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Canadian Bibliography of 2012–2018 Publications Linked to the 2016–2020 NPAFC Science Plan

by

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Abstract
The current bibliography lists publications in primary scientific journals and other documents published during 2012–2018 by Fisheries and Oceans Canada scientists and their collaborators relevant to the 2016–2020 NPAFC Science Plan. The bibliography lists 112 publications, many with abstracts, corresponding to three of the key research components of the NPAFC Science Plan.

Introduction

The Science Sub-Committee of the North Pacific Anadromous Fish Commission (NPAFC) developed a five-year Science Plan (2016–2020) (http://www.npafc.org/new/publications/Science%20Plan/SciPlan%202016-20/NPAFC_science_plan2016-2020.pdf) with five research themes intended to help understand variations in Pacific salmon productivity in a changing climate:

1. Status of Pacific Salmon and Steelhead Trout
2. Pacific Salmon and Steelhead Trout in a Changing North Pacific Ocean
3. New Technologies
4. Management Systems
5. Integrated Information Systems

The current bibliography lists publications in primary scientific journals and other documents published during 2012–2018 by Fisheries and Oceans Canada scientific staff and their collaborators. These documents outline results from Canadian research relevant to the current NPAFC Science Plan. The bibliography lists publications, many with abstracts, corresponding to the first three research components of the Science Plan. Although each publication is listed under one research theme, some are relevant to more than one research theme.

Theme 1: Status of Pacific Salmon and Steelhead Trout

Akenhead, S.A., J.R. Irvine, K.D. Hyatt, S.C. Johnson, S.C.H. Grant, and C.G.J. Michielsens. 2016. Habitat manipulations confound the interpretation of sockeye salmon recruitment patterns at Chilko Lake, British Columbia. N. Pac. Anadr. Fish Comm. Bull. 6: 391–414. doi:10.23849/npafcb6/391.414.

An examination of metadata associated with a population of sockeye salmon changed our interpretation of the purported benefits of salmon enhancement projects and improved our understanding of the stock-recruitment relationship. Efforts to increase the production of sockeye salmon (*Oncorhynchus nerka* Walbaum, 1792) from Chilko Lake (Fraser River watershed in British Columbia, Canada) included simultaneously fertilizing the lake and operating a spawning channel. To investigate the effects of these manipulations, we analyzed data for spawners, smolts, and returns including metadata associated with these fish and their watershed. Incorporating factors derived from metadata in stock-recruit analysis reduced the total variance to be explained before considering stock-density effects, and allowed us to explore the effect of imprecise data. When Beverton and Holt models were applied to data for smolts from spawners and returns from spawners, estimates of productivity and capacity for broods affected by the spawning channel (1988–2003) were lower than for broods before and after its operation. Observations during this period suggested that many salmon fry, emerging from natural spawning areas downstream of the channel and destined for Chilko Lake, entered the channel or could not pass it, and perished. Applying metadata related to the precision of annual return estimates reduced our confidence in published conclusions about a positive effect on egg to smolt survival from adding fertilizer to Chilko Lake. We further investigated a factor for smolt to adult survival based on the survival of other populations of Fraser River sockeye, noting this factor, and others, affect estimates for both capacity and productivity. Lastly we investigated changes in the fecundity of spawners and in the primary productivity of Chilko Lake, establishing that both have changed on a decadal scale. In summary, adding categorical and ordinal variables (factors) to account for natural and man-made habitat manipulations reduced the variance to be explained by stock-recruit models, thereby enabling more effective analyses of habitat capacity and density-dependent survival, which should lead to improved fisheries management decisions. The importance of analysts becoming familiar with metadata cannot be overstated.

Akenhead, S.A., J.R. Irvine, K.D. Hyatt, S.C. Johnson, and S.C.H. Grant. 2016. Stock recruit analyses of Fraser River sockeye salmon. North Pacific Anadromous Fish Commission Bulletin 6: 363–390. doi:10.23849/npafcb6/363.390.

Three types of stock-recruit models (log-log, Ricker, Beverton-Holt) were applied to 57 years of adult returns (R) and effective female spawners (E) data from 17 biologically-based Conservation Units (CUs) of sockeye salmon from the Fraser River in British Columbia, Canada (hereafter "Fraser sockeye"). Log-log regressions of R on E showed little evidence of effects of density (within CUs) on survival, implying that habitat capacity does not presently limit Fraser sockeye abundance. Shared survival among CUs, the first principal component of log(R/E), accounted for 46% of the variance, remarkable given the wide variety of freshwater and marine habitats experienced by the CUs. Six low-survival events in six decades accounted for much of the shared survival pat- tern. The r2 values for Ricker models were low, indicating that attempts to manage and/or assess Fraser sockeye using Ricker curves fit to individual CUs will, in general, face low explanatory power. A suite of increasingly complicated Bayesian regressions, based on the Beverton-Holt model, quantified the precision of capacity estimates, but these were always imprecise and the Widely Applicable Information Criterion (WAIC) indicated over- fitting in all but the simplest models. A variance factor for the relative precision of estimates of R, based on the proportion of spawners from each CU in groups of co-migrating CUs (i.e., runs), was effective only in models in which WAIC indicated over-fitting. Improving the precision of capacity estimates for Fraser sockeye salmon, using similar models, will require mobilizing biological knowledge (i.e., historical metadata) about each CU, including estimates of abundance with identified precision and indicators of habitat capacity at multiple life-history stages including the abundance of potential competitors in marine habitats. Researchers analyzing stock recruitment data for salmon populations and other species are strongly encouraged to pay attention to factors affecting the various categories of data in their models, i.e., to examine the associated metadata.

Araujo, H.A., C. Holt, J.M. Curtis, I. Perry, J.R. Irvine, and C.G. Michielsens. 2013. Application of Bayesian Belief Networks to improve understanding and management of young coho salmon *Oncorhynchus kisutch* during their residence in the Strait of Georgia. Progress in Oceanography 115:41–62.

Chaput, G., Cass, A., Grant, S., Huang, A.-M. and Veinott, G. 2012. Considerations for defining reference points for semelparous species, with emphasis on anadromous salmonid species including iteroparous salmonids. Can. Sci. Advis. Sec. Res. Doc. 2012/146. v + 48 pp. http://waves-vagues.dfo-mpo.gc.ca/Library/362194.pdf

The document was prepared in support of an advisory process meeting to produce a technical guidance document to assist science practitioners responsible for developing the science elements of the Precautionary Approach (PA) framework. It reviews the use of reference points in the assessment and management of semelparous species and anadromous salmonids including iteroparous salmon. Semelparous species and anadromous salmonids are treated collectively and separately from other aquatic species because they share a number of life history and population dynamic characteristics which are distinct from those of other aquatic organisms. In British Columbia and Yukon, the Wild Salmon Policy (WSP) guides the implementation of the precautionary approach in the management of fisheries on Pacific salmon. In the WSP, biological benchmarks are developed for four main classes of indicators: trends in abundance, abundance, fishing mortality, and spawning ground distribution as data permits. These indicators are further integrated into a single category of biological status. There are no management actions which are associated directly with a given status or benchmark. Rather, the biological benchmarks aid in the development of fishery reference points along with socio-economic factors and issues related to risk tolerance. Empirical methods consisting of life history models that use life history process parameters borrowed from a large range of studies on the species of interest are considered. In data limited situations for unstudied populations but for which information exists from other populations, reference points are frequently transported based on values from studied populations which are standardized using an exchangeable and transportable metric.

Ferris, B.E., M. Trudel, and B.R. Beckman. 2014. Assessing marine pelagic ecosystems: regional and inter-annual trends in marine growth rates of juvenile salmon off the British Columbia Coast. Mar. Ecol. Prog. Ser. 503: 247–261.

We measured insulin-like growth factor 1 (IGF1) concentrations (a proxy for growth) from juvenile coho *Oncorhynchus kisutch*, sockeye *O. nerka*, chum *O. keta*, and Chinook salmon *O. tshawytscha* collected in 8 regions of British Columbian coastal waters, in June of 2009, 2010, and 2011. We found annual differences in IGF1 for all 4 species, as well as species- specific regional differences in IGF1 concentrations in coho, chum, and sockeye salmon. Sockeye and chum salmon had consistently higher levels in the northern regions of the Dixon Entrance, Haida Gwaii, Hecate Strait, and lower levels in Queen Charlotte Strait. Regional differences in coho, chum, and sockeye salmon were highly correlated (R2 = 0.61–0.75). These results demonstrate that salmon growth responds to local environmental variability on a scale of several hundred kilometers. Thus, IGF1 measures should generate insight into fish production on relatively local regional and temporal scales, and these same measures may allow the assessment of how habitats vary on these same scales.

Fisher, J.P., L. Weitkamp, D.J. Teel, S.A. Hinton, J.A. Orsi, E.V. Farley, Jr, J.F.T. Morris, M.E. Thiess, R.M. Sweeting, and M. Trudel. 2014. Early ocean dispersal patterns of Columbia River Chinook and coho salmon. Trans. Am. Fish. Soc. 143: 252–272.

Several evolutionarily significant units (ESUs) of Columbia River asin Chinook Salmon *Oncorhynchus tshawytscha* and Coho Salmon *O. kisutch* are listed as threatened or endangered under the U.S. Endangered Species Act. Yet little is known about the spatial and temporal distributions of these ESUs immediately following ocean entry, when year-class success may be determined. We documented differences in dispersal patterns during the early ocean period among groups defined by ESU, adult run timing, and smolt age. Between 1995 and 2006, 1,896 coded-wire-tagged juvenile fish from the Columbia River basin were recovered during 6,142 research trawl events along theWest Coast of North America. Three distinct ocean dispersal patterns were observed: (1) age-1 (yearling) mid and upper Columbia River spring-run and Snake River spring–summer-run Chinook Salmon migrated rapidly northward and by late summer were not found south of Vancouver Island; (2) age-0 (subyearling) lower Columbia River fall, upper Columbia River summer, upper Columbia River fall, and Snake River fall Chinook Salmon dispersed slowly, remaining mainly south of Vancouver Island through autumn; and (3) age-1 lower Columbia River spring, upper Columbia River summer, and upper Willamette River spring Chinook Salmon and Coho Salmon were widespread along the coast from summer through fall, indicating a diversity of dispersal rates. Generally, the ocean dispersal of age-1 fish was faster and more extensive than that of age-0 fish, with some age-1 fish migrating as fast as 10–40 km/d (0.5–3.0 body lengths/s). Within groups, interannual variation in dispersal was moderate. Identification of the distinct temporal and spatial ocean distribution patterns of juvenile salmon from Columbia River basin ESUs is important in order to evaluate the potential influence of changing ocean conditions on the survival and long term sustainability of these fish populations.

Grant, S.C.H. & G. Pestal. 2012. Integrated biological status assessments under the Wild Salmon Policy using standardized metrics and expert judgement: Fraser River Sockeye salmon (*Oncorhynchus nerka*) Case Studies. Can. Sci. Advis. Sec. Res. Doc. 2012/106. v + 132 pp. http://waves-vagues.dfo-mpo.gc.ca/Library/349637.pdf

The 24 Fraser Sockeye Conservation Units (CUs) were used as case studies to explore methods of status integration for Strategy 1 of the Wild Salmon Policy (WSP): Standardized Monitoring of Wild Salmon Status. Status integration was evaluated during a three day technical workshop, which included the development of both final integrated status for each Fraser Sockeye CU (which include one or more WSP status zones) and commentaries on the information used to assess status. For the workshop, two page standardized data summaries were produced for each Fraser Sockeye CU case study. Data summaries included WSP biological status information for a number of metrics (e.g. relative abundance, short-term trends in abundance, and long-term trends in abundance) and other biological data relevant to their interpretation. Case studies were evaluated 'blind', with generic labels rather than CU names. The decision to evaluate case studies 'blind' was made to facilitate the development of a standardized WSP status integration approach, to focus discussion on the metrics presented in Grant et al. (2011) for status integration, and to facilitate discussion between experts with detailed local and CU-specific knowledge and those with broader salmonid and status evaluation experience. Each CU case study was evaluated first in small group sessions (four to six participants per group) and, subsequently, in plenary sessions (all 34 workshop participants). On the final day of the workshop, the integrated status for each CU, developed in the previous days' plenary sessions, were re-visited with the goal to narrow down a CU's status to a final single status zone (where possible), and to fine tune commentaries. Also on the final day of the workshop, CU names were revealed to provide participants with the opportunity to introduce any specific supplementary information that might support a change in integrated status designation or that could be added to the CU status commentaries. Integrated status results from this workshop complete WSP status determinations for Fraser Sockeye, which follows up on the recently published exploration of uncertainty in WSP status metrics for these CUs. Final statuses for the 24 Fraser Sockeye CUs included the following: seven Red, four Red/Amber, four Amber, two Amber/Green, five Green, one "Data Deficient", and one "Undetermined.

Grant, S.C.H. & MacDonald, B.L. 2012. Pre-season run size forecasts for Fraser River Sockeye (*Oncorhynchus nerka*) and Pink (O. gorbuscha) salmon in 2013. DFO Can. Sci. Advis. Sec. Res. Doc. 2012/145. vi + 42 pp. http://waves-vagues.dfo-mpo.gc.ca/Library/348273.pdf

The 2013 Fraser Sockeye forecast indicates a one in ten chance (10% probability) the total Fraser Sockeye return will be at or below 1,554,000 (lowest observed on this cycle) and a nine in ten chance (90% probability) it will be at or below 15,608,000, assuming productivity is similar to past observations. The mid-point of this distribution (50% probability) is 4,765,000 (there exists a one in two chance the return will be at or below this value). The four year old percentage of the total forecast is 90%, and ranges from 13% to 100%, depending on the stock. The 2013 forecast is larger than the 2012 forecast, attributed to higher escapements in the 2009 versus 2008 brood year. Summer Run stocks, particularly Chilko and Quesnel, contribute 78% to the total return forecast, whereas Late Run (12%), Early Summer (5%) and Early Stuart Run stocks (4%) each contribute considerably less. The Harrison 2013 forecast is particularly uncertain, and returns have a higher likelihood of falling outside the forecast distribution. The total forecasted 2013 Fraser Sockeye return largely falls (up to a three in four chance, based on past observations) below the cycle average (8,579,000), due to the below average 2009 and 2008 brood year escapements for most stocks. Conversely, there is a one in four chance the return will be above the cycle average, if Fraser Sockeye productivity falls at the high end of past observations. If low productivity conditions resume, returns could be considerably lower, based on a sensitivity analysis forecast that ranges from 523,000 to 5,419,000 at the 10% to 90% probability level.

Holt, C.A., and J.R. Irvine. 2013. Distinguishing benchmarks of biological status from management reference points: A case study on Pacific salmon in Canada. Environmental Conservation 40(4): 345-355. doi:10.1017/S0376892913000209

For fisheries with multiple, competing objectives, identifying and applying reference points for management can present difficult trade-offs between long-term biological and shorter-term socioeconomic considerations. The term biological benchmarks is proposed to demarcate zones of population status based on conservation and production considerations. These scientifically derived benchmarks contrast with management reference points that generally require additional shorter-term socioeconomic information best obtained through public consultations. This paper illustrates the distinction between biological benchmarks to categorize status of demographically isolated populations, and decision-support tools, such as management reference points, to integrate biological information with appropriate social and economic information. In the Fraser River (British Columbia, Canada), the selection of management reference points for sockeye salmon (*O. nerka*) fisheries explicitly considered trade-offs between the probability of meeting long-term biological objectives on component populations and harvest objectives on population aggregates. Decisions about reference points were made in a consultative process that included extensive stakeholder engagement. Other agencies are urged to distinguish biological benchmarks from management reference points to ensure transparency in the relative influence of biological versus socioeconomic information in decision making.

Irvine, J.R., and S.A. Akenhead. 2013. Understanding smolt survival trends in Sockeye Salmon. Marine and Coastal Fisheries: Dynamics, Management, and Ecosystem Science: 5: 303–328. DOI: 10.1080/19425120.2013.831002

Many populations of Sockeye Salmon *Oncorhynchus nerka* in the eastern North Pacific Ocean experienced significant productivity declines that began about 1990, but there is no consensus on the mechanisms responsible. To better understand Sockeye Salmon survival trends, we examined the 50-year time series for two age-classes of Sockeye Salmon smolts from Chilko Lake in central British Columbia. Arranging survival time series for both age-classes by ocean entry year and combining them, weighted by a proxy model of sampling variance, reduced the sampling variance in the original age-1 smolt survivals sufficiently to indicate a linear trend of increasing survival from 1960 to 1990 that suddenly changed at or near 1991 to a lower and declining trend from 1992 to 2008. Neither density nor mean length influenced smolt survival. Returns in a given year were not good predictors of siblings returning in subsequent years. Time spent at sea increased linearly beginning around 1970. Although smolt survivals differed between ecosystem regimes, there was only the one clear pattern break about 1991. To improve our understanding of mechanisms, survival trends were compared with environmental indices that included catches and hatchery releases of potentially competing salmon from around the North Pacific Ocean. Smolt survivals were more similar to abundance indices of Sockeye Salmon, Chum Salmon *O. keta*, and Pink Salmon *O. gorbuscha* than to indices of global, regional, or local ocean climate. Our results are consistent with the hypothesis that salmon productivity in the North Pacific declined soon after 1990. We present a simple model to illustrate how increased competition at sea, related to the release of large numbers of hatchery salmon, in conjunction with changes in ocean productivity, may have played a significant role in improving Sockeye Salmon survivals while reducing their growth before 1991. After 1991, these factors may have acted to reduce survivals while the growth of survivors showed no effect.

Irvine, J.R., M. O'Neill, L. Godbout, and J. Schnute. 2013. Effects of varying smolt release timing and size on the survival of hatchery-origin coho salmon in the Strait of Georgia. Progress in Oceanography 115:111–118. doi: http://dx.doi.org/10.1016/j.pocean.2013.05.014

Altering release sizes and timings of coho salmon smolts from hatcheries in the Strait of Georgia will not reverse the precipitous survival declines of the past three decades. We modeled the effects on survival of ocean entry year, mean smolt size (weight), and release day. Ocean entry year was by far the most important. During 1979–2006, smolt to adult survivals declined similarly for hatchery and wild coho salmon, although wild salmon consistently survived at higher rates. Best models differed among hatcheries, implying location-specific differences in the optimal size and timing of release. At four of five hatcheries, heavier smolts survived significantly better than lighter smolts. At one hatchery, a significant interaction between ocean entry year and smolt weight reflected an increased positive effect of weight later in the time series. At two Vancouver Island hatcheries, early release groups appeared to survive better than later releases in early years, while later release groups survived best in recent years. We recommend: (1) hatchery managers release coho salmon smolts throughout the outmigration period of higher surviving wild coho salmon smolts and (2) an experimental approach using hatcheries to evaluate density-dependent effects on coho salmon growth and survival.

Irvine, J.R. and G.T. Ruggerone. 2016. Provisional estimates of numbers and biomass for natural-origin and hatchery-origin pink, chum, and sockeye salmon in the North Pacific, 1952–2015. NPAFC Doc. 1660. 45 pp.

Irvine, J.R., J. Sandher, R. Houtman, and L. Fitzpatrick. 2013. Recent Canadian Enhanced Salmonid Production and Commercial Kept Catch Estimates (1979-2012). NPAFC Doc. 1470. Rv. 1, 9 pp.

Jeffrey, K.M., I.M. Côté, J.R. Irvine, and J.D. Reynolds. 2016. Changes in body size of Canadian Pacific salmon over six decades. Can. J. Fish. Aquat. Sci. 74: 191–201 (2017) dx.doi.org/10.1139/cjfas-2015-0600.

Body size can sometimes change rapidly as an evolutionary response to selection or as a phenotypic response to changes in environmental conditions. Here, we revisit a classic case of rapid change in body size of five species of Pacific salmon (*Oncorhynchus spp.*) caught in Canadian waters, with a six-decade analysis (1951–2012). Declines in size at maturity of up to 3 kg in Chinook (*Oncorhynchus tshawytscha*) and 1 kg in coho salmon (*Oncorhynchus kisutch*) during the 1950s and 1960s were later reversed to match or exceed earlier sizes. In contrast, there has been little change in sockeye salmon (*Oncorhynchus nerka) sizes* and initial declines in pink (*Oncorhynchus gorbuscha*) and chum salmon (*Oncorhynchus keta*) sizes have halted. Biomass of competing salmon species contributed to changes in size of all five species, and ocean conditions, as reflected by the North Pacific Gyre Oscillation and the Multivariate ENSO (El Niño – Southern Oscillation) indices, explained variation in four of the species. While we have identified a role of climate and density dependence in driving salmon body size, any additional influence of fisheries remains unclear.

Kaev, A.M. and J.R. Irvine. 2016. Population dynamics of pink salmon in the Sakhalin-Kuril Region, Russia. North Pacific Anadromous Fish Commission Bulletin 6: 297–305. doi:10.23849/npafcb6/297.305

Pink salmon abundance has increased over the past four decades for much of the Sakhalin-Kuril region. Other than in the southern Kuril islands (Iturup and Kunashir), pink salmon returning in odd-numbered years were usually more numerous than genetically isolated even-year pink salmon; differences between these brood lines generally intensified in recent years. For three areas where we have the most confidence in our estimates (southeastern Sakhalin, Aniva Bay, and Iturup Island), marine survival indices and numbers of returning adults for both the odd-year and even-year lines increased. Downstream migrating fry numbers increased in Aniva Bay, but not in southeastern Sakhalin or Iturup Island, implying that increasing adult returns, at least to the latter two areas, were the result of improved marine conditions. Changing marine conditions were also important for pink salmon returning to Aniva Bay as evidenced by higher marine survival. Paired comparisons of data from the three areas found that the range of correlation coefficients for pink salmon returns and indices of marine survival were wider than correlations for adult size. This is consistent with what one would expect if early marine conditions in coastal areas were primarily responsible for discrepancies among stocks in terms of abundance and survival, while final fish size was chiefly the result of conditions later when salmon were farther off shore. This study demonstrates the importance of long time series of abundance data at the fry (smolt) and adult life-history stages, which enable the partitioning of survival patterns between freshwater and marine environments. Further work is necessary to understand reasons for declining returns for some groups during the last several years.

Kasugai, K., M. Nagata, K.Takeuchi, M. Torao, Y. Murakami, Y. Sasaki, Y. Miyakoshi, and J.R. Irvine. 2016. Migratory timing of masu salmon and Dolly Varden smolts exiting the Uebetsu River near the Shiretoko World Heritage Site, Hokkaido, Japan, and potential angling effects. Ichthyol. Res. 63:181–186. DOI 10.1007/s10228-015-0477-4

Numbers of masu salmon and Dolly Varden in streams in the Shiretoko Peninsula, location of the Shiretoko World Heritage Site in north eastern Hokkaido, appear to be declining. One concern is whether masu salmon smolts continue to migrate during July, after the existing May to June angling closure established to protect migrating smolts in eastern Hokkaido. Smolt timing and relative abundances were monitored in the Uebetsu River near the World Heritage Site from May to July during 2005–2007. Each year some masu salmon smolts emigrated during July, especially in 2005 when 82% of smolts captured were caught that month. In contrast, most anadromous Dolly Varden smolts emigrated prior to early June when stream temperatures <8°C. Mean fork lengths of smolts in both species decreased during the runs. The current fishing closure period (May to June) may be insufficient to protect masu salmon smolts in this unique area from angling.

Kasugai, K., M. Torao, M. Nagata, and J.R. Irvine. 2013. The relationship between migration speed and release date for chum salmon *Oncorhynchus keta* fry exiting a 110 km northern Japanese river. Fisheries Science 79: 569–577. DOI: 10.1007/s12562-013-0615-8

The relationship between release date and migration speed was examined for hatchery chum salmon *Oncorhynchus keta* fry exiting the Nishibetsu River in eastern Hokkaido, northern Japan so that future releases might be scheduled so that fry arrive at the ocean during periods favoring high survival. Separate marked groups of chum salmon released in early April, mid-April, and early May in 2008, late March and mid-April in 2009, and mid-April in 2010 were recaptured with a rotary screw trap 12 km above the river mouth. Chum salmon in later release groups tended to migrate downstream faster than fish in earlier release groups. Those released after mid-April arrived in the lower river on average 9 days after release, while those released before mid-April arrived on average 26–28 days after release. Most marked fish arrived in the lower river during late April to mid-May. These results suggest that chum salmon are adapted to adjust their migratory speed so as to arrive at the ocean during a relatively discrete period, presumably during a time of high productivity favoring good survival.

MacDonald, B.L. & Grant, S.C.H. 2012. Pre-season run size forecasts for Fraser River Sockeye salmon (Oncorhynchus nerka) in 2012. DFO Can. Sci. Advis. Sec. Res. Doc. 2012/011. v + 64 pp. http://www.dfo-mpo.gc.ca/csas-sccs/Publications/ResDocs-DocRech/2012/2012_011-eng.html

In the absence of leading survival indicators, Fraser Sockeye forecasts have been particularly uncertain in recent years, due to the systematic declines in productivity exhibited by most stocks, which culminated in the lowest productivity on record in the 2005 brood year (2009 four year old and 2010 five year old returns). Subsequently, productivity appears to have improved in the 2006 (2010 four year old returns) and 2007 (2011 four year old returns) brood years. A single forecast scenario is presented in 2012. Forecasts were produced using either recent productivity or long-term productivity (full time series) models, which were selected on a stock-specific basis based on their ability to predict true returns over the full stock-recruitment time series. Jackknife, rather than retrospective analysis, was used to generate a time series of forecasts for the model evaluation process, and a revised set of criteria and procedures were used in the model selection process. An additional sensitivity analysis was conducted to examine model performance over the most recent period of data (brood years 1997–2004), which for most stocks exhibited lower productivity. To capture inter-annual random (stochastic) variability in Fraser Sockeye survival, forecasts are presented as standardized cumulative probabilities (10%, 25%, 50%, 75%, and 90%). The 2012 forecast indicates a one in ten chance (10% probability) the total Fraser Sockeye return will be at or below 750,000, and a nine in ten chance (90% probability) it will be at or below 6.6 million, assuming survival is similar to past observations. The mid-point of this distribution (50% probability) is 2.1 million (there exists a one in two chance the return will be above or below this value). Summer Run stocks, particularly Chilko, Late Stuart and Stellako, contribute 67% to the total return forecast, whereas Early Stuart (5%), Early Summer (17%) and Late Run stocks (11%) each contribute considerably less. The forecasted 2012 Fraser Sockeye return falls largely (up to a three in four chance, based on past observations) below the cycle average (3.8 million). This below average return forecast is attributed to the well below average 2008 brood year escapements of the Early Summer and Late Run stocks. If Fraser Sockeye productivity returns to the low trend of recent decades, the 2012 return has the potential to be amongst the lowest observed on this cycle.

McKinnell, S. and J.R. Irvine. 2016. On the relationship between survival of Chilko Lake sockeye salmon smolts and sea surface temperature and satellite derived chlorophyll concentrations. NPAFC Doc. 1648. 23 pp.

Nagata, M., Y. Miyakoshi, M. Fujiwara, K. Kasugai, D. Ando, M. Torao, H. Saneyoshi, and J.R. Irvine. 2016. Adapting Hokkaido hatchery strategies to regional ocean conditions can

improve chum salmon survivals and reduce variability. N. Pac. Anadr. Fish Comm. Bull. 6: 73–85. doi:10.23849/npafcb6/73.85.

Returns of chum salmon in Hokkaido, Japan, have increased remarkably since the 1970s, but there have been significant regional variations in survival. We surveyed chum salmon dynamics in several regions to test the hypothesis that variations in survival were related to the nearshore ocean environment, especially sea surface temperatures (SSTs). Time series analyses of return rate data for chum salmon from 14 regions around Hokkaido revealed 4 geographical groups (Japan Sea, Okhotsk Sea, Nemuro Strait, and Pacific Ocean) that had distinct survival patterns. In the Okhotsk Sea, Nemuro Strait, and Eastern Pacific Ocean, survival patterns were associated with SST patterns in the nearshore environment at the times and places occupied by young chum salmon. In the Okhotsk Sea, SSTs below 8°C appeared to restrict the off shore movement of juvenile chum salmon, while SSTs over 13°C accelerated their off shore movement, apparently resulting in salmon moving prematurely. We recommend that SSTs of 7–11°C are most appropriate for the release of chum salmon. As SSTs are expected to warm but also become increasingly variable as a result of climate change, we encourage
an adaptive approach whereby the nearshore environment is monitored in order to align juvenile chum salmon releases with optimal conditions.

Ogden, A.D., J.R. Irvine, M. O'Brien, N. Komick, G. Brown, and A. Tompkins. 2014. Canadian commercial catches and escapements of Chinook and coho salmon separated into hatchery- and wild-origin fish. NPAFC Doc. 1531. 19 pp.

This report presents preliminary estimates of Canadian salmon abundance time series partitioned into hatchery- and wild-origin fish for return years 1975–2012. We present a novel coded-wire tag based method to estimate the numbers of hatchery-origin coho and Chinook salmon in the Canadian catch, a method developed that also identifies the jurisdiction of origin of hatchery fish. Escapements were also estimated and partitioned into hatchery- and wild-origin coho and Chinook salmon using spawner escapement data, hatchery-origin escapement estimates, and hatchery release numbers. Missing data in time series of annual escapement were imputed using a method of infilling expected values in contingency tables. When taking into account the entire time series for each species, wild fish were always more abundant than hatchery fish in both catch and escapement, except for Chinook catches off the West Coast of Vancouver Island. Catches of migrating U.S. hatchery fish resulted in higher proportions of hatchery fish in the catch than escapements for coho on the West Coast Vancouver Island and Chinook throughout British Columbia. We are currently making refinements to the methods that may result in changes to the preliminary results presented here.

Ruggerone, G.T., B.A. Agler, B. Connors, E.V. Farley, Jr., J.R. Irvine, L. Wilson, and E.M. Yasumiishi. Pink and sockeye salmon interactions at sea and its influence on forecast error of Bristol Bay sockeye salmon. North Pacific Anadromous Fish Commission Bulletin 6: 349–361. doi:10.23849/npafcb6/349.361.

Total sockeye abundance in Alaska tends to be positively correlated with North Pacific pink salmon abundance, leading to questions about the importance of competition at sea between these two species. We examined annual scale growth of Bristol Bay sockeye salmon at sea and quantified forecast error of Bristol Bay sockeye stocks over the past 40 years to test the hypothesis that competition with pink salmon reduces the growth and survival of sockeye salmon. Sockeye growth during the second and third years at sea exhibited a strong alternating-year pattern and was negatively correlated with pink salmon abundance from eastern Kamchatka and central Alaska. In addition, forecast error of sockeye stocks from southeastern Bristol Bay (Kvichak, Naknek, Egegik, and Ugashik) exhibited an alternating-year pattern suggesting competition with pink salmon also affected survival. After standardizing forecast error relative to adjacent years, forecasts in even-years were too high and forecasts in odd-years were too low, likely reflecting competition with pink salmon during the year prior to the return year. Sockeye salmon from northwestern Bristol Bay (Wood River) exhibited weaker growth and forecast error relationships with pink salmon abundance, which is consistent with their more easterly distribution at sea. Sockeye scale growth during the first year at sea was not related to pink salmon abundance, as expected, and the observed greater growth during this early marine period in recent decades likely contributed to the greater abundance of Bristol Bay salmon. These findings highlight sockeye growth and survival dynamics that cannot be explained by physical oceanographic patterns and support the hypothesis that competition with pink salmon adversely affects the growth and survival of Bristol Bay sockeye salmon.

Ruggerone, G.T., and J.R. Irvine. 2018. Numbers and Biomass of Natural- and Hatchery-Origin Pink Salmon, Chum Salmon, and Sockeye Salmon in the North Pacific Ocean, 1925–2015. Marine and Coastal Fisheries: Dynamics, Management, and Ecosystem Science 10:152-168. DOI: 10.1002/mcf2.10023.

Numerical abundance and biomass values presented here for Pink Salmon *Oncorhynchus gorbuscha*, Chum Salmon *O. keta*, and Sockeye Salmon *O. nerka* in the North Pacific Ocean span 90 years (1925–2015), representing the most comprehensive compilation of these data to date. In contrast to less populous species of salmon, these species are more abundant now than ever, averaging 665 × 106 adult salmon each year (1.32 × 106 metric tons) during 1990–2015. When immature salmon are included, recent biomass estimates approach 5 × 106 metric tons. Following an initial peak during 1934–1943, abundances were low until the 1977 regime shift benefited each species. During 1990–2015, Pink Salmon dominated adult abundance (67% of total) and biomass (48%), followed by Chum Salmon (20%, 35%) and Sockeye Salmon (13%, 17%). Alaska produced approximately 39% of all Pink Salmon, 22% of Chum Salmon, and 69% of Sockeye Salmon, while Japan and Russia produced most of the remainder. Although production of natural-origin salmon is currently high due to generally favorable ocean conditions in northern regions, approximately 60% of Chum Salmon, 15% of Pink Salmon, and 4% of Sockeye Salmon during 1990–2015 were of hatchery origin. Alaska generated 68% and 95% of hatchery Pink Salmon and Sockeye Salmon, respectively, while Japan produced 75% of hatchery Chum Salmon. Salmon abundance in large areas of Alaska (Prince William Sound and Southeast Alaska), Russia (Sakhalin and Kuril islands), Japan, and South Korea are dominated by hatchery salmon. During 1990–2015, hatchery salmon represented approximately 40% of the total biomass of adult and immature salmon in the ocean. Density-dependent effects are apparent, and carrying capacity may have been reached in recent decades, but interaction effects between hatchery- and natural-origin salmon are difficult to quantify, in part because these fish are rarely separated in catch and escapement statistics. The following management changes are recommended: (1) mark or tag hatchery salmon so that they can be identified after release, (2) estimate hatchery- and natural-origin salmon in catches and escapement, and (3) maintain these statistics in publicly accessible databases.

Tompkins, A., S. Hamilton, J. Bateman, and J.R. Irvine. 2016. Canadian salmon catch and enhanced salmon production in 2014 and 2015 with a historical overview of recreational steelhead catches. NPAFC Doc. 1654 (Rev. 1). 9 pp.

Trudel, M., and S. Tucker. 2013. Depth distribution of 1SW Chinook salmon in Quatsino Sound, British Columbia, during winter. North Pacific Anadromous Fish Commission Document No. 1453.

We conducted a trawl survey in Quatsino Sound, British Columbia, to determine the vertical distribution of Chinook salmon during their first winter at sea (1SW) and to test the hypothesis that 1SW Chinook salmon migrate to deeper waters as they get larger. Fifteen-minute tows were performed at 0m, 15m, 30m, and 45 m at seven locations within Quatsino Sound and associated Inlets. We also performed a 15-minute tow at 60 m in four of these locations. Catches peaked at 30-45 m at three locations and were low but stable at all other sites, indicating that the vertical distribution of 1SW Chinook salmon varied among sites within Quatsino Sound. Overall, the size of 1SW Chinook salmon increased with depth, though a bimodal size-frequency distribution was observed at 60 m. Further research will thus be required to understand the processes affecting the distribution of Chinook salmon in the marine environment.

Velez-Espino, L.A., J.R. Irvine, I. Winther, R. Dunlop, G. Mullins, K. Singer, and N. Trouton. 2016. Robust and defensible mark-recapture methodologies for salmon escapement: modernizing the use of data and resources. North American Journal of Fisheries Management: 36(1):183–206. DOI: 10.1080/02755947.2015.1114540

Estimates of population size, required for most ecological investigations, are often achieved by mark–recapture experiments, frequently by applying pooled or stratified Petersen estimators. Unfortunately, the closure assumption required by Petersen estimators is frequently violated in the estimation of salmonid escapement, even though the consequences of this violation have been known for decades. We illustrate how biologists and analysts can and should make better use of statistical, mathematical, and computational advances in their analysis of mark–recapture data. Modern, easily applied approaches address and minimize the effects of violations to the model assumptions on which abundance estimators are based. Using examples from research estimating the numbers of Chinook Salmon *Oncorhynchus tshawytscha* escaping fisheries to spawn, this study demonstrates and provides evidence in support of the use of a robust and defensible approach to salmonid escapement estimation based on the analysis of individual encounter histories. The main attributes of the approach include (1) testing for demographic closure, (2) allowing different hypotheses about the demographic attributes and capture history of the studied population to be expressed within a model selection framework, encompassing suites of open- or closed-population approaches, and (3) optimizing the use of information by embracing the opportunities that mark–recapture experiments generate to increase our knowledge of salmonid ecology and hence improve both future study designs and management decisions. This study also demonstrates that discrepancies (positive) in abundance estimates produced with the Petersen estimator relative to those produced by the “best models” from robust estimators are inversely proportional to sampling rates.

Theme 2: Pacific Salmon and Steelhead Trout in a Changing North Pacific Ocean

Anttila, K, E.J. Eliason, K.H. Kaukinen, K.M. Miller, and A.P. Farrell. 2014. Facing warm temperatures during migration – cardiac mRNA responses of two adult sockeye salmon *Oncorhynchus nerka* populations to warming and swimming challenges. Journal of Fish Biology 84: 1439–1456.

The main findings of the current study were that exposing adult sockeye salmon *Onchorhynchus nerka* to a warm temperature that they regularly encounter during their river migration induced a heat shock response at an mRNA level, and this response was exacerbated with forced swimming. Similar to the heat shock response, increased immune defence-related responses were also observed after warm temperature treatment and with a swimming challenge in two different populations (Chilko and Nechako), but with some important differences. Microarray analyses revealed that 347 genes were differentially expressed between the cold (12–13° C) and warm (18–19° C) treated fish, with stress response (GO:0006950) and response to fungus (GO:0009620) elevated with warm treatment, while expression for genes involved in oxidative phosphorylation (GO:0006119) and electron transport chain (GO:0022900) elevated for cold-treated fish. Analysis of single genes with real-time quantitative PCR revealed that temperature had the most significant effect on mRNA expression levels, with swimming and population having secondary influences. Warm temperature treatment for the Chilko population induced expression of heat shock protein (*hsp*) *90α*, *hsp90β* and *hsp30* as well as *interferon-inducible protein*. The Nechako population, which is known to have a narrower thermal tolerance window than the Chilko population, showed even more pronounced stress responses to the warm treatment and there was significant interaction between population and temperature treatment for *hsp90β* expression. Moreover, significant interactions were noted between temperature treatment and swimming challenge for *hsp90α* and *hsp30*, and while swimming challenge alone increased expression of these *hsp*s, the expression levels were significantly elevated in warm-treated fish swum to exhaustion. In conclusion, it seems that adult *O. nerka* currently encounter conditions that induce several cellular defence mechanisms during their once-in-the-lifetime migration. As river temperatures continue to increase, it remains to be seen whether or not these cellular defences provide sufficient protection for all *O. nerka* populations.

Araujo, H.A., C.A. Holt, J.M.R. Curtis, R.I. Perry, J.R. Irvine, and C.G.J. Michielsens 2013. Building an ecosystem model using mismatched and fragmented data: a probabilistic network of early marine survival for coho salmon, *Oncorhynchus kisutch*, in the Strait of Georgia. Progress in Oceanography 115:41–52.

We evaluated the effects of biophysical conditions and hatchery production on the early marine survival of coho salmon *Oncorhynchus kisutch* in the Strait of Georgia, British Columbia, Canada. Due to a paucity of balanced multivariate ecosystem data, we developed a probabilistic network that integrated physical and ecological data and information from literature, expert opinion, oceanographic models, and in situ observations. This approach allowed us to evaluate alternate hypotheses about drivers of early marine survival while accounting for uncertainties in relationships among variables. Probabilistic networks allow users to explore multiple environmental settings and evaluate the consequences of management decisions under current and projected future states. We found that the zooplankton biomass anomaly, calanoid copepod biomass, and herring biomass were the best indicators of early marine survival. It also appears that concentrating hatchery supplementation during periods of negative PDO and ENSO (Pacific Decadal and El Niño Southern Oscillation respectively), indicative of generally favorable ocean conditions for salmon, tends to increase survival of hatchery coho salmon while minimizing negative impacts on the survival of wild juveniles. Scientists and managers can benefit from the approach presented here by exploring multiple scenarios, providing a basis for open and repeatable ecosystem-based risk assessments when data are limited.

Beacham, T. D., H. Andres Araujo, Strahan Tucker, and Marc Trudel. 2018. Validity of inferring size-selective mortality in Pacific salmon from scale circuli spacing. PLoS ONE in press

Size-selective mortality, either through predation during early marine rearing or lack of energy reserves during the first marine winter, has been suggested to be of paramount importance during the first year of marine rearing for many species of Pacific salmon. Scale circulus spacing has been interpreted as an index for body size, and we reviewed the effect of size-selective mortality on descriptive statistics for a scale circulus spacing index (SCSI). In order to invoke size selection as an important driver of mortality during the first year of ocean rearing, it is necessary to demonstrate not only that size-selective mortality is directed towards the smaller members of the population, but that the selective nature of the mortality can account for a substantial portion of the observed mortality. If the assumption is made that a random sample of a single juvenile population has been obtained, then studies that employ a SCSI to infer size-selective mortality coupled with a critical size must demonstrate a shift toward larger values of the SCSI, but also a concomitant reduction in the variance and range of the SCSI and an increase in the skewness and kurtosis of the SCSI values. Through simulation we found that the percentage of adults that displayed a SCSI value greater than the maximum observed in the juvenile sample was highly dependent on the initial juvenile sample size and size-selective mortality rate. Geographical distributions of juvenile Pacific salmon can be stratified by size, with larger individuals migrating earlier from local ocean entry locations than smaller individuals, and thus differential timing migration of juveniles based upon body size prior to the collection of the marine juvenile sample may be a more plausible explanation of published trends in the SCSI, rather than invoking substantial size-selective mortality and a critical size limit.

Beacham,T. D., Richard J. Beamish, John R. Candy, Strahan Tucker, Jamal H. Moss, and Marc Trudel. 2014. Stock-specific migration pathways of juvenile sockeye salmon in British Columbia waters and in the Gulf of Alaska. Transactions of the American Fisheries Society 143: 1386–1403.

We outlined the route and relative timing of juvenile Sockeye Salmon Oncorhynchus nerka migration by analyzing stock composition and relative CPUE in marine sampling conducted in coastal British Columbia and the Gulf of Alaska. Variation at 14 microsatellites was analyzed for 10,500 juvenile Sockeye Salmon obtained from surveys conducted during 1996–2011. Using a 404-population baseline, we identified the sampled individuals to 47 populations or stocks of origin. Stock compositions of the mixtures increased in diversity in more northerly sampling locations, indicating a general northward movement of juveniles. The primary migration route of Columbia River and Washington stocks was northward along the west coast of Vancouver Island, with a majority of the juveniles subsequently migrating through Queen Charlotte Sound and Dixon Entrance. Fraser River stocks migrated principally through the Strait of Georgia and Johnstone Strait. Some Fraser River populations, such as the Cultus Lake population, appeared to spend little time rearing in the Strait of Georgia, as individuals from this population were primarily observed in July samples from Hecate Strait, Dixon Entrance, and Southeast Alaska. Other Fraser River populations, such as the Chilko Lake and Quesnel Lake populations, were widely distributed during July surveys, as they were observed from the Gulf of Alaska to the Strait of Georgia. For the British Columbia central coast and Owikeno Lake stocks, not all individuals migrated northward in the summer: some individuals were still present in local areas during the fall and winter after spring entry into the marine environment. Juvenile Fraser River Sockeye Salmon dominated the catch of juveniles at the Yakutat, Prince William Sound, Kodiak Island, and Alaska Peninsula sampling locations. There was a wide divergence among stocks in dispersion among sampling locations.

Beacham,T. D., Richard J. Beamish, John R. Candy, Strahan Tucker, Jamal H. Moss, and Marc Trudel. 2014. Stock-specific size of juvenile sockeye salmon in British Columbia waters and in the Gulf of Alaska. Transactions of the American Fisheries Society 143: 876–888.

The variation at 14 microsatellites was analyzed for 10,500 juvenile Sockeye Salmon *Oncorhynchus nerka* obtained from coastal British Columbia and Gulf of Alaska surveys during 1996–2011. A 404-population baseline was used to determine the individual identifications of the fish sampled, with individuals being identified to 47 populations or stocks of origin. Columbia River and Washington juveniles were consistently larger than those from British Columbia and Alaska. During July, larger individuals from the same Fraser River stock were observed in more northerly locations compared with those in the Strait of Georgia. There was a relationship between the timing of northward migration from the Strait of Georgia and juvenile body size, with individuals from larger populations or stocks migrating earlier than individuals from smaller stocks which remain resident for longer. There was a wide divergence among stocks in juvenile size and dispersion among sampling locations.

Beacham, T. D., R.J. Beamish, J.R. Candy, S. Tucker, J.H. Moss, and M. Trudel. 2013. Stock-specific Migration Pathways and Size of Juvenile Sockeye Salmon (*Oncorhynchus nerka*) in Nearshore Waters and in the Gulf of Alaska. North Pacific Anadromous Commission Technical Report 9: 31–32.

Beacham,T. D., Richard J. Beamish, Chrys M. Neville, John R. Candy, Colin Wallace, Strahan Tucker, and Marc Trudel. 2016. Stock-specific size and migration of juvenile Coho Salmon in British Columbia and southeastern Alaskan waters. Marine and Coastal Fisheries 8: 292–314.

Variation at 17 microsatellites was analyzed for 5,270 juvenile Coho Salmon (*Oncorhynchus kisutch*) obtained from coastal British Columbia and Gulf of Alaska surveys during 1998-2012. A 270-population baseline was used to determine the individual identification of the fish sampled, with individuals identified to 22 stocks of origin. Columbia River and Washington juveniles were consistently larger than those from British Columbia and Alaska. During June, larger individuals within a stock were observed in more northerly locations compared with those in more southern sampling regions. There was a relationship between timing of northward migration and juvenile body size, with larger individuals from stocks migrating earlier than individuals from the same stocks which remain resident for longer. Stock composition was more diverse in the northern sampling regions compared with those in southern British Columbia. There was only a modest change in stock composition between fall and winter sampling in both the Strait of Georgia and west coast of Vancouver Island sampling regions, indicating that the extent of juvenile migration had largely been completed by the fall. There was a wide divergence among stocks in juvenile size and dispersion among sampling locations.

Beacham,T. D., Chrys M. Neville, John R. Candy, Strahan Tucker, and Marc Trudel. 2017. Is there evidence for biologically significant size-selective mortality of Coho Salmon during the first winter of marine residence? Transactions of the American Fisheries Society 146: 395–407.

In the current study we examined whether individual Coho Salmon (*Oncorhynchus kisutch*) in southern British Columbia had to achieve a sufficient size by the end of the first marine summer to be able to survive through the ensuing fall and winter. Descriptive statistics of seasonal weight distributions were determined. The expected body weight of an individual sampled in one season was projected to the next season with a growth equation tested on Pink Salmon (*O. gorbuscha*). Projected weight frequencies were then compared with observed weight frequencies in the next season in order to evaluate whether it was necessary to invoke size-selective mortality to explain the observed weight frequencies in the next season. After growth between July and September had been estimated, a maximum of 9% of the stock in the Strait of Georgia may have been subjected to size-selective mortality, far lower than the previously estimated 63% to 74% mortality in other studies. Similarly, between September and November, there was basically no size-selective mortality during this period, yet mortality of 48% between September and December had been reported previously. We could find no evidence of any critical size that age 1.0 Coho Salmon juveniles in southern British Columbia had to attain by the end of the first summer or fall of marine rearing to enable them to survive the subsequent winter in the ocean, and thus no support for the hypothesis that Coho Salmon had to achieve a sufficient size (the "critical" size) by the end of the first marine summer or fall to be able to survive during the winter of their first year of ocean rearing.

Beamish, R. J., Chrys M. Neville, Ruston M. Sweeting, Terry D. Beacham, Joy Wade, and Lingbo Li. 2016. Early ocean life history of Harrison River Sockeye Salmon and their contribution to the biodiversity of Sockeye Salmon in the Fraser River, British Columbia, Canada. Transactions of the American Fisheries Society 145: 348–362.

During a study of the early marine survival of Chinook Salmon *Oncorhynchus tshawytscha* and Coho Salmon *O. kisutch* in the Strait of Georgia from 1998 to 2010, moderate abundances of juvenile Sockeye Salmon *O. nerka* were observed to remain in the strait much longer than previously thought. In 2008, DNA stock identification showed that these juveniles were from the Harrison River, a population with a sea-type life history in which juveniles enter the ocean during the year of emergence from the gravel. Using information collected in 1998–2010, we describe the early ocean life and production of Harrison River sea-type Sockeye Salmon. Juveniles entered the Strait of Georgia from the Fraser River over an extended period, with most entering after mid-July—about 8 weeks later than lake-type juveniles, which had virtually all left the strait by that time. The September diets of sea-type juveniles were highly selective for hyperiid amphipods, which were not abundant in the zooplankton. Interaction with juvenile Pink Salmon *O. gorbuscha* during this early marine period was identified as potentially affecting the age structure of returning adults. Juvenile Sockeye Salmon remained in the strait until the fall and then moved offshore, where they remained until returning as age-3 or age-4 adults. There was a strong positive relationship between the September CPUE of juveniles in the Strait of Georgia and the total adult return of Harrison River Sockeye Salmon, indicating that total production in recent years was likely related to conditions in the strait. From 2005 to 2011, Harrison River Sockeye Salmon production exhibited a large increase in comparison with the total production of Sockeye Salmon in the Fraser River system. This recent increase in production of late-ocean-entering juveniles with a sea-type life history identifies the importance of managing for biodiversity of Sockeye Salmon populations within the Fraser River drainage.

Beamish, R.J. and C.M Neville 2016. Applying the Krogh Principle to Find Shortcuts to Understanding Pacific Salmon Production. North. Pac. Anad. Fish Comm. Bull. No. 6: 455–468, 2016

The Krogh Principle states that the selection of a particular animal can greatly facilitate understanding a particular mechanism. The principle could be applied to populations of Pacific salmon that are particularly productive within a region as a way of understanding more easily the mechanisms that regulate the productivity of all Pacific salmon. We show that an aggregate of Chinook salmon populations from the South Thompson River in the Fraser River drainage in British Columbia have anomalously high production, most likely related to their late ocean-entry life history. Similarly, sea-type Harrison River sockeye salmon from the same drainage also have a late ocean-entry life-history type and also have been exceptionally productive in recent years. These examples provide evidence that the exceptional production of late ocean-entry populations of Chinook and sockeye salmon may be caused by climate-related abundance increases in particular species of plankton in the early summer in the Strait of Georgia. The increased abundance of a preferred prey would allow the late ocean-entering juveniles to grow faster and be in better condition in the early marine period than the earlier ocean-entering juveniles. An understanding of the genetic, metabolic, and hormonal reasons for the improved productivity of these populations could help identify common mechanisms affecting productivity of other species of Pacific salmon.

Chen, J., M.W. Cooke, J.-F. Mercier, B. Ahier, M. Trudel, G. Workman, M. Wyeth, and R. Brown. 2015. A report on radioactivity measurements of fish samples from the west coast of Canada. Radiat. Prot. Dosim. 163: 261–266.

Even though many studies have shown that radioactive caesium levels in fish caught outside of Japan were below experimental detection limits of a few Bq kg^{-1}, significant public concern has been expressed about the safety of consuming seafood from the Pacific Ocean following the Fukushima-Daiichi nuclear accident. To address the public concerns, samples of commonly consumed salmon and groundfish harvested from the Canadian west coast in 2013 were analysed for radioactive caesium. None of the fish samples analysed in this study contained any detectable levels of ^{134}Cs and ^{137}Cs under given experimental setting with the average detection limit of ∼2 Bq kg^{-1}. Using a conservative worst-case scenario where all fish samples would contain ^{137}Cs exactly at the detection limit level and ^{134}Cs at half of the detection limit level (to account for much shorter half-life of ^{134}Cs), the resulting radiation dose for people from consumption of this fish would be a very small fraction of the annual dose from exposure to natural background radiation in Canada. Therefore, fish, such as salmon and groundfish, from the Canadian west coast are of no radiological health concern.

Chittenden, C.M., R. Sweeting, C.M. Neville, K. Young, M. Galbraith, E. Carmack, S. Vagle, M. Dempsey, J. Eert, R.J. Beamish. 2018. Estuarine and marine diets of out-migrating Chinook Salmon smolts in relation to local zooplankton populations, including harmful blooms. Estuarine, Coastal and Shelf Science 200:335–348.

Changes in food availability during the early marine phase of wild Chinook Salmon (O. tshawytscha) are being investigated as a cause of their recent declines in the Salish Sea. The marine survival of hatchery smolts, in particular, has been poor. This part of the Salish Sea Marine Survival Project examined the diet of young out-migrating Chinook Salmon for four consecutive years in the Cowichan River estuary and in Cowichan Bay, British Columbia, Canada. Local zooplankton communities were monitored during the final year of the study in the Cowichan River estuary, Cowichan Bay, and eastward to the Salish Sea to better understand the bottom-up processes that may be affecting Chinook Salmon survival. Rearing environment affected body size, diet, and distribution in the study area. Clipped smolts (hatchery-reared) were larger than the unclipped smolts (primarily naturally-reared), ate larger prey, spent very little time in the estuary, and disappeared from the bay earlier, likely due to emigration or mortality. Their larger body size may be a disadvantage for hatchery smolts if it necessitates their leaving the estuary prematurely to meet energy needs; the onset of piscivory began at a fork length of approximately 74 mm, which was less than the average fork length of the clipped fish in this study. The primary zooplankton bloom occurred during the last week of April/first week of May 2013, whereas the main release of hatchery-reared Chinook Salmon smolts occurs each year in mid-Maydthis timing mismatch may reduce their survival. Gut fullness was correlated with zooplankton biomass; however, both the clipped and unclipped smolts were not observed in the bay until the bloom of harmful Noctiluca was finished 20 days after the maximum recorded zooplankton abundance. Jellyfish medusa flourished in nearshore areas, becoming less prevalent towards the deeper waters of the Salish Sea. The sizable presence of Noctiluca and jellyfish in the zooplankton blooms may be repelling young salmon from a critical early marine food source and reducing their survival.

Debertin, D.J., J.R. Irvine, C.A. Holt, G.Oka, and M.Trudel. 2017. Marine growth patterns of southern British Columbia chum salmon explained by interactions between density-dependent competition and changing climate. Can J Fish Aquat Sci. 74: 1077–1087 (2017) dx.doi.org/10.1139/cjfas-2016-0265

Thirty-nine years of scale growth measurements from Big Qualicum River chum salmon (*Oncorhynchus keta*) in southern British Columbia demonstrated that competition and climate variation affect marine growth and age-at-maturity. A longitudinal study design that accounted for correlation among individuals revealed growth at all ages was reduced when the biomass of North American chum, sockeye (*Oncorhynchus nerka*), and pink salmon (*Oncorhynchus gorbuscha*) was high. When North Pacific Gyre Oscillation (NPGO) was positive, indicating increased primary productivity, predicted growth increased. Climate variation influenced competition effects. For instance, density-dependent competition effects increased when NPGO became more positive and Pacific Decadal Oscillation became more negative (indicating cool conditions), causing the greatest range in predicted scale size. Chum salmon are likely to exhibit continued reduction in growth at age due to increased ocean temperatures driven by climate change and high aggregate salmon biomass that includes hatchery releases. If evidence of biomass and climate effects presented here are common among Pacific salmon populations, reduction of hatchery releases should be considered.

DFO (Department of Fisheries and Oceans). 2015. Guide to Identifying Salmon and Char in the Arctic, Second Edition. By: P. Vecsei, K. Dunmall, and J. Reist. 24 pages. https://www.researchgate.net/publication/275771789_Guide_to_Identifying_Salmon_and_Char_in_the_Arctic_Second_Edition

There are many different kinds of salmon and char and many different local names for the same fish. Salmon and char species breed in fresh water but migrate to the sea to feed and grow. The external appearance of the same fish can look different depending on where and when they are harvested. In the sea, maturing salmon and char exhibit a 'Silver Phase Colour Pattern' but when in fresh water they can show a 'Spawning Phase Colour Pattern'. Char can also show a "Silver Phase Colour Pattern" when in fresh water as they may not spawn each year.

Salmon are being increasingly harvested in the Canadian Arctic. The numbers, kinds, and locations of salmon being harvested appear to be changing. Therefore, the presence of salmon may be indicating wider changes in the oceans or in the rivers. Monitoring variations in salmon harvest patterns in the Canadian Arctic will help us prepare for and adapt to a future, and perhaps different, Arctic environment. Increasing numbers of salmon may offer the possibility of new fisheries and may also interact with native fishes such as char. These increasing salmon harvests also indicate the need for outreach products to aid local fishers and community members for monitoring purposes.

The purposes of this guide are to assist in:

1. Differentiating among Pacific salmon, Atlantic Salmon, and char;

2. Identifying among the different kinds of Pacific salmon;

3. Identifying among the different kinds of char.

DFO. 2014. Pre-season run size forecasts for Fraser River Sockeye (*Oncorhynchus nerka*) Salmon in 2014. DFO Can. Sci. Advis. Spec. Resp. 2014/040. 46 pp. http://waves-vagues.dfo-mpo.gc.ca/Library/363748.pdf

DFO. 2015. Pre-season run size forecasts for Fraser River Sockeye (*Oncorhynchus nerka*) and Pink (*O. gorbuscha*) Salmon in 2015. DFO Can. Sci. Advis. Spec. Resp. 2015/014. 56 pp. http://waves-vagues.dfo-mpo.gc.ca/Library/363748.pdf

DFO. 2016. Pre-season run size forecasts for Fraser River Sockeye (*Oncorhynchus nerka*) in 2016. DFO Can. Sci. Advis. Sec. Spec. Resp. 2016/021. 68 pp. http://waves-vagues.dfo-mpo.gc.ca/Library/365999.pdf

DFO. 2017. Pre-season run size forecasts for Fraser River Sockeye (*Oncorhynchus nerka*) and Pink Salmon (*O. gorbuscha*) in 2017. DFO Can. Sci. Advis. Sec. Spec. Resp. 2017/016. 61 pp. http://waves-vagues.dfo-mpo.gc.ca/Library/40624808.pdf

The previous 4 reports, written by S.C.H. Grant and B.L. MacDonald, are produced annually to provide pre-season return forecasts for 27 individual Fraser Sockeye stocks. Background is provided on return and productivity trends for these stocks and marine and freshwater survival for the Chilko indicator stock. A variety of models are used to forecast return abundances for each stock, and these vary depending on model performance, and expert judgement. Bayesian methods are used to generate forecasts to capture uncertainty. Forecasts are presented for each stock across a probability distribution that ranges from the 10% to 90% probability that returns will fall at or below a forecast value. Environmental co-variates are used to capture Fraser River discharge and ocean temperatures experienced by these stocks during, respectively, their downstream migration as smolts, and their early ocean distributions in the Strait of Georgia.

DFO. 2014. Supplement to the pre-season return forecasts for Fraser River Sockeye Salmon in 2014. DFO Can. Sci. Advis. Spec. Resp. 2014/041. 57 pp. http://www.dfo-mpo.gc.ca/csas-sccs/Publications/ScR-RS/2014/2014_041-eng.html

DFO. 2015. Supplement to the pre-season return forecasts for Fraser River Sockeye Salmon in 2015. DFO Can. Sci. Advis. Sec. Spec. Resp. 2015/028. 49 pp. http://waves-vagues.dfo-mpo.gc.ca/Library/363787.pdf

DFO 2016. Supplement to the pre-season return forecasts for Fraser River Sockeye Salmon in 2016. DFO Can. Sci. Advis. Sec. Spec. Resp. 2016/047. 61 pp. http://waves-vagues.dfo-mpo.gc.ca/Library/363748.pdf

The three previous reports, edited by S.C.H. Grant and B.L. MacDonald, are produced annually to support the Fraser Sockeye return forecast process. These reports integrate research across the Fraser Sockeye life-history stages and ecosystem conditions to provide insight into survival of these populations for a particular return year. These reports synthesize information on adult Fraser River upstream migration conditions, escapements, spawner success, fry abundance and condition, the lake rearing conditions for fry (if available, and applicable to lake-type stocks only), and juvenile migration and ocean conditions in the Fraser River and Strait of Georgia (SOG). In addition, proportions of key lake-type stocks in various sampling components of the 2012 brood year are compared: 2012 escapements, 2014 smolt Fraser River downstream migration, 2014 juvenile ocean migration, and 2016 return forecasts.

Dunmall, K.D. 2018. Pacific salmon in the Canadian Arctic: Indicators of change. Ph.D. thesis, University of Manitoba, Winnipeg, MB . https://mspace.lib.umanitoba.ca/handle/1993/32856

The Arctic is rapidly changing. Warming temperatures are both facilitating new opportunities and threatening biodiversity. Despite a global effort to conserve biodiversity, and the recent acceleration of related conservation initiatives in Canada, species are already responding to a changing Arctic. However, our abilities to assess these changes, including shifting distributions and their impacts, are limited. Therefore, innovative approaches are necessary to focus the vastness of the Arctic to key habitats, the breadth of species diversity to key indicators of change, and to integrate knowledge in order to predict and manage a future Arctic. In this thesis, I establish Pacific salmon *Oncorhynchus* spp. as indicators of ecosystem-level change in the Canadian Arctic. More broadly, however, I have developed tools and strategies to help assess the impending biodiversity crisis in the Arctic. I developed a novel model to successfully apply citizen science to monitor rapidly shifting biodiversity in the Canadian Arctic and I extend the breadth of community-based monitoring across species and their habitats to encompass broad-scale areas and fine-scale assessments. By aligning thermal tolerances with thermal regimes at critical groundwater spring oases, I developed a novel model that predicts watersheds vulnerable to colonizations by salmon, and identifies the associated risk of competition with native char. I also use genetic tools to establish that chum salmon O. keta colonized the upper Mackenzie River at deglaciation, and that vagrants are currently accessing the Mackenzie River via coastal pathways. Together, I advance science regarding: 1) the application of citizen science to monitor biodiversity shifts in the Arctic; 2) predictions of distributional shifts to extreme environments; and 3) assessing the viability of the Arctic freshwater and marine environments as fish habitat over the past several thousand years. By integrating the subsistence way-of-life with scientific approaches, we can better manage the development opportunities and predict the conservation impacts in a future Arctic.

Dunmall, K.D., Mochnacz, N.J., Zimmerman, C.E., Lean, C., and Reist, J.D. 2016. Using thermal limits to assess establishment of fish dispersing to high elevation and high latitude watersheds. Can. J. Fish. Aquat. Sci. 73(12): 1750–1758. doi: 10.1139/cjfas-2016–2051

Distributional shifts of biota to higher latitudes and elevations are presumably influenced by species-specific physiological tolerances related to warming temperatures. However, it is establishment rather than dispersal that may be limiting colonizations in these cold frontier areas. In freshwater ecosystems, perennial groundwater springs provide critical winter thermal refugia in these extreme environments. By reconciling the thermal characteristics of these refugia with the minimum thermal tolerances of life stages critical for establishment, we develop a strategy to focus broad projections of northward and upward range shifts to the specific habitats that are likely for establishments. We evaluate this strategy using chum salmon (*Oncorhynchus keta*) and pink salmon (*Oncorhynchus gorbuscha*) that seem poised to colonize Arctic watersheds. Stream habitats with a minimum temperature of 4 °C during spawning and temperatures above 2 °C during egg incubation were most vulnerable to establishments by chum and pink salmon. This strategy will improve modelling forecasts of range shifts for cold freshwater habitats and focus proactive efforts to conserve both newly emerging fisheries and native species at northern and upper distributional extremes.

Dunmall, K.D., J.D. Reist, E.C. Carmack, J.A. Babaluk, M.P. Heide-Jørgensen, and M.F. Docker. 2013. Pacific Salmon in the Arctic: Harbingers of Change. In: F.J. Mueter, D.M.S. Dickson, H.P. Huntington, J.R. Irvine, E.A. Logerwell, S.A. MacLean, L.T. Quakenbush, and C. Rosa (eds.), Responses of Arctic Marine Ecosystems to Climate Change. Alaska Sea Grant, University of Alaska Fairbanks. doi:10.4027/ramecc.2013.07

Pacific salmon appear to be expanding their range into Arctic ecosystems and may be acting as effective sentinels of climate change. Salmon harvests voluntarily reported through the Pacific Salmon Collection Program (PSCP) suggest recent increases in both the abundance and distribution of Pacific salmon in the Arctic over the past decade. In the Canadian western Arctic, chum salmon have been harvested annually since 1997 and more abundant harvests appear to have increased in frequency. Pink salmon harvest has increased from the sporadic catch of individual fish prior to 2003 to 41 pink salmon reported in 2004, 18 reported in 2008, three reported in 2011, and eight reported in 2012 (i.e., predominantly in even-numbered years). Recent reports also expand the known distribution of this species upstream in the Mackenzie River, eastward in the Beaufort Sea and one putative pink salmon was recorded off the east coast of Greenland. Since 2003, one kokanee, one coho, seven Chinook, and ten sockeye salmon have also been reported in the Mackenzie River watershed. Multiple fish identified by local subsistence harvesters as “unusual” were captured near Arctic Bay, Nunavut, in 2011 and 2012. Although abundance and distribution data obtained from voluntary harvest reports need to be interpreted with caution, Pacific salmon may be following thermally suitable habitat northward and benefiting from increased productivity in the Arctic. Reduced sea ice extent and longer durations of open water in the Arctic may also facilitate expanded marine migrations of juvenile and adult salmon. Efforts to document the harvest of Pacific salmon will continue. Pacific salmon may be demonstrating new marine pathways that facilitate the expansion of other similarly opportunistic species and, as such, may be harbingers highlighting major arctic changes.

Farley, E.V. Jr., Starovoytoox, A., Naydenko, S., Heintz, R., Trudel, M., Guthrie, C., Eisner, L., and Guyon, J.R. 2013. Implications of a warming Bering Sea for Bristol Bay Sockeye Salmon. North Pacific Anadromous Fish Commission Technical Report 9: 255–258.

Freshwater, C., Burke, B.J., Scheuerell, M.D., Grant, S.C.H., Trudel, M., Juanes, F. 2017. Coherent population dynamics associated with sockeye salmon juvenile life history strategies. Can. J. Fish. Aquat. Sci. (in press) https://doi.org/10.1139/cjfas-2017-0251

Although the importance of diversity to maintaining metapopulation stability is widely recognized, the ecological characteristics that lead to synchronous dynamics within population aggregates are often unclear. We used a constrained dynamic factor analysis to explore patterns of covariance in productivity among 16 Fraser River sockeye salmon (*Oncorhynchus nerka*) conservation units (CUs). Specifically, we tested whether coherent trends in productivity covaried with five distinct ecological attributes: physical characteristics of nursery lakes, large-scale management interventions, genetic similarity, adult migration phenology, or juvenile migratory traits. The top-ranked model had two trends based on nursery lake characteristics and juvenile migratory traits. One trend represented the dynamics of CUs that rear in nursery lakes prior to ocean entry and undergo relatively rapid marine migrations. The second included a sea-type CU, Harrison River, which enters the marine environment without rearing in a nursery lake and migrates more slowly. The uniform response of lake-type CUs, as well as Harrison River CU's unique life history, suggests that coherent trends are structured by traits that covary with broad life history type, rather than fine-scale characteristics. Furthermore, we document substantial temporal variability in the strength of synchronous dynamics among Fraser River CUs. Greater synchrony in recent years suggests that the importance of shared regional drivers, relative to local processes, may have increased.

Freshwater, C., Marc Trudel, Terry D. Beacham, L. Godbout, C.-E. Neville, Strahan Tucker, and F. Juanes. 2016. Divergent migratory strategies associated with body size and ocean entry phenology in juvenile Sockeye Salmon. Canadian Journal of Fisheries and Aquatic Sciences 73: 1723–1732.

Survival during early marine life stages is hypothesized to contribute disproportionately to variation in salmonid recruitment, yet estimates of cumulative mortality are constrained by knowledge of how long juveniles reside in specific regions. We used otolith microstructure techniques to examine the relationship between migratory rate and ocean entry characteristics of juvenile sockeye salmon (*Oncorhynchus nerka*). We observed differences in migratory rate between catch locations that are consistent with divergent migratory behaviours. Individuals captured in northern regions were typically older, larger at ocean entry, and migrated more rapidly. Migratory rate was also correlated with entry size, phenology, population group, and year. Next, we compared "lingering" individuals captured nearshore during fall surveys to juveniles from the same populations captured during the peak summer migratory period. We determined that individuals that entered after 24 May and at smaller sizes (<85 mm) had a greater probability of being captured late in the year. Our findings demonstrate that the entry characteristics of sockeye salmon are strongly correlated with migratory variation within populations and suggest these traits may directly influence juvenile behaviour.

Freshwater, C., Marc Trudel, Terry D. Beacham, Chrys Neville, Strahan Tucker, and F. Juanes. 2015. Validation of daily increments and a marine entry check in the otoliths of Sockeye Salmon post-smolts. Journal of Fish Biology 87: 169–178.

Juvenile sockeye salmon *Oncorhynchus nerka* that were reared and smolted in laboratory conditions were found to produce otolith daily increments, as well as a consistently visible marine-entry check formed during their transition to salt water. Field-collected *O. nerka* post-smolts of an equivalent age also displayed visible checks; however, microchemistry estimates of marine-entry date using Sr:Ca ratios differed from visual estimates by *c.* 9 days suggesting that microstructural and microchemical processes occur on different time scales.

Freshwater, C., Marc Trudel, Terry D. Beacham, L. Godbout, C.-E. Neville, Strahan Tucker, and F. Juanes. 2016. Disentangling individual- and population-scale processes affecting a latitudinal size-gradient in Sockeye Salmon. Canadian Journal of Fisheries and Aquatic Sciences 73: 1190–1201.

We examined how individual processes contribute to a latitudinal gradient in body size within populations of migrating juvenile sockeye salmon (*Oncorhynchus nerka*) while simultaneously testing for size-selective mortality, a potentially confounding population scale process. Using otolith microstructure techniques and structural equation modeling, we determined that ocean entry size and phenology had strong, direct effects on size at capture. Population identity and freshwater age also had strong indirect effects, moderated by size at entry. Conversely, marine growth rates immediately after entry or before capture were relatively weak predictors of size during migration. We next tested for shifts in size distribution indicative of selective mortality, but detected no evidence of smaller individuals experiencing lower survival during early marine migrations. These results indicate that the migratory distributions of juvenile sockeye salmon are influenced by body size and that this variation is predominantly driven by traits present prior to freshwater outmigration, rather than marine growth or differential survival. We suggest integrating individual variation in migratory characteristics with the effects of environmental conditions experienced en route to provide an improved understanding of migratory species.

Freshwater, C., Marc Trudel, Terry D. Beacham, Sue C.H. Grant, Stewart C. Johnson, Chrys-Ellen M. Neville, Strahan Tucker, and Francis Juanes. 2017. Effects of density during freshwater and early marine rearing on juvenile sockeye salmon size, growth, and migration. Marine Ecology Progress Series 579: 97–110.

We tested for density-dependent effects on the body size, ocean entry date, growth rate, and migration speed of juvenile sockeye salmon *Oncorhynchus nerka* in 2 yr with contrasting competitor densities during freshwater residence (intraspecific), as well as the first 2 yr of marine residence (intra- and interspecific). Juvenile sockeye salmon entering the marine environment during a year with high competitor densities (conspecifics and 9 other pelagic species groups) were, on average, 11% smaller and entered the ocean almost a week earlier. Differences between the high- and low-density years in entry size, but not entry date, were strongest in nursery lakes with high parental spawner abundance, consistent with density-dependent effects on freshwater growth. Mean daily growth rates of sockeye salmon during early marine residence did not vary between years after accounting for variation in ocean entry size and timing, even though the catch per unit effort of the most abundant juvenile salmon species increased more than 5-fold. However, juvenile sockeye salmon entering in the high-density year did migrate away from their ocean entry points significantly more rapidly (estimated ~40% increase in body lengths per second). Our results suggest that juvenile sockeye salmon growth during early marine residence may not be strongly limited by competition and that shifts in migration speed or spatial distribution may buffer individuals from competitive interactions.

Grant, S.C.H., B.L. MacDonald, and C.G.J. Michielsens. 2017. Fraser River sockeye: abundance and productivity trends and forecasts. NPAFC Doc. 1722. 8 pp.

Fraser sockeye salmon total returns have varied substantially over time. In the past decade, overall returns improved on the current large cycle year (2010 and 2014) compared to previous decades but declined on the other cycles. In 2016, returns (853,000) were the lowest on the 100+ year record for the Fraser Sockeye aggregate. Marine and freshwater factors both contribute to the variability in returns. Chilko is the only sockeye salmon stock where total survival can consistently be partitioned into freshwater and marine survival over a long time series. This stock also contributes significant proportions to the total returns in most years. In the past decade, Chilko sockeye have generally exhibited average to above average freshwater survival, compared to the previous period in the 1990's where freshwater survival had been below average. Marine survival on the other hand has not improved to the same extent since the decline in the 1990s and remained predominantly below average in the last decade. In the 2015 and 2016 return years, poor marine survival drove the poor returns for Chilko sockeye. In the past few years (second half of 2013 to 2016), warmer ocean temperature anomalies (the 'warm blob') occurred in the Northeast Pacific Ocean. Broadly, both marine and freshwater conditions were generally warmer than average during this period. Although these warm conditions coincided with particularly poor marine survival for Chilko Sockeye, and poor productivity for similar summer-run (based on adult sockeye migration timing in the Fraser River) stocks, productivity of other stocks has been variable. Median predictions of Fraser Sockeye returns in 2017 (4.4 million) are expected to be below the cycle average (8.4 million), due to warmer temperatures that may influence particularly the more abundant summer run stocks, including Chilko sockeye.

Hertz, E., <u>M. Trudel</u>, R.D. Brodeur, E.A. Daly, L. Eisner, E.V. Farley Jr, J.A. Harding, R.B. MacFarlane, S. Mazumder, J.H. Moss, J.M. Murphy, and A. Mazumder. 2015. Continental-scale variability in the feeding ecology of juvenile Chinook salmon along the coastal Northeast Pacific Ocean. Mar. Ecol. Prog. Ser. 537: 247–263.

Trophic interactions within and among species vary widely across spatial scales and species' ontogeny. However, the drivers and implications of this variability are not well understood. Juvenile Chinook salmon *Oncorhynchus tshawytscha* have a wide distribution, ranging from northern California to the eastern Bering Sea in North America, but it is largely unknown how their feeding ecology varies and changes with ontogeny across this range. We collected juvenile Chinook salmon and zooplankton using standardized protocols along the coastal Northeast Pacific Ocean. Using a combination of stomach contents and stable isotopes of nitrogen ($\delta^{15}N$) and carbon ($\delta^{13}C$) to characterize feeding ecology, we found regional differences in prey utilization by juvenile Chinook salmon. With growth and ontogeny, juvenile salmon in all regions became equilibrated with oceanic isotopic values. There were regional differences in the $\delta^{13}C$ values of juvenile Chinook salmon that may correspond to regional differences in sea surface temperature. There were also regional differences in stable isotope-derived trophic level, and these estimates differed from those derived from stomach contents, possibly due to the different periods over which these metrics integrate. Dietary niche width, as indicated by stable isotopes, corresponded to the expected dietary diversity from stomach contents, combined with the isotopic variability seen in baseline values. Our results indicate strong geographic and ontogenetic differences in feeding ecology of juvenile Chinook salmon. These differences are likely influenced by a combination of ocean-entry date, ocean-entry size, ontogeny, growth rates and regional conditions.

Hertz, E., <u>M. Trudel</u>, M.K. Cox, and A. Mazumder. 2015. Effects of fasting and nutritional restriction on the isotopic ratios of nitrogen and carbon: a meta-analysis. Ecol. Evol. 5: 4829–4839.

Many organisms experience fasting in their life time, and this physiological process has the potential to alter stable isotope values of organisms, and confound interpretation of food web studies. However, previous studies on the effects of fasting and starvation on stable isotopes show disparate results, and have never been quantitatively synthesized. We performed a laboratory experiment and meta-analysis to determine how stable isotopes of $\delta^{15}N$ and $\delta^{13}C$ change with fasting, and we tested whether moderators such as taxa and tissue explain residual variation. We collected literature data from a wide variety of taxa and tissues. We surveyed over 2000 papers, and of these, 26 met our selection criteria, resulting in 51 data points for $\delta^{15}N$, and 43 data points for $\delta^{13}C$. We determine that fasting causes an average increase in the isotopic value of organisms of 0.5‰ for $\delta^{15}N$ and that the only significant moderator is tissue type. We find that the overall effect size for $\delta^{13}C$ is not significant, but when the significant moderator of tissue is considered, significant increases in blood and whole organisms are seen with fasting. Our results show that across tissues and taxa, the nutritional status of an organism must be considered when interpreting stable isotope data, as fasting can cause large differences in stable isotope values that would be otherwise attributed to other factors.

Hertz, E., Marc Trudel, Rana W. El-Sabaawi, Strahan Tucker, Terry D. Beacham, and Asit Mazumder. 2013. Interannual and Spatial Variability in the Feeding Ecology of Juvenile Chinook Salmon and Effects on Survival and Growth. North Pacific Anadromous Commission Technical Report 9: 97–98.

Hertz, E., M.Trudel, S. Tucker, T. D. Beacham, and A.Mazumder. 2017. Overwinter shifts in the feeding ecology of juvenile Chinook Salmon. ICES Journal of Marine Science 74: 226–233.

Winter is thought to be a critical period for many fish in the ocean, but their ecology during this time tends to be poorly understood. We quantified the feeding ecology of juvenile Chinook salmon (*Oncorhynchus tshawytscha*) off the west coast of Vancouver Island in British Columbia, Canada, in autumn and winter to determine how seasonality could affect diet. Using stomach contents and stable isotopes, we tested the hypothesis that the winter diet of juvenile Chinook salmon differs from that of the autumn diet. Stomach-content data showed a shift from a primary reliance on amphipods in autumn to euphausiids in winter. This finding was generally corroborated by the stable isotope analysis, although mixing models suggested a greater contribution of fish prey to the diet in both autumn and winter. Understanding the diet of fish during winter may provide useful information for management as a first step in understanding the factors influencing mortality across life stages.

Hertz, E., M.Trudel, S. Tucker, T. D. Beacham, C. Parken, D. Mackas, and A. Mazumder. 2016. Influences of ocean conditions and feeding ecology on the survival of juvenile Chinook Salmon (*Oncorhynchus tshawytscha*). Fisheries Oceanography 25: 407–419.

Recruitment variability in many fish populations is postulated to be influenced by climatic and oceanographic variability. However, a mechanistic understanding of the influence of specific variables on recruitment is generally lacking. Feeding ecology is one possible mechanism that more directly links ocean conditions and recruitment. We test this mechanism using juvenile Chinook Salmon (*Oncorhynchus tshawytscha*) collected off the west coast of Vancouver Island, British Columbia, Canada, in 2000–2009. Stable isotopes of carbon ($\delta^{13}C$), an indicator of temperature or primary productivity, and nitrogen ($\delta^{15}N$), an indicator of trophic position, were taken from muscle tissues of genetically stock-identified salmon. We also collated large-scale climate indices (e.g., Pacific Decadal Oscillation, North Pacific Gyre Oscillation), local climate variables (e.g., sea surface temperature) and copepod community composition across these years. We used a Bayesian network to determine how ocean conditions influenced feeding ecology, and subsequent survival rates. We found that smolt survival of Chinook Salmon is predicted by their $\delta^{13}C$ value, but not their $\delta^{15}N$. In turn, large-scale climate variability determined the $\delta^{13}C$ values of salmon, thus linking climate to survival through feeding ecology, likely through qualities propagated from the base of the food chain.

Hertz, E. J. M., Marc Trudel, Rana W. El-Sabaawi, Strahan Tucker, John F. Dower, Terry D. Beacham, Andrew M. Edwards, and Asit Mazumder. 2016. Hitting the moving target: modelling gradual ontogenetic niche shifts using stable iostopes. Journal of Animal Ecology 85: 681–691.

1. Ontogenetic niche shifts are widely prevalent in nature and are important in shaping the structure and dynamics of ecosystems. Stable isotope analysis is a powerful tool to assess these shifts, with $\delta^{15}N$ providing a measure of trophic level and $\delta^{13}C$ a measure of energy source.
2. Previous applications of stable isotopes to study ontogenetic niche shifts have not considered the appreciable time lag between diet and consumer tissue associated with isotopic turnover. These time lags introduce significant complexity into field studies of ontogenetic niche shifts.
3. Juvenile Chinook salmon (*Oncorhynchus tshawytscha*) migrate from freshwater to marine ecosystems and shift their diet from feeding primarily on invertebrates to feeding primarily on fish. This dual ontogenetic habitat and diet shift, in addition to the long time lag associated with isotopic turnover, suggests that there is potential for a disconnect between the prey sources that juvenile salmon are consuming, and the inferred prey sources from stable isotopes.
4. We developed a model that considered ontogenetic niche shifts and time lags associated with isotopic turnover, and compared this 'ontogeny' model to one that considered only isotopic turnover. We used a Bayesian framework to explicitly account for parameter uncertainty.
5. Data showed overwhelming support for the ontogeny model relative to the isotopic turnover model. Estimated variables from best model fits indicate that the ontogeny model predicts a much greater reliance on fish prey than does the stomach content data. Overall, we found that this method of quantifying ontogenetic niche shifts effectively accounted for both isotopic turnover and ontogenetic diet shifts; a finding that could be widely applicable to a variety of systems.

Irvine, J. R. and L. Logerwell. 2015. PICES-NPAFC Collaborative Workshop: Linkages between the winter distribution of Pacific salmon and their marine ecosystems and how this might be altered with climate change. NPAFC Newsletter No. 37 (February 2015): 25–27.

Irvine, J. R., C. J. G. Michielsens, M. O'Brien, B.A. White, and M. Folkes. 2014. Increasing dominance of odd-year returning Pink Salmon. Transactions of the American Fisheries Society 4(14): 939–956.

Irvine, J.R., C.J.G. Michielsens, M. O'Brien, B.A. White & M. Folkes. 2014 Increasing Dominance of Odd-Year Returning Pink Salmon, Transactions of the American Fisheries Society 143:4, 939–956, DOI: 10.1080/00028487.2014.889747

The hypothesis that abundance patterns differ between even- and odd-year returning Pink Salmon *Oncorhynchus gorbuscha* was examined using data from the eastern and western North Pacific Ocean, northern and southern British Columbia, and biologically based conservation units, which are Canadian groupings of salmon that are genetically and/or ecologically distinct from each other. Detailed data from (mostly) southern British Columbia were examined to test hypotheses that the differences between even- and odd-year broodlines were due to fishing, broodline interactions, limitations in freshwater or the ocean, and/or density dependence. The odd-year broodline has become increasingly predominate over the genetically distinct even-year broodline on both sides of the Pacific and in five of six British Columbia regions. Five analytical approaches revealed abundances were generally increasing for odd-year conservation units and declining or stable for even-year conservation units. Recent increases in odd-year spawner abundance in southern British Columbia were correlated with decreased fishery exploitation, but exploitation was higher for odd-year than for even-year salmon, refuting the hypothesis that differential exploitation is responsible for the changing dominance. Significant negative interactions between even- and odd-year broodlines were found in several of the British Columbia regions tested, but there was little evidence of competition between broodlines in the marine environment. Odd-year populations in the Fraser River increased despite density-dependent reductions in freshwater production, while there was no indication of changes in marine productivity. Our results, combined with literature findings indicating a more southerly glacial refugium for odd-year than for even-year Pink Salmon and temperature-related survival differences between these broodlines, suggest that recent climate conditions are benefiting odd-year returning Pink Salmon more than even-year salmon, especially in the southern part of their range.

Jeffries, K.M. Scott G. Hinch, Marika Kirstin Gale, Timothy D. Clark, Andrew G. Lotto, Matthew T. Casselman, Shaorong Li, Erin L. Rechisky, Aswea D. Porter, David W. Welch and Kristina M. Miller. 2014. Immune response genes and pathogen presence predict migration survival in wild salmon smolts. Molecular Ecology 23:5803–5815.

We present the first data to link physiological responses and pathogen presence with subsequent fate during migration of wild salmonid smolts. We tagged and non-lethally sampled gill tissue from sockeye salmon (*Oncorhynchus nerka*) smolts as they left their nursery lake (Chilko Lake, BC, Canada) to compare gene expression profiles and freshwater pathogen loads with migration success over the first ~1150 km of their migration to the North Pacific Ocean using acoustic telemetry. Fifteen per cent of smolts were never detected again after release, and these fish had gene expression profiles consistent with an immune response to one or more viral pathogens compared with fish that survived their freshwater migration. Among the significantly upregulated genes of the fish that were never detected postrelease were MX (interferon-induced GTP-binding protein Mx) and STAT1 (signal transducer and activator of transcription 1-alpha/beta), which are characteristic of a type I interferon response to viral pathogens. The most commonly detected pathogen in the smolts leaving the nursery lake was infectious haematopoietic necrosis virus (IHNV). Collectively, these data show that some of the fish assumed to have died after leaving the nursery lake appeared to be responding to one or more viral pathogens and had elevated stress levels that could have contributed to some of the mortality shortly after release. We present the first evidence that changes in gene expression may be predictive of some of the freshwater migration mortality in wild salmonid smolts.

Jenkins, E.S., Trudel, M., Dower, J.F., El-Sabaawi, R.W., and Mazumder, A., 2013. Density-dependent trophic interactions between juvenile Pink (Oncorhynchus gorbuscha) and Chum Salmon (O. keta) in coastal marine ecosystems of British Columbia and Southeast Alaska. North Pacific Anadromous Fish Commission Technical Report 9: 136–138.

Journey, M., M. Trudel, G. Young and B.R. Beckman. 2018. Testing the Trophic Gauntlet Hypothesis: physiological measures of juvenile salmon growth in Johnstone and Queen Charlotte Straits. Fish. Oceanogr. 27: 174–183.

Juvenile salmon traveling northwestward to the Pacific Ocean from the Strait of Georgia migrate through and take residence in both Johnstone and Queen Charlotte Straits. Johnstone Strait is a narrow and deep passage that is tidally mixed daily, resulting in a nearly isothermal water column, surface to the bottom (approximately 250 m). The trophic gauntlet hypothesis (McKinnell, Curchitser, Groot, Kaeriyama, & Trudel, 2014) suggests that Johnstone Strait provides a poor growth environment for fish required to transit this area during their migration, due to the oceanographic conditions found there. Using insulin-like growth factor-1 (IGF1), a hormone used to assess short-term growth (within 5–7 days) in fishes, growth was measured in individual juvenile salmon from five species in the Northern Strait of Georgia, Johnstone Strait, Queen Charlotte Strait, and Queen Charlotte Sound in the summer of 2012, 2013, and

2014. All five juvenile salmon species had significantly lower IGF1 concentration in both Johnstone and Queen Charlotte Straits as compared to the Northern Strait of Georgia. These results are consistent with some aspects of the tropic gauntlet hypothesis as growth of juvenile salmon in both Johnstone and Queen Charlotte Straits were significantly lower than found in the Northern Strait of Georgia across all salmon species and all years. In addition, these results demonstrate the utility of growth indices for assessing the effects of environmental variation on juvenile salmon in the presence of a strong ecological driver.

Mahony, A.M., S.C. Johnson, C.M. Neville, M.E. Thiess and S.R.M. Jones. 2017. *Myxobolus arcticus* and *Parvicapsula mnibicornis* infections in sockeye salmon *Oncorhynchus nerka* following downstream migration in British Columbia. Dis. Aquat. Org. 126:89–98.

Factors influencing the health of sockeye salmon *Oncorhynchus nerka* in British Columbia, Canada, are important for fisheries management and conservation. Juvenile salmon originating from the Fraser River were screened for 3 enzootic parasites (Myxobolus arcticus, Parvicapsula minibicornis, Ceratonova shasta) and the bacterium Renibacterium salmoninarum. Fish were collected from the Strait of Georgia in 2010, 2011 and 2012 and genotyped to stock of origin. Trends in infection status were estimated by year, spawning zone and catch area. The annual prevalences of P. minibicornis (n = 1448) were 23.3, 6.5 and 8.1%, and for M. arcticus (n = 1343), annual prevalences were 40.4, 66.3 and 27.4%, respectively. Logistic regression showed that P. minibicornis was most strongly associated with salmon from the lower Fraser River spawning zone and increased with distance caught from the mouth of the Fraser River. In contrast, infection with M. arcticus was most strongly associated with salmon from the middle Fraser River spawning zone, and there was no trend related to distance from the Fraser River. Neither R. salmoninarum nor C. shasta were detected. These observations are discussed in the context of salmon life history and pathogen biology.

Mazumder, A., Brodeur, R., Eisner, L., Farley, E., Harding, J., MacFarlane, B., Mazumder, S., Moss, J., and Trudel, M. 2013. Continental-scale comparative analyses of feeding and resource ecology of juvenile Chinook Salmon along the Pacific Coast of North America. North Pacific Anadromous Fish Commission Technical Report 9: 99.

McKinnell, S.M., E. Curchitser, K. Groot, and M. Kaeriyama, and M. Trudel. 2014. Oceanic and atmospheric extremes motivate a new hypothesis for variable marine survival of Fraser River sockeye salmon. Fish. Oceanogr. 23: 322–341.

In spite of a relatively optimistic pre-season forecast, the total return of adult sockeye salmon (*Oncorhynchus nerka*) to the Fraser River (British Columbia, Canada) in 2009 was the lowest recorded since quantitative records began in the late 1940s. A plausible mechanism is proposed that links a sequence of extreme oceanic and climatic events to poor marine survival. It began with record-setting snow packs in the coastal mountain range during the winter of 2007 that led to the development of unprecedented oceanographic conditions in the spring of 2007 from Queen Charlotte Strait in central British Columbia to Southeast Alaska. When combined with equally extreme atmospheric anomalies in the region in the spring of 2007, with a winter wind regime persisting through July, a coastal surface ocean with characteristics that are known to be associated with lower marine survival was established. Most of the sockeye salmon that were expected to return to the Fraser River as adults in 2009 passed through this atypical ocean as juveniles on their migration to the open ocean in 2007. A trophic gauntlet hypothesis is proposed as a new paradigm to describe the oceanic environment faced by sockeye salmon after they emigrate northward from the Strait of Georgia. The hypothesis identifies a new type of high nutrient low chlorophyll region that can explain how oceanographic extremes at critical locations along the migration route beyond the Strait of Georgia can reduce marine survival in some years.

McKinnell, S., and <u>M. Trudel</u>. 2014. SALOSIS (Salmon Ocean Surveillance Information System. North Pacific Anadromous Fish Commission Document No. 1524. 22 pp.

The overarching objective is to understand the distribution of Pacific salmon in relation to oceanographic features that can be measured remotely from satellites or other global ocean observing assets. This first pilot project examined the relation between salmon and sea surface temperature. An historical data analysis and literature review was conducted to develop and understanding of monthly sea surface temperature frequency distributions where pink salmon and sockeye salmon were caught beyond territorial limits in the North Pacific Ocean, particularly in the Gulf of Alaska where British Columbia salmon are known to be abundant. For comparison, a preliminary exploration of the northwestern North Pacific was conducted using Hokkaido University's HUFODAT database to understand the relationship between salmon distribution there and sea surface temperature. Maps of suitable thermal habitat for pink and sockeye salmon in the Gulf of Alaska were computed for the months April through July 2013 using the NOAA/OIv2SST 1° x 1° lat/long database. Extrapolation of suitable thermal habitat, based on measurements in the Gulf of Alaska, to the northwestern North Pacific did not accurately represent known distributions. Salmon are known to be subarctic animals, so the monthly position of the Subarctic Boundary was computed monthly for 2013 using salinity data that are transmitted from profiling lagrangian floats (deployed by Project Argo) to the USGODAE Argo server. While the Subarctic Boundary may potentially be a relevant feature in the northwestern North Pacific, in the eastern North Pacific, it veers sharply southward and does not correspond with the known offshore limits to salmon distribution. SST frequency data where salmon have been known to be caught, combined with the monthly SST data described above for 2013 produced monthly coloured maps of salmon relative vulnerability to IUU fishing at 1° x 1° lat/long. Vulnerability is a function of the overlap of the salmon-SST probability distribution function (pdf) with the SST pdf. No overlap indicates no vulnerability to IUU fishing, and complete overlap indicates high exposure. Mismatches in some regions between suitable thermal habitat and known salmon distributions suggests that surveillance planning will require a more comprehensive view of salmon oceanic habitat than can be ascertained from SST alone. Ocean colour, hydrography, and altimetry are sources of additional information that could be fruitfully explored, perhaps within the context of an ocean circulation model

McKinnell, S., and <u>M. Trudel</u>. 2015. SALOSIS Project: Associations Between Hydrographic Properties of the North Pacific Ocean and Salmon Catches on the High Seas Along 155°E, 175°E, and 145°W From 1988–2001. NPAFC Doc. No. 1593. 36 pp.

The distribution of Pacific salmon is associated with the major oceanographic features that define the Subarctic North Pacific Ocean and Bering Sea. The region is characterized by a strong seasonal cycle, relatively fresh salinity, and cooler temperatures with winter sea ice at the northern and western margins. The intent of this study was to examine oceanic properties at and below the surface in the hope of finding an index of where Pacific salmon are found, and where they are not found. Historically, the most readily measured and easily available hydrographic data are sea surface temperatures (SST); a parameter that can also be measured remotely from satellites. Three meridians of longitude (155°E, 175°E, and 145°W) were selected initially for closer inspection because training vessels from Hokkaido University had repeatedly combined gillnet fishing and hydrographic casts along meridional transects between 1988 and 2001. The southernmost stations along 145°W were not at low enough latitudes to understand where the southern limit occurred. Therefore, study focused on the two meridians in the western North Pacific. Over the years, gillnet fishing along 155°E generally occurred in two temporal modes: one in early June and one in late June. Fishing along 175°E occurred in late July. The analysis of Pacific salmon range extremes found that no single oceanographic variable provided a no risk criterion for surveillance. Both latitude and SST (which are highly correlated) were effective in minimizing the latitudinal overlap between gillnet fishing operations with no catch and those producing catch in the area where (and when) the fish were caught. It does not seem likely that a single criterion can be found that applies to the entire Pacific basin but a full-scale analysis of this was not conducted. Future work should focus on filling data gaps with new sampling, and providing an assessment to develop criteria that provide the maximum benefit of surveillance from the least cost of ship/aircraft operations.

Miller, K.M., A. Teffer, S. Tucker, S. Li, A.D. Schulze, M. Trudel, F. Juanes, A. Tabata, K.H. Kaukinen, N.G. Ginther, T.J. Ming, S.J. Cooke, M. Hipfner, D.A. Patterson, and S.G. Hinch. 2014. Infectious disease, shifting climates and opportunistic predators: cumulative factors potentially impacting wild salmon declines. Evol. Appl. 7: 812-855.

Emerging diseases are impacting animals under high-density culture, yet few studies assess their importance to wild populations. Microparasites selected for enhanced virulence in culture settings should be less successful maintaining infectivity in wild populations, as once the host dies, there are limited opportunities to infect new individuals. Instead, moderately virulent microparasites persisting for long periods across multiple environments are of greatest concern. Evolved resistance to endemic microparasites may reduce susceptibilities, but as barriers to microparasite distributions are weakened, and environments become more stressful, unexposed populations may be impacted and pathogenicity enhanced. We provide an overview of the evolutionary and ecological impacts of infectious diseases in wild salmon and suggest ways in which modern technologies can elucidate the microparasites of greatest potential import. We present four case studies that resolve microparasite impacts on adult salmon migration success, impact of river warming on microparasite replication, and infection status on susceptibility to predation. Future health of wild salmon must be considered in a holistic context that includes the cumulative or synergistic impacts of multiple stressors. These approaches will identify populations at greatest risk, critically needed to manage and potentially ameliorate the shifts in current or future trajectories of wild populations.

Miller, K.M., A. Teffer, S. Tucker, S. Li, A.D. Schulze, M. Trudel, F. Juanes, A. Tabata, K.H. Kaukinen, N.G. Ginther, T.J. Ming, S.J. Cooke, J.M. Hipfner, D.A. Patterson, and S.G. Hinch. 2014. Infectious disease, shifting climates and opportunistic predators: cumulative factors potentially impacting wild salmon declines. Evolutionary Applications 7: 812-855. doi: 10.1111/eva.12164

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Miller, K.M., S. Li, T. Ming, K. Kaukinen, N. Ginther, D.A. Patterson, and M. Trudel. 2017. Survey of infectious agents detected in juvenile Chinook and sockeye salmon from British Columbia and Washington. NPAFC Doc. 1718.

The contribution of infectious diseases to annual variations in salmon survival in the ocean is poorly understood, largely owing to the inability to observe mortality. We developed a novel microfluidics quantitative PCR system to survey 46 infectious agents (viruses, bacteria, fungal and protozoan parasites), known or suspected to cause disease in salmon worldwide, in 96 samples at once. The platform was applied to juvenile Sockeye (*Oncorhynchus nerka*) and Chinook (*O. tshawytscha*) Salmon sampled in southern British Columbia from 2008-2013. Twenty-one infectious agents were detected at a prevalence greater than 1% in ocean-migrating Chinook Salmon, and 17 in Sockeye Salmon. Among species, the most commonly observed agents were the bacterium *Candidatis Brachiomonas cysticola*, parasites *Myxobolus arcticus, Paranucleospora theridion,* and *Parvicapsula minibicornis,* and erythrocytic necrosis virus.

Miller, K.M., Trudel, M., Patterson, D.A., Schulze, A., Kaukinen, K., Li, S., Ginther, N., Ming, T., and Tabata, A. 2013. Are smolts healthier in years of good ocean productivity? North Pacific Anadromous Fish Commission Technical Report 9: 165–168.

Moss, J., Marc Trudel, Brian Beckman, William Crawford, Wyatt Fournier, Emily Fergusson, and Terry Beacham. 2013. Benefits of Living Life on the Edge: Enhanced Growth and Foraging Opportunities for Juvenile Salmon Inhabiting the Margins of the Sitka Eddy. North Pacific Anadromous Commission Technical Report 9: 77–78.

Myers, K.W., J.R. Irvine, E. A. Logerwell, S. Urawa, S.V. Naydenko, A.V. Zavolokin, and N.D. Davis. Pacific salmon and steelhead: life in a changing winter ocean. North Pacific Fish Commission Bulletin 6: 113–138. doi:10.23849/npafcb6/113–138. doi:10.23849/npafcb6/113–138

How Pacific salmon and steelhead (*Oncorhynchus* spp.) respond to climate-driven changes in their oceanic environment is highly uncertain, in part due to limited information on winter distribution in international waters (high seas) of the North Pacific Ocean and Bering Sea. We review what is known and summarize what should be known to properly address the question: *Where do Pacific salmon go in the high seas during winter and why, and how might this be affected by climate change?* Historical high-seas research (1950s–1970s, all seasons) discovered that there are species and stock-specific distributions in the high seas; winter survey results provided some clues as to important winter locations and dominant oceanographic features of winter habitat. In succeeding decades (1980–2015), new fisheries-oceanographic survey methods, stock-identification techniques, remote-sensing technologies, and analytical approaches have enabled us to expand our knowledge of the winter distribution and ecology of salmon, although empirical data are still very limited. In general, we learned that the "why" of ocean distribution of salmon is complex and variable, depending on spatio-temporal scale and synergies among heredity, environment, population dynamics, and phenotypic plasticity. The development of quantitative multispecies, multistage models of salmon ocean distribution linked to oceanographic features would help to identify key factors influencing winter distribution and improve understanding of potential climate change effects.

Neville, C.M., R.J. Beamish and C.M. Chittenden. 2015. Poor Survival of Acoustically-Tagged Juvenile Chinook Salmon in the Strait of Georgia, British Columbia, Canada. Trans. Am. Fish. Soc. 144:25–33.

The collapse of the commercial fishery and the major decline in catches in the recreational fishery for Chinook Salmon Oncorhynchus tshawytscha in the Strait of Georgia since the mid-1990s represents a major economic loss to British Columbia. Early marine residence is critical for survival of Chinook salmon, but measuring the amount of mortality has been difficult. Acoustic tags can be used to measure marine mortality and study migratory behavior. We surgically implanted 278 juvenile Chinook Salmon with acoustic tags to monitor when and how many tagged fish moved out of the Strait of Georgia. Only eight tagged fish were detected leaving the Strait of Georgia, indicating that there could have been substantial mortality of the tagged juvenile Chinook Salmon within the strait. Tagging mortality was minimal, and the detection of tags was shown not to be a major source of error in this study. A major change in population structure between the spring and fall tagging periods meant that it was unlikely that most of the fish tagged in June and July remained within the Strait of Georgia. The decline in abundance of juvenile Chinook Salmon in November 2008 also indicates that the lack of detections of all tagged fish is unlikely a consequence of fish remaining in the Strait of Georgia. This information and the low catches in winter surveys indicated that most juvenile Chinook salmon were no longer in the strait in the late fall and winter. If the tagged fish were representative of the untagged fish, the current brood-year strength probably is largely determined within the Strait of Georgia.

Neville, C. M., S. C. Johnson, T. D. Beacham, T. Whitehouse, J. Tadey, and M. Trudel. 2016. Initial Estimates from an Integrated Study Examining the Residence Period and Migration Timing of Juvenile Sockeye Salmon from the Fraser River through Coastal Waters of British Columbia. NPAFC Research Bulletin 6:45-60.

Many stocks of Pacific salmon enter into and transit through the Strait of Georgia during their migration to off shore waters. Knowledge of the duration of juvenile sockeye salmon residency in the Strait of Georgia and when they migrate out of the strait is essential to understand both natural and anthropogenic factors that may be regulating their early marine survival. We present results from the first year of a multi-year integrated study that demonstrates stock-specific differences in the migration timing of juvenile Fraser River sockeye salmon over the first eight to 12 weeks of their marine life. The geography of the study region provides a unique opportunity to sample virtually the entire population as they migrate down the Fraser River and as they leave the Strait of Georgia through the Discovery Islands and lower Johnstone Strait. This analysis indicated that juvenile 1-year-old sockeye salmon were resident in the Strait of Georgia for seven to eight weeks in 2014. The catch rates in the Discovery Islands indicated that, in 2014, the peak migration period for Fraser River sockeye salmon occurred over approximately two weeks, with about 80% of all sockeye salmon caught between June 12 and June 19. The results suggest that the Strait of Georgia and the Discovery Islands/Johnstone Strait regions function in a similar manner as the nursery lakes and main river ways in the Fraser River watershed. The Strait of Georgia provides abundant food in a relatively protected habitat similar to their rearing lakes in the watershed. The Discovery Islands and Johnstone Strait, an area of lower food availability, is similar to the river, where fish move in concentrated numbers through high current flow areas over a relatively short period of time.

Neville, C.-E. M., Trudel, M., Beamish, R.J., and Johnson. S.C. 2013. The early marine distribution of juvenile Sockeye Salmon produced from the extreme low return in 2009 and the extreme high in 2010. North Pac. Anad. Fish Comm. Tech. Rep. 9:65-68.

Returns of sockeye salmon (*Oncorhynchus nerka*) to the Fraser River in British Columbia are highly variable. Since 1990, there has been a general decline in the returns for all run cycles with three of the four lowest returns on record occurring in 2007, 2008, and 2009. The extremely low 2009 return of 1.6 million sockeye salmon (escapement of 1.1 million fish) led, on the recommendation of the Prime Minister of Canada, to an Order in Council that established a Commission of Inquiry into the decline of sockeye salmon in the Fraser River (Cohen Commission). In 2010, shortly after the Cohen Commission was initiated, a total return of 28.4 million sockeye salmon or spawning escapement of 13.6 million sockeye salmon returned to the Fraser River. This was the largest return in recorded history demonstrating the resiliency of this species. In addition, neither of the extreme returns had been forecasted, indicating our relatively poor understanding of the factors that regulate their production and survival.

Ogden, A.D., and J.R. Irvine. 2015. Bibliography of sockeye, pink and chum salmon marine growth and size-at-age publications. NPAFC Doc. 1575. 64 pp.

Ogden, A.D., J.R. Irvine, K.K. English, S. Grant, K.D. Hyatt, L. Godbout, and C.A. Holt. 2015. Productivity (recruits-per-spawner) data for sockeye, pink, and chum salmon from British Columbia. Can. Tech. Rep. Fish. Aquat. Sci. 3130: vi + 57 p.

Peacock, S.J., B.M. Connors, M. Krkošek, J.R. Irvine, and M.A. Lewis. 2014. Can reduced predation offset negative effects of sea louse parasites on chum salmon? Journal of the Royal Society B: 281: 20132913. http://dx.doi.org/10.1098/rspb.2013.2913.

The impact of parasites on hosts is invariably negative when considered in isolation, but may be complex and unexpected in nature. For example, if parasites make hosts less desirable to predators then gains from reduced predation may offset direct costs of being parasitized. We explore these ideas in the context of sea louse infestations on salmon. In Pacific Canada, sea lice can spread from farmed salmon to migrating juvenile wild salmon. Low numbers of sea lice can cause mortality of juvenile pink and chum salmon. For pink salmon, this has resulted in reduced productivity of river populations exposed to salmon farming. However, for chum salmon, we did not find an effect of sea louse infestations on productivity, despite high statistical power. Motivated by this unexpected result, we used a mathematical model to show how a parasite induced shift in predation pressure from chum salmon to pink salmon could offset negative direct impacts of sea lice on chum salmon. This shift in predation is proposed to occur because predators show an innate preference for pink salmon prey. This preference may be more easily expressed when sea lice compromise juvenile salmon hosts, making them easier to catch. Our results indicate how the ecological context of host–parasite interactions may dampen, or even reverse, the expected impact of parasites on host populations.

Trudel, M., and Hertz, E. 2013. Recent Advances in Marine Juvenile Pacific Salmon Research in North America. North Pacific Anadromous Fish Commission Technical Report 9: 11-20.

Tucker, S., M. E. Thiess, J. F. T. Morris, D. Mackas, W. T. Peterson, J. R. Candy, T. D. Beacham, E. M. Iwamoto, D. J. Teel, M. Peterson, and M. Trudel. 2015. Ocean distribution and consequent factors influencing marine survival of endangered Redfish Lake sockeye salmon. Transactions of the American Fisheries Society 144: 107-123.

Snake River Sockeye Salmon *Oncorhynchus nerka* were declared endangered in 1991 after several years of decreasing abundance. Several factors, including poor marine survival, likely contributed to the decline of Snake River Sockeye Salmon. Little is known about their migration and ocean distribution and the factors influencing their production. We sampled (1) coastal waters from southern British Columbia (BC) to southeast Alaska during June–July, October–November, and February–March 1998–2011; and (2) Oregon and Washington coastal waters during May–June and September 2007–2010. In total, 8,227 juvenile Sockeye Salmon were captured. Despite their extremely low abundance relative to other stocks, 15 coded-wire-tagged juveniles from Redfish Lake were recovered since 2007, primarily in spring and summer surveys off the BC coast. Genetic analyses revealed that an additional eight Redfish Lake juveniles were also present in this area during summer. Snake River smolts undertook a rapid northward migration that brought them well beyond the Columbia River estuary and plume, exposing them to ocean conditions prevailing off BC. Through a multimodel inference approach, we characterized associations between the number of returning adults and a suite of ocean and river variables. Seven ocean variables and five river variables were chosen for the model selection analysis (e.g., copepod biomass anomalies, coastal upwelling indices, date of the spring transition, river discharge, river temperature, and the proportion of smolts transported through the hydropower system). Although adult returns were highly correlated with smolt abundance, our analyses suggest that ocean conditions encountered during the first growing season (as indexed by copepod anomalies) contribute to the variability in total adult returns. There was also evidence for a negative effect of transporting smolts through the hydropower system, with the caveat that we used transportation data for steelhead *O. mykiss* as a proxy.

Tucker, S., Mark Hipfner, John R. Candy, Colin Wallace, Terry D. Beacham, and Marc Trudel. 2013. Stock-Specific Predation of Rhinoceros Auklets (*Cerorhinca monocerata*) on Juvenile Salmon in Coastal British Columbia. North Pacific Anadromous Commission Technical Report 9: 95-96. return in 2010. North Pacific Anadromous Fish Commission Technical Report 9: 65-68.

<u>Tucker, S.</u>, J.M. Hipfner, and <u>M. Trudel</u>. 2016. Size- and condition-dependent predation in a marine pelagic system: a seabird disproportionately targets substandard individual juvenile salmon. Ecology 97: 461-471.

Selection of prey that are small and in poor body condition is a widespread phenomenon in terrestrial predator-prey systems and may benefit prey populations by removing substandard individuals. Similar selection is widely assumed to operate in aquatic systems. Indeed, size-selective predation is a longstanding and central tenet of aquatic food web theory. However it is not known if aquatic predators select prey based on their condition or state, compared to their size. Surprisingly, no comparable information is available for marine systems because it is exceedingly difficult to make direct observations in this realm. Thus the role of body condition in regulating susceptibility to predation remains a black box in the marine environment. Here we have exploited an ideal model system to evaluate selective predation on pelagic marine fish: comparing characteristics (fork length, mass corrected for fork length) of fresh, whole, intact juvenile Pacific salmon delivered by a seabird to its single nestling with salmon collected concurrently in coastal trawl surveys. Three species of juvenile salmon (*Oncorhynchus* spp.) are consumed by provisioning Rhinoceros auklets (*Cerorhinca monocerata*); an abundant, colonial, pursuit-diving seabird. Samples were collected from multiple colonies and fisheries surveys in coastal British Columbia in 2 years. As predicted, auklets preyed on small individuals in poor condition and consistently selected them at levels higher than their relative availability. This is the first study to provide direct evidence for both size- and condition-selective predation on marine fish in the wild. We anticipate that our results will be a starting point in evaluating how selective predation may structure or influence marine fish populations and bridges a fundamental incongruity between ecological theory and application; although 'bigger is better' is considered a fundamental tenet of marine food webs, marine predators are often assumed to consume indiscriminately.

Urawa, S. J.R. Irvine, J.K. Kim, A. Zavolokin, E. Volk, T. Azumaya, T. Beacham, A. Bugaev, E. Farley, J. Guyon, S.G. Kim, M. Kishi, N. Klovach, M. Koval, D.H. Lee, S. Naydenko, D. Oxman, T. Saito, S. Sato, M. Saunders, O. Temnykh, A. Tompkins, M. Trudel, V. Volobuev, and K. Warheit. 2016. Review of 2011-2015 NPAFC Science Plan: Forecast of Pacific Salmon Production in the Ocean Ecosystems under Changing Climate. NPAFC Research Bulletin 6: 501-534.

In recent decades, the marine production of Asian and North American Pacific salmon and steelhead populations has undergone significant variability linked to climate change. Improved forecasts of the abundance and distribution of salmon are needed that will benefit stock management in all salmon producing countries around the North Pacific Rim. The North Pacific Anadromous Fish Commission (NPAFC) Science Plan is a long-term comprehensive strategy for international cooperative research. The primary goal of the 2011–2015 Science Plan was to explain and forecast annual variations in Pacific salmon production. The plan was developed with an overarching research theme “Forecast of Pacific

Salmon Production in the Ocean Ecosystems under Changing Climate" and five research topics. This paper describes progress made on each research topic and the overarching theme, much of which was assessed at an international symposium in Kobe, Japan, on May 17–19, 2015. In summary, the reliability of stock identification methods including genetic and otolith mark analyses has improved, enabling better monitoring of stock-specific ocean distribution and abundance. Salmon marine survival depends on early marine coastal environments but also on conditions later in life, including winter. Models incorporating fish mortality and various environmental factors improve our ability to forecast returns of specific salmon stocks. However, limitations on our ability to accurately explain and forecast annual variations in Pacific salmon production remain, in part because of uncertainty in the factors responsible for salmon mortality and from the effects of climate warming on the marine distribution and abundance of salmon. It is more important than ever to promote cooperative and innovative international research to identify and better understand the ecological mechanisms regulating the distribution and abundance of salmon populations for sustainable salmon and steelhead management.

Ye, H., Beamish, R., Glaser, S.M., Grant, S.C.H., Hsieh, C-h, Richards, L.J., Schnute, J.T., Sugihara, G. 2015. Equation-free mechanistic ecosystem forecasting using empirical dynamic modelling. Proc. Nat. Acad. Sci. 112 (13): 1569-1576.

It is well known that current equilibrium-based models fall short as predictive descriptions of natural ecosystems, and particularly of fisheries systems that exhibit nonlinear dynamics. For example, model parameters assumed to be fixed constants may actually vary in time, models may fit well to existing data but lack out-of-sample predictive skill, and key driving variables may be misidentified due to transient (mirage) correlations that are common in nonlinear systems. With these frailties, it is somewhat surprising that static equilibrium models continue to be widely used. Here, we examine empirical dynamic modeling (EDM) as an alternative to imposed model equations and that accommodates both nonequilibrium dynamics and nonlinearity. Using time series from nine stocks of sockeye salmon (*Oncorhynchus nerka*) from the Fraser River system in British Columbia, Canada, we perform, for the first time to our knowledge, real-data comparison of contemporary fisheries models with equivalent EDM formulations that explicitly use spawning stock and environmental variables to forecast recruitment. We find that EDM models produce more accurate and precise forecasts, and unlike extensions of the classic Ricker spawner–recruit equation, they show significant improvements when environmental factors are included. Our analysis demonstrates the strategic utility of EDM for incorporating environmental influences into fisheries forecasts and, more generally, for providing insight into how environmental factors can operate in forecast models, thus paving the way for equation-free mechanistic forecasting to be applied in management contexts.

Zimmerman, M., J.R. Irvine, M. O'Neill, J.H. Anderson, C.M. Greene, J. Weinheimer, M. Trudel, and K. Rawson. 2015. Spatial and temporal patterns in smolt survival of wild and hatchery Coho Salmon (*Oncorhynchus kisutch*) in the Salish Sea. Marine and Coastal Fisheries: Dynamics, Management, and Ecosystem Science, 7:1, 116-134, DOI: 10.1080/19425120.2015.1012246

Understanding the factors contributing to declining smolt-to-adult survival (hereafter "smolt survival") of Coho Salmon *Oncorhynchus kisutch* originating in the Salish Sea of southwestern British Columbia and Washington State is a high priority for fish management agencies. Uncertainty regarding the relative importance of mortality operating at different spatial scales hinders the prioritization of science and management activities. We therefore examined spatial and temporal coherence in smolt survivals for Coho Salmon based on a decision tree framework organized by spatial hierarchy. Smolt survival patterns of populations that entered marine waters within the Salish Sea were analyzed and compared with Pacific coast reference populations at similar latitudes. In all areas, wild Coho Salmon had higher survival than hatchery Coho Salmon. Coherence in Coho Salmon smolt survival occurred at multiple spatial scales

during ocean entry years 1977–2010. The primary pattern within the Salish Sea was a declining smolt survival trend over this period. In comparison, smolt survival of Pacific coast reference populations was low in the 1990s but subsequently increased. Within the Salish Sea, smolt survival in the Strait of Georgia declined faster than it did in Puget Sound. Spatial synchrony was stronger among neighboring Salish Sea populations and occurred at a broader spatial scale immediately following the 1989 ecosystem regime shift in the North Pacific Ocean than before or after. Smolt survival of Coho Salmon was synchronized at a more local scale than reported by other researchers for Chinook Salmon *O. tshawytscha*, Pink Salmon *O. gorbuscha*, Chum Salmon *O. keta*, and Sockeye Salmon *O. nerka*, suggesting that early marine conditions are especially important for Coho Salmon in the Salish Sea. Further exploration of ecosystem variables at multiple spatial scales is needed to effectively address linkages between the marine ecosystem and Coho Salmon smolt survival within the Salish Sea. Since the relative importance of particular variables may have changed during our period of record, researchers will need to carefully match spatial and temporal scales to their questions of interest.

Theme 3: New Technologies

Araujo, H. Andres, John R. Candy, Terry D. Beacham, Bruce White, and Colin Wallace. 2014. Advantages and challenges of genetic stock identification in fish stocks with low genetic resolution. Transactions of the American Fisheries Society 143: 479-488.

Genetic stock identification (GSI) is widely applied to mixed-stock fisheries for many commercially exploited species. However, the accuracy of GSI depends on the level of differentiation among stocks. To evaluate our ability to estimate contributions in mixed-stock fisheries of Pink Salmon *Oncorhynchus gorbuscha*, a species with limited population genetic differentiation, we analyzed 46 odd-year Pink Salmon stocks belonging to a baseline of genotypes from southern British Columbia, the Fraser River, and Puget Sound. Samples were obtained without replacement from the baseline (known mixtures), and 16 microsatellite loci were used for analysis with two software packages (cBayes and ONCOR) to evaluate the accuracy of using this marker set to identify the correct region, subregion, and spawning site. The correct subregion was identified for Pink Salmon from southern British Columbia and Puget Sound. However, incorrect assignments were observed for the Fraser River subregions and the stock-specific estimates. In addition, we used simulated baselines with the average genetic differentiation index F_{ST} ranging from 0.0007 to 0.04 (the range of F_{ST} values observed in Pink Salmon stocks) to identify biases in the GSI software programs. The results suggested that stock-level genetic identification is subject to significant biases (>15%) when the average F_{ST} among baseline stocks is less than 0.01. ONCOR was more accurate than cBayes in identifying the correct stock at small mean F_{ST} values (<0.01), but there was no significant difference between the software packages at larger F_{ST} values. Our results can help to improve GSI methods and to identify their limitations, especially for stocks with low genetic separation.

Beacham, T. D., S. Cox-Rogers, C. MacConnachie, B. McIntosh, and C. G. Wallace. 2014. Population structure and run timing of sockeye salmon in the Skeena River, British Columbia. North American Journal of Fisheries Management 34: 335-348.

Determination of run timing is an important component of salmonid fisheries management and was the major focus of the current study. Population structure of Sockeye Salmon *Oncorhynchus nerka* was examined in the Skeena River, northern British Columbia. Variation at 14 microsatellites was surveyed for 27 populations in the drainage. There were 9,473 individuals sampled in a lower river test fishery during 2000–2011 in order to provide information on relative abundance and time of arrival of specific populations or stocks near the mouth of the river. Within-lake or within-river tributary structuring of populations was the general pattern observed, with 10 populations from Babine Lake clustering together in 91% of dendrograms evaluated, and two populations from Lakelse Lake clustering together in 100% of dendrograms evaluated. The 27 populations sampled were arranged in 12 reporting groups for genetic stock identification applications. The estimated stock composition of known-origin mixtures was within 2% of the correct estimate for all 12 reporting groups present in the mixtures. Sockeye Salmon typically began arriving at the test fishery on the lower Skeena River by June 10, peaking in daily abundance in late July or early August, and finished migrating past the test fishery by mid-September. Relative timing of the 12 reporting groups, from earliest to latest, was as follows: Lakelse Lake, Alastair Lake, Zymoetz River, Morice Lake, Kispiox River, Sustut Lake, Babine Lake, Slamgeesh Lake, Motase Lake, Bear Lake, Kitsumkalum Lake, and Kitwanga Lake. Genetic mixed-stock analysis, coupled with a test fishery in the lower river, can assist managers in regulating fisheries directed at Skeena River Sockeye Salmon.

Beacham, T. D., J. R. Candy, S. Sato, and S. Urawa. 2014. Microsatellite Identification of Sockeye Salmon Rearing in the Bering Sea During 2009-2013. NPAFC Document 1511. 18 pp.

Stock composition of sockeye salmon (*Oncorhynchus nerka*) caught in the southern central Bering Sea during Japanese research cruises in the summers of 2009, 2011, 2012, and 2013 was estimated through an analysis of microsatellite variation. Variation at 14 microsatellites was analyzed for immature sockeye salmon, and a 404-population baseline spanning Japan, Russia, Alaska, Canada, and Washington State was used to determine the stock composition of the fish sampled. Alaskan-origin sockeye salmon were the most abundant in the catch, comprising 86.1% of all sockeye salmon caught (United States total 86.1%), with the catch dominated by sockeye salmon of Bristol Bay origin. Russian-origin salmon accounted for an average of 10.6% of the annual catch, while Canadian-origin sockeye salmon accounted for 3.4% of the annual catch.

Beacham, T. D., J. R. Candy, S. Sato, and S. Urawa. 2016. Microsatellite identification of Sockeye Salmon rearing in the Bering Sea during 2009-2014. NPAFC Research Bulletin 6: 421-432.

Stock composition of sockeye salmon (*Oncorhynchus nerka*) caught in the southern central Bering Sea during Japanese research cruises in the summers of 2009, 2011, 2012, 2013, and 2014 was estimated through an analysis of microsatellite DNA variation. Ocean age x.1 individuals were well separated from ocean age x.2 and x.3 individuals in fork length, with a bimodal distribution observed in fork length for all five sampling years. Body weight distributions were similarly well defined between age x.1 and x.2 individuals, with x.1 individuals typically less than 800 g in weight, reflective of the bimodal distribution of body weight. Based upon geography and relative abundance, sockeye salmon of Bristol Bay origin should be expected to dominate catches of immature sockeye rearing in the Bering Sea, with sockeye salmon originating from Russia the next most abundant stock. These were precisely the results observed from our analysis of immature sockeye salmon rearing in the central Bering Sea
in July and August (2009–2014). Alaskan-origin sockeye salmon were the most abundant in the catch, comprising approximately 85% of all sockeye caught, with the catch dominated by sockeye of Bristol Bay origin. Russian origin salmon accounted for approximately 10% of the annual catch, while Canadian-origin sockeye accounted for 5% of the annual catch.

Beacham, T. D., C. Wallace, S. Sato, and S. Urawa. 2016. Microsatellite Identification of Sockeye Salmon Rearing in the Bering Sea During summer 2015. NPAFC Document 1627. 11 pp.

Stock composition of Sockeye Salmon (*Oncorhynchus nerka*) caught in the southern central Bering Sea during a Japanese research cruise in the summer of 2015 was estimated through an analysis of microsatellite variation. Variation at 14 microsatellites was analyzed for immature Sockeye Salmon, and a 415-population baseline spanning Japan, Russia, Alaska, Canada, and Washington State was used to determine the stock composition of the fish sampled. Alaskan-origin Sockeye Salmon were the most abundant in the catch, comprising 91% of all Sockeye Salmon caught, with the catch dominated by Sockeye Salmon of Bristol Bay origin (74%). Canadian-origin salmon accounted for an average of 8% of the annual catch, while Russian-origin Sockeye Salmon accounted for 1% of the annual catch.

Beacham, T. D, and R. E. Withler. 2017. Population structure of sea-type and lake-type Sockeye Salmon and Kokanee in the Fraser River and Columbia River drainages. PLoS ONE 12(9): e0183713. https://doi.org/10.1371/journal.pone.0183713

Population structure of three ecotypes of *Oncorhynchus nerka* (sea-type Sockeye Salmon, lake-type Sockeye Salmon, and Kokanee) in the Fraser River and Columbia River drainages was examined with microsatellite variation, with the main focus as to whether Kokanee population structure within the Fraser River drainage suggested either a monophyletic or polyphyletic origin of the ecotype within the drainage. Variation at 14 microsatellite loci was surveyed for sea-type and lake-type Sockeye Salmon and Kokanee sampled from 121 populations in the two river drainages. An index of genetic differentiation, F_{ST}, over all populations and loci was 0.087, with individual locus values ranging from 0.031 to 0.172. Standardized to an ecotype sample size of 275 individuals, the least genetically diverse ecotype was sea-type Sockeye Salmon with 203 alleles, whereas Kokanee displayed the greatest number of alleles (260 alleles), with lake-type Sockeye Salmon intermediate (241 alleles). Kokanee populations from the Columbia River drainage (Okanagan Lake, Kootenay Lake), the South Thompson River (a major Fraser River tributary) drainage populations, and the mid-Fraser River populations all clustered together in a neighbor-joining analysis, indicative of a monophyletic origin of the Kokanee ecotype in these regions, likely reflecting the origin of salmon radiating from a refuge after the last glaciation period. However, upstream of the mid-Fraser River populations, there were closer relationships between the lake-type Sockeye Salmon ecotype and the Kokanee ecotype, indicative of the Kokanee ecotype evolving independently from the lake-type Sockeye Salmon ecotype in parallel radiation. Kokanee population structure within the entire Fraser River drainage suggested a polyphyletic origin of the ecotype within the drainage. Studies employing geographically restricted population sampling may not outline accurately the phylogenetic history of salmonid ecotypes.

Beacham, T. D., C. Wallace, C. MacConnachie, K. Jonsen, B. McIntosh, J. R. Candy, R. Devlin, and R. E. Withler. 2017. Population and individual identification of coho Salmon in British Columbia through parentage-based tagging and genetic stock identification: an alternative to coded-wire tags. Canadian Journal of Fisheries and Aquatic Sciences 74: 1391-1410.

Parentage-based tagging (PBT) and genetic stock identification (GSI) were used to identify individual Coho Salmon (*Oncorhynchus kisutch*) to specific populations and broodyears. In total, 20,242 individuals from 117 populations were genotyped at 304 single nucleotide polymorphisms (SNPs) via direct sequencing of amplicons. Coho Salmon from 15 populations were assigned via parentage analysis that required the genotypes of both parents. The overall accuracy of assignment for 1,939 Coho Salmon to the correct population was 100%, and to correct broodyear within population was also 100%. Inclusion of individuals requiring only a single parental genotype for identification resulted in assignments of 2,101 individuals, with an accuracy of 99.95% (2,000/2,001) to population and 100.0% to age. With 23 regions defined by the CWT program, and individuals displaying an assignment probability < 0.85 excluded from the analysis, average regional assignment accuracy of individuals via GSI was 98.4% over all 23 regions. A PBT/GSI or PBT system of identification will provide an alternate method of identification in the assessment and management of Canadian-origin Coho Salmon relative to the existing CWT program.

Beacham, T. D., C. Wallace, S. Sato, and S. Urawa. 2017. Microsatellite Identification of Sockeye Salmon Rearing in the Bering Sea During summer 2016. NPAFC Document 1683. 12 pp.

Stock composition of Sockeye Salmon (*Oncorhynchus nerka*) caught in the southern central Bering Sea during a Japanese research cruise in the summer of 2016 was estimated through an analysis of microsatellite variation. Variation at 14 microsatellites was analyzed for immature Sockeye Salmon, and a 415-population baseline spanning Japan, Russia, Alaska, Canada, and Washington State was used to determine the stock composition of the fish sampled. Alaskan-origin Sockeye Salmon were the most abundant in the catch of immature individuals, comprising 85.3% of all Sockeye Salmon caught, with the catch dominated by Sockeye Salmon of Bristol Bay origin (80.0%). Canadian-origin salmon accounted for an average of 3.3% of the catch, while Russian-origin Sockeye Salmon accounted for 11.3% of the catch, with 382 individuals of the catch genotyped.

Beacham, T. D., C. Wallace, C. MacConnachie, K. Jonsen, B. McIntosh, J. R. Candy, R. Devlin, and R. E. Withler. 2018. Population and individual identification of Chinook Salmon in British Columbia through parentage-based tagging and genetic stock identification with single nucleotide polymorphisms. Canadian Journal of Fisheries and Aquatic Sciences in press.

A study was undertaken to evaluate whether a parentage-based tagging (PBT) and genetic stock identification (GSI) program has the potential to emulate the results from an existing coded-wire tag

(CWT) assessment program in British Columbia. A PBT/GSI approach was used to identify Chinook Salmon (*Oncorhynchus tshawytscha*) to specific populations and broodyears where 36,241 individuals from 45 populations were genotyped at 321 single nucleotide polymorphisms (SNPs). Known-origin and known-age age 1 juveniles from seven test populations were assigned via PBT (two-parental genotypes required, 538 of 656 juveniles assigned; one parental genotype required, 636 of 656 juveniles assigned) with a minimum accuracy of 99.9%. Assignment accuracy via PBT of 1,026 age 1, 2 or 3 Chinook Salmon returning to nine populations in 2015 or 2016 (two-parental genotypes required, 556 of 1,026 individuals assigned; one parental genotype required, 898 of 1,026 individuals assigned) was a minimum of 99.8%. A PBT/GSI or PBT system of identification may provide an alternate cost-effective method of identification in the assessment and management of Canadian-origin Chinook Salmon relative to the existing CWT program.

Bernatchez, L, M. Wellenreuther, C. Araneda, D. T. Ashton, J. M. I. Barth, T. D. Beacham, G. E. Maes, J. T. Marinsohn, K. M. Miller, K. A. Naish, J. R. Ovenden, C. R. Primmer, Y. S' Ho, N. O. Therkildsen, and R. E. Withler. 2017. Harnessing the power of genomics to secure the future of seafood. Trends in Ecology and Evolution 32: 665-680.

Best use of scientific knowledge is required to maintain the fundamental role of seafood in human nutrition. While it is acknowledged that genomic-based methods allow the collection of powerful data, their value to inform fisheries management, aquaculture, and biosecurity applications remains underestimated. We review genomic applications of relevance to the sustainable management of seafood resources, illustrate the benefits of, and identify barriers to their integration. We conclude that the value of genomic information towards securing the future of seafood does not need to be further demonstrated. Instead, we need immediate efforts to remove structural roadblocks and focus on ways that support integration of genomic-informed methods into management and production practices. We propose solutions to pave the way forward.

Jeffries, K.M., S.G. Hinch, T. Sierocinski, P. Pavlidis, and K.M. Miller. 2014. Transcriptomic responses to high water temperature in two species of Pacific salmon. Evolutionary Applications 7(2): 286-300.

Characterizing the cellular stress response (CSR) of species at ecologically relevant temperatures is useful for determining whether populations and species can successfully respond to current climatic extremes and future warming. In this study, populations of wild-caught adult pink (*Oncorhynchus gorbuscha*) and sockeye (*Oncorhynchus nerka*) salmon from the Fraser River, British Columbia, Canada, were experimentally treated to ecologically relevant 'cool' or 'warm' water temperatures to uncover common transcriptomic responses to elevated water temperature in non-lethally sampled gill tissue. We detected the differential expression of 49 microarray features (29 unique annotated genes and one gene with unknown function) associated with protein folding, protein synthesis, metabolism, oxidative stress and ion transport that were common between populations and species of Pacific salmon held at 19°C compared with fish held at a cooler temperature (13 or 14°C). There was higher mortality in fish held at 19°C, which suggests a possible relationship between a temperature-induced CSR and mortality in these species. Our results suggest that frequently encountered water temperatures ≥19°C, which are capable of inducing a common CSR across species and populations, may increase risk of upstream spawning migration failure for pink and sockeye salmon.

Le Luyer J., M. Laporte, T. D. Beacham, K. H. Kaukinen, R. E. Withler, , B. Koop, L. Bernatchez. 2017. Parallel epigenetic modifications induced by hatchery rearing in a Pacific salmon. Proceedings of the National Academy of Sciences (USA) DOI10.1073/pnas.1711229114

Wild stocks of Pacific salmonids have experienced sharp declines in abundance over the past century. Consequently, billions of fish are released each year for enhancing abundance and sustaining fisheries. However, the beneficial role of this widely used management practice is highly debated since fitness decrease of hatchery-origin fish in the wild has been documented. Artificial selection in hatcheries has often been invoked as the most likely explanation for reduced fitness, and most studies to date have focused on finding signatures of hatchery-induced selection at the DNA level. We tested an alternative hypothesis, that captive rearing induces epigenetic reprogramming, by comparing genome-wide patterns of methylation and variation at the DNA level in hatchery-reared coho salmon (*Oncorhynchus kisutch*) with those of their wild counterparts in two geographically distant rivers. We found a highly significant proportion of epigenetic variation explained by the rearing environment that was as high as the one explained by the river of origin. The differentially methylated regions show enrichment for biological functions that may affect the capacity of hatchery-born smolts to migrate successfully in the ocean. Shared epigenetic variation between hatchery-reared salmon provides evidence for parallel epigenetic modifications induced by hatchery rearing in the absence of genetic differentiation between hatchery and natural-origin fish for each river. This study highlights epigenetic modifications induced by captive rearing as a potential explanatory mechanism for reduced fitness in hