten southern resident orca whales in the Salish Sea. Population growth today is limited by the nutritional impacts on pregnancy success, with two thirds of pregnancies lost among the Southern Residents because of nutritional stress (Wasser et al. 2017). As we have recognized that capturing whales for captive display is no longer wise for population sustainability, we can make other management decisions favoring their existence. The Southern Residents have long been a symbol of our region, and are considered relatives by many Coast Salish Indigenous peoples. But inhospitable conditions and weak protective regulations will hinder their long-term survival.

PERSISTENT, CONTINUING, AND EMERGING IMPACTS

In assessing cumulative effects, we must consider the decades of ecosystem injury that have previously occurred in our urban ecosystem and the effects of that harm that remain. For example, legacy contaminants remain in the ecosystem, having had deleterious impacts in the past, but also affecting contemporary populations of organisms through continued interaction or accumulation (O'Neill & West 2009; Good et al. 2014; Conn et al. 2020). New stressors, like climate-driven increases in precipitation may bring additional new impacts, such as diseases, into our waterbodies and add to concern (Chhetri et al. 2019). Marine disease is another complex topic, relying on a triad of the pathogen, host, and environment to produce disease conditions. Seastar wasting disease has ravaged the native seastar (*Pycnopodia helianthoides*) from California to British Columbia, with warm temperatures from the marine heatwave implicated as the cause (Harvell et al. 2019). The ecosystem effects of the loss of this predator are as of yet unclear but may not be limited to loss of seastars. As temperatures warm and immune responses in biota are compromised from other insults ("sub-lethal stressors,"; Jeffries et al. 2018; Williams et al. 2019), marine disease may play an increasingly important role in structuring communities in the Salish Sea (Burge and Hershberger 2020). The multiple layers of impacts are not acting in isolation and each new stressor adds additional scope for interactive effects.

While ecosystem impacts are cumulative at one time (multiple stressors), they are also cumulative across time (legacy and contemporary impacts interacting). Additionally, novel conditions brought about by climate change and cumulative local impacts, may further tip the balance, exacerbating the response of organisms to one or more stressors. Ecosystem conditions may ameliorate stressors in some situations, for example, in areas with high flushing where continual replacement of the water mass mitigates low oxygen or high temperature. But in other areas where residence times for water masses are longer, the cumulative stressors of increased temperature, low dissolved oxygen, and nutrient inputs may be more pronounced.

There are numerous other activities not discussed in this report that are occurring within the Salish Sea and that threaten the sustainability and resilience of the ecosystem (see Vignette 18, Bellingham Bay). Some of these activities have been persistent over past decades, while others are emerging concerns. The following table provides a selection of these additional persistent and emerging impacts, organized by the stressor to the Salish Sea ecosystem. Included are references for further reading and an indication if the threat is considered a continuing impact (a recent and ongoing threat) or an emerging impact (new or previously unidentified threat). Legacy impacts (of historical origin but lingering impact) are also of concern, as described in numerous examples in this report.

Additional Emerging and Continuing Stressors in the Salish Sea

Stressor	Cause(s)	Description	Stressor Status
Disease	Aquaculture (finfish), climate change, cumulative stress	Diseases are gaining attention as ecosystem stressors in the marine environment, beginning with sea star wasting disease in the 2010s along the Pacific coast (see vignette about Eelgrass Wasting Disease and emerging concerns). (Hershberger et al. 2013)	Continuing and Emerging
Acute Trauma to Mammals	Vessel strikes	Marine traffic has resulted in trauma to mammals. (Raverty et al. 2020)	Continuing
Underwater Noise	Vessel traffic, military operations	Noise produced by transiting maritime vessels and airplanes can cause disorientation to marine mammals, birds, and other organisms. Frequently occurring operations may be more disruptive, even if less severe. (Clarke et al. 2009; Rolland et al. 2012; Erbe et al. 2018)	Continuing and Emerging
Light Disruption	Light pollution, light disruption, urbanization	With growing human population, the light regime along shorelines has been dramatically altered with impacts to fishes and birds foraging or seeking refuge from predation. This includes the addition of artificial light at night and the impeding of natural light during the day due to docks and overwater structures. (Nightingale and Simenstad 2001; Ono et al. 2010; Davies et al. 2014; Beauchamp 2018)	Continuing and Emerging
Invasive Species	Ballast water, aquaculture	Invasive species brought into the Salish Sea via ballast water or other aquatic activities have been a concern for some time. A detection and monitoring system is important for identifying problem species. European green crab (<i>Carcinus maenas</i>) is actively being monitored in the United States (see Vignette 19, European Green Crab) and Canada. There are several tunicate species that are invasive in the Salish Sea as well. (Fisheries and Oceans Canada 2018; Strait of Georgia Data Centre 2021; Washington Invasive Species Council 2021)	Continuing and Emerging
Oil Spill Risk	Large spills possible in shipping channels	A spill of nearly any magnitude would cause devastating impact. Removal technologies at very best pick up very small quantities of oil or other contaminants. Heavy fuels like bitumen would sink, with impacts to benthic organisms. (Brace 2018)	Continuing and Emerging

SUMMARY OF CUMULATIVE EFFECTS IN THE SALISH SEA

Identifying cumulative impacts in ecosystems, particularly marine ecosystems, is a challenge in the Anthropocene, where multiple human activities have led to declines in ecosystem condition across prolonged time scales. Assessments can demonstrate the associations among multiple interacting stressors and declining functions of ecosystems (Luoma et al. 2001; Crain et al. 2008; Darling & Côté 2008), but these must be comprehensive investigations and are typically limited to evaluating outcomes on a specific habitat (e.g., eelgrass) or marine species and are rarely on multiple variables simultaneously.

