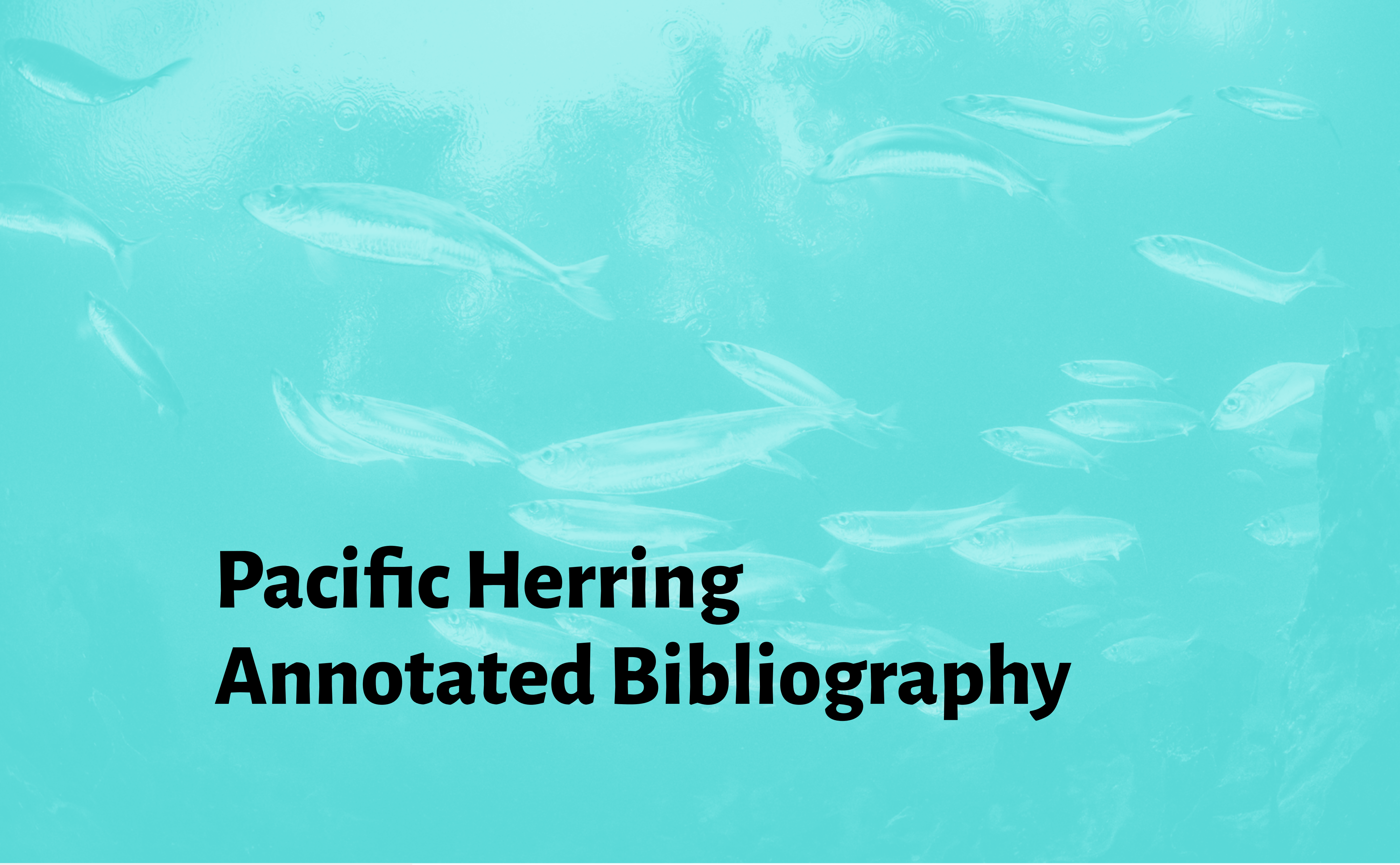

Pacific Herring Annotated Bibliography

PACIFIC**WILD**

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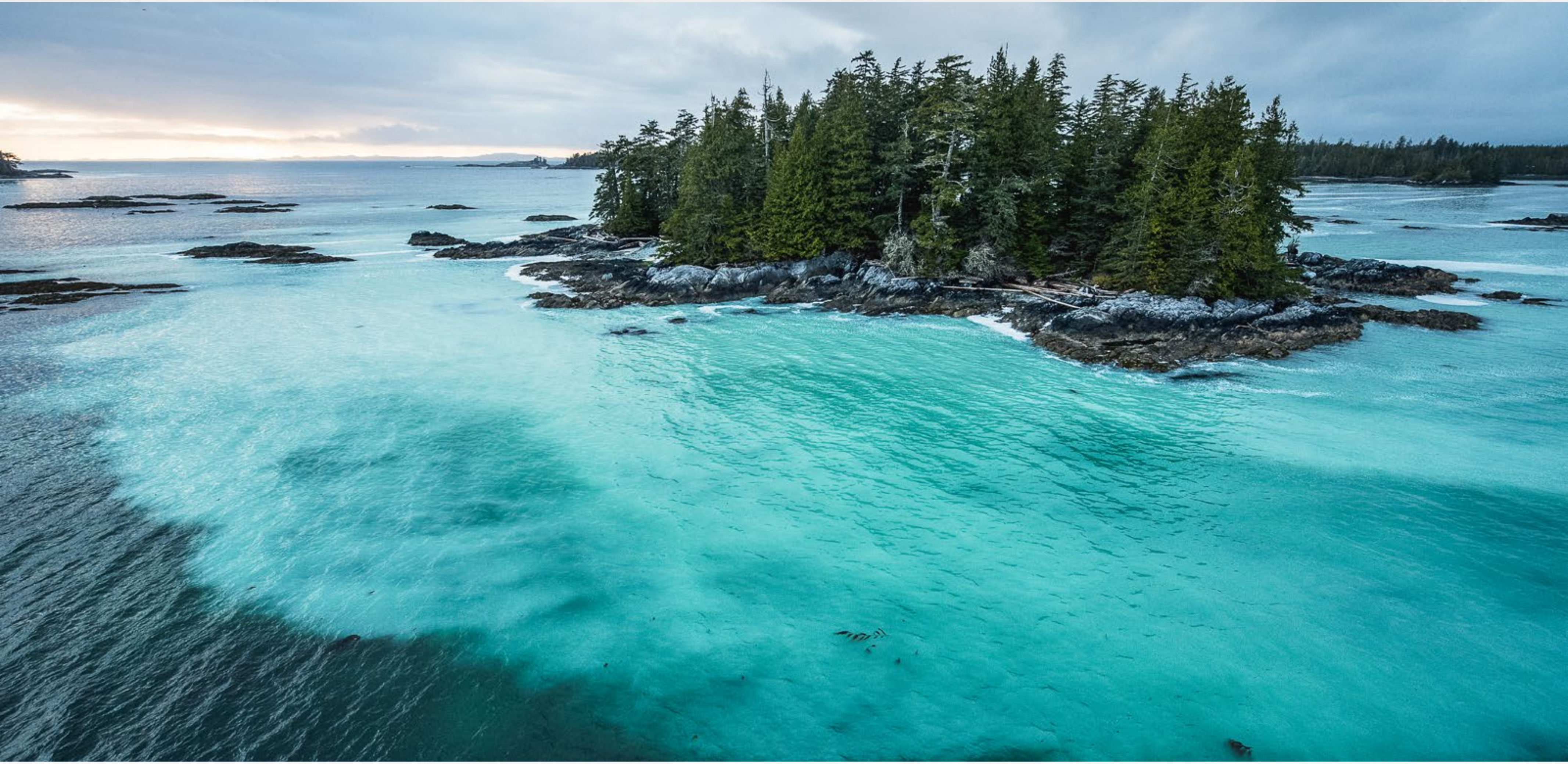
Note to the reader:

This annotated bibliography was compiled based on a file review in addition to a literature review and comprises a collection of references including research articles, records, and resources pertinent to Pacific herring. It is not an exhaustive inclusion of references or topics related to Pacific herring, in acknowledgment of financial and other limitations. However, this document provides a considerable collection of information as a concrete starting point, which can evolve and be expanded upon further.



Contents

1 Herring Biology: Reproduction, Growth, Survival and Behaviour

1.1 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

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.

This study researched maturation and fecundity of Pacific herring using experimental netpens. Fish were placed in the netpens 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 were 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.

1.1.2 Pacific and Atlantic Herring Produce Burst Pulse Sounds

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**

Sound production of Pacific herring is studied. Specifically, the sounds made by captive wild-caught herring are described. 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 regimes did not affect their frequency, and fish produced FRT sounds without direct access to 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 are greater and social mediation appears likely. These sounds may have consequences for our understanding of herring behaviour and the effects of noise pollution.

1.1.3 An Index of Relative Biomass, Abundance, and Condition of Juvenile Pacific Herring (Clupea pallasi) in the Strait of Georgia, British Columbia

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.

The purpose of this report was to update the time-series information based on the Strait of Georgia juvenile herring and the 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 represented 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.

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, 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.

This study 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, 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 3 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 BC 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.

2 Historic Abundance

2.1 Historic Abundance

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

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

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 single-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. Analyses 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, suggest that spawning locations were formerly more abundant and geographically extensive than is recorded by modern surveys.

