

Assessment and Management of Pacific Herring in the Salish Sea: Conserving and Recovering a Culturally Significant and Ecologically Critical Component of the Food Web

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I. Executive Summary

Pacific herring are a critical species in the Salish Sea ecosystem, with broad connections throughout the food web. Evidence suggests that some herring are resident in the southern Salish Sea, though evidence suggests an oceanic component to the life cycle for many stocks. As a result, herring represent a significant annual influx of carbon to the Salish Sea, providing energy to lower trophic levels (egg predators) as well as to upper trophic levels (predators of larvae, juveniles, and adults). Herring are also a culturally important species for Native Tribes and First Nations in the region, and are economically valuable to commercial fisheries in British Columbia (BC) and in Puget Sound (PS). While herring biomass in the Strait of Georgia, BC, is near historical high levels, many of the stocks in PS have declined over the past 40 years, with the greatest reduction (nearly 97%) occurring in the Cherry Point stock, once the most abundant in US waters. Additionally, some spawning locations in the southwest Strait of Georgia (SoG) that were occupied for decades have ceased to be utilized in recent years. Developing a coherent regional management strategy for the whole of the Salish Sea requires coordinated research and monitoring between herring users and stakeholders, and across international boundaries.

Meaningful, effective action to recover fish and wildlife populations occupying the Salish Sea must be informed by the best available science, be cognizant of the programmatic, policy, and management contexts within which recovery actions occur, and acknowledge interactions among ecological, economic, and social components of the ecosystem. While a Forage Fish Management Plan was developed by the Washington Department of Fish and Wildlife and its partners in 1998, followed by a Forage Fish Ecosystem-based Management Study Panel convened in 2013 by the Puget Sound Institute, at present there are no specific strategies for reaching recovery targets for Pacific herring stocks in Puget Sound (PS), and such strategies must be developed by a multi-institutional, transboundary, interdisciplinary recovery team that recognizes the regional socio-ecological context of forage fish resources at large.

To advance conservation and management of Pacific herring in the Salish Sea, an Assessment and Management Strategy Team (the Team) was convened, composed of representatives from government agencies from Washington and BC; social and natural scientists from universities, First Nations, and Tribes; and other stakeholders. The Team performed an expert data elicitation to assess the historic and current status of herring stocks in the Salish Sea and compile a library of relevant publications and grey (unpublished) data. Furthermore, we asked members of the Team and their colleagues to evaluate the state of knowledge, and synthesize their experience and knowledge to provide hypotheses regarding the influence of specific stressors on herring population declines and limitations to recovery, assess ongoing monitoring and management programs for herring and these stressors, and identify priority actions and key uncertainties that must be addressed to advance herring conservation and sustainable management.

Responses from the elicitation were used to develop a Salish Sea-wide conceptual model of factors affecting herring populations and a qualitative network model (QNM) that serves as a heuristic tool for assessing potential management actions and strategies by simulating herring population responses to variation in the relative intensity of key stressors under various scenarios. At a two-day workshop, the Team and a diverse panel of stakeholders considered the state of our compiled knowledge, the two models, and the ability of the QNM to adequately simulate effects of possible management actions. Broad consensus about the cultural and ecological importance of herring, and the nature and relative extent of stressors, existed but some regional differences in stressor intensity and impact were noted. While the conceptual model was sound, the QNM was substantially recast and reparameterized as a result of feedback from this workshop. Further development and performance testing of the QNM will occur in

coming months, but it is presented here in a form that can be tailored to location-specific needs and used to evaluate potential changes in stressor intensity or prevalence as a result of management actions.

Urbanization and coastal development, predation, and compromised water quality were the primary factors identified as both suppressing population levels and limiting recovery potential, and an extensive suite of priority actions associated with comprehensive monitoring and research were identified.

Trends in the abundance and distribution of Salish Sea herring observed are:

- Decrease in adult spawner abundance (measured via egg surveys) in some Puget Sound stocks
- Change in distribution among Strait of Georgia stocks, north- and west-ward, including a loss of some south and eastern spawning sites
- Change in distribution among Puget Sound stocks, including a decrease or loss of some southern spawning sites
- Vulnerability to depensatory dynamics, including from fishing and other pressures

Threats to Pacific herring populations identified as common across the Salish Sea include

- Predation by marine mammal populations undergoing population increases (Harbor seals, Harbor porpoises, sea lions, humpback whales)
- Noise from vessel traffic
- Water quality degradation
- Habitat degradation, including loss of submerged vegetation and shoreline hardening
- Cumulative impacts of shoreline development, including noise, ambient light, poor water quality, and habitat degradation

Threats to Pacific herring populations identified as unique to areas of the Salish Sea

- Contaminants that increase embryo mortality and embryo and larval malformations (Puget Sound)
- Fishing that may cause local extinctions when interacting with populations having certain migration patterns (Strait of Georgia)

Management actions that may be possible to implement

- Protect eggs from predation by birds
- Reduce vessel noise (current priority of Washington State Governor's Southern Resident Killer Whale task force)
- Reduce risk of oil spills (current priority of Washington State Governor's Southern Resident Killer Whale task force)
- Reduce contaminants (piling removals, and via Puget Sound Toxics in Fish Implementation Strategy)
- Improve water quality (via Puget Sound Marine Water Quality Implementation Strategy)

Management actions that are more difficult to implement

- Reduce predation by pinnipeds
- Reduce light pollution
- Modify hatchery salmon release timing to reduce competition from forage fish

The data compilation and evaluation effort presented here considers the suite of ecosystem and socioeconomic benefits provided by herring in the Salish Sea at large and the importance of population

dynamics that occur on local as well as regional scales. It then identifies shared factors influencing, and potentially causing, sustained low biomass and/or lack of stock vitality in some locales and identifies key uncertainties, research, and monitoring needs that can be addressed to promote long-term, sustainable management. Finally, it produces a pair of models that can be used to consider how changes in the intensity and extent of identified stressors as a consequence of specific management actions are likely to affect herring population status. This represents the first time that such a foundation for comprehensive management strategy evaluation pertinent to Pacific herring has existing for the full extent of the Salish Sea.

II. Introduction

In marine ecosystems around the globe forage fish species such as sardine and herring (*Clupeidae*), anchovy (*Engraulidae*), and smelt (*Osmeridae*) occupy a central position in the food web and are highly relied upon by predatory fishes, marine mammals, and seabirds alike (Pikitch et al., 2014; Robinson et al., 2014; Bakun et al., 2015). This reliance can predispose populations of piscivorous species to episodic collapse when forage fish abundance fluctuates in response to broad-scale perturbations, such as shifts in sea surface temperature or intensive fishing pressure (Cury et al., 2011; Pikitch et al., 2014; Gulka et al., 2017). Though the fishery exploitation rate of forage fish species varies substantially by locale, an average of 37% of annual wild finfish harvest on a world-wide basis consists of forage fish (Alder et al., 2008). During the period from 2010-14, ~25% of finfish landed in the U.S. were forage fish (NMFS, 2016).

Pacific herring (*Clupea pallasii*) are a foundational species in the Salish Sea, providing critical ecological, economic, and social benefits (Therriault et al., 2009; Liedtke et al., 2013; Levin et al., 2016). Herring, like several other species of forage fish, are more economically and ecologically valuable when left in the water to support higher trophic levels versus being captured in commercial fisheries (Pikitch et al., 2012, 2014). In the Salish Sea, herring directly and indirectly support a suite of species in the food web, many of which are culturally important (Ainsworth et al., 2008; Harvey et al., 2012), including salmonids (Duffy et al., 2010), seabirds (Lance & Thompson, 2005), and marine mammals (Thomas et al., 2011). Because of their role in the food web, Pacific herring are also considered an indicator of ecosystem health in Puget Sound (Puget Sound Partnership Indicators Action Team, 2009). In the southern Salish Sea (SSS; the waters of Puget Sound, Hood Canal, the Strait of Juan de Fuca, San Juan Islands and the portion of the southern SoG below the international border) herring also support a small (~272 short tons annually) commercial bait fishery, which is managed by the Washington Department of Fish and Wildlife (WDFW). Though small, this fishery is economically and culturally significant because it represents the only source of local, fresh baitfish for recreational anglers targeting various species of salmon and groundfish. Northern Salish Sea (Strait of Georgia, SoG) herring support significant annual commercial roe, food, and bait fisheries, with a total average annual catch of 20,600 metric tonnes (2013-2017, DFO 2018). Throughout the Strait of Georgia herring and herring eggs are also harvested for food, social and ceremonial purposes by local First Nations.

Though herring abundance trends are highly variable, as is typical for many forage fish species, evidence suggests that Pacific herring abundance at numerous locations in the southern Salish Sea is in decline (Stick et al., 2014; Siple & Francis, 2015). Several of these stocks have been declining for at least three decades, despite widespread fishery closures/limitations and focused efforts to conserve and restore spawning habitat (Stick & Lindquist, 2009; Liedtke et al., 2013; Friends of the San Juans, 2014). Evidence suggests that these trends are largely being driven by local dynamics (Shelton et al., 2014) and are having observable impacts on some herring resource predators (Stout et al., 2001; Vilchis et al., 2014). The most dramatic reduction has occurred in the herring stock that spawns at Cherry Point (US southern Strait of Georgia), which has declined nearly 97% since population monitoring began in 1973 (Stick et al., 2014). Possible reasons for the decline of the Cherry Point stock include exposure to toxic contaminants (West & O'Neill, 2007; West et al., 2008, 2014), disease and the oceanographic cofactors influencing infection dynamics (Gregg et al., 2011; Hershberger et al., 2013, 2016), predation (Jeffries et al., 2003; Gustafson et al., 2006; Anderson et al., 2009), and habitat destruction/degradation (Gustafson et al., 2006). There are additional, unique potential stressors on early life stages, such as predation by benthic invertebrates and heat stress, which can cause high levels of mortality (Palsson, 1984; Purcell et al., 1990; Shelton et al., 2014). While a management plan was developed for forage fish, including Pacific herring, in Washington waters in 1998 that acknowledged many of the factors affecting population abundance and distribution

(Bargmann, 1998), and a subsequent status review was conducted by NOAA Fisheries (Stout et al., 2001), a comprehensive, contemporary accounting of the relative impact of these factors does not exist.

Abundance and distribution patterns of Pacific herring in the northern Salish Sea (BC) are markedly different from the southern Salish Sea (US). While overall herring biomass in the northern portion of the Strait of Georgia (BC) is at near-record high levels (DFO, 2015), the biomass distribution has shifted to the northwest (Therriault et al., 2009; Priekshot et al., 2013), and many of the lower Strait of Georgia spawning sites are no longer utilized (Hay et al., 2009). In addition, the age, or weight at age, structure of many herring stocks in the Salish Sea has changed (Therriault et al., 2009; Stick et al., 2014), generally toward smaller, younger individuals. An analysis of regional variation in demographic patterns of stocks occurring throughout BC waters showed that both prey and predator biomass were correlated with recruitment, growth, and survival for some, but not all, herring populations (Tanasichuk, 2017).

A geographically extensive assessment of herring population trends in the California Current Ecosystem (from California to BC) provided evidence that fluctuations were linked with the Pacific Decadal Oscillation in northern populations, and that increasing variability in southern populations was a harbinger of broad-scale climate change (Thompson et al., 2017). This analysis, however, focused on broad forcing factors rather than site-specific local dynamics, thus likely omitting key drivers of population variability. By expanding the scale of exploration across the international boundary to encompass the whole of the Salish Sea (i.e., the Strait of Georgia down to South Puget Sound), we can learn more about likely mechanisms behind declining trends and changes in the distribution of herring spawning grounds that have been documented on a localized basis. We can also more adequately address actions to curb stressors whose sources and causes may span international boundaries, or be linked with factors like intense urbanization that are highly site-specific.

Implementation Strategies (ISs) are the regional recovery action frameworks established by the U.S. Environmental Protection Agency (EPA) and the regional recovery agency, the Puget Sound Partnership, to guide EPA's National Estuary Program investments in Puget Sound recovery. ISs focus on identifying pathways towards recovery for negatively trending Puget Sound ecosystem Vital Sign indicators, one of which is Pacific herring spawning stock biomass, separated into three genetic lineages (Puget Sound Partnership Indicators Action Team, 2009). The first steps of an IS, which we partially address here, are to: 1) convene the recovery team responsible for developing and guiding the recovery plan; 2) conduct an in-depth discussion and exploration of the technical, social, and political landscape associated with recovery of the indicator; and 3) conduct a rigorous analysis of the research needs, data availability, and programmatic and management contexts that will inform the steps of a recovery plan.

Here, we jump-start the IS process, and elevate Pacific herring in the ranks of ecosystem indicators for which fully-fledged recovery plans may be developed in the next 1-2 years, by creating a cross-institutional, cross-border, and interdisciplinary effort to synthesize and evaluate the available knowledge pertinent to Salish Sea herring status, trends, and the potential stressors that limit recovery of populations. This exploration included a detailed review of existing data sets and an evaluation of stock-specific reasons for geographically explicit decreases in spawning biomass. Our aims were to: 1) consider the broad suite of socio-ecological benefits provided by herring, including to indigenous people in the Salish Sea; 2) identify shared stressors for suites of stocks/populations; 3) identify tractable research and management actions to minimize or eliminate these stressors in the immediate future and in the long term; and 4) develop decision support tools for modeling likely outcomes of potential conservation and management actions. Our major outcome is a Salish Sea-wide accounting of Pacific herring status that identifies key uncertainties, research, and monitoring needs, as well as pathways for conservation and, as

appropriate, recovery. For some Puget Sound stocks of herring in obvious decline this lays the framework for development of a formal “recovery plan,” while for the overall Salish Sea herring resource it represents a “conservation framework,” developed by a diverse group of stakeholders that may be used to actively and sustainably manage Pacific herring throughout the region.

III. Cultural and socioeconomic significance of Pacific herring in the Salish Sea

As a crucial node in marine ecosystems, the habitat and preferences of Pacific herring were thoroughly known by Indigenous communities for millennia throughout the coast. These prolific forage fish and their eggs were used as nutrient rich foods and when smoked were highly suitable for storage. The collective experience and observations of dozens of generations of human harvesters provides an important but underappreciated guidance for contemporary management. Of particular relevance are fish bones recovered from archaeological sites that occur throughout the coast. These archives of millennia of human harvest effort provide insight in the relative proportion of herring across space and time.

Notably, Pacific herring were observed to be the single most commonly harvested fish species across the coast and, in a 2014 study, particularly high abundances of herring in archaeological sites were found to be directly associated with historically known spawning areas. This indicates that sites that have high herring bone abundance likely indicate former spawning grounds that are often not currently monitored for spawn and may not be included in restoration plans.

Such proxy evidence from the last few millennia can provide an important additional guide for contemporary management and habitat protection as well as scope out candidate sites for restoration. Foreshore and nearshore areas in proximity to archaeologically identified spawning grounds provide an additional layer of evidence to support restoration and also to engage tribes in co-management initiatives.

Pacific herring have been utilized by the indigenous peoples of the Salish Sea region for millennia, including First Nations in BC and Native American Tribes in Washington (Stewart, 1977; Bargmann, 1998; Gustafson et al., 2006; Thornton, 2015). Not only have adult fish been collected by a variety of means for human consumption, but eggs are also gathered and eaten. Pacific herring differs from its Atlantic cousin primarily by spawning on intertidal and shallow subtidal vegetation rather than on deep gravel substrate (Drapeau, 1973). Once harvested, surplus fish can be smoked and/or dried for consumption during lean times, or for use as trade goods. Furthermore, the predilection of herring to spawn on nearshore vegetation was historically exploited by placing hemlock branches in the water, watching for eggs to be attached, and then towing the branches to areas to promote future spawning in a new location (Thornton, 2015). This thoughtful cultivation of a critical source of marine protein and lipids allowed indigenous people to effectively farm a reliable source of sustenance from year to year, providing a degree of food security for their family and communities.

Industrial era, commercial herring fisheries in greater Puget Sound (i.e., the US portion of the Salish Sea) have a long history characterized by periodic shifts in harvest methods and fishery products targeted. Extensive coverage of these fisheries is provided by Trumble (1983) and Williams (1959), and summarized in Washington State herring stock status reports (Stick & Lindquist, 2009; Stick et al., 2014). Briefly, commercial fisheries in the early 1900s harvested adult herring for export, but this market collapsed after World War I. From the 1920s-40s herring were landed predominantly using traps that intercepted migrating spawners, which were used domestically as bait for commercial halibut, crab, and shark fisheries. In the early 1950s harvest was re-routed to supply bait to growing recreational salmon fisheries, a practice that continues today. The next shift occurred in 1957 when regulations authorized reduction of

herring to oil and meal (termed the “general purpose” fishery), in addition to the continuation of landings for commercial crab bait. This was phased out by regulation in the early 1980s due to concerns about effects on local herring stock abundance, particularly herring that spawn at Cherry Point. Coincident with the general purpose fishery, a sac-roe fishery targeting spawning adults of the Cherry Point herring stock began in 1972 but was also eliminated by the mid-1980s due to conservation concerns. Landings in this treaty and non-treaty fishery topped 4,000 short tons in 1974 (Figure 1). [Note that US biomass and harvest estimates, unless otherwise noted, are presented in tons (a.k.a. US tons or short tons) or pounds (lbs.); 1 ton = 0.907185 metric tons (“tonnes”) = 907.185 kilograms = 2,000 pounds.] Based in part on a perceived reduction in the rate of population decline, in 1988 a non-tribal spawn-on-kelp fishery was developed and a tribal sac-roe fishery was reinvigorated on the Cherry Point stock. A subsequent precipitous decline in stock abundance began in 1995, resulting in a closure of these fisheries that continues to the present day.

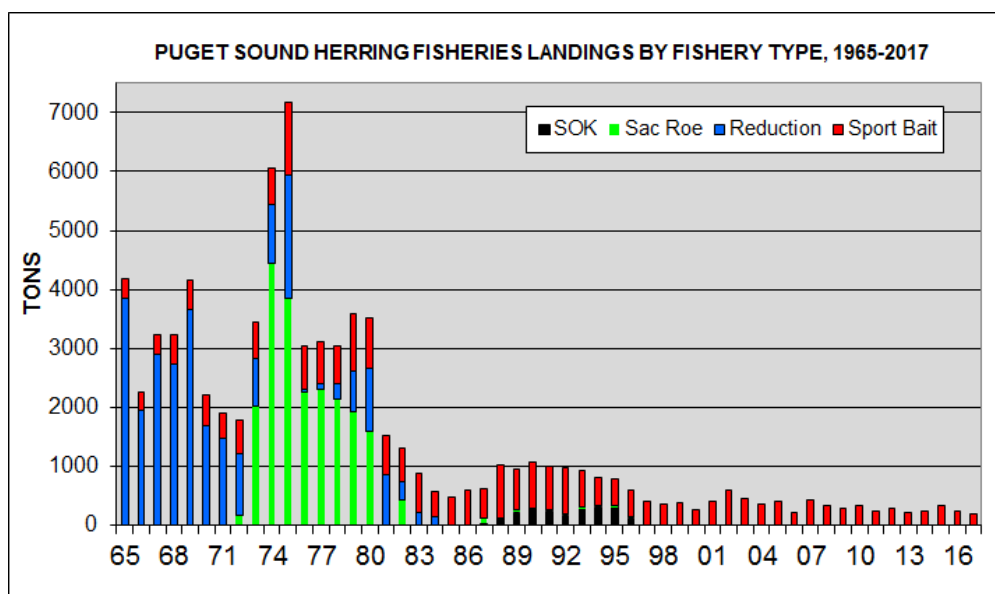


Figure 1. Commercial landings of Pacific herring in U.S. waters of the Salish Sea by all methods from 1965-2017.

The commercial Pacific herring fishery started in BC in the 19th century for the local food market, and quickly expanded into a dry salt fishery for export. In 1937, a reduction fishery was also established to produce fishmeal and fish oil (Hourston & Haegle, 1980). In the late 1940s, Pacific herring became the major fishery off Canada’s Pacific coast, and catches steadily increased to over 200,000 tonnes in the early 1960s (Beamish et al., 2004).

From the early 1930s to the late 1960s, herring were commercially harvested and processed into relatively low-value products such as fishmeal and oil. Commercial catches in BC increased dramatically in the early 1960s, but were unsustainable. By 1965, most of the older fish had been removed from the spawning population by a combination of overfishing and by a sequence of weak year-classes attributed to unfavorable environmental conditions and a low spawning biomass. As a result, the commercial fishery collapsed and was closed by the Canadian federal government in 1967 to rebuild the resource. During the closure from 1967 to 1971, limited fishing activity occurred at low levels (Hourston, 1980). At this time, there was a growing interest in harvesting roe herring for export to Japan, where herring stocks had been decimated. A small experimental roe harvest began in 1971 and expanded rapidly until 1983, when a fixed

harvest rate was introduced to regulate catch. A series of above average year-classes occurred in the early 1970s, rapidly rebuilding stocks and permitting the re-opening of all areas to commercial fishing.

There are currently four commercial fisheries operating in the northern SoG. They are: the Winter fishery - food and bait herring (FB) that operates November - February; Seine Roe (SN) that operates February - March; Gillnet Roe (GN) that operates February - March; and Special Use (SU) that uses multiple gear types and operates year round (although mainly in the fall/ winter period). First Nations FSC fisheries operate within traditional territories of individual Nations, fishing both whole herring (year round) and spawn-on-boughs (February - March).

IV. Stock Structure

The importance of stock structure has always been recognized by Native American tribes. In the southern Salish Sea, 21 site-specific, demographically independent spawning stocks are recognized (Stick et al., 2014; Siple & Francis, 2015) (Figure 2). Early studies in Puget Sound based on spawn timing and location, as well as vertebrae counts, concluded that individual spawning stocks were independent of each other and that there was little exchange among them (Chapman et al., 1941; Williams, 1959). On the other hand, extensive tagging efforts in British Columbia suggested some homing, but also considerable straying rates (4%-25%) even on regional scales (Hay et al., 2001). Similar to Atlantic herring, such straying rates would be sufficient to prevent accumulation of neutral genetic differentiation, but may still allow local adaptation. Indeed, initial molecular studies failed to detect genetic differentiation among Puget Sound stocks (Grant & Utter, 1984; Schweigert & Withler, 1990), and subsequent microsatellite studies revealed genetic differentiation only of populations that spawned late or in isolated inlets (Beacham et al., 2008). Similarly, microsatellite studies revealed differentiation of the only known spring spawning population at Cherry Point (a late-spawning Elliott Bay stock was detected in 2012) and of an inlet population in the far south of Puget Sound, at Squaxin Pass (Small et al., 2005; Mitchell, 2006). No differentiation was found among the other stocks, which are therefore monitored independently but managed as an aggregate by the WDFW (Stick et al., 2014).

Similar to Atlantic herring, there is considerable circumstantial evidence for local adaptation of stocks in Pacific herring. Spawn timing of each stock is remarkably consistent from year to year, but ranges among stocks within the central Puget Sound region from late January to early April (Stick et al., 2014) (Figure 3). Spawning habitat also varies among stocks, as herring typically spawn in sheltered bays (Haegele & Schweigert, 1985), but Cherry Point herring spawn along a very exposed coast in close proximity to deep water (Gustafson et al., 2006). Tagging (O'Toole et al., 2000; Stick et al., 2014), otolith (Gao et al., 2001), pollutant (West et al., 2008), and parasite (Hershberger et al., 2002) studies suggest differences in migratory behavior among stocks. Cherry Point herring embryos show much higher temperature tolerance compared to other Puget Sound stocks (Marshall, 2011), which may be related to their late spawn time and may provide an important advantage under conditions of rapid environmental change.

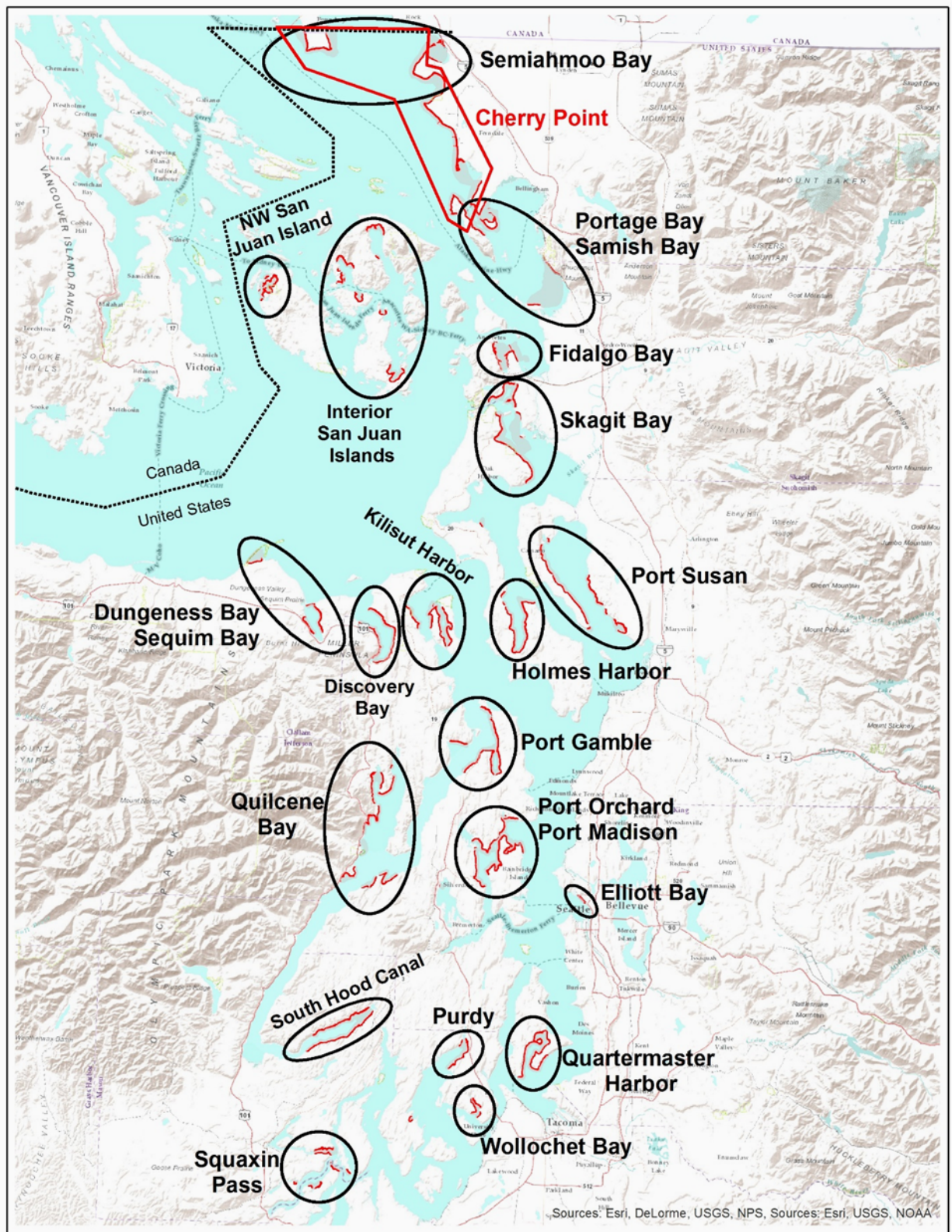


Figure 2. Known spawning stocks of Pacific herring in U.S. waters of the Salish Sea as of 2018.

Though the Semiahmoo stock and the Cherry Point stock overlap in geography, their spawn timing is sufficiently distinct that they are genetically differentiated.

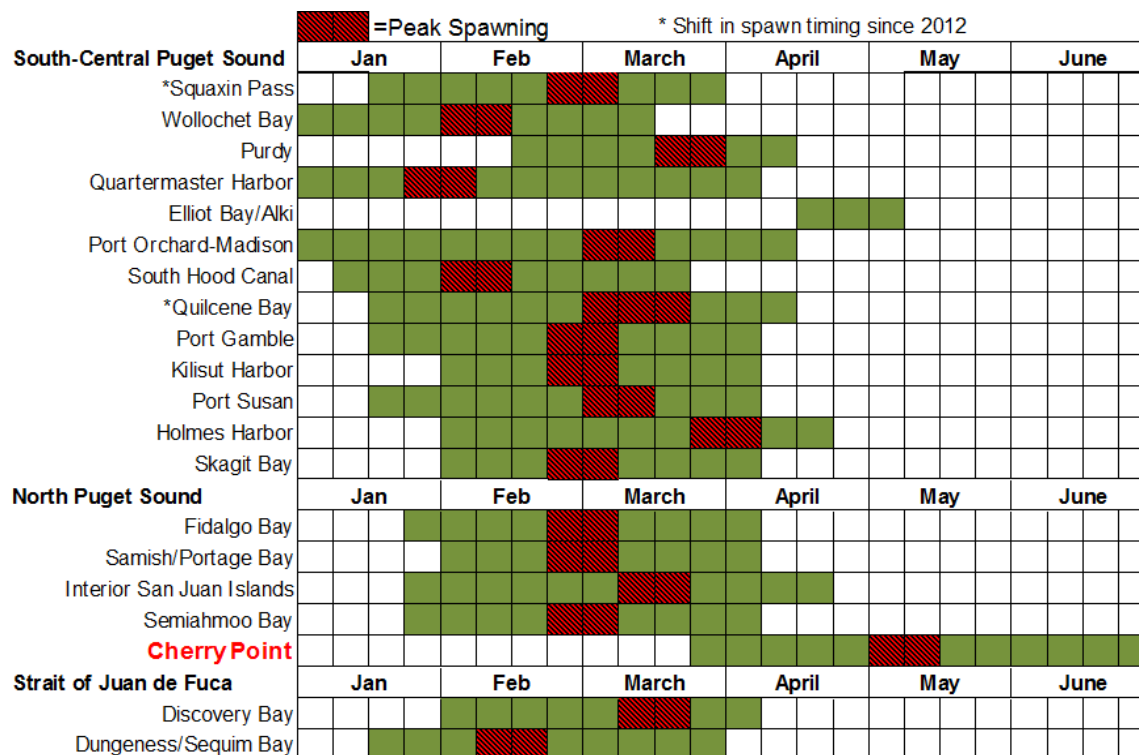


Figure 3. Documented peak spawn timing and ranges for Pacific Herring stocks in the Southern Salish Sea.

Additional collection of genetic samples occurred during WDFW's 2016-17 Mid-water Acoustic Trawl study, which was designed to sample the pelagic fish community at eighteen sites throughout the Southern Salish Sea, and investigations are currently underway to determine whether stock-specific signatures can be identified using restriction site associated DNA markers. This study is being conducted in collaboration with Lorenz Hauser and Eleni Petrou at the University of Washington. Should genetic differentiation of additional stocks become possible as a result of this research the WDFW is prepared to respond appropriately to ensure persistence of unique stocks, in accordance with its Forage Fish Management Plan (Bargmann, 1998).

The stock concept for BC herring has changed over time in response to the need for fisheries management. In recent years, migratory stocks have been the target for the roe and food and bait fisheries although some resident stocks, usually found within inlets, are thought to also support bait fisheries. BC herring stocks are managed as five major and two minor stock areas (Figure 4), based on geography and biomass. Stock boundaries encompass the habitat range of relatively discrete migratory herring stocks, and are based on historical records of commercial catch and spawning locations. Each stock assessment region (SAR) is comprised of herring Statistical Areas that are further broken down into herring Sections and then Locations. The Strait of Georgia comprises one of the major SARs.