For integrative species, like salmon and seabirds, that rely on multiple connected habitats for their life histories, cumulative effects must be documented beyond the Salish Sea in its strict sense (i.e., the estuarine waters). Moreover, it is in these very integrative species where differences in abundance (Ethier et al. 2020) and survival (Zimmerman et al. 2015; Kendall et al. 2017; Ruff et al. 2017; Sobocinski et al. 2018) within and outside of the Salish Sea occur. These

examples both indicate compromised condition and function within the Salish Sea that is having negative effects on biota.

The two primary threats identified in this report—global climate change and the escalation of human impacts to the seascape from local population growth and urbanization—are multifaceted, persistent, and continuing threats to the Salish Sea ecosystem and region. Both could be considered “press perturbations” (i.e., ongoing stressors to an ecosystem; *sensu* Glasby & Underwood 1997). They are chronic and periodically interrupted by additional acute pulses of disturbance from which the ecosystem rebounds (e.g., the Blob event discussed in Section 4). There are multiple interacting and cumulative stressors driven by these overarching threats. Theory and observation suggest an eventual tipping point (Selkoe et al. 2015; Milkoreit et al. 2018). It’s unknown if the Salish Sea has the capacity to recover from short-term disruptions while being chronically and increasingly exposed to the ultimate press perturbations discussed in this report.

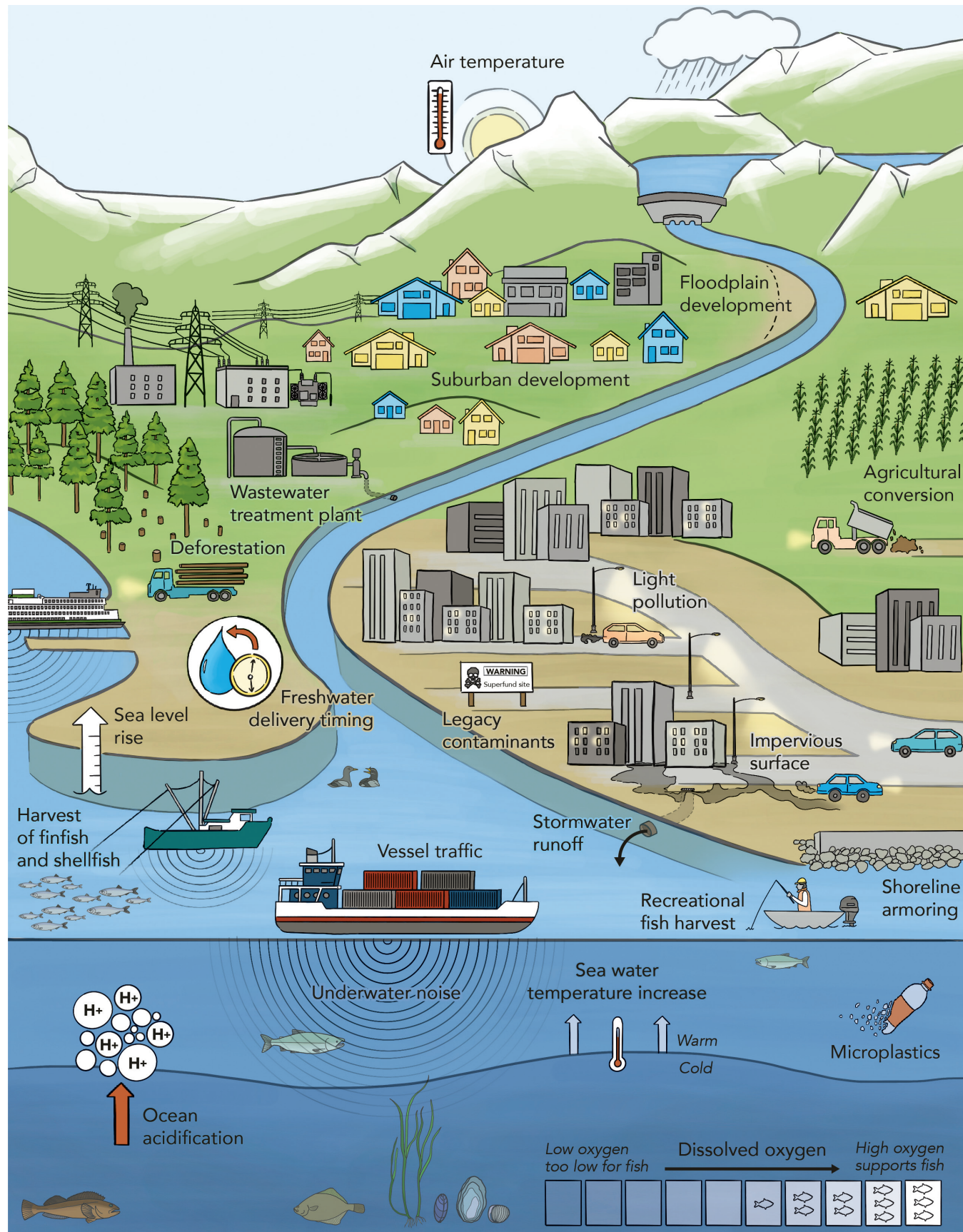


Figure 5.7 An illustration of cumulative effects. Source: Emily M. Eng for the Salish Sea Institute.

The “Wicked Problem” of Maintaining Healthy Ecosystems in the Anthropocene

Much of this report was written during the social complexities and uncertainties brought on by the SARS-CoV-2 coronavirus (Covid-19) pandemic of 2020-2021. The challenges associated with solving such a large-scale, constantly evolving public health problem are similar to those faced in environmental management. These problems, often termed complex or “wicked” problems (sensu Rittel & Webber 1973), are policy problems that are difficult to define and typically do not have a single solution. Examples in the literature and in practice include human health, disease prevention and cures, poverty, climate change, urban planning, development of school curricula, and environmental protection.

Discovering and developing solutions to wicked problems, particularly for those involving large seascapes, is challenging due to the multiplicity of actors (landowners, stakeholders) and levels of governance (from municipal to state/provincial to federal), many of them overlapping on the same parts of the seascape (Imperial et al. 2016; Parrot 2017). But the multiplicity of actors is also a benefit, with numerous invested Indigenous groups, agencies, community organizations, and educational outlets already in place. Building a better future will require an ability to anticipate how societies, economies, and ecosystems are linked across scales—and across the international border—and an understanding of how to shift these coupled systems toward more desirable states (Bennett et al. 2019).

The solutions to these wicked problems may be approached from multiple, often competing perspectives, with multiple stakeholders each valuing potential solutions over other potential solutions (e.g., wearing masks versus wiping surfaces to combat the coronavirus until a more complete solution is developed and available in the form of a vaccine). In reality, no solution will be perfect, and some argue wicked problems are in fact relentless and unsolvable by definition, but diverse approaches are necessary for improvement—even if not a perfect solution (e.g., wearing masks and wiping surfaces and social distancing and wide-spread testing and vaccination).

As Ed Yong wrote in his piece *America Is Trapped in a Pandemic Spiral* (2020), “People forget that controlling the pandemic means doing many things at once.” This same observation holds true for maintaining the health and ecological integrity of complex ecosystems like the Salish Sea. Many things will need to be done at once: increasing understanding in the face of a changing ecosystem, limiting further inputs of contaminants that we know cause harm, protecting remaining stretches of shoreline with high function, and enacting policies that move the needle toward resilience and ecosystem health.

Olivia Klein, Salish Sea Institute

This vignette draws information primarily from an interview with Ian Fawley at the Washington State Department of Ecology and the agency's website on Bellingham Bay cleanup.

There are thousands of contaminated sites in the Salish Sea region, causing environmental and economic impacts to people and wildlife. From estuarine deltas to urban shorelines, years of milling, manufacturing, landfilling, and a variety of industrial and municipal activities have contributed to extensive contamination of shorelines and associated waterways.

Bellingham Bay, home to twelve designated hazardous waste cleanup sites, is one example that illustrates the harm of past practices as well as the effectiveness of cleanup efforts. Since 2000, the Bellingham Bay cleanup has focused on

the removal of contaminated sediment and soils introduced from a wide variety of sources, including construction and other industrial and municipal activities. Bellingham Bay cleanup is managed by the Washington State Department of Ecology (under the authority of Washington State's Model Toxic Control Act) in coordination with a multi-agency Bellingham Bay Action Team.

Prominent on the waterfront of Bellingham Bay, and often listed as a key contributor of the contaminated sediment and soils in the Bay, are the remains of the Georgia Pacific pulp and paper mill. The factory closed its doors in 2007, leaving behind several pollutants still detected today, including heavy metals, petroleum hydrocarbons, volatile organic compounds, and dioxins/furans. But contamination in the Bay goes well beyond the mill.

Former shipyards with contaminated soil and groundwater account for three of the twelve contamination sites in Bellingham. Other sites include a rock-crushing plant in operation from 1963 to 1992, a frozen food processing company that existed from 1946 to 1959, and a seafood processing plant in operation since 1959 (and still in operation). All are linked to the presence of hazardous substances in Bellingham Bay's marine sediment.

It's not just manufacturing—historic landfill practices contribute additional contaminants to Bellingham Bay. For example, an historic 13-acre landfill near the Old Town district of Bellingham

operated in the early 1900s. Property owners filled portions of the site with dredge spoils and other materials to increase usable upland areas, and dumping of municipal waste followed. Landfill disposal practices of the time were vastly different than today, leaving a legacy of contamination.

The collective activities resulted in soil runoff, contaminated groundwater, and particulates like dust and smoke settling from the air, eventually finding its way into Bellingham Bay. Combined with stormwater outfalls carrying surface-born contamination, these pollutants and processes add



Shoreline cleanup and restoration at Bellingham Bay
Photo: Washington State Department of Ecology



Dredging of contaminated sediment
Photo: Washington State Department of Ecology

to the collective annual cost of approximately \$16 billion in environmental degradation of sediments in the United States, according to the EPA.

