Pacific Herring

Resource List

Pacific Wild

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Pacific Herring: Resource List

Note to the reader:

This resource list, compiled based on a file and literature review, is a collection of research articles, records, and other documents pertinent to Pacific herring. It is not an exhaustive compendium of references or topics related to Pacific herring, but provides a concrete starting point that can evolve and expand as new research becomes available. The 2025 update features annotated resources from *The Fighting Fish: An historical review of our relationship with Pacific herring in British Columbia* and highlights new and notable research published since 2021.

1 Herring Biology: Reproduction, Growth, Survival and Behaviour

1.1.1 *Maturation and fecundity of Pacific herring (*Clupea harengus pallas*): An experimental study with comparisons to natural populations*

This study researched maturation and fecundity of Pacific herring using experimental net pens. Hay and Brett placed fish in the net pens three months prior to spawning. Fecundity decreased as the fish ripened. Concurrently, ovary weight and egg weight increased and somatic weight decreased. Length-specific fecundities of fed and unfed fish were similar, but the unfed fish had higher weight-specific fecundities, corresponding to a greater loss of somatic tissue during impoundment. Feeding accelerated the rate of maturity, and fed fish spawned earlier with heavier eggs than unfed fish. Relative fecundity (eggs per gram) was highest among the unfed fish. Reduction in preovulatory egg numbers was a consequence of follicular atresia (observed but not quantified here). Age-, length-, and weight-specific fecundity of impounded herring varied within the range observed for naturally maturing populations. Fecundity in impounded fish varied no more than observed in nature: there was a greater difference in age-, length-, and weight-specific fecundity between years than there was between experimental treatments. The authors suggest that reduction in the number of maturing oocytes occurs naturally and reflects a mechanism that allows herring to adjust their egg size and egg number according to energetic resources and environmental conditions.

Hay, D.E., & Brett, I.R. (1988). Maturation and fecundity of Pacific herring (*Clupea harengus pallas*): An experimental study with comparisons to natural populations. *Can. J. Fish. Aquat. Sci., 45*, 399–406.

1.1.2 *Pacific and Atlantic herring produce burst pulse sounds*

Wilson et al. studied the sounds made by captive wild-caught Pacific herring Pacific herring produce distinctive bursts of pulses, termed Fast Repetitive Tick (FRT) sounds. These trains of broadband pulses (1.7–22 kHz) lasted between 0.6 s and 7.6 s. Most were produced at night; feeding regime did not affect their frequency, and fish produced FRT sounds without direct access to the air. Digestive gas or gulped air transfer to the swim bladder, therefore, do not appear to be responsible for FRT sound generation. Atlantic herring also produce FRT sounds, and video analysis showed an association with bubble expulsion from the anal duct region (i.e. from the gut or swim bladder). To the best of the authors' knowledge, sound production by such means had not previously been described. The function(s) of these sounds are unknown, but as the per capita rates of sound production by fish at higher densities were greater, social mediation appears likely. These sounds may have consequences for our understanding of herring behaviour and the effects of noise pollution.

Wilson, B., Batty, R., & Dill, L. (2004). Pacific and Atlantic herring produce burst pulse sounds. Proceedings: Biological Sciences, 271(Supplement 3), S95-S97. Retrieved from www.jstor.org/stable/4142568

1.1.3 *An index of relative biomass, abundance, and condition of juvenile Pacific Herring (*Clupea pallasi*) in the Strait of Georgia, British Columbia*

The purpose of this report was to update the time-series information based on the Strait of Georgia juvenile herring and nearshore pelagic ecosystem survey. The time-series information is used to estimate the relative biomass (abundance) of age-0 herring, to potentially forecast recruitment to the adult spawning population, and represents trends in prey availability to predators. Results showed that estimates of age-0 herring biomass (abundance) were correlated with abundance estimates of age-3 recruits (of the same year class) from the stock assessment model, supporting the notion that survey catches of age-0 herring may be indicative of the number of recruits joining the population 2.5 years later.

Boldt, J.L., Thompson, M., Fort, C., Rooper, C.N., Schweigert, J., Quinn II, T.J., Hay, D., and Therriault, T.W. (2015). An index of relative biomass, abundance, and condition of juvenile Pacific Herring (*Clupea pallasi*) in the Strait of Georgia, British Columbia. *Can. Manuscr. Rep. Fish. Aquat. Sci.* 3081: x + 80 p.

1.1.4 *An investigation of the biological basis of recruitment, growth and adult survival rate variability of Pacific herring (*Clupea pallasi*) from British Columbia: a synthesis*

Tanasichuk evaluates the biological basis of variation in recruitment (age-3 abundance), growth and age-specific adult survival rate for the major herring populations [West Coast Vancouver Island (WCVI), Strait of Georgia (SOG), Central Coast, North Coast and Haida Gwaii]. The study determined a relationship to describe recruitment in one of the five populations, as well as growth and adult age-specific survival for all populations. Recruitment was not correlated among populations. Recruitment variability was explained for WCVI herring only, as a consequence of prey (the euphausiid *Thysanoessa spinifera*) biomass during August in each of the first three years of life, and the biomass of piscivorous Pacific hake during the first year of life. Recruit mass and adult mass-at-age were correlated among populations and over ages within populations. Recruit mass was affected by *T. spinifera* biomass in August of the first and third years of life. Adult mass-at-age variability was determined mainly by size at the beginning of the growth season, but also by biomass in August. Age-specific adult survival rates were not correlated among the five populations. Survival rates decreased with age; there were additional population-specific effects of body mass and *T. spinifera* biomass in August. The goal of the study was to learn enough about the biological basis of B.C. herring productivity to investigate the effect of biological or physical oceanographic factors on production quantitatively. The findings allowed this further exploration for WCVI herring. When prey biomass was low, WCVI herring were not emaciated. Therefore, lower herring population fecundity, or productivity, was determined to be an adaptive biological response to reduce prey biomass and not suppression.

Tanasichuk, R.W. (2017). An investigation of the biological basis of recruitment, growth and adult survival rate variability of Pacific herring (*Clupea pallasi*) from British Columbia: a synthesisions. *Fisheries Oceanography, 26*(4), 413–438.

1.1.5 The highs and lows of herring: A meta-analysis of patterns and factors in herring collapse and recovery

Trochta et al. analyzed the dynamics of 64 herring populations globally, emphasizing recovery and decline patterns in relation to recruitment and biomass. The authors identified that herring populations decline at lower biomass minima and recover at higher maxima compared to other forage fish. On average, populations recovered within 11 years. Drivers such as sea surface temperature and sea surface height anomalies explained biomass recovery, while higher variability shortened recovery times, and recruitment failure correlated with lower biomass. The study revealed that differences in management strategies for Pacific and Atlantic herring fisheries did not significantly influence recovery times. Furthermore, the findings underscore high variability and limited resilience in herring populations. The authors recommend sustainable management approaches, emphasizing the critical reliance of local communities on herring and the lingering uncertainties surrounding the complexities of herring population dynamics.

Trochta, J. T., Branch, T. A., Shelton, A. O., & Hay, D. E. (2020). The highs and lows of herring: A meta-analysis of patterns and factors in herring collapse and recovery. *Fish and Fisheries, 21*(4), 639–662. https://doi.org/10.1111/faf.12452

1.1.6 Predation by marine mammals explains recent trends in natural mortality of Pacific herring (Clupea pallasii) and changes expectations for future biomass

Doherty et al. examined the impact of recovering marine mammal populations on the natural mortality of Pacific herring along the west coast of Vancouver Island (WCVI). Using a model integrating predator consumption rates and herring population dynamics, the authors found that predator consumption, especially by humpback whales, significantly contributed to recent increases in natural mortality rates of Pacific herring. Models incorporating these higher predation-driven mortality rates produced lower estimates of equilibrium for unfished biomass compared to traditional models that assumed constant historical mortality. Despite recent fishing closures, herring populations have struggled to recover, partly due to high predator-induced mortality. These findings challenge traditional stock assessment models that assume constant historical mortality, suggesting that predator-driven mortality reduces unfished biomass and hinders herring recovery, even with fishing closures. The authors provide a framework for integrating predation effects into fisheries management, emphasizing the importance of accounting for ecosystem dynamics to improve future stock assessments and management strategies.

Doherty, B., Johnson, S. D. N., Benson, A. J., Cox, S. P., Cleary, J. S., & Lane, J. (2024). Predation by marine mammals explains recent trends in natural mortality of Pacific herring (*Clupea pallasii*) and changes expectations for future biomass. *ICES Journal of Marine Science.* https://doi.org/10.1093/icesjms/fsae183

2 Historic Abundance

*2.1.1 Archaeological data provide alternative hypotheses on Pacific herring (*Clupea pallasii*) distribution, abundance, and variability*

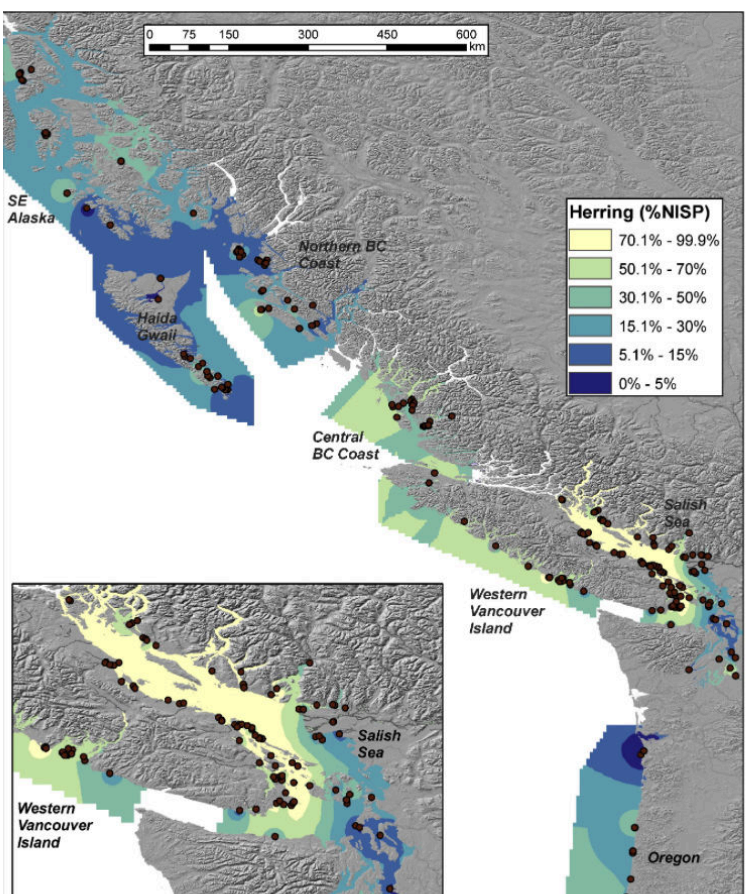
Researchers assembled data on fish bones from 171 archaeological sites from Alaska, British Columbia, and Washington to provide proxy measures of past herring distribution and abundance. The dataset represents 435,777 fish bones, dating throughout the Holocene, but primarily to the last 2,500 years. Herring is the most ubiquitous fish taxon (99% ubiquity) and among the two most abundant taxa in 80% of individual assemblages. Herring bones are archaeologically abundant in all regions, but are superabundant in the northern Salish Sea and southwestern Vancouver Island areas. Analysis of temporal variability in 50 well-sampled sites reveals that herring exhibits consistently high abundance (>20% of fish bones) and consistently low variance (<10%) within the majority of sites (88% and 96%, respectively). The archaeological record, in combination with local and traditional knowledge, early historical records, and palaeoecological records, suggests that spawning locations were formerly more abundant and geographically extensive than is recorded by modern surveys. These data, particularly in the context of high harvest levels during the early industrial fishery and the subsequent contraction of effective spawning range, indicate that the current ecological baseline of the mid-20th century is inadequate for modern management. The findings support the idea that if past populations of Pacific herring exhibited substantial variability, then this variability was expressed around a high enough mean abundance that there was adequate herring available for Indigenous fishers to sustain their harvests while avoiding the extirpation of local populations. Therefore these records demonstrate a fishery that was sustainable at local and regional scales over millennia, and a resilient relationship between harvesters, herring, and environmental change that has been absent in the modern era. Archaeological data have the potential to provide a deep-time perspective on the interaction between humans and the resources on which they depend. Furthermore, the data can contribute significantly toward developing temporally meaningful ecological baselines that avoid the biases of shorter-term records. These results provide baseline information prior to herring depletion and can inform modern management.

McKechnie, I., Lepofsky, D., Moss, M.L., Butler, V.L., Orchard, T.J., Coupland, G., Foster, F., Caldwell, M., & Lertzman, K. (2014). Archaeological data provide alternative hypotheses on Pacific herring (*Clupea pallasii*) distribution, abundance, and variability. *Proceedings of the National Academy of Sciences, 111*(9), 807–816

2.1.2 Meta-analysis in zooarchaeology expands perspectives on Indigenous fisheries of the Northwest Coast of North America

McKechnie and Moss examined archaeological fisheries data from coastal British Columbia and adjacent regions over the late Holocene. The authors used meta-analysis methods and GIS-based spatial visualizations to survey the single largest compilation of fine-screened zooarchaeological fisheries data reported to date, including 513,605 fish remains identified at 222 sites from Oregon to southeast Alaska. Pacific herring is the single-most common taxon, present in 98% of all examined sites. Pacific salmon species (representing seven potential species) were a close second, present in 95% of sites. These observations affirm other analyses demonstrating the importance of herring in Indigenous fisheries on the Northwest Coast. Assemblages composed predominantly of herring (over 60%) are found in all regions with available data (e.g., central British Columbia Coast, southeast Alaska, Haida Gwaii, western Vancouver Island, Salish Sea) and are present and consistently abundant in many places where they are not regularly observed today. Herring exhibit a hyper-abundance in the Salish Sea region and on the West Coast of Vancouver Island. Specifically, of all the regions examined, the researchers noted higher ubiquity and rank order abundance for herring in the Salish Sea and WCVI regions. Moreover, herring occur consistently over time.

McKechnie, I., and Moss, M.L. (2016). Meta-analysis in zooarchaeology expands perspectives on Indigenous fisheries of the Northwest Coast of North America. *Journal of Archaeological Science: Reports, 8*, 470–485



Geographic patterning of relative abundance of herring versus all other identified fish as interpolated by inverse distance weighting from archaeological sites with available data (dots) (McKechnie and Moss, 2016).

2.1.3 Ancient DNA reveals phenological diversity of Coast Salish herring harvests over multiple centuries

Petrou et al. investigated the contributions of genetically and phenologically distinct herring populations in Indigenous food systems through the analysis of ancient DNA extracted from herring bones on Coast Salish archaeological sites. Genetic and phenological diversity are significant in maintaining productivity and resilience in Pacific herring populations. While contemporary spawning groups represented the dominant catches from these ancient sites, May spawners were also identified as an additional herring population harvested by Coast Salish ancestors. This extended foraging opportunity may have acted as a buffer enabling long-term sustainability in Indigenous harvesting practices and signifies the importance of intraspecific biodiversity in supporting ecosystem services. As herring are an essential forage fish responsible for nourishing ecosystems and supporting socio-economic wellbeing, we must mitigate erosion of biodiversity and further investigate long-term patterns for success.

Petrou, E. L., Kopperl, R., Lepofsky, D., Rodrigues, A. T., Yang, D., Moss, M. L., Speller, C. F., & Hauser, L. (2022). Ancient DNA reveals phenological diversity of Coast Salish herring harvests over multiple centuries. *Scientific Reports, 12*, 13512. https://doi.org/10.1038/s41598-022-17656-4

3 Indigenous Knowledge and Management

3.1 Governance and Forecasting

3.1.1 Divided waters: Heiltsuk spatial management of herring fisheries and the politics of Native sovereignty

Through kinship claims, the Heiltsuk Nation and other coastal Indigenous people established a system of marine space that facilitated effective fisheries management. These dynamic cultures thrived in part because they developed beliefs and practices that helped sustain the local environment. Most significantly, nearly all groups claimed their territory's best harvest sites and restricted their access to kin. Through these tribal and intra-tribal claims, coastal Indigenous groups established a system of marine space that heeded the relationship between stock concentration and harvest distribution. Rather than treat Pacific fish stocks as amorphous wholes, First Nations established regulatory schemes that allowed for regional specificity while also limiting total yields. The Heiltsuk managed their extensive Indigenous herring spawn fishery through precisely such a system. After overriding Indigenous claims on the basis of open access, the Canadian Department of Fisheries and Oceans conceded that efficacious regulation required exclusive harvest zones. Nonetheless, courts continued to disregard Heiltsuk spatial claims when assessing fishing rights.

Miles Powell. (2012). Divided waters: Heiltsuk spatial management of herring fisheries and the politics of Native sovereignty. *Western Historical Quarterly, 43*(4), 463–484. doi:10.2307/westhistquar.43.4.0463

3.1.2 Central Coast Marine Plan overview

This document provides an overview of the Central Coast Marine Plan on the vision, purpose, plan area, scope, approach, key issues and opportunities, management direction, and implementation and monitoring. The Plan was prepared as part of the Marine Planning Partnership for the North Pacific Coast (MaPP) initiative, partnering with the provincial government and 18 member First Nations, represented by three First Nations organizations: the Coastal First Nations–Great Bear Initiative, the North Coast–Skeena First Nations Stewardship Society and the Nanwakolas Council. The Central Coast Plan Area includes Queen Charlotte Sound and extends from Laredo Channel and the northern tip of Aristazabal Island in the north to the southern limit of Rivers Inlet and Calvert Island. The Central Coast Marine Plan focuses on the marine areas and uses in the foreshore (intertidal zone), coastal “inland waters,” and the lands covered by these waters. It considers the uses, plans, zones, tenures and legal designations that are in place on the land adjacent to marine areas and the seabed. The Central Coast Marine Plan covers a major portion of the territories of the Heiltsuk, Kitasoo/Xai’Xais, Nuxalk and Wuikinuxv Nations. These First Nations assert Aboriginal title and rights, including ownership, jurisdiction, and management over the lands, waters, and resources, encompassing the marine spaces, throughout their respective territories. The MaPP planning process used a marine ecosystem-based management (EBM) approach, which is an adaptive approach to managing human activities that seeks to ensure the coexistence of healthy, fully-functioning ecosystems and human communities.

Heiltsuk, Kitasoo/Xai’Xais, Nuxalk and Wuikinuxv Nations & Province of British Columbia (2015). *Central Coast Marine Plan overview*. Retrieved from https://coastalfirstnations.ca/wp-content/uploads/2017/06/cc_mapp_overview_v3.84_web.pdf

3.1.3 Forecasting the return of British Columbia’s Central Coast herring

The goal of this presentation on Central Coast herring population forecasting was to (a) summarize assumptions used in current forecast modelling, and (b) demonstrate a better forecasting method with more appropriate model assumptions. It was argued that current model assumptions are not appropriate since (1) herring samples have not been collected the same way since 1951 so there is no long-term dataset for the stock assessment model to use for forecasting; (2) the number of eggs spawned does not affect how many new spawners are produced; (3) older herring die faster; and (4) half the eggs do not disappear before the spawns are surveyed. The researchers suggested a new way of forecasting herring returns: the pre-fishery biomass from the year before. Specifically, they suggest using known data from the previous year on both catch biomass and spawning biomass (mature fish stock that reproduced known from spawning surveys). The biomasses can be added to get the pre-fishery biomass. A fluctuating limit reference point (the biomass at which fishing should stop) was also suggested based on recent ocean conditions that affect herring (i.e. decline in krill and increase in sea lion abundance). The lowest tonne of spawn plus catch in the last ten years was proposed as a more realistic limit reference point.

Tanasichuk, R. (2015). *Forecasting the return of British Columbia's Central Coast herring*. Heiltsuk Science Team. [PowerPoint slides]. Retrieved from https://oceanmodelingforum.org/wp-content/uploads/2015/06/18_Tanasichuk-BC-Central-Coast-herring-forecasting.pdf

3.1.4 Kitasoo/Xai'xais Management Plan for Pacific Herring

Pacific herring have been a primary food of Indigenous people for over ten thousand years. Herring also sustains the traditional diet indirectly; they are prey to other species, such as salmon, rockfish, halibut and lingcod. The background information highlights the main stressors to Pacific herring (a) climate change and fisheries, (b) predators, (c) vessel noise on spawning herring, and (d) short-term information perspectives. Given climate change and ocean acidification, herring fisheries must become more conservative and marine protected areas should be used as management tools for sustainability. Biomass targets used for fishery management need to be conservative to allow for uncertainty in predator-inflicted mortality (e.g., sea lions). Noise disturbance must be managed. Most notable is the concern with Fisheries and Oceans Canada management decisions being based on short-term fisheries data information that does not represent a meaningful baseline. Examples include (a) snapshots of spawning distributions, or (b) including herring in biomass assessments that are only in the area for a few days (i.e., staging) that actually spawn elsewhere.

The plan highlights the importance of including Indigenous information in fisheries models, such as the roe fishery that kills spawning adults and the more sustainable traditional fisheries that harvest eggs only (spawn on kelp and Food, Social and Ceremonial [FSC]). DFO models treat the entire Central Coast as a single stock but traditional knowledge and science show that individual spawning areas likely are distinct stocks. Therefore management must occur at much finer spatial scales—at the level of individual spawning areas.

Kitasoo/Xai'xais First Nation (2018). *Kitasoo/Xai'xais Management Plan for Pacific Herring*. Retrieved from https://klemtu.com/wp-content/uploads/2018/05/KX-Herring-Mgmt-Plan-Jan-2018-final.pdf

3.1.5 *Forecasting Indigenous nationhood and herring governance: strategies for the reassertion of Indigenous authority and inter-Indigenous solidarity regarding marine resources*

Von der Porten et al. explored the strategies and tools used by three Indigenous coastal nations to apply pressure on the colonial government to undertake its asserted authority over herring governance. Motivated by a time-honored relationship to herring, the researchers discuss how these Indigenous nations have strategized to regain authority over herring governance to protect species and Indigenous access to the fishery. This study examined the relations among three Indigenous coastal nations (Nuu-chah-nulth, Heiltsuk, and Haida), the DFO, and the commercial fishing industry to follow the strategies and actions of Indigenous resurgence related to herring governance over a two-year period (2014–2015). Findings indicated that Indigenous coastal nations used both new and old technologies to organize with each other over herring protection and *sui generis* rights to fisheries governance. New technologies included social media, blogs, email, and online videos, and traditional forms of organizing included in-person meetings, travel by water between Indigenous territories, potlatches, and celebrations. Social media was one of many tools employed toward the protection of herring and marine resources. Other strategies, such as on-the-ground resistance, issuing notices to fishermen, and continuing traditional practices, were among the collection of strategies being used to reinvigorate Indigenous governance of herring. Furthermore, tactics included circumventing DFO by negotiating directly with industry and undertaking legal and court challenges. This ocean-based resurgence is discussed in the context of global Indigenous movements for the reassertion of self-determining authority. Strengthening the exchange of interests, ideas, values, and goals between Indigenous nations has the potential to reinforce Indigenous movements at broader scales.

von der Porten, S., Corntassel, J., & Mucina, D. (2019). Indigenous nationhood a herring governance: strategies for the reassertion of Indigenous authority and inter-Indigenous solidarity regarding marine resources. *AlterNative: An International Journal of Indigenous Peoples, 15*(1), 62–74. https://doi.org/10.1177/1177180118823560

3.1.6 *Strategies for assertion of conservation and local management rights: A Haida Gwaii herring story*

Jones et al. examined the Haida Nation's long-standing efforts to conserve Pacific herring stocks in Haida Gwaii, secure local management rights, and challenge federal decisions to reopen commercial herring fisheries in Haida territory. These efforts stemmed from concerns over persistently low herring stocks, the cultural and ecological significance of herring, and distrust of federal management strategies. The Haida Nation successfully combined strategies of negotiation, litigation, and direct action, resulting in a 2015 Federal Court injunction that blocked the Canadian government from reopening the fishery. Key factors driving the Haida Nation's success included recognized Aboriginal rights that raised legal standards for consultation, a co-management agreement under the Gwaii Haanas Marine Agreement, persistent conservation concerns, and strategic engagement in forums for dispute resolution. The case illustrates the power of local Indigenous governance and conservation priorities to influence broader fisheries management policies, highlighting the need for integrating Indigenous rights and ecological sustainability into resource management frameworks.

Jones, R., Rigg, C., & Pinkerton, E. (2017). Strategies for assertion of conservation and local management rights: A Haida Gwaii herring story. *Marine Policy, 80*, 154–167. https://doi.org/10.1016/j.marpol.2016.09.031

3.1.7 Haida Gwaii Herring Rebuilding Plan: Ecosystem-based approach for Pacific herring recovery

The Haida Gwaii Herring Rebuilding Plan addresses the long-standing decline of Pacific herring populations around Haida Gwaii. Herring populations have remained at low levels for over 25 years, leading to ecological, cultural, and socio-economic disruptions. The Herring Rebuilding Plan was developed through a collaborative effort between the Council of the Haida Nation (CHN), Fisheries and Oceans Canada (DFO), and Parks Canada. The plan integrates an ecosystem-based management (EBM) approach rooted in Haida principles of *yahgudáng* (respect) and reconciliation. Key components of the plan include rebuilding herring populations while safeguarding Haida traditional fisheries, integrating Haida traditional knowledge with scientific analyses, and emphasizing sustainable, low-impact fisheries such as spawn-on-kelp (SOK).

The plan identifies multiple factors contributing to herring declines, including overfishing during the reduction fishery period, habitat degradation, changing ocean conditions, and increased predation. Modelling suggests that under current natural mortality and environmental conditions, substantial population rebuilding is unlikely within the next 15 years. The rebuilding strategy emphasizes managing herring at the sub-stock level to address local variability, setting biomass reference points for recovery, and incorporating short- and long-term rebuilding targets. Importantly, commercial fisheries will only resume when the herring population demonstrates sustained recovery above established thresholds.

The plan also outlines recommendations for research, monitoring, and governance, including addressing data gaps for unmonitored regions (e.g. Skidegate Inlet, Masset Inlet, Naden Harbour), enhancing co-management processes, and strengthening conservation-focused practices. A phased approach to rebuilding will involve annual assessments and five-year reviews with the goal of achieving ecological balance, cultural resilience, and economic sustainability in Haida Gwaii's herring fisheries.

Council of the Haida Nation, Fisheries and Oceans Canada, & Parks Canada. (2023). *Haida Gwaii Herring Rebuilding Plan: Ecosystem-based approach for Pacific herring recovery*. Draft document.

3.2 Importance of Diverse Knowledge Systems

3.2.1 Thirty-two essential questions for understanding the social–ecological system of forage fish: the case of Pacific herring

Levin, Francis, and Taylor built a conceptual model of the Pacific herring social–ecological system (SES) in the Northeast Pacific and used it to identify questions that if answered would significantly increase our ability to sustainably manage the herring SES. The objective was to generate a road map for scientists who wish to conduct useful forage fish research, for resource managers who wish to develop new research efforts that could fill critical gaps, and for public agencies and private foundations seeking to prioritize funding on forage fish issues in the Pacific. With this socio-cultural centrality comes complexity for fisheries management. The participatory process highlighted the value of conceptualizing the full SES, overcame disciplinary differences in scientific approaches, research philosophy, and language, charting a path for future research and management for forage species. The conceptual model describes herring and human wellbeing as impacted by several components of the SES: (1) global and regional climate and oceanographic conditions; (2) global economic and social drivers, which include trade and economic policy; (3) institutions and governance structure, which dictate resource management practices, resource allocation policy, and access to the decision and knowledge processes; (4) human activities, which include industrial, commercial, recreational, and subsistence fisheries, impacts on the landscape, pollution; and (5) habitat structure and function, which impact herring and their food web at multiple life stages and is itself also affected by the first three external drivers. The conceptual model illustrates that management will be most successful when it includes a full reckoning of the influences of climate and ocean conditions, habitat, human activities, economics and societal forces, governance processes, and institutions on both herring and human wellbeing.

Levin, P. S., T. B. Francis, and N. G. Taylor. (2015). Thirty-two essential questions for understanding the social–ecological system of forage fish: the case of Pacific herring. *Ecosystem Health and Sustainability, 2*(4).

3.2.2 Neoliberal and neo-communal herring fisheries in Southeast Alaska: Reframing sustainability in marine ecosystems

This paper demonstrates how the transformation of Pacific herring fisheries from communal to commons to neoliberal regulation occurred through three key re-framings of Southeast herring populations under modern scientific management: (1) a reductionist framing of single species productivity models, expressed as herring “biomass,” within space and time (baseline scale framing); (2) the selective framing and privileging of human industrial predation under maximum sustainable yield (MSY) within a dynamic ecosystem of multiple predator populations (actor relations framing); and (3) the strategic framing of spawning failure events and policy responses to those events by professional fisheries managers (event–response framing). This transformation has had significant impacts on the health and sustainability of marine ecosystems on the

Northwest Coast of North America. Due to their abundance, seasonality, and sensitivity in disturbance, herring were carefully cultivated and protected by coastal Tlingit, Haida, and Tsimshian communities. The early industrial fishing era undermined this communalist approach in favour of an unregulated commons for bait and reduction fisheries, attracting non-local fleets and leading to conflicts with local Natives and tragedy of the commons style overexploitation of herring stocks by the mid-twentieth century. Since the 1970s, a re-regulated neoliberal sac roe fishery for Japanese markets has provided new opportunities for limited commercial permit holders, but with further depredations on local spawning populations. The authors argue for a new social–ecological systems approach, based on Indigenous models of herring cultivation, to sustain a commercial, subsistence, and restoration economy for the fishery. Tlingit and Haida peoples have intimate knowledge, experience, and techniques in place-based marine ecosystem stewardship, which have proven effective over time and may be useful yet as adaptive management tools. These tools, including habitat protection, cultivation and enhancement techniques, and herring transplant and harvest management strategies, could become the basis for stronger ecosystem management, habitat revitalization, and sustainable fisheries in the future.

Thornton, T.F., and Hebert, J. (2015). Neoliberal and neo-communal herring fisheries in Southeast Alaska: Reframing sustainability in marine ecosystems. *Marine Policy, 61*, 366–375.

3.2.3 Integrating expert perceptions into food web conservation and management

This research paper quantifies how scientific, local, and traditional knowledge experts vary in their perceptions of food webs centered on Pacific herring—a valuable ecological, economic, and cultural resource in Haida Gwaii, B.C., Canada. Since expert knowledge and perceptions of social-ecological system (SES) structure and function vary; understanding how these perceptions differ is critical to building knowledge and developing sustainability solutions. Expert perceptions of the herring food web varied markedly in structure, and a simulated herring recovery with each of these unique mental models demonstrated wide variability in the perceived importance of herring to the surrounding food web. Among-expert variability in perceptions of the number and strength of connections between herring and the rest of the food web results in variable management advice by experts when it comes to: (1) protected species (e.g., seabirds and marine mammals) that consume herring, (2) sustainable harvest of commercially valuable fishes that prey upon herring (e.g., groundfishes and salmon), and(3) marine ecosystem-based management in the Northeast Pacific. Using this general approach to determine the logical consequences of expert perceptions of SES structure in the context of potential future management actions, decision-makers can work explicitly toward filling knowledge gaps while embracing a diversity of perspectives.

Stier, A.C., Samhouri, J.F., Gray, S., Martone, R.G., Mach, M.E., Halpern, B.S., Kappel, C.V., Scarborough, C. and Levin, P.S. (2017). Integrating expert perceptions into food web conservation and management. *Conservation Letters, 10*, 67–76.

3.2.4 Diverse knowledge systems reveal social–ecological dynamics that inform species conservation status

This research paper synthesized knowledge sources (zooarchaeological, historical, traditional, and western science) to understand changes in northern abalone (marine mollusc) over larger timescales. Abalone are presently scarce compared to the mid-1900s, but more abundant than before the early 1800s, calling their endangered status into question. This is an example of how linking multiple knowledge sources can build social–ecological system understanding, facilitate power sharing, and support ecologically sustainable and socially just conservation outcomes. An example of Pacific herring is provided within the background of this study: zooarchaeological and ethnographic data from Canada's west coast suggested high Pacific herring abundances for millennia, declining only within the last century of commercial fishing. This combined knowledge can alter conservation perspectives by broadening the timescale over which social–ecological interactions and species abundances are assessed.

Lee, L.C, Thorley, J., Watson, J., Reid, M., and Salomon, A.K. (2018). Diverse knowledge systems reveal social–ecological dynamics that inform species conservation status. *Conservation Letters*. https://doi.org/10.1111/conl.12613

3.2.5 Historical and contemporary Indigenous marine conservation strategies in the North Pacific

Ban, Wilson, and Neasloss reviewed and assessed marine conservation strategy approaches of the Kitasoo/Xai'xais First Nation in British Columbia. The authors evaluated the conservation actions classification system by the Conservation Measures Partnership to determine if it was able to encompass this Nation's conservation approaches. All first-order conservation actions aligned with the Kitasoo/Xai'xais First Nation's historical and contemporary marine conservation actions. The Kitasoo/Xai'xais's embodiment of conservation actions as part of their worldview, rather than as requiring actions separate from everyday life (the norm in non-Indigenous cultures), was missing from the conservation action classification system. The case study highlights that with the Canadian government's declared willingness to work toward reconciliation, there is an opportunity to enable First Nations to lead on marine and other conservation efforts. Further, global conservation efforts would benefit from enhanced support for Indigenous conservation approaches, including expanding the conservation actions classification to encompass a new category of conservation or sacredness ethic.

This case study provides an example specific to Pacific herring of hereditary chiefs using their authority to oppose non-Kitasoo/Xai'xais decisions imposed on them. In the 2010s, the Kitasoo/Xai'xais created their own herring management plan and members protested against the commercial herring roe fishery, reacting to concerns about declines in herring populations and unsustainable federal fisheries management.

Ban, N.C., Wilson, E. and Neasloss, D. (2020). Historical and contemporary Indigenous marine conservation strategies in the North Pacific. *Conservation Biology, 34*, 5-14. doi:10.1111/cobi.13432

See also:
Ban, N.C., Wilson, E. and Neasloss, D. (2019). Strong historical and ongoing Indigenous marine governance in the northeast Pacific Ocean: a case study of the Kitasoo/Xai'xais First Nation. *Ecology and Society 24*(4):10. https://doi.org/10.5751/ES-11091-240410

3.2.6 "Everything revolves around the herring": the Heiltsuk-herring relationship through time

Gauvreau et al. explored the relationship between Pacific herring and the Heiltsuk First Nation of British Columbia. Post-contact, colonial institutions have disrupted traditional governance systems for herring. The study emphasizes how traditional ecological knowledge (TEK) continues to shape modern herring management, particularly for the purpose of enhancing sustainability and upholding Indigenous rights. The paper highlights the value of integrating TEK with scientific research to foster a holistic, sustainable, and culturally-respectful approach to herring management. The authors recommend strengthening joint learning and collaboration between state fisheries agencies and Indigenous communities to develop more informed, inclusive, and effective management strategies.

Gauvreau, A. M., Lepofsky, D., Rutherford, M., & Reid, M. (2017). "Everything revolves around the herring": The Heiltsuk–herring relationship through time. *Ecology and Society, 22*(2), 12. https://www.jstor.org/stable/26270079

3.2.7 Local and traditional knowledge and the historical ecology of Pacific herring in Alaska

Thornton et al. examined the historical ecology of Pacific herring in Alaska over the past century by synthesizing data from 86 individuals, archaeological site reports, and biological studies. Herring are a critical source of energy for marine animals and Alaska First Nations. Herring populations have faced heavy impacts from commercial fishing (to produce oil and fertilizer) and more recently by sac roe fisheries. Their exploitation has led to local and regional population declines. Even after management measures were implemented in the 1960s, there has been no full recovery and the authors suggest that shifting baseline syndrome has changed the perception of fisheries managers surrounding norms for herring populations. Because many traditional management strategies (e.g. selective harvest, predator control, habitat restoration) aim to enhance herring populations, the authors conclude that integrating Indigenous knowledge and practices could help reverse herring declines. An ecosystem-based, collaborative approach is recommended for the future of herring management.

Thornton, T. F., Moss, M. L., Butler, V. L., Hebert, J., & Funk, F. (2010). Local and traditional knowledge and the historical ecology of Pacific herring in Alaska. *Journal of Ecological Anthropology, 14*(1), 81–88. http://dx.doi.org/10.5038/2162-4593.14.1.7

3.2.8 Understanding the past to inform future conservation policy: Mapping traditional ecological knowledge of Pacific herring spawning areas through time

Gerrard mapped the spatial distribution of herring spawn events from the 1940s to the 2000s in British Columbia through the traditional ecological knowledge of the Heiltsuk First Nation. The findings show a total length of coastline with observed spawn and a shift towards inland locations. Factors contributing to these changes may include decreases in stock biomass, reduced social transfer of migration patterns due shortened age, and changes in observation efforts. Gerrard recommends that Indigenous and Western knowledge systems be integrated to improve ecosystem management and create innovative solutions for sustainable fisheries. Furthermore, Gerrard suggests a shift from a biomass-based assessment to a systems-oriented approach to account for the complexities and diversity of herring populations in British Columbia.

Gerrard, A. L. (2009). *Understanding the past to inform future conservation policy: Mapping traditional ecological knowledge of Pacific herring spawning areas through time* (Master's thesis, Simon Fraser University). School of Resource and Environmental Management. Report No. 601.

4 Fisheries Management

4.1 Historical Herring Fisheries Management

4.1.1 Historical government reporting (1901–1956)

The British Columbia Legislative Assembly published annual reports to the fisheries commissioner from 1901 through 1956. These reports recorded and described the major fisheries occurring in B.C., their landed catches, and their values to the provincial economy. Each annual report contains various appendices that include details of departmental research work for that year, descriptions of studies being conducted, and key findings of the day. These reports are indexed in government archives as sessional papers and comprise some 5,000 pages within the series. Due to recent digitization efforts of the B.C. Legislative Library, these reports are now available online. The report series, broadly, is not specific to herring, but rather includes extensive information pertaining to early fisheries (for example, salmon and halibut). The key years of reporting that are specific to herring begin in 1916 and carry forward through 1956. Prior to 1916, provincial reporting narrowly identified general landed herring catches and values. Selected excerpts from various reports 1916–1956 are annotated further in this guide with individualized referencing provided. The report series is first addressed here for referencing purposes.

Archival note: Title varies: 1901–1906, Report of Fisheries Commissioner for British Columbia; 1907–1935, Report of the Commissioner of Fisheries; 1936–1944, Report of the Provincial Fisheries Department; 1945, Provincial Fisheries Department report; 1946–1956, Provincial Department of Fisheries report.

Province of B.C.. (1901-1956). *Report of the fisheries commissioner* [annual sessional papers] [55 reports]. Victoria, B.C.: Legislative Assembly of B.C.. Retrieved from: https://vufind.llbc.leg.bc.ca/Search/Results?sort=year+asc&lookfor=fisheries+AND+report&type=Title

4.1.2 Life-history and early studies

There are many scientific and fisheries management documents that discuss the life-history of Pacific herring in B.C.. Annotating each one of these documents is not necessary or time efficient. Instead, this guide provides a brief overview of one of the first pieces of work on the life-history of B.C.'s Pacific herring (Thompson, 1916), and then groups four additional selected publications (Tester, 1934; Outram, 1965; Outram & Humphreys, 1974; Hourston & Haegele, 1980; referenced below in alphabetical order) which built upon each other over successive decades to form a foundation of knowledge regarding Pacific herring life-history in B.C..

In 1916, the fisheries departments within both the federal and provincial governments began to see herring as a new fishery (salmon being the main fishery until this time). In the early 1900s, the provincial government commissioned a research project to map the life-history of Pacific herring. The results of this project (Thompson, 1916) are provided in the 1916 report of the fisheries commissioner and represent the first major contribution to our understanding of Pacific herring in B.C.. This understanding, including the addition of Indigenous harvesting practices and various succinct descriptions of the herring fishery and markets that supported it over the years, were provided during the B.C. Herring Investigations in the 1930s–1950s, and later synthesized in the reports of Tester (1934), Outram & Humphreys (1974), and Hourston & Haegele (1980). A comprehensive understanding of herring eggs, hatching, larva, and spawn cycles are described in detail along with fisheries practices.

Archival note: *Except for Thompson (1916), each reference in this section overlaps with the B.C. Herring Investigations and various official government reports to the fisheries commissioner over multiple decades.*

Thompson, W. (1916). *A contribution to the life-history of the Pacific herring: Its Bearing on the condition and future of the fishery*. In the B.C. provincial report of the commissioner of fisheries. (1916). Victoria, B.C.: Legislative Assembly, King's

Printer. Retrieved from: http://www.llbc.leg.bc.ca/public/pubdocs/bcdocs2015_2/128144/1916.pdf

Hourston, A. & Haegele, C. (1980). *Herring on Canada's Pacific coast*: *Canadian special publication of fisheries and aquatic sciences 48*. Nanaimo, B.C.: Department of Fisheries and Oceans, Resource Services Branch, Pacific Biological Station.

Outram, D. (1965). *Canada's Pacific herring.* Nanaimo, B.C.: Fisheries Research Board of Canada, Nanaimo Biological Station.

Outram, D. & Humphreys, R. (1974). *The Pacific Herring in British Columbia waters*. Nanaimo, B.C.: Fisheries and Marine Services Pacific Biological Station.

Tester, A. (1934). *The herring fishery of British Columbia: Past and Present*. In the B.C. provincial report of the commissioner of fisheries (1934). Victoria, B.C.: Legislative Assembly, King's Printer.

4.1.3 The B.C. herring investigations

The British Columbia herring investigations were a series of early tagging and stock assessment studies conducted by the Nanaimo Biological Station in B.C. (Hart & Tester, 1939-1942; Tester, 1943–1945; Tester & Stevenson, 1946; Stevenson & Lanigan, 1949; Stevenson & Hourston, 1950–1951; Stevenson & Outram, 1952; Taylor, 1954; Taylor, Outram & Hourston, 1955). The long-term studies, which began in the late 1930s and continued into the 1950s, focused on identifying travel and spawning patterns of Pacific herring. As the studies progressed through time, there was a recognition that herring were largely a non-migratory fish, forming localized resident populations. The studies detailed percentages of intermingling between herring populations. The concept of tagging and tracking of herring in B.C. continues today with more modern tools. Researchers with the Department of Fisheries and Oceans, Canada, conducted a succinct review of herring tagging (1936–1992) in 1999 (Hay, McCarter & Daniel 1999). The results confirmed the presence of herring that are resident populations but challenged earlier results of herring tagging work.

Hart, J. & Tester, A. (1939). *Tagging of herring in British Columbia: Insertions and recoveries* during 1939–1940. In the B.C. provincial report of the commissioner of fisheries (1939). Victoria, B.C.: Legislative Assembly.

Hart, J.; Tester, A. & McHugh, J. (1940). *Tagging of herring in British Columbia: Insertions and recoveries* during 1940–1941. In the B.C. provincial report of the commissioner of fisheries (1940). Victoria, B.C.: Legislative Assembly, King's Printer.

Hart, J.; Tester, A. & Boughton, R. (1941). *Tagging of herring in British Columbia: Insertions and recoveries* during 1941–1942. In the B.C. provincial report of the commissioner of fisheries (1941). Victoria, B.C.: Legislative Assembly, King's Printer.

Hart, J.; Tester, A. & Boughton, R. (1942). *Tagging of herring in British Columbia: Insertions and recoveries* during 1942–1943. In the B.C. provincial report of the commissioner of fisheries (1942). Victoria, B.C.: Legislative Assembly, King's Printer.

Hay, D., McCarter, P., & Daniel, K. (1999). *Pacific herring tagging from 1936–1991: A re-evaluation of homing based on additional data.* Ottawa, Canada: Fisheries and Oceans Canada, Biological Services Branch (Nanaimo, B.C.).

Stevenson, J. (1948). *Results of the West Coast of Vancouver Island herring investigation, 1947–1948*. In the B.C. provincial report of the commissioner of fisheries (1948). Victoria, B.C.: Legislative Assembly, King's Printer.

Stevenson, J. & Lanigan, J. (1949). *Results of the West Coast of Vancouver Island herring investigation, 1949–1950*. In the B.C. provincial report of the commissioner of fisheries (1949). Victoria, B.C.: Legislative Assembly, King's Printer.

Stevenson, J.; Hourston, A. & Lanigan, J. (1950). *Results of the West Coast of Vancouver Island herring investigation, 1950–1951*. In the B.C. provincial report of the commissioner of fisheries (1950). Victoria, B.C.: Legislative Assembly, King's Printer.

Stevenson, J.; Hourston, A.; Jackson, K. & Outram, D. (1951). *Results of the West Coast of Vancouver Island herring investigation, 1951–1952*. In the B.C. provincial report of the commissioner of fisheries (1951). Victoria, B.C.: Legislative Assembly, Queen's Printer.

Stevenson, J. & Outram, D. (1952). *Results of Investigation of the herring populations on the West coast and lower East coast of Vancouver Island in 1952–1953, with an analysis of fluctuations in population abundance since 1946–47. the West Coast of Vancouver Island herring investigation, 1951–1952*. In the B.C. provincial report of the commissioner of fisheries (1952). Victoria, B.C.: Legislative Assembly, Queen's Printer.

Taylor, F. (1954). *The status of the major herring stocks in British Columbia in 1954–1955*. In the B.C. report of the provincial fisheries department (1954). Victoria, B.C.: Legislative Assembly, Queen's Printer.

Taylor, F.; Hourston, A.; Outram, D. (1955). *The status of the major herring stocks in British Columbia in 1955–1956*. In the B.C. report of the provincial fisheries department (1955). Victoria, B.C.: Legislative Assembly, Queen's Printer.

Tester, A. (1943). *Tagging of herring in British Columbia: Insertions and recoveries* during 1943–1944. In the B.C. provincial report of the commissioner of fisheries (1943). Victoria, B.C.: Legislative Assembly, King's Printer.

Tester, A. (1944). *Tagging of herring in British Columbia: Insertions and recoveries* during 1944–1945. In the B.C. provincial report of the commissioner of fisheries (1944). Victoria, B.C.: Legislative Assembly, King's Printer.

Tester, A. (1945). *Tagging of herring in British Columbia: Insertions and recoveries* during 1945–1946. In the B.C. provincial report of the commissioner of fisheries (1945). Victoria, B.C.: Legislative Assembly, King's Printer.

Tester, A. & Stevenson, J. (1946). *Results of the West Coast of Vancouver Island herring investigation, 1946–1947*. In the B.C. provincial report of the commissioner of fisheries (1946). Victoria, B.C.: Legislative Assembly, King's Printer.