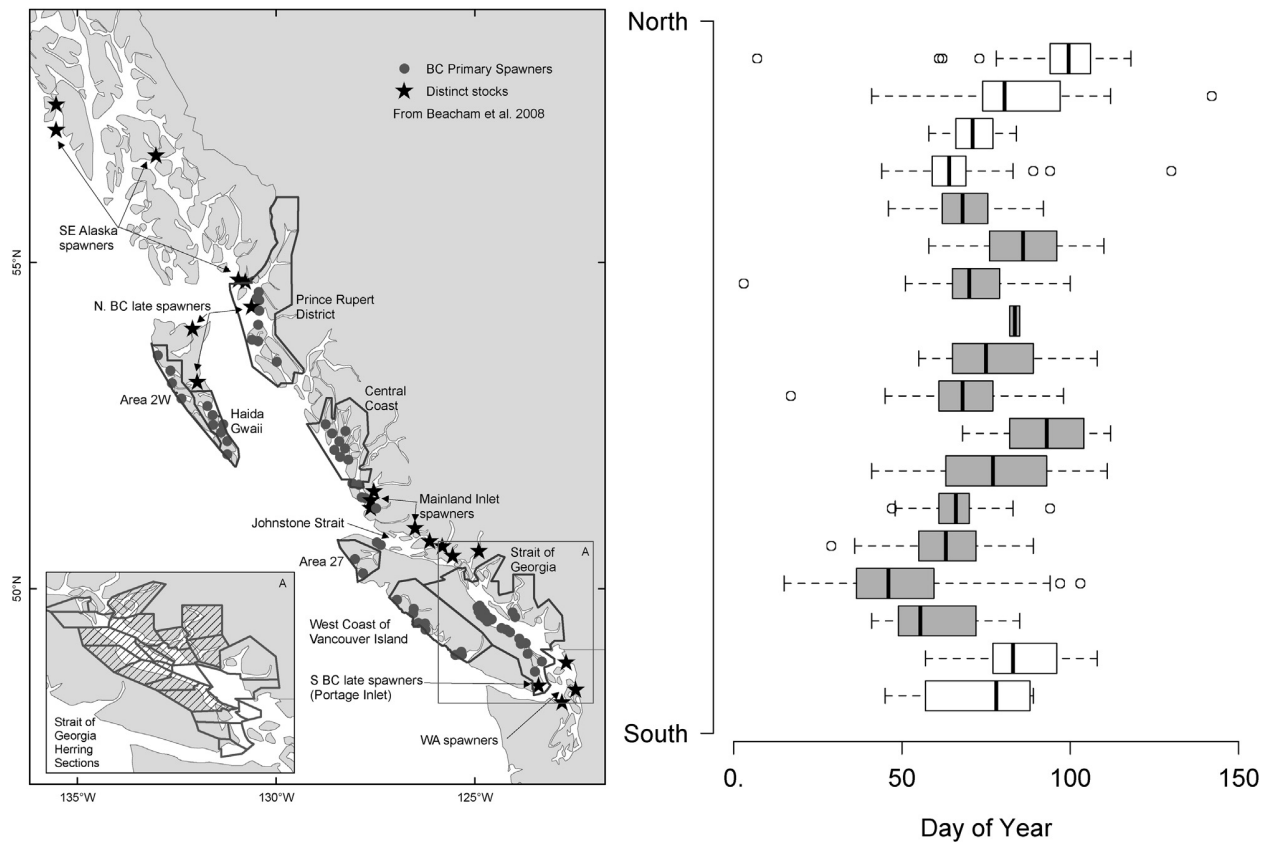


Figure 4. British Columbia Pacific herring management areas (outlines) and spawning locations.

Shown are primary spawners (grey symbols) and other genetically distinct stocks (stars), including some Washington State-managed stocks. Shaded boxplots on right correspond to grey symbols in inset A of the left panel. Boxplots in right panel summarize the median, 25th, and 75th percentiles of spawning dates, the whiskers correspond to the 5th and 95th percentiles, and the open circles are outliers. *From Benson et al., 2015., Figure 1.*

Pacific herring in the Northern Salish Sea (SoG) SAR are assessed and managed by Fisheries and Oceans Canada as a single migratory stock. These herring spawn primarily in March, with adult herring migrating to the west coast of Vancouver Island shortly after spawning to summer/fall feeding areas. The limited genetic differentiation observed among BC herring is consistent with straying rates resulting in homogeneous allele frequencies over broad areas. However, the straying rate may be insufficient to offset the risks posed by overexploitation in specific regions (Beacham et al., 2008). Herring from the east side of the Strait of Georgia (mainland inlet stocks) are thought to be predominantly “resident,” while populations from more seaward locations along the central coast and Johnstone Strait are also thought to migrate to offshore summer feeding grounds (west coast Vancouver Island and possibly other areas) (Beacham et al., 2008).

The analysis of stable isotopes (delta Carbon (ΔC) and delta Nitrogen (ΔN)) in herring provides a coarse scale of onshore vs. offshore distribution (an analogy would be the longitude of the areas where these fish are feeding when not on the spawning grounds) over the previous six months (personal

communications, Jim West and Sandie O'Neill, T-BIOS group, WDFW; Gina Ylitalo, NOAA). The Port Orchard/Pt. Madison and Squaxin Pass populations have enriched isotopes indicative of residency in Puget Sound. Other herring populations, except Quilcene Bay (Hood Canal), share a similar isotope pattern that is indicative of a more coastal marine distribution, suggesting these fish migrate out of Puget Sound after spawning. The Quilcene Bay herring carbon signature is different, falling between the coastal and inner Puget Sound signatures, so at present it is unclear where they reside and feed when not spawning; they could remain in Hood Canal year-round. The stable isotope signature also indicates that the Cherry Point and Semiahmoo Bay stocks cluster more tightly with herring from other populations from the west coast of North America (e.g. Central Coast of B.C., West coast of Vancouver Island), whereas the inner Puget Sound herring stocks comprise a separate cluster. This suggests that the Semiahmoo Bay stock is migrating offshore to coastal marine waters in summer but at present it is unclear where the Cherry Point fish are feeding when not on the spawning grounds.

The analysis of persistent organic pollutants (POPs) from herring tissue is another tool that provides a refined description of marine distribution and feeding patterns. Along the west coast of North America, DDTs are more elevated in prey from southern California, PCBs and PBDEs are more elevated in prey from Puget Sound, and HCBs more elevated in prey from the north coast (West Coast Vancouver Island and beyond). The POP "fingerprint" is thus analogous to latitude, providing a measure of the north to south marine distribution of herring feeding grounds. Collectively, both the stable isotopes (longitude) and the contaminant fingerprints (latitude) provide us with an understanding of where herring populations feed along the west coast of North America (http://www.psp.wa.gov/vitalsigns/toxics_in_fish.php).

In their study of the geographic distribution and magnitude of three persistent organic pollutants (POPs) in herring, West et al. (2008) suggest strong environmental segregation of herring samples from inner Puget Sound (Squaxin Pass, Quatermaster Harbor, Port Orchard) compared to the Strait of Georgia (Cherry Point, Semiahmoo Bay, Hornby/Denman Island, B.C.). They concluded the observed segregation likely resulted from differential exposure to contaminants related to the locations where populations (two and three year old herring) reside and feed. All three "Strait of Georgia" samples were strongly isolated from the "inner Puget Sound" samples based on multidimensional scaling (MDS) mapping of POPs.

More recent work has also shown that herring from Quilcene Bay in Hood Canal have a unique toxics profile and confirms that the herring from Cherry Point and Semiahmoo have a very different toxic fingerprint than those from Port Orchard and Squaxin Pass, indicating that these subpopulations feed in different marine locations. However, the POP data also suggest that the Cherry Point stock's contaminant profile is slightly different than that of Semiahmoo Bay, so it is unclear where they reside outside of spawning season; Cherry Point herring may remain in the SoG year-round. On a broader scale, these data show that Puget Sound herring populations (collectively) have toxic fingerprints that are different than other herring populations sampled along the west coast of North America, indicative of the segregation of these populations into a discrete marine distribution and feeding area (personal communications, Jim West and Sandie O'Neill, T-BIOS group, WDFW).

V. Fisheries Management

A. British Columbia/Strait of Georgia

Pacific herring in the Northern Salish Sea (SoG) are assessed and managed by Fisheries and Oceans Canada as a single migratory stock. These herring spawn primarily in March, with adult herring migrating to the west coast of Vancouver Island shortly after spawning, to summer/ fall feeding areas. SoG herring are managed using a harvest control rule that outputs intended annual harvest rate based on estimated

abundance from a stock assessment model, and is reduced to zero as the abundance drops to 25% of estimated unfished biomass. The harvest control rule combines constant escapement and constant harvest rate policies, allowing harvest to be reduced in areas (Figure 5) where the intended 20% annual harvest rate would bring the forecast pre-fishery mature spawning biomass (i.e., the 'escapement') to below 25% of unfished biomass (Cleary et al., 2010; Cleary & Schweigert, 2012).

In addition, while a recent assessment concluded that SoG herring stocks did not show signs of a persistent 'low-production, low-biomass' (LP-LB) state, a biological limit reference point of 30% of unfished biomass was recommended for the SoG stock, to align with best practice recommendations, and because SoG stocks are geographically adjacent to stocks recently identified as being in LP-LB states (Kronlund et al. 2017).

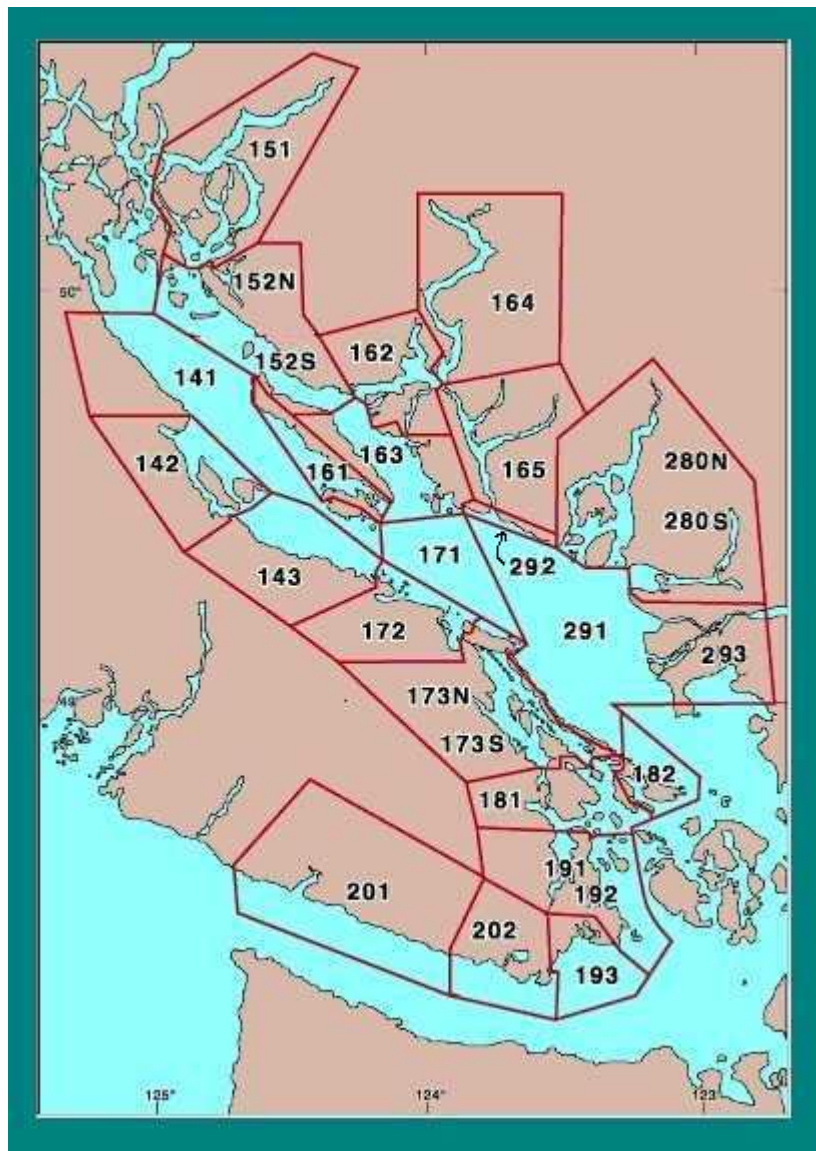


Figure 5. Statistical areas of the Strait of Georgia stock assessment area (SAR).

Source: http://www.pac.dfo-mpo.gc.ca/science/species-especes/pelagic-pelagique/herring-hareng/herspawn/sog_map-eng.html. Accessed July 29, 2018.

B. Washington State

Though widespread and substantial herring fisheries occurred historically in the U.S. waters of the Salish Sea for decades, as noted above, the only commercial fishery currently operating is the “sport bait” fishery, which includes on average six fishermen annually. The conservative fishing principles detailed in the WDFW’s Forage Fish Management Plan (Bargmann, 1998) dictate regulation of this fishery and the current annual maximum harvest guideline is set at 10% of the total annual estimated spawning biomass for stocks in southern and central Puget Sound (i.e., all but the Cherry Point and Squaxin Pass stocks). Management efforts in Washington focus on maintaining viable populations at each documented local spawning ground through time, supported by annual monitoring. By policy, the WDFW requires a minimum estimated spawning biomass of 3,200 short tons for the Cherry Point stock before harvest may be considered, and abundance has not been above this level since 1995 (Stick et al., 2014; WDFW unpublished data). The recent estimate of only 372 tons in 2017, in fact, suggests a nearly 97% decline in the spawning biomass of this stock relative to its documented peak in 1973 (Sandell et al, report in progress, WDFW). Annual landings from 2003-2015 generally fell below 6% of the total annual estimated spawning biomass for stocks in southern and central Puget Sound (Figure 6) (Stick et al., 2014). Though current harvest levels of herring from the sport bait fishery are a small fraction of what was harvested in the 1960s and 70s, this fishery remains culturally important because it represents one of only a few non-salmon commercial fisheries in Puget Sound, and provides local bait for recreational salmon and groundfish fisheries in the region.

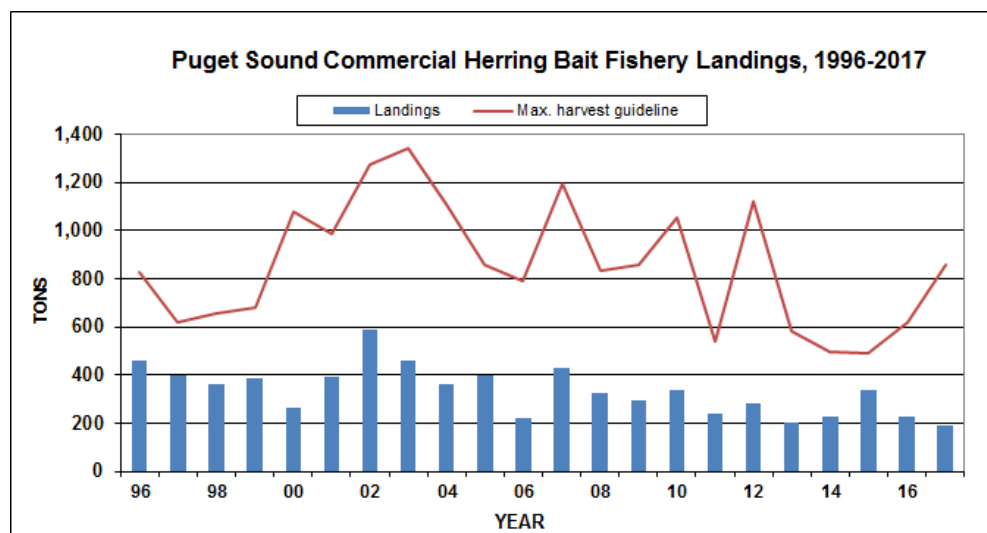


Figure 6. Maximum harvest guideline and actual landings of Pacific herring in the “sport bait” fishery from 1996-2017.

The harvest guideline is calculated as 10% of the aggregate estimated spawning biomass of all stock in Puget Sound, except the Cherry Point and Squaxin Pass stocks.

VI. Status and Trends

A. Southern Salish Sea distribution and abundance summary

The importance of herring and forage fish has long been recognized in Washington State and as early as 1915, several herring preserves were created, closing them to fishing during the spawning season to help restore abundance (Bargmann, 1998). As consistent differences in spawn timing and distribution became better recognized, stock-specific monitoring began in an effort to avoid localized depletion. Since 1973, after the “Baitfish” (now Forage Fish) Unit was organized by the WDFW, attempts have been made annually to monitor the spawning biomass of the Cherry Point stock, and eventually all other stocks. Initially these estimates were based on hydroacoustic-trawl evaluations of prespawning adults, combined with back extrapolation of spawning biomass from egg deposition surveys (Millikan & Penttila, 1972). Between 1976 and 1996, spawning biomass for the 10-12 largest Puget Sound stocks was estimated annually, with the remaining smaller stocks surveyed on a rotational basis. Beginning in 1996, annual estimates of all known herring stocks in Puget Sound have been attempted to track abundance of this important component of the food web. As noted above, in Washington stocks are defined as those fish that utilize specific and discrete spawning grounds during a given temporal window, and that typically vary consistently in growth and size distribution (Trumble, 1983). In 2009 hydroacoustic surveys were discontinued, and the primary assessment method is now egg deposition surveys.

An aggregate approach to evaluating herring stock status has been used by the Puget Sound Partnership, in coordination with the WDFW, to develop one of their Dashboard Indicators of Puget Sound health (Puget Sound Partnership Vital Signs). In this context, “Puget Sound” includes all U.S. waters of the Salish Sea. The resultant three groups, based on genetic distinction, are: Cherry Point; Squaxin Pass; and the Other Stocks Complex (all other stocks combined). Abundance trends for these groupings are described below.

The estimated total spawning biomass for herring in the Southern Salish Sea (SSS) has declined since 1973, with considerable annual variation (Figures 7-9). The majority of this decline has been in the late-spawning Cherry Point stock (southern Strait of Georgia, Figure 2), which made up over half of all spawning herring in the SSS when surveys began. At Cherry Point, spawning activity has contracted and shifted northward in recent years, with most observed spawn deposition located near Birch Point. The other genetically distinct stock, Squaxin Pass (at the southern terminus of the Salish Sea, Figure 2), has held relatively constant (with a slight increase in the early 2000s) over the same period, while the remaining, genetically homogenous stock complex has contributed an average of 11,967 short tons over the same period (estimates for any given stock in a year in which no surveys occurred were estimated from the average) (Figure 6).

In Hood Canal, the Quilcene Bay herring stock was considered to be one of the state’s largest through the 1950s (Stick et al., 2014), though this was quantified only anecdotally. Hood Canal stocks were considered to be relatively small stocks when quantitative assessments began in the 1970s, until the late 1990s when the Quilcene Bay stock exhibited a dramatic increase in abundance. *Since 2000, the three stocks in Hood Canal (primarily Quilcene Bay) have contributed an average of nearly a third of all herring spawn in the SSS, and since 2016, over half.* This has occurred despite a number of anoxic events in southern Hood Canal, although these generally occur later in the summer, after herring larvae have become mobile juveniles that may avoid anoxic areas. If Hood Canal stocks are excluded, the herring biomass in the Central and South Sound region has decreased dramatically (Figure 7) and is now considered to be depressed (only 29% of the 25-year mean). Three of these stocks have had little or no spawn since 2015 (Sandell et al., 2018, report in progress, WDFW) and the WDFW is currently considering management actions to address this lack of spawning (Figure 9). Both resource managers and environmental advocacy

groups have noted that this portion of the SSS is heavily populated and, as a result, impacted by diverse stressors that may be driving this apparent stock collapse.

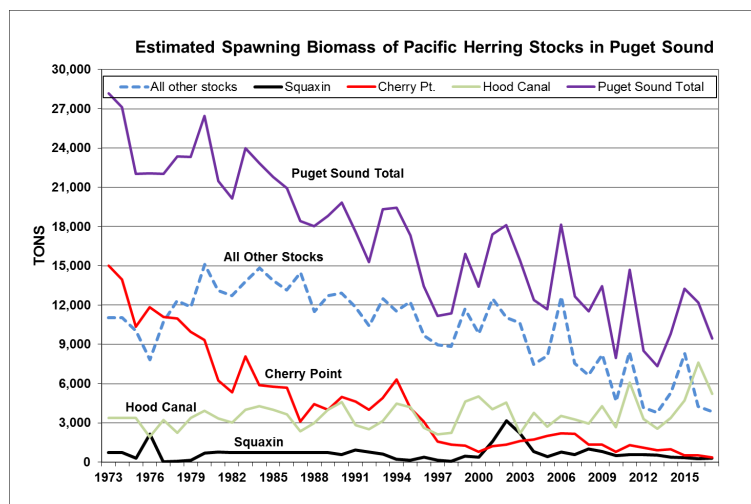


Figure 7. Estimated herring stock biomass estimates for the southern Salish Sea.

Note that the Hood Canal stock is not genetically distinct from the “Other Stock Complex” (all other stocks) but is highlighted here to show recent increases in abundance.

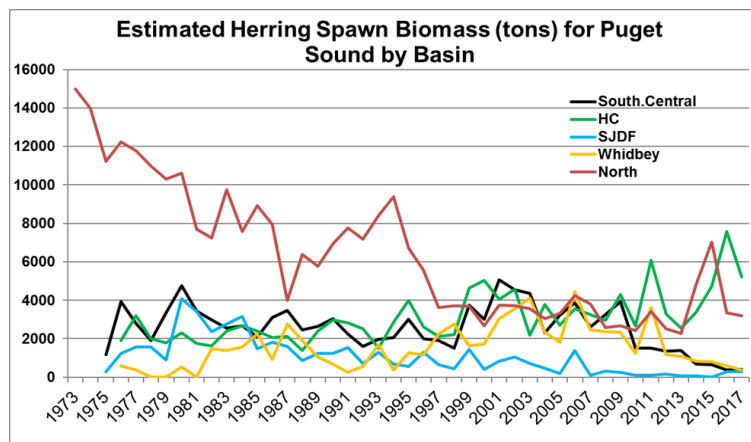


Figure 8. Estimated herring biomass estimates for the southern Salish Sea, by sub-basin, 1973-2017.

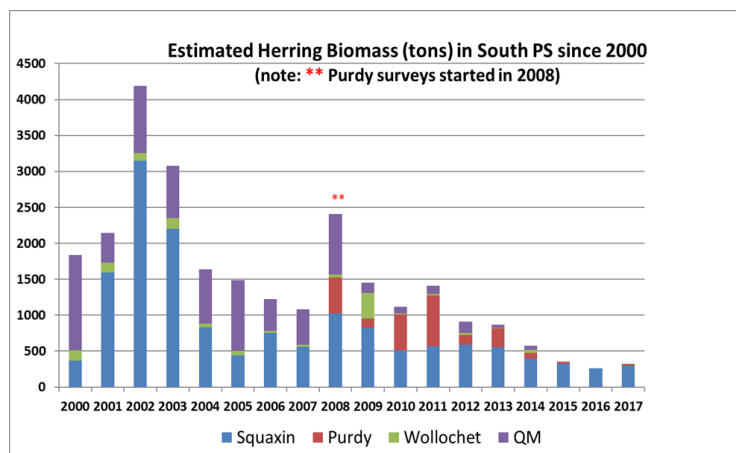


Figure 9. Estimated herring spawn biomass for South Puget Sound stocks, 2000-2017.

The eastern Strait of Juan de Fuca region's stock status has been primarily classified as critical since 1994, with the exception of 2006 when a significant one-year increase in the estimated spawning biomass of the Discovery Bay stock was documented. The condition and spawning biomass of the Discovery Bay stock has been considered an enigma since assessment surveys were started there in 1976. Estimated spawning biomass was over 3,000 short tons in the 1980s, followed by an unexplained steady decrease to little or no documented spawning activity since 2000, other than the event in 2006 (Stick et al., 2014). No recent direct fishery harvest, relatively undisturbed spawning grounds, and good water quality add to the mystery of this stock's recent spawning biomass history. However, reports by Chapman et al. (1941) and Williams (1959) indicate similar trends in abundance for Discovery Bay herring between the early 1900s and the 1950s; ranging from high levels of abundance early, followed by a decrease in the 1930s, and a return to "relatively high" levels by the 1950s.

B. Northern Salish Sea distribution and abundance summary

In British Columbia, the overall biomass of Northern Salish Sea herring is orders of magnitude larger than stocks in Washington state (Fig. 10). For the past two decades herring spawning activity (egg deposition) in the Strait of Georgia has been largely concentrated from Nanaimo to Comox (Areas 14 and 17N - see Figure 5). For example, in 2017, 81% of herring spawn deposition occurred in Areas 14 and 17N, similar to the recent 10-year average of 83%. This northward concentration of herring spawning over the past two decades also coincides with a near absence of spawn deposition along the eastern side of the Strait of Georgia (Sunshine Coast) and in spawning areas south of Nanaimo (the south eastern portion of Vancouver Island). As noted for the SSS, these recent declines in local abundance of herring spawn coincide geographically with high densities of human population, and associated stressors, which has been correlated to reductions in forage fish (Greene et al., 2015).

Strait of Georgia herring spawn is surveyed annually using SCUBA surveys. Additionally, biological data on herring length, weight, and age-structure is collected from commercial fisheries and through a biological sampling program targeting pre-spawning aggregations of herring. DFO produces annual estimates of spawning biomass using a statistical catch-age model. The 2017 assessment of the Strait of Georgia herring stock estimates an increasing trend in spawning biomass since 2010 (Figure 10, DFO 2018). The median estimate of spawning biomass in 2017 is 114,626 tonnes, equal to 81% of the unfished equilibrium spawning biomass. Thus, the northward concentration of herring spawning also coincides with near historic high biomass levels in recent 2-3 years.

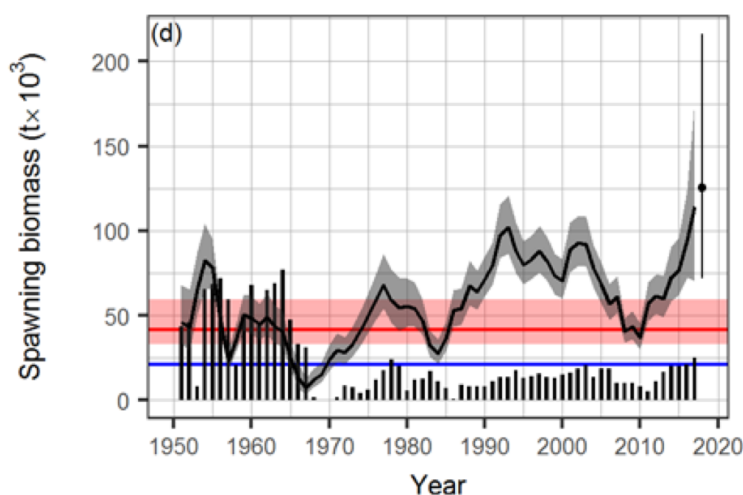


Figure 10. Strait of Georgia herring spawning biomass.

Posterior estimate of spawning biomass (SB_t) for each year t in thousands of metric tonnes ($t \times 10^3$). Line and shaded area indicate median and 90% credible interval, respectively. Vertical lines indicate commercial catch (metric tonnes).

VII. Factors affecting herring distribution and abundance

A. Anthropogenic stressors

1. Exploitation

There are currently four commercial fisheries operating in the northern SoG. Stock assessments by Fisheries and Oceans Canada show an increasing trend in spawning stock biomass since 2010 (Figure 10), suggesting that herring stocks in SoG have not declined in response to fishing pressure as they have in other BC management areas. However, changes in the distribution of SoG herring spawn, i.e., disappearance of spawn from historic spawning sites, are somewhat consistent with predicted impacts of exploitation on herring with a socially-learned migration behavior (MacCall et al., 2018). Those model results suggest taking a somewhat longer view of time in stock assessments, so as to incorporate years of low and high productivity.

As noted above, the only commercial herring fishery currently operating in U.S. waters of the Salish Sea is the “sport bait” fishery. Fishing occurs predominantly in Admiralty Inlet and the vicinity of the Tacoma Narrows, from May through October, and juvenile fish aged 1+ to 2+ that originate from an aggregate of Salish Sea stocks are the target. Average sport bait catch over the last ten years has been <6% of total average catch for all Puget Sound herring fisheries during the peak of exploitation in the 1970s (Stick et al. 2014), making this a minor fishery relatively to historic levels. Since 2016, however, several herring stocks in the southern portion of Puget Sound have exhibited exceptionally low, or even no, spawning activity (Sandell et al., 2018, report in progress, WDFW) and the WDFW has been evaluating management options to address concerns about this trend without unduly closing fisheries that target an aggregate of Salish Sea stocks. Fisheries in the southern portion of the region (i.e., around the Tacoma Narrows) have not seen significant declines in catch per unit effort and fishermen report having no issue finding or capturing fish. Despite localized lack of spawning for stocks in this vicinity, then, it appears that production of stocks elsewhere in the SSS is sufficient to generate robust schools of juveniles throughout Puget Sound. Regulation using a conservative harvest limit that is rarely approached, and evidence that juvenile production from strong stocks can offset localized spawner depletion in regional fisheries, suggest that commercial exploitation is likely a minor factor affecting overall herring population status in the SSS.

While some recreational fishers prefer to jig their own herring for immediate use as bait, the extent of this harvest is poorly documented by existing creel survey methods and valid estimates are unavailable. Qualitative indicators, such as frequency of reporting jigging activity when asked during creel surveys, suggest the practice is common in the summer and fall during periods of high salmon and bottom fish fishing intensity but rare during late winter and early spring when most herring stocks are spawning (WDFW unpublished data). As such, recreational jigging for personal use as bait is likely a minor threat to the persistence of herring stocks in the SSS, though this represents a data gap in need of further study.

2. Water quality

Temperature

The SoG has seen a gradual warming of the entire water column (400 m) from 1970-2005, with “vertically averaged temperatures in the central Strait of Georgia...increasing at a rate of $0.24 \pm 0.01^{\circ}\text{C}/\text{year}$. This rate is comparable to the warming observed offshore near the surface, but exceeds, by a factor of at least two, the rate of warming measured offshore below 100 m” (Masson & Cummins, 2007). Water temperatures are also rising in Puget Sound; temperature increases ranged

from +0.8 to +1.6 °F from 1950 to 2009 for stations located at Admiralty Inlet, Point Jefferson, and in Hood Canal (Bassin et al., 2011).

Pacific herring are exposed to diverse water conditions throughout their lives: nearshore habitats for spawning and rearing, and offshore pelagic habitats for growth and maturation. As such, they must be physiologically resilient to fairly broad variations in temperature, salinity, and other physicochemical parameters. Though juvenile and adult herring can typically thermoregulate behaviorally by selecting locations and depths that meet their preferred temperature range, herring eggs are typically affixed to benthic vegetation. Temperature is a critical factor in determining the duration of incubation for many marine fish species, including Pacific herring (Alderdice & Velsen, 1971; Palsson, 1984, Shelton et al., 2014), and surface water temperatures in the Salish Sea range from 7-16°C during the winter and late spring. When water temperature rises above normal ranges, such as during periods of low tide and intense insolation, it can lead to denaturation of proteins in the developing eggs, resulting in mortality. Increased temperature may also accelerate desiccation rate and increase mortality, as has been demonstrated for Surf Smelt *Hypomesus pretiosus* (Rice, 2006), though herring eggs are generally deposited in subtidal location and only exposed to the air during a small temporal window in the tidal cycle. As global climate change results in increased surface water temperatures and broader variation in tidal ranges, temperature-related stress on herring eggs in the Salish Sea may increase and spawn timing may also be affected.

Salinity

Eggs attached to vegetation in the shallow subtidal or intertidal may be bathed in salt water much of the day, but exposed to freshwater from upland sources twice daily, during periods of low tide. Such exposure may also occur during periods of abnormally high flow from rivers with mouths that enter salt water in proximity to herring spawning grounds, or whose waters are dispersed to spawning grounds by wind and/or currents. Monitoring in British Columbia has shown that rearing salinities measured at various point during incubation can vary from 4.5–42‰, though 12–17‰ is optimal for hatching of viable larvae (Alderdice & Hourston, 1985). Herring have long evolved to handle such fluctuations, however, and viable larvae will hatch despite marked deviation from optimality, albeit at reduced levels of success. Herring spawn timing may also be associated salinity; Puget Sound herring tend to spawn later in years when salinity levels are lower (TB Francis, pers. comm.).

Dissolved Oxygen

Dissolved oxygen (DO) levels have been declining in Puget Sound since 2000, in both surface and deep waters (Mohamedali et al., 2011). Dissolved oxygen concentrations are also declining in the SoG: May-June oxygen concentrations at depth have declined between 1971-2009 by –13% to –29%, likely owing to coastal upwelling of low-oxygen waters (Johannessen et al., 2014). Herring eggs require oxygenated water for survival. Low concentrations of dissolved oxygen, though a substantial threat to benthic-demersal eggs in deep water, may be of less concern for herring eggs in shallow water due to wave mixing. Nevertheless, increasing nutrient enrichment (see below) and reduced oxygen may trigger food web responses, particularly in primary producers, that may negatively affect herring at various life stages, owing to their dependence on planktonic food resources.

Nutrient enrichment

Puget Sound nitrate peaked at most stations in 2008 and has since declined. However, there has been an increase in annual nitrate anomalies relative to ocean-source waters since 2017 (Figure 11).

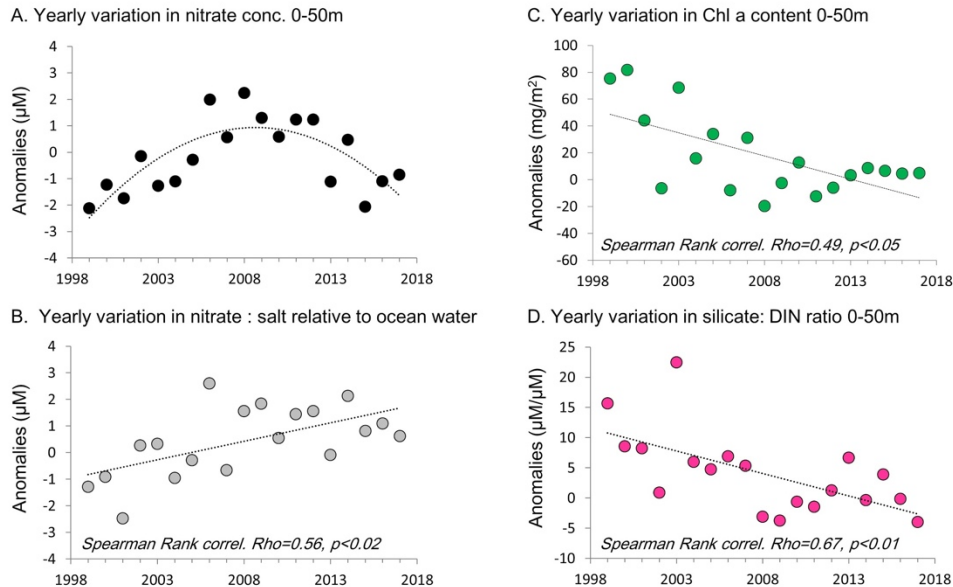


Figure 11. Puget Sound water quality trends (from C. Krembs, Washington Department of Ecology).

There has been a declining trend in Chlorophyll (Chl-a), a proxy for phytoplankton biomass, which is significantly correlated with non-oceanic nitrate concentrations, suggesting plankton community-nutrient links. The silicate to dissolved inorganic nitrogen (DIN) ratio is a recognized eutrophication indicator (Turner, 2002) and has consistently declined over the last 19 years.

The potential consequences of these water quality trends for herring are via food web interactions. Shifts in the composition of the phytoplankton community away from a dominance by diatoms towards dinoflagellates have been noted. This could result in a change in timing or magnitude of the spring phytoplankton bloom and associated zooplankton increases. Because herring hatch is somewhat fixed in time - varying only up to 3 weeks over 30 years, at most (Figures 3, 4), with some peak hatch times unchanged over that same time period - herring larvae are timed to the availability of appropriately-sized food. Changes in the community composition of plankton in response to water quality shifts could have consequences for plankton-feeding life stages of herring. We lack data to evaluate whether observed changes in herring are associated with shifts in the plankton, and consider this an important data gap. However, previous studies have found links between herring abundance trends and food supply, especially as mediated by oceanic conditions such as temperature (Schweigert et al. 2010), suggesting this is a dynamics worth evaluating further.

3. Toxics

Contaminant levels in Puget Sound herring could contribute to natural mortality, either directly or indirectly, via non-lethal effects of contaminants on herring development. The primary contaminant guilds evaluated for herring are polychlorinated biphenyls (PCBs), polybrominated diphenylethers (PBDEs), and polycyclic aromatic hydrocarbons (PAHs). Herring sampled from lower/south Puget Sound (Squaxin Pass, Quartermaster Harbor, and Port Orchard) were 3 to 9 times more contaminated with PCBs, and 1.5 to 2.5 times more contaminated with dichloro-diphenyl-trichloroethanes (DDTs), than those from the Strait of Georgia (Semiahmoo Bay, Cherry Point, and Denman/Hornby Island, B.C.) (West et al., 2008; Figure 12).

Different contaminant levels may result from higher regional sources of POPs, a much smaller drainage area, Puget Sound's relative isolation from cleaner oceanic waters, and environmental segregation between "Puget Sound" and "Strait of Georgia."

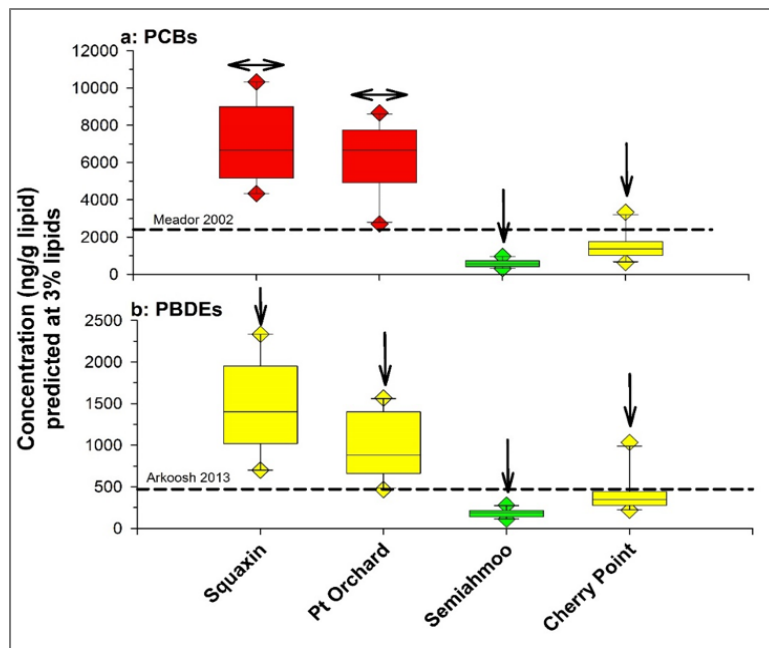


Figure 12. Summary of status and trends for PCBs and PBDEs in Pacific herring.

Box plots represent median tissue concentrations with interquartile (box ends) and 5th and 95th percentiles (diamonds). Red indicates more than 5% of current samples were above the Puget Sound Partnership recovery threshold and there is no declining trend. Yellow indicates more than 5% of most current samples were above the recovery threshold but there is a declining trend. Green indicates at least 95% of most current samples were below the recovery threshold (i.e., the upper diamond, or 95th percentile is below the dashed line) and there is no increasing trend (recovery goal met). Arrows above box plots indicate trends. Horizontal dashed lines indicate the fish health critical tissue level. From the Puget Sound National Estuary Program Toxics in Fish Implementation Strategy Starter Package, Figure 2-1.

The high concentration of PCBs and lack of their decline in herring from the central and southern basin highlight the persistent nature of these chemicals and possibly a failure to control PCBs still entering Puget Sound waters (see Ecology, 2011). These results, as well as data related to contaminants in other guilds, indicate the contamination of the Puget Sound pelagic food web (West et al., 2011a, b; O'Neill et al., 2009; Cullon et al., 2009; Ross et al., 2013).

PAHs have not been fully evaluated, but preliminary analyses using new analytical methods suggest PAHs are high in the two urban populations (Port Orchard and Squaxin), are lower in Semiahmoo, and are below a clean reference condition in Cherry Point herring (Figure 13). Herring exposed to stormwater, which contains a mixture of chemical constituents, including PAHs, in the laboratory are negatively affected: shorter larval body length, smaller eyes, lower yolk sack absorption, and cardiac defects (Harding et al., 2018).

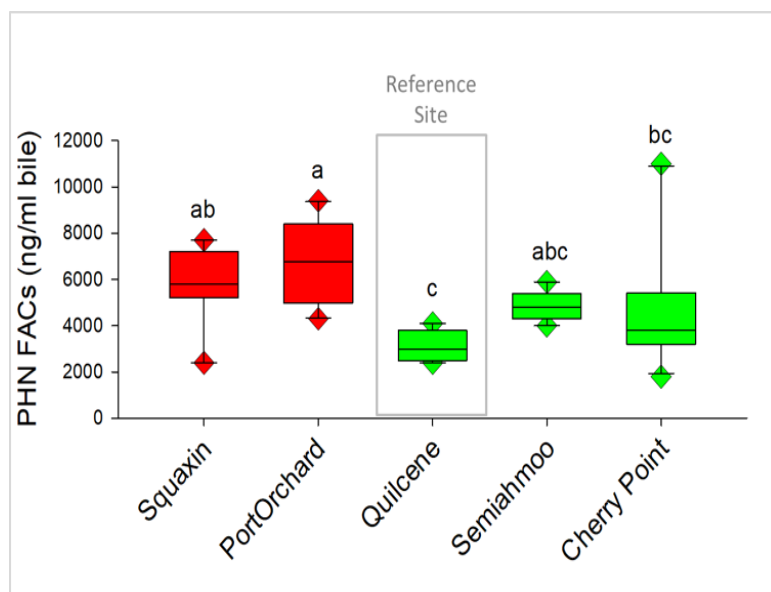


Figure 13. Comparison of phenanthrene (PHN) biliary fluorescing aromatic compounds (FACs) PAHs in five Salish Sea herring populations.

Quilcene (Hood Canal) is the clean reference site. Sites with PHN-FAC concentrations significantly greater than the reference site are considered to exceed the threshold and are shown in red. Sites that are not significantly different than the reference site are shown in green. Data from T-BIOS, WDFW.

Although CP herring have among the lowest levels of contaminants, they are also among the lowest in lipid levels at spawning (due to overwinter fasting). This may mean that they re-metabolize lipophilic pollutants around spawning, in effect getting a second dose (J. West, pers. comm.).

4. Vessel Noise

Current noise levels in the Salish Sea are at levels that impair communication for marine mammals (Williams et al., 2013), though impacts on fish including herring are less well known. However, proposed increases in vessel traffic within the Salish Sea, particularly oil tanker shipping traffic, would lead to an increase in anthropogenic noise in the marine environment, with a broad range of organisms likely to be affected.

Noise can affect herring behavior directly, by changing their behavior, or indirectly, by changing the behavior and/or efficiency of their predators. Research on anthropogenic noise effects on fish has provided varying results. In the European eel (*Anguilla anguilla*), increases in shipping noise led to reduced predator avoidance (by increasing the time needed to initiate escape responses) and reduced performance, as well as triggering stress responses (increased ventilation and metabolic rates) (Simpson et al., 2015). In schooling fish such as Atlantic herring (*Clupea harengus*), a study of military sonar noises produced no effect in overwintering herring, while playback of killer whale sounds generated vertical and horizontal shifts in fish position (Doksaeter et al., 2009). Several studies examined the effects of acoustic survey vessel noise on herring to establish if behavioral changes may affect acoustic estimates of fish biomass. Avoidance responses (diving, lateral movements) were common but not consistently observed, as some schools moved towards the vessel path and were “herded” in front of the vessel targeting them (Misund et al., 1996; and see the review by De Robertis & Handegard, 2013). Herring in shallower water tended to have stronger avoidance reactions, although a study on spawning Atlantic herring in shallow water found little effect of passing vessels (Skaret et al., 2005). The same authors noted moderate reactions (diving) to a survey vessel among pre-spawning herring, particularly during daytime passes. However, the presence of epibenthic gadoid predators was hypothesized to have dampened the magnitude of the response (Skaret, 2006).

From the literature currently available, it appears that a variety of factors influence herring reactions to vessel noise (including fish age, ripeness - spawning fish are relatively oblivious, schooling depth, light levels, time of year, etc.), while the noise characteristics of any given vessel and aspects of the water through which the noise is being transmitted also play a role (De Robertis & Handegard, 2013). As such, it is not possible at this time to predict how more anthropogenic noise due to increases in vessel traffic in the Salish Sea would affect Pacific herring. However, given the prevalence of noise in the Salish Sea, the likely increase in such noise in the future, and the known impacts on herring predators, it warrants further investigation.

5. Nearshore light pollution

Dramatic increases in Artificial Light At Night (ALAN) have been reported globally over recent decades (Falchi et al., 2016), causing considerable ecological concerns about mal-adaptive behavior, movement, and mortality for nocturnal migrants (e.g., bats, birds, sea turtles, insects) and disruption of circadian rhythms and food web interactions in terrestrial and aquatic systems. ALAN affects the nocturnal environment both through the obvious direct spillover of light onto adjacent waters and by more diffuse but far-reaching “sky-glow” that reflects off the atmosphere back to the surface. The effects of sky-glow reach many tens of kilometers from its source, and is evident as the lighted dome surrounding cities at night. The effects of sky-glow are enhanced by cloud cover, which reflect 4x more light back to the surface on average than during cloudless nights (Kyba et al., 2011). In the Salish Sea region, accelerating land development that began in the 1980s, coupled with technological shifts toward higher-intensity lighting (e.g., halogen and now LED lights), has significantly increased ALAN and stimulated observed shifts in behavior, distribution, and predator-prey interactions among salmon and their predators and prey in nearshore and open water habitats.

Fish-eating fish, mammals, and birds (piscivores) rely primarily on vision to feed in pelagic habitats and are thus strongly influenced by spatial and temporal changes in the visual environment. Prey fishes, like herring, juvenile salmon and other forage fishes attempt to minimize predation risk by either forming schools or shoals or by remaining at darker depths during daylight. Declining light and increasing turbidity reduce reaction distances and search volumes for visual predators (Beauchamp et al., 1999, Mazur & Beauchamp 2003, 2006; Hansen et al., 2013). Under natural day-twilight-night light regimes, dawn and dusk are typically periods of high predation by visual predators. Although the visual field for piscivores declines during twilight, prey fish such as herring become more available, as schools disperse and individuals ascend from deeper daytime depths to feed while sufficient light remains at the shallower depths where food is concentrated, thus enabling feeding under less predation risk than during full daylight.

Increasing ALAN in the region has created a period of perpetual twilight from dusk until dawn, and has reduced or eliminated the nocturnal dark refuge for feeding and migrating fishes in the Salish Sea region. By applying experimentally-measured visual capabilities of predatory fish to estimated light levels at different depths during periods preceding artificial lighting and contemporary periods, researchers estimate that the resulting risk from visually-feeding predators has undergone a 7-fold increase across depths commonly occupied by herring, juvenile salmon, and other forage fishes in Puget Sound (Mazur & Beauchamp, 2003; Hansen et al., 2013) (Figure 14).

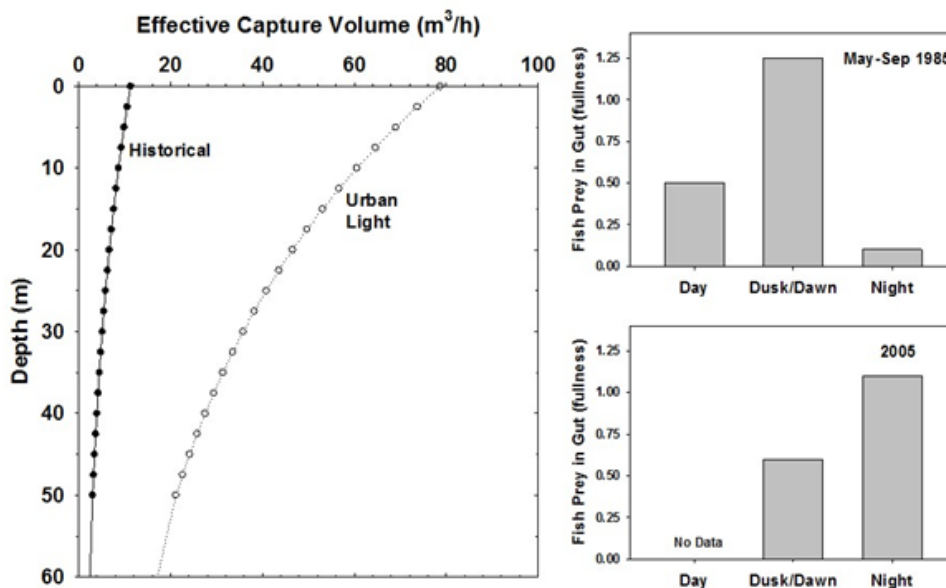


Figure 14. Effect of light on predation by salmonids.

(Left panel) The effect of nocturnal light penetration on the effective capture volume of predatory sea-run Cutthroat trout or resident Chinook/Coho salmon hunting for herring, juvenile salmon, or other forage fishes in open water habitats of the Puget Sound region. The solid line and filled symbols represent the estimated historical condition before pervasive electric lighting compared to the 7-fold increase indicated by the open circles representing contemporary conditions. Right panel: diel feeding chronology of predatory trout in Lake Washington showing that peak predation on juvenile salmon and forage fishes was primarily confined to twilight periods in 1985, but increased through the night when a similar study was repeated in 2005.

Lake Washington offers an example of how increased ALAN has increased predation risk in the region. In the 1980s, around-the-clock sampling indicated that predation on juvenile salmon and forage fishes peaked during twilight periods at dawn and dusk with no apparent predation occurring at night and minimal predation during daylight (Beauchamp, 1990; Beauchamp et al., 1992). However, similar studies 20 years later revealed that predation still increased dramatically at dusk, but then continued to increase through the night (Figure 14). Consequently, over the past 20-30 years, the period of highest predation threat has increased from approximately 3 hours of twilight during just dusk and dawn to 8 hours from dusk through dawn during June (2.7-fold increase) to 15 hours during December (5-fold increase). Moreover, the depth of effective predation risk has increased considerably, thus encroaching deeper into the effective foraging zones for plankton-feeding fishes like herring, juvenile salmon and other forage fishes. Thus, increases ALAN may be interacting with increasing predator abundances (see below) and other factors to increase natural mortality in herring.

6. Habitat degradation and destruction

Less attention and focused funding has been dedicated to anthropogenic habitat loss and change than on other potential impacts (Penttila, 2007; Toft et al., 2007). Nevertheless, habitat degradation and loss have had extensive impacts on forage fish in nearshore intertidal and shallow subtidal ecosystems (Miller et al., 1980; Greene et al., 2015; Sheaves et al., 2015). These habitats play a key role in the life cycle of many forage fish species, and Pacific herring is no exception. Fresh et al. (2011) reviewed nearshore

anthropogenic impacts on habitat and noted four major changes in Puget Sound: substantial loss of river delta habitat; elimination of small, coastal embayments; interruption of sediment transport pathways that erode bluffs and form beaches; and a dramatic loss of tidal wetlands. In terms of simple measures such as shoreline length, all habitat types across Puget Sound have decreased (Simenstad et al., 2011) by 8-48%, with shallow, protected habitats exhibiting the greatest loss in shoreline length. Specific human activities that individually and collectively affect nearshore habitat include construction of bulkheads or other hardened structures in place of natural shorelines, erection of piers and docks, dredging and filling, removal of riparian vegetation, and pollution (Toft et al., 2007; West et al., 2008; Sobocinski et al., 2010; Munsch et al., 2015a,b).

Pacific herring are likely to be most sensitive to nearshore habitat conditions during early life stages ranging from when eggs are attached to surfaces to when postlarval stages recruit to pelagic waters. Habitat conditions that may affect herring include turbidity (affecting larval feeding), vegetation for spawning, wave energy (impacting larval retention), and others.

Long-term data on forage fish use of nearshore ecosystems in Puget Sound consist of a few studies of pelagic communities associated with shoreline areas (Toft et al., 2007; Greene et al., 2015). These studies show variable regional trends in forage fish catch over time and linkages between anthropogenic activities and forage fish abundance. However, evidence for long-term habitat change relevant to herring populations have been challenging to obtain. Some evidence for changes in pelagic habitat conditions exists from sediment cores (e.g., Brandenburger et al., 2011), but deserve better analysis. Less is known about changes in specific nearshore habitats affecting herring. There is some evidence of higher herring egg mortality rates in association with shoreline development, including amount of shoreline armor and watershed imperviousness (Shelton et al., 2014).

Of the many nearshore environments used by forage fish, beds of aquatic vegetation such as eelgrass and kelp are of particular importance to Pacific herring for use as spawning substrate or as shelter for early life stages. The extent of change in eelgrass, as measured from occurrence of raked eelgrass during herring spawn surveys, indicates that declines on the order of 1-2% occurred at 5 of 14 sites over the last 40 years (Shelton et al., 2017), and a substantial loss of eelgrass has occurred at the San Juan Island herring spawning sites, where herring abundance has also dramatically declined. Eelgrass at other sites remains steady or has increased, though spawning site fidelity may dictate that the location of vegetation *within a site* is critical to use by herring. Unknown is how other habitat features have changed at herring spawning sites across the Salish Sea, though abandonment of southern SoG spawning sites is concomitant with increasing urbanization (J. Cleary, pers. comm.).

It is quite possible that a range of factors associated with coastal development - light, noise, nutrient inputs, contaminants, habitat loss - together have cumulative negative effects on herring, but as yet there is not enough evidence to draw such conclusions.

B. Population Factors

Critical size of schools and spawning aggregations

Pacific herring and their relatives are well-known for their schooling and spawning aggregation behavior. Schooling likely benefits individuals by conserving swimming energy (Johansen et al., 2010), improving foraging efficiency (Milne et al., 2005) and reducing predation mortality (Brock & Riffenburgh, 1960; Landeau & Terborgh, 1986; Rieucou et al., 2014; Domenici et al., 2017). Spawning aggregations are important in broadcast spawners to locate mates (Dennis, 1989), achieve egg fertilization (Leviton et al., 1992), and possibly to promote offspring diversity (Rowe & Hutchings, 2003). All these benefits are known

as Allee effects (Liermann & Hilborn, 1997; Courchamp et al., 1999; Stephens & Sutherland, 1999), which are improvements in individual fitness with increases in population densities. For such factors, if population levels decline, individual growth, survival, and reproduction can diminish, resulting in thresholds (“inverse density dependence” or “critical depensation”, Liermann & Hilborn, 1997) below which a population’s productivity declines. In a metapopulation situation, these interactions can have important effects on dispersal, as individuals will prefer to associate with larger groups (Greene & Stamps, 2001). The consequences of populations under threat can be that the number of aggregations declines as individuals associate with the larger groups (Hutchings, 1996; Greene, 2003). This process can facilitate population stability to the extent that individuals in the entire metapopulation does not decline below threshold levels (Greene, 2003).

Allee effects in herring populations can be substantial. Increased energy conservation has been found to occur better in large schools (Johansen et al., 2010), where the number of “followers” in a school greatly surpasses the number of “leaders” (the fish at the moving front of the school). Lake herring in larger schools had higher gut fullness, suggesting increased foraging efficiency (Milne et al., 2005), and Makris et al. (2009) found that schools with a threshold density of less than 0.18 fish/m² lost cohesion and velocity. While it is unclear whether larger groups reduce predation -- while the probability of predation within a group declines as a function of group size, predators may be attracted to larger aggregations -- larger schools improve evasion of predators due to better coordination of escape response (Domenici et al., 1997) and resulting confusion in predators (Landeau and Terborgh, 1986), and Brock and Riffenburgh (1960) found that individual survival increased as a function of school size. While reproductive benefits of larger spawning aggregations have not been extensively studied in herring, there does seem to be some down-sides to large aggregations in that fertilized eggs can be smothered by excessive layering of eggs (Hay, 1985).

Are Pacific herring susceptible to critical depensation resulting from Allee effects? In their extensive reviews of fish populations, both Myers et al. (1995) and Liermann & Hilborn (1997) both found Atlantic herring stocks to be one of a few reviewed stocks that demonstrated critical depensation. Furthermore, Liermann and Hilborn (1997) found that uncertainty, particularly from lack of data at low levels of abundance, was high for much of the dataset, thereby limiting conclusions about the extent of critical depensation across taxa. While this question has not been addressed for Salish Sea herring stocks, observations of the potential outcomes of Allee effects on dispersal have been observed in spawning aggregations. In the Strait of Georgia, the number of spawning aggregations has declined, even as the local spawning densities appear to have remained the same over the same time period (Therriault et al., 2009). In Puget Sound, spawning surveys have revealed that local spawning aggregations have been lost (see above) or become spatially concentrated, such that current local spawning distributions are a fraction of historical maps of the local distribution. Puget Sound stock abundance trends are declining where egg predation is high (TB Francis, unpublished data), suggesting an increased per-capita effect of egg predation as the school size declines. Hence, it appears possible that Pacific herring populations in the Salish Sea are approaching levels where critical depensation at various life stages may play an increasing role. In light of changes in the abundance of potential predators and environmental conditions affecting aggregations (e.g., dissolved oxygen: Domenici et al., 2017), the Salish Sea may be a good candidate for examining possible depensation.

C. Food web interactions

1. Predation

Adult herring mortality rates have nearly doubled for some age groups since 1970, suggesting that predation on adults is a major source of population decline (Siple et al., 2017). In addition to the groups highlighted below, stable isotope analysis has shown that herring spawn provides nutrients to a broad range of invertebrate species, as well as to aquatic macroalgae (Fox et al., 2018).

Pinnipeds

Globally, herring (spp.) are recognized as an important food source for almost all marine mammals including: dolphins, porpoises, humpback (*Megaptera novaeangliae*) and minke whales (*Balaenoptera acutorostrata*), seals and sea lions (Surma et al., 2018). Pacific herring are one of the most important prey for Stellar sea lions (*Eumetopias jubatus*), as determined via energy-based ecosystem modeling and other methods (Everett et al., 1981; Scordino, 2010; Surma et al., 2018). Sea lion distribution is also heavily correlated with herring biomass and spatial and temporal distribution patterns (Womble & Sigler, 2006; Gende & Sigler, 2006; Sigler et al., 2017). Harbor seal (*Phoca vitulina*) diets are similar and dominated primarily by Pacific herring, especially during the winter and spring (Bromaghin et al., 2013; Lance and Jeffries, 2007; Lance et al., 2012; Luxa and Acevedo-Gutierrez, 2013). Although harbor seals, Stellar and California sea lions (*Zalophus californianus*) prefer a diet rich in Pacific herring, the decline of herring available for their consumption (Trites & Donnelly, 2003; McClatchie et al., 2016) has not had a negative influence on their population size. **In fact, for harbor seals, a 7-10-fold increase in population size has occurred since conservation regulations associated with the Marine Mammal Protection Act went into effect in the 1970s (Jeffries et al., 2003).** The common explanation for the lack of correlation between predator and prey here is that pinnipeds readily switch to other abundant forage fish such as smelt and sand lance (Gregs, 2004; Vollenweider et al., 2006), and episodic booms in anchovy (*Engraulis mordax*) abundance in the Salish Sea (Duguid et al., 2018) may support predators during periods when herring are not abundant. Additionally, ecosystem changes affecting their wild juvenile and adult salmonid prey base are largely offset by industrial scale hatchery supplementation, stabilizing prey availability. This may be an important factor when considering how high pinniped abundance may, or may not, influence herring differently during periods of varying prey abundance the Salish Sea.

Cetaceans (piscivorous)

Whales: Humpback whales are the most abundant cetacean predator of herring. Surma et al. (2018a) considered herring to be the most important prey item to Alaskan humpback whales based on their energy-based ecosystem model. Sharpe and Dill (1997) also documented herring as a primary prey species for humpback whales and further established this whale species, among other individual prey seeking (vs. other bulk-feeding predators) as a dominant predator for herring. Historically, declines in herring populations have coincided with declines in Humpback populations (Stout et al., 2001; Falcone et al., 2005). **Humpback whales in the North Pacific have dramatically increased from a low of 1,400 in 1986 to nearly 20,000 in 2008 (Barlow et al., 2011), and sightings in the Salish Sea by conservation groups have increased steadily over the last 10 years.** This has led many to hypothesize that declines in herring abundance are associated with increasing humpback abundance throughout the North Pacific.

Killer whales off coastal Norway and Iceland depend on Atlantic herring (Similä et al., 1996), but herring are not considered a common or preferred prey item for Killer whales (*Orcinus orca*) in the Salish Sea despite the fact that large herring aggregations during spawning are a significant attractant for other large marine mammals (e.g., sea lions) (Ford et al., 1998; Ford & Ellis, 2006). There has been speculation as to whether Killer whales will turn to forage fish, such as Pacific herring, for sustenance as the depletion of their primary prey of choice, Chinook salmon, continues.

The little diet data available on minke whales suggests that they do feed on forage fish and this most likely includes herring. Only about twelve individuals are observed in the Salish Sea. Conversely, there are no records of Grey whales (*Eschrichtius robustus*) consuming herring in the Salish Sea. Nearshore Grey whale disruption of sediment while consuming mysids and ghost shrimp could possibly have a detrimental impact on recently spawned and post-larval herring.

Dolphin and Porpoise: Information is abundant for both harbor (*Phocoena phocoena*) and Dall's porpoise (*Phocoenoides dalli*) (Smith & Gaskin, 1974; Recchia & Reed, 1989). **Harbor porpoises caught in the Strait of Juan de Fuca feed heavily on herring and smelt (64% to 89% of stomach contents) with adult porpoises being more selective toward herring than smelt (Gearin et al., 1994).** Walker et al. (1998), Hall (2004) and Nichol et al. (2013) found that herring were common prey for both harbor and Dall's porpoise, often contributing to 60% of the total caloric intake for harbor porpoises. Temporally, Pacific herring was the most widely distributed prey taxa for both species of porpoise in the region (Nichol et al., 2013) and made up 45% of the diet by frequency of occurrence and high caloric contribution to their diets. **Harbor porpoise numbers have tripled since the 1990s and, coupled with their preference for herring as prey, pose a substantial pressure for herring populations.** Conversely, Dall's porpoise seem to be absent from the Salish Sea, despite a historical presence, with only a few documented sightings of rare individuals in the San Juan Islands and the Strait of Juan de Fuca, suggesting their impact on herring is not worth consideration. Like Dall's porpoise, white-sided dolphins (*Lagenorhynchus obliquidens*) are occasionally present in small numbers in the Salish sea but there is little diet data available from the literature.

Predatory Fishes

Among predatory fishes in the Salish Sea, the reliance of Chinook and coho salmon on forage fish is perhaps the best studied. Post-larval herring serve as prey for juvenile Chinook and coho salmon, cutthroat, and steelhead trout. The consumption of herring by salmon is dictated by size restrictions (primarily mouth gape), but herring can be an important contributor to age-0 Chinook and coho salmon diets in northern Puget Sound and the Strait of Georgia, where late spawning (Cherry Point and some Canadian) stocks provide younger, smaller post-larval herring that can be easily consumed by salmon. Larger herring may be even more important in older salmon diets: "resident forms of Chinook salmon (>300mm) rely heavily on herring throughout their entire marine life with herring contributing about 80% of their lifetime energy budget" (PSC report, Beauchamp & Duffy, 2011). Herring are considered the second highest energy-rich forage fish in the Salish Sea after eulachon (*Thaleichthys pacificus*), with values that overlap, but generally exceed, those of Pacific sand lance (Surma et al., 2018).

Pacific Hake (aka Whiting; *Merluccius productus*) are an abundant predator of herring both in the Salish Sea and coastal waters. Juvenile hake may compete with herring for prey resources, but as they grow they become piscivorous and herring can become a substantial part of their diet for both Salish Sea resident and coastal hake stocks. During the spring it is estimated that herring may compose 15%-20% of the hake diet in the Strait of Georgia, potentially accounting for thousands of metric tonnes of herring consumed by hake during this time (McFarlane & Beamish, 1985). Herring were also noted as the dominant prey species for hake in coastal waters off of the Pacific Northwest by Buckley & Livingston (1997), accounting

for over 50% of the diet by weight of hake collected off the west coast of Vancouver Island and northwest Washington. The biomass of Pacific hake in Puget Sound has declined 85% and failed to recover despite a closure of the commercial fishery in 1991; spawning areas in Puget Sound include Port Susan, Dabob Bay and near Carr Inlet, and spawning aggregations in the Strait of Georgia are found in south-central and northwest Georgia Strait, as well as in Stuart Channel and Saanich Inlet (reviewed in Chittaro et al., 2013). Recently, reduced average size and length at maturity has been observed in Salish Sea resident hake populations, and both resident and coastal populations have fluctuated (King & McFarlane 2006; Edwards et al., 2018). It is unclear how these changes in abundance and growth rates may affect hake predation rates on herring.

Spiny dogfish are another prominent predator in the Salish Sea, with an estimated 2 to 4 million individuals present during the summer (Beamish & Sweeting, 2009). Dogfish diets are composed primarily of euphausiids and teleosts, including herring, but vary seasonally and by size (Jones & Geen, 1977). Invertebrates comprise a larger component of dogfish diets during summer months, and teleosts are more prominent in the diets of larger (>60cm) dogfish, and during winter months (Jones & Geen, 1977; Beamish and Sweeting, 2009). Jones and Geen (1977) noted herring was the principle food item for dogfish sampled in British Columbia waters, and suggested that dogfish may consume 5 times the annual commercial catch of herring during that time.

Predation upon herring eggs by benthic-demersal fishes is another point of concern. In the Baltic sea, where three-spine stickleback (*Gasterosteus aculeatus*) are the dominant resident fish species in near-shore waters, predation upon Atlantic herring (*Clupea harengus*) eggs was significant at temperatures between 11° and 15°C and may shape the success of herring recruitment in the region (Kotterba et al., 2014). Threespine stickleback numbers have increased over a forty-year period in Puget Sound (Greene et al., 2015), but little data is available on herring egg predation. Demersal fish species in the North Atlantic ocean (primarily haddock, *Melanogrammus aeglefinus*) are considered a significant predator of Atlantic herring eggs (Rankine & Morrison, 1989; Toresen, 1991), but egg predation by similar species in the Salish Sea (e.g., greenlings, hake, and walleye pollock) has not been documented, perhaps because Pacific herring spawn at shallower depths (Rooper et al., 2000; Kotterba et al., 2014). Herring are also cannibalistic on their own eggs (reviewed in Willson & Womble, 2006).

Seabirds

Herring are widely considered to be among the most important prey species for piscivorous seabird species in the Salish Sea. Their importance in the diets of different seabird species varies depending on herring life stage (Therriault et al., 2009). Herring spawn events offer tremendous nutritional benefits to seabirds, but are temporally and spatially limited, and many Salish Sea spawning sites have shown decreasing herring egg production over the last few decades (Therriault et al., 2009; Stick et al., 2014). A number of species that rely on herring spawn and juvenile and adult herring have shown marked decreases in abundance (Bower, 2009). Piscivores, in particular, account for most of the marine bird species showing major declines (Figure 15) (Piatt & Arimitsu, 2005; Vilchis et al., 2014).

Many seabirds aggregate at herring spawn events, sometimes numbering in the tens of thousands. Reviewing accounts of multiple spawn events shows that the seabird assemblages at any one event may be unique, but that most assemblages include loons, grebes, cormorants, ducks, gulls, and alcids (Monro & Clemens, 1931; Haegerle, 1993; Terrance Wahl, unpublished data). Species commonly found at spawn events include western grebes (historically, but now much reduced), glaucous-winged gulls, surf scoters, white-winged scoters, harlequin ducks, greater scaup, and long-tailed duck, but other species are locally common as well.

Seabird predation on herring eggs is also high and often the most significant egg predation factor (Anderson et al., 2009; Rooper et al., 2000; Lok et al., 2012). Much research has focused on surf scoter use of herring spawn, with results suggesting that spawn is critical to compensating for overwinter declines in body mass as well as for storing energy for migration and possibly reproduction. Surf scoters, for instance, have been shown to increase their body mass significantly during spawn events (Anderson et al., 2009). Surf scoters increase daily movements in order to feed on spawn as compared to non-spawning periods (Lok et al., 2008). Many surf scoters appear to time their northward migration to take advantage of herring spawn events, with 60% of tracked surf scoters attending at least one spawn event (Lok et al., 2012). Importantly, high egg predation rates are observed at sites with high numbers of observed scoters (T. Francis, unpublished data). In addition, herring populations with high egg mortality rates show declining abundance trends.

Understanding the causes of abundance decreases is a complex problem and requires consideration of the life history and the unique set of environmental issues impacting each species. That said, decreased herring stocks, and particularly decreased availability of herring spawn, has likely played a role in the decrease of piscivorous seabird species in the Salish Sea.

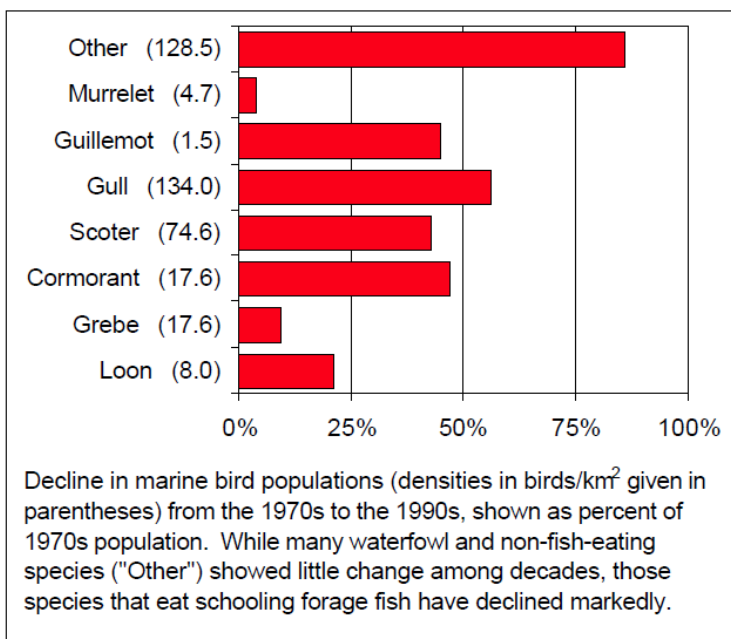


Figure 15. Declines in piscivorous and other marine birds in Puget sound and surrounding waters

(Figure from Piatt & Arimitsu, 2005).

2. Competition

Herring are among the most abundant, if not the most abundant, planktivore in the Salish Sea. They also face competition from a number of other species for zooplankton resources. **Importantly, data on distribution, abundance, and community composition of zooplankton in the Salish Sea has been a major data gap for years.** A new zooplankton monitoring program has launched, but results are of limited usefulness in evaluating bottom-up effects on herring, given the short time series. Previous studies have found links between abundance trends in British Columbia Pacific herring and the abundance of some zooplankton species (Schweigert et al. 2010), but we presently lack data to evaluate those links for Salish Sea herring.

Forage fish

Herring eat primarily copepods and hyperiid amphipods during early life stages and add increasingly large fractions of gammarid amphipods, euphausiids, and larval crab as their size increases (regulated by predator-prey size relationships) (Duffy et al., 2010; Beauchamp & Duffy, 2011). Herring diets overlap extensively with that of juvenile Chinook salmon (Schoener's overlap index 60-85%), regardless of the presence (every other year) of juvenile pink salmon (Figure 16; Beauchamp & Duffy, 2011; Kemp et al., 2013). In addition, estimates of population-level consumption via bioenergetics modeling "indicated that herring consumed approximately 10-50 times more biomass of the major prey eaten by juvenile Chinook salmon...in Puget Sound within the Southern, Central and Whidbey Basins and Admiralty Inlet" (Beauchamp & Duffy, 2011). In the San Juan Islands, herring were shown to overlap in habitat use with juvenile (<150mm fork length) salmon (Beamer & Fresh, 2012) and to compete with juvenile salmon and other forage fish species; larger herring (>150mm) in pelagic environments also compete with coho salmon (>150mm FL) for larger euphausiids, amphipods, and brachyurans (Fresh et al., 1981). When analyzed by trophic guild, herring formed the largest, zooplankton-feeding guild (14 species total) and did not change guild with shifts in season; summer diets were found to converge as seasonal resources increased, but winter diets suggested a greater degree of specialization with less diet overlap (Reum & Essington, 2008). Modeling factors affecting age zero (young-of-the-year) herring in the SoG, Boldt et al. (2018) found that density-dependent processes (e.g. intraspecific competition) likely governed populations, and that conditions that favored juvenile herring also favored their predators and competitors.

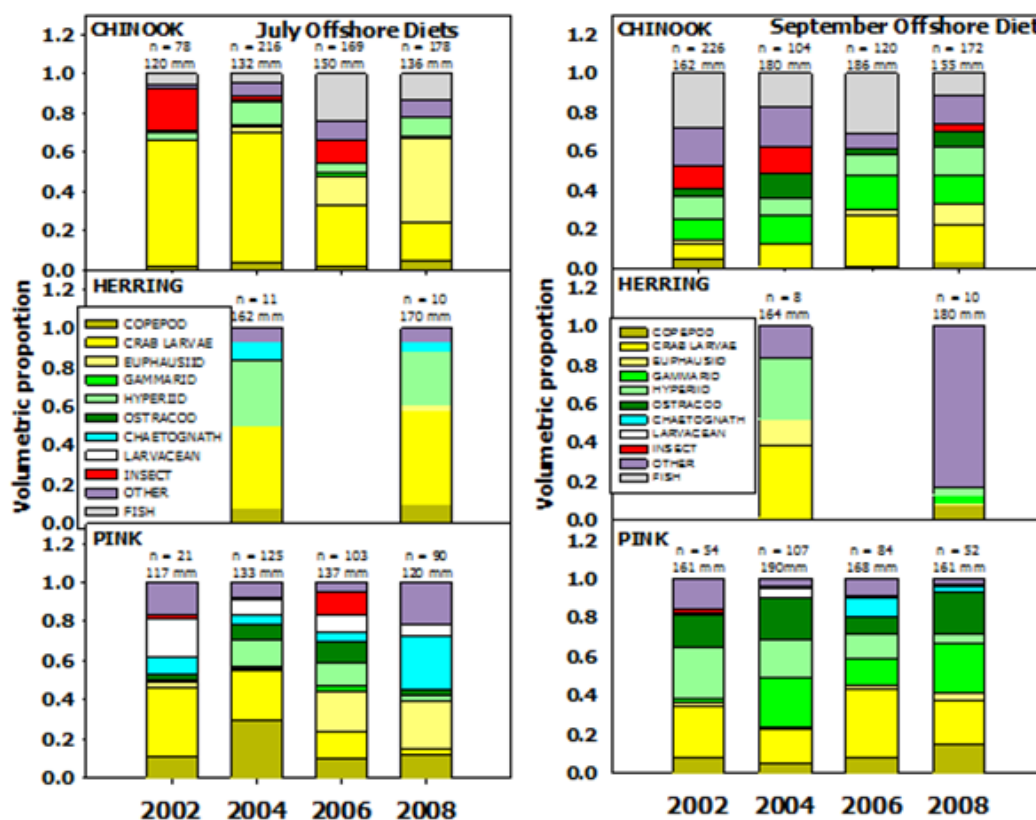


Figure 16. Diet comparisons among herring and herring competitors.

Offshore diet composition during July (left panels) and September (right panels) for age-0 Chinook salmon (upper), Pacific herring >130mm FL (middle), and age-0 pink salmon (lower) in pelagic habitats of Puget Sound during 2002, 2004, and 2006. Sample sizes and average fork lengths are listed above each bar. (Source: Beauchamp and Duffy 2011)

Post-larval herring serve as both competitors (with juvenile salmon for phyto- and zooplankton prey) and prey for juvenile Chinook and coho salmon, cutthroat, and steelhead trout. Competition with herring was identified as “a probable cause for food limitation, based on the significant amount of diet overlap for important prey, high spatial-temporal overlap among juvenile salmon and herring, and the many-fold higher biomass of herring relative to all species of juvenile salmon and other planktivorous fishes” (Beauchamp & Duffy, 2011).

The diets of other nearshore forage species (primarily surf smelt and sand lance) also indicate considerable overlap that would lead to competition, although anchovy, which are pelagic spawners, also rely on phytoplankton and zooplankton (Pentilla et al., 1985, 1986). Surf smelt diets consist primarily of copepods, Oikopleura, and Cladocera (reviewed in Garrison & Miller, 2002). Pacific sand lance are found both near-shore (Sellek et al., 2015) and in deep wave fields in the San Juan Islands (Bizzarro et al., 2016; Greene et al., 2017) and perhaps elsewhere. Sand lance feed primarily on calanoid copepods, *Coscinodiscus* diatoms, and polychaete worms (Simenstad et al., 1977; Tribble, 2000; Sisson & Baker, 2017) but are dormant through much of the winter, exhibiting a significant decrease in condition factor (Sisson & Baker, 2017). The population of sand lance in the San Juan Island wave field was estimated at over 63 million fish (Blaine, 2006).

Northern anchovy have returned to abundance in recent years throughout the Salish Sea (Duguid et al., 2018), although an historical analysis of scales in core samples taken in Saanich Inlet (BC) estimated that they comprised only 3% of total scales (with herring and hake forming the majority) (cited in Therriault et al., 2002). More recent studies of First Nations archaeological sites also placed anchovy as the third most abundant species at sites up to 3000 years old (Pierson, 2011), and anchovy scales were found to be ubiquitous at 35% of archaeological sites throughout the Salish Sea (McKechnie & Moss, 2016). In comparison, smelt species (difficult to separate by osteology) were also ubiquitous at 35% of sites, while herring were the dominant species, ubiquitous at over 98% of sites examined (McKechnie & Moss, 2014, 2016). Thus, herring appear to be the most numerous forage fish species in the Salish Sea both at present and in the past, although the sparsity of data on other forage species (especially those not typically considered forage fish, e.g. three-spine stickleback, shiner perch, juvenile hake, etc.), and large temporal changes in species' abundance, makes it difficult to assess competitive interactions on a broad scale.

Sardine are not commonly found in the Salish Sea, but they do occur in the coastal waters off Washington and British Columbia where some herring stocks feed. Since the initial closure of the sardine fishery in 1967, estimated sardine biomass increased to about one million metric tonnes in 2006 (Hill et al. 2017). Sardine diet is composed primarily of diatoms, copepods, and euphausiids (McFarlane et al., 2010). Herring stocks that migrate to coastal waters to feed face competition from Pacific Sardine for common prey, and fluctuations in sardine stocks may impact herring stocks, particularly those stocks that do not remain within the Salish Sea (Schweigert et al., 2010).

Gelatinous zooplankton (“Jellyfish”)

Gelatinous zooplankton consist of a diverse group of organisms; in this discussion, we use “jellyfish” in reference to “medusae of the phylum Cnidaria (hydromedusae, siphonophores and scyphomedusae) and to planktonic members of the phylum Ctenophora. Though not closely related, these organisms share many characteristics including their watery or ‘gelatinous’ nature, and a role as higher-order carnivores in

plankton communities” (Mills, 2001). There are many examples of large increases in jellyfish abundance, e.g. the Baltic Sea (as a result of a species translocation via vessel bilge water) and in coastal waters off Korea, Japan and China, among others (Mills 2001; Uye, 2011; Brotz et al., 2012). Jellyfish are a concern for herring populations because they consume herring larvae and compete with juvenile and adult herring for planktonic prey, and because jellyfish can occur in large numbers.

A contributing factor to jellyfish population increases is “hardening” of the marine environment through the construction of seawalls, jetties, aquaculture structures, oil platforms, etc. These structures provide solid benthic surfaces for the attachment of jellyfish (cnidarian) polyps, which can then quickly reproduce asexually, leading to blooms under favorable conditions (Graham, 2001; Lo et al., 2008). There is some evidence that artificial substrates are preferred over natural ones, although jellyfish species with polyp stages may also benefit from marine trash and macroalgae mariculture for the same reasons (Duarte, 2013). Other factors which may lead to increases in jellyfish populations, and blooms, include (from Purcell et al., 2007 and Richardson et al., 2009):

- (a) overfishing, leading to reductions in competition and predatory pressures (particularly on polyp and ephyrae stages of jellyfish)
- (b) sea water temperature increases, which enables rapid jellyfish reproduction (through increases in productivity) and water column stratification, resulting in nutrient-poor surface waters that favor jellyfish
- (c) eutrophication, leading to phytoplankton blooms that may encourage jellyfish blooms; jellyfish are able to feed in low-visibility conditions common under eutrophication, whereas most fish are not
- (d) anoxic conditions, to which jellyfish are resistant; this may allow them to outcompete competitors such as planktivorous fishes
- (e) Dams, which alter hydrologic regimes and shift salinity gradients and estuarine circulation patterns in ways that favor jellyfish

A major concern is that the above factors may increase jellyfish reproduction while simultaneously reducing competition and predation, creating a feedback loop “whereby jellyfish can form an alternative stable state in marine ecosystems... replacing the more common and productive food webs dominated by higher trophic-level organisms such as fish” (Purcell, 2007). A study of diverse food web models indicated that the ratio of forage fish to jellyfish and total jellyfish biomass were among the best indicators of ecosystem health (Samhuri et al., 2009).

Recent modeling efforts show the shift in dominance from forage fish to jellyfish associated with changing levels of primary production and water quality (Schnedler-Meyer et al., 2016). In the main basin of Puget Sound, a comparison of surface trawling data collected intermittently over a 40 year period showed a 3-9 fold increase in the frequency of large jellyfish blooms in the Central and South basins, accompanied by a two-fold decline in herring and surf smelt over the same period (Greene et al., 2015). However, the dynamics at work in Puget Sound may differ from other coastal ocean regions; the same study noted “Intriguingly, jellyfish catch-per-unit-effort (CPUE) was negatively associated with forage fish harvest.” The answer may lie in another correlation, namely that jellyfish abundance was also negatively correlated with the growth of the human population in this now heavily urbanized estuary, suggesting that the suite of effects caused by elevated human population densities are also detrimental to jellyfish (Greene et al., 2015).

A similar surface-trawl study with better spatial but limited temporal coverage (May-August of 2003 only) found that jellyfish accounted for over 60% of the total wet biomass captured; jellyfish made up almost

90% of the biomass in Central and South Puget Sound but less than 45% of the biomass in the more northern basins (Whidbey and “Rosario”, the eastern Strait of Juan de Fuca north to Bellingham Bay) (Rice et al., 2012). These results were mirrored in a WDFW mid-water acoustic trawl survey of the southern Salish Sea in 2016-17, in which nearly 60% of the biomass captured during the summer months consisted of invertebrates, primarily jellyfish (Burger et al., 2018, WDFW, report in progress).

In contrast, Mills (2001) observed a decline in the abundance of *Aequorea victoria* medusae in the area around Friday Harbor (San Juan Island) through the year 2000, although it is unclear if this is the result of nearly three decades of collections (for the harvest of *aequorin* and green fluorescent protein) or environmental variability. Until recently “jellyfish” (again, an amalgamation of a wide range of organisms with varied life histories) were largely ignored in fisheries research efforts; as a result, we are largely uninformed about the dynamics of jellyfish populations in the Salish Sea. In the northern SoG, less data focusing on jellyfish is available, but two studies covering zooplankton over ~20-year time periods (ending in 2010) indicate that jellyfish abundance has shifted. In analyzing data from deep (>100m) waters, Mackas et al. (2013) noted “Much of the biomass in each season and also in the overall annual average is accounted for by only about a dozen crustacean taxa and their gelatinous predators”. A study of the shallow, nighttime zooplankton community noted a steep decline in gelatinous zooplankton in June from the 1990s vs. the 2000s, although the effect was reversed in samples taken in September, although the magnitude of the shift was much smaller (Li et al., 2013). Overall, there does not appear to be a consistent increase in the jellyfish contribution to the plankton in the northern SoG, as noted by Greene et al., 2015 in Puget Sound, but recent data are limited.

At present, there is little direct evidence that jellyfish act as predators upon Pacific herring. Direct predation is unlikely due to timing differences in Pacific herring and jellyfish life cycles. With the exception of the late-spawning stocks (e.g. Cherry Point, WA), most early life stages of Pacific herring do not overlap the main pulse of jellyfish biomass, which occurs in the summer. Hence, the risk of predation might be limited to years in which jellyfish bloom early in the spring, such as years of anomalously high spring temperature. However, jellyfish have been observed to consume 95% of herring larvae at a single spawning site (Sandra Emry, unpublished data), and with warming ocean temperatures, there is concern that jellyfish blooms are occurring earlier in the year, increasing the chance of overlap with herring larvae. Currently, there is limited information on the role of jellyfish as competitors with herring.

3. Disease

As with Pacific herring throughout the greater North Pacific Ocean, those in the Salish Sea are host to numerous pathogens including sea lice, nematodes, trematodes, cestodes, myxosporeans, ciliated protozoans, coccidians, protists, bacteria, and viruses (Marty et al., 1998; Hershberger et al., 2008; Friend et al., 2016). Among these, viral hemorrhagic septicemia virus (VHSV), erythrocytic necrosis virus (ENV), and *Ichthyophonus*, generate the most concern to resource managers because of their documented population-level impacts to Pacific herring and other forage species. Under typical conditions, a delicate balance occurs between host, pathogen, and environmental conditions, resulting in an endemic state where these pathogens occur in the apparent absence of disease. However, periodic changes in host and environmental conditions facilitate the transition of this balanced condition into an overt disease state. The relative contributions of these stochastic disease outbreaks towards the overall annual mortality of Pacific herring in the Salish Sea are difficult to deduce, but mortality from disease remains a leading hypothesis accounting for abundance crashes and demographic patterns in several herring populations. For example, ENV causes recurring epizootics in juvenile Pacific herring (Meyers et al., 1986; Hershberger et al., 2009), VHS causes recurring kills of free-ranging and impounded herring (Garver et al., 2013, Hershberger et al., 2016), and ichthyophoniasis causes recurring population-level impacts to clupeid

populations around the world (Burge et al., 2014). Ongoing efforts in the Salish Sea are underway to assess the population-level impacts of these diseases, forecast disease potential, and develop adaptive management strategies to mitigate disease impacts to Pacific herring.

D. Physical and broad-scale environmental factors

1. Climate Change

Anthropogenic activities are changing the global climate, which has significant implications for the Salish Sea. These changes include increases in temperature (both air and water), increases in the frequency and magnitude of heavy rainfall, sea level rise (SLR), shifts in circulation, and ocean acidification (discussed in the following section) (Mauger et al., 2015; see <https://cig.uw.edu/resources/special-reports/ps-sok/>). A full discussion of these changes is beyond the scope of this report, but herein we focus on how these changes are likely to affect Pacific herring in the Salish Sea (acknowledging that there is little research specific to the topic to draw upon).

Global air temperatures have risen over the last century by 0.74°C and are projected to rise another 1.1 to 6.4°C by 2100 (IPCC, 2007). This has led to ocean warming, and, in the SoG, a gradual warming of the entire water column (400 m) from 1970-2005, with “vertically averaged temperatures in the central Strait of Georgia...increasing at a rate of $0.24 \pm 0.01^\circ\text{C}/\text{year}$. This rate is comparable to the warming observed offshore near the surface, but exceeds, by a factor of at least two, the rate of warming measured offshore below 100 m” (Masson & Cummins, 2007). The region has also experienced El Nino and La Nina climate events with increasing frequency (Guan et al., 2017); El Nino events can lead to delayed upwelling in the California Current System and have been linked with delays in the timing of the spring phytoplankton bloom, with effects on planktivorous fish spawn timing (e.g. Northern Anchovy; reviewed in Asch, 2015). **Direct effects of increasing temperature that may affect herring, but to an unknown degree, include: plankton bloom timing mismatches, leading to decreased larval survival (Cushing 1969; Schweigert 2013; Asch 2015; Boldt et al., 2018); acceleration of embryo development; and northward geographic expansion of the range of herring predators, competitors, parasites, and diseases.**

In addition to temperature increases, changes in hydrology are predicted to occur, affecting salinity, turbidity, and other physiochemical parameters, as well as the volume of runoff. While little change in precipitation is forecast for the Salish Sea region in total, heavy rainfall will increase. Shifts from snow in winter to mostly rain will alter the timing of maximum runoff, which may lead to earlier surface water warming, more stratification, and earlier plankton blooms. More storms are also predicted under climate change, which could increase egg loss due to perturbation, displacement, and destruction of nearshore vegetation on spawning grounds.

Herring larvae exposed to elevated temperatures during embryonic development are smaller than those incubated at cooler temperatures (16 vs 10 degrees C), and there are more frequent morphological deformities in the spine and jaw (reviewed by Love et al., 2018). These results suggest future warming may put additional pressure on herring populations.

Climate may impact the distribution of herring, as they migrate northward in response to warming temperatures, salinity, or river flow (Checkley, 2017; Conner et al. unknown date). Climate may increase phenological mismatches if seasonal cues (e.g., day length) become decoupled from seasonal processes (e.g., temperature), and if herring phenological response to climate change differs from the responses of their prey or predators (Asch, 2015).

The depth distribution of submerged aquatic vegetation (SAV), upon which herring rely as spawning habitat, may change with increased eutrophication and/or sea level rise, resulting in SAV becoming a limiting factor for Salish Sea herring populations, as it is for Baltic herring populations (Moll et al., 2018).

Wave energy has a negative effect on herring egg survivorship (Shelton et al., 2014), and storm frequency and intensity is predicted to increase (Coumou & Rahmstorf, 2012; Woth et al., 2006), which may increase pressure on this early life stage for herring. Such additive impacts of depth-limited SAV and increased storm frequency has been shown to result in up to 30% of egg loss in a single spawning bed (Moll et al., 2018).

If hypoxic summer conditions in Hood Canal continue to grow more frequent and extensive as predicted (Essington & Paulsen, 2010), we would anticipate an interaction between dissolved oxygen conditions and the foraging success of hypoxia-tolerant jellyfish compared to zooplanktivorous fishes such as Pacific hake and Pacific herring (Moriarty et al., 2012).

Increased inputs of freshwater from rivers, resulting from the warmer temperature and higher rain:snow, may reduce salinity in nearshore habitats. Herring spawn later in warmer years with lower salinity, which could impact their egg survivability or availability of appropriate prey during critical life stages.

Sea level is also projected to rise by 0.2 to 0.6 m or more by 2100 (Hansen et al. 2007; IPCC, 2007). The magnitude of the effect of SLR in some ways depends on human response. Increased shoreline armoring/levees etc. will create habitat for jellyfish polyps and could increase jellyfish populations (refer to jellyfish section). “Bath tub” effects of rising water will eventually raise local sea levels in areas with armoring; deeper water (and potentially more turbid water if warmer temperatures and increased stratification lead to more/heavier blooms) will eventually lead to a loss of suitable habitat for macroalgae, reducing vegetation band width and spawning habitat. At present we have seen little changes in total eelgrass (Shelton et al., 2014), and herring do not appear spawning habitat limited in Puget Sound.

2. Ocean acidification

Increasing ocean acidification (OA) is another factor that could be negatively impacting herring abundance in Washington waters. An increase in the acidity of Salish Sea waters has been documented and is expected to increase in the future (Feeley et al., 2010; and see <https://www.pmel.noaa.gov/co2/story/Acidified+waters+in+Puget+Sound> and <http://www.dfo-mpo.gc.ca/science/oceanography-oceanographie/impacts/acidification-eng.html>). Its impact on important post-larval herring prey, particularly crustaceans such as krill, calanoid copepods, and crab zoea is concerning. Clear negative effects of high-pCO₂ (resulting in a lowering of pH, an increase in acidity) have been shown on zooplankton that build calcium carbonate shells (e.g., pteropods, bivalves, and echinoderms) (Kroeker et al., 2013; Wittmann & Pörtner, 2013), even at pCO₂ -levels already observed in the California Current and Puget Sound. The direct effects on other zooplankton are less clear, although published studies provide broad evidence of negative effects of elevated pCO₂ - on mesozooplankton (Busch & McElhany, 2016). Negative effects on taxa which are important herring prey (especially copepods, krill, crab and shrimp larvae) have been reported. pCO₂ levels that are currently found in some regions of Puget Sound have negative effects on krill (*Euphausia pacifica*) survival and development (McLaskey et al., 2016). Copepods have shown mixed responses to OA: globally, many studies have found that adult copepods are generally robust to modest changes in pH (those predicted for the surface ocean by the end of the century) (Kurihara & Ishimatsu, 2008; McConville et al., 2013; Hildebrandt et al., 2014; Runge et al., 2016), but younger life stages and some species are more sensitive (e.g., Thor & Oliva 2015; Aguilera et al., 2016; Lewis et al., 2013; Cripps et al., 2014). There is also growing evidence of sub-lethal

effects of elevated $p\text{CO}_2$ (e.g., on growth) that could have important implications for copepod populations (Li & Gao, 2012; Fitzer et al., 2012; Thor & Oliva, 2015; Thor & Dupont, 2015).

Indirectly, there are a variety of ways increased $p\text{CO}_2$ can affect zooplankton through their phytoplankton prey, including changes in phytoplankton abundance or cell size which can influence zooplankton grazing, and changes in phytoplankton quality as food through changes in their fatty acid composition. Laboratory and mesocosm studies have shown variable results of OA on these links making the effects difficult to generalize. Some studies have reported strong negative effects on development, growth, and egg production rates of copepods when feeding on phytoplankton cultured at high CO_2 (Rossoll et al., 2012; Schoo et al., 2013; Cripps et al., 2016), yet other studies have shown more complex responses, including minimal effects (Rossoll et al., 2013) or even moderate positive responses (McLaskey & Keister, unpublished data).

Most of the current research on the effects of OA on marine fish to date have focused on larval stages because these are thought to be the most susceptible, with contrasting results between and within species. Atlantic herring larvae have been shown to be resistant to the combined effects of elevated acidity resulting from increases in atmospheric CO_2 (Maneja et al., 2014; Sswat et al., 2018a), even though elevated temperatures alone increased swimming activity and decreased larval instantaneous growth and survival (Sswat et al., 2018a). Atlantic herring larvae swimming performance and feeding were not affected by elevated $p\text{CO}_2$ in another study (Maneja et al., 2015), and larvae were shown to benefit from $p\text{CO}_2$ -stimulated increases in primary production that increased larval herring growth and survival (Sswat et al., 2018b). However, intraspecific differences have also been noted; Baltic herring tissues were resilient to increases in $p\text{CO}_2$ but overall mortality increased (Bodenstein et al., 2012), and Norwegian Atlantic herring exposed to elevated $p\text{CO}_2$ were negatively affected in terms of development, growth and condition (Frommel et al., 2014)).

Experiments on larval herring raised from Cherry Point stock (collected by DFW) examined the effects of ambient vs. elevated $p\text{CO}_2$ (600 and 1200 μatm , respectively) and temperature (10 and 16 °C), plus the various combinations, to look for synergistic effects and to help forecast the effects of climate variability on this important stock. The research showed that:

- 1) fertilization rates exceeded 80% in all treatments, without significant differences
- 2) the elevated temperature significantly reduced hatching success (66% at 10°C, and 32% at 16°C)
- 3) larval abnormalities at hatching averaged 17% and were not influenced by the different treatments
- 4) embryo mortality was significantly higher (26%) at 16°C (600 μatm) than at 10°C (600 μatm)
- 5) at 16°C, elevated CO_2 also increased embryo mortality, from 16% (600 μatm) to 58% (1200 μatm) (from a study by Cristina Villalobos and Brooke Love, Western Washington University, personal communication).

These results are particularly important because the Cherry Point (CP) stock, which is the latest spawning stock in the Salish Sea (typically mid-May to mid-June over the past decade), is already spawning during periods when the water temperature is in the range of 14-15°C; by the end of June, 2018, temperatures in Birch Bay exceeded 16°C (DFW, unpublished data). A study comparing the survival of larval herring from five different stocks at five different temperatures, including two elevated temperatures (18 and 20°C), showed that survival was reduced in all stocks at 18°C and was extremely poor at 20°C (Figure 17) (Marshall, 2011). The study was testing the hypothesis that Cherry Point herring may have evolved tolerance to higher temperatures due to their later historical spawning date. Cherry Point herring did have higher tolerance than all other stocks tested (including San Francisco Bay stock, which is genetically distinct from stocks in the Salish Sea), but none of the stocks tested exceeded 50% survival at 18°C except for CP. In combination with the results of the elevated pCO₂ and temperature studies discussed above (Cristina Villalobos and Brooke Love, WWU), these data suggest that herring in the Salish Sea will have reduced larval survival as warming marine water temperatures and increased acidity (pCO₂) converge.

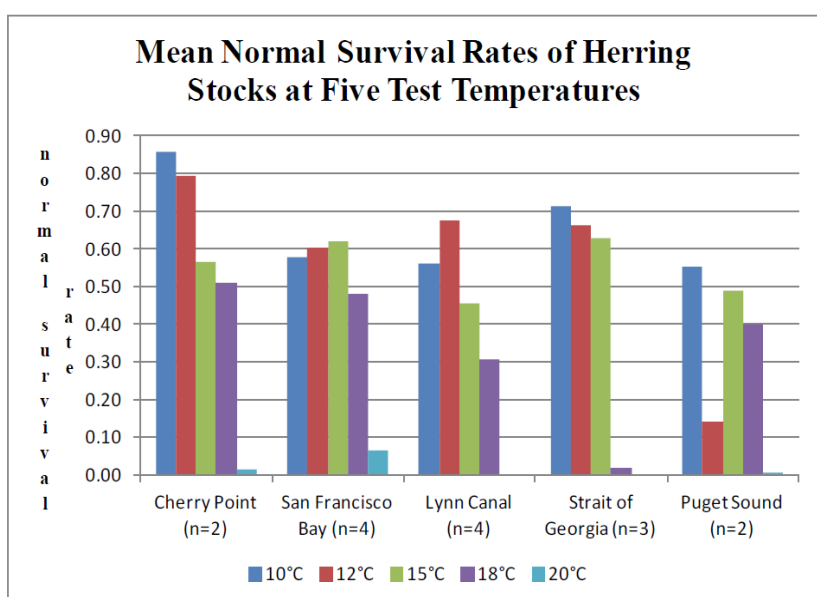


Figure 17. Herring survival rates at across temperature ranges.

Normal survival rate responses of five different Pacific herring stocks at five temperatures (from Appendix C of the report by the Washington Department of Ecology; n refers to the number of test chambers and varies by location. Report available at

www.ecy.wa.gov/biblio/1110086.html).

The swimming kinematics of other temperate fish larvae, such as Atlantic cod (*Gadus morhua*; Maneja et al., 2013) and walleye pollock (*Theragra chalcogramma*) from Puget Sound (Hurst et al., 2012), both pelagic spawners, were unaffected by increases in pCO₂. A study of sand smelt (*Atherina presbyter*) from Portugal exposed to elevated pCO₂ for up to 15 days found that swimming speeds were not affected, but biomarkers related to oxidative stress and energy metabolism were elevated at intermediate levels. Interestingly, the fish exposed to the highest pCO₂ levels grew faster and appeared to compensate, but likely only because of excess energy provided by the high amounts of prey fed, which does not simulate the natural environment (Silva et al., 2013).

However, a study of adult, female three-spine stickleback from Sweden reported behavioral changes in “boldness, exploratory behavior, lateralization, and learning” in a species known for its resilience to environmental extremes; the behavioral results were similar to the findings of many studies in coral reef fish (Jutfelt et al., 2013). Overall, these various studies appear to differ by species and based on pCO₂ exposure levels and duration, feeding levels, and co-stressors. It also appears that inter-individual

variation in the behavioral responses of some fishes to elevated $p\text{CO}_2$ selects for tolerant individuals, possibly resulting in perceived resilience to ocean acidification (Munday et al., 2012). “In this context, when measurements are made on individuals that have been exposed to high $p\text{CO}_2$ for some time... one could be observing those individuals that have been selected for their tolerance to $p\text{CO}_2$ — and that might be why there is no effect” (Maneja et al., 2015). Little data are currently available for the effects of OA on other forage fish species endemic to the Pacific Northwest, and so at present it is difficult to generalize across species because of the number of potential pathways and developmental processes that accompany diverse life histories.

VIII. Summary of key data gaps and uncertainties

From Herring Technical Team Workshop

1. How has spawn timing (variance, duration, onset, peak) changed over the past decades, and especially at sites where herring have declined or disappeared?
2. Are there interactive effects of spawning area truncation and bird predation on herring eggs?
3. What are mortality rates, abundance, and distribution patterns of larval herring? (Ichthyoplankton surveys)
4. What are hot spots of predation by harbor seals on herring? What is the cumulative predation of herring by pinnipeds (Chasco et al., 2017 analysis for herring).
5. What are the population-level effects of egg mortality versus adult mortality (elasticity analysis)?
6. How has submerged aquatic vegetation (non-eelgrass) distribution changed over time, and are those changes associated with herring abundance? Eelgrass in San Juan Islands?
7. What are human development patterns near the spawning sites in southern Strait of Georgia that have disappeared recently? Do these resemble areas in Puget Sound where herring are also in decline?
8. What are the physical impacts of shoreline armor? Nearshore sediments, vegetation type and distribution, turbidity.
9. How is the distribution of available herring habitat predicted to change under climate change scenarios?
10. Is predation by grey whales a major source of herring egg loss?

From previous compilations (Pentilla, 2007 and others)

1. Location and ecological roles of herring in the non-spawning months
2. Is critical depensation limiting productivity of stocks reduced to relatively low levels?
3. Causes of perennial herring spawn mass mortalities in certain Puget Sound bays

Certain subareas of some Puget Sound herring spawning grounds have exhibited a tendency to suffer unusual mass mortalities of herring eggs during their incubation period. Causes have not been determined but may involve sediment toxicity or water quality issues of significance to other nearshore resources as well.

4. Effectiveness of eelgrass and shoreline restoration for supporting herring recovery

There seems to be a growing sense of assurance that marine vegetation beds, including those used by spawning herring, are amenable to mitigation techniques to compensate for loss or damage due to shoreline development. Likewise shoreline armoring. However, there is high uncertainty of the true costs of such projects and the likelihood that they will succeed in replacing herring spawning habitat at a reasonable cost in perpetuity. Appropriate monitoring of permitted projects is extremely important. Any perception of apparent Marine Forage Fishes in Puget Sound success in mitigating for herring spawning habitat may undermine current regulatory efforts to preserve natural spawning grounds intact.

5. Causes of marine vegetation/herring spawning substrate disappearances in certain Puget Sound bays

Striking declines in the geographical distribution and abundance of eelgrass, including known herring spawning habitats, have been documented in a number of small bays in northern Puget Sound (e.g. NW San Juan Islands). The causes of these abrupt, marked declines are currently unknown and should be investigated for the benefit of not only herring critical habitat conservation but also the ecosystem in general. Eelgrass stock status monitoring should continue throughout the Puget Sound Basin to detect declines should they occur elsewhere (Dowty et al., 2005: http://file.dnr.wa.gov/publications/aqr_nrsh_03_04_svmp_rpt.pdf).

6. Population biology, ecology and status of stocks of the calanoid copepods and euphausiids that form the main diet of herring and other forage fishes (long-term zooplankton surveys)

The distribution, life history, ecology and potential stressors of the primary macro-zooplanktonic food items of herring, the next lower level of the Puget Sound neritic food web, are poorly known. Any such plankton investigations should perhaps be geared to also assess lower food-web levels, phytoplankton, and the micro-oceanographic processes and features at work within the southern Salish Sea.

7. Pinniped predation

The sections above dedicated to marine mammals indicate large-scale temporal changes in populations for several species (e.g. Killer and Humpback whale declines, Harbor porpoise increases). Additionally, some of these species easily adapt to secondary prey (seals and sea lions) while others are less successful (Killer whales). All of these factors could have unanticipated effects on the Salish Sea Pacific herring population. To gain a clearer understanding of these factors we need to continue to apply a myriad of diverse research approaches. Examples could include further analyses of fatty acids and stable isotopes, new ecological models, and a closer look at stock assessments documenting observed populations trends, natural mortality rates and shifts in age class dynamics.

Crawford et al. (2008) advocates best for the use of stable isotopes in these situations as: “The ability to use SIA to quantify prey items over differing temporal and spatial scales has allowed greater resolution of prey switching, scavenging or seasonal changes in foraging behavior (Darimont

& Reimchen, 2002; Roth, 2003; Ben-David et al., 2004). Obtaining empirical evidence to determine prey switching and the dynamics of energy flow within ecosystems has greatly improved our understanding of the interactions within communities and how these change over time. This work has led to further research more focused on how introduced prey affects the competition for resources among top predators.” For the trophic role of herring to be properly represented, local ecosystem models may need focus on the energy content contributions of local herring stocks in light of recovering marine mammal populations (Surma et al. 2018). Models must also consider how increased herring predation by marine mammals may impact other herring predators including fish and seabirds. Stock assessment models often give a rate of natural herring mortality. Researchers in other regions have compared the level of marine mammal consumption to these models (Read & Brownstein, 2003) and similar work might assist in filling in Salish sea data gaps. It may also be helpful to look more closely at specific age classes of herring as prey as some marine mammals show selectivity that may alter the age structure of the population (Gannon et al., 1998).

IX. Analytical decision support tools

Understanding the dynamic links between food webs, physical and biological factors, and human influences, and devising management actions to support recovery and conservation goals, requires developing appropriate tools to conduct the relevant assessments and analyses (Lester et al., 2010). The ecosystem-based management and assessment toolkit includes large soup-to-nuts ecosystem models, such as Atlantis (Fulton et al., 2005; Kaplan et al., 2012), mass-balance food-web models such as Ecopath with Ecosim (EwE; Christensen et al., 2005; Harvey et al., 2010), and ecosystem indicator analysis (Eero et al., 2012).

A variety of analytical tools have been developed, or are in the development process, that might inform conservation and management of Salish Sea herring. Most notably, such tools can help explore the relative importance of or support for alternative hypotheses about what is causing change in Salish Sea herring populations. Modeling tools can help highlight key uncertainties and interactions that have undue influence on system dynamics, and that warrant further research to support management action. Last, decision support tools can explore potential management scenarios, by evaluating the potential impact of management actions on herring and the entire ecosystem. Below is a brief description of some of the analytical, modeling, and decision support tools currently in development, or that should be developed to support herring conservation. Additional results from quantitative analyses and models are also incorporated into the sections above. The below examples emphasize ecosystem-scale and decision support tools particularly aimed at system dynamics and management scenarios.

A. EcoPath

A food web model of Central Puget Sound was developed in 2010 (Harvey et al., 2010). and has been as yet underutilized to evaluate impacts of food web changes on Puget Sound herring. While the geographic scope of the model is limited to the central basin of Puget Sound, herring are explicitly accounted for, in multiple life stages, and the key species identified as being of concern in this report, cetaceans, pinnipeds, etc., are also well represented in the model. Food web scenarios could be explored as part of an effort to evaluate impacts of change on Pacific herring in the Salish Sea.

An additional food web model focused solely on South Puget Sound has been developed (Priekshot et al., 2013), primarily to explore scenarios related to increases in shellfish aquaculture and changes in primary productivity. This model predicted a decrease in Pacific herring with a doubling of jellyfish abundance. The model also predicted that a halving of the sea lion population would increase herring by 50%. Similarly

to the Central Puget Sound model, the South Puget Sound model deserves further attention and exploration with respect to its utility for exploring herring-related actions and their potential consequences.

B. Atlantis

The Atlantis ecosystem model (Fulton, 2004; Fulton et al., 2011) is a spatially-explicit, end-to-end modeling approach that includes climate and oceanography, food web dynamics, habitat, biogeochemistry, and human impacts. At least 28 Atlantis ecosystem models have been applied in over a dozen ecosystems globally (Fulton et al., 2011), and an additional 16 are in development (E. Fulton, pers. comm.). Closest to home, the model has been applied to the California Current System to investigate management strategies for groundfish (Horne et al., 2010), ocean acidification (Kaplan et al., 2010), and cumulative effects of fisheries (Kaplan et al., 2012).

An Atlantis model for the Puget Sound is presently in development, focused on evaluating the drivers of early marine survival of Chinook salmon. This model development is a collaboration between NOAA Fisheries Northwest Fisheries Science Center and Long Live the Kings, and being led by Hem Nalini Morzaria, Isaac Kaplan, and Chris Harvey. The Atlantis model follows directly on the QNM developed by Sobocinski et al. (2017), also focused on early marine survival of Chinook. The model includes herring specifically, and includes the southern Salish Sea up to the United States/Canada border. Thus, it incorporates some, but not all of the herring spawning sites in the SoG. The model will test several hypothesized influences on Chinook survival: changes in food supply, as zooplankton composition and timing, and phytoplankton; impacts of competition for shared prey; and impacts of marine mammal predation. A second iteration of the model will explore the impacts of nutrients and pollutants.

While the Atlantis model is being configured to specifically address concerns related to Chinook, many of the results have potential implications for understanding herring dynamics and how the drivers explored in the model impact herring. Members of the Atlantis modeling team and their advisors have been working closely with the co-chairs of this report, on identification of key stressors for herring and QNM model development.

C. Management strategy evaluation

A food web model parameterized for northern British Columbia (excluding Strait of Georgia and Vancouver Island) demonstrated moderate impacts of fishing on herring stocks that would be more pronounced under a maximum sustainable yield approach (Surma et al., 2018). While the model was developed primarily to explore different fishery management strategies, and was not spatially explicit enough to show impacts on spawn distribution with fishing, such as has been hypothesized here, it did show that a collapse in herring would negatively affect humpback whales, dolphins and sea lions - all major herring predators. Thus, the model demonstrates the central role herring play in the food web.

D. Qualitative network models

Qualitative network modeling is another tool in the ecosystem-based management toolkit, which can be used to describe indirect linkages and the effects of changes in network state that are otherwise quantitatively difficult to describe, owing to system complexity or limited quantitative information about linkages (Puccia & Levins, 1985). Qualitative models are mathematically rigorous approaches to describing general relationships and trends in complex ecosystems in the absence of exact interaction strengths, information that is often lacking or imprecise, particularly in marine ecosystems. Qualitative network

models are particularly helpful in evaluating dynamics in social-ecological systems, when quantitative links between system components are often lacking; when attempting to account for interactions outside of food webs, for example the influence of terrestrial stressors, or for the influence of multiple factors, such as biogenic as well as physical habitat degradation; in exploring competing hypotheses about system dynamics; or in evaluating the potential system response to management actions (Dambacher et al., 2009).

Qualitative network analysis operates by perturbing the state (abundance or amount) of one or more components of a system, and evaluating the effects of that change on all other individual components of the system. Recent local applications of qualitative network models include evaluating the impact of different drivers on the California Current social-ecological system (Harvey et al. 2016); identifying the potential influence of various factors on survival of juvenile salmon in Puget Sound (Sobocinski et al. 2017); and assessing key interactions and potential responses to management actions related to bivalve aquaculture in Puget Sound (Reum et al., 2015).

Here we report on early efforts to evaluate the relative importance of multiple factors hypothesized to affect herring abundance and distribution in the Salish Sea, including: increased predation by pinnipeds, egg predation by seabirds, terrestrial-based contaminants, habitat loss and degradation. We used an expert elicitation process to construct a conceptual model of the herring ecosystem, including key food web interactions and exogenous factors influencing herring (Figure 18). The conceptual model included known and hypothesized direct positive or negative interactions between components. The conceptual model was subsequently used to construct a qualitative network model (QNM). Our use of QNMs followed roughly the methods of Melbourne-Thomas et al. (2012) as outlined by Reum et al. (2015) using the QPress package in R.

Because the factors hypothesized to influence herring abundance and distribution, as well as the food web interactions, are presumed to affect different life stages of herring, and to best inform potential management actions, our QNM initially included four life stages of herring: eggs, larvae, juveniles, and adults. Our aim was to explore scenarios by simulating positive perturbations (i.e., increases) on the factor hypothesized to affect herring, and to compare the results for their effect on the state (abundance) of each herring life stage. Those results could then be compared against existing data from herring biomass surveys in the Salish Sea to evaluate the support for the model.

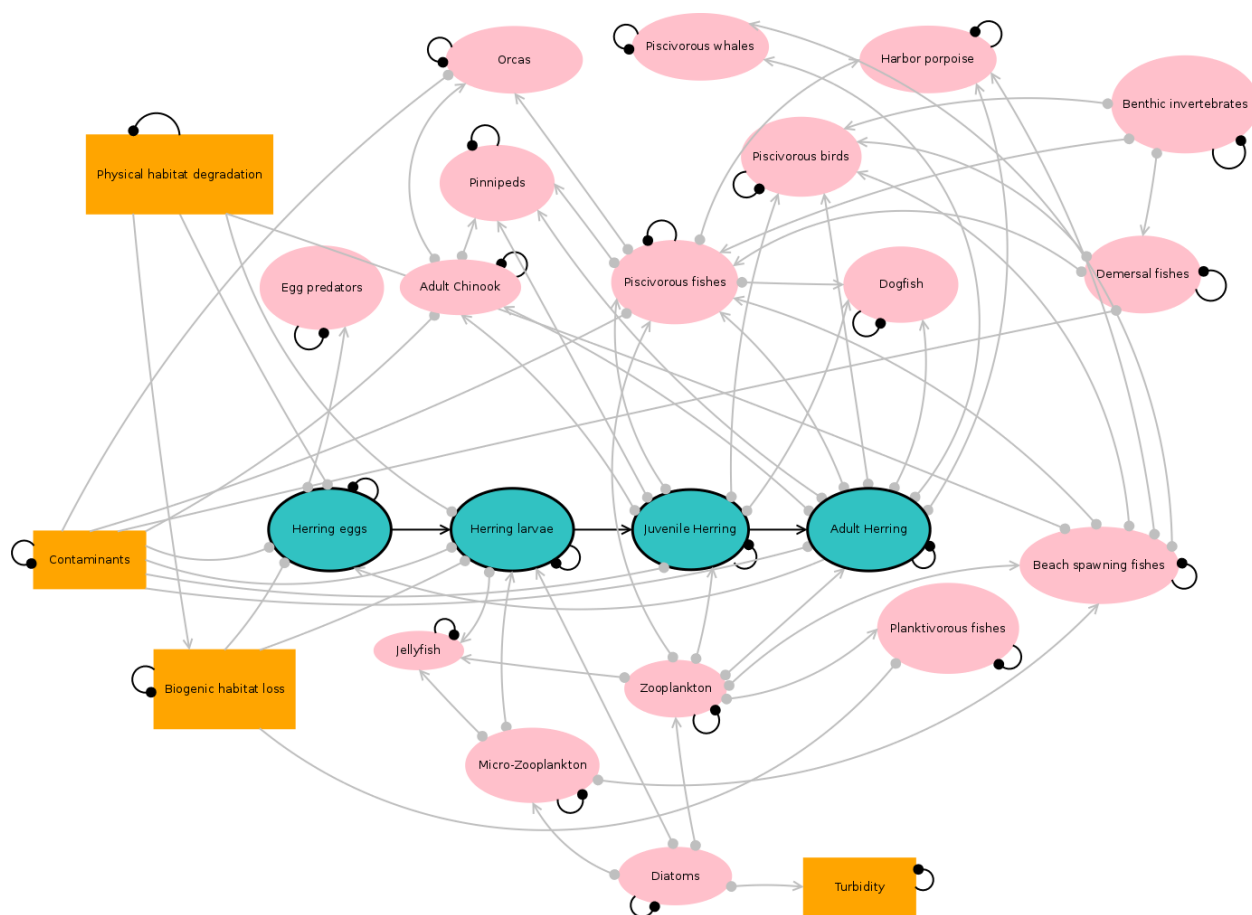


Figure 18. Conceptual model of the Salish Sea Herring system used for qualitative network model analysis.

Grey lines represent direct interactions between groups. Arrow endings show the direction of positive effects; circle endings show the direction of negative effect. All groups have self-limiting negative effects.

None of the five scenarios evaluated were consistent with observed trends in many substocks of herring in the Salish Sea, i.e., reduced adult abundance (Figure 19). Many of the model results showed negative impacts on early life stages of herring (eggs, larvae, juveniles), but not in the adult stages. Further exploration of the results revealed what are likely inherent flaws in model structure, i.e., the links between life stages of herring, which precluded impacts to early life stages affecting the adults. This is a logical flaw in the model structure: if eggs, larvae, and juvenile herring decline, how could that not affect the adult stages? Therefore, additional work is required on this model to resolve this issue. The likely next step is to pursue potential multi-model approach, wherein a separate population model generates predictions for the individual life stages that are then linked into the full QNM. This work will be pursued in the near future, but is currently beyond the scope of this report.

However, the model did reveal negative impacts of all the perturbations, save increased predation by pinnipeds and whales, on the early life stages of herring, suggesting that these are potentially important stressors on herring and should be investigated for potential management actions. Such potential actions are addressed in the below management section (Section IX).

PERTURBATION	Increase habitat loss		Increase egg predators		Increase pinnipeds		Increase Contaminants		Increase whales	
<i>direct effect on herring</i>	<i>neg on early life stages</i>		<i>neg on eggs</i>		<i>neg on adults & juv</i>		<i>neg on all life stages</i>		<i>neg on adults</i>	
<i>QNM configuration</i>	<i>complex</i>	<i>simple</i>	<i>complex</i>	<i>simple</i>	<i>complex</i>	<i>simple</i>	<i>complex</i>	<i>simple</i>	<i>complex</i>	<i>simple</i>
response variable										
Contaminants										
Biogenic habitat loss										
Turbidity										
Physical habitat degradation										
Orcas										
Harbor Porpoise										
Piscivorous whales										
Egg predators										
Planktivorous fishes										
Adult Chinook										
Dogfish										
Demersal fishes										
Benthic invertebrates										
Piscivorous fishes										
Piscivorous birds										
Pinnipeds										
Jellyfish										
Beach spawning fishes										
Zooplankton										
Micro-zooplankton										
Diatoms										
Adult Herring										
Juvenile Herring										
Herring larvae										
Herring eggs										
Herring										

Figure 19. Qualitative network model-predicted responses to simulated perturbations.

Shown are comparisons between a complex (including four herring life stages: eggs, larvae, juveniles, adults) and a simple (one herring group) model structure. Five perturbations were explored, based on leading hypotheses of causes of herring declines: habitat loss, egg predation, pinniped predation, whale predation, and contaminants. Results are shown for 10,000 stable model runs. Green cells indicate more than 80% of runs predicted a positive effect of the perturbation; orange cells indicate more than 80% of runs predicted a negative effect of the perturbation. Grey cells indicate an ‘indeterminate’ effect, i.e., less than 80% of either positive or negative effects were predicted. Black cells indicate nodes that were not affected by the perturbation. Black outlines indicate different results between the complex and simple model structures.

X. Potential management and conservation actions

The Salish Sea Pacific Herring Assessment and Management Strategy Team identified several actions that could influence factors that potentially limit herring recovery. Ideas for addressing specific stressors are described here, along with regulatory tools and constraints under U.S. and Washington State laws. Many of the Team’s proposed conservation actions are consistent with strategies proposed during other Puget Sound recovery planning efforts, so the following discussion focuses on new actions not addressed in other plans.

A. Reduce fishing effort

In recent years, several of the South Sound stocks had no or very low observed spawn, which is of particular concern because the sport bait fishery operates primarily in the south and central basins

(historically Hood Canal has been considered the same region due to a lack of genetic divergence, but no commercial herring harvest is allowed in Hood Canal). The WDFW has increased standard survey effort in response and initiated exploratory spawn surveys to determine if new spawning locations are in use. Despite these concerns about potential localized depletion of South Sound herring stocks, the existing commercial fishery is unlikely to have a significant effect on the persistence of herring in the SSS, and the harvested fish are generally juveniles originating from mixed stocks. Considering the cultural importance of this source of local, fresh bait and the minimal impact of the fishery the WDFW is highly unlikely to completely eliminate it but, rather, continue to manage it under the conservative framework now in place.

Strait of Georgia fisheries management practices have resulted in increasing or stable catch and biomass estimates over recent years, despite decreasing trends in other management areas. There is new research that supports the idea that fishing may be interacting with migratory behavior such that the population is experiencing local extinction (MacCall et al., 2018).

B. Reduce predation

1. Pinnipeds

The Strategy Team discussed reducing predation pressures on herring by decreasing the population of harbor seals and California sea lions. This could potentially be accomplished through lethal and/or nonlethal actions such as culling, fertility control, or disruption of haul-out areas. However, the U.S. Marine Mammal Protection Act (MMPA) would constrain implementation such measures. MMPA prohibits harassment, hunting, killing, and capture of pinnipeds without a take permit from NOAA.

Section 120 of MMPA does allow for lethal removal of individual sea lions provided they are causing significant harm to a population of salmon or steelhead protected under the Endangered Species Act. This MMPA take exemption was designed to deal with a few problem animals at areas of restricted fish passage (e.g., Ballard Locks and Bonneville Dam). States must apply to NOAA Fisheries for authority to remove “individually identifiable pinnipeds which are having a significant negative impact on the decline or recovery” of at-risk salmonids. This take permit process is administered on an animal-by-animal basis. A California sea lion must be present for five separate days, observed eating salmon, and subjected to hazing before going through the process of being listed for authorized removal.

Implementing lethal pinniped population control actions in Puget Sound would likely require amendment to the MMPA. Political readiness for such action may be low, as several proposed amendments to make it easier for state and tribal wildlife managers to cull sea lion predators of salmon and steelhead in the lower Columbia River have been introduced but none have passed (most recently H.R. 2083 *Endangered Salmon and Fisheries Predation Act* in 2017). If an amendment authorizing lethal removal to limit Puget Sound stock size did become law, the history of Section 120 implementation in the lower Columbia River indicates that years of litigation would likely follow.

Attempting to decrease populations via fertility control may be a more socially acceptable option. Immunocontraceptives have been successfully used to reduce wild horse and white-tail deer populations, as well as control births in captive California sea lions (Frank et al. 2005, Turner et al. 2008, Kirkpatrick et al. 2008). The porcine zona pellucida (PZA) vaccine is longer lasting than hormonal birth control, but multiple administrations are generally required. PZA has been demonstrated to have high efficacy in captive California sea lions (Frank et al. 2005). Brown et al. (1997) demonstrated effective contraception using a liposomal preparation of PZA in wild grey seals in coastal Nova Scotia; a single administration

reduced pup production by about 90% and no diminishing trend was observed during the 5-year study period.

2. Seabirds

Taking steps to reduce egg predation by seabirds is another management action proposed by the Strategy Team. Permits are not needed to harass protected birds (excluding species listed as threatened or endangered and bald eagles), so visual and sound frightening devices could be employed to modify feeding behaviors. Implementing this type of program would likely require National Environmental Policy Act or State Environmental Policy Act compliance, depending on whether the lead agency is federal or state. Each law has public notice and comment requirements. Management actions to reduce Caspian tern and cormorant predation of salmon smolts in the lower Columbia River have been controversial and subject to lawsuits.

One potential action is to protect herring eggs from seabird predation by covering them with cages. This could be explored at a limited set of herring spawning sites to evaluate their effectiveness in increasing recruitment. However, marine birds in Puget Sound have experienced significant declines and are protected under the federal Migratory Bird Treaty Act.

3. Jellyfish

Unlike pinnipeds and marine birds, jellyfish are not a protected species. Harvesting jellyfish would be the simplest predator control action to implement from regulatory and public relations perspectives, provided that bycatch (juvenile salmon, etc.) is minimal. Jellyfish have been harvested for human consumption for centuries in China and are currently a growing component of the aquaculture and fishing industries in Asia, where jellyfish hatcheries are used to supplement wild populations (Purcell et al., 2007; Richardson et al., 2009). Some researchers (Gibbons et al., 2016) have cautioned that, given our lack of understanding of the drivers of jellyfish blooms, fishing is likely not a ‘panacea’.

At present the best way to minimize the influence of jellyfish on herring and other forage fish is to reduce eutrophication, overfishing, marine hardening, and to minimize the effects of global warming (Richardson et al., 2009; Purcell et al., 2012), all of which may lead to expanded jellyfish populations in the Salish Sea.

C. Habitat Restoration

Several recent Puget Sound recovery planning efforts have focused on nearshore habitat improvements that would likely benefit herring. These include a Puget Sound Eelgrass Recovery Strategy (WDNR 2015), Puget Sound Estuaries Implementation Strategy (PSP 2015), Chinook Salmon Implementation Strategy (PSP 2018), and Shoreline Armoring Implementation Strategy (Habitat Strategic Initiative 2018). A major unknown is how current habitat restoration projects are supporting herring recovery. Also unknown are the habitat status of Strait of Georgia sites where herring spawning has been lost. Last, a landscape-scale approach to understanding nearshore habitat requirements for herring at early life stages is needed to inform restoration activities.

D. Reduce nearshore stressors

1. Light pollution

Managing nearshore light pollution could potentially reduce nocturnal predation risk for small fishes like herring. Regulation of lighting most commonly occurs in county and municipal zoning codes. Measures

that could reduce direct spillover of light onto nearshore waters include eliminating unnecessary lighting; manipulating placement, color, and intensity (e.g., directed luminaires, shielded light sources, recessed fixtures, lower pole-mounting, motion-detector switches); and ensuring bulbs emit the least disruptive color (long-wavelength light sources have been shown to have less impact on some species).

Such mitigation measures are often considered during environmental reviews for larger projects. For example, impacts to salmonids protected under the Endangered Species Act were factored into lighting evaluations/decisions for the SR 520 Floating Bridge over Lake Washington. However, there is a lack of retrofit programs for existing development. Encouraging lighting retrofits along Puget Sound shorelines through an incentive program could be a way to reduce the impact of this stressor.

Tackling urban sky-glow would require a regional approach. Less than 20 U.S. states have laws in place to reduce light pollution and Washington is not one of them. Drivers of existing lighting regulation include energy conservation, public safety, aesthetics, sky-gazing/astronomy, and wildlife conservation. Highlighting a link between lighting and negative impacts on the marine food web could be an opportunity to drive larger and more widespread actions to reduce light pollution.

2. Small vessel activity

Strategy Team members identified small vessel activity in the nearshore as a potential stressor to herring. Vessel anchoring, wakes, and associated sediment suspension could increase egg mortality. Impacts could be reduced through management measures such as placement of waterway markers, designation of slow-no-wake areas, and voluntary no anchor zones in spawning areas. Local jurisdictions have the authority to establish restricted mooring zones and speed limits.

Expansion of eelgrass compatible boating infrastructure in high-use mooring areas was identified as a priority for action in Puget Sound Eelgrass Recovery Strategy (WDNR 2015). The Jefferson Marine Resources Committee has created voluntary no anchor zones by placing marker buoys along the outer edge of eelgrass beds. Placement of this type of infrastructure does require several types of permits and authorizations from federal, state, and local governments as well as annual installation and maintenance (buoys are in place only during peak boating season).

E. Improve water quality

1. Toxics

An Implementation Strategy for the Toxics in Fish Vital Sign is currently under development. PCBs and PAHs are two of the chemical groups that are a focus of this effort, and herring is an indicator species for the Toxics in Fish Vital Sign. The role herring plays in trophic transfer of contaminants within Puget Sound has been central in discussions among the group developing the IS.

One topic that is not the focus of the TIF Implementation Strategy, but may be important for herring, is removal of creosote-contaminated pier and dock pilings. Experimental removals in Port Gamble and Quilcene Bay have demonstrated that, if done correctly, piling removal can result in lower PAH burdens in herring embryos, which may increase survival rates in those areas (West et al. 2018: <https://www.eopugetsound.org/magazine/sssec2018/pilings>).

2. Nutrients

Reducing nutrient inputs is the focus of the Department of Ecology's ongoing Puget Sound Nutrient Source Reduction Project and a Marine Water Quality Implementation Strategy which will be developed beginning in summer 2018.

F. Manage shipping traffic

1. Noise

Identifying management measures to reduce noise associated with vessel traffic is a focus of the Southern Resident Killer Whale Task Force's Vessel Work Group.

2. Oil spill risk

Modeling efforts to determine the population-level effects of potential oil spills indicate that the healthy stocks remaining in Puget Sound could withstand short term impacts, but depressed and unhealthy stocks are vulnerable to an increased risk of localized extinction (Stromberg et al. 2018: <http://www.psp.wa.gov/oilspills.php>). Reducing oil spill risk is also a focus of the Southern Resident Killer Whale Task Force's Vessel Work Group. Their work will be informed recent efforts to identify and implement risk mitigation measures, including updated Vessel Traffic Risk Assessment (VTRA) modeling and a 2016 workshop on Salish Sea Vessel Oil Spill Risk Assessment and Management (Van Dorp & Merrick 2017; Department of Ecology 2016).

G. Population Interventions

1. Transplant herring eggs to increase survival

Egg mortality rates are high (as high as 99.99%) at some Salish Sea spawning sites (TB Francis, pers. comm.). If the egg stage is a limiting stage for herring populations, boosting egg production and survival may increase herring abundance.

Members of the Pacific Northwest tribes, in addition to utilizing herring as food and bait, have apparently translocated herring spawn either to re-establish herring in locations where a spawn disappearance has occurred or to move them to better habitat following shoreline disturbance. In Tlingit, Haida and Sitka oral histories, mythic figures ("salmon boy" and the "herring maiden") collected herring eggs and used them to establish new spawning areas (Thornton, 2015 is recommended reading). Oral histories recount how natives frequently placed hemlock boughs or macroalgae anchored with rocks in water from 6 feet above to 3 feet below mean low water and moved the eggs to new areas to translocate spawning herring with success, but only when appropriate respect and customs were followed. Tlingits also discussed the "Wind of the washing of the spawn," a special storm typically occurring within several days after the herring spawned, as important in helping distribute and break up the herring spawn (Thornton, 2015), which may have helped thin layers of heavy spawn in which the inner layers would otherwise suffocate. Scientists at the Department of Fisheries and Oceans (DFO), Canada, attempted to emulate this practice in British Columbia. Spawn that had washed ashore as windrows (and thus not expected to survive otherwise) was gathered and transported to a new, suitable location (17,000 kg in 1982 and 9,000 kg in 1984). The eggs were carefully monitored to ensure viability and, after transfer and successful hatching, were detected as viable larvae in the water column for roughly three weeks, but adult herring did not

return in following years to spawn independently (Hay and Marlaive, 1988). Further attempts were discontinued over concern that it might risk “creating the mistaken impression among the public, politicians, resource managers, and industrial developers that this approach can be used to mitigate the effects of industrial or recreational developments on establish spawning areas....**The approach cannot be used or cited, at the present time, as a method to compensate for the destruction of established spawning habitat**” (Hay and Marlaive, 1988; emphasis added). Those concerns are well-founded. However, windrows of heavy spawn were found in Quilcene Bay in 2018 (WDFW), one of the few bright spots for herring in the SSS in the last decade, and similar experiments could be attempted.

Compliance could be relatively straightforward – one would need to obtain a WDFW scientific collection permit and WDFW transport, release or planting permit.

2. Artificial Production of Forage Fish

The artificial propagation of forage fish in the Puget Sound (via hatcheries) has been suggested as a potential measure to improve survival and abundance of species such as Chinook salmon. Herring have been cultured in Japan, anadromous herring (Evans et al., 2018) and smelt have been successfully cultured on the east coast of the U.S., and Delta smelt have been raised in California (<https://fccl.ucdavis.edu/>); most of these efforts have been to re-establish extirpated populations in areas where habitat has been restored, or have focused on preventing extinction of very small populations. As a result, producing forage fish in hatcheries seems to be technically feasible.

A number of data gaps remain to be filled before a hatchery approach for herring could be considered. There is a long list of potential unintended consequences, ranging from increased prevalence of diseases such as viral hemorrhagic septicemia (VHS) that could impact herring stocks, especially those in confinement (Hershberger et al., 1999; 2001; 2015), to competition from hatchery fish with other forage species and/or juvenile salmon, all of which need to be better understood.

Another unknown is whether there are sufficient prey resources to support increased production in herring. There is evidence that the food web in the Salish Sea is governed by “bottom-up” processes, i.e. the number of forage fish (and their predators) is dictated in large part by physical, chemical and biological factors controlling the production of phytoplankton and zooplankton (Mackas et al., 2013; Boldt et al., 2018). Long-term datasets on phytoplankton and zooplankton are essential to our understanding of the trophic ecology of the Salish Sea, as well as our ability to detect and understand the influences of climate change in the region. There is also some evidence for “top-down” control (i.e. predation) on age-0 herring condition (Boldt et al., 2018), because less fit individuals are removed from the population, and on recruitment of herring to the West Coast Vancouver Island stocks (outside the SS) as a result of Pacific hake abundance/predation (Tanasichuk, 2017). However, there is little evidence for the “Wasp-waist” model (Curry & Bakun, 2000; Bakun et al., 2010) of ecosystem control by forage fish that is commonly found in coastal oceanic systems, where the abundance of forage fish structures the ecosystem (in that model, recruitment is also bottom-up influenced as oceanic variables heavily influence forage fish survival and fluctuations in stock size). As a result, the addition of forage fish from hatcheries into the Salish Sea may only result in more starving forage fish, which may ultimately feed benthic predators, jellyfish or seabirds but might have no positive effect on Chinook salmon or Killer whales; in fact, hatchery herring may end up competing with juvenile Chinook salmon for food.

Finally, there are lessons to be learned from the attempts at artificial production of Pacific salmon species throughout the Northeast Pacific. Despite the allocation of significant research and hundreds of millions

of dollars annually (in the U.S. alone) in funding for salmon hatcheries, we are faced with an expanding list of ESA (U.S.) or SARA (Canada) protected salmon stocks and declining salmon returns. Only in the past two decades have we begun to understand the negative, unanticipated consequences of salmon hatcheries (an excellent review is the special issue on hatcheries in the PNW: *Environmental Biology of Fish*, 2012, volume 94); we should not ignore those lessons.

3. Modify hatchery salmon release timing

As outlined above, juvenile salmon and adult herring may compete for food resources, primarily larger zooplankton (euphausiids and crab megalopae). The availability of such prey is dictated by the timing of the spring and fall phytoplankton blooms, which then result in expansion of zooplankton populations. Since hatchery herring release timing can be altered to better match these natural events, this may be an avenue worthy of further inquiry; note this approach may require ESA Section 7 consultations.

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XII. References

- Aguilera, Victor M., Cristian A. Vargas, Marco A. Lardies, and María J. Poupin. 2016. "Adaptive Variability to Low-PH River Discharges in *Acartia tonsa* and Stress Responses to High PCO₂ Conditions." *Marine Ecology* 37 (1): 215–26. <https://doi.org/10.1111/maec.12282>.
- Ainsworth, C. H., T. J. Pitcher, J. J. Heymans, and M. Vasconcellos. 2008. "Reconstructing Historical Marine Ecosystems Using Food Web Models: Northern British Columbia from Pre-European Contact to Present." *Ecological Modelling* 216 (3): 354–68. <https://doi.org/10.1016/j.ecolmodel.2008.05.005>.
- Alder, Jacqueline, Brooke Campbell, Vasiliki Karpouzi, Kristin Kaschner, and Daniel Pauly. 2008. "Forage Fish: From Ecosystems to Markets." *Annual Review of Environment and Resources* 33 (1): 153–66. <https://doi.org/10.1146/annurev.enviro.33.020807.143204>.
- Alderice, D. F., and A. S. Hourston. 1985. "Factors Influencing Development and Survival of Pacific Herring (*Clupea harengus*) Eggs and Larvae to Beginning of Exogenous Feeding." *Canadian Journal of Fisheries and Aquatic Sciences* 42 (S1): s56–68. <https://doi.org/10.1139/f85-262>.

- Alderdice, D. F., and F. P. J. Velsen. 1971. "Some Effects of Salinity and Temperature on Early Development of Pacific Herring (*Clupea Pallasii*).*" Journal of the Fisheries Research Board of Canada* 28 (10): 1545–62. <https://doi.org/10.1139/f71-234>.
- Anderson, Eric M., James R. Lovvorn, Daniel Esler, W. Sean Boyd, and Kurt C. Stick. 2009. "Using Predator Distributions, Diet, and Condition to Evaluate Seasonal Foraging Sites:: Sea Ducks and Herring Spawn." *Marine Ecology Progress Series* 386: 287–302.
- Asch, Rebecca G. 2015. "Climate Change and Decadal Shifts in the Phenology of Larval Fishes in the California Current Ecosystem." *Proceedings of the National Academy of Sciences* 112 (30): E4065–74. <https://doi.org/10.1073/pnas.1421946112>.
- Babson, A. L., M. Kawase, and P. MacCready. 2006. "Seasonal and Interannual Variability in the Circulation of Puget Sound, Washington: A Box Model Study." *Atmosphere-Ocean* 44 (1): 29–45. <https://doi.org/10.3137/ao.440103>.
- Bakun, A., B. A. Black, S. J. Bograd, M. García-Reyes, A. J. Miller, R. R. Rykaczewski, and W. J. Sydeman. 2015. "Anticipated Effects of Climate Change on Coastal Upwelling Ecosystems." *Current Climate Change Reports* 1 (2): 85–93. <https://doi.org/10.1007/s40641-015-0008-4>.
- Bakun, Andrew, Elizabeth A. Babcock, Salvador E. Lluch-Cota, Christine Santora, and Christian J. Salvadeo. 2010. "Issues of Ecosystem-Based Management of Forage Fisheries in 'Open' Non-Stationary Ecosystems: The Example of the Sardine Fishery in the Gulf of California." *Reviews in Fish Biology and Fisheries* 20 (1): 9–29. <https://doi.org/10.1007/s11160-009-9118-1>.
- Bargmann, Greg. 1998. "Forage Fish Management Plan: A Plan for the Forage Fish Resources and Fisheries of Washington." Olympia, WA: WDFW.
- Bassin, C.J. et al., 2011. "Decadal Trends in Temperature and Dissolved Oxygen in Puget Sound: 1932-2009." Hood Canal Dissolved Oxygen Program Integrated Assessment & Modeling Study Report, Chapter 3, Section 2, <http://www.hoodcanal.washington.edu/news-docs/publications.jsp>.
- Beacham, T. D., J. F. Schweigert, C. MacConnachie, K.D. Le, and L. Flostrand. 2008. "Use of Microsatellites to Determine Population Structure and Migration of Pacific Herring in British Columbia and Adjacent Regions." *Transactions of the American Fisheries Society* 137: 1795–1811.
- Beamer, Eric, and Kurt L Fresh. 2012. "Juvenile Salmon and Forage Fish Presence and Abundance in Shoreline Habitats of the San Juan Islands, 2008-2009." LaConner, WA: Skagit River Cooperative.
- Beamish, Richard J, and Ruston M Sweeting. 2009. "Spiny Dogfish in the Pelagic Waters of the Strait of Georgia and Puget Sound." In *Biology and Management of Dogfish Sharks*, 101–18.
- Beamish, R.J., A.J. Benson, R.M. Sweeting, and C.M. Neville. 2004. "Regimes and the History of the Major Fisheries off Canada's West Coast." *Progress in Oceanography* 60 (2–4): 355–85. <https://doi.org/10.1016/j.pocean.2004.02.009>.
- Beauchamp, David A. 1990. "Diel and Seasonal Food Habits of Rainbow Trout Stocked as Juveniles in Lake Washington." *Transactions of the American Fisheries Society* 119 (3): 475–82. [https://doi.org/10.1577/1548-8659\(1990\)119<0475:SADFHO>2.3.CO;2](https://doi.org/10.1577/1548-8659(1990)119<0475:SADFHO>2.3.CO;2).
- Beauchamp, David A, and Elisabeth J Duffy. 2011. "Stage-Specific Growth and Survival during Early Marine Life of Puget Sound Chinook Salmon in the Context of Temporal-Spatial Environmental Conditions and Trophic Interactions." Final Report to the Pacific Salmon Commission. Washington Cooperative Fish and Wildlife Research Unit.
- Beauchamp, David A., Sharon A. Vecht, and G. L. Thomas. 1992. "Seasonal, Diel, and Size-Related Food Habits of Cutthroat Trout in Lake Washington." *Northwest Science* 66: 149–59.
- Ben-David, Merav, Kimberly Titus, and LaVern R. Beier. 2004. "Consumption of Salmon by Alaskan Brown Bears: A Trade-off between Nutritional Requirements and the Risk of Infanticide?" *Oecologia* 138 (3): 465–74. <https://doi.org/10.1007/s00442-003-1442-x>.
- Benson, Ashleen J., Sean P. Cox, and Jaclyn S. Cleary. 2015. "Evaluating the Conservation Risks of Aggregate Harvest Management in a Spatially-Structured Herring Fishery." *Fisheries Research* 167 (July): 101–13. <https://doi.org/10.1016/j.fishres.2015.02.003>.

- Bizzarro, Joseph J., Ashley N. Peterson, Jennifer M. Blaine, Jordan P. Balaban, H. Gary Greene, and Adam P. Summers. 2016. "Burrowing Behavior, Habitat, and Functional Morphology of the Pacific Sand Lance (*Ammodytes Personatus*).¹" *Fishery Bulletin* 114 (4): 445–60. <https://doi.org/10.7755/FB.114.4.7>.
- Blaine, Jennifer. 2006. "Pacific Sand Lance (*Ammodytes Sp.*) Present in the Sandwave Field of Central San Juan Channel, WA: Abundance, Density, Maturity, and Sediment Association." Friday Harbor Laboratories.
- Bodenstein, Sophie. 2012. "Effects of Ocean Acidification and Temperature on Chloride Cells in Atlantic Herring (*Clupea Harengus*) Embryos and Larvae." Kiel, Germany: Christian Albrechts University.
- Boldt, J.L., M. Thompson, C.N. Rooper, D.E. Hay, J.F. Schweigert, T.J. Quinn II, J.S. Cleary, and C.M. Neville. 2018. "Bottom-up and Top-down Control of Small Pelagic Forage Fish: Factors Affecting Age-0 Herring in the Strait of Georgia, British Columbia." *Marine Ecology Progress Series* (April): 1–14. <https://doi.org/10.3354/meps12485>.
- Brock, V.E., and R.H. Riffenburgh. 1960. "Fish Schooling: A Possible Factor in Reducing Predation." *ICES Journal of Marine Science* 25 (3): 307–17.
- Bromaghin, Jeffrey F., Monique M. Lance, Elizabeth W. Elliott, Steven J. Jeffries, Alejandro Acevedo-Gutiérrez, and John M. Kennish. 2013. "New Insights into the Diets of Harbor Seals (*Phoca Vitulina*) in the Salish Sea Revealed by Analysis of Fatty Acid Signatures." *Fishery Bulletin* 111 (1). <https://doi.org/10.7755/FB.111.1.2>.
- Broetz, Lucas, William W. L. Cheung, Kristin Kleisner, Evgeny Pakhomov, and Daniel Pauly. 2012. "Increasing Jellyfish Populations: Trends in Large Marine Ecosystems." *Hydrobiologia* 690 (1): 3–20. <https://doi.org/10.1007/s10750-012-1039-7>.
- Brown, R. G, W.D. Bowen, J.D. Eddington, W.C. Kimmins, M. Mezei, J.L. Parsons, and B. Pohajdak. 1997. "Evidence for a Long-Lasting Single Administration Contraceptive Vaccine in Wild Grey Seals." *Journal of Reproductive Immunology* 35 (1): 43–51. [https://doi.org/10.1016/S0165-0378\(97\)00047-8](https://doi.org/10.1016/S0165-0378(97)00047-8).
- Buckley, T. W. and P. A. Livingston. 1997. Geographic Variation in the Diet of Pacific Hake, with a Note on Cannibalism. CalCOFI Rep., Vol. 38.
- Burge, C.A., C.M. Eakin, C.S. Friedman, B. Froelich, P. K. Hershberger, E.E. Hofmann, L.E. Petes, et al. 2014. "Climate Change Influences on Marine Infectious Diseases: Implications for Management and Society." *Annual Review of Marine Science* 6: 249–77.
- Burger, M., T. Sandell, C. Fanshier, A. Lindquist, P. Biondo, and D. Lowry, 2018 (in progress). "2016-'17 Puget Sound Acoustic Mid-water Trawl Survey Final Report," WDFW Marine Fish Division, Olympia.
- Busch, D. Shallin, and Paul McElhany. 2016. "Estimates of the Direct Effect of Seawater PH on the Survival Rate of Species Groups in the California Current Ecosystem." *PLOS ONE* 11 (8): e0160669. <https://doi.org/10.1371/journal.pone.0160669>.
- Chapman, W.M., M. Katz, and D.W. Erickson. 1941. "The Races of Herring in the State of Washington." Washington Biological Report 38A. Olympia, WA.
- Chasco, Brandon E., Isaac C. Kaplan, Austen C. Thomas, Alejandro Acevedo-Gutiérrez, Dawn P. Noren, Michael J. Ford, M. Bradley Hanson, et al. 2017. "Competing Tradeoffs between Increasing Marine Mammal Predation and Fisheries Harvest of Chinook Salmon." *Scientific Reports* 7 (1): 15439. <https://doi.org/10.1038/s41598-017-14984-8>.
- Checkley, David M., Jurgen Alheit, Yoshioki Oozeki, and Claude Roy. 2009. *Climate Change and Small Pelagic Fish*. New York: Cambridge University Press.
- Checkley, David M., Rebecca G. Asch, and Ryan R. Rykaczewski. 2017. "Climate, Anchovy, and Sardine." *Annual Review of Marine Science* 9 (1): 469–93. <https://doi.org/10.1146/annurev-marine-122414-033819>.
- Chittaro, Paul M., Richard W. Zabel, Wayne Palsson, and Chris Grandin. 2013. "Population Interconnectivity and Implications for Recovery of a Species of Concern, the Pacific Hake of Georgia Basin." *Marine Biology* 160 (5): 1157–70. <https://doi.org/10.1007/s00227-013-2168-x>.
- Christensen, Villy, and Carl J Walters. 2005. "Using Ecosystem Modeling for Fisheries Management: Where Are We?," ICES Annual Conference, Aberdeen, Scotland, pp.16.

- Cleary, J. S., S. P. Cox, and J. F. Schweigert. 2010. "Performance Evaluation of Harvest Control Rules for Pacific Herring Management in British Columbia, Canada." *ICES Journal of Marine Science* 67 (9): 2005–11. <https://doi.org/10.1093/icesjms/fsq129>.
- Cleary, J. S., and J. F. Schweigert. 2012. "Stock Assessment and Management Advice for the British Columbia Herring Stocks: 2010 Assessment and 2011 Forecasts." 2011/115. DFO Can. Sci. Advis. Sec.
- Cleary, J.S., Hawkshaw, S., Grinnell, M.H., Grandin, C. 2018. Status of B.C. Pacific Herring (*Clupea pallasii*) in 2017 and forecasts for 2018 DFO Can. Sci. Advis. Sec. Res. Doc. 2018/nnn. vii + 273 p.
- Condon, Robert H., William M. Graham, Carlos M. Duarte, Kylie A. Pitt, Cathy H. Lucas, Steven H.D. Haddock, Kelly R. Sutherland, et al. 2012. "Questioning the Rise of Gelatinous Zooplankton in the World's Oceans." *BioScience* 62 (2): 160–69. <https://doi.org/10.1525/bio.2012.62.2.9>.
- Coumou, D., and Stefan Rahmstorf. 2012. "A Decade of Weather Extremes." *Nature Climate Change* 2: 491–96.
- Courchamp, Franck, Tim Clutton-Brock, and Bryan Grenfell. 1999. "Inverse Density Dependence and the Allee Effect." *Trends in Ecology & Evolution* 14 (10): 405–10. [https://doi.org/10.1016/S0169-5347\(99\)01683-3](https://doi.org/10.1016/S0169-5347(99)01683-3).
- Crawford, Kerry, Robbie A. McDonald, and Stuart Bearhop. 2008. "Applications of Stable Isotope Techniques to the Ecology of Mammals." *Mammal Review* 38 (1): 87–107. <https://doi.org/10.1111/j.1365-2907.2008.00120.x>.
- Cripps, Gemma, Kevin J. Flynn, and Penelope K. Lindeque. 2016. "Ocean Acidification Affects the Phyto-Zoo Plankton Trophic Transfer Efficiency." *PLOS ONE* 11 (4): e0151739. <https://doi.org/10.1371/journal.pone.0151739>.
- Cripps, Gemma, Penelope Lindeque, and Kevin Flynn. 2014. "Parental Exposure to Elevated PCO₂ Influences the Reproductive Success of Copepods." *Journal of Plankton Research* 36 (5): 1165–74. <https://doi.org/10.1093/plankt/fbu052>.
- Cury, P. 2000. "Small Pelagics in Upwelling Systems: Patterns of Interaction and Structural Changes in 'Wasp-Waist' Ecosystems." *ICES Journal of Marine Science* 57 (3): 603–18. <https://doi.org/10.1006/jmsc.2000.0712>.
- Cury, Philippe M., Ian L. Boyd, Sylvain Bonhommeau, Tycho Anker-Nilssen, Robert J. M. Crawford, Robert W. Furness, James A. Mills, et al. 2011. "Global Seabird Response to Forage Fish Depletion—One-Third for the Birds." *Science* 334 (6063): 1703–6.
- Cushing, D.H. 1969. "Regularity of Spawning Season of Some Fishes." *Journal Du Conseil* 33 (1): 81.
- Dambacher, Jeffrey M., Daniel J. Gaughan, Marie-Joëlle Rochet, Philippe A. Rossignol, and Verena M. Trenkel. 2009. "Qualitative Modelling and Indicators of Exploited Ecosystems." *Fish and Fisheries* 10 (3): 305–22. <https://doi.org/10.1111/j.1467-2979.2008.00323.x>.
- Darimont, C. T., and T. E. Reimchen. 2002. "Intra-Hair Stable Isotope Analysis Implies Seasonal Shift to Salmon in Gray Wolf Diet." *Canadian Journal of Zoology* 80 (9): 1638–42. <https://doi.org/10.1139/Z02-149>.
- Department of Fisheries and Oceans, Canada (DFO). 2015. Proceedings of the Pacific regional peer review on Stock Assessment and Management Advice for BC Pacific Herring: 2014 Status and 2015 Forecast; September 3-4, 2014. DFO Can. Sci. Advis. Sec. Proceed. Ser. 2015/006.
- De Robertis, A., and N. O. Handegard. 2013. "Fish Avoidance of Research Vessels and the Efficacy of Noise-Reduced Vessels: A Review." *ICES Journal of Marine Science* 70 (1): 34–45. <https://doi.org/10.1093/icesjms/fss155>.
- Dennis, B. 1989. "Allee Effects: Population Growth, Critical Density, and the Chance of Extinction." *Natural Resource Modeling* 3: 481–538.
- Doksæter, Lise, Olav Rune Godø, Nils Olav Handegard, Petter H. Kvadsheim, Frans-Peter A. Lam, Carl Donovan, and Patrick J. O. Miller. 2009. "Behavioral Responses of Herring (*Clupea Harengus*) to 1–2 and 6–7kHz Sonar Signals and Killer Whale Feeding Sounds." *The Journal of the Acoustical Society of America* 125 (1): 554–64. <https://doi.org/10.1121/1.3021301>.
- Domenici, Paolo, John F. Steffensen, and Stefano Marras. 2017. "The Effect of Hypoxia on Fish Schooling." *Phil. Trans. R. Soc. B* 372 (1727): 20160236. <https://doi.org/10.1098/rstb.2016.0236>.

- Drapeau, G. 1973. Sedimentology of herring spawning ground on Georges Bank. International Commission for the Northwest Atlantic Fisheries (ICNAF) Research Bulletin 10: 151-162.
- Duarte, Carlos M, Kylie A Pitt, Cathy H Lucas, Jennifer E Purcell, Shin-ichi Uye, Kelly Robinson, Lucas Brotz, et al. 2013. "Is Global Ocean Sprawl a Cause of Jellyfish Blooms?" *Frontiers in Ecology and the Environment* 11 (2): 91–97.
- Duffy, Elisabeth J., David A. Beauchamp, Ruston M. Sweeting, Richard J. Beamish, and James S. Brennan. 2010. "Ontogenetic Diet Shifts of Juvenile Chinook Salmon in Nearshore and Offshore Habitats of Puget Sound." *Transactions of the American Fisheries Society* 139 (3): 803–23. <https://doi.org/10.1577/T08-244.1>.
- Duguid, William D.P., Jennifer L. Boldt, Lia Chalifour, Correigh M. Greene, Moira Galbraith, Douglas Hay, Dayv Lowry, et al. 2018. "Historical Fluctuations and Recent Observations of Northern Anchovy *Engraulis mordax* in the Salish Sea." *Deep Sea Research Part II: Topical Studies in Oceanography*, May. <https://doi.org/10.1016/j.dsr2.2018.05.018>.
- Edwards, A.M., I.G. Taylor, C.J. Grandin, and A.M. Berger. 2018. Status of the Pacific Hake (whiting) stock in U.S. and Canadian waters in 2018. Prepared by the Joint Technical Committee of the U.S. and Canada Pacific Hake/Whiting Agreement, National Marine Fisheries Service and Fisheries and Oceans Canada. 222 p.
- Eero, Margit, Martin Lindegren, and Friedrich W. Köster. 2012. "The State and Relative Importance of Drivers of Fish Population Dynamics: An Indicator-Based Approach." *Ecological Indicators* 15 (1): 248–52. <https://doi.org/10.1016/j.ecolind.2011.09.035>.
- Essington, Timothy E., and Caroline E. Paulsen. 2010. "Quantifying Hypoxia Impacts on an Estuarine Demersal Community Using a Hierarchical Ensemble Approach." *Ecosystems* 13 (7): 1035–48. <https://doi.org/10.1007/s10021-010-9372-z>.
- Evans, Heather K., Kara B. Carlson, Russ Wisser, Morgan E. Raley, Katy M. Potoka, and Kevin J. Dockendorf. 2018. "Genetics and Hatchery Management: A Parentage-Based Tagging Approach to Blueback Herring Conservation." *Journal of Fish and Wildlife Management* 9 (1): 4–13. <https://doi.org/10.3996/022017-JFWM-011>.
- Everitt, R.D., Gearin, P.J., Skidmore, J.S. and DeLong, R.L., 1981. Prey items of harbor seals and California sea lions in Puget Sound, Washington. *The Murrelet*, 62(3), pp.83-86.
- Falchi, Fabio, Pierantonio Cinzano, Dan Duriscoe, Christopher C. M. Kyba, Christopher D. Elvidge, Kimberly Baugh, Boris A. Portnov, Nataliya A. Rybnikova, and Riccardo Furgoni. 2016. "The New World Atlas of Artificial Night Sky Brightness." *Science Advances* 2 (6): e1600377. <https://doi.org/10.1126/sciadv.1600377>.
- Falcone, E., Calambokidis, J., Steiger, G.H., Malleson, M. and Ford, J., 2005, March. Humpback whales in the Puget Sound/Georgia Strait Region. In *Proceedings of the 2005 Puget Sound Georgia Basin Research Conference*.
- Feely, Richard A., Simone R. Alin, Jan Newton, Christopher L. Sabine, Mark Warner, Allan Devol, Christopher Krembs, and Carol Maloy. 2010. "The Combined Effects of Ocean Acidification, Mixing, and Respiration on PH and Carbonate Saturation in an Urbanized Estuary." *Estuarine, Coastal and Shelf Science* 88 (4): 442–49. <https://doi.org/10.1016/j.ecss.2010.05.004>.
- Fitzer, Susan C., Gary S. Caldwell, Andrew J. Close, Anthony S. Clare, Robert C. Upstill-Goddard, and Matthew G. Bentley. 2012. "Ocean Acidification Induces Multi-Generational Decline in Copepod Naupliar Production with Possible Conflict for Reproductive Resource Allocation." *Journal of Experimental Marine Biology and Ecology* 418–419 (May): 30–36. <https://doi.org/10.1016/j.jembe.2012.03.009>.
- Ford, John K. B., and Graeme M. Ellis. 2006. "Selective Foraging by Fish-Eating Killer Whales (*Orcinus orca*) in British Columbia." *Marine Ecology Progress Series* 316: 185–99.
- Ford, John KB, Graeme M Ellis, Lance G Barrett-Lennard, Alexandra B Morton, Rod S Palm, and Kenneth C Balcomb III. 1998. "Dietary Specialization in Two Sympatric Populations of Killer Whales (*Orcinus orca*) in Coastal British Columbia and Adjacent Waters." *Canadian Journal of Zoology* 76 (8): 1456–71. <https://doi.org/10.1139/z98-089>.

- Fox, C.H., P.C. Paquet, and T.E. Reimchen. 2018. "Pacific Herring Spawn Events Influence Nearshore Subtidal and Intertidal Species." *Marine Ecology Progress Series* 595 (May): 157–69. <https://doi.org/10.3354/meps12539>.
- Frank, Kimberly M., Robin O. Lyda, and Jay F. Kirkpatrick. 2005. "Immunocontraception of Captive Exotic Species." *Zoo Biology* 24 (4): 349–58. <https://doi.org/10.1002/zoo.20060>.
- Fresh, Kurt L, Rick D. Cardwell, and Robert R. Koons. 1981. "Food Habits of Pacific Salmon, Baitfish, and Their Potential Competitors and Predators in the Marine Waters of Washington, August 1978 to September 1979." Progress Report 145. Olympia, WA: Washington Department of Fisheries.
- Fresh, Kurt L, Megan N Dethier, Charles A Simenstad, Miles Logsdon, Hugh Shipman, Curtis D Tanner, Tom M Leschine, et al. 2011. "Implications of Observed Anthropogenic Changes to the Nearshore Ecosystems in Puget Sound."
- Friend, Sarah E., Jan Lovy, and Paul K. Hershberger. 2016. "Disease Surveillance of Atlantic Herring: Molecular Characterization of Hepatic Coccidiosis and a Morphological Report of a Novel Intestinal Coccidian." *Diseases of Aquatic Organisms* 120 (2): 91–107. <https://doi.org/10.3354/dao03016>.
- Friends of the San Juans. 2014. Healthy beaches for people and fish: protecting shorelines from the impacts of armoring today and rising seas tomorrow. Final Report, Friday Harbor, WA. 21 pp.
- Frommel, Andrea Y., Rommel Maneja, David Lowe, Arne M. Malzahn, Audrey J. Geffen, Arild Folkvord, Uwe Piatkowski, Thorsten B. H. Reusch, and Catriona Clemmesen. 2011. "Severe Tissue Damage in Atlantic Cod Larvae under Increasing Ocean Acidification." *Nature Climate Change* 2 (1): 42–46. <https://doi.org/10.1038/nclimate1324>.
- Frommel, Andrea Y., Rommel Maneja, David Lowe, Christine K. Pascoe, Audrey J. Geffen, Arild Folkvord, Uwe Piatkowski, and Catriona Clemmesen. 2014. "Organ Damage in Atlantic Herring Larvae as a Result of Ocean Acidification." *Ecological Applications* 24 (5): 1131–43. <https://doi.org/10.1890/13-0297.1>.
- Fulton, E, A Smith, and A Punt. 2005. "Which Ecological Indicators Can Robustly Detect Effects of Fishing?" *ICES Journal of Marine Science* 62 (3): 540–51. <https://doi.org/10.1016/j.icesjms.2004.12.012>.
- Fulton, Elizabeth A., Jason S. Link, Isaac C. Kaplan, Marie Savina- Rolland, Penelope Johnson, Cameron Ainsworth, Peter Horne, et al. 2011. "Lessons in Modelling and Management of Marine Ecosystems: The Atlantis Experience." *Fish and Fisheries* 12 (2): 171–88. <https://doi.org/10.1111/j.1467-2979.2011.00412.x>.
- Gannon, Damon P., James E. Craddock, and Andrew J. Read. 1998. "Autumn Food Habits of Harbor Porpoises, *Phocoena phocoena*, in the Gulf of Maine." *Fishery Bulletin* 96 (3): 428–37.
- Gao, Y.W., S.H. Joner, and G.G. Bargmann. 2001. "Stable Isotopic Composition of Otoliths in Identification of Spawning Stocks of Pacific Herring (*Clupea Pallasii*) in Puget Sound." *Canadian Journal of Fisheries and Aquatic Sciences* 58 (11): 2113–20. <https://doi.org/10.1139/cjfas-58-11-2113>.
- Garver, Ka, Gs Traxler, Lm Hawley, J Richard, J Ross, and aJ Lovy. 2013. "Molecular Epidemiology of Viral Haemorrhagic Septicaemia Virus (VHSV) in British Columbia, Canada, Reveals Transmission from Wild to Farmed Fish." *Diseases of Aquatic Organisms* 104 (2): 93–104. <https://doi.org/10.3354/dao02588>.
- Gearin, P.J., Melin, S.R., DeLong, R.L., Kajimura, H. and Johnson, M.A., 1994. Harbor porpoise interactions with a chinook salmon set-net fishery in Washington State. *Rep. Int. Whal. Commn. Special*, (15), pp.427-438.
- Gende, Scott M., and Michael F. Sigler. 2006. "Persistence of Forage Fish 'Hot Spots' and Its Association with Foraging Steller Sea Lions (*Eumetopias jubatus*) in Southeast Alaska." *Deep Sea Research Part II: Topical Studies in Oceanography* 53 (3–4): 432–41. <https://doi.org/10.1016/j.dsr2.2006.01.005>.
- Gibbons, M. J., F. Boero, and L. Brotz. 2016. "We Should Not Assume That Fishing Jellyfish Will Solve Our Jellyfish Problem." *ICES Journal of Marine Science* 73 (4): 1012–18. <https://doi.org/10.1093/icesjms/fsv255>.
- Graham, W.M. 2001. "Numerical Increases and Distributional Shifts of *Chrysaora quinquecirrha* (Desor) and *Aurelia aurita* (Linné) (Cnidaria: Scyphozoa) in the Northern Gulf of Mexico." In *Jellyfish Blooms: Ecological and Societal Importance*, edited by J.E. Purcell, W.M. Graham, and J.H. Dumont. Developments in Hydrobiology 155. Dordrecht: Springer.

- Grant, W.S., and F.M. Utter. 1984. "Biochemical Population Genetics of Pacific Herring (*Clupea Pallasii*)."
Canadian Journal of Fisheries and Aquatic Sciences 41: 856–64.
- Greene, C, L Kuehne, C Rice, K Fresh, and D Penttila. 2015. "Forty Years of Change in Forage Fish and Jellyfish Abundance across Greater Puget Sound, Washington (USA): Anthropogenic and Climate Associations." *Marine Ecology Progress Series* 525 (April): 153–70. <https://doi.org/10.3354/meps11251>.
- Greene, Correigh M. 2003. "Habitat Selection Reduces Extinction of Populations Subject to Allee Effects." *Theoretical Population Biology* 64 (1): 1–10. [https://doi.org/10.1016/S0040-5809\(03\)00025-X](https://doi.org/10.1016/S0040-5809(03)00025-X).
- Greene, Correigh M., and Judy A. Stamps. 2001. "Habitat Selection at Low Population Densities." *Ecology* 82 (8): 2091–2100. <https://doi.org/10.2307/2680218>.
- Greene, H., David Cacchione, and Monty Hampton. 2017. "Characteristics and Dynamics of a Large Sub-Tidal Sand Wave Field—Habitat for Pacific Sand Lance (*Ammodytes personatus*), Salish Sea, Washington, USA." *Geosciences* 7 (4): 107. <https://doi.org/10.3390/geosciences7040107>.
- Gregg, Jake L., Johanna J. Vollenweider, Courtney A. Grady, Ron A. Heintz, and Paul K. Hershberger. 2011. "Effects of Environmental Temperature on the Dynamics of Ichthyophthiriasis in Juvenile Pacific Herring (*Clupea Pallasii*)." *Journal of Parasitology Research* 2011: 1–9. <https://doi.org/10.1155/2011/563412>.
- Gregg, E.J., 2004. Marine mammals in the Hecate Strait ecosystem. Fisheries and Oceans Canada, Science Branch, Pacific Region, Pacific Biological Station.
- Guan, Lu, John F. Dower, Skip M. McKinnell, Pierre Pepin, Evgeny A. Pakhomov, and Brian P. V. Hunt. 2015. "A Comparison of Spring Larval Fish Assemblages in the Strait of Georgia (British Columbia, Canada) between the Early 1980s and Late 2000s." *Progress in Oceanography* 138 (November): 45–57. <https://doi.org/10.1016/j.pocean.2015.09.006>.
- . 2017. "Interannual Variability in the Abundance and Composition of Spring Larval Fish Assemblages in the Strait of Georgia (British Columbia, Canada) from 2007 to 2010." *Fisheries Oceanography* 26 (6): 638–54.
- Gulka, Julia, Paloma C. Carvalho, Edward Jenkins, Kelsey Johnson, Laurie Maynard, and Gail K. Davoren. 2017. "Dietary Niche Shifts of Multiple Marine Predators under Varying Prey Availability on the Northeast Newfoundland Coast." *Frontiers in Marine Science* 4. <https://doi.org/10.3389/fmars.2017.00324>.
- Gustafson, Richard, Jonathan Drake, Michael Ford, James Myers, Elizabeth Holmes, and Robin Waples. 2006. "NOAA Technical Memorandum NMFS-NWFSC-76. Status Review of Cherry Point Pacific Herring (*Clupea pallasii*) and Updated Status Review of the Georgia Basin Pacific Herring Distinct Population Segment Under the Endangered Species Act," 203.
- Habitat Strategic Initiative. 2018. Narrative. Shoreline Armoring Implementation Strategy. Washington Department of Fish and Wildlife and Washington Department of Natural Resources. <https://pspwa.box.com/v/PublicIS-ShoreArmoring>
- Haegle, C. W. 1993. "Seabird Predation of Pacific Herring, *Clupea pallasii*, Spawn in British Columbia." *The Canadian Field-Naturalist* 107 (1): 73–82.
- Haegle, C. W., and J. F. Schweigert. 1985. "Distribution and Characteristics of Herring Spawning Grounds and Description of Spawning Behavior." *Canadian Journal of Fisheries and Aquatic Sciences* 42 (S1): s39–55. <https://doi.org/10.1139/f85-261>.
- Hall, A.M., 2011. Foraging behaviour and reproductive season habitat selection of northeast Pacific porpoises (Doctoral dissertation, University of British Columbia).
- Hansen, Adam G., David A. Beauchamp, and Erik R. Schoen. 2013. "Visual Prey Detection Responses of Piscivorous Trout and Salmon: Effects of Light, Turbidity, and Prey Size." *Transactions of the American Fisheries Society* 142 (3): 854–67. <https://doi.org/10.1080/00028487.2013.785978>.
- Hansen, J., M. Sato, R. Ruedy, P. Kharecha, A. Lacis, R. Miller, L. Nazarenko, et al. 2007. "Climate Simulations for 1880–2003 with GISS ModelE." *Climate Dynamics; Heidelberg* 29 (7–8): 661–96. <http://dx.doi.org/10.1007/s00382-007-0255-8>.
- Harding, Louisa and Jenifer McIntyre, 2018. "The cocktail that kills coho: Stormwater runoff problems and solutions". Puyallup Research and Extension Center, Washington State University School of the Environment.

- Harvey, Chris J., Gregory D. Williams, and Phillip S. Levin. 2012. "Food Web Structure and Trophic Control in Central Puget Sound." *Estuaries and Coasts* 35(3):821–38. <https://doi.org/10.1007/s12237-012-9483-1>.
- Hay, D. E. 1985. "Reproductive Biology of Pacific Herring (*Clupea harengus pallasii*)." *Canadian Journal of Fisheries and Aquatic Sciences* 42 (S1): s111–26. <https://doi.org/10.1139/f85-267>.
- Hay, D E, and J.B. Marliave. 1988. "Transplanting Pacific Herring Eggs in British Columbia: A Stocking Experiment." *American Fisheries Society Symposium* 47:49–59.
- Hay, D.E., P.B. McCarter, and K.S. Daniel. 2001. "Tagging of Pacific Herring *Clupea pallasii* from 1936-1992: A Review with Comments on Homing, Geographic Fidelity, and Straying." *Canadian Journal of Fisheries and Aquatic Sciences* 58: 1356–70. <https://doi.org/10.1139/cifas-58-7-1356>.
- Hay, Douglas E, P Bruce McCarter, Kristen S Daniel, and Jacob F Schweigert. 2009. "Spatial Diversity of Pacific Herring (*Clupea pallasii*) Spawning Areas." *ICES Journal of Marine Science* 66: 1662–1666.
- Hershberger, P K. 2002. "Incidence of *Ichthyophonus hoferi* in Puget Sound Fishes and Its Increase with Age of Pacific Herring." *Journal of Aquatic Animal Health* 14:50-56.
- Hershberger, P. K., N. E. Elder, C. A. Grady, J. L. Gregg, C. A. Pacheco, C. Greene, C. Rice, and T. R. Meyers. 2009. "Prevalence of Viral Erythrocytic Necrosis in Pacific Herring and Epizootics in Skagit Bay, Puget Sound, Washington." *Journal of Aquatic Animal Health* 21 (1): 1–7. <https://doi.org/10.1577/H08-035.1>.
- Hershberger, P. K., R. M. Kocan, N. E. Elder, G. D. Marty, and J. Johnson. 2001. "Management of Pacific Herring Spawn-on-Kelp Fisheries to Optimize Fish Health and Product Quality." *North American Journal of Fisheries Management* 21 (4): 976–81. [https://doi.org/10.1577/1548-8675\(2001\)021<0976:MOPHSO>2.0.CO;2](https://doi.org/10.1577/1548-8675(2001)021<0976:MOPHSO>2.0.CO;2).
- Hershberger, Paul K., Kyle A. Garver, and James R. Winton. 2016. "Principles Underlying the Epizootiology of Viral Hemorrhagic Septicemia in Pacific Herring and Other Fishes throughout the North Pacific Ocean." *Canadian Journal of Fisheries and Aquatic Sciences* 73 (5): 853–59. <https://doi.org/10.1139/cjfas-2015-0417>.
- Hershberger, Pk, Rm Kocan, Ne Elder, Tr Meyers, and Jr Winton. 1999. "Epizootiology of Viral Hemorrhagic Septicemia Virus in Pacific Herring from the Spawn-on-Kelp Fishery in Prince William Sound, Alaska, USA." *Diseases of Aquatic Organisms* 37: 23–31. <https://doi.org/10.3354/dao037023>.
- Hershberger, P.K., C.A. Pacheco, J. L. Gregg, M.K. Purcell, and S. E. LaPatra. 2008. "Differential Survival of *Ichthyophonus* Isolates Indicates Parasite Adaptation to Its Host Environment." *The Journal of Parasitology* 94 (5): 1055–59.
- Hershberger, P.K., M.K. Purcell, L.M. Hart, J.L. Gregg, R.L. Thompson, K.A. Garver, and J.R. Winton. 2013. "Influence of Temperature on Viral Hemorrhagic Septicemia (Genogroup IVa) in Pacific Herring, *Clupea pallasii* Valenciennes." *Journal of Experimental Marine Biology and Ecology* 444 (June): 81–86. <https://doi.org/10.1016/j.jembe.2013.03.006>.
- Hildebrandt, Nicole, Barbara Niehoff, and Franz Josef Sartoris. 2014. "Long-Term Effects of Elevated CO2 and Temperature on the Arctic Calanoid Copepods *Calanus glacialis* and *C. hyperboreus*." *Marine Pollution Bulletin* 80 (1): 59–70. <https://doi.org/10.1016/j.marpolbul.2014.01.050>.
- Hill, K.T., P.R. Crone, J.P. Zwolinski. 2017. Assessment of the Pacific sardine resource." U.S. management in 2017-18. Pacific Fishery Management Council, Portland, Oregon. 146 p.
- Horne, P.J., I.C. Kaplan, K.N. Marshall, P.S. Levin, C.J. Harvey, A.J. Hermann, and E.A. Fulton. 2010. "Design and Parameterization of a Spatially Explicit Ecosystem Model of the Central California Current." NOAA Technical Memorandum NMFS-NWFSC-104. NOAA.
- Hourston, A.S., and C.W. Haegele. 1980. "Herring on Canada's Pacific Coast." Canadian Special Publication of Fisheries and Aquatic Sciences 48. Ottawa.
- Hurst, T.P., E.R. Fernandez, J.T. Mathis, J.A. Miller, C.M. Stinson, and E.F. Ahgeak. 2012. "Resiliency of Juvenile Walleye Pollock to Projected Levels of Ocean Acidification." *Aquatic Biology* 17 (3): 247–59. <https://doi.org/10.3354/ab00483>.
- Hutchings, J A. 1996. "Spatial and Temporal Variation in the Density of Northern Cod and a Review of Hypotheses for the Stock's Collapse." *Canadian Journal of Fisheries and Aquatic Sciences* 53 (5): 943–62. <https://doi.org/10.1139/f96-097>.

- IPCC. 2007. "Climate Change 2007: Synthesis Report. Contribution of Working Groups I, II and III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change." Geneva, Switzerland.
- Jeffries, Steven, Harriet Huber, John Calambokidis, and Jeffrey Laake. 2003. "Trends and Status of Harbor Seals in Washington State: 1978-1999." *The Journal of Wildlife Management* 67 (1): 207. <https://doi.org/10.2307/3803076>.
- Johansen, J. L., R. Vaknin, J. F. Steffensen, and P. Domenici. 2010. "Kinematics and Energetic Benefits of Schooling in the Labriform Fish, Striped Surfperch *Embiotoca lateralis*." *Marine Ecology Progress Series* 420 (December): 221–29. <https://doi.org/10.3354/meps08885>.
- Jones, Barry C., and Glen H. Geen. 1977. "Food and Feeding of Spiny Dogfish (*Squalus acanthias*) in British Columbia Waters" *Journal of the Fisheries Research Board of Canada* 34 (11): 2056–66.
- Jutfelt, Fredrik, Karine Bresolin de Souza, Amandine Vuylsteke, and Joachim Sturve. 2013. "Behavioural Disturbances in a Temperate Fish Exposed to Sustained High-CO₂ Levels." *PLOS ONE* 8 (6): e65825. <https://doi.org/10.1371/journal.pone.0065825>.
- Kaplan, Isaac C., Peter J. Horne, and Phillip S. Levin. 2012. "Screening California Current Fishery Management Scenarios Using the Atlantis End-to-End Ecosystem Model." *Progress in Oceanography* 102 (September): 5–18. <https://doi.org/10.1016/j.pocean.2012.03.009>.
- Kaplan, Isaac C., Phillip S. Levin, Merrick Burden, and Elizabeth A. Fulton. 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 (12): 1968–82. <https://doi.org/10.1139/F10-118>.
- Kemp, Iris M, David A Beauchamp, Ruston Sweeting, and Carol Cooper. 2013. "Potential for Competition Among Herring and Juvenile Salmon Species in Puget Sound, Washington." Technical Report 9. North Pacific Anadromous Fish Commission.
- King, J. R. and G. A. McFarlane. 2006. Shift in Size-at-Age of the Strait of Georgia Population of Pacific Hake (*Merluccius productus*). CalCOFI Rep., Vol. 47.
- Kirkpatrick, Jay F., and Allison Turner. 2008. "Achieving Population Goals in a Long-Lived Wildlife Species (*Equus caballus*) with Contraception." *Wildlife Research* 35 (6): 513–19. <https://doi.org/10.1071/WR07106>.
- Kotterba, Paul, Carsten Kühn, Cornelius Hammer, and Patrick Polte. 2014. "Predation of Threespine Stickleback (*Gasterosteus aculeatus*) on the Eggs of Atlantic Herring (*Clupea harengus*) in a Baltic Sea Lagoon." *Limnology and Oceanography* 59 (2): 578–87. <https://doi.org/10.4319/lo.2014.59.2.0578>.
- Krembs, C. (2012). Eyes Over Puget Sound: Integrating Multiple Observations to Report Current Conditions of Water Quality in Puget Sound and the Strait of Juan de Fuca. Salish Sea Ecosystem Conference, Seattle, WA.
- Kroeker, Kristy J., Rebeca L. Kordas, Ryan Crim, Iris E. Hendricks, Laura Ramajo, Gerald S. Singh, Carlos S. Duarte, and Jean-Pierre Gattuso. 2013. "Impacts of Ocean Acidification on Marine Organisms: Quantifying Sensitivities and Interaction with Warming." *Global Change Biology* 19 (6): 1884–96.
- Kronlund, A.R. et al., 2017. "The Selection and Role of Limit Reference Points for Pacific Herring (*Clupea pallasii*) in British Columbia, Canada." 2017/030. Canadian Science Advisory Secretariat Pacific Region Science Advisory Report. Fisheries and Oceans Canada.
- Kurihara, Haruko. 2008. "Effects of CO₂ -Driven Ocean Acidification on the Early Developmental Stages of Invertebrates." *Marine Ecology Progress Series* 373: 275–84.
- Kyba, Christopher C. M., Thomas Ruhtz, Jürgen Fischer, and Franz Hölker. 2011. "Cloud Coverage Acts as an Amplifier for Ecological Light Pollution in Urban Ecosystems." *PLOS ONE* 6 (3): e17307. <https://doi.org/10.1371/journal.pone.0017307>.
- Lance, M.M., W.Y. Chang, S.J. Jeffries, S.F. Pearson, and A. Acevedo-Gutiérrez. 2012. "Harbor Seal Diet in Northern Puget Sound: Implications for the Recovery of Depressed Fish Stocks." *Marine Ecology Progress Series* 464 (September): 257–71. <https://doi.org/10.3354/meps09880>.
- Lance, Monique M., and Steven J. Jeffries. 2007. "Harbor Seal Diet in Hood Canal, South Puget Sound and the San Juan Island Archipelago," 39.

- Landeau, Laurie, and John Terborgh. 1986. "Oddity and the 'Confusion Effect' in Predation." *Animal Behaviour* 34 (5): 1372–80. [https://doi.org/10.1016/S0003-3472\(86\)80208-1](https://doi.org/10.1016/S0003-3472(86)80208-1).
- Lester, Sarah E., Karen L. McLeod, Heather Tallis, Mary Ruckelshaus, Benjamin S. Halpern, Phillip S. Levin, Francisco P. Chavez, et al. 2010. "Science in Support of Ecosystem-Based Management for the US West Coast and Beyond." *Biological Conservation* 143 (3): 576–87. <https://doi.org/10.1016/j.biocon.2009.11.021>.
- Levin, Phillip S., Tessa B. Francis, and Nathan G. Taylor. 2016. "Thirty-Two Essential Questions for Understanding the Social–Ecological System of Forage Fish: The Case of Pacific Herring." *Ecosystem Health and Sustainability* 2 (4): e01213. <https://doi.org/10.1002/ehs2.1213>.
- Levitán, Don R., Mary A. Sewell, and Fu-Shiang Chia. 1992. "How Distribution and Abundance Influence Fertilization Success in the Sea Urchin *Strongylocentrotus franciscanus*." *Ecology* 73 (1): 248–54. <https://doi.org/10.2307/1938736>.
- Lewis, Ceri N., Kristina A. Brown, Laura A. Edwards, Glenn Cooper, and Helen S. Findlay. 2013. "Sensitivity to Ocean Acidification Parallels Natural PCO₂ Gradients Experienced by Arctic Copepods under Winter Sea Ice." *Proceedings of the National Academy of Sciences* 110 (51): E4960–67. <https://doi.org/10.1073/pnas.1315162110>.
- Li, Lingbo, Dave Mackas, Brian Hunt, Jake Schweigert, Evgeny Pakhomov, R. Ian Perry, Moira Galbraith, and Tony J. Pitcher. 2013. "Zooplankton Communities in the Strait of Georgia, British Columbia, Track Large-Scale Climate Forcing over the Pacific Ocean." *Progress in Oceanography* 115 (August): 90–102. <https://doi.org/10.1016/j.pocean.2013.05.025>.
- Li, Wei, Kunshan Gao, and John Beardall. 2012. "Interactive Effects of Ocean Acidification and Nitrogen-Limitation on the Diatom *Phaeodactylum tricornutum*." *PLOS ONE* 7 (12): e51590. <https://doi.org/10.1371/journal.pone.0051590>.
- Liedtke, T., C. Gibson, D. Lowry, and D. Fagergren, 2013. Conservation and ecology of marine forage fishes - proceedings of a research symposium, September 2012. USGS Open-File Report 2013-1035. U.S. Department of the Interior, U.S. Geological Survey. 24 pp.
- Liermann, M., and R. Hilborn. 1997. "Depensation in Fish Stocks: A Hierarchic Bayesian Meta-Analysis." *Canadian Journal of Fisheries and Aquatic Sciences* 54 (9): 1976–84. <https://doi.org/10.1139/f97-105>.
- Lok, Erika K., Daniel Esler, John Y. Takekawa, Susan W. De La Cruz, W. Sean Boyd, David R. Nysewander, Joseph R. Evenson, and David H. Ward. 2012. "Spatiotemporal Associations between Pacific Herring Spawn and Surf Scoter Spring Migration." *Marine Ecology Progress Series* 457: 139–50.
- Lok, Erika K., Molly Kirk, Daniel Esler, and W. Sean Boyd. 2008. "Movements of Pre-Migratory Surf and White-Winged Scoters in Response to Pacific Herring Spawn." *Waterbirds* 31 (3): 385–93. <https://doi.org/10.1675/1524-4695-31.3.385>.
- Lotze, Heike K., Hunter S. Lenihan, Bruce J. Bourque, Roger H. Bradbury, Richard G. Cooke, Matthew C. Kay, Susan M. Kidwell, Michael X. Kirby, Charles H. Peterson, and Jeremy B. C. Jackson. 2006. "Depletion, Degradation, and Recovery Potential of Estuaries and Coastal Seas." *Science* 312 (5781): 1806–9. <https://doi.org/10.1126/science.1128035>.
- Love, B., C. Villalobos and M.B. Olson, 2018. "Interactive effects of ocean acidification and ocean warming on Pacific herring (*Clupea pallasii*) early life stages." Salish Sea Ecosystem Conference, Seattle, WA. <https://cedar.wvu.edu/cgi/viewcontent.cgi?article=2993&context=ssec>
- Luxa, Katie, and Alejandro Acevedo-Gutierrez. 2013. "Food Habits of Harbor Seals (*Phoca vitulina*) in Two Estuaries in the Central Salish Sea." *Aquatic Mammals* 39 (1): 10–22. <https://doi.org/10.1578/AM.39.1.2013.10>.
- MacCall, Alec D., Tessa B. Francis, André E. Punt, Margaret C. Siple, Derek R. Armitage, Jaclyn S. Cleary, Sherri C. Dressel, et al. 2018. "A Heuristic Model of Socially Learned Migration Behaviour Exhibits Distinctive Spatial and Reproductive Dynamics." *ICES Journal of Marine Science*. <https://doi.org/10.1093/icesjms/fsy091>.
- Mackas, David, Moira Galbraith, Deborah Faust, Diane Masson, Kelly Young, William Shaw, Stephen Romaine, et al. 2013. "Zooplankton Time Series from the Strait of Georgia: Results from Year-Round

- Sampling at Deep Water Locations, 1990–2010.” *Progress in Oceanography* 115 (August): 129–59. <https://doi.org/10.1016/j.pocean.2013.05.019>.
- Makris, N. C., P. Ratilal, S. Jagannathan, Z. Gong, M. Andrews, I. Bertsatos, O. R. Godo, R. W. Nero, and J. M. Jech. 2009. “Critical Population Density Triggers Rapid Formation of Vast Oceanic Fish Shoals.” *Science* 323 (5922): 1734–37. <https://doi.org/10.1126/science.1169441>.
- Maneja, R. H., A. Y. Frommel, H. I. Browman, C. Clemmesen, A. J. Geffen, A. Folkvord, U. Piatkowski, et al. 2013. “The Swimming Kinematics of Larval Atlantic Cod, *Gadus morhua* L., Are Resilient to Elevated Seawater PCO₂.” *Marine Biology; Heidelberg* 160 (8): 1963–72. <http://dx.doi.org/10.1007/s00227-012-2054-y>.
- Maneja, Rommel H., R. Dineshram, Vengatesen Thiagarajan, Anne Berit Skiftesvik, Andrea Y. Frommel, Catriona Clemmesen, Audrey J. Geffen, and Howard I. Browman. 2014. “The Proteome of Atlantic Herring (*Clupea harengus* L.) Larvae Is Resistant to Elevated pCO₂.” *Marine Pollution Bulletin* 86 (1–2): 154–60. <https://doi.org/10.1016/j.marpolbul.2014.07.030>.
- Maneja, Rommel H., Andrea Y. Frommel, Howard I. Browman, Audrey J. Geffen, Arild Folkvord, Uwe Piatkowski, Caroline M.F. Durif, Reidun Bjelland, Anne Berit Skiftesvik, and Catriona Clemmesen. 2015. “The Swimming Kinematics and Foraging Behavior of Larval Atlantic Herring (*Clupea harengus* L.) Are Unaffected by Elevated PCO₂.” *Journal of Experimental Marine Biology and Ecology* 466 (May): 42–48. <https://doi.org/10.1016/j.jembe.2015.02.008>.
- Marshall, Randall. 2011. “Final Report on Pacific Herring (*Clupea pallasii*) Test Development and Validation.” 11-10-086. Olympia, WA: Washington Department of Ecology.
- Marty, Gary D., Ellen F. Freiberg, Theodore R. Meyers, John Wilcock, Thomas B. Farver, and David E. Hinton. 1998. “Viral Hemorrhagic Septicemia Virus, *Ichthyophonus hoferi*, and Other Causes of Morbidity in Pacific Herring *Clupea pallasii* Spawning in Prince William Sound, Alaska, USA.” *Diseases of Aquatic Organisms* 32 (1): 15–40. <https://doi.org/10.3354/dao032015>.
- Masson, Diane, and Patrick F. Cummins. 2007. “Temperature Trends and Interannual Variability in the Strait of Georgia, British Columbia.” *Continental Shelf Research* 27 (5): 634–49. <https://doi.org/10.1016/j.csr.2006.10.009>.
- Mauger, G.S., J.H. Casola, H.A. Morgan, R.L. Strauch, B. Jones, B. Curry, T.M. Busch Isaksen, L. Whitely Binder, M.B. Krosby, and A.K. Snover. 2015. “State of Knowledge: Climate Change in Puget Sound.” Report prepared for the Puget Sound Partnership and the National Oceanic and Atmospheric Administration. Seattle, WA: Climate Impacts Group, University of Washington.
- Mazur, Michael M., and David A. Beauchamp. 2003. “A Comparison of Visual Prey Detection Among Species of Piscivorous Salmonids: Effects of Light and Low Turbidities.” *Environmental Biology of Fishes; Dordrecht* 67 (4): 397–405. <http://dx.doi.org/10.1023/A:1025807711512>.
- McClatchie, Sam, John Field, Andrew R. Thompson, Tim Gerrodette, Mark Lowry, Paul C. Fiedler, William Watson, Karen M. Nieto, and Russell D. Vetter. 2016. “Food Limitation of Sea Lion Pups and the Decline of Forage off Central and Southern California.” *Royal Society Open Science* 3 (3): 150628. <https://doi.org/10.1098/rsos.150628>.
- McConville, Kristian, Claudia Halsband, Elaine S. Fileman, Paul J. Somerfield, Helen S. Findlay, and John I. Spicer. 2013. “Effects of Elevated CO₂ on the Reproduction of Two Calanoid Copepods.” *Marine Pollution Bulletin* 73 (2): 428–34.
- McFarlane, G. A., and R. J. Beamish. 1985. “Biology and Fishery of Pacific Whiting, *Merluccius productus*, in the Strait of Georgia.” *Marine Fisheries Review* 47: 23–34.
- McFarlane, G., J. Schweigert, J. Detering, and V. Hodes. 2010. Diet Analysis of Pacific Sardine (*Sardinops sagax*) off the West Coast of Vancouver Island, British Columbia from 1997 to 2008. CalCOFI Rep. 51.
- McKechnie, Iain, Dana Lepofsky, Madonna L. Moss, Virginia L. Butler, Trevor J. Orchard, Gary Coupland, Fredrick Foster, Megan Caldwell, and Ken Lertzman. 2014. “Archaeological Data Provide Alternative Hypotheses on Pacific Herring (*Clupea pallasii*) Distribution, Abundance, and Variability.” *Proceedings of the National Academy of Sciences* 111 (9): E807–16. <https://doi.org/10.1073/pnas.1316072111>.

- McKechnie, Iain, and Madonna L. Moss. 2016. "Meta-Analysis in Zooarchaeology Expands Perspectives on Indigenous Fisheries of the Northwest Coast of North America." *Journal of Archaeological Science: Reports* 8 (August): 470–85. <https://doi.org/10.1016/j.jasrep.2016.04.006>.
- McLaskey, Anna K., Julie E. Keister, Paul McElhany, M. Brady Olson, D. Shallin Busch, Michael Maher, and Amanda K. Winans. 2016. "Development of *Euphausia pacifica* (Krill) Larvae Is Impaired under PCO₂ Levels Currently Observed in the Northeast Pacific." *Marine Ecology Progress Series* 555 (August): 65–78. <https://doi.org/10.3354/meps11839>.
- Melbourne-Thomas, J., S. Wotherspoon, B. Raymond, and A. Constable. 2012. "Comprehensive Evaluation of Model Uncertainty in Qualitative Network Analyses." *Ecological Monographs* 82 (4): 505–19. <https://doi.org/10.1890/12-0207.1>.
- Meyers, T. R., A. K. Hauck, W. D. Blankenbeckler, and T. Minicucci. 1986. "First Report of Viral Erythrocytic Necrosis in Alaska, USA, Associated with Epizootic Mortality in Pacific Herring, *Clupea harengus pallasi* (Valenciennes)." *Journal of Fish Diseases* 9 (6): 479–91. <https://doi.org/10.1111/j.1365-2761.1986.tb01045.x>.
- Millikan, Alan, and Dan Penttila. 1972. "Puget Sound Baitfish Project." Marine Fish Investigations Project Report. Department of Fisheries: WDFW.
- Mills, Claudia E. 1993. "Natural Mortality in NE Pacific Coastal Hydromedusae: Grazing Predation, Wound Healing and Senescence." *Bulletin of Marine Science* 53: 10.
- Mills, Claudia E. 2001. "Jellyfish Blooms: Are Populations Increasing Globally in Response to Changing Ocean Conditions?" In *Jellyfish Blooms: Ecological and Societal Importance*, edited by J. E. Purcell, W. M. Graham, and H. J. Dumont, 55–68. Dordrecht: Springer Netherlands. https://doi.org/10.1007/978-94-010-0722-1_6.
- Milne, S W, B J Shuter, and W G Sprules. 2005. "The Schooling and Foraging Ecology of Lake Herring (*Coregonus artedii*) in Lake Opeongo, Ontario, Canada." *Canadian Journal of Fisheries and Aquatic Sciences* 62 (6): 1210–18. <https://doi.org/10.1139/f05-030>.
- Misund, Ole Arve, Jan Tore Øvredal, and Magnus Thor Hafsteinsson. 1996. "Reactions of Herring Schools to the Sound Field of a Survey Vessel." *Aquatic Living Resources* 9 (1): 5–11. <https://doi.org/10.1051/alr:1996002>.
- Mitchell, Danielle M. 2006. "Biocomplexity and Metapopulation Dynamics of Pacific Herring in Puget Sound, Washington." Seattle, WA: University of Washington.
- Mohamedali, T. et al., 2011. "Puget sound dissolved oxygen model nutrient load summary for 1998-2008." Washington State Department of Ecology, Olympia, WA.
- Moll, Dorothee, Paul Kotterba, Lena von Nordheim, and Patrick Polte. 2018. "Storm-Induced Atlantic Herring (*Clupea harengus*) Egg Mortality in Baltic Sea Inshore Spawning Areas." *Estuaries and Coasts* 41 (1): 1–12. <https://doi.org/10.1007/s12237-017-0259-5>.
- Moriarty, P.E., K.S. Andrews, C.J. Harvey, and M. Kawase. 2012. "Vertical and Horizontal Movement Patterns of Scyphozoan Jellyfish in a Fjord-like Estuary." *Marine Ecology Progress Series* 455 (May): 1–12. <https://doi.org/10.3354/meps09783>.
- Mumford, T.F. 2007. Kelp and Eelgrass in Puget Sound. Puget Sound Nearshore Partnership Report No. 2007-05. Published by Seattle District, U.S. Army Corps of Engineers, Seattle, Washington.
- Munday, P. L., M. I. McCormick, and G. E. Nilsson. 2012. "Impact of Global Warming and Rising CO₂ Levels on Coral Reef Fishes: What Hope for the Future?" *Journal of Experimental Biology* 215 (22): 3865–73. <https://doi.org/10.1242/jeb.074765>.
- Munro JA, Clemens WA (1931) Waterfowl in relation to the spawning of herring in British Columbia. Bulletin of the Biological Board of Canada No. 17:1-46.
- Munsch, Sh, Jr Cordell, and Jd Toft. 2015. "Effects of Seawall Armoring on Juvenile Pacific Salmon Diets in an Urban Estuarine Embayment." *Marine Ecology Progress Series* 535 (September): 213–29. <https://doi.org/10.3354/meps11403>.
- Munsch, Stuart H., Jeffery R. Cordell, and Jason D. Toft. 2015. "Effects of Shoreline Engineering on Shallow Subtidal Fish and Crab Communities in an Urban Estuary: A Comparison of Armored Shorelines and

- Nourished Beaches.” *Ecological Engineering* 81 (August): 312–20.
<https://doi.org/10.1016/j.ecoleng.2015.04.075>.
- Myers, R. A., N. J. Barrowman, J. A. Hutchings, and A. A. Rosenberg. 1995. “Population Dynamics of Exploited Fish Stocks at Low Population Levels.” *Science* 269 (5227): 1106–8.
- National Marine Fisheries Service (NMFS). 2016. Fisheries of the United States 2015. Lowther, A. and M. Liddel (eds.). National Marine Fisheries Service Office of Science and Technology, Silver Springs, MD. 135 pp.
- Nichol, Linda M., Anna M. Hall, Graeme M. Ellis, Eva Stredulinsky, Melissa Boogaards, and John K. B. Ford. 2013. “Dietary Overlap and Niche Partitioning of Sympatric Harbour Porpoises and Dall’s Porpoises in the Salish Sea.” *Progress in Oceanography*, Strait of Georgia Ecosystem Research Initiative (ERI), 115 (August): 202–10. <https://doi.org/10.1016/j.pocean.2013.05.016>.
- O’Connell, J.M., 1998. Holocene fish remains from Saanich Inlet, British Columbia, Canada: A paleoecological study (M.Sc. Thesis). University of Victoria, British Columbia, Canada.
- Palsson, Wayne. 1984. “Egg Mortality upon Natural and Artificial Substrata within Washington State Spawning Grounds of Pacific Herring.” Seattle, WA: University of Washington.
- Pentilla, Dan. 1986. “Early Life History of Puget Sound Herring.” Fifth Pacific Coast Herring Workshop. Canadian Manuscript Report of Fisheries and Aquatic Sciences.
- . 2007. “Marine Forage Fishes of Puget Sound.” 2007–03. Olympia, WA: WDFW.
- Penttila, Dan. 1985. “Early Life History of Puget Sound Herring.” 1871. Canadian Manuscript Report of Fisheries and Aquatic Sciences.
- Pierson, N., 2011. Bridging troubled waters: zooarchaeology and marine conservation on Burrard Inlet, southwest British Columbia (MA Thesis). Simon Fraser University, British Columbia, Canada.
- Pikitch, E. K. 2012. “The Risks of Overfishing.” *Science* 338 (6106): 474–75.
<https://doi.org/10.1126/science.1229965>.
- Pikitch, Ellen K, Konstantine J Rountos, Timothy E Essington, Christine Santora, Daniel Pauly, Reg Watson, Ussif R Sumaila, et al. 2014. “The Global Contribution of Forage Fish to Marine Fisheries and Ecosystems.” *Fish and Fisheries* 15 (1): 43–64. <https://doi.org/10.1111/faf.12004>.
- Preikshot, Dave, Richard J. Beamish, and Chrys M. Neville. 2013. “A Dynamic Model Describing Ecosystem-Level Changes in the Strait of Georgia from 1960 to 2010.” *Progress in Oceanography* 115 (August): 28–40. <https://doi.org/10.1016/j.pocean.2013.05.020>.
- Puccia, Charles J., and Richard Levins. 1985. *Qualitative Modeling of Complex Systems. an Introduction to Loop Analysis and Time Averaging*. Cambridge, Massachusetts: Harvard University.
- Puget Sound Ecosystem Monitoring Program, 2018: <https://sites.google.com/a/psemp.org/psemp/>
- Puget Sound Partnership Indicators Action Team, 2009: <http://www.psp.wa.gov/evaluating-vitalsigns.php>
- Puget Sound Partnership. 2015. Puget Sound Estuaries Implementation Strategy Narrative (Phase I Final). <https://pspwa.app.box.com/v/est-phase1>
- Puget Sound Partnership. 2018. Chinook Salmon Implementation Strategy Final Narrative. <https://pspwa.app.box.com/v/PublicIS-Chinook/file/263787854359>
- Purcell, Jennifer E., Daniel Grosse, and Jill J. Grover. 1990. “Mass Abundances of Abnormal Pacific Herring Larvae at a Spawning Ground in British Columbia.” *Transactions of the American Fisheries Society* 119 (3): 463–69. [https://doi.org/10.1577/1548-8659\(1990\)119<0463:MAOAPH>2.3.CO;2](https://doi.org/10.1577/1548-8659(1990)119<0463:MAOAPH>2.3.CO;2).
- Purcell, Jennifer E, Shin-ichi Uye, and Wen-Tseng Lo. 2007. “Anthropogenic Causes of Jellyfish Blooms and Their Direct Consequences for Humans: A Review.” *Marine Ecology Progress Series* 35: 153–74.
- Rankine, P. W., and J. A. Morrison. 1989. “Predation on Herring Larvae and Eggs by Sand-Eels *Ammodytes marinus* (Rait) and *Hyperoplus lanceolatus* (Lesauvage).” *Journal of the Marine Biological Association of the United Kingdom* 69 (2): 493–98. <https://doi.org/10.1017/S0025315400029556>.
- Read, Andrew, and Carrie Brownstein. 2003. “Considering Other Consumers: Fisheries, Predators, and Atlantic Herring in the Gulf of Maine.” *Conservation Ecology* 7 (1). <https://doi.org/10.5751/ES-00474-070102>.

- Recchia, Cheri A., and Andrew J. Read. 1989. "Stomach Contents of Harbour Porpoises, *Phocoena phocoena* (L.), from the Bay of Fundy." *Canadian Journal of Zoology* 67 (9): 2140–46. <https://doi.org/10.1139/z89-304>.
- Reum, Jonathan C. P., and Timothy E. Essington. 2008. "Seasonal Variation in Guild Structure of the Puget Sound Demersal Fish Community." *Estuaries and Coasts* 31 (4): 790–801.
- Reum, Jonathan C. P., P. Sean McDonald, Bridget E. Ferriss, Dara M. Farrell, Chris J. Harvey, and Phillip S. Levin. 2015. "Qualitative Network Models in Support of Ecosystem Approaches to Bivalve Aquaculture." *ICES Journal of Marine Science: Journal Du Conseil* 72 (8): 2278–88. <https://doi.org/10.1093/icesjms/fsv119>.
- Rice, Casimir A. 2006. "Effects of Shoreline Modification on a Northern Puget Sound Beach: Microclimate and Embryo Mortality in Surf Smelt (*Hypomesus pretiosus*)." *Estuaries and Coasts* 29 (1): 63–71.
- Rice, Casimir A., Jeffrey J. Duda, Correigh M. Greene, and James R. Karr. 2012. "Geographic Patterns of Fishes and Jellyfish in Puget Sound Surface Waters." *Marine and Coastal Fisheries* 4 (1): 117–28. <https://doi.org/10.1080/19425120.2012.680403>.
- Richardson, Anthony J., Andrew Bakun, Graeme C. Hays, and Mark J. Gibbons. 2009. "The Jellyfish Joyride: Causes, Consequences and Management Responses to a More Gelatinous Future." *Trends in Ecology & Evolution* 24 (6): 312–22. <https://doi.org/10.1016/j.tree.2009.01.010>.
- Rieucou, G., A. De Robertis, K. M. Boswell, and N. O. Handegard. 2014. "School Density Affects the Strength of Collective Avoidance Responses in Wild-Caught Atlantic Herring *Clupea harengus*: A Simulated Predator Encounter Experiment." *Journal of Fish Biology* 85 (5): 1650–64. <https://doi.org/10.1111/jfb.12520>.
- Robinson, Kelly L., James J. Ruzicka, Mary Beth Decker, Richard D. Brodeur, Frank J. Hernandez, Javier Quiñones, E. Marcelo Acha, Shin-ichi Uye, Hermes Mianzan, and William M. Graham. 2014. "Jellyfish, Forage Fish, and the World's Major Fisheries." *Oceanography* 27 (4): 104–15.
- Rooper, Christopher N., Lewis J. Haldorson, and Terrance J. Quinn II. 1999. "Habitat Factors Controlling Pacific Herring (*Clupea pallasii*) Egg Loss in Prince William Sound, Alaska." *Canadian Journal of Fisheries and Aquatic Sciences* 56: 1133–42.
- Rossoll, D., U. Sommer, and M. Winder. 2013. "Community Interactions Dampen Acidification Effects in a Coastal Plankton System." *Marine Ecology Progress Series* 486 (July): 37–46. <https://doi.org/10.3354/meps10352>.
- Rossoll, Dennis, Rafael Bermúdez, Helena Hauss, Kai G. Schulz, Ulf Riebesell, Ulrich Sommer, and Monika Winder. 2012. "Ocean Acidification-Induced Food Quality Deterioration Constrains Trophic Transfer." *PLOS ONE* 7 (4): e34737. <https://doi.org/10.1371/journal.pone.0034737>.
- Roth, James D. 2003. "Variability in Marine Resources Affects Arctic Fox Population Dynamics." *Journal of Animal Ecology* 72 (4): 668–76. <https://doi.org/10.1046/j.1365-2656.2003.00739.x>.
- Rowe, Sherrylynn, and Jeffrey A. Hutchings. 2003. "Mating Systems and the Conservation of Commercially Exploited Marine Fish." *Trends in Ecology & Evolution* 18 (11): 567–72. <https://doi.org/10.1016/j.tree.2003.09.004>.
- Runge, Jeffrey A., David M. Fields, Cameron R. S. Thompson, Steven D. Shema, Reidun M. Bjelland, Caroline M. F. Durif, Anne Berit Skiftesvik, and Howard I. Browman. 2016. "End of the Century CO2 Concentrations Do Not Have a Negative Effect on Vital Rates of *Calanus finmarchicus*, an Ecologically Critical Planktonic Species in North Atlantic Ecosystems." *ICES Journal of Marine Science* 73 (3): 937–50. <https://doi.org/10.1093/icesjms/fsv258>.
- Samhouri, Jameal F., Phillip S. Levin, and Cameron H. Ainsworth. 2010. "Identifying Thresholds for Ecosystem-Based Management." Edited by Steven J. Bograd. *PLOS ONE* 5 (1): e8907. <https://doi.org/10.1371/journal.pone.0008907>.
- Sandell, Todd A., Adam Lindquist, Kurt C. Stick, and Dayv Lowry. 2018. "2016 Washington State Herring Stock Status Report (in Progress)." Fish Program Technical Report. Olympia, WA: WDFW.
- Schnedler-Meyer, Nicolas Azaña, Patrizio Mariani, and Thomas Kjørboe. 2016. "The Global Susceptibility of Coastal Forage Fish to Competition by Large Jellyfish." *Proc. R. Soc. B* 283 (1842): 20161931. <https://doi.org/10.1098/rspb.2016.1931>.

- Schoo, Katherina L., Arne M. Malzahn, Evamaria Krause, and Maarten Boersma. 2013. "Increased Carbon Dioxide Availability Alters Phytoplankton Stoichiometry and Affects Carbon Cycling and Growth of a Marine Planktonic Herbivore." *Marine Biology; Heidelberg* 160 (8): 2145–55. <http://dx.doi.org/10.1007/s00227-012-2121-4>.
- Schweigert, J. F., and R.E. Withler. 1990. "Genetic Differentiation of Pacific Herring Based on Enzyme Electrophoresis and Mitochondrial DNA Analysis." In , 7:459–69. AFS.
- Schweigert, Jacob F., Jennifer L. Boldt, Linnea Flostrand, and Jaclyn S. Cleary. 2010. "A Review of Factors Limiting Recovery of Pacific Herring Stocks in Canada." *ICES Journal of Marine Science* 67 (9): 1903–13. <https://doi.org/10.1093/icesjms/fsq134>.
- Schweigert, J.F., M. Thompson, C. Fort, D.E. Hay, T.W. Therriault, and L.N. Brown. 2013. "Factors Linking Pacific Herring (*Clupea pallasii*) Productivity and the Spring Plankton Bloom in the Strait of Georgia, British Columbia, Canada." *Progress in Oceanography* 115 (August): 103–10. <https://doi.org/10.1016/j.pocean.2013.05.017>.
- Scordino, J. 2010. West coast pinniped program investigations on California sea lion and Pacific Harbor seal impacts on salmonids and other fishery resources. 106; Pacific States Marine Fisheries Commission.
- Selleck, James R, Caroline F Gibson, Suzanne Shull, and Joseph K Gaydos. 2015. "Nearshore Distribution of Pacific Sand Lance (*Ammodytes personatus*) in the Inland Waters of Washington State." *Northwestern Naturalist* 96 (3): 185–95. <https://doi.org/10.1898/1051-1733-96.3.185>.
- Sharpe, F. A., and L. M. Dill. 1997. "The Behavior of Pacific Herring Schools in Response to Artificial Humpback Whale Bubbles." *Canadian Journal of Zoology* 75 (5): 725–30. <https://doi.org/10.1139/z97-093>.
- Sheaves, Marcus, Ronald Baker, Ivan Nagelkerken, and Rod M. Connolly. 2015. "True Value of Estuarine and Coastal Nurseries for Fish: Incorporating Complexity and Dynamics." *Estuaries and Coasts* 38 (2): 401–14. <https://doi.org/10.1007/s12237-014-9846-x>.
- Shelton, Andrew O., Tessa B. Francis, Blake E. Feist, Gregory D. Williams, Adam Lindquist, and Philip S. Levin. 2017. "Forty Years of Seagrass Population Stability and Resilience in an Urbanizing Estuary." *Journal of Ecology* 105 (2): 458–70. <https://doi.org/10.1111/1365-2745.12682>.
- Shelton, A.O., T.B. Francis, G.D. Williams, B. Feist, K. Stick, and P.S. Levin. 2014. "Habitat Limitation and Spatial Variation in Pacific Herring Egg Survival." *Marine Ecology Progress Series* 514 (November): 231–45. <https://doi.org/10.3354/meps10941>.
- Sigler, Michael F., Scott M. Gende, and David J. Csepp. 2017. "Association of Foraging Steller Sea Lions with Persistent Prey Hot Spots in Southeast Alaska." *Marine Ecology Progress Series* 571 (May): 233–43. <https://doi.org/10.3354/meps12145>.
- Silva, Cátia S.E., Sara C. Novais, Marco F.L. Lemos, Susana Mendes, Ana P. Oliveira, Emanuel J. Gonçalves, and Ana M. Faria. 2016. "Effects of Ocean Acidification on the Swimming Ability, Development and Biochemical Responses of Sand Smelt Larvae." *Science of The Total Environment* 563–564 (September): 89–98. <https://doi.org/10.1016/j.scitotenv.2016.04.091>.
- Silva, Filipa F.G., Aril Slotte, Arne Johannessen, James Kennedy, and Olav Sigurd Kjesbu. 2013. "Strategies for Partition between Body Growth and Reproductive Investment in Migratory and Stationary Populations of Spring-Spawning Atlantic Herring (*Clupea harengus* L.)." *Fisheries Research* 138 (February): 71–79. <https://doi.org/10.1016/j.fishres.2012.07.013>.
- Simenstad, Charles A., Bruce A. Miller, J.N. Cross, Kurt L. Fresh, S.N. Steinfort, and J.C. Fegley. 1977. "Nearshore Fish and Macroinvertebrate Assemblages along the Strait of Juan de Fuca Including Food Habits of Nearshore Fish." FRI-UW-7729. Seattle, WA: Fisheries Research Institute, University of Washington.
- Simenstad, Charles A., M. Ramirez, J. Burke, M. Logsdon, H. Shipman, C. Tanner, J. Toft, et al. 2011. "Historical Change of Puget Sound Shorelines: Puget Sound Nearshore Ecosystem Project Change Analysis." Puget Sound Nearshore Ecosystem Project Change Analysis 2011–01. WDFW, Army Corps of Engineers.
- Similä, T, J C Holst, and I Christensen. 1996. "Occurrence and Diet of Killer Whales in Northern Norway: Seasonal Patterns Relative to the Distribution and Abundance of Norwegian Spring-Spawning

- Herring.” *Canadian Journal of Fisheries and Aquatic Sciences* 53 (4): 769–79.
<https://doi.org/10.1139/f95-253>.
- Simpson, Stephen D., Julia Purser, and Andrew N. Radford. 2015. “Anthropogenic Noise Compromises Antipredator Behaviour in European Eels.” *Global Change Biology* 21 (2): 586–93.
<https://doi.org/10.1111/gcb.12685>.
- Siple, Margaret C., and Tessa B. Francis. 2016. “Population Diversity in Pacific Herring of the Puget Sound, USA.” *Oecologia* 180 (1): 111–25. <https://doi.org/10.1007/s00442-015-3439-7>.
- Siple, Margaret C., Andrew O Shelton, Tessa B Francis, Dayv Lowry, Adam P Lindquist, Timothy E Essington, 2018. “Contributions of Adult Mortality to Declines of Puget Sound Pacific Herring.” *ICES Journal of Marine Science* 75 (1): 319–29. <https://doi.org/10.1093/icesjms/fsx094>.
- Sisson, Nicholas B., and Matthew R. Baker. 2017. “Feeding Ecology of Pacific Sand Lance in the San Juan Archipelago.” *Marine and Coastal Fisheries* 9 (1): 612–25.
<https://doi.org/10.1080/19425120.2017.1370043>.
- Skaret, G, B Axelsen, L Nottestad, A Ferno, and A Johannessen. 2005. “The Behaviour of Spawning Herring in Relation to a Survey Vessel.” *ICES Journal of Marine Science*, July.
<https://doi.org/10.1016/j.icesjms.2005.05.001>.
- Skaret, Georg, Aril Slotte, Nils Olav Handegard, Bjørn Erik Axelsen, and Roar Jørgensen. 2006. “Pre-Spawning Herring in a Protected Area Showed Only Moderate Reaction to a Surveying Vessel.” *Fisheries Research* 78 (2–3): 359–67. <https://doi.org/10.1016/j.fishres.2005.11.007>.
- Small, Maureen P., Janet L. Loxterman, Alice E. Frye, Jennifer F. Von Bargen, Cherril Bowman, and Sewall F. Young. 2005. “Temporal and Spatial Genetic Structure among Some Pacific Herring Populations in Puget Sound and the Southern Strait of Georgia.” *Transactions of the American Fisheries Society* 134 (5): 1329–41. <https://doi.org/10.1577/T05-050.1>.
- Sobocinski, Kathryn L., Jeffery R. Cordell, and Charles A. Simenstad. 2010. “Effects of Shoreline Modifications on Supratidal Macroinvertebrate Fauna on Puget Sound, Washington Beaches.” *Estuaries and Coasts* 33 (3): 699–711. <https://doi.org/10.1007/s12237-009-9262-9>.
- Sobocinski, Kathryn L., Correigh M. Greene, and Michael W. Schmidt. 2018. “Using a Qualitative Model to Explore the Impacts of Ecosystem and Anthropogenic Drivers upon Declining Marine Survival in Pacific Salmon.” *Environmental Conservation* 45 (3): 278–90. <https://doi.org/10.1017/S0376892917000509>.
- Smith, G.J.D. and Gaskin, D.E., 1974. The diet of harbor porpoises (*Phocoena phocoena* (L.)) in coastal waters of eastern Canada, with special reference to the Bay of Fundy. *Canadian Journal of Zoology*, 52(6), pp.777-782.
- Sswat, Michael, Martina H. Stiasny, Fredrik Jutfelt, Ulf Riebesell, and Catriona Clemmesen. 2018. “Growth Performance and Survival of Larval Atlantic Herring, under the Combined Effects of Elevated Temperatures and CO₂.” Edited by Heather M. Patterson. *PLOS ONE* 13 (1): e0191947.
<https://doi.org/10.1371/journal.pone.0191947>.
- Sswat, Michael, Martina H. Stiasny, Jan Taucher, Maria Algueró-Muñiz, Lennart T. Bach, Fredrik Jutfelt, Ulf Riebesell, and Catriona Clemmesen. 2018. “Food Web Changes under Ocean Acidification Promote Herring Larvae Survival.” *Nature Ecology & Evolution* 2 (5): 836–40. <https://doi.org/10.1038/s41559-018-0514-6>.
- Stephens, Philip A., and William J. Sutherland. 1999. “Consequences of the Allee Effect for Behaviour, Ecology and Conservation.” *Trends in Ecology & Evolution* 14 (10): 401–5.
[https://doi.org/10.1016/S0169-5347\(99\)01684-5](https://doi.org/10.1016/S0169-5347(99)01684-5).
- Stewart, H, 1977. Indian Fishing: Early Methods on the Northwest Coast. University of Washington Press, Seattle, WA. 181 pp.
- Stick, Kurt C., and Adam Lindquist. 2009. “2008 Washington State Herring Stock Status Report, Washington Department of Fish and Wildlife.” Fish Program Technical Report. Olympia, WA: WDFW.
- Stick, Kurt C., Adam Lindquist, and Dayv Lowry. 2014. “2012 Washington State Herring Stock Status Report. Washington Department of Fish and Wildlife.” Fish Program Technical Report No. FPA-14-09. Olympia, WA: WDFW.

- Stout, H.A., R.G. Gustafson, W.H. Lenarz, B.B. McCain, D.M. VanDoornick, T.L. Builder, and R.D. Methot. 2001. "Status Review of Pacific Herring (*Clupea pallasii*) in Puget Sound, Washington." Seattle, WA: Northwest Fisheries Science Center, NMFS.
- Surma, S, Ea Pakhomov, and Tj Pitcher. 2018. "Energy-Based Ecosystem Modelling Illuminates the Ecological Role of Northeast Pacific Herring." *Marine Ecology Progress Series* 588 (February): 147–61. <https://doi.org/10.3354/meps12430>.
- Surma, Szymon, Tony J. Pitcher, Rajeev Kumar, Divya Varkey, Evgeny A. Pakhomov, and Mimi E. Lam. 2018b. "Herring Supports Northeast Pacific Predators and Fisheries: Insights from Ecosystem Modelling and Management Strategy Evaluation." Edited by Andrea Belgrano. *PLOS ONE* 13 (7): e0196307. <https://doi.org/10.1371/journal.pone.0196307>.
- Sutherland, David A., Parker MacCready, Neil S. Banas, and Lucy F. Smedstad. 2011. "A Model Study of the Salish Sea Estuarine Circulation." *Journal of Physical Oceanography; Boston* 41 (6): 1125–43.
- Tanasichuk, R. W. 2017. "An Investigation of the Biological Basis of Recruitment, Growth and Adult Survival Rate Variability of Pacific Herring (*Clupea pallasii*) from British Columbia: A Synthesis." *Fisheries Oceanography* 26 (4): 413–38. <https://doi.org/10.1111/fog.12206>.
- Therriault, T W, A N McDiarmid, W Wulff, and D Hay. 2002. "Review of Northern Anchovy (*Engraulis mordax*) Biology and Fisheries, with Suggested Management Options for British Columbia," 28.
- Therriault, Thomas W, Douglas E Hay, and J. Schweigert. 2009. "Biological Overview and Trends in Pelagic Forage Fish Abundance in the Salish Sea (Strait of Georgia, British Columbia)." *Marine Ornithology* 37: 3–8.
- Thomas, A.C., M.M. Lance, S.J. Jeffries, B.G. Miner, and A. Acevedo-Gutiérrez. 2011. "Harbor Seal Foraging Response to a Seasonal Resource Pulse, Spawning Pacific Herring." *Marine Ecology Progress Series* 441 (November): 225–39. <https://doi.org/10.3354/meps09370>.
- Thompson, Sarah Ann, William J Sydeman, Julie A. Thayer, Anna Weinstein, Katherine L Krieger, Doug Hay, 2017. "Trends in the Pacific Herring (*Clupea pallasii*) Metapopulation in the California Current Ecosystem." CalCOFI.
- Thor, Peter, Allison Bailey, Claudia Halsband, Ella Guscetti, Elena Gorokhova, and Agneta Fransson. 2016. "Seawater PH Predicted for the Year 2100 Affects the Metabolic Response to Feeding in Copepodites of the Arctic Copepod *Calanus glacialis*." *PLOS ONE* 11 (12): e0168735. <https://doi.org/10.1371/journal.pone.0168735>.
- Thor, Peter, and Sam Dupont. 2015. "Transgenerational Effects Alleviate Severe Fecundity Loss during Ocean Acidification in a Ubiquitous Planktonic Copepod." *Global Change Biology* 21 (6): 2261–71. <https://doi.org/10.1111/gcb.12815>.
- Thor, Peter, and Elisenda Oliver Oliva. 2015. "Ocean Acidification Elicits Different Energetic Responses in an Arctic and a Boreal Population of the Copepod *Pseudocalanus acuspes*." *Marine Biology; Heidelberg* 162 (4): 799–807. <http://dx.doi.org/10.1007/s00227-015-2625-9>.
- Thornton, Thomas F. 2015. "The Ideology and Practice of Pacific Herring Cultivation among the Tlingit and Haida." *Human Ecology* 43 (2): 213–23. <https://doi.org/10.1007/s10745-015-9736-2>.
- Toft, Jason D., Jeffery R. Cordell, Charles A. Simenstad, and Lia A. Stamatiou. 2007. "Fish Distribution, Abundance, and Behavior along City Shoreline Types in Puget Sound." *North American Journal of Fisheries Management* 27 (2): 465–80. <https://doi.org/10.1577/M05-158.1>.
- Toresen, Reidar. 1991. "Predation on the Eggs of Norwegian Spring-Spawning Herring (*Clupea harengus* L.) on a Spawning Ground on the West Coast of Norway." *ICES Journal of Marine Science* 48: 15–21.
- Trites, Andrew W., Volker B. Deecke, Edward J. Gehr, John K.B. Ford, and Peter F. Olesiuk. 2007. "Killer Whales, Whaling, and Sequential Megafaunal Collapse in the North Pacific: A Comparative Analysis of the Dynamics of Marine Mammals in Alaska and British Columbia Following Commercial Whaling." *Marine Mammal Science* 23 (4): 751–65. <https://doi.org/10.1111/j.1748-7692.2006.00076.x>.
- Trumble, Robert J. 1983. "Management Plan for Baitfish Species in Washington State." Progress Report 195. Olympia, WA: WDFW.
- Turner, John W., Allen T. Rutberg, Ricky E. Naugle, Manpreet A. Kaur, Douglas R. Flanagan, Henk J. Bertschinger, and Irwin K. M. Liu. 2008. "Controlled-Release Components of PZP Contraceptive

- Vaccine Extend Duration of Infertility.” *Wildlife Research* 35 (6): 555–62.
<https://doi.org/10.1071/WR07159>.
- Turner, R. E. 2002. “Element Ratios and Aquatic Food Webs.” *Estuaries* 25 (4): 694–703.
<https://doi.org/10.1007/BF02804900>.
- Uye, Shin-ichi. 2011. “Human Forcing of the Copepod–Fish–Jellyfish Triangular Trophic Relationship.” *Hydrobiologia* 666 (1): 71–83. <https://doi.org/10.1007/s10750-010-0208-9>.
- Vilchis, L. Ignacio, Christine K. Johnson, Joseph R. Evenson, Scott F. Pearson, Karen L. Barry, Peter Davidson, Martin G. Raphael, and Joseph K. Gaydos. 2015. “Assessing ecological correlates of marine bird declines to inform marine conservation.” *Conservation Biology* 29 (1): 154–63.
<https://doi.org/10.1111/cobi.12378>.
- Vollenweider J, Womble J, Heintz R (2006) Estimation of seasonal energy content of Steller sea lion (*Eumetopias jubatus*) diet. In Trites AW, Atkinson SK, DeMaster DP, Fritz LW, Gelatt TS and others (eds) Proc Symp Sea Lions of the World: Conservation and Research in the 21st Century. Alaska Sea Grant College Program, Fairbanks, AK, p 155–176.
- Walker, W.A., Hanson, M.B., Baird, R.W. and Guenther, T.J., 1998. Food habits of the harbor porpoise, *Phocoena phocoena*, and Dall's porpoise, *Phocoenoides dalli*, in the inland waters of British Columbia and Washington. *AFSC Processed Report*, pp.98-10.
- Washington State Department of Natural Resources. 2015. Puget Sound Eelgrass (*Zostera marina*) Recovery Strategy. Aquatic Resources Division, Nearshore Habitat Program.
https://www.dnr.wa.gov/publications/aqr_nrsh_eelgrass_strategy_final.pdf
- West, J. E., and S. M. O'Neill. 2007. Thirty years of Persistent Bioaccumulative Toxics in Puget Sound: time trends of PCBs and PBDE flame retardants in three fish species. Research in the Georgia Basin and Puget Sound Conference. Puget Sound Action Team. Vancouver, B.C.
- West, James E., Sandra M. O'Neill, and Gina M. Ylitalo. 2008. “Spatial Extent, Magnitude, and Patterns of Persistent Organochlorine Pollutants in Pacific Herring (*Clupea pallasii*) Populations in the Puget Sound (USA) and Strait of Georgia (Canada).” *Science of The Total Environment* 394 (2–3): 369–78.
<https://doi.org/10.1016/j.scitotenv.2007.12.027>.
- West, James E., Sandra M. O'Neill, Gina M. Ylitalo, John P. Incardona, Daniel C. Doty, and Margaret E. Dutch. 2014. “An Evaluation of Background Levels and Sources of Polycyclic Aromatic Hydrocarbons in Naturally Spawned Embryos of Pacific Herring (*Clupea pallasii*) from Puget Sound, Washington, USA.” *Science of The Total Environment* 499 (November): 114–24.
<https://doi.org/10.1016/j.scitotenv.2014.08.042>.
- Williams, R.W. 1959. “The Fishery for Herring (*Clupea pallasii*) on Puget Sound.” Washington Department of Fisheries Research Paper. Olympia, WA.
- Williams, R., G. A. Vikingsson, A. Gislason, C. Lockyer, L. New, L. Thomas, and P. S. Hammond. 2013. “Evidence for Density-Dependent Changes in Body Condition and Pregnancy Rate of North Atlantic Fin Whales over Four Decades of Varying Environmental Conditions.” *ICES Journal of Marine Science* 70 (6): 1273–80. <https://doi.org/10.1093/icesjms/fst059>.
- Willson, Mary F., and Jamie N. Womble. 2006. “Vertebrate Exploitation of Pulsed Marine Prey: A Review and the Example of Spawning Herring.” *Reviews in Fish Biology and Fisheries* 16 (2): 183–200.
<https://doi.org/10.1007/s11160-006-9009-7>.
- Wittmann, Astrid C., and Hans-O. Pörtner. 2013. “Sensitivities of Extant Animal Taxa to Ocean Acidification.” *Nature Climate Change* 3 (11): 995–1001. <https://doi.org/10.1038/nclimate1982>.
- Womble, Jamie N., and Michael F. Sigler. 2006. “Seasonal Availability of Abundant, Energy-Rich Prey Influences the Abundance and Diet of a Marine Predator, the Steller Sea Lion *Eumetopias jubatus*.” *Marine Ecology Progress Series* 325: 281–93.
- Womble, J.N. and Sigler, M.F., 2006. Temporal variation in Steller sea lion diet at a seasonal haul-out in southeast Alaska. *Sea lions of the world*. Edited by AW Trites, SK Atkinson, DP DeMaster, LW Fritz, RS Gelatt, LD Rea, and KM Wynne. Alaska Sea Grant College Program, University of Alaska Fairbanks, Anchorage, pp.141-154.

Woth, Katja, Ralf Weisse, and Hans von Storch. 2006. "Climate Change and North Sea Storm Surge Extremes: An Ensemble Study of Storm Surge Extremes Expected in a Changed Climate Projected by Four Different Regional Climate Models." *Ocean Dynamics; Heidelberg* 56 (1): 3–15.
<http://dx.doi.org/10.1007/s10236-005-0024-3>.