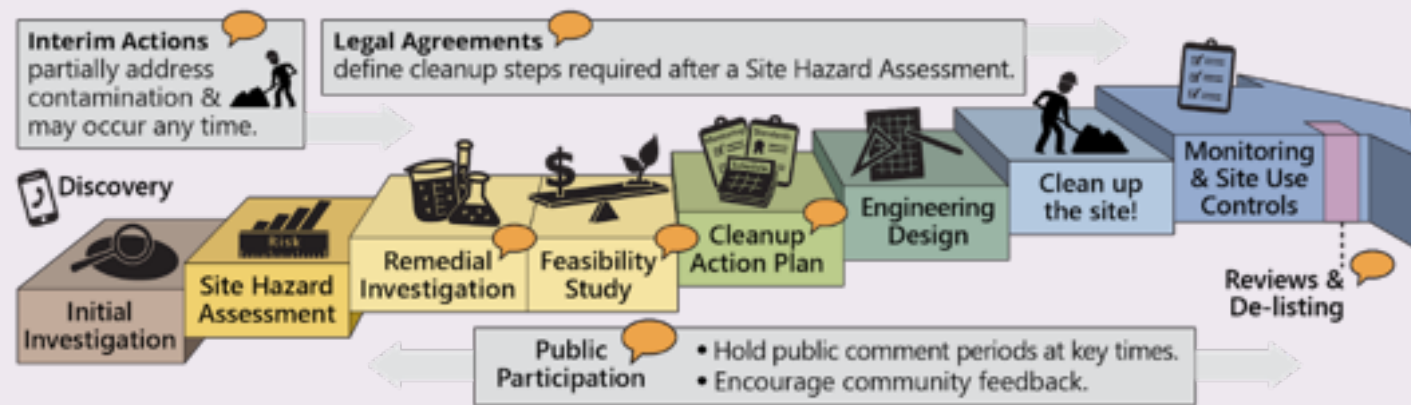
Fortunately, restoration efforts are taking place, bringing hope for a cleaner future in the Salish Sea. Bellingham Bay's twelve individual cleanup sites (see chart at right) each have different needs depending on the severity and type of pollution, as well as levels of engineering and management complexity. Management processes for the cleanup sites fall into three categories: the construction of a multi-layered capping system, the treatment of contamination in place, and contamination removal.

Cleanup is legally and technically complicated, costly, and time consuming. From 2017-18, the Washington State Department of Ecology managed the removal of 14,500 cubic yards of sediment, 3,200 cubic yards of contaminated soil, 36,900 square feet of over-water

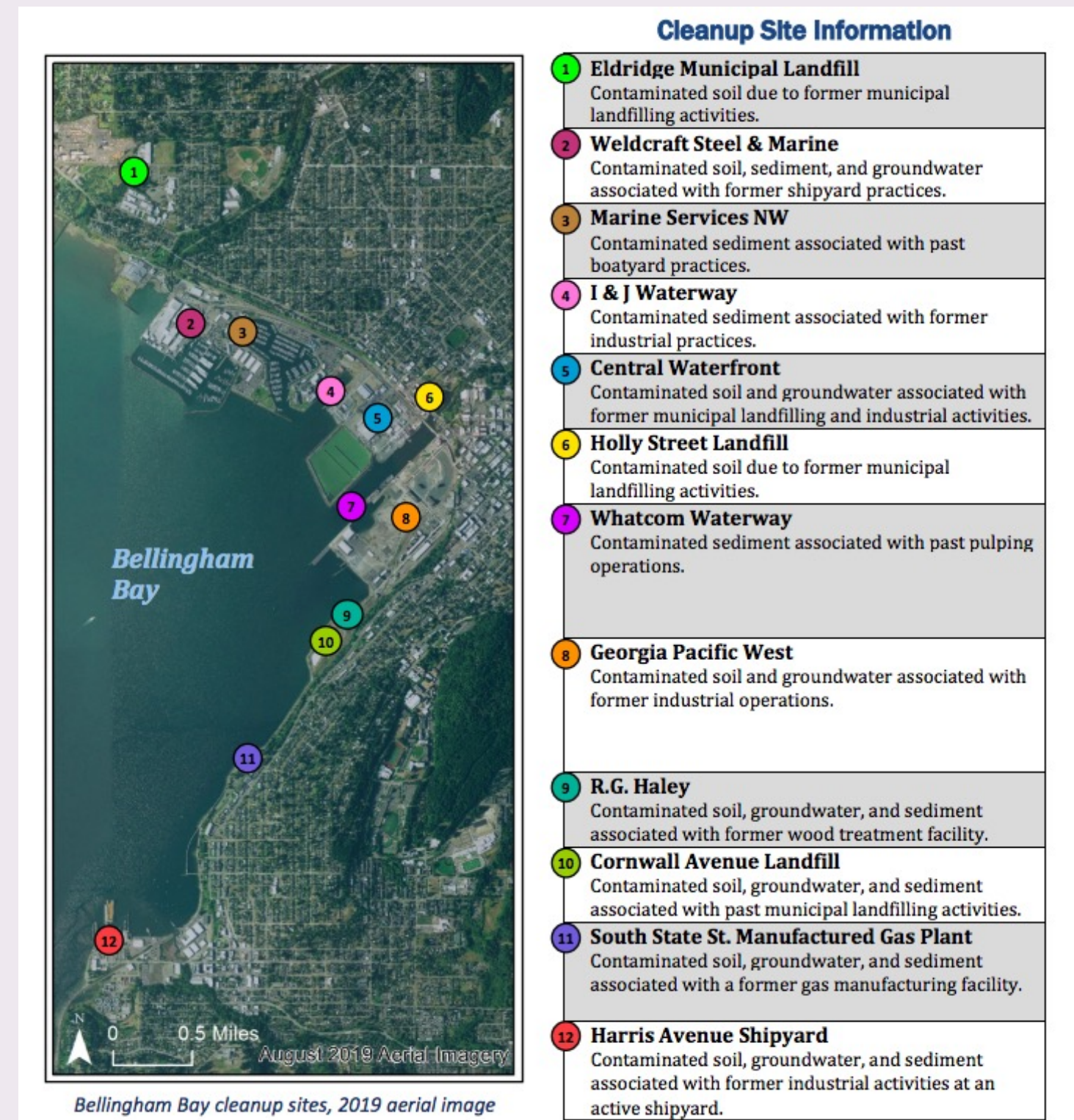
structures, and 905 creosote-treated pilings. This work was followed more recently by additional planning and cleanup documents to prepare for construction in 2021 and beyond. Supporting work includes legal agreements, a remedial investigation/feasibility study, two cleanup action plans, and two engineering design documents (see process diagram below).

Today, two of the original twelve sites have been completely cleaned up, and most of the other ten are on their way to completion within a few years. Additionally, the removal of legacy contaminants from some of the sites means they will not migrate to the marine waters of the Salish Sea, further protecting biota.

Although Bellingham Bay cleanup is not yet complete, it is significantly cleaner today than 20 years ago and a step closer to regenerative use of Bellingham Bay shorelines and the connected marine waters.



Stages of cleanup of contaminants in Bellingham Bay. Source: Washington State Department of Ecology



Sites cleanup of contaminants in Bellingham Bay. Source: Washington State Department of Ecology

19 | INVASIVE EUROPEAN GREEN CRAB

Jeff Adams, Washington Sea Grant; Dr. Emily Grason, Washington Sea Grant; Dr. P. Sean McDonald, University of Washington; Allen Pleus, Washington Department of Fish and Wildlife; Dr. Jude Apple, Padilla Bay National Estuarine Research Reserve; Roger Fuller, Padilla Bay National Estuarine Research Reserve; Dr. Lucas Hart, Northwest Straits Commission; and Alexandra Simpson, Northwest Straits Commission

European green crab (*Carcinus maenas*, EGC; Figure 1) pose documented threats to cultured and wild shellfish, eelgrass, and shoreline habitats and ecosystems. EGC diets include clams, oysters, mussels, marine worms, and small crustaceans. Because they can prey on juvenile crabs and shellfish, dense populations of EGC in the Salish Sea region could put fisheries and aquaculture resources in peril. EGC also play a role as ecosystem engineers, disturbing sediments and destroying below-ground tissue of plants while digging for food and burrows,

decreasing stability of saltmarsh banks, drastically reducing eelgrass density (up to 75% in Nova Scotia and Newfoundland), and damaging nesting and feeding habitat for shorebirds and nursery grounds for fish and invertebrates.

After Fisheries and Oceans Canada researchers reported an established EGC population in Sooke Basin, BC in 2012, the Washington Department of Fish and Wildlife (WDFW) worked with Washington Sea Grant (WSG) to secure Puget Sound Marine and Nearshore Grant Program funding and establish

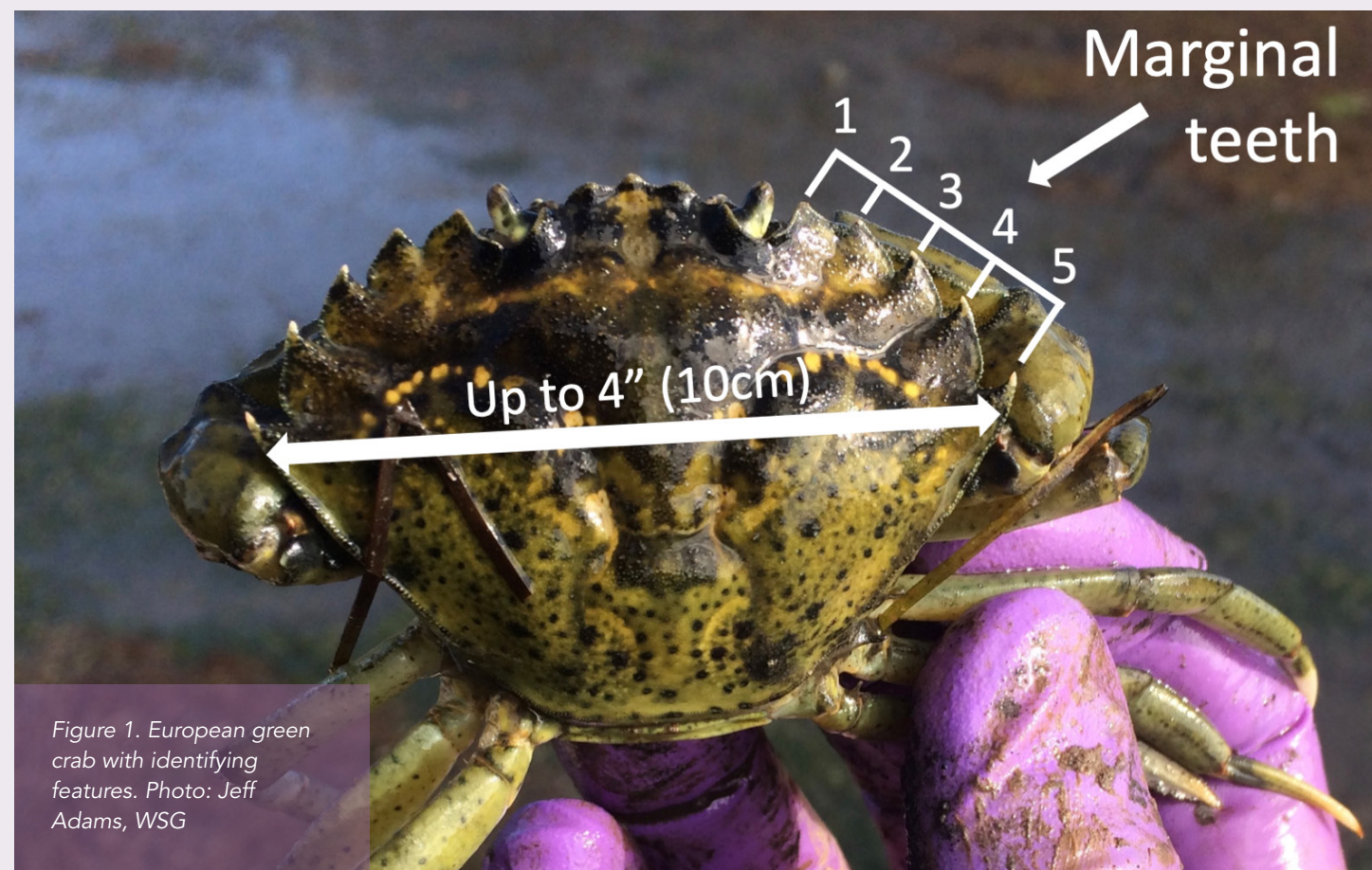


Figure 1. European green crab with identifying features. Photo: Jeff Adams, WSG

a volunteer-based early detection and monitoring program (Figure 2). WSG launched Crab Team (wsg.washington.edu/crabteam) in 2015 with seven pilot sites. The program expanded to 26 sites the following year and has monitored more than 50 sites each year since, engaging hundreds of community members and partner staff in monthly monitoring of invertebrates, fish, and habitat in Puget Sound pocket estuaries, lagoons, and tideflats. Concurrent with early detection monitoring, a team led by WDFW developed the Salish Sea Transboundary Action Plan for Invasive European Green Crab, providing a foundation for prevention, early detection, rapid response, research, and coordinated management throughout the Salish Sea.

The first EGC detections in Puget Sound were made in 2016 by Crab Team volunteers on San Juan Island and by Padilla Bay National Estuary Research Reserve (PBNERR) staff in Padilla Bay (Figure 2). Follow-up rapid assessments detected only a molt on San Juan Island and three additional EGC along the shores of Padilla Bay. In 2017, the first discovery of more than two EGC at a single Puget Sound location occurred at Dungeness National Wildlife Refuge. The response by Refuge staff and volunteers, with support from WDFW, WSG, and other partners, was swift, intense, and sustained. Thousands of trap sets since then

have removed over 220 EGC around Dungeness Spit, resulting in a catch per unit effort (CPUE) of 2.44 EGC/100 trap days (2016-2019). These efforts have been largely successful in reducing the abundance of EGC within the refuge; CPUE in 2020 was only 0.2 EGC/100 trap days.

At the same time, detections have increased in other locations. In 2019, EGC were reported across a broad swath of northern Puget Sound. Aquaculture partners in Samish Bay, WDFW staff in Chuckanut Bay, and Crab Team volunteers in Drayton Harbor all recovered evidence of EGC, prompting rapid assessment efforts in 2019 and a sustained response in 2020. Across northern Puget Sound in 2020, CPUE ranged from a low of 0.8 EGC/100 trap days

in Padilla Bay to a high of 75.3 EGC/100 trap days in Lummi Bay within the Lummi Sea Pond. Multiple cohorts were observed at many locations, as well as some evidence of local reproduction.

COVID-19 restrictions and precautions slowed and delayed the response in 2020, but the Lummi Nation, WDFW, and Northwest Straits Commission (NWSC) were eventually able to deploy crews for both removal and exploratory trapping. WSG volunteers and PBNERR staff continued long-term monitoring

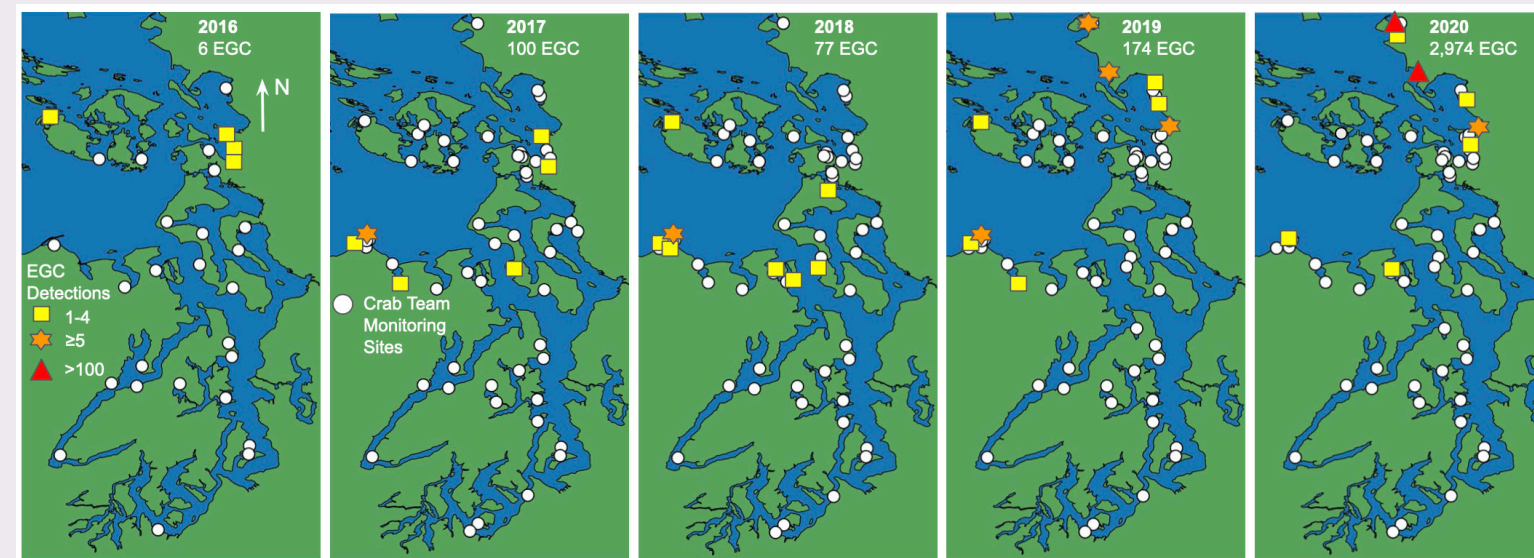


Figure 2. European green crab trapping in Puget Sound by location and year. Yellow squares indicate sites where fewer than five EGC were detected in the year, orange stars indicate sites with 5-99 detections within the year, and red triangles indicates sites with 100 or more detections within the year. Crab Team monthly monitoring network (with the exception of Pysht, west of Port Angeles and beyond the map extent) are identified by white circles. The interactive map is available at tinyurl.com/wagreencrab.

without interruption, and aquaculture partners were able to set traps in Samish Bay. The Lummi Nation continues to devote staff and resources to trapping in Lummi Bay, and the NWSC was able to secure a local coordinator for Drayton Harbor using USEPA National Estuary Program funding for 2019-2020, which continues to present. The Washington State Legislature also provided funding to WFDW to implement an enhanced collaborative response and monitoring effort in Puget Sound as well as assessment efforts on the state's Pacific Coast; these efforts are ongoing. In addition to monitoring and removal, research continues on several fronts, including population genetics, parasite prevalence, and diet composition. This work, as well as lessons

from removal trapping at Dungeness Spit, Makah Bay, and elsewhere, will continue to inform detection and control efforts across the Puget Sound region to reduce risk of spread and impact from EGC.

The coordinated response by WDFW and WSG Crab Team, along with tribal, state, and federal partners, and committed volunteers serves as a model for management of invasive species within the Salish Sea. Indeed, efforts to identify and eliminate nascent infestations have proven successful in many locations because of early detection and rapid response. However, as prevalence of EGC increases elsewhere in the northeastern Pacific, it is important to increase capacity to address the threat regionally.

As part of the Washington Sea Grant's Crab Team program, volunteers evaluate habitat and monitor for invasive European green crab with baited traps. Source: University of Washington



A cadre of pleasure boats in Saanich Inlet. Photo: Ginny Broadhurst

20 | FRASER RIVER ESTUARY IN NEED OF URGENT INTENSIVE CARE

Dr. Laura Kehoe, Oxford University and The Nature Conservancy, and Dr. Tara G. Martin, University of British Columbia

If the Fraser River Estuary were a hospital patient, she would be rushed to the intensive care unit. She would need urgent attention from many different specialists. But if we provide her the care she needs in a timely way, she can heal, and one day thrive. She could once again be bursting with life, bountiful runs of salmon, pods of orcas, and millions of migratory birds.

The Fraser River is the lifeline of the Salish Sea, influencing its stratification, circulation, and primary productivity. Historically, the Fraser River was home to the largest salmon runs in the world. These days, an impressive number of fish still frequent this rich ecosystem. Millions of juvenile salmon spend weeks to months in the estuary before embarking on their ocean migration. Above the water, 1.4 million migratory shorebirds stopover in the estuary at peak season. However, everything is not well in the Fraser. Annual salmon returns and bird numbers have been declining for decades and are now at record lows.

Our research finds that within the mighty Fraser River estuary, 102 species are at risk of extinction. Over the past 150 years, multiple and cumulative pressures, including urbanization, agricultural and industrial development, pollution, overexploitation, disease, and climate change, have severely impacted these species. However, we also discovered it's not too late to save them.

The Fraser River estuary isn't just crucial to wildlife, humans rely on this estuary too. Coast Salish First Nations have lived in and found both spiritual and physical nourishment from the Fraser's natural resources for millennia. Today, this resilient and diverse estuary is host to the busiest port in Canada, home to half of British Columbia's rapidly expanding urban population (Vancouver and surrounds), and is



Audrey Siegl member of Musqueam First Nation, one of over 30 nations who live in and rely on the Fraser River Estuary
Photo: Michael Snyder.

particularly vulnerable to sea level rise and continued industrial development.

The need for a costed prospectus to deliver long-term ecological resilience to this highly contested region has never been more urgent. Our research delivered exactly that. For the 102 species at risk of extinction in the Fraser River estuary, a suite of conservation strategies, spanning aquatic habitat



Southern Resident killer whale in the Fraser River Estuary
Photo: Tom Middleton.

restoration to better farmland management, is needed to save them from extinction.

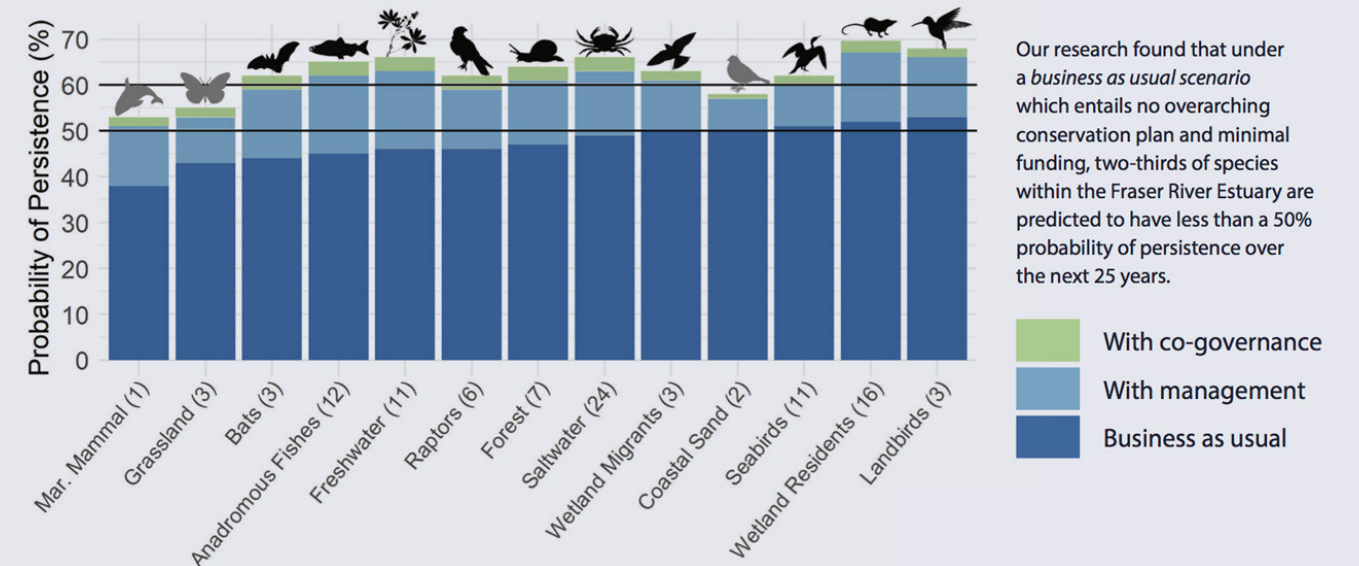
The comprehensive action plan that we developed is estimated to cost \$381 million over 25 years, or \$15 million a year to implement. This might sound like a lot, but it is only \$6 per Vancouverite each year, the cost of one measly beer a year. It's a drop in the ocean compared to the \$26 million per year that whale tourism earns in the Salish Sea and the \$300 million per year that fisheries in the estuary were estimated to be worth in the 90s. If we all raised a toast to the Fraser, we could save it.

On the other hand, if we don't take strong action to conserve the Fraser River estuary, two-thirds of the species at risk in this region are predicted to have a less than 50% chance of survival. Many of the region's most iconic species could disappear, including the southern resident killer whale, salmon, sturgeon and a raft of internationally recognized migratory birds.

While often overlooked, governance is a key factor influencing the feasibility of conservation management, particularly in regions of high competing interests. Despite this, surprisingly little is known about whether the conservation benefits of building and supporting environmental governance

The cost of doing nothing is staggering

Priority management and co-governance are crucial for species recovery.



Our research found that under a *business as usual* scenario which entails no overarching conservation plan and minimal funding, two-thirds of species within the Fraser River Estuary are predicted to have less than a 50% probability of persistence over the next 25 years.

Loss of 8 of 13 species groups representing 67 species, including Southern Resident killer whales.

Loss of whale tourism worth \$26M per year.

Loss of Fraser river fishery worth \$300M per year.

Probability of persistence for each of 13 species groups under increasing levels of investment over 25 years. Baseline (dark blue) represents species persistence probabilities under no additional management; management (light blue) represents implementing all management strategies; co-governance (green) represents the implementation of an overarching co-governance strategy. Under full management and co-governance, 10 of 13 species groups (black species silhouettes, representing 96 of 102 species) reach a 60% probability of persistence. Species groups are ordered from lowest to highest probability of persistence under baseline scenario. Source: Kehoe et al. (2021).



The Fraser River Estuary is a critical stopover site for western sandpipers. Photo: Jason Puddifoot.

outweigh the costs, especially since effective governance is likely to determine the success or failure of conservation interventions.

Our action plan tested the cost-effectiveness of a co-governance model that sees First Nation, local, provincial, and federal governments working together to implement these cost-effective strategies and ensure their success. We found that co-governance was critical to successful conservation outcomes, as it increased the feasibility and cost-effectiveness of all our conservation actions.

On top of conservation outcomes, we found a wealth of additional benefits of co-governance. These benefits include: better cohesion between partners, stricter adherence to regulations, long-term collaboration on projects, the security of ongoing funding, participatory decision making, a

better balance between healthy ecosystems and development opportunities, savings in time and resources, and more public engagement. Our technique is the first to explicitly quantify the cost-effectiveness of co-governance in terms of species conservation and provides a blueprint for future work on assessing the potential for co-governance in imperiled regions.

Co-governance allows for coordinated action to better conserve species under threat—but what about stopping those threats at their source? Multiple large-scale industrial threats face our study region, including (but not limited to): the Trans Mountain Pipeline, a new terminal at Roberts Bank (an ecologically sensitive area), and a new bridge that would allow for more shipping traffic into the estuary.

Alongside prioritizing the most cost-effective management strategies for this imperiled region, we included an assessment of halting future major industrial development. We found that the continuation of industrial development would jeopardize the future of many iconic species such as the southern resident killer whale, anadromous fishes, including salmon and sturgeon, and saltwater species, including the migratory western sandpiper. The gravity of these future threats is underscored with our finding that the benefits from halting future major industrial development are estimated to be greater than nine out of the ten management strategies we assessed. Our research emphasizes that along with restoration action we must prevent further developments that could undermine restoration success.

Our research shows that conservation action combined with environmental governance is a pathway for a brighter future in highly contested regions, such as estuaries, and that the return on investment likely offsets the cost of management. In a world of rapid urban sprawl and ongoing biodiversity declines, our methodology identifies the most cost-effective strategies to conserve nature in areas important to both humans and wildlife. We have the tools to conserve the many wonders of the natural world, but we must employ them while there is still time to act.

Vignette adapted from Kehoe et al. (2021)