4.1.4 Herring workshop series

The Fisheries Research Board of Canada held seven Pacific Coast Herring Workshops between 1973 and 1994. These workshops aimed to facilitate the direct communication of current knowledge between scientific personnel of Pacific Coast resource agencies involved in herring research and management. The workshop proceedings can be found in the Federal Science Library.

Day, D. (1974). Proceedings of Pacific coast herring workshop. Nanaimo, B.C. : Fisheries Research Board of Canada. Report No. 1333. Retrieved from https://waves-vagues.dfo-mpo.gc.ca/Library/73933.pdf

Outram, D.N. (1975). Proceedings of the second annual Pacific coast herring workshop, October 30–31, 1974. Nanaimo, B.C. : Fisheries Research Board of Canada. Manuscript Report Series No. 1342. Retrieved from https://waves-vagues.dfo-mpo.gc.ca/Library/73940.pdf

Blankenbeckler, D. (1977). Proceedings of the Third Pacific Coast Herring Workshop June 22–23, 1976. Nanaimo, B.C. : Pacific Biological Station, Fisheries Research Board of Canada. Manuscript Report Series No. 1421. Retrieved Retrieved from https://waves-vagues.dfo-mpo.gc.ca/Library/18456.pdf

Buchanan, K. (1983). Proceedings of the Fourth Pacific Coast Herring Workshop, October 7–8, 1981. Nanaimo, British Columbia : Department of Fisheries and Oceans, Fisheries Research Branch, Pacific Biological Station. Report No. 1700. Retrieved from https://waves-vagues.dfo-mpo.gc.ca/Library/60884.pdf

Haegele, C.W. (1986). Proceedings of the fifth Pacific coast herring workshop, October 29–30, 1985. Nanaimo, B.C. : Dept. of Fisheries and Oceans, Fisheries

Research Branch, Pacific Biological Station. Report No. 1871. Retrieved from http://waves-vagues.dfo-mpo.gc.ca/Library/11852.pdf

O'Toole, M.F. (1990). Proceedings of the sixth Pacific Coast Herring Workshop, February 2–3, 1989. Olympia, Wash. : Dept. of Fisheries. Report can be requested from https://science-catalogue.canada.ca/record=3915259~S6

Hay, D.E., and McCarter, P.B. (1995). Proceedings of the Seventh Pacific Coast Herring Workshop, January 27–28, 1994. Nanaimo, B.C. : Dept. of Fisheries and Oceans, Biological Sciences Branch. Report No. 2060. Retrieved from https://waves-vagues.dfo-mpo.gc.ca/Library/191554.pdf

4.1.5 Additional historical reading & reference materials

The Fisheries Research Board of Canada produced a report in 1964 (authored by F. Taylor and indexed as bulletin #143) that captured a holistic picture of the past and contemporary state of the herring fishery. This document covers a brief life-history of Pacific herring in B.C., a historical review of major fisheries and regulations, a discussion on the current science of the day, and summarizes various experiments that had been conducted earlier with specific reference to uncontrolled fishing along the B.C. west coast. Taylor breaks down herring populations by region and provides a review of historical and current spawn depositions by population. This report is of historical significance as it was published just prior to a significant population decline in the province and subsequent closure of the herring fishery in B.C..

Taylor, F. (1964). *Life history and present status of British Columbia herring stocks***.** Ottawa, Canada: Fisheries Research Board of Canada.

This publication is a detailed chronological reference list of 286 publications and reports on Pacific herring, as compiled from (then) current records (1977) at the Pacific Biological Station. This comprehensive list is of specific historical importance and is worthy of review during herring research.

Author's Note: **"***It includes all reports (other than those of a confidential nature) of investigations on herring conducted by that station, which are known to the author. Selected reports on closely related work carried out by other agencies, stations, and individuals in which the station had some involvement have also been included."*

Archival department note: *"These reports contain scientific and technical information that represents an important contribution to existing knowledge but which for some reason may not be appropriate for primary scientific (i.e. Journal) publication. They differ from Technical Reports in terms of subject scope and potential audience: Manuscript Reports deal primarily with national or regional problems and distribution is generally restricted to institutions or individuals located in particular regions of Canada. No restriction is placed on subject matter and the series reflects the broad interests and* *policies of the Fisheries and Marine Service, namely, fisheries management, technology and development, ocean sciences and aquatic environments relevant to Canada."*

Hourston, A. (1977, July). *Publications and reports on Pacific herring arising from investigations conducted at or in cooperation with the Pacific Biological Station: Fisheries & Marine Service Manuscript Report No. 1427*. Nanaimo, B.C.: Department of Fisheries and Environment (Pacific Biological Station). Retrieved from: https://waves-vagues.dfo-mpo.gc.ca/Library/18122.pdf

This brief publication focuses on a synthesized history of the herring fishery in B.C.. It is included here as a stand-alone reference because of its description of certain gear restrictions and netting techniques that caused early conservation concerns (1910–1913) with *purse seine* techniques.

Taylor, F. (1954). *Summary of the exploitation of and research on the Pacific herring along the west coast of Canada*. Nanaimo, B.C.: Pacific Biological Station. Retrieved from: https://waves-vagues.dfo-mpo.gc.ca/Library/40630055.pdf

This book is affectionately referred to as the "fish bible" by many individuals within the commercial fishing industry in B.C.. The author takes advantage of historical archives of the B.C. Packers and compiles a comprehensive historical account of commercial fisheries activities in B.C.. The majority of the manuscript does not pertain directly to herring, but rather other species and commercial fishing history within the province. However, local herring populations and the importance of herring to the provincial economy is provided on pages 438–475, page 558, pages 566–567, pages 574–575, and 582–619. Annual landed catches and historical information synthesized from provincial fisheries reports and commercial data is provided along with descriptions of the fishery from a commercial, non-governmental perspective.

Lyons, C. (1969). *Salmon is our heritage*. Vancouver, B.C.: B.C. Packers Limited.

4.2 Modern herring fisheries management

At present, the Pacific herring fisheries in B.C. consist of commercial fishing for food and bait Pacific herring, spawn-on-kelp products, and roe herring; First Nations food, social, and ceremonial fisheries (FSC); and recreational fishing.

DFO proceedings, research documents, Science Advisory Reports, and Science Response reports are available through DFO's Canadian Science Advisory Secretariat (CSAS) site. Science Advisory Reports and Science Responses summarize advice generated from peer reviews, and are often in the form of stock assessments. Research Documents contain the technical basis for advice and proceedings reports document peer review meeting discussions.

Integrated Fisheries Management Plans (IFMPs) identify the main objectives and requirements of the Pacific region fishery, as well as the management measures used to achieve these objectives. The document communicates the information to DFO staff and stakeholders in order to provide common understanding. The most recently published IFMPs for various species are available from DFO's IFMP webpage: https://www.pac.dfo-mpo.gc.ca/fm-gp/ifmp-eng.html. The latest draft versions of management plans are available on the consultation page of the species of interest. Archived Management Plans since 2003 can be found in the Federal Science Library. Also note that not all IFMPs are available online and some are only available as summaries; contact information for full IFMPs are provided in the summary reports.

4.2.1 Science Advisory Reports

Science Advisory Reports summarize the advice from an evaluation of working papers and the peer-review assessment. Science Advisory Reports pertaining to Pacific Herring include evaluations of management procedures, review of limit reference points for harvest control rules, and stock assessment reports.

The most recent Science Advisory Report pertaining to Pacific Herring was an evaluation of management procedures in the Strait of Georgia and the west coast of Vancouver Island areas. This was conducted as part of the renewal of the management framework to include conducting Management Strategy Evaluations (MSE). Ten candidate management procedures (MP) were evaluated for both SOG and WCVI, using three different models that varied in assumptions of mortality (constant and time-varying). The performance of each management procedure is ranked against the conservation objective. The conservation objective is defined by a minimum biomass that must be avoided with high probability. For Pacific Herring, key uncertainties in modelling include historical and future trends in natural mortality, steepness of the stock-recruitment relationship and stock-recruitment functional form, potential changes in survey coverage and sampling, an unknown relationship between herring biomass and spawn survey index (estimated by the parameter q), and uncertainty in spatial population dynamics. It was determined that the WCVI results were sensitive to trends in natural mortality, suggesting additional management procedure modifications may be required.

DFO. (2019). Evaluation of Management Procedures for Pacific Herring (Clupea pallasii) in the Strait of Georgia and the West Coast of Vancouver Island Management Areas of British Columbia. DFO Can. Sci. Advis. Sec. Sci. Advis. Rep. 2019/001. Retrieved from https://waves-vagues.dfo-mpo.gc.ca/Library/40760133.pdf

4.2.2 Science Response Reports

Science Response Reports summarize advice based on an evaluation process. They typically do not involve the same level of analysis or peer-review since they are usually conducted for requests that are new and urgent, don't require a thorough advisory process, or require a review on existing information. Science Response documents include stock status updates, evaluations of management procedures, stock assessment and management advice.

The most recent Science Response Report pertaining to Pacific herring is a stock status update for 2019 and predictions for 2020. An analysis of stock trend information is completed for major stock assessment regions. Pacific Herring abundance is assessed using a statistical catch–age model. In 2017, estimation of stock productivity and current stock status relative to a new limit reference point of 30% of the unfished spawning biomass was introduced. The stock status update report outlines modelling scenarios for different management procedure options that meet a conservation objective (30% unfished spawning biomass) with high probability (>75%). Detailed analysis information is provided including input data, parameter values, and management procedure performance. The findings from this report were used to inform the management measures and stock assessment advice presented in the 2019/2020 IFMP.

Fisheries and Oceans Canada. (2020). Stock Status Update with Application of Management Procedures for Pacific Herring (*Clupea pallasi*) in British Columbia: Status in 2019 and Forecast for 2020. Canadian Science Advisory Secretariat (CSAS). Science Response 2020/004. Retrieved from http://www.dfo-mpo.gc.ca/csas-sccs/Publications/ScR-RS/2020/2020_004-eng.pdf

4.2.3 Integrated Fisheries Management Plans (IFMPs)

Integrated Fisheries Management Plans were introduced in the mid-1990s. IFMPs provide the framework for the conservation and sustainable use of fisheries resources and the process by which a given fishery will be managed for a period of time. Science and Indigenous traditional knowledge on fish species are combined with industry data to determine best practices for harvest. IFMPs ensure that DFO sectors and stakeholders are integrated in a consistent manner and they provide a document for all stakeholders outlining DFOs management practices. IFMPs are not legally binding instruments and cannot form the basis of a legal challenge. The IFMP development process is triggered by the post-season review of a fishery.

IFMPs for Pacific herring consider stock assessment, science and traditional knowledge; social, cultural, and economic values of the fishery and management issues; allocation and management procedures; key shared stewardship arrangements with First Nations and other organizations; and fisheries management objectives for Pacific Herring.

The most recent IFMP for Pacific herring is for November 2024 to November 2025. Management measures are summarized based on stock assessment advice in the form of a Science Response. Recommendations for commercial fisheries included the following:

- **HG:** Closed. Continued closure as stock biomass and growth has been low for over 20 years. A Rebuilding Plan is underway.
- **PRD:** Open to a 5% harvest rate for FSC, Spawn on Kelp, and Roe herring
- **CC:** SOK opportunities only up to a maximum of 900 tons (4.7% harvest rate). This stock shows a steady increase in spawning biomass since a low in the late 2000s, with a slight decrease in forecasted spawning biomass in recent years.
- **SOG:** Open to a 14% harvest rate for FSC, Food and Bait, Special Use, and Roe herring opportunities to a maximum of 12,787 tons.
- **WCVI:** Closed to commercial gillnet and seine harvest. Open to Food Social Ceremonial (FSC), treaty domestic harvest, and commercial Spawn on Kelp opportunities to First Nations.

The IFMP describes ecosystem interactions, noting the critical role of herring. Specifically, herring support species including seabirds, especially diving birds such as cormorants and murres; fish, including salmon, perch, and hake; and several marine mammals. Further, the IFMP highlights that herring provide value beyond individual fish or their roe in their importance to Indigenous people. Herring returning to spawn in winter brought with them sea birds, chinook salmon, lingcod, halibut and other groundfish species, which could then be harvested to feed communities or trade.

The IFMP also discusses Pacific herring in relation to other species of concern in the context of the Species at Risk Act (SARA) and any amended or new regulations. In May 2018, DFO determined that the Southern Resident Killer Whales (SRKWs; *Orcinus orca*) faced imminent threat to survival and recovery. For the 2020/2021 fishing season, DFO planned to review the 2019 fishery management actions that support Chinook prey availability to SRKWs. The suite of measures introduced in 2019 included “area-based fishing closures to increase Chinook salmon availability in Southern Resident Killer Whale foraging areas.” The IFMP indicated that any updates to actions for the 2020/2021 season should be implemented by Spring of 2020, coinciding with the return of the SRKWs. For the 2025 fishing season, the Government of Canada is working with Indigenous groups and stakeholders to inform potential changes to vessel measures for 2025.

Fisheries and Oceans Canada. (2019). Pacific Herring Integrated Fisheries Management Plan November 26, 2019 – November 6, 2020. Retrieved from https://waves-vagues.dfo-mpo.gc.ca/Library/40851448.pdf

4.2.4 Species Profile: Pacific Herring [web log]

This website is a Canadian federal government depository of research, stock assessment, and other documents pertaining to Pacific herring. Some records identified below have been referenced in other works conducted by Pacific Wild. Additional records and research information are categorized and contained under the following headings:

Clupea pallasii

- Spawn on kelp fishery
- Food and Bait fishery
- Roe Herring fishery
- Consultations
- Integrated Fishery Management Plans
- Commercial Fishery Notices, 1999 to now

Science projects

- Herring Geographical Bulletin, 1888–2015.
- Herring tagging and movements, 1936–2006.
- Herring migratory behaviour and life history variations, 2012.
- Ichthyoplankton surveys, 1985+
- Herring Spawn Survey Manual, revised 2013 [PDF]
- HGB

CSAS Documents and Stock Status Reports

***Special note: Headings redacted for space. Stock assessment and early research information located and cited under individual documents between 1982 and 2015 [94 documents]. Subject matter spans a variety of topics.*

Herring Links

- Herring Conservation and Research Society
  British Columbia, Canada.
- California Herring Fishery
  California Dept. Fish and Game.
- Alaska Herring Fisheries
  Alaska Dept. Fish and Game.
- Atlantic Herring
  Gulf of Maine Aquarium (USA and Canada).

Fisheries and Oceans Canada. (2016). Pacific herring [web log]. Ottawa, Canada: Government of Canada. Retrieved from: http://www.dfo-mpo.gc.ca/species-especes/profiles-profils/herring-hareng-eng.html

4.2.5 Value- and ecosystem-based management approach: The Pacific herring fishery conflict

Lam et al. used a value- and ecosystem-based management approach (VEBMA) to address the Pacific herring fishery conflict in British Columbia. This method aims to resolve resource conflicts while facilitating inclusive, transparent, and accountable decision-making. Ecosystem modeling assesses the ecological impacts and risks of alternative herring management scenarios. Participatory research reveals perspectives within the herring industry and local Indigenous communities. The VEBMA results highlight ecological viability, socio-economic feasibility, and management scenarios. Overall, the community favours an ecosystem-based approach whereas the industry prefers its current management strategy. Lam et al. suggest that ecosystem health should be prioritized over stakeholder preferences.

Lam, M. E., Pitcher, T. J., Surma, S., Scott, J., Kaiser, M., White, A. S. J., Pakhomov, E. A., & Ward, L. M. (2019). Value- and ecosystem-based management approach: The Pacific herring fishery conflict. *Marine Ecology Progress Series, 617*, 341–364. https://doi.org/10.3354/meps12972

4.2.6 An evidence-based approach for selecting a limit reference point for Pacific herring (Clupea pallasii) stocks in British Columbia, Canada

Forrest et al. presented a method for diagnosing serious harm and selecting limit reference points (LRPs) of five Pacific herring stocks in British Columbia. The authors used a semi-empirical approach to examine surplus production in relation to spawning biomass and identify low productivity and biomass states. Based on these findings, an LRP of 30% of unfished spawning biomass was recommended and adopted for managing all five major stocks. Forrest et al. emphasized the importance of setting LRPs as thresholds to avoid undesirable stock conditions and fishery closures. It is recommended that ongoing monitoring and adaptive management strategies consider spatial stock structure and ecosystem dynamics in Pacific herring management. It is also emphasized that MPs be assessed against LRPs to ensure that conservation and management goals are met in British Columbia.

Forrest, R. E., Kronlund, A. R., Cleary, J. S., & Grinnell, M. H. (2023). An evidence-based approach for selecting a limit reference point for Pacific herring (Clupea pallasii) stocks in British Columbia, Canada. *Canadian Journal of Fisheries and Aquatic Sciences, 80*, 1071–1083. https://doi.org/10.1139/cjfas-2022-0168

4.2.7 The biological features of Pacific herring (Clupea pallasii) and prospects for the current herring fishery on the shelf of the southern Kuril Islands.

Zolotov et al. examined the stock dynamics of Pacific herring in the southern Kuril Islands with a focus on their distribution, migration, and spawning patterns. The authors reported a significant increase in Pacific herring abundance between 2014 and 2017, following decades of low stock levels. The stock is predominantly composed of three- to four-year-old individuals, which accounted for 76–82% of the total catch in 2020–2021. The researchers identified the eastern side of the deep-sea canyon off the western coast of Kunashir Island as the likely wintering grounds for herring. From there, they migrate to spawning grounds along the Pacific coast of Kunashir Island, with secondary migrations along the Sea of Okhotsk coast. Herring spawning occurs from late April to mid-May, with peak spawning varying between early and mid-May in different years. Unlike other populations, Pacific herring in this region do not undertake extensive post-spawning migrations and, instead, remain on the southern Kuril shelf to feed. This research also highlights the rapid development of the herring fishery, with annual catches increasing from 140 tons in 2018 to 1,010 tons in 2021. Overall, Zolotov et al. provide updated insights into the biological features, distribution, migration patterns, and rising stock recovery of the Pacific herring population in the southern Kuril Islands. These findings are a relevant reminder that herring populations have regional features that distinguish them from neighboring populations and require individualized management strategies for optimal health

Zolotov, A. O., Buslov, A. V., & Ponomarev, S. S. (2022). The biological features of Pacific herring (*Clupea pallasii*) and prospects for the current herring fishery on the shelf of the southern Kuril Islands. *Russian Journal of Marine Biology, 48*, 608–622. https://doi.org/10.1134/S1063074022070161.

5 Spatially Structured Metapopulations

5.1.1 Metapopulation structure and dynamics of British Columbia herring

Ware and Schweigert integrated knowledge pertaining to dispersal and population dynamics of the five major B.C. herring stocks into a structured metapopulation model. A metapopulation is a set of interacting, local, breeding populations, which are linked by dispersal (gene flow). The model quantified straying that occurred from 1977 to 1998 based on tagging studies. Dispersal rates for the five major stocks ranged from 14% to 36% per year, and appeared to increase with greater biomass of the spawning stock. Most herring dispersed to nearby populations, but a few strayed to the most distant ones. This means that all of the major B.C. stocks are genetically linked by dispersal and there is unlikely any genetic differentiation between the populations. The model suggests that dispersal is important because it tends to stabilize the spatial distribution of spawners in the metapopulation and increases the persistence time of less productive populations. These conclusions only apply to the warm climate regime which prevailed during the period analyzed. It is noted that straying dynamics during cool climate regimes would be examined later.

Ware, D., and Schweigert, J. (2001). Metapopulation structure and dynamics of British Columbia herring. Fisheries and Oceans Canada, Canadian Science Advisory Secretariat. Research Document 2001/127.

5.1.2 Pacific herring spawn disappearance and recolonization events

This paper (fourth in a series) provides evidence that British Columbia herring are spatially structured and interact as a metapopulation. The metapopulation concept provides an ecological basis for explaining that small, herring spawning aggregations can disappear for a time due to dispersal and other natural causes. And that vacant habitat will eventually be recolonized, when suitable conditions return. Spawn time series (from 1943 to 2002) were analyzed for indications of “disappearance” and "recolonization" events in 76 spatial sections where herring spawn in B.C.. Findings identified 82 spawn disappearance events (one or more in 55% of the sections). Small sections experience more disappearance and recolonization events than sections with larger amounts of spawn habitat. The vacant sections were recolonized by stray spawners from other areas, between <5 years to a maximum of 35 years (11 years on average). Only 53% of the recolonization attempts were successful. In Southern B.C., the disappearance rate increased significantly and was much higher than the recolonization rate after 1976 when the warm regime began, so the number of sections occupied by spawners declined. In 34 of the 76 sections examined, there were no spawn disappearance events. These important sections contain about 85% of the total herring spawn habitat in B.C., and therefore should be protected from shoreline development, pollution and other sources of habitat degradation. Loss of these habitats will almost certainly have a negative impact on the dynamics and resilience of the metapopulation.

Ware, D.M., & Tovery, C. (2004). Pacific herring spawn disappearance and recolonization events. Fisheries and Oceans Canada, Canadian Science Advisory Secretariat. Research Document 2004/008.

5.1.3 Use of microsatellites to determine population structure and migration of Pacific herring in British Columbia and adjacent regions

Beacham et al. assessed the genetic population structure of Pacific herring by analyzing DNA microsatellite variation. Genetic variation was surveyed in approximately 26,000 Pacific herring from 90 sample locations. The mean genetic differentiation index F_{ST} value over the 90 samples and 14 loci surveyed was 0.003, indicative of only limited differentiation among populations. Genetic diversity varied little among regional groups of Pacific herring. Paired comparison between populations showed genetic distinction between populations in Washington and British Columbia. Similarly, in B.C., differences in timing of spawning are the main isolating mechanisms among stocks, although geographic isolation of the spawning populations may also have some effect in maintaining the genetic distinctiveness of each stock. In the Strait of Georgia, Pacific herring spawning in Esquimalt Harbour were clearly distinct from spawners in more-northerly areas along the east coast of Vancouver Island. Portage Inlet–Esquimalt Harbour Pacific herring spawn in late March, later than Pacific herring in most other locations in the Strait of Georgia; thus, both geographic isolation and differences in spawn timing may be acting to maintain the distinctiveness of this population. If a goal of management is to include genetically undifferentiated populations within a management area, then the southwestern boundary of the Strait of Georgia management area should be evaluated.

Beacham, T.D., Schweigert, J.F., MacConnachie, C., Le, K.D., Flostrand, L. (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*(6), 1795-1811.

5.1.4 Evaluating the conservation risks of aggregate harvest management in a spatially-structured herring fishery

Benson et al. evaluated whether managing spatially complex fish stocks as large-scale aggregates leads to greater conservation risks. The researchers developed a closed-loop simulation model that represents a range of dispersal scenarios and includes imperfect management knowledge about the abundances and dynamics of interacting Pacific herring sub-populations, as well as weak management control of how exploitation is allocated among sub-populations. The latter is driven by the spatial dynamics of the fishing fleet as it seeks to optimize profitability. Simulated management outcomes did not always lead to increased risks under all scenarios of dispersal, fishery spatial dynamics, and management errors. Instead, these processes interacted to either mediate or intensify the impact of inappropriate management assumptions and stock assessment errors. Management strategies aimed directly at limiting exploitation risk consistently protected spatially complex populations in the presence of incorrect management assumptions about stock structure, high fishing power, and persistent stock assessment errors. Given the prevalence of these errors in fisheries, the researchers recommended further evaluation of spatial-temporal population complexity for strategic management.

Benson, A.J., Cox, S.P., & Cleary, J.S. (2015). Evaluating the conservation risks of aggregate harvest management in a spatially structured herring fishery. *Fisheries Research, 167*, 101–113.

5.1.5 A heuristic model of socially learned migration behaviour exhibits distinctive spatial and reproductive dynamics

MacCall et al. modelled the spatial distribution of Pacific herring recruits using the “go with the older fish” (GWOF) mechanism of learned migration behaviour where recruits learn a viable migration path by randomly joining a school of older fish. For Pacific herring, this mechanism is well supported in the literature and by traditional knowledge. Chief Gidansta (Guujaaw) of the Haida Nation stated that the impact of intense fishing on age structure was associated with loss of migratory knowledge: “Once herring lost the elders they lost their way to their spawning grounds.” The authors compared two models where recruits return to their natal spawning site: a diffusion (DIFF) strategy, where recruits adopt spawning sites near their natal site *without regard to older fish*, and the GWOF model, where recruits adopt the same spawning sites, *but in proportion to the abundance of adults using those sites*. The GWOF model leads to *higher spatial variance in biomass*. As total mortality increases (e.g. from fishing), the DIFF strategy results in an approximately proportional decrease in biomass among spawning sites, whereas the GWOF strategy results in *abandonment of less productive sites and maintenance of high biomass at more productive sites*. A DIFF strategy leads to dynamics comparable to non-spatially structured populations. The aggregate response of the GWOF strategy is distorted, non-stationary, and slow to equilibrate, with a production curve that is distinctly flattened and relatively unproductive. These results indicate that fishing will disproportionately affect populations with GWOF behaviour. The authors showed that including GWOF in spatial models of population dynamics can generate spatial patterns and dynamics that are distinct from those produced by behaviourally neutral diffusion, and, moreover, that these distinct patterns resemble those exhibited by Pacific herring and other clupeids. The GWOF hypothesis provides insights into population and fishery behaviour that should be useful to the assessment and management of Pacific herring. The GWOF model indicates that productivity of fished populations may decline over decades due to spatial reorganization of the population. An important implication of these results is the tendency toward local site extinction when fishing interacts with the GWOF strategy. This local loss of sites is potentially overlooked by standard stock assessment procedures.

MacCall, A. D., Francis, T. B., Punt, A. E., Siple, M. C., Armitage, D. R., Cleary, J. S., Dressel, S. C., Jones, R. R., Kitka, H., Lee, L. C., Levin, P. S., McIsaac, J., Okamoto, D. K., Poe, M., Reifenstuhl, S., Schmidt, J. O., Shelton, A. O., Silver, J. J., Thornton, T. F., Voss, R., and Woodruff, J. (2018). A heuristic model of socially learned migration behaviour exhibits distinctive spatial and reproductive dynamics. *ICES Journal of Marine Science, (76)*2, 598-608. doi:10.1093/icesjms/fsy091.

5.1.6 When are estimates of spawning stock biomass for small pelagic fishes improved by taking spatial structure into account?

Punt et al. used a simulation-estimation approach to evaluate the efficacy of stock assessment methods that incorporate various levels of spatial complexity. The evaluated methods estimate historical and future biomass for a situation that roughly mimics Pacific herring at Haida Gwaii. The baseline operating model theorizes ten areas arranged to allow for post-recruitment dispersal among all areas. The authors generated simulated data (catches, catch age-composition, estimates of spawning stock biomass and its associated age structure) for each area and analyzed it using estimation methods that range in complexity from ignoring spatial structure to explicitly modelling ten areas. Estimation methods that matched the operating model in terms of spatial structure performed best for hindcast performance and short-term forecasting, meaning that adding spatial structure to assessments improved estimation performance. Even with similar time trajectories among sub-stocks, accounting for spatial structure when conducting the assessment leads to improved estimates of spawning stock biomass. In contrast, assuming spatial variation in productivity when conducting assessments did not appreciably improve estimation performance, even when productivity actually varied spatially. Estimates of forecast biomass and of spawning stock biomass relative to the unfished level were poorer than estimates of biomass for years with data, i.e., hindcasts. Overall, the results of this study further support efforts to base stock assessments for small pelagic fishes on spatially-structured population dynamics models when there is a reasonable likelihood of identifying the sub-stocks that should form the basis for the assessment.

Punt, A.E., Okamoto, D.K., Maccall, A.D., Shelton, A.O., Armitage, D.R., Cleary, J.S., Davies, I.P., Dressel, S.C., Francis, T.B., Levin, P.S., Jones, R.R., Kitka, H., Lee, L.C., McIsaac, J.A., Poe, M.R., Reifenstuhl, S., Silver, J.J., Schmidt, J., Thornton, T.F., Voss, R., & Woodruff, J. (2018). When are estimates of spawning stock biomass for small pelagic fishes improved by taking spatial structure into account. *Fisheries Research, 206*, 65-78.

5.1.7 Fishing, environment, and the erosion of a population portfolio

Stier et al. examined a 65-year dataset in a mechanistic time-series model on herring spawn and catch records from 11 subpopulations in Haida Gwaii. The results highlight population erosion over time, with seven of nine focal subpopulations exhibiting significant declines in growth since the 1990s. The authors identified commercial fishing as a key factor since exploitation rates often exceeded 15% and, in some years, reached 65%. Increased natural predator populations, like humpback whales, could also contribute to reductions in recent years—particularly where commercial fisheries have closed. The authors recommend that management strategies are developed at a finer spatial scale to ensure greater regional resource reliability. Capacity building may require more funding for implementation and monitoring costs.

Stier, A. C., Shelton, A. O., Samhouri, J. F., Feist, B. E., & Levin, P. S. (2020). Fishing, environment, and the erosion of a population portfolio. *Ecosphere, 11*(11), e03283. https://doi.org/10.1002/ecs2.3283

6 Species Interactions

6.1 Chinook Salmon

6.1.1 Chinook Salmon Diet

6.1.1.1 Food of juvenile Chinook, Oncorhynchus tshawytscha*, and coho,* O. kisutch*, salmon off the northern Oregon and southern Washington coasts, May–September 1980*

Emmett et al. analyzed the food of juvenile Chinook (*Oncorhynchus tshawytscha*) and coho (*Oncorhynchus* kisutch) salmon captured in the northern Oregon and southern Washington coastal zones during three cruises, May–September 1980. Fishes were primary prey for both species during the first cruise. Although diets overlapped, fishes and crab larvae were primary prey for chinook salmon in the second cruise, while fishes and the euphausiid *Thysanoessa spinifera* were important prey for coho salmon. During the third cruise, hyperiid amphipods were primary prey for both species. Healey (1980) observed that fish (mainly Pacific herring) were an important prey of juvenile Chinook and coho salmon in the Strait of Georgia. The data from this study herein indicated that herring were important only in late summer. The difference in herring consumption was probably a result of availability. This study confirmed previous studies that juvenile salmon fed on different prey in different geographic areas, possible due to patchy distributions of prey and to relative prey abundance.

Emmett, R.L., Miller, D.R., and Blahm, T.H. (1986). Food of juvenile Chinook, *Oncorhynchus tshawytscha*, and coho, *O. kisutch*, salmon off the northern Oregon and southern Washington coasts, May–September 1980. *Calif. Fish and Game, 72*(1), 38–46

*6.1.1.2 Food consumption of juvenile coho (*Oncorhynchus kisutch*) and Chinook salmon (*O. tshawytscha*) on the continental shelf off Washington and Oregon*

This study highlights the variability between years in the availability of prey consumed by juvenile Chinook and coho salmon during their first year in the ocean. Food consumption varied substantially among the four years, within the same month, between 1981–1984. In particular, during the El Niño of 1983, several prey groups were consumed at high levels relative to their estimated availability and the biomass of these taxa may not have been sufficient to sustain the total population of salmon. During May and June of the El Niño of 1983, estimated consumption of prey fish was extremely high (6.5–10.7% per day) compared to available biomass. Therefore, juvenile coho and Chinook salmon as well as other predators could easily exhaust the available fish resources. Food limitation may be the cause of low early marine survival for juvenile Chinook and coho salmon in some years, and are likely to predate on the resulting slower growing or physically weakened individuals.

Brodeur, R. B., Francis, R. C., and Pearcy, W. G. (1992). Food consumption of juvenile coho (*Oncorhynchus kisutch*) and Chinook salmon (*O. tshawytscha*) on the continental shelf off Washington and Oregon. *Can. j. Fish. Aquat. Sci., 49*, 1670–1685.

6.1.1.3 Ontogenetic diet shifts of juvenile Chinook salmon in nearshore and offshore habitats of Puget Sound

Duffy et al. examined the diet of juvenile Chinook salmon in Puget Sound during their first marine growing season (April–September). Juvenile Chinook shifted to offshore feeding during July–September. Diet composition varied significantly among sampling regions (northern, central, and southern), habitats (nearshore, offshore), years, months, and fish size-classes. In offshore habitats, Chinook salmon fed mainly on Pacific herring. The researchers found similar findings determined in the late 1970s, Pacific herring continued to be the predominant prey fish. The authors suggest that recent declines in Pacific herring may be impacting Chinook salmon in two ways by (1) reducing the quality of feeding conditions in Puget Sound and (2) potentially reducing a species that may act as a buffer to predation by larger salmon and many other species. Further investigation into Puget Sound Pacific herring stocks and trophic linkages was recommended to understand the declines in Puget Sound Chinook salmon.

Duffy, E.J., Beauchamp, D.A., Sweeting, R.M., Beamish, R.J., Brennan, J.S. (2010). Ontogenetic diet shifts of juvenile Chinook salmon in nearshore and offshore habitats of Puget Sound. *Transactions of the American Fisheries Society, 139*, 803–823.

6.1.1.4 Canadian Salish Sea Marine Survival Program: Program summaries and status reports

The Salish Sea Marine Survival Project (SSMSP) publishes reports, status and findings, and research plans that aim to determine the principal factors affecting the survival of juvenile salmon and steelhead in the Salish Sea. Background information of the importance of forage fish in salmon diets is described. The survival of salmon species in the North Pacific has been linked to food availability during their early life history and coho and Chinook, which are generally switching to piscivory early in their marine life, are likely strongly affected by the availability of prey fish when they enter the marine environment. In the Strait of Georgia, the marine survival of Chinook salmon is strongly correlated to the proportion of young-of-the-year herring in their diet (R. Sweeting, unpublished). Thus, understanding the factors affecting the recruitment dynamics of herring in the SOG may be key to understanding the variability in the marine survival of coho and Chinook Salmon in the Strait of Georgia. The SOG juvenile herring and nearshore pelagic ecosystem survey provided a data set that can be used to estimate the relative biomass of age-0 herring. This provides an indicator of adult herring biomass and prey availability to predators in the SOG such as Chinook salmon. Another project affiliated with the SSMSP studied variation in juvenile Cowichan River Chinook salmon distribution, diet, and growth rate. One of the key findings was that failure of Chinook salmon to reach a size facilitating piscivory on young of the year herring may slow growth. This is a potential mechanism linking match-mismatch & critical size-critical period hypotheses. Herring availability and the size of the chinook relative to juvenile herring may be crucial factors.

Pearsall, I., Riddell, B. (2016). Canadian Salish Sea Marine Survival Program: 2015 Program Summary. Pacific Salmon Foundation. Salish Sea Marine Survival Project. https://marinesurvivalproject.com/wp-content/uploads/PSF-Canadian-SSMSP-Status-and-Findings-to-Date-2015.pdf

Pearsall, I., Riddell, B. (2017). Canadian Salish Sea Marine Survival Program: 2016 Program Summary. Pacific Salmon Foundation. Salish Sea Marine Survival Project. https://marinesurvivalproject.com/wp-content/uploads/Canadian-SSMSP-Status-and-Findings-to-Date-2016.pdf

Pearsall, I., Riddell, B. (2017). Canadian Salish Sea Marine Survival Program: Strait of Georgia Research Plan Version 1: 2017-2018 Research Plan. Pacific Salmon Foundation. Salish Sea Marine Survival Project.

https://marinesurvivalproject.com/wp-content/uploads/Strait-of-Georgia-Marine-Survival-Research-Plan-2017-2018.pdf

6.1.1.5 Historical diets of forage fish and juvenile Pacific salmon in the Strait of Georgia, 1966–1968

The Strait of Georgia provides important feeding and rearing habitat for forage fish, such as Pacific herring and eulachon as well as all species of North American Pacific salmon during their juvenile out-migration. In recent decades, this region has undergone large-scale physical and biological changes. Pacific herring and Pacific salmon populations have experienced dramatic population fluctuations, while eulachon have failed to recover from precipitous declines in the 1990s. Archival records of stomach content data from the 1960s were collected primarily from juvenile Pacific salmon, Pacific herring and eulachon were used to investigate diet variability in these species 60 years ago. Consistent with contemporary reports, it was found that all species except eulachon had generalist diets. In contrast to recent studies finding that Pacific herring are the most important fish prey, eulachon were the most frequently consumed fish, occurring in 28% of all piscivorous fish stomachs. This suggests that Pacific Herring are an important component of some Pacific salmon diets now, but only because lipid-rich Eulachon are no longer available. Historical data, such as those presented in this study, offer a unique opportunity to investigate temporal differences in foraging ecology, informing management on how changes in the Strait of Georgia ecosystem may impact the trophic interactions between species.

Osgood, G.J., Kennedy, L.A., Holden, J.J., Hertz, E., McKinnell, S., & Juanes, F. (2016). Historical diets of forage fish and juvenile Pacific salmon in the Strait of Georgia, 1966–1968. *Marine and Coastal Fisheries: Dynamics, Management, and Ecosystem Science, 8*(1), 580–594.

6.1.1.6 How relative size and abundance structures the relationship between size and individual growth in an ontogenetically piscivorous fish

This study evaluated the spatial and temporal variation in growth rate and the relationship between size and growth rate for juvenile Chinook salmon in Puget Sound, Washington, as a function of the relative size and abundance of both Chinook salmon and Pacific herring, a species which commonly co-occurs with salmonids in nearshore marine habitats. The abundance of Chinook salmon and Pacific herring varied substantially among the sub-basins as a function of outmigration timing and spawn timing, respectively, while size varied systematically and consistently for both species. Growth rates were different among sub-basins. In general, size was positively correlated with growth rate, although the slope of the relationship was considerably higher where Pacific herring were more abundant than Chinook salmon; specifically where smaller individual herring, relative to Chinook salmon, were more abundant.The noticeable positive effect of relative Pacific herring abundance on the relationship between size and individual growth rates likely represents a shift to predation based on increased growth, for individual Chinook salmon that are large enough to incorporate fish into their diet and co-occur with the highest abundances of Pacific herring. The findings suggest that the observed variability in the size-growth relationship reflects differences in community structure and a localized, size-mediated switch to piscivory, both of which ultimately influence growth opportunity for individual Chinook salmon. Numerous studies have determined that individual growth during the early marine portion of the life history increases the probability of juvenile salmon survival to subsequent life stages, and may determine overall marine survival of salmon populations in the Pacific Northwest. Should the presence of herring indeed provide a greater growth opportunity to juvenile salmon, the observed trends in herring abundance could impact individual growth and thus overall survival.

Chamberlin, J. W., Beckman, B. R., Greene, C. M., Rice, C. A., & Hall, J. E. (2017). How relative size and abundance structures the relationship between size and individual growth in an ontogenetically piscivorous fish. *Ecology and Evolution, 7*(17).

See also:
Chamberlin, J. W., Greene, C. M., Beckman, B. R., Rice, C. A., & Hall, J. E. Predator or competitor: How interactions between Chinook salmon and Pacific herring affect individual growth rates in Puget Sound [Power Point Presentation]. Retrieved from https://www.nwfsc.noaa.gov/news/events/soem_oral_presentations2017/SOEM%20Workshop%20-%205%20Chamberlin.pdf

See also:
https://marinesurvivalproject.com/research_activity/list/population-specific-consumption-pacific-herring-juvenile-sub-adult-chinook-salmon-puget-sound/

6.1.1.7 Energy dynamics of subyearling Chinook salmon reveal the importance of piscivory to short-term growth during early marine residence

The objective of this study was to examine the energy dynamics of subyearling Chinook salmon following freshwater emigration. A population of Chinook salmon and their marine prey were repeatedly sampled from June to September over two years in coastal waters off Oregon and Washington. Subyearlings from the same population were also reared under laboratory conditions. Using a bioenergetics model evaluated in the laboratory, researchers found that growth rate variability in the field was associated more with differences in northern anchovy consumption and less with variation in diet energy density or ocean temperature. Highest growth rates (2.43–3.22% body weight/day) occurred in months when anchovy biomass peaked, and the timing of peak anchovy biomass varied by year. These results support a general pattern among subyearling Chinook salmon occurring from Alaska to California that feeding rates contribute most to growth rate variability during early marine residence, although dominant prey types can differ seasonally, annually, or by ecosystem. Pacific herring appears to be the dominant forage in British Columbia and other parts of the Salish Sea. Identifying factors that influence the seasonal development of the prey field and regulate prey quantity and quality will improve understanding of salmon growth and survival during early marine residence.

Litz, M.N.C., Miller, J.A., Brodeur, R.D., Daly, E.A., Weitkamp, L.A., Hansen, A.G., Claiborne, A.M. (2018). Energy dynamics of subyearling Chinook salmon reveal the importance of piscivory to short-term growth during early marine residence. *Fisheries Oceanography, 28*(3), 273-290.

6.1.1.8 Using salmon to sample the Salish Sea: Diets of recreationally harvested Chinook and coho salmon as an ecosystem monitoring tool

This scientific poster details the development of a low-cost, ongoing program in partnership with recreational anglers to sample Chinook and coho salmon diets throughout the year from around the Canadian Salish Sea. The need for this program was based on the surprisingly sparse existence of data on the diets of adult Chinook and coho Salmon in the Canadian Salish Sea (Straits of Georgia and Juan de Fuca), with no published work since the 1980s and a total lack of information on winter diets. It is indicated that this knowledge is important since Chinook salmon are primary prey of the endangered Southern Resident Killer Whales and an extensive body of recent and current research has investigated declining juvenile marine survival of these species. Results are reported for the pilot year (2017), which indicated regional and seasonal variation in Chinook salmon diet and corroborate recent observations of forage fish dynamics in the Salish Sea. Pacific herring were the most important component of Chinook salmon diet in all regions and seasons. Young of the year Pacific herring were consumed by Chinook salmon from June through January; larger individuals were consumed all year.

Qualley, J., Duguid, W., Innes, K., Juanes, F. (2018). Using salmon to sample the Salish Sea: Diets of recreationally harvested Chinook and coho salmon as an ecosystem monitoring tool [Conference Presentation]. Salish Sea Ecosystem Conference. 291. Retrieved from https://www.researchgate.net/publication/323432049_Using_salmon_to_sample_the_Salish_Sea_diets_of_recreationally_harvested_Chinook_and_Coho_Salmon_as_an_ecosystem_monitoring_tool. Details also available from https://cedar.wwu.edu/ssec/2018ssec/allsessions/291/

6.1.1.9 COSEWIC assessment and status report on the Chinook salmon **Oncorhynchus tshawytscha***, Designatable Units in Southern British Columbia (Part One: Designatable Units with no or low levels of artificial releases in the last 12 years), in Canada*

In 2018, COSEWIC completed status assessments for 16 of 28 Designatable Units (DUs) of Southern British Columbia Chinook Salmon populations. This is part 1 of a 2-part report. The following status designations were made:

DU 2: Lower Fraser, Ocean, Fall population	Threatened

DU 3: Lower Fraser, Stream, Spring population	Special Concern
DU 4: Lower Fraser, Stream, Summer (Upper Pitt) population	Endangered
DU 5: Lower Fraser, Stream, Summer population	Threatened
DU 7: Middle Fraser, Stream, Spring population	Endangered
DU 8: Middle Fraser, Stream, Fall population	Endangered
DU 9: Middle Fraser, Stream, Spring (MFR+GStr) population	Threatened
DU 10: Middle Fraser, Stream, Summer population	Threatened
DU 11: Upper Fraser, Stream, Spring population	Endangered
DU 12: South Thompson, Ocean, Summer population	Not at risk
DU 14: South Thompson, Stream, Summer 1.2 population	Endangered
DU 16: North Thompson, Stream, Spring population	Endangered
DU 17: North Thompson, Stream, Summer population	Endangered
DU 19: East Vancouver Island, Stream, Spring population	Endangered
DU 27: Southern Mainland, Ocean, Summer population	Data Deficient
DU 28: Southern Mainland, Stream, Summer population	Data Deficient

The report describes the rationale for status designations. The report also provides information on Chinook salmon distribution, habitat, biology, population sizes, trends, and threats. The main threats are noted to be harvest, changes in freshwater and marine habitat, climate change, hatcheries, and pathogens/aquaculture.

COSEWIC. 2018. COSEWIC assessment and status report on the Chinook Salmon Oncorhynchus tshawytscha, Designatable Units in Southern British Columbia (Part One – Designatable Units with no or low levels of artificial releases in the last 12 years), in Canada. Committee on the Status of Endangered Wildlife in Canada. Ottawa. xxxi + 283 pp. Retrieved from: https://wildlife-species.canada.ca/species-risk-registry/virtual_sara/files/cosewic/ChinookSalmon-v00-2019-Eng.pdf

6.1.1.10 Ocean ecology of Chinook salmon. In book: Ocean Ecology of Pacific Salmon and Trout

This book chapter is a comprehensive summary and interpretation of the research published on the ocean ecology of Chinook salmon. The importance of Pacific herring in the diet of Chinook salmon is discussed, particularly in the Strait of Georgia. Pelagic trawl surveys from 1998 to 2009 showed that 98% of the fish in the surface 30 metres of the Strait of Georgia in the spring and early summer were juvenile Pacific herring and Pacific salmon. Pacific herring is also the most common forage fish in the diets of Chinook salmon. In addition to the importance of Pacific herring as food for Chinook salmon, the importance of competition is also discussed. The link between Pacific herring recruitment and Chinook salmon survival is indicated to be most apparent from research by Beamish *et al*. (2012), which showed that an environmental event which occurred in the Strait of Georgia in 2007 greatly reduced survival of Chinook salmon and Pacific herring. The authors describe predators on Chinook salmon, noting that marine mammals have been identified as predators on juvenile and adult Chinook salmon over the past 25 years. In particular, two species are represented as predators on Chinook salmon: Harbour seals and killer whales. The association of Chinook salmon and killer whales in the Salish Sea has gained public interest in competing Chinook salmon conservation objectives: sustaining fisheries versus the recovery of the resident killer whales. Several papers are cited which report the specialization of resident killer whales on Chinook salmon. Regarding sharing of Chinook production between human uses and killer whale consumption, a science panel (Hilborn *et al.* 2012) made a key point that "The best potential for increased Chinook Salmon abundance is restoration of freshwater habitat, reducing downstream migration mortality and a change in ocean conditions."

Riddell, B., Brodeur, R., Bugaev, A., Moran, P., Murphy, J., Orsi, J., Trudel, M., Weitkamp, L., Wells, B., Wertheimer, A. (2018). Ocean ecology of Chinook salmon. In book: Ocean Ecology of Pacific Salmon and Trout, Edition: First, Chapter: 5, Publisher: American Fisheries Society, Editors: Richard J. Beamish, pp.555-696.

6.1.1.11 Dynamics of juvenile salmon and forage fishes in nearshore kelp forests

Shaffer et al. evaluated seven years of survey videos from kelp forest ecosystems in the northeast Pacific region to analyze movements, co-occurrences, and predatory behaviors between juvenile salmon and forage fish species. The study observed Chinook, coho, chum, and pink salmon interactions with Pacific herring, surf smelt, and sand lance with peak abundances occurring in June and July. Primary interactions (e.g. schooling, intermingling, predation events) were between Chinook and coho salmon on herring. These interactions suggest a shift towards piscivory in juvenile salmon occurring months earlier than previously thought. The results show 78 per cent of interactions in kelp habitats, suggesting that kelp forests play a critical role in these interactions. Given that kelp forest ecosystems are currently declining due to climate change and coastal development, the authors recommend that conservation efforts target kelp restoration to support the ecosystem services they provide for salmon and forage fish.

Shaffer, A., Gross, J., Black, M., Kalagher, A., & Juanes, F. (2023). Dynamics of juvenile salmon and forage fishes in nearshore kelp forests. *Aquatic Conservation: Marine and Freshwater Ecosystems*, *33*(4), 822–832. https://doi.org/10.1002/aqc.3957

6.1.1.12 Phenological diversity of a prey species supports life-stage specific foraging opportunity for a mobile consumer

Chamberlin et al. used genetic stock identification to investigate the dynamics of prey resources impacting the marine survival of Chinook salmon. The study reveals that adult Chinook salmon predominantly consume spawning herring from March–April across their geographic range. In contrast, juvenile Chinook salmon demonstrate seasonal diet variability as well as significant reliance on January–February spawners during the summer. These results highlight the value of herring population diversity and suggest a link between the various spawning groups and Chinook salmon growth. The research reveals a dispersion of Pacific herring beyond known spawning areas. These results emphasize the importance of better understanding seasonal distributions to better support Chinook salmon foraging during their critical growth period. Given that herring form more than 75% of pelagic fish communities, a high abundance of herring in the Salish Sea provides crucial energy. Therefore, variability in timing and distribution holds major implications for predator–prey relationships. The authors recommend that more research on seasonal distributions and abundance dynamics for phenologically distinct herring groups is considered in salmon management strategies.

Chamberlin, J., Petrou, E., Duguid, W., Barsh, R., Juanes, F., Qualley, J., & Hauser, L. (2021). Phenological diversity of a prey species supports life-stage specific foraging opportunity for a mobile consumer. *ICES Journal of Marine Science*, *78*(9), 3089–3100. https://doi.org/10.1093/icesjms/fsab176

6.1.1.13 Variable prey consumption leads to distinct regional differences in Chinook salmon growth during the early marine critical period

Davis et al. explored how spatiotemporal and demographic differences in prey consumption influence early marine growth in subyearling Chinook salmon in Puget Sound. Juvenile salmon in northern Puget Sound (especially near the San Juan Islands) consumed energy-rich prey like forage fish and large crustaceans, resulting in faster growth rates compared to fish in central and southern Puget Sound, which relied more on crustaceans and insects. Fish consuming forage fish exhibited significantly higher scale-derived growth rates and insulin-like growth factor-1 (IGF-1) concentrations, reflecting improved growth and body condition. Subyearling salmon in the San Juan Islands had fuller stomachs and greater growth than those in other regions, highlighting the importance of prey quality and quantity in promoting growth during the critical early marine period. Hatchery-reared salmon were initially larger than their wild counterparts, but this size advantage diminished by mid-summer, emphasizing the role of regional prey availability over hatchery origin in growth outcomes. The study underscores the critical role of prey availability and dietary quality in shaping growth trajectories and survival prospects for Chinook salmon during their early marine phase.

Davis, M. J., Chamberlin, J. W., Gardner, J. R., Connelly, K. A., Gamble, M. M., Beckman, B. R., & Beauchamp, D. A. (2020). Variable prey consumption leads to distinct regional differences in Chinook salmon growth during the early marine critical period. *Marine Ecology Progress Series, 640*, 147–169. https://doi.org/10.3354/meps13279

6.1.1.14 The synchronous failure of juvenile Pacific salmon and herring production in the Strait of Georgia in 2007 and the poor return of sockeye salmon to the Fraser River in 2009

Beamish et al. investigated the synchronized failure of juvenile Pacific salmon and Pacific herring production in the Strait of Georgia in 2007, which corresponded with the poor return of sockeye salmon to the Fraser River in 2009. The research showed a significant drop in juvenile Pacific salmon and herring abundance in 2007, with high mortality rates likely caused by poor food production in the early marine environment. Pacific herring, an essential prey for juvenile salmon, experienced record-low recruitment in 2007 due to extreme environmental conditions, including low plankton production and anomalous climate patterns. Juvenile salmon (coho, Chinook, chum, and sockeye) were smaller, had poor body conditions, and exhibited a high percentage of empty stomachs, reflecting food shortages. The poor condition of juvenile sockeye salmon in 2007 resulted in exceptionally low marine survival, contributing to historically low adult returns to the Fraser River in 2009. Climate anomalies, such as reduced sunlight, increased rainfall, and shallow mixing layers, disrupted the food web and resulted in widespread early marine mortality for both salmon and herring. The authors conclude that the early marine period was a critical bottleneck, with poor environmental conditions driving low survival and subsequent low recruitment for these species.

Beamish, R. J., Neville, C., Sweeting, R., & Lange, K. (2012). The synchronous failure of juvenile Pacific salmon and herring production in the Strait of Georgia in 2007 and the poor return of sockeye salmon to the Fraser River in 2009. *Marine and Coastal Fisheries*, 4(1), 403–414. https://doi.org/10.1080/19425120.2012.676607

6.1.1.15 Does predation by returning adult pink salmon regulate pink salmon or herring abundance?

Sturdevant et al. examined whether predation by returning adult pink salmon impacts the abundance of juvenile pink salmon and Pacific herring in Prince William Sound (PWS) and Southeast Alaska (SEAK). The study revealed that predation on juvenile pink salmon by adult pink salmon is minimal, with low frequency and little effect on subsequent population cycles. However, localized predation on herring was significant in certain years, particularly in PWS during 2010 when adult pink salmon abundance and feeding overlapped spatially and temporally with herring. Coho and Chinook salmon were more consistent and significant predators of both herring and juvenile salmon, with predation levels influenced by climatic conditions. Predation interactions varied by year, location, and environmental conditions, highlighting the role of climate in shaping predator–prey dynamics.

Sturdevant, M. V., Brenner, R., Fergusson, E. A., Orsi, J. A., & Heard, W. R. (2013). Does predation by returning adult pink salmon regulate pink salmon or herring abundance? *NPAFC Technical Report*, *9*, 153–164. Retrieved from https://www.researchgate.net/publication/264897364

6.1.2 Chinook Salmon and Herring Interspecific Interactions (Competition)

6.1.2.1 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

A part of this study focused on the competition between juvenile Chinook salmon and Pacific herring in Puget Sound. Simulation modeling was used to model consumption demand by both species for common prey species. Results indicated that diet overlap was high, attributed primarily to crab larvae and secondarily to hyperiid amphipods, copepods, or euphausiids. Herring consumed approximately 10–50 times more biomass of the major prey eaten by juvenile Chinook salmon during the critical May–July growth period. 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. The study points out that very limited data were available at that time on the seasonal distribution, abundance, size structure, diet, and feeding of herring. Further, in light of the general concern for forage fish populations, the results of this study show strong trophic linkages that also strongly influence the population dynamics of Chinook salmon, underscores the important need for integrated research, monitoring, and management of these species collectively in the future.

Beauchamp, D.A., Duffy, E.J. (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. Washington Cooperative Fish and Wildlife Research Unit. Report # WACFWRU-11-01.

6.1.2.2 Potential for competition among herring and juvenile salmon species in Puget Sound, Washington

This research identifies that Pacific herring compete with juvenile salmon for food. During the summer growth period in Puget Sound, juvenile salmon and herring exhibit generally high spatial-temporal overlap and variable but often high dietary overlap. Based on trawl catches during July and September/October between 2001 and 2011, stomach contents for all salmon species and Pacific herring were identified, and a bioenergetic model was used to estimate feeding rates for salmon and Pacific herring over the July to fall period. Diets of Chinook and coho were the most similar, followed by Pacific herring, and the least similar were chum salmon. Because of their greater population biomass, herring have the potential to remove substantially more of the prey base than do salmon. These observations, paired with previous research linking variable feeding rates and growth to variable survival for Chinook salmon (Beauchamp and Duffy 2011), are consistent with the hypothesis that competition influences feeding over the summer growth period, thereby affecting marine survival rates of Puget Sound Chinook salmon. Results suggest that any assessment of marine carrying capacity will need to account for the population and feeding dynamics of all major daylight planktivores in Puget Sound.

Kemp, I.M., Beauchamp, D.A., Sweeting, R., Cooper, C. (2013). Potential for competition among herring and juvenile salmon species in Puget Sound, Washington. North Pacific Anadromous Fish Commission. Technical Report No. 9. 139–143.

6.2 Southern Resident Killer Whales (SRKWs)

6.2.1 Selective foraging by fish-eating killer whales Orcinus orca *in British Columbia*

Ford and Ellis conducted field studies on the foraging behaviour of resident killer whales to examine potential variation in prey selection by season, geographical area, group membership and prey availability. Foraging by resident killer whales was found to frequently involve sharing by two or more whales. Prey fragments left at kill sites resulted mostly from handling and breaking up of prey for sharing, and all species and sizes of salmonids were shared. Resident killer whale groups in all parts of the study area forage selectively for chinook salmon, probably because of the species' large size, high lipid content, and year-round availability in the whales' range. Chum salmon *Oncorhynchus keta*, the second largest salmonid, were also taken when available, but smaller sockeye *O. nerka* and pink *O. gorbuscha* salmon were not significant prey despite far greater seasonal abundance. Strong selectivity for Chinook salmon by resident killer whales probably has a significant influence on foraging tactics and seasonal movements, and also may have important implications for the conservation and management of both predator and prey.

Ford, J.K., & Ellis, G.M. (2006). Selective foraging by fish-eating killer whales *Orcinus orca* in British Columbia. *Marine Ecology Progress Series, 316*, 185-199.

6.2.2 Quantifying the effects of prey abundance on killer whale reproduction

This study used modelling to assess whether killer whale reproduction (NRKWs and SRKWs) is limited by availability of Chinook salmon (i.e. prey abundance). Additional risk factors were also assessed (e.g., anthropogenic factors, climate variables, temporal effects, and population variables). Results indicated that killer whale fecundity is highly correlated with the abundance of Chinook salmon. For example, the probability of a female calving differed by 50% between years of low salmon abundance and high salmon abundance. The authors found little evidence linking fecundity to other variables, such as sea surface temperature. There was strong data support for reproductive deterioration with age (senescence) in female killer whales. This pattern of rapid maturity and gradual decline of fecundity with age commonly seen in terrestrial mammals has been documented in few marine mammal species. Maximum production for this species occurs between ages 20–22, and reproductive performance declines gradually to menopause over a period of 25 years. These findings provide strong evidence for reproductive senescence in killer whales, and more importantly, that killer whale fecundity is strongly tied to the abundance of Chinook salmon, a species that is susceptible to environmental variation and has high commercial value to fisheries. This strong predator-prey relationship highlights the importance of understanding which salmon populations overlap with killer whales seasonally and spatially, so that those salmon populations important as prey for killer whales can be identified and targeted for conservation efforts. In this case, the authors considered stocks in the fishery of the west coast of Vancouver Island fishery (i.e., salmon from Puget Sound, and the Columbia and Fraser rivers), and highlighted the Fraser River Chinook as the most likely to be tied to killer whale demography.

Ward, E.J., Holmes, E.E., and Balcom, K.C. (2009). Quantifying the effects of prey abundance on killer whale reproduction *Journal of Applied Ecology*, (46), 632–640.

6.2.3 Chinook salmon predation by resident killer whales: seasonal and regional selectivity, stock identity of prey, and consumption rates

This report describes the results of field studies and analyses aimed at improving our understanding of the role played by Chinook salmon in the seasonal foraging ecology and energetics of resident killer whales. Chinook salmon is the resident killer whale's primary prey species, most likely because of its large size, high lipid content, and year-round occurrence in coastal waters. Chinook salmon availability appears to be important to the survival and recovery of resident killer whale populations. Results show that Chinook salmon are important to resident killer whales in most seasons and coastal areas. Killer whales feed on Chinook salmon originating from a variety of regions between Southeast Alaska and Oregon, with stocks in the Fraser River system being of particular importance both coast-wide and in critical habitats. Fraser River stock regions comprised 64% of Chinook consumed by Northern Resident Killer Whales (NRKWs) in their critical habitat, and 75% of Chinook taken by southern residents in their critical habitat. Long-term data show the correlation between survival of resident killer whales and Chinook salmon abundance, though recent declines in Chinook abundance have not yet shown increased mortality rates. Although there is considerable uncertainty in the actual proportion of the whales' year-round diet that is composed of Chinook, a reasonably conservative estimate is that about 70% of their nutritional needs may be supplied by this species. This suggests that resident killer whale populations at their current abundance may require over 1,000,000 Chinook per year, roughly equivalent to recent annual levels of harvests of this species in commercial and recreational marine fisheries.

Estimates of Chinook salmon requirements for Northern and Southern Resident Killer Whale populations in their critical habitats were also provided, as is an estimate of the Chinook abundance that would be required to support killer whale recovery over the next decade since the research took place. Assuming that resident killer whale populations grew at their maximum rate of 2.6% over 10 years, an estimated 1.5–1.8 million Chinook may have been needed to support these populations each year by

2018. Extensive prey sampling in Critical Habitats suggested that Chinook salmon represents about 90% of resident killer whale diet during July–August. Southern residents foraging in Critical Habitat (in Canadian and U.S. waters combined) would thus require approximately 1200–1400 Chinook salmon per day, or roughly 67,000–81,000 over the two month period. On average, only 14.5% of the northern resident population uses their designated critical habitat on a daily basis during July–August. As a result, Chinook salmon requirements in this area are less than for southern resident critical habitat: about 420–500 fish per day, or 26,000–31,000 total over the two months. As the great majority of Chinook taken in both critical habitat areas are from Fraser River stocks, it can be concluded that adequate Chinook production in this river system is essential to the continued function of resident killer whale critical habitats.

Ford, J.K.B, Wright, B.M., Ellis, G.M., and Candy, J.R. (2010). Chinook salmon predation by resident killer whales: seasonal and regional selectivity, stock identity of prey, and consumption rates. DFO Can. Sci. Advis. Sec. Res. Doc. 2009/101.

DFO. (2010). Chinook salmon abundance levels and survival of resident killer whales. DFO Can. Sci. Advis. Sec., Sci. Advis. Rep. 2009/075.

[Also summarized in presentation slides: https://archive.fisheries.noaa.gov/wcr/publications/protected_species/marine_mammals/killer_whales/esa_status/ford-analysis.pdf]

6.2.4 Linking killer whale survival and prey abundance: Food limitation in the oceans' apex predator?

Using 25 years of demographic data from Northern and Southern Resident Killer Whale populations, researchers show that population trends are driven largely by changes in survival, and that survival rates are strongly correlated with the availability of their principal prey species, Chinook salmon. The striking correspondence between changes in Chinook salmon abundance and mortality of Northern and Southern Resident Killer Whales suggests that prey limitation was an important factor in population declines.

Results suggest that although these killer whales may consume a variety of fish species, they are highly specialized and dependent on this single salmonid species to an extent that it is a limiting factor in their population dynamics. Other ecologically specialized killer whale populations may be similarly constrained to a narrow range of prey species by culturally inherited foraging strategies, and thus are limited in their ability to adapt rapidly to changing prey availability.

Ford JK, Ellis GM, Olesiuk PF, Balcomb KC. (2010). Linking killer whale survival and prey abundance: Food limitation in the oceans' apex predator?. *Biol Lett, 6*(1), 139-142. doi:10.1098/rsbl.2009.0468

6.2.5 Species and stock identification of prey consumed by endangered Southern Resident Killer Whales in their summer range

Recovery plans for endangered Southern Resident Killer Whales identified reduced prey availability as a risk to the population. This research paper further explores this risk to understand what specific Chinook stocks were the most important. The researchers studied prey selection from 2004 to 2008 in two regions of the whales' summer range: San Juan Islands, Washington and the western Strait of Juan de Fuca, British Columbia. Following the whales in a small boat, fish scales and tissue remains from predation events and feces were collected using a fine mesh net. Visual fish scale analysis and molecular genetic methods were used to identify the species consumed. Chinook salmon, a relatively rare species, was by far the most frequent prey item, confirming previous studies. For Chinook salmon prey, genetic identification methods were used to estimate the spawning region of origin. Of the Chinook salmon sampled, 80 to 90% were inferred to have originated from the Fraser River, and only 6 to 14% were inferred to have originated from Puget Sound area rivers. Within the Fraser River, the Upper Fraser, Middle Fraser, South Thompson River and Lower Fraser stocks were inferred to currently be sequentially important sources of Chinook salmon prey through the summer. This information is important in guiding management actions to recover the southern resident killer whale population.

Hanson, M.B., Baird, R.W., Ford, J.K.B., Hempelmann-Halos, J., Van Doornik, D.M., Candy, J.R., Emmons, C.K., Schorr, G.S., Gisborne, B., Ayres, K.L., Wasser, S.K., Balcomb, K.C., Balcomb-Bartok, K., Sneva, J.G., Ford, M.J. (2010). Species and stock identification of prey consumed by endangered Southern Resident Killer Whales in their summer range. *Endangered Species Research, 11*, 69-82.

6.2.6 Estimated field metabolic rates and prey requirements of resident killer whales

Noren examined energy requirements of Southern Resident Killer Whales to assess whether prey availability of Chinook salmon is sufficient. Noren estimated body mass, field metabolic rate (FMR), and daily prey energy requirements (DPERs) for each individual in the population. FMRs were calculated from body mass, assuming they range from five to six times Kleiber-predicted basal metabolic rates. FMRs of adults were also calculated from resident killer whale activity budgets and the metabolic cost of swimming at speeds associated with daily activities. These two methods yielded similar results. Total FMRs varied by age and sex, which is partly due to the long developmental period and sexual dimorphism in killer whales. FMRs for males (465–4,434 kg) ranged from 35,048 to 228,216 kcal/d while FMRs for females (465–3,338 kg) ranged from 35,048 to 184,444 kcal/d. DPERs were calculated from FMRs assuming a standard digestive efficiency. Corresponding DPERs ranged from 41,376 to 269,458 kcal/d and 41,376 to 217,775 kcal/d, respectively. Coarse estimates or the number of individual fish consumed per day are presented, in order to illustrate how diverse species-specific consumption rates can be. Prey consumption rates

(PCRs) for Chinook and chum (*Oncorhynchus keta*) salmon were calculated (since they are the two most prevalent salmon species in the diets of resident killer whales). PCR ranges of Chinook and chum salmon were calculated from killer whale DPERs (kcal/d) and caloric densities (kcal/fish) of Chinook (Fraser River adult average: 16,386 kcal/fish) and chum (Puget Sound adult average: 3,877 kcal/fish) salmon, assuming a single-species diet (for simplicity). When subsisting only on Chinook, the daily consumption rate for the 82 animals ≥1 yr of age in the 83-member SRKW population ranges from 792 to 951 fish/d (289,131–347,000 fish/yr). Fish consumption increases significantly to 3,348–4,018 fish/d (1,222,003–1,466,581 fish/yr) when the population consumes only chum. Noren concludes that a much larger prey base will need to be available to SRKWs when the total area of the foraging ground and the energetic cost of searching for prey are considered.

Noren, D.P. (2011). Estimated field metabolic rates and prey requirements of resident killer whales. *Marine Mammal Science, 27*(1), 60-77.

6.2.7 Competing conservation objectives for predators and prey: estimating killer whale prey requirements for Chinook salmon

Williams et al. modelled SRKW’s prey requirements for Chinook salmon, highlighting competing conservation objectives for at-risk killer whales and Chinook salmon important to fisheries. Individual killer whale prey requirements were modelled based on feeding and growth records of captive killer whales and morphometric data from historic live-capture fishery and whaling records worldwide. Predictions of salmon quantities needed to maintain and recover the SRKW population were made using the model combined with the caloric value of salmon, and demographic and diet data for wild killer whales. The number of fish required as prey for SRKWs is large relative to annual returns and fishery catches. The SRKW population, numbering only 87 individuals in 2009, may easily consume 12–23% of available Fraser River Chinook in the region from May–September. These plausible summer estimates are large relative to the 10–40% natural mortality considered in regional fisheries stock assessment models, because they ignore likely consumption of Chinook in winter months, consumption by peripatetic Northern Resident Killer Whales, consumption by Steller sea lions, sharks and other predators, and the fact that wild, free-ranging killer whales likely have higher metabolic demands than captive animals. Consumption of Fraser River Chinook by SRKWs may exceed those from all fisheries in the region combined. When the demands of a recovered population is considered, the already substantial number of Chinook salmon required would be expansive. As an example, a U.S. recovery goal (2.3% annual population growth of killer whales over 28 years) implies a 75% increase in energetic requirements. The plausible summertime estimates presented build a compelling case for competition between conservation objectives for killer whales and Chinook salmon, even at the killer whale population’s current size. Reducing salmon fisheries may serve as a temporary mitigation measure to allow time for management actions to improve salmon productivity to take effect. As ecosystem-based fishery management becomes more prevalent, trade-offs between conservation objectives for predators and prey will become increasingly necessary. It is faster to reduce take of salmon than to increase salmon production, and it is faster to increase salmon production than promote population growth in killer whales. The efficacy of salmon habitat restoration actions can often be measured within a decade, whereas similar measurements will take decades in studies of long-lived species like killer whales. This mismatch has implications for adaptive management strategies.

Williams, R., Krkošek, M., Ashe, E., Branch, T. A., Clark, S., Hammond, P. S., Hoyt, E., Noren, D. P., Rosen, D., & Winship, A. (2011). Competing conservation objectives for predators and prey: estimating killer whale prey requirements for Chinook salmon. *PloS one, 6*(11).

*6.2.8 Distinguishing the impacts of inadequate prey and vessel traffic on an endangered killer whale (*Orcinus orca*) population*

Ayres et al. examined two stressors on Southern Resident Killer Whales (inadequate prey and vessel traffic) using non-invasive physiological techniques to evaluate the relative impacts of each stressor. The authors measured Fecal thyroid (T3) and glucocorticoid (GC) hormone. GC increases in response to nutritional and psychological stress, whereas thyroid hormone declines in response to nutritional stress but is unaffected by psychological stress. The inadequate prey hypothesis argues that the killer whales have become prey-limited due to reductions of their dominant prey, Chinook salmon. The vessel impact hypothesis argues that high numbers of vessels in close proximity to the whales cause disturbance via psychological stress and/or impaired foraging ability. The GC and T3 measures supported the inadequate prey hypothesis. GC concentrations were negatively correlated with short-term changes in prey availability. T3 concentrations varied by date and year in a manner that corresponded with more long-term prey availability. Physiological correlations with prey overshadowed any impacts of vessels since GCs were lowest during the peak in vessel abundance, which also coincided with the peak in salmon availability. Results suggest that prey availability has a greater physiological impact on SRKWs than does vessel traffic. Identification and recovery of strategic salmon populations in the SRKW diet are important to effectively promote SRKW recovery. Also interesting is that the temporal trend in T3 concentrations within and between years suggest that the sampled SRKWs might be feeding on a nutritious early spring food source acquired prior to their arrival in the Salish Sea. Available information (fish scale samples and observations of whales foraging at the mouth of the Columbia River) suggests that the whales may be feeding on Columbia River salmon and these spring-run stocks might be of particular importance for the nutrition of this population.

Ayres, K. L., Booth, R. K., Hempelmann, J. A., Koski, K. L., Emmons, C. K., Baird, R. W., Balcomb-Bartok, K., Hanson, M. B., Ford, M. J., & Wasser, S. K. (2012). Distinguishing the impacts of inadequate prey and vessel traffic on an endangered killer whale (*Orcinus orca)* population. *PloS one, 7*(6).

6.2.9 *Relative importance of Chinook salmon abundance on resident killer whale population growth and viability*

The Southern Resident Killer Whales and Northern Resident Killer Whales are both listed under the Endangered Species Act. One of the major threats recognized for these two populations is nutritional stress associated with prey abundance levels and availability. Multiple studies have shown that Chinook salmon play a dominant role in the summer diets of both SRKWs and NRKWs and remain a key part of their diet throughout the year.. The availability of Chinook salmon has been identified as a potential limiting factor to the RKWs population dynamics. Studies have demonstrated that RKWs have strong selectivity for Chinook even when Chinook abundance is low relative to other salmon. The purpose of this study was to quantify RKW–Chinook salmon interactions and their influence on RKW population growth rates and viability. In spite of the trophic linkages between RKW and Chinook salmon evidenced by diet composition studies and the relevant interactions detected in this study, the results of this analysis indicated that the effects of these interactions on RKW population growth and viability are relatively small and/or uncertain and in need of further research. Other factors (genetic, environmental and/or anthropogenic) could be at play limiting RKW population growth and possibly masking and confounding the detection of stronger interactions between RKW vital rates and Chinook salmon abundance. Given the current state of information, it is highly uncertain whether the allocation of Chinook salmon resources for RKW would be an effective management action in RKW recovery plans. The study did highlight that given the higher vulnerability of SRKWs, the greater importance of management decisions. Further research is needed to identify the causes of depressed production (fecundity of old reproductive females) and survival of calves in SRKW. Future studies could evaluate relationships between POP levels in Chinook salmon tissue and RKW vital rates.

Vélez-Espino, L. A., Ford, J. K. B., Araujo, H. A., Ellis, G., Parken, C. K., and Sharma, R. (2015). Relative importance of chinook salmon abundance on resident killer whale population growth and viability. *Aquatic Conserv: Mar. Freshw.* Ecosyst., (25), 756– 780. doi: 10.1002/aqc.2494.

6.2.10 *Estimation of a killer whale (*Orcinus orca*) population's diet using sequencing analysis of DNA from feces*

Ford et al. conducted genetic analysis on fecal material from Southern Resident Killer Whales, in order to estimate diet composition in their summer range in the Salish Sea. The analysis entailed DNA sequencing of 175 fecal samples collected between May and September from five years between 2006 and 2011. After several quality control steps, 4,987,107 individual sequences were aligned to a custom sequence database containing 19 potential fish prey species and the most likely species of each fecal-derived sequence was determined. Based on these alignments, salmonids made up >98.6% of the total sequences and thus of the inferred diet. Of the six salmonid species, Chinook salmon made up 79.5% of the sequences, followed by coho salmon

(15%). Over all years, a clear pattern emerged with Chinook salmon dominating the estimated diet early in the summer, and coho salmon contributing an average of >40% of the diet in late summer. Sockeye salmon appeared to be occasionally important, at >18% in some sample groups. Non-salmonids were rarely observed. These results are consistent with earlier results based on surface prey remains, and confirm the importance of Chinook salmon in this population's summer diet.

Ford, M. J., J. Hempelmann, M. B. Hanson, K. L. Ayres, R. W. Baird, C. K. Emmons, J. I. Lundin, G. S. Schorr, S. K. Wasser, and L. K. Park. (2016). Estimation of a killer whale (*Orcinus orca*) population's diet using sequencing analysis of DNA from feces. *PLOS ONE 11*(1).

6.2.11 Estimates of Chinook salmon consumption in Washington State inland waters by four marine mammal predators from 1970 to 2015

This study evaluates the consumption of Chinook salmon by three protected pinniped species (the harbour seal, Steller sea lion and California sea lion), relative to endangered killer whales in the Puget Sound region. Recovery has led to an increased abundance of these protected pinnipeds, which may be adversely affecting the recovery of threatened Chinook salmon and killer whales. Between 1970 and 2015, the annual biomass of Chinook salmon consumed by pinnipeds was estimated to have increased from 68 to 625 metric tons. Converting juvenile Chinook salmon into adult equivalents, the researchers found that by 2015, pinnipeds consumed double that of resident killer whales and six times greater than the combined commercial and recreational catches. These results demonstrate the importance of interspecific interactions when evaluating species recovery. As more protected species respond positively to recovery efforts, managers should attempt to evaluate tradeoffs between these recovery efforts and the unintended ecosystem consequences of predation and competition on other protected species.

Chasco, B.E., Kaplan, I.C., Thomas, A.C., Acevedo-Gutiérrez, A., Noren, D.P., Ford, M.J., Hanson, M.B., Scordino, J.J., Jeffries, S.J., Pearson, S.F., Marshall, K.N., & Ward, E.J. (2017). Estimates of Chinook salmon consumption in Washington State inland waters by four marine mammal predators from 1970 to 2015. *Canadian Journal of Fisheries and Aquatic Sciences, 74*, 1173–1194.

6.2.12 Competing tradeoffs between increasing marine mammal predation and fisheries harvest of Chinook salmon

This study is similar to "Estimates of Chinook salmon consumption in Washington State inland waters by four marine mammal predators from 1970 to 2015," but Chasco et al. used a spatial-temporal bioenergetics model to make larger-scale regional estimates in the Northeast Pacific Ocean. Specifically, the researchers quantify how predation by three species of pinnipeds and killer whales on Chinook salmon has changed since the 1970s along the west coast of North America (eight regions from California to Alaska), and compare these estimates to salmon fisheries. Findings show that from 1975 to 2015, biomass of Chinook salmon consumed by pinnipeds and killer whales increased from 6,100 to 15,200 metric tons (from 5 to 31.5 million individual salmon). Though there is variation across regions in the model, overall, killer whales consume the largest biomass of Chinook salmon, but harbor seals consume the largest number of individuals. The decrease in adult Chinook salmon harvest from 1975–2015 was 16,400 to 9,600 metric tons. Thus, Chinook salmon removals (harvest + consumption) increased in the past 40 years despite catch reductions by fisheries, due to consumption by recovering pinnipeds and endangered killer whales. Long-term management strategies for Chinook salmon will need to consider potential conflicts between rebounding predators or endangered predators and prey. Regionally, for Salish Sea Chinook salmon, strong increases in predation greatly exceed harvest; this is driven largely by local increases in pinniped abundance in the Salish Sea. Predation has also increased on Northern Chinook salmon stocks (Washington, west coast of Vancouver Island and coastal British Columbia, and Southeast Alaska), but for these stocks predation is presently near or below the harvest.

Chasco, B. E., Kaplan, I. C., Thomas, A. C., Acevedo-Gutiérrez, A., Noren, D. P., Ford, M. J., Hanson, M. B., Scordino, J. J., Jeffries, S. J., Marshall, K. N., Shelton, A. O., Matkin, C., Burke, B. J., & Ward, E. J. (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

*6.2.13 Population growth is limited by nutritional impacts on pregnancy success in endangered Southern Resident Killer Whales (*Orcinus orca*)*

Southern Resident Killer Whale population growth is constrained by low offspring production for the number of reproductive females in the population. Lack of prey, increased toxins, and vessel disturbance have been listed as potential causes of the whale's decline, but partitioning these pressures has been difficult. This study validated and applied temporal measures of progesterone and testosterone metabolites to assess occurrence, stage and health of pregnancy from genotyped killer whale feces collected using detection dogs. Thyroid and glucocorticoid hormone metabolites were measured from these same samples to assess physiological stress. These methods enabled the researchers to assess pregnancy occurrence and failure as well as how pregnancy success was temporally impacted by nutritional and other stressors, between 2008 and 2014. Up to 69% of all detectable pregnancies were unsuccessful; of these, up to 33% failed relatively late in gestation or immediately postpartum, when the cost is especially high. Low availability of Chinook salmon appears to be an important stressor among these fish-eating whales as well as a significant cause of late pregnancy failure, including unobserved perinatal loss. However, release of lipophilic toxicants during fat metabolism in the nutritionally deprived animals may also provide a contributor to these cumulative effects. Results point to the importance of promoting Chinook salmon recovery to enhance population growth of Southern Resident Killer Whales. The physiological measures used in this study can also be used to monitor the success of actions aimed at promoting adaptive management of this important apex predator to the

Pacific Northwest. Results of the SRKW study strongly suggest that recovering Fraser River Chinook (FRC) and Columbia River Chinook (CRC) runs should be among the highest priorities for managers aiming to recover this endangered population of killer whales. SRKW are suffering significant reproductive loss due to lack of Chinook prey and associated effects (e.g., release of lipophilic toxins into circulation). The FRC run is a major prey source for the SRKW population during summer and early fall, and appears to be key to providing the needed reserves to carry the whales through the subsequent winter. The early spring CRC runs likely serve to replenish energetic reserves expended during the previous winter as well as help sustain the whales until the occurrence of the subsequent late summer peak in the FRC runs.

Wasser, S. K., Lundin, J. I., Ayres, K., Seely, E., Giles, D., Balcomb, K., Hempelmann, J., Parsons, K., & Booth, R. (2017). Population growth is limited by nutritional impacts on pregnancy success in endangered Southern Resident Killer Whales (*Orcinus orca*). *PloS one*, *12*(6), e0179824. https://doi.org/10.1371/journal.pone.0179824

6.2.14 Evaluating anthropogenic threats to endangered killer whales to inform effective recovery plans

Understanding cumulative effects of multiple threats is key to guiding effective management to conserve endangered species. The critically endangered Southern Resident Killer Whale population of the northeastern Pacific Ocean provides a data-rich case to explore anthropogenic threats on population viability. Primary threats include: limitation of preferred prey, Chinook salmon; anthropogenic noise and disturbance, which reduce foraging efficiency; and high levels of stored contaminants, including PCBs. Researchers constructed a population viability analysis to explore possible demographic trajectories and the relative importance of anthropogenic stressors. The population is fragile, with no growth projected under current conditions, and decline expected if new or increased threats are imposed. Improvements in fecundity and calf survival are needed to reach a conservation objective of 2.3% annual population growth. Prey limitation is the most important factor affecting population growth. However, to meet recovery targets through prey management alone, Chinook abundance would have to be sustained near the highest levels since the 1970s. The most optimistic mitigation of noise and contaminants would make the difference between a declining and increasing population, but would be insufficient to reach recovery targets. Reducing acoustic disturbance by 50% combined with increasing Chinook by 15% would allow the population to reach 2.3% growth.

Lacy, R.C., Williams, R., Ashe, E. *et al.* (2017). Evaluating anthropogenic threats to endangered killer whales to inform effective recovery plans. *Scientific Reports, 7*(14119). https://doi.org/10.1038/s41598-017-14471-0

6.2.15 Killer whale movements on the Norwegian shelf are associated with herring density

Vogel et al. investigated the offshore foraging behaviour and distribution of killer whales in relation to the distribution of spring-spawning herring in Norwegian waters. The study uses satellite telemetry data from 29 male killer whales to track their movement alongside herring density through acoustic trawl survey data and ecosystem modelling. The results observe that killer whales track herring migrations over long distances and their movements are coupled with changes in herring density. While killer whales are not direct predators of Pacific herring in the Salish Sea, these results still provide valuable insights into the foraging strategies of marine predators and, particularly, the ecological interactions between apex predators and prey populations.

Vogel, E. F., Biuw, M., Blanchet, M.-A., Jonsen, I. D., Mul, E., Johnsen, E., Hjøllo, S. S., Olsen, M. T., Dietz, R., & Rikardsen, A. (2021). Killer whale movements on the Norwegian shelf are associated with herring density. *Marine Ecology Progress Series*, *665*, 217–231. https://doi.org/10.3354/meps13685

6.3 Bears

6.3.1 Novel species interactions: American black bears respond to Pacific herring spawn

This study investigated the interaction between American black bears (*Ursus americanus*) and Pacific herring at spawn events in Quatsino Sound, B.C.. Cameras used to monitor bear activity in supratidal and intertidal zones determined that the quantity of Pacific herring eggs was a leading predictor of black bear activity. An analysis of bear scats indicated that Pacific herring egg mass was the highest predictor of egg consumption by bears. The research represents the first scientific evidence of a cross-ecosystem interaction between Pacific herring and American black bears. Combined, evidence of anthropogenic constraints on both black bears and Pacific herring suggests that bear-herring interactions were potentially stronger and more widespread in the past.

Fox, C.H., Paquet, P.C., Reimchen, T.E. (2015). Novel species interactions: American black bears respond to Pacific herring spawn. *BMC Ecology, 15*(14).

6.4 Seabirds

6.4.1 Global seabird response to forage fish depletion—one-third for the birds

Cury et al. quantified the effect of fluctuations in food abundance on seabird breeding success using a global database. Seven ecosystems and fourteen bird species were examined within the Atlantic, Pacific, and Southern Oceans. This information was used to identify a threshold in forage fish prey abundance below which seabirds experience consistently reduced and more variable productivity. The threshold approximated one-third of the maximum prey biomass observed in long-term studies. This provides an indicator of the minimal forage fish biomass needed to sustain seabird productivity over the long term.

Cury, P. M., Boyd, I. L., Bonhommeau, S., Anker-Nilssen, T., Crawford, R. J., Furness, R. W., Mills, J. A., Murphy, E. J., Osterblom, H., Paleczny, M., Piatt, J. F., Roux, J. P., Shannon, L., & Sydeman, W. J. (2011). Global seabird response to forage fish depletion—one-third for the birds. *Science (New York, N.Y.), 334*(6063), 1703–1706.

6.4.2 Persisting worldwide seabird-fishery competition despite seabird community decline

Grémillet assessed temporal trends in seabird-fishery competition on a worldwide scale. Catch reconstructions were used for all fisheries targeting taxa that are also seabird prey to demonstrate that average annual fishery catch increased from 59 to 65 million metric tons between 1970–1989 and 1990–2010 (+10%). For the same period, it was estimated that global annual seabird food consumption decreased from 70 to 57 million metric tons (-19%). Despite this decrease, findings revealed sustained global seabird-fishery food competition between 1970–1989 and 1990–2010. Enhanced competition was identified in 48% of all areas, notably the Southern Ocean, Asian shelves, Mediterranean Sea, Norwegian Sea, and Californian coast. Fisheries generate severe constraints for seabird populations on a worldwide scale, and those need to be addressed.

Grémillet, D., Ponchon, A., Paleczny, M., Palomares, M. D., Karpouzi, V., & Pauly, D. (2018). Persisting worldwide seabird-fishery competition despite seabird community decline. *Current biology: CB, 28*(24), 4009–4013.

7 Trophic Role of Herring in the Food Web

7.1.1 Biodiversity along the west coast of Vancouver Island: Lessons learned and application to the Strait of Georgia

This presentation discusses a west coast Vancouver Island ecosystem monitoring program as a framework that can be applied to the Strait of Georgia. Specifically, the biological basis for production variability in WCVI herring has been investigated since 1991. For WCVI recruit herring (first-time spawners, Age 3), the biomass of *Thysanoessa spinifera* (krill) longer than 17 mm in August of each of the first three years of life, and hake predation during the first year of life, explain changes in recruit herring abundance. For adult herring, decreasing survival is explained by natural increasing mortality rates with age and also by the decline of the August biomass of krill >17 mm. Growth variation in recruits is determined by krill biomass in August of each of the first three years of life. Size-at-age of older fish is determined by recruit size and to a lesser extent, krill biomass in August. The theme of the presentation is that the WCVI study methodology can be applied to create a monitoring program encompassing a number of sampling sites in the SOG. Long-term monitoring of ecosystem diversity, including species interactions and variations in distribution are crucial to understanding and managing biological resources. The results can be used to learn the biological basis of production variability and then make informed decisions about biological resource use to optimize ecosystem health and communities.

Tanasichuk, R. (unknown year). Biodiversity along the west coast of Vancouver Island: Lessons learned and application to the Strait of Georgia. Pacific Biological Station. [PowerPoint slides]. Retrieved from https://slideplayer.com/slide/221738/

7.1.2 Energy-based ecosystem modelling illuminates the ecological role of Northeast Pacific herring

Researchers investigated the influence of energy content on the trophic role of Pacific herring off northern B.C. and southeast Alaska and tested the viability and utility of energy-based ecosystem models. Pacific herring act as a conduit for energy flow from zooplankton to higher predators. Compared to other northeast Pacific coastal fish, they have high energy content, making them preferred high quality prey by active species such as whales and seabirds. Current models of pacific herring are based on biomass. However, biomass-based diet compositions may underestimate the importance of Pacific herring as prey to many seabirds, mammals and fish. When energy content differences between functional groups are accounted for, herring emerges as an important item in the diets of small odontocetes (dolphins and porpoises), humpback and minke whales, seals and sea lions, piscivorous seabirds (including many cormorants, alcids and gulls), inshore rockfish, lingcod, and Pacific hake. While low-quality prey dominate the total ecosystem biomass, high-quality prey (e.g. adult herring) may be more important to many predators than prey biomasses would suggest. These findings corroborating other studies place adult herring among the most energy-rich forage fish in the subarctic North Pacific. The findings also indicate that food web structure, complexity, and ultimately overall productivity (including fisheries yield) of marine communities is likely enhanced when high-energy forage fish dominate. In accounting for prey energy content differences, and explicitly representing the thermodynamic basis of trophic interactions and ecosystem structure, an expanded and improved energy-balance approach could enhance both the realism and predictive capacity of food web models. Furthermore, given the demonstrated potential for climatically driven seasonal and interannual shifts in energy-rich zooplankton abundance to reduce northeast Pacific fish energy content and recruitment, these concerns gain additional urgency.

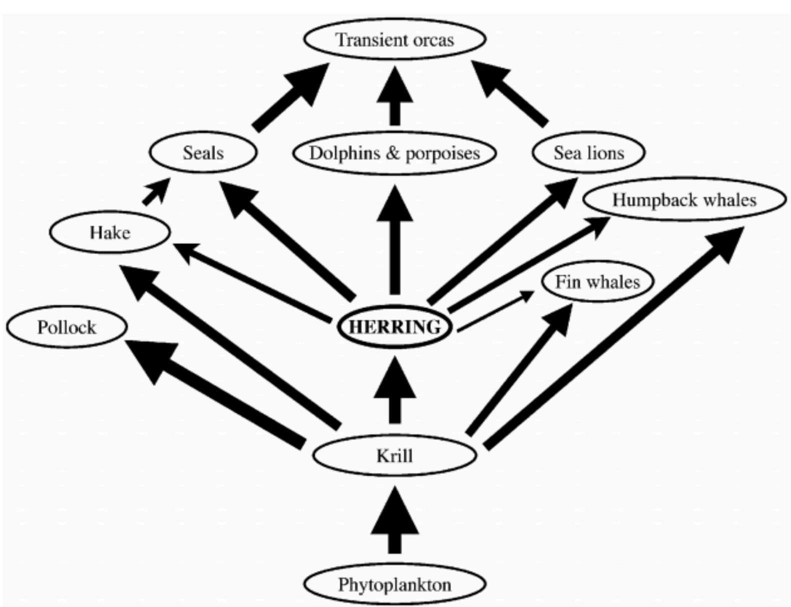
Surma, S., Pakhomov, E.A., Pitcher, T.J. (2018). Energy-based ecosystem modelling illuminates the ecological role of Northeast Pacific herring. *Marine Ecology Progress Series, 588*, 147-161.

7.1.3 Herring supports Northeast Pacific predators and fisheries: Insights from ecosystem modelling and management strategy evaluation

Researchers analyzed the trophic role of Pacific herring, the potential consequences of depletion, and the impacts of alternative herring fishing strategies on a Northeast Pacific food web in relation to precautionary, ecosystem-based management.

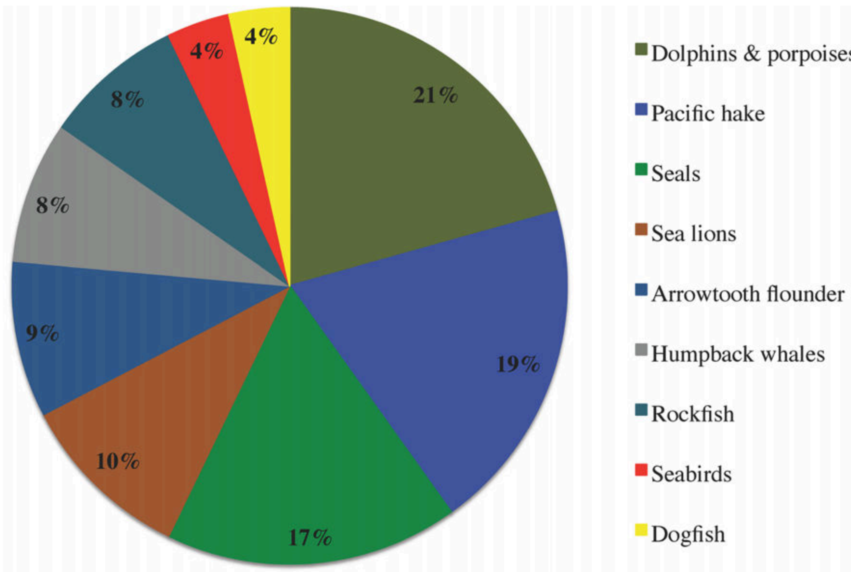
Contrary to a single-species framework, ecosystem-modelling places forage fish (e.g. Pacific herring) in the context of the entire food web, from their prey (zooplankton) to their predators (seabirds, marine mammals, larger fish) and fisheries. Simulation models showed that herring stock collapse would have cascading impacts on much of the pelagic food web. Mammalian predators whose diets contain 20% herring (humpback whales, dolphins and porpoises, seals) declined strongly, reducing the biomass of mammal-eating transient orcas. By contrast, largely planktivorous fish (walleye pollock, Pacific Ocean perch, and rockfish) and baleen whales (blue, fin and sei whales) benefited from reduced competition with herring for shared zooplankton prey, triggering increases in predators of planktivorous fish (dogfish, sperm whales, resident orcas, blue and salmon sharks). Simulation results indicate that herring play an important role in the Northeast Pacific food web as both *prey* to predators and *competitors* to planktivores. Effects of herring collapse in the Northeast Pacific would likely cascade through much of the food web to yield an ecosystem composition similar to that currently present in western Alaska, where forage fish and their pinniped predators have declined while walleye pollock have flourished following an oceanic regime shift.

Evaluation of management strategies indicate that herring and their predators suffer moderate impacts from the existing British Columbia harvest control rule, although more precautionary management strategies (i.e., low fishing mortality rates, high biomass limits) could substantially reduce these impacts. The traditional spawn-on-kelp fishery (non-capture) practiced by Alaskan Indigenous peoples was found to have extremely limited ecological impacts. Simulations also suggest that adopting a maximum sustainable yield management strategy in Northeast Pacific herring fisheries could generate strong, cascading food web effects. Climate shifts producing poor primary productivity, especially when combined with herring stock assessment errors, could strongly reduce the biomasses and resilience of herring and its predators.



Simplified diagram showing the major trophic interactions involving herring in the modelled food web. Arrow thickness is proportional to biomass flux between functional groups (Surma *et al.,* 2018).

Proportions of total herring consumption by predators attributable to each predator



Surma, S., Pitcher, T.J., Kumar, R., Varkey, D., Pakhomov, E.A,. Lam, M.E. (2018). Herring supports Northeast Pacific predators and fisheries: Insights from ecosystem modelling and management strategy evaluation. *PLoS ONE, 13*(11).

7.1.4 *Pacific herring* (Clupea pallasii) *as a key forage fish in the southeastern Gulf of Alaska*

Surma et al. examined whether Pacific herring act as a key forage fish in marine ecosystems in the Gulf of Alaska. The authors analyzed the trophic role of herring through mass-balanced and energy-balanced ecosystem modeling. In the mass-balanced models, herring did not meet the Supportive Role of Fishery (SURF) index, which quantifies predator dependence on forage fish. In the energy-balanced models, one model parameterized with extremely high herring energy content values and classified herring as a key forage fish given their high energy content. The results indicate that herring depletion and collapse has a strong negative impact on predators like humpback whales, minke whales, and inshore rockfish. The researchers conclude that while herring may not universally qualify as a key forage fish, the findings support precautionary ecosystem-based management of Pacific herring fisheries.

Surma, S., Pakhomov, E. A., & Pitcher, T. J. (2022). Pacific herring (*Clupea pallasii*) as a key forage fish in the southeastern Gulf of Alaska. *Deep-Sea Research Part II:*

Topical Studies in Oceanography, *187*, 105001. https://doi.org/10.1016/j.dsr2.2021.105001

7.1.5 Trade-offs and uncertainties in the northeast Pacific herring fisheries: Ecosystem modelling and management strategy evaluation

Surma et al. examined the ecological and socioeconomic impacts of northeast Pacific herring fisheries management strategies. Through mass-balanced ecosystem modeling, the results demonstrate a notable tradeoff between stable herring catches and high biomasses of herring and several predators. The authors recommend a precautionary strategy for forage fish to balance ecosystem benefits and socioeconomic costs. The findings highlight the importance of understanding and accounting for uncertainties and risk when developing and implementing fisheries management strategies for herring. Additionally, the findings indicate that relying on survey data from 1951 will at best maintain already depleted stocks, whereas considering “shifting baselines” would be optimal for ecosystem restoration.

Surma, S., Pitcher, T. J., & Pakhomov, E. A. (2021). Trade-offs and uncertainties in northeast Pacific herring fisheries: Ecosystem modelling and management strategy evaluation. *ICES Journal of Marine Science*, *78*(7), 2466-2479. https://doi.org/10.1093/icesjms/fsab125

7.1.6 Predicting the effects of whale population recovery on Northeast Pacific food webs and fisheries: An ecosystem modelling approach

Surma and Pitcher investigated the potential effects of the recovery of depleted large cetacean populations on northeast Pacific ecosystems and fisheries through ecosystem modeling. The authors used surplus production models based on historical whaling catch records to reconstruct the populations of blue, fin, sei, humpback, and sperm whales in the waters surrounding Haida Gwaii, and found that the population levels were significantly higher before the onset of whaling. Based on the models, abundant whale populations would consume large proportions of the annual production of their principal prey, ranging up to 88% for Pacific herring and 72% for piscivorous rockfish. The results support the hypothesis that humpback recovery could be reducing herring biomasses in some areas, but whale recovery is unlikely the sole or even major cause of the herring stock declines. The authors suggest that the demands of recovering whale populations warrant the introduction of an ecosystem-based management approach, such as the use of ecosystem-based harvest control rules for forage fish fisheries to facilitate whale recovery.

Surma, S., & Pitcher, T. J. (2015). Predicting the effects of whale population recovery on Northeast Pacific food webs and fisheries: An ecosystem modelling approach. *Fisheries Oceanography*, *24*(4), 291–305. https://doi.org/10.1111/fog.12109

7.1.7 Seasonal and spatial dynamics of the planktonic trophic biomarkers in the Strait of Georgia (northeast Pacific) and implications for fish

Costalago et al. used a combination of fatty acid and stable isotope analyses to examine the trophic pathways and nutritional quality of the plankton community in the Strait of Georgia. The results show seasonality as a driver for variability in plankton fatty acid composition. In the spring, the plankton food web is supported by diatom production. In the summer, a rise of flagellate abundances increases the proportion of docosahexaenoic acid (DHA), an important fatty acid for fish growth and development. This change translates to zooplankton with higher nutritional value in the summer compared to spring. Spatially, the southern region of the Strait of Georgia displayed higher levels of DHA in zooplankton compared to the central and northern regions. This suggests the southern region may provide better quality prey for juvenile salmon and herring. When comparing zooplankton species, only a few taxa (e.g. fish larvae, copepod *Paraeuchaeta elongata*) had optimal fatty acids for juvenile salmon and herring. The results elucidate the variable mechanisms in plankton nutritional quality and must be considered when evaluating the growth and survival of higher trophic level consumers in this productive coastal ecosystem.

Costalago, D., Forster, I., Nemcek, N., Neville, C., Perry, R., Young, K., & Hunt, B. V. (2020). Seasonal and spatial dynamics of the planktonic trophic biomarkers in the Strait of Georgia (northeast Pacific) and implications for fish. *Scientific Reports*, *10*, 8517. https://doi.org/10.1038/s41598-020-65557-1

8 Climate Change Vulnerability

8.1.1 Simulated herring growth responses in the Northeastern Pacific to historic temperature and zooplankton conditions generated by the 3-dimensional NEMURO nutrient–phytoplankton–zooplankton model

Rose et al. used northern Pacific nutrient–phytoplankton–zooplankton modelling data as input to a Pacific herring bioenergetics model and predict herring weights-at-age and growth from 1948 to 2000 for the west coast Vancouver Island (WCVI), Prince William Sound (PWS), and Bering Sea (BS) locations. Herring growth rates, annual temperature, and zooplankton density time series were analyzed statistically for coincident shifts in their mean values. Herring growth rates were also simulated using the 1948–2000 time series and averaged (climatological) temperature and zooplankton densities to determine the relative importance of temperature and zooplankton to predicted herring growth responses. All three locations showed a shift in herring growth during the mid and late 1970s. Herring growth decreased in WCVI and PWS, and increased in BS; these changes coincided with a warming of temperature and a decrease in predatory zooplankton density. Herring growth responses in PWS and BS were more complex than those predicted for WCVI, with additional shifts predicted besides the late 1970s shift. Interannual variation in zooplankton densities caused the herring growth response for WCVI. Temperature and zooplankton densities affected the herring growth responses in both Alaskan locations, with zooplankton dominating the response for PWS and temperature dominating the response for BS. Understanding regime shift effects on fish is critical to their proper management, yet unraveling the influence of climate on fishes is a challenging task. The difficulties in using simulation to detect and explain regime shifts are discussed. The authors were optimistic that advances in data collection methods and modeling capabilities, and the formation of the necessary collaborative networks of scientists, are steadily approaching the point when we can soon generate realistic forecasts of climate effects on fish population dynamics.

Rose, K.A., Werner, F.E., Mergrey, B.A. Aita, M.N. (2007). Simulated herring growth responses in the Northeastern Pacific to historic temperature and zooplankton conditions generated by the 3-dimensional NEMURO nutrient–phytoplankton–zooplankton model. *Ecological Modelling, 202*(1), 184-195

8.1.2 Impacts of climate and climate change on the key species in the fisheries in the North Pacific

This is the first report by an international group of experts that looks at the impact of climate change on key species in the fisheries in the North Pacific. For each of the six PICES member countries, summaries are provided for key fisheries species. The following is a summary for Pacific herring.

Pacific herring traditionally have been a major fishery on Canada's Pacific coast. The current fishery removes between 30,000 and 40,000 tonnes annually, but fisheries in the late 1950s and early 1960s had annual landings exceeding 200,000 tonnes. There was a change in climate in the 1960s and herring recruitment declined suddenly. Unfortunately, the reduced recruitment was not detected and the population was severely overfished. After the fishery was closed in 1967, stocks recovered relatively quickly and fishing commenced in the 1970s. The lesson learned was that climate and ocean conditions can have profound impacts on the recruitment and abundance trends. Another lesson is that Pacific herring appear to be responsive to short-term, climate-related variability. Presently, the abundance trends of Pacific herring are closely associated with climate-related changes in the ocean habitat. The dominant mode of variability may be the El Niño–Southern Oscillation (ENSO)-scale rather than the regime scale. Pacific herring populations are generally healthy with the population in the Strait of Georgia at historic high levels. Off the west coast of Vancouver Island, the abundance of herring is affected by predation from Pacific hake. Global warming is expected to increase the numbers of Pacific hake that move north into the feeding areas off Vancouver Island which will increase the natural mortality of Pacific herring and reduce their abundance. Because Pacific herring are dependent on nearshore habitats for spawning, sea level rise and increased storminess would be expected to affect the dynamics of herring populations. Temperature, salinity and ocean circulation patterns are influential in the survival of Pacific herring eggs and larvae. Pacific herring stocks over the next 50 years are expected to continue to fluctuate in abundance as they have in the past 25 years.

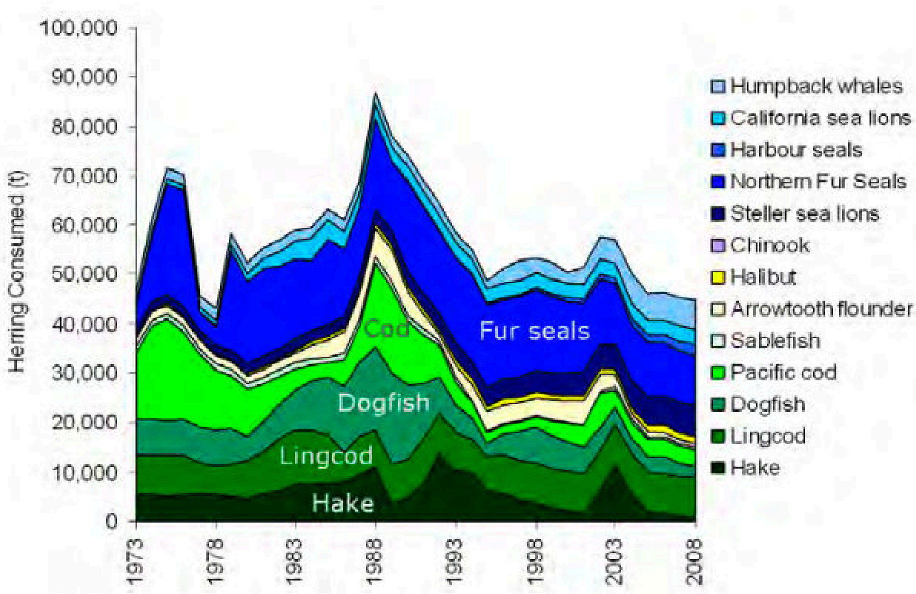
North Pacific Marine Science Organization (PICES), PICES Working Group on Climate Change, Shifts in Fish Production, and Fisheries Management. (2008). Impacts of climate and climate change on the key species in the fisheries in the North Pacific. (PICES Scientific Report No. 35). Retrieved from https://pices.int/publications/scientific_reports/Report35/Sci_Rep_35.pdf

8.1.3 A review of factors limiting recovery of Pacific herring stocks in Canada

Researchers investigated the effect of bottom-up forcing by zooplankton abundance, top-down forcing by fish and mammal predators, and the effects of sardine abundance as potential competitors on the natural mortality of the herring stock on the west coast of Vancouver Island. Herring mortality was positively related to *Thysanoessa spinifera* and southern chaetognaths and negatively to pteropod abundance. Estimated predation on herring decreased significantly during the years 1973–2008, with the main consumers changing from fish to mammals in 1995 caused by decreased fish biomass and an increase in the abundance of some marine mammals. However, the correlation with herring mortality was negative, whereas there was a significant positive relationship with sardine abundance. The dynamics of population recovery are likely species- and ecosystem-specific. Despite the WCVI being the best-studied area of the B.C. coast, it was extremely difficult to synthesize the information available on even the major predators. Top-down effects require further research and better data. Any large-scale changes in the ecosystem may present a stressor on the niche of the target population. In this case, the large increases in Pacific sardine since the early 1990s and their seasonal occupation of the WCVI could have a profound effect on herring as a potential competitor for food, as well as an attractor of predators that may supersede its role as a buffer against predation. Population recovery is expected to be facilitated by a combination of factors, including adequate food supply, limited or reduced predation (including fishing), and limited competition, where different forage species may occupy similar niches.

PICES Working Group on Forecasting Climate Change Impacts on Fish and Shellfish Scientific Report No. 45 (2013) references the following figure from Schweigert et al. (2010), stating that “the figure illustrates the intense, temporally variable predation pressure experienced by herring and is used as an example of the importance of examining multiple processes in light of climate driven changes in systems and impacts on key species.”

Estimates of the biomass of Pacific herring consumed by 13 different piscivorous fish and marine mammals (Schweigert *et al.,* 2010).



Schweigert, J.F., Boldt, J.L., Flostrand, L. and Cleary, J.S. (2010). A review of factors limiting recovery of Pacific herring stocks in Canada. *ICES Journal of Marine Science, 67*, 1903-1913.

8.1.4 Herring Aid: Can new ecosystem-based science save the herring?

In this 2017 presentation, Dr. Pitcher asked three questions: (1) Does fishing herring affect the rest of the ecosystem? (2) What impacts could climate change have on our herring populations? and (3) Do herring go home to spawn? He talks about the history of the B.C. herring fishery based on newly published data from the 1950s onward, largely from the Russian fleet. In the 50s and 60s, countries only had a twelve nautical mile territorial border that other countries could approach to fish and sometimes enter. By 2017, those zones had expanded to 200 nautical miles. Since fishery records began in 1888 and into the 1900s, fishers caught an abundance of herring in Burrard Inlet and sold the fish dry salted products. Catches progressively decreased. By 1950, Canadians reported that foreign fleets were entering Canada's territorial borders unofficially to illegally fish. The total catch reported peaked to half a million tons; this is more than twice the figure recorded by the Canadian government. The fishery collapsed. In 1968, the Canadian government closed the herring fishery for at least four years. It reopened as the reduction fishery. In the early 1970s, the roe fishery opened to supply eggs to Japan.

Pitcher discussed one of DFO's stocks: the Haida Gwaii herring fishery, which has been closed for a number of years. The current DFO stock assessment only takes into account egg production and is based on a single species. Current assessments ignore the food of herring and the herring eaters. Two feeding methods are ignored: herring bite food and filter feeding. Finally, the herring diet varies with location and time.

Pitcher developed an ecosystem-based simulation model for Haida Gwaii which incorporated the varying amount of phytoplankton in the water over time, three different types of herring fisheries with fishing thresholds and rates, and food web models. When run, the model shows the changes in biomass (impacts) to 78 species groups. Dr. Pitcher explained that when the model is run with the current DFO fishery policy with the 25% cut off and 20% fishing rate, the fishery is reasonably precautionary, especially when compared to maximum sustainable yield models used in Europe. However, when climate change is considered in the model, the current DFO policy leads to significant risk to the biomass of a number of species groups including herring. The problem with the current fishing policy is not that it's not precautionary on average, but that it is not precautionary in terms of hedging the risks to climate change.

Pitcher addressed the question of whether herring go home to spawn. Pitcher used otoliths (fish inner ear bone) to determine distinct populations of herring by analyzing the chemical elements in the growth layers of the ear bone. Pitcher's study found differences between the centre of the bone, which developed where they were born, and the outer layers. Herring stocks can be distinguished from only ten kilometres away. Preliminary data suggests there are small stocklets in B.C. herring. This is important to management, because if the fishing quota is concentrated to a relatively small area, if those fish are genetically distinct, you could wipe out that population.

Pitcher concluded that fishing herring does affect the rest of the ecosystem, but its impact can be hedged. Climate change could have serious impacts on herring populations. Herring do go home to spawn and that must be considered in management.

Pitcher, T.J. (2017, November 30). *Herring Aid: Can new ecosystem-based science save the herring?* [Video file]. Hornby Island Herring School. Retrieved from https://youtu.be/7c09djpvFBw

*8.1.5 Interactive effects of ocean acidification and ocean warming on Pacific herring (*Clupea pallasi*) early life stages*

While adult fish are effective acid-base regulators, early life stages may be more susceptible to environmental stressors. The combined impacts of ocean acidification and ocean warming on Pacific herring embryos are explored. Embryos were incubated under two temperatures (10°C and 16°C) and two ocean acidification levels (measures as partial pressure of CO_2: pCO_2 600 µatm, 1200 µatm) from fertilization to hatch. Elevated *p*CO2 was associated with a small increase in embryo mortality. However, elevated temperature was associated with greater embryo mortality, greater embryo heart rates and yolk areas upon hatch, lower percent normal hatch, and decreased larval lengths. The interaction of elevated temperature and *p*CO2 was associated with greater embryo respiration rates and yolk areas. This study indicates that temperature will likely be the primary global change stressor affecting Pacific herring embryology, and interactive effects with *p*CO2 may introduce additional challenges.

Vallalobos, C. (2018). Interactive effects of ocean acidification and ocean warming on Pacific herring (*Clupea pallasi*) early life stages (Master's thesis). WWU Graduate School Collection. 755. https://cedar.wwu.edu/wwuet/755

Also see:
https://www.eopugetsound.org/articles/climate-change-and-ocean-acidification-may-affect-herring-development

*8.1.6 Variability of Pacific herring (*Clupea pallasii*) spawn abundance under climate change off the West Coast of Canada over the past six decades*

Nonlinear relationships between herring spawn abundance and environmental variables were explored for four major spawning regions in B.C. (the Prince Rupert District, Haida Gwaii, the Central Coast, and the west coast of Vancouver Island). Specifically the relationships between herring spawn abundance and two indices of Pacific Ocean basin-scale variability (the PDO: Pacific Decadal Oscillation; and the NPGO: North Pacific Gyre Oscillation) and regional scale wind-stress off the B.C. coast were modelled. Study results found a "bowl-shaped" relationship between herring spawn abundance and two environmental variables (the PDO and NPGO) across all spawning regions and a "dome-shaped" relationship between spawn abundance and upwelling-favourable wind-stress, the latter indicating that there is an optimal range of wind stress values that favour herring spawn abundance. Results also suggest that, in Haida Gwaii, herring spawn abundance has been primarily governed by the NPGO and downwelling-favourable alongshore wind-stress; in contrast, the PDO and upwelling-favourable alongshore wind-stress are top contributors to spawn fluctuations in all other regions. These results help facilitate our understanding of how changes in physical environmental conditions affect herring spawn abundance as well as subsequent population dynamics.

Xu, Y., Fu, C., Peña, A., Hourston, R., Thomson, R., Robinson, C., Cleary, J., Daniel, K., & Thompson, M. (2019). Variability of Pacific herring (*Clupea pallasii*) spawn abundance under climate change off the West Coast of Canada over the past six decades. *Journal of Marine Systems, 200*.

8.1.7 The combined effects of acidification and acute warming on the embryos of Pacific herring

Singh et al. examined the effects of temperature and ocean acidification on Pacific herring embryos from different spawning populations. The researchers collected embryos from winter-spawning (Port Gamble) and spring-spawning (Cherry Point) Pacific herring populations and exposed them to a range of temperatures and carbon dioxide levels to assess survival, metabolism, and cardiac function. Researchers found that embryos could withstand up to 20°C but their survival was greatly reduced after two to three hours at 25°C. Elevated pCO2 had limited effects on critical thermal tolerance, but did reduce survival as it interacted with higher temperatures (beyond 16°C). Elevated temperatures and pCO2 levels increased oxygen consumption rates and therefore metabolic demand. Embryos displayed some acclimation at higher incubation temperatures and there are clear differences in thermal tolerance between those from winter- and spring-spawning embryos. Overall, the embryos demonstrate tolerance of ocean acidification, but vulnerability to acute temperature stress. The study provides valuable insights into the environmental tolerances and vulnerabilities that Pacific herring face under increasingly frequent marine heat waves caused by climate change.

Singh, N. R., Love, B., Murray, C. S., Sobocinski, K. L., & Cooper, W. J. (2023). The combined effects of acidification and acute warming on the embryos of Pacific herring (*Clupea pallasii*). *Frontiers in Marine Science*, *10*, Article 1307617. https://doi.org/10.3389/fmars.2023.1307617

8.1.8 Temporal, environmental, and demographic correlates of Ichthyophonus sp. *infections in mature Pacific herring populations*

Groner et al. analyzed infection patterns of the pathogen *Ichthyophonus sp*. on Pacific herring between 2007–2019 by comparing infection rates between a collapsed population in Prince William Sound and a more stable population in Sitka Sound. The results show that the infection rates of the collapsed population were 54% higher than in the robust population. Based on several demographic, environmental, and statistical analyses connecting factors like herring age and environmental change, the study indicated that older herring are more likely to exhibit infections. Additionally, the results show a negative correlation between Pacific Decadal Oscillation values and infection prevalence. These results suggest that warmer ocean conditions impact the severity and transmission of the infections. Although more research is needed to clarify the interaction between disease dynamics and population health in forage fish, the paper highlights the necessity of integrating diverse data types to understand epidemiological trends affecting forage fish. The authors recommend that these variables and mechanisms be integrated into new management strategies for herring stocks, particularly in the context of climate change.

Groner, M. L., Bravo-Mendosa, E. D., MacKenzie, A. H., Gregg, J. L., Conway, C. M., Trochta, J. T., & Hershberger, P. K. (2023). Temporal, environmental, and demographic correlates of *Ichthyophonus* sp. infections in mature Pacific herring populations. *ICES Journal of Marine Science*, *80*(9), 2342–2355. https://doi.org/10.1093/icesjms/fsad147

8.1.9 Fishing, predation, and temperate drive herring decline in a large marine ecosystem

Boyce et al. conducted a time-series data analysis on the physical, ecological, and anthropogenic factors affecting Atlantic herring of the Scotian Shelf–Bay of Fundy in Canada. The results identify exploitation by fisheries as a primary driver for variability in herring spawning stock biomass. Predation by haddock had a positive effect on herring recruitment by mitigating density-dependent resource limitations. Water temperature had a negative effect on early life-stage survival and recruitment. The results emphasize the importance of considering diverse ecosystem and climate factors in managing forage fish. Although specifics relating to Pacific herring would differ to Atlantic herring, the study highlights the value of a multivariate approach in understanding the complex interactions between biological, physical, and anthropogenic drivers of population dynamics. These considerations may be relevant for the management of Pacific herring fisheries.

Boyce, D. G., Petrie, B., & Frank, K. T. (2021). Fishing, predation, and temperature drive herring decline in a large marine ecosystem. *Ecology and Evolution*, *11*(1), 1–12. https://doi.org/10.1002/ece3.8411

*8.1.10 Effects of elevated pCO2 on bioenergetics and disease susceptibility in Pacific herring (*Clupea pallasii*)*

Murray et al. reared herring from hatching under ambient, intermediate, and high CO2 partial pressures to examine how ocean acidification can impact mortality rates. The results showed that elevated CO2 did not impact larval growth or energy. While ambient and intermediate concentrations did not increase mortality from VHS, high pCO2 treatments did increase mortality. Furthermore, survivors from the high pCO2 treatment exhibited a lower condition factor, suggesting long-term health consequences such as metabolic dysfunction and impaired immunity. These results highlight serious implications for the health of Pacific herring under ocean acidification and its effect on pathogen interactions. While moderate increases in pCO2 may not directly hinder development, extreme acidification could pose significant risks to Pacific herring health and exacerbate disease outbreaks in coastal ecosystems. The research emphasizes the necessity for ongoing studies on how environmental change affects immune responses during critical life stages.

Murray, C. S., Gregg, J. L., Mackenzie, A. H., Jayasekera, H. T., Hall, S., Klinger, T., & Hershberger, P. K. (2024). Effects of elevated pCO2 on bioenergetics and disease susceptibility in Pacific herring (*Clupea pallasii*). *Marine Ecology Progress Series*, *738*, 225–242. https://doi.org/10.3354/meps14607

*8.1.11 The effects of ocean acidification and temperature rise on the thermal tolerance and critical thermal limit of Pacific herring (*Clupea pallasii*)*

Singh investigated the effects of ocean acidification and temperature rise on the critical thermal limit of Pacific herring by exposing Pacific herring embryos to varying levels of pCO2 (ambient and high) and temperatures (10–16°C).The results show a negative correlation between temperature and hatching success, and a positive correlation between temperature and larval deformities. While pCO2 did not impact hatching success or larval deformities, oxygen consumption rates were positively correlated for both pCO2 concentrations and temperature. Survival during critical thermal maximum trials declined for both winter- and spring-spawning populations at temperatures above 20°C. Heart rate measurements during the critical thermal maximum trials showed more respiratory acclimation for those reared at higher temperatures. Overall, results show that Pacific herring embryos have some resilience to moderate pCO2 and temperature stress, but they are vulnerable to acute temperature increase and this may be exacerbated by interactions with elevated pCO2. Additional research is needed to factor climate change into herring management strategies.

Singh, N. R. (2022). The effects of ocean acidification and temperature rise on the thermal tolerance and critical thermal limit of Pacific herring (*Clupea pallasii*). *WWU Graduate School Collection*, 1134. https://cedar.wwu.edu/wwuet/1134

*8.1.12 Ocean acidification and ocean warming effects on Pacific herring (*Clupea pallasii*) early life stages*

Villalobos et al. evaluated the combined effects of elevated temperatures and ocean acidity in early life-stage Pacific herring by incubating Pacific herring embryos at two temperatures (10°C or 16°C) and two pCO2 treatments (600 µatm or 1200 µatm). Elevated temperatures decreased hatching success by 22% and increased embryo mortality rates from 16% to 42%. Elevated temperatures reared embryos with larger yolk areas and smaller larvae at hatch. Elevated pCO2 combined with elevated temperatures reared embryos with higher heart rates, but pCO2 alone did not impact the embryos in a significant way. Overall, the study indicates that while ocean acidification may not have a major direct effect on Pacific herring early life stages, the combined stressors do exacerbate significant physiological challenges and could have major consequences at population-level for forage fish communities.

Villalobos, C., Love, B. A., & Olson, M. B. (2020). Ocean acidification and ocean warming effects on Pacific herring (*Clupea pallasii*) early life stages. *Frontiers in Marine Science*, *7*, 597899. https://doi.org/10.3389/fmars.2020.597899

8.1.13 Accounting for direct and indirect cumulative effects of anthropogenic pressures on salmon- and herring-linked land and ocean ecosystems

Vivitskaia et al. quantified and compared the cumulative effect of human-driven pressures on interconnected species in salmon and herring-linked ecosystems through risk assessment in western Canada. The findings reveal that indirect risks account for a 68% increase of total risk for land species and 15% total risk increase for marine species. Climate change pressures were identified as the primary contributor for heightened risks in low trophic level marine species (like herring). The results highlight the complexities of ecosystem change and underscore the necessity of considering both direct and indirect human impacts on ecosystem resilience. Further, sensitivity analyses revealed a positive correlation between the number of species linkages and overall risk. The successful management of keystone species, like the Pacific herring, is critical for reducing ecosystem risks. These findings are valuable for defining the foundational role that herring play in maintaining ecosystem structure and function. Herring management is ecosystem management. The authors recommend that future research explore the linkages between ecosystem resilience factors and keystone species health to improve management strategies.

Vivitskaia, J. D., Adams, M. S., Martin, T. G., Tulloch, A. I. T., Martone, R., Avery-Gomm, S., & Murray, C. C. (2022). Accounting for direct and indirect cumulative effects of anthropogenic pressures on salmon- and herring-linked land and ocean ecosystems. *Philosophical Transactions of the Royal Society B: Biological Sciences, 377*, 20210130. https://doi.org/10.1098/rstb.2021.0130

8.1.14 Disentangling abiotic and biotic controls of age-0 Pacific herring population stability across the San Francisco Estuary

Pak et al. investigated the driver of age-0 Pacific herring population dynamics in the San Francisco Estuary over a 35 year period. The researchers used a combination of wavelet analyses, multivariate autoregressive state-space models, and portfolio effect analyses to identify the abiotic and biotic factors that affect population stability and spatial structure. Their results revealed that temperature, but not salinity, fluctuated synchronously across regions, while the multivariate model highlighted strong regional population structures and varying responses to environmental factors. Generally, age-0 herring were associated with cooler and saltier conditions in the spring and fluctuations in abundance were more stable across the entire estuary than in individual regions. It is recommended that ecosystem-based fisheries management strategies include eelgrass and tidal marsh restoration measures to stabilize herring populations by increasing the estuary's carrying capacity. These findings underscore the importance of understanding spatiotemporal variability in environmental conditions and population responses, particularly in the face of climate change. Management strategies must consider ecosystems as a whole to sustain the health of herring populations.

Pak, N., Colombano, D. D., Greiner, T., Hobbs, J. A., Carlson, S. M., & Ruhi, A. (2023). Disentangling abiotic and biotic controls of age-0 Pacific herring population stability across the San Francisco Estuary. *Ecosphere*. https://doi.org/10.1002/ecs2.4440

8.1.15 *Evaluating factors affecting the distribution and timing of Pacific herring (*Clupea pallasii*) spawn in British Columbia.*

Rooper et al. examined 31 years of spawning data to investigate factors influencing the temporal and spatial distribution of Pacific herring spawning in British Columbia. The researchers found that the timing of spawning was influenced by the number of daylight hours exceeding 10.5 hours, cumulative degree days surpassing 100°C, and salinity levels around 30.5. Spatial distribution was consistent over time and the probability of spawning in a particular transect was determined by the biomass of herring and its location relative to the centre of spawning. Environmental factors that varied at individual transects played a smaller role in determining spawn distribution. During years of high biomass, herring stocks, such as those in Haida Gwaii, showed no expansion of the spawning area. These variables are valuable to consider when evaluating the impacts of climate change on Pacific herring. Rooper et al. suggested that climate change-induced warming could lead to an earlier spawning event in the spring and cause a mismatch between larval hatch time and prey availability. This mismatch may reduce growth and survival of larval herring and affect recruitment to important herring stocks. These findings are an important reminder of impending impacts climate change poses to forage fish populations.

Rooper, C. N., Boldt, J. L., Cleary, J., Peña, M. A., Thompson, M., & Grinnell, M. (2023). Evaluating factors affecting the distribution and timing of Pacific herring (*Clupea pallasii*) spawn in British Columbia. *Marine Ecology Progress Series*. https://doi.org/10.3354/meps14274

8.1.16 *Influence of environmental and population factors on Prince William Sound herring spawning phenology.*

Dias et al. investigated the various environmental and population level-factors influencing the spawn timing shifts of Pacific herring over a 27-year period (1980–2007) to better understand the implications for herring population recovery. Through data collected in Prince William Sound, the researchers identified 15 environmental and population-level covariates such as biomass, mean age, winds, and Pacific-North American teleconnection patterns. In particular, the results show significant shifts in the timing of herring spawning over the years. These findings were attributed to a combination of environmental factors like sea surface temperature, sea ice cover, and river discharge in tandem with population-level factors like herring biomass and density. It is suggested that earlier spawning may lead to mismatches with optimal environmental conditions for larval survival. Overall, the study underscores the complex interactions between environmental change, population dynamics, and spawning phenology. These findings are a valuable contribution to fisheries management strategies, which should aim to promote the resilience of herring populations in the face of climate change and environmental variability.

Dias, B. S., McGowan, D. W., Campbell, R., & Branch, T. A. (2022). Influence of environmental and population factors on Prince William Sound herring spawning phenology. *Marine Ecology Progress Series*. https://doi.org/10.3354/meps14133

8.1.17 Climate challenges for fish larvae: Interactive multi-stressor effects impair acclimation potential of Atlantic herring larvae.

Franke et al. investigated the impact of temperature increase and Vibrio exposure on herring larval microbiota composition and the subsequent implications for the decline in recruitment of western Baltic spring-spawning herring. The authors reared eggs and larvae at varying temperatures with exposure to *Vibrio alginolyticus* and *Vibrio anguillarum* and assessed mRNA and miRNA transcriptomes, microbiota composition, growth, and survival. High temperatures and Vibrio exposure separately led to downregulation of gene expression. Additionally, the combined stressors impaired the plasticity of gene expression, led to a significant shift in miRNA expression (affecting gene regulation) and significantly altered microbiota composition. These results highlight that a healthy microbiota in herring larvae can be destabilized by temperature stress and lead to decreases in microbial richness and diversity. These losses in microbiome richness and diversity present a challenge to larval growth, development, and immune response. Furthermore, the changes to gene expression suggests a lack of phenotypic plasticity and may present vulnerability in later larval stages. The authors recommend that future researchers assess herring sensitivity to climate change related stressors. They also suggest that management strategies consider larval stress thresholds for multiple climate change-related stressors as these limitations appear to impair recruitment.

Franke, A., Bayer, T., Clemmesen, C., Wendt, F., Lehmann, A., Roth, O., & Schneider, R. F. (2024). Climate challenges for fish larvae: Interactive multi-stressor effects impair acclimation potential of Atlantic herring larvae. *The Science of the Total Environment, 175659*. https://doi.org/10.1016/j.scitotenv.2024.175659

8.1.18 Future climate change and marine heatwaves: Projected impact on key habitats for herring reproduction.

Gröger et al. used climate projections from the Coupled Model Intercomparison Project to explore the impacts of marine heatwaves and changes in sea surface temperature in the western Baltic Sea region. Under the model, marine heat waves tripped from 34 days per year historically to 102 days/year under the 1.5 degree target of global climate warming. The results show that the Baltic Sea faces significant abiotic disturbances due to global warming and these changes may shorten the duration of winters and increase the risk for winter-spawning herring. In these scenarios, it is unclear how herring stocks would respond. It is suggested that beside changes in winter timing, thermal thresholds would challenge herring larvae growth rates and cardiac function. Furthermore, a cascading effect creating oxygen deficiencies and losses of vulnerable seagrasses could have combinatory effects. The authors emphasize that herring are particularly vulnerable to marine heatwaves and recommend that climate change be considered in ecosystem management.

Gröger, M., Borgel, F., Karsten, S., Meier, H. E. M., Safonova, K., Dutheil, C., Receveur, A., & Polte, P. (2024). Future climate change and marine heatwaves: Projected impact on key habitats for herring reproduction. *The Science of the Total Environment, 175756*. https://doi.org/10.1016/j.scitotenv.2024.175756

*8.1.19 Assessment of the southern Gulf of St. Lawrence (NAFO Division 4TV) spring and fall spawner components of Atlantic herring (*Clupea harengus*) with advice for the 2022 and 2023 fisheries*

Fisheries and Oceans Canada researchers assessed stocks of spring- and fall-spawning Atlantic herring in the southern Gulf of St Lawrence. The assessment highlights staggering declines in recruitment, largely attributed to environmental changes in temperature, dating back to 2006. As Atlantic herring have critically declined today, experts caution that recovery may not be possible without improvements in environmental conditions. It is currently a challenge to make accurate predictions without a strong ecological foundation and an understanding of dynamics in population trends, predator–prey relations, and environmental factors. In contrast, Pacific herring management strategies, particularly in climate change mitigation, may be implemented before it is too late. As populations of Pacific herring disappear from their traditional spawning grounds, the critical state of Atlantic herring populations should serve as an indicator for the need for precautionary management in the Pacific in preparation for temperature increases beyond biological thresholds.

DFO. (2022). *Assessment of the southern Gulf of St. Lawrence (NAFO Division 4TVn) spring and fall spawner components of Atlantic herring (Clupea harengus) with advice for the 2022 and 2023 fisheries* (DFO Can. Sci. Advis. Sec. Sci. Advis. Rep. 2022/021). Fisheries and Oceans Canada.

9 Additional Resources and Further Reading

9.1.1 Herring school

In the early 2000s, the Tula Foundation's Haikai Institute, a Canadian environmental charity and research organization, launched a multi-year herring research program. The research project was considered an interdisciplinary and cross-culture collaborative effort between researchers, multiple Indigenous communities, and various government and NGO sponsors. The project culminated in the completion of a digital archive of information, records, and Indigenous knowledge pertaining to B.C.'s Pacific herring. This archive was made public through a graphic website titled *Pacific herring: Past, present, future.* Simon Fraser University remains the custodian of the raw research records. At the time of publication (2025), the website was still active and contained detailed information under the structured headings and subheadings of:

Fact List

- Herring
- Ecology
- Distribution
- Numbers
- First Nations and Herring
- Industrial Fisheries
- Threats
- Management
- Governance
- Causes of Change
- The Hakai Herring School

Explore: Ecology and people

- Life cycle [graphic]
- Food web [graphic]
- Studies [graphic]
- Human interaction [graphic]

Stories: Listen to the people

***Special note: Video archive of interviews with coastal communities. Videos listed by title and author/interviewee. Subject matter varies [95 videos].*

Timeline: Past to present

***Special note: Digital graphic sliding timeline with photos and captions covering the herring fishery from the 1800s to late 2000s.*

Outlook: Future of herring

***Special note: Digital graphic page of researcher comments pertaining to the conservation of herring and concerns with herring management.*

Herring school. (2015). Pacific herring: Past, present, future [web archives]. Retrieved from: https://www.pacificherring.org/home

9.1.2 The economic value of Pacific herring in the Strait of Georgia [web log]

In 2019, Pacific Wild commissioned a report on the economic value of the commercial herring fishery. The resulting report concluded that the value of the fishery has continued to decline as a result of higher fishing costs, lower catches, and poor market values. The report contains information and graphs on the historical economic and current trends of the fishery.

Cashion, T. (2019). The economic value of Pacific herring in the Strait of Georgia [web log]. Victoria, B.C.: Pacific Wild. Retrieved from: https://pacificwild.org/the-economic-value-of-pacific-herring-in-the-strait-of-georgia/

9.1.3 Little fish, big impact: Managing a crucial link in ocean food webs

In 2012, the Lenfest Ocean Program and the Institute for Ocean Conservation Science produced a comprehensive and collaborative report on the importance of forage fish. While inclusive of but not specific to Pacific herring, the report covers a wide array of food web links between forage fish, fisheries management practices, and other marine species. It also advances a new complex scientific model for the assessment of forage fish sustainability. There are nine key findings pertaining to forage fish which result in the review team recommending certain fisheries management practices be amended:

1. "Forage fish abundance is highly variable and often unpredictable.
2. Forage fish are easily caught, even when their abundance decreases.
3. Forage fish populations are vulnerable to overfishing and collapse and do not always recover readily from depletion.
4. Globally, the economic value of forage fish as prey for other commercial fisheries is twice the value of forage fish as catch.
5. Predators highly dependent on forage fish (for 50 percent or more of their diet) are common, occurring in three-fourths of marine ecosystems we examined.
6. Predators dependent on forage fish in their diet are more sensitive to changes in forage fish abundance than are less-dependent species.

7. Conventional fisheries management targets and limits are not conservative enough to protect forage fish populations from collapse or to prevent impacts on other species.
8. Model simulations showed that forage fish populations and their dependent predators were reliably sustained when fishing pressure was half as high and forage fish biomass in the ocean was twice as large as traditionally practiced.
9. Temporal and spatial management will often be useful, and at times crucial, for managing the impact of forage fisheries on dependent predators." (pg. 84-87).

Pikitch, E.; et al. (2012). Little fish, big impact: Managing a crucial link in ocean food webs. Washington, DC: Lenfest Ocean Program. Retrieved from: https://www.lenfestocean.org/-/media/assets/extranets/lenfest/len_little_fish_big_impact.pdf

9.1.4 Food for all: Small fish with a big influence

The World Wildlife Foundation (WWF) produced a synthesized pamphlet style report on the importance of forage fish in 2016. Inclusive of herring, the pamphlet makes the general case that forage fish are vulnerable to overfishing and that forage fish are more valuable to marine ecosystems people if they are left in the water. The report includes economic and fisheries graphics. Three main points are contended, with additional references not cited here:

- "Forage fish abundances can fluctuate greatly from year to year because of changes in environmental conditions. Intense fishing can exacerbate the rate of decline (Essington et al., 2015).
- Even when their abundance decreases, forage fish remain easy to harvest as they aggregate in large shoals (Essington et al., 2015).
- Conventional management approaches do not account for the large natural fluctuations or the role forage fish play in marine ecosystems. (Pikitch et al., 2012)." (pg. 2).

World Wildlife Foundation (WWF). (2016). Food for all: Small fish with a big influence. Toronto, Canada: WWF. Retrieved from: http://awsassets.wwf.ca/downloads/food_for_all___small_fish_with_big_influence___wwf_forage_fish_report.pdf

9.1.5 Potential population-level impacts of future oil spills on Pacific herring stocks in Puget Sound

Spromberg et al. investigated the potential impacts of oil spills on Pacific herring populations in Puget Sound through a series of models accounting for a variety of environmental conditions, predation, and spatial dynamics among various stock populations. The authors found that early life stages, being spawned in shallow coastal waters where crude oils accumulate, are particularly susceptible to pollution from oil spills. Exposure can be both lethal and have chronic effects impacting survival rate during early life stages. The models show that current declining stocks of Pacific herring are particularly vulnerable to productivity losses and extinction risks following oil spill events (even small ones). It is suggested that the existing population modeling methods be improved by integrating our knowledge on oil toxicity with herring population demographics. Overall, the authors emphasize that oil spill-based population declines are a greater threat to declining populations. The paper calls for management strategies which act preemptively to account for future oil spill incidents.

Spromberg, J. A., Allan, S. E., & Scholz, N. L. (2024). Potential population-level impacts of future oil spills on Pacific herring stocks in Puget Sound. *Human and Ecological Risk Assessment: An International Journal*, *30*(1-2), 138–163. https://doi.org/10.1080/10807039.2023.2301529

9.1.6 *Assessing size-based exposure to microplastics and ingestion pathways in zooplankton and herring in a coastal pelagic ecosystem of British Columbia, Canada*

Mahara et al. investigated pathways of microplastic ingestion into the pelagic food web in British Columbia through the analysis of zooplankton and larval Pacific herring samples collected from Baynes Sound (March–September 2019). The researchers found that surface water contained an average of 0.59 microplastic particles per litre, zooplankton showed an average microplastic concentration of 0.0007 ind.-1, larval herring showed an average concentration of 0.0017 ind.-1, and juvenile herring showed an average microplastic concentration of 0.089 ind.-1. The results show that juvenile herring were more vulnerable to microplastic consumption due to the higher ratio of microplastic particles to potential food. It is valuable to understand these ingestion pathways as previous studies have indicated that microplastic ingestion could reduce growth in early fish stages. The authors recommend that further research investigates the ecological implications of these findings to enhance mitigation strategies toward plastic contamination of marine food webs. This research identifies an additional variable that may influence the marine survival of Pacific herring.

Mahara, N., Alava, J. J., Kowal, M., Grant, E., Boldt, J. L., Kwong, L. E., Hunt, B. P. V., & *et al.* (2022). Assessing size-based exposure to microplastics and ingestion pathways in zooplankton and herring in a coastal pelagic ecosystem of British Columbia, Canada. *Marine Ecology Progress Series*. https://doi.org/10.3354/meps13966

9.1.7 Biological responses of Pacific herring embryos to crude oil are quantifiable at exposure levels below conventional limits of quantitation for PAHs in water and tissues.

Incardona et al. investigated the impact of oil exposure on Pacific herring embryos with a focus on how water-soluble components of crude oil disrupt the physiological functions of embryonic herring hearts. The paper reveals that herring embryos are highly susceptible to toxicity from chemical leaching in intertidal and subtidal zones. These interactions trigger a disruption of the cardiomyocytes in the embryonic herring heart and, consequently, compromise juvenile heart structure, function, and overall fitness. These findings demonstrate that cyp1a gene expression serves as a more sensitive metric for oil exposure than typical PAH quantitative methods via GC-MS. These sensitivity metrics are important for understanding the risks of oil exposure on the development of marine organisms. These results support our understanding of how different anthropogenic variables impact the early life stages of Pacific herring.

Incardona, J. P., Linbo, T. L., Cameron, J. R., French, B. L., Bolton, J. L., Gregg, J. L., Donald, C. E., Hershberger, P. K., & Scholz, N. L. (2023). Biological responses of Pacific herring embryos to crude oil are quantifiable at exposure levels below conventional limits of quantitation for PAHs in water and tissues. *Environmental Science & Technology, 57*(19), 19214–19222. https://doi.org/10.1021/acs.est.3c03458

9.1.8 Behavioural responses of wild Pacific salmon and herring to boat noise

Van Der Knaap et al. examined the behavioural responses of wild Pacific herring and juvenile salmon to boat noise in the Broughton Archipelago, British Columbia. The authors conducted open-net pen experiments and used underwater cameras to continuously monitor fish school behaviour alongside generated boats traveling at various speeds. The researchers observed that both species exhibited anti-predator behaviors (e.g. tightening schools, increasing swimming speeds, diving downward) as a response to boat noise. The herring were quicker to respond to sounds of lower decibels compared to the salmon. The authors concluded that repeated exposure to boat noise would lead to increased energy expenditure and reduce foraging activity for both species. These findings emphasize that different anthropogenic inputs can have major population level consequences for the health of Pacific herring. Anthropogenic noise must be considered a variable in fisheries management and conservation efforts.

Van Der Knaap, I., Ashe, E., Hannay, D., Ghoul Bergman, A., Nielsen, K. A., Lo, C. F., & Williams, R. (2021). Behavioural responses of wild Pacific salmon and herring to boat noise. *Marine Pollution Bulletin, 174*, 113257. https://doi.org/10.1016/j.marpolbul.2021.113257

9.1.9 Behavioural responses of wild Pacific salmon and herring to boat noise

Surma et al., employed high-resolution trophic models to analyze the structure and function of the Haida Gwaii marine ecosystem in the northeastern Pacific. Using Ecopath with Ecosim, Surma et al. reconstruct ecosystem states from 1900, 1950, and the present, incorporating enhanced taxonomic and ecological resolution. The authors focus on Pacific herring as a keystone forage species, evaluating its trophodynamic role and the effects of fishing and environmental changes.

The findings indicate that the ecosystem has not undergone a radical structural shift since 1900, despite extensive exploitation of marine mammals and fish. Mixed trophic impact analysis reveals that herring plays a central role in the food web, interacting with numerous predators, prey, and competitors. Dynamic simulations demonstrate that fishing mortality, trophic interactions, and primary productivity (linked to the Pacific Decadal Oscillation) collectively drive ecosystem behaviour. The authors also suggest that certain herring, salmon, and groundfish stocks may have become partially decoupled from primary productivity due to changes in copepod composition. Furthermore, the results highlight biodiversity loss and evidence of "fishing down the food web" since 1950. Surma et al. provide a refined model for future ecosystem simulations, offering insights into the management of herring fisheries and broader ecological trends.