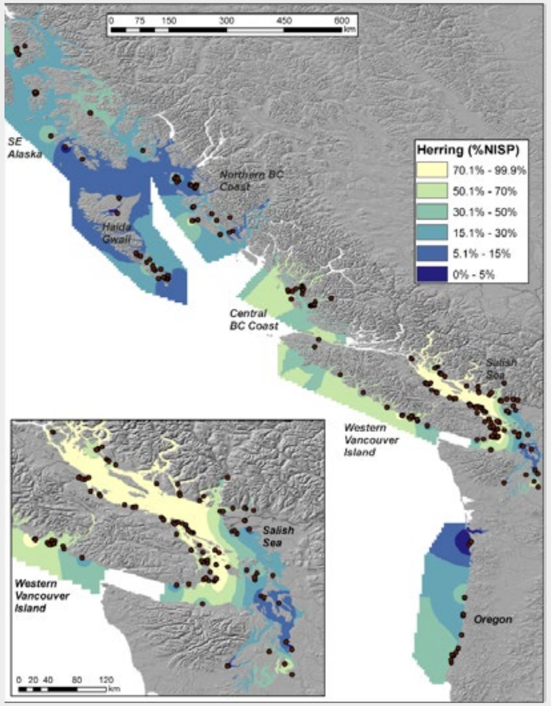
This data, particularly in the context of high harvest levels during the early industrial fishery and the subsequent contraction of effective spawning range, indicate that the current ecological baseline of the mid 20th century is inadequate for modern management. The findings support the idea that if past populations of Pacific herring exhibited substantial variability, then this variability was expressed around a high enough mean abundance such 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.

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

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

Archaeological fisheries data from coastal British Columbia and adjacent regions was examined over the late Holocene. Meta-analysis methods and GIS-based spatial visualizations were used 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 west coast of Vancouver Island regions. Moreover, herring occur consistently over time.



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).

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

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

Through kinship claims, the Heiltsuk Nation and other coastal Indigenous peoples 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 Aboriginal herring spawn fishery through precisely such a system. After overriding Aboriginal 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.

3.1.2 Central Coast Marine Plan Overview

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

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 members being 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, including 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.

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

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**

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 aren't 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 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 10 years was proposed as a more realistic limit reference point.

3.1.4 Kitasoo/Xai'xais Management Plan for Pacific Herring

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**

Pacific herring have been a primary food for Indigenous peoples 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 importance of including Indigenous information in fisheries models is highlighted; this is inclusive of both 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.

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, S., Corntassel, J., & Mucina, D. (2019). Indigenous nationhood and 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**

Researchers 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 discussed how these Indigenous nations have strategized to try 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 2-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 Indigenous rights to fisheries governance. New technologies included social media, blogs, email, 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 fisherman, 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.

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, 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).

Researchers built a conceptual model of the Pacific Herring social–ecological system (SES) in the Northeast Pacific. Questions were then identified 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, and charted a path forward 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 associated with Herring and their food web.

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

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.

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 Indigenous communities and a 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 Aboriginal models of herring cultivation, to sustain a commercial, subsistence, and restoration economy for the fishery. Tlingit and Haida peoples have in-depth 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, herring transplant, and harvest management strategies could become the basis for a stronger ecosystem management, habitat revitalization, and sustainable fisheries in the future.

3.2.3 Integrating Expert Perceptions into Food Web Conservation and Management

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.

This research paper quantifies how scientific, local, and traditional knowledge experts vary in their perceptions of food webs centred on Pacific herring—a valuable ecological, economic, and cultural resource in Haida Gwaii, BC, 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., groundfish 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.

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

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

This research paper synthesized knowledge sources (zooarchaeological, historical, traditional, and western science) to understand changes in northern abalone (marine mollusk) 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 (SES) 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.

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

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

Marine conservation strategy approaches of the Kitasoo/Xai'xais First Nation in British Columbia are reviewed and assessed. The conservation actions classification system by the Conservation Measures Partnership was evaluated 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 highlighted that with the Canadian government's declared willingness to work toward reconciliation, there is an opportunity to enable First Nations to lead 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.

Specific to Pacific herring, this case study provides an example of hereditary chiefs using their authority to oppose non-Kitasoo/Xai'xais decisions imposed on them. In the 2010's 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.

4 Fisheries Management

4.1 Historical Herring Fisheries Management

4.1.1 Historical Government Reporting (1901-1956)

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

Annual reports to the fisheries commissioner were published by the British Columbia Legislative Assembly from 1901 through to 1956. The purpose of these reports was to record and describe 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 are comprised of 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 began in 1916 and carry forward through to 1956. Prior to 1916, provincial reporting narrowly identified general landed herring catches and values. Selected excerpts from various reports 1916 to 1956 are annotated further in this guide with individualized references 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.

4.1.2 Life-History and Early Studies

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 BC provincial report of the commissioner of fisheries. (1916). Victoria, BC: 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, BC: Department of Fisheries and Oceans, Resource Services Branch, Pacific Biological Station.

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

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

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

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 BC's Pacific herring (Thompson, 1916), and then groups 4 additional selected publications (Tester, 1934; Outram, 1965; Outram & Humphreys, 1974; Hourston & Haegele, 1980) which built upon each other over successive decades, forming an eventual foundation of knowledge regarding Pacific herring life-history in BC (referenced below in alphabetical order).

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 over the years and markets that supported it, were provided during the B.C. Herring Investigations in the 1930s to 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 BC Herring Investigations and various official government reports to the fisheries commissioner over multiple decades.*

4.1.3 The B.C. Herring Investigations

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

Hart, J.; Tester, A. & McHugh, J. (1940). *Tagging of herring in British Columbia: Insertions and recoveries* during 1940-1941. In the BC provincial report of the commissioner of fisheries (1940). Victoria, BC: 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 BC provincial report of the commissioner of fisheries (1941). Victoria, BC: 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 BC provincial report of the commissioner of fisheries (1942). Victoria, BC: 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, BC).

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

Stevenson, J. & Lanigan, J. (1949). *Results of the West Coast of Vancouver Island herring investigation, 1949-1950*. In the BC provincial report of the commissioner of fisheries (1949). Victoria, BC: 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 BC provincial report of the commissioner of fisheries (1950). Victoria, BC: 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 BC provincial report of the commissioner of fisheries (1951). Victoria, BC: 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 BC provincial report of the commissioner of fisheries (1952). Victoria, BC: Legislative Assembly, Queen's Printer.

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

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

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

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

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

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 focused on identifying travel and spawning patterns of Pacific herring and began in the late 1930s, carrying forward until their termination in the 1950s. As the studies progressed through time, there was a recognition that herring were largely a non-migratory fish, forming localized resident populations. Various percentages of intermingling between herring populations is detailed, with different years producing various results. To some extent the concept of tagging and tracking of herring in B.C. continues today with more modern tools. A succinct review of herring tagging (1936-1992) was conducted in 1999 by researchers with the Department of Fisheries and Oceans, Canada (Hay, McCarter & Daniel 1999). The results confirmed the presence of herring that are resident populations but challenged earlier results of herring tagging work.

4.1.4 Herring workshop series

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**

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**

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**

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

Seven Pacific Coast Herring Workshops were held between 1973 and 1994. The purpose of these workshops were to provide for 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**

4.1.5 Additional historical reading & reference materials

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

The Fisheries Research Board of Canada produced a report in 1964 (authored by F. Taylor and indexed as bulletin #143) that captured, in fair detail, a holistic picture of the past and current state of the herring fishery as of 1964. This document covers a brief life-history of Pacific herring in BC, 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 early (with specific reference to uncontrolled fishing along the BC west coast). Herring populations are broken down by region and a review of historical and current spawn depositions is provided 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 BC.

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 – reproduced from article: *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.*

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, BC: Department of Fisheries and Environment (Pacific Biological Station). Retrieved from: **https://waves-vagues.dfo-mpo.gc.ca/Library/18122.pdf**

Archival departmental note – reproduced from department: 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.

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

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

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 form provincial fisheries reports and commercial data is provided along with descriptions of the fishery from a commercial, non-governmental perspective.

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 (SOK) 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

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

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 (SOG) and the West Coast of Vancouver Island (WCVI) areas. This was conducted as part of renewal of 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.

4.2.2 Science Response

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**

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 new and urgent requests; requests that don't require a thorough advisory process; or requests that 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 un-fished spawning biomass was introduced. The stock status update report outlines modelling scenarios for different management procedure options that meet a conservation objective (30% un-fished 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.

4.2.3 Integrated Fisheries Management Plans (IFMPs)

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**

Integrated Fisheries Management Plans (IFMPs) 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 2019 to November 2020. 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 almost 20 years. A Rebuilding Plan is underway with a target date of December 2020.

PRD: Closed. Stock biomass and growth has remained low but steady.

CC: SOK opportunities only up to a maximum of 1,715 tons (5.2% harvest rate). This stock shows a steady increase in spawning biomass since a low in the late 2000's, with a slight decrease in forecasted spawning biomass for 2020.

SOG: Food and Bait, Special Use, and Roe herring opportunities (20% harvest rate) to a maximum of 11,960 tons.

WCVI: Closed. Continued closure as low biomass and growth have persisted since 2005.

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, as part of the description of importance to Indigenous people, it is highlighted that herring provide value beyond individual fish or their roe. 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 to trade.

Also noteworthy, is the discussion on other species of concern, discussed in the context of the Species at Risk Act (SARA), and any amended or new regulations. Particularly, the Southern Resident Killer Whales (SRKWs) are considered in light of DFO determining in May 2018 that they face imminent threat to survival and recovery. For the 2020/2021 fishing season, DFO planned to review the 2019 fishery management actions that were implemented to support Chinook prey availability to SRKWs. The suite of measures implemented in 2019 included "implemented area-based fishing closures to increase Chinook salmon availability in Southern Resident Killer Whale foraging areas." It was indicated that any updates to actions for the 2020/2021 season may be implemented by Spring of 2020, coinciding with the return of the SRKWs. Consultations on this took place in **March 2020** and it has been anticipated that a similar approach will be taken in 2020 with small modifications to the measures.

4.2.4 Species Profile: Pacific Herring [web log]

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**

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 Alliance. 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 to 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).

5 Spatially Structured Metapopulations

5.1 Spatially Structured Metapopulations

5.1.1 Metapopulation structure and dynamics of British Columbia herring

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.

This research document integrates 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.

5.1.2 Pacific Herring Spawn Disappearance and Recolonization Events

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.

This paper (4th 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. Also, 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.

5.1.3 Use of Microsatellites to Determine Population Structure and Migration of Pacific Herring in British Columbia and Adjacent Regions

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.

This study 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 FST 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 Washington and British Columbia populations. 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.

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

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.

This study evaluates 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 (*Clupea pallasi*) 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.

5.1.5 Evaluating Contribution to the Themed issue: 'Plugging spatial ecology into sustainable fisheries and EBM': A heuristic model of socially learned migration behaviour exhibits distinctive spatial and reproductive dynamics

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.

The spatial distribution of Pacific herring recruits is modelled 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 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". Two models where recruits return to their natal spawning site were compared: 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. While 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.

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

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.

A simulation-estimation approach is used 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 such that there is post-recruitment dispersal among all areas. Simulated data (catches, catch age-composition, estimates of spawning stock biomass and its associated age structure) generated for each area are analyzed 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, i.e., 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.

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, 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

The food of juvenile chinook (*Oncorhynchus tshawytscha*) and coho (*Oncorhynchus* kisutch) salmon captured in northern Oregon and southern Washington coastal zones during three cruises, May-September 1980, was described. 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. Another study 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.

6.1.1.2 Food Consumption of Juvenile Coho (Oncorhynchus kisutch) and Chinook Salmon (O. tshawytscha) on the Continental Shelf off Washington and Oregon

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.

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 to 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.

6.1.1.3 Ontogenetic Diet Shifts of Juvenile Chinook Salmon in Nearshore and Offshore Habitats of Puget Sound

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.

This study examines 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 study suggests 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.

Canadian Salish Sea Marine Survival Program: Program Summaries and Status Reports

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

The Salish Sea Marine Survival Project (SSMSP) publishes reports, status and findings, and research plans that aim to determine the principle 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 (SOG), 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.

6.1.1.4 Historical Diets of Forage Fish and Juvenile Pacific Salmon in the Strait of Georgia, 1966–1968

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.

The Strait of Georgia, British Columbia, 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.

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

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/

This study evaluated the spatial and temporal variation in growth rate and the relationship between size and growth rates for juvenile Chinook salmon in Puget Sound, WA, USA. As a function of the relative size and abundance of both Chinook salmon and Pacific herring, are 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 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 effects 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.

6.1.1.6 Energy dynamics of subyearling Chinook salmon reveal the importance of piscivory to short-term growth 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.

The objective of this study was to examine the energy dynamics of subyearling Chinook salmon (*Oncorhynchus tshawytscha*) following freshwater emigration. A population of Chinook salmon and their marine prey were repeatedly sampled from June to September over 2 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. In British Columbia and other parts of the Salish Sea, Pacific herring appeared to be the dominant forage. 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.

6.1.1.7 Using salmon to sample the Salish Sea: diets of recreationally harvested Chinook and Coho salmon as an ecosystem monitoring tool

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/**

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.

6.1.1.8 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

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

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 and trends and threats. The main threats are noted to be harvest, changes in freshwater and marine habitat, climate change, hatcheries, and pathogens/aquaculture.

6.1.1.9 6.1.1.10 Ocean ecology of Chinook salmon. In book: Ocean Ecology of Pacific Salmon and Trout

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.

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.

Predators on Chinook salmon are described, noting that over the past 25 years, marine mammals have been identified as predators on juvenile and adult Chinook salmon. 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".

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

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.

A part of this study focused on the competition between juvenile Chinook salmon and Pacific herring in Puget Sound. Simulation modelling 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, secondarily to hyperiid amphipods, copepods, and euphausiids. Herring consumed approximately 10-50 times more biomass of the major prey eaten by juvenile Chinook salmon during the critical May to 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, herring, 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 was 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, which underscores the importance and need for integrated research, monitoring, and management of these species collectively in the future.

6.1.2.2 Potential for Competition Among Herring and Juvenile Salmon Species in Puget Sound, Washington

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.

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. Due to 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.

6.2 Southern Resident Killer Whales (SRKWs)

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

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.

Field studies were conducted 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 or breaking up of prey for sharing; all species and sizes of salmonids were shared. Resident killer whale groups in all parts of the study area foraged 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.

6.2.2 Quantifying the effects of prey abundance on killer whale reproduction

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.

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. Weak evidence exists for 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 to 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; those salmon populations are important as prey for killer whales that can be identified and targeted for conservation efforts. In this case, stocks in the West Coast Vancouver Island fishery were considered (i.e., salmon from Puget Sound, and the Columbia and Fraser rivers), and the importance of Fraser River Chinook was highlighted as the most likely to be tied to killer whale demography.

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

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**]

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 (*Oncorhynchus tshawytscha*) 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 residents 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 reasonable conservative estimate is that about 70% of their nutritional needs may be supplied by this species. This suggest 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 represented about 90% of resident killer whale diet during July to August. Southern residents foraging in Critical Habitat (in Canadian and U.S. waters combined) would require approximately 1200 to 1400 Chinook salmon per day or roughly 67,000 to 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 to August. As a result, Chinook salmon requirements in this area are less than for southern resident Critical Habitat: about 420 to 500 fish per day, or 26,000 to 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.

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

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

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 (*Oncorhynchus tshawytscha*). The striking correspondence between changes in Chinook salmon abundance and mortality of the 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 are limited in their ability to adapt rapidly to changing prey availability.

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

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.

Recovery plans for endangered Southern Resident Killer Whales *Orcinus orca* 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, Canada. 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.

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

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

Energy requirements of Southern Resident Killer Whales are examined. This is essential to assessing whether prey availability of Chinook salmon is sufficient as Killer Whales are limited by prey availability. Body mass, field metabolic rate (FMR), and daily prey energy requirements (DPERs) were estimated 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 to 4,018 fish/d (1,222,003–1,466,581 fish/yr) when the population consumes only chum. It is noted 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.

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

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).

Southern Resident Killer Whale (SRKW) prey requirements for Chinook salmon are modelled; highlighting competing conservation objectives for at-risk Killer Whales and at-risk 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, 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% to 23% of available Fraser River Chinook in the region from May to September. These plausible summer estimates are large relative to the 10% to 40% natural mortality considered in regional fisheries stock assessment models because they ignore likely consumption of Chinook in winter months; consumption by parapatric northern resident killer whales, consumption by Steller sea lions, sharks, 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 takes of salmon than to increase salmon production; 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.

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

Two stressors on Southern Resident Killer Whales; inadequate prey and vessel traffic were investigated using non-invasive physiological techniques to evaluate the relative impacts of each stressor. Fecal thyroid (T3) and glucocorticoid (GC) hormone were measured. GC increase 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. In particular, GC concentrations were negatively correlated with short-term changes in prey availability. Whereas, 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, it is interesting 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.

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

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**.

The Southern Resident Killer Whales (SRKWs) and Northern Resident Killer Whales (NRKWs) 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. The prominence of Chinook salmon in the summer diets of both SRKWs and NRKWs (RKWs) has been shown and studies have further indicated prevalence of Chinook salmon in the year-round diet. 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.

6.2.10 Estimation of a Killer Whale (Orcinus orca) population's diet using sequencing analysis of DNA from feces

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).

Genetic analysis was conducted on fecal material from Southern Resident Killer Whales (SRKWs) 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 controls 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.

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

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.

This study evaluates the consumption of Chinook salmon by three protected pinniped species 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.

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

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

This study is similar to Estimates of Chinook salmon consumption in Washington State inland waters by four marine mammal predators from 1970 to 2015; however, a spatial-temporal bioenergetics model was used 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 (8 regions from California to Alaska), and compared 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 harbour seals consume the largest number of individuals. The decrease in adult Chinook salmon harvest from 1975 to 2015 was 16,400 to 9,600 metric tons. 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, W.Coast Vancouver Island and coastal British Columbia, and Southeast Alaska), but for these stocks predation is presently near or below the harvest.

6.2.13 Population growth is limited by nutritional impacts on pregnancy success in endangered Southern Resident killer whales (Orcinus orca)

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

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 post-partum, 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 (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.

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

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

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 reduced 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.

6.3 Bears

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

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).

This study investigated the interaction between American black bears (*Ursus americanus*) and Pacific herring at spawn events in Quatsino Sound, BC, Canada. 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.

6.4 Seabirds

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

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.

The effect of fluctuations in food abundance on seabird breeding success is quantified 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.

6.4.2 Persisting Worldwide Seabird-Fishery Competition Despite Seabird Community Decline

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.

Temporal trends in seabird-fishery competition were assessed 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 to 1989 and 1990 to 2010 (+10%). For the same periods, 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 to 1989 and 1990 to 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.

7 Trophic Role of Herring in the Food Web

7.1 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

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/

This presentation discusses a West Coast Vancouver Island (WCVI) ecosystem monitoring program as a framework that can be applied to the Strait of Georgia (SOG). Specifically, the biological basis for production variability in WCVI herring was 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 3 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.

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

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.

Researchers investigated the influence of energy content on the trophic role of Pacific herring off northern B.C. and SE 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 NE 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), humpbacks, minke whales, seals, 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 NE Pacific fish energy content and recruitment, these concerns gain additional urgency.

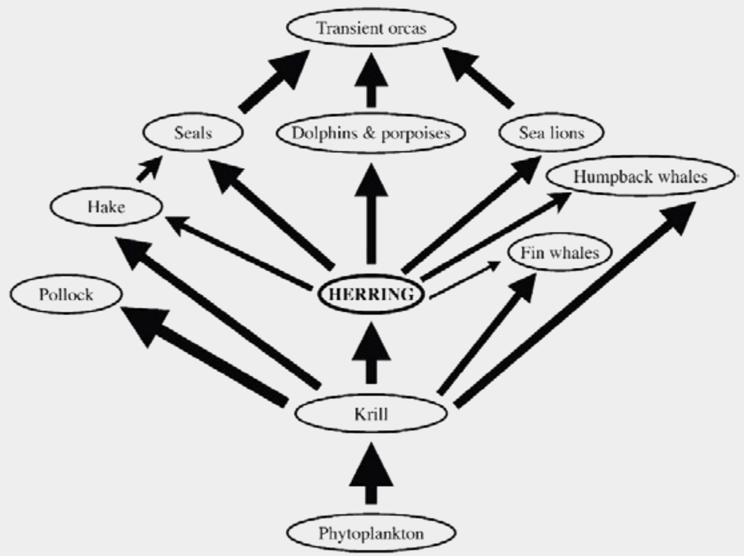
7.1.3 Herring supports Northeast Pacific predators and fisheries: Insights from ecosystem modelling and management strategy evaluation

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).

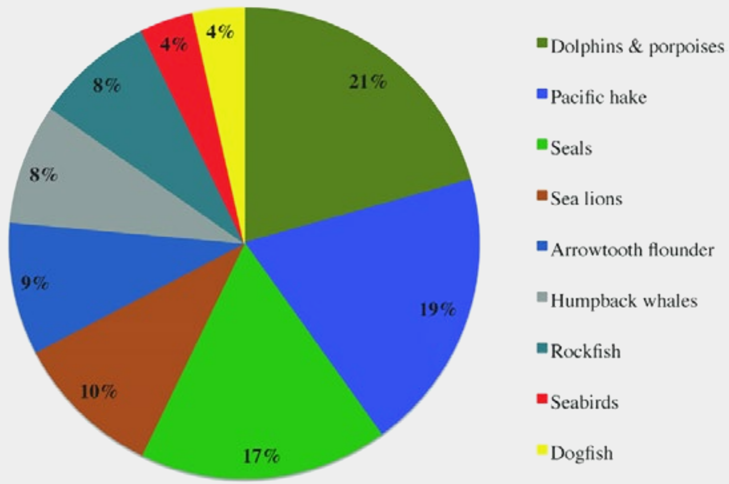
Researchers analyzed the trophic role of Pacific herring; the potential consequences of depletion and the impacts of alternative herring fishing strategies on a Northeast Pacific food web in relation to precautionary, ecosystem-based management.

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 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 plays an important role in the Northeast Pacific food web as both *prey* to predators and *competitor* 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 (Ecopath model; Surma *et al.*, 2018).

8 Climate Change Vulnerability

8.1 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, 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

Northern Pacific nutrient–phytoplankton–zooplankton modelling data is used as input to a Pacific herring (Clupea pallasi) 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 to 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 modelling capabilities. Also, the formation of the necessary collaborative networks of scientists are steadily approaching the point where they can soon generate realistic forecasts of climate effects on fish population dynamics.

8.1.2 Impacts of Climate and Climate Change on the Key Species in the Fisheries in the North Pacific

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**

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 (North Pacific Marine Science Organization), member countries, summaries are provided for key fisheries species. The following is a summary for Pacific herring.

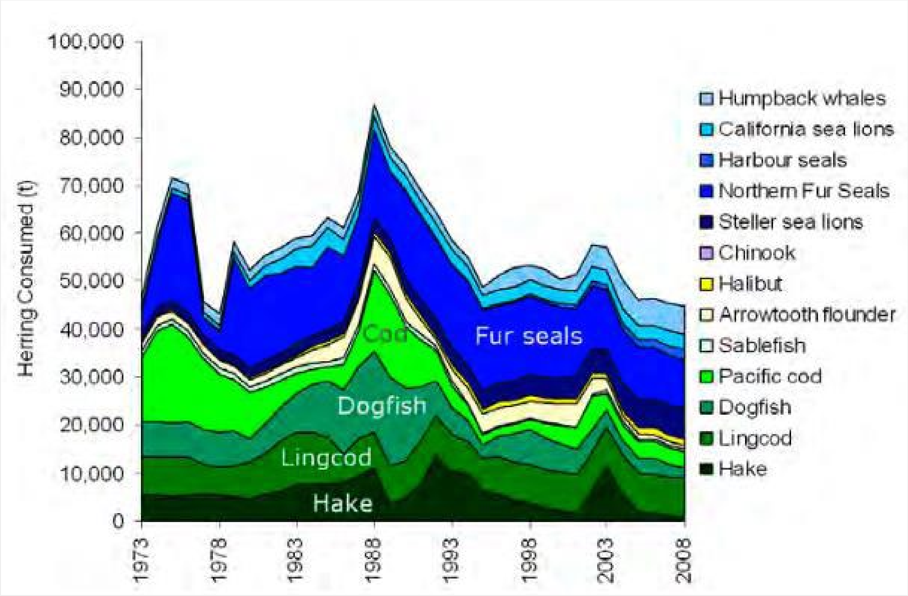
Pacific herring traditionally have been a major fishery on Canada's Pacific coast. The current fishery removes between 30,000 and 40,000 tonnes annually but fisheries in the late 1950s and early 1960s had annual landings exceeding 200,000 tonnes. There was a change in climate in the 1960s and herring 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 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 historically 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. Since Pacific herring are dependent on nearshore habitats for spawning, sea levels would 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.

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

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.

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 (WCVI). Herring mortality was positively related to Thysanoessa spinifera, southern chaetognaths, and negatively to pteropod abundance. Estimated predation on herring decreased significantly during the years of 1973 to 2008, with the main consumers changing from fish to mammals in 1995 which was 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 analysis. 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.

Noteworthy, is that the 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).

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

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/7c09djpvF-Bw**

In his presentation Dr. Pitcher asks 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 and largely from the Russian fleet. In the 1950s and 1960s, countries only had a twelve nautical mile territorial borders where other countries could come up to, fish, and sometimes came within. Now we have a 200 nautical mile zone. The earliest recorded fishery was 1888 where an abundance of herring were caught in Burrard inlet and used for fertilizer and dry salted products into the 1900s. Catches continued to decrease. By 1950, foreign fleets came in and considerable unreported and illegal catch was reported by Canadians. The total catch reported peaked to half a million tons; this is more than twice the figure recorded in government records. The fishery collapsed and was closed in 1968 for 4 to 5 years. Following this, the reduction fishery ensued. The roe fishery began in the early 1970s to supply eggs to Japan.

Dr. 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 egg production into account 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's diet varies with location and time.

Dr. Pitcher discussed the development of an ecosystem based simulation model for Haida Gwaii which incorporates the varying amounts of phytoplankton in the water over time, three different types of herring fisheries with fishing thresholds and rates, who eats what's based on food web models. When run, the model shows the changes in biomass (impacts) to 78 species groups. Dr. Pitcher explains 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 its not precautionary on average but that it is not precautionary in terms of hedging the risks to climate change.

Dr. Pitcher also discussed if herring go home to spawn. Otoliths (fish inner ear bone) were used to determine distinct populations of herring by analyzing the chemical elements in the growth layers of the ear bone. Differences can be seen between the centre of the bone (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 those fish are genetically distinct; you could wipe out that population.

To summarize, fishing herring does affect the rest of the ecosystem but it 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.

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

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

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 pCO_2 was associated with a small increase in embryo mortality. However, elevated temperature was associated with greater embryo mortality, greater embryo heart rates, yolk areas upon hatch, lower percent normal hatch, and decreased larval lengths. The interaction of elevated temperature and pCO_2 was associated 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 pCO_2 may introduce additional challenges.

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

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*.

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. They also found 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 suggest that in Haida Gwaii, herring spawn abundance has been primarily governed by the NPGO and downwelling-favourable alongshore wind-stress; in contrast to 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.

9 Additional Resources and Further Reading

9.1 Additional Resources and Further Reading

9.1.1 Herring school

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

The Tula Foundation's Haikai program (a Canadian environmental charity and research organization) launched a multi-year herring research program in the early 2000s. 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 and records pertaining to BC's Pacific herring and Indigenous herring knowledge. 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 this annotated bibliography (2020), 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.*

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

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

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.

9.1.3 Little Fish, Big Impact: Managing a Crucial Link in Ocean Food Webs

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**

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. The report is professionally laid out with accompanying graphics. 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).

9.1.4 Food for all: Small fish with a big influence

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**

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 is professionally laid out with 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).

9.1.5 Emerging Thoughts on Herring

Lam M.E., Pitcher T.J., Surma S., Scott J. et al. (2019) Value- and ecosystem-based management approach: the Pacific herring fishery conflict. Mar Ecol Prog Ser 617-618:341-364. **https://doi.org/10.3354/meps12972**

Petrou E.L., Fuentes-Pardo A.P., Rogers L.A., Orobko M., Tarpey C., Jiménez-Hidalgo I., Moss M.L., Yang D., Pitcher T.J., Sandell T., Lowry D., Ruzzante D.E., Hauser L. (2021) Functional genetic diversity in an exploited marine species and its relevance to fisheries management. Proc Biol Sci. Feb 24;288(1945):20202398. doi: 10.1098/rspb.2020.2398. Epub 2021 Feb 24. PMID: 33622133.

Surma S., Christensen V., Kumar R., Ainsworth C.H., Pitcher T.J. (2019). High-Resolution Trophic Models Reveal Structure and Function of a Northeast Pacific Ecosystem. Frontiers in Marine Science. 6 (625). doi=10.3389/fmars.2019.00625. https://www.frontiersin.org/article/10.3389/fmars.2019.00625

Surma S., Pitcher T.J., Kumar R., Varkey D., Pakhomov E.A., et al. (2018) Herring supports Northeast Pacific predators and fisheries: Insights from ecosystem modelling and management strategy evaluation. PLOS ONE 13(7): e0196307. **https://doi.org/10.1371/journal.pone.0196307**

Surma S., Pakhomov E.A., Pitcher T.J. (2018) Energy-based ecosystem modelling illuminates the ecological role of Northeast Pacific herring. Mar Ecol Prog Ser 588:147-161. **https://doi.org/10.3354/meps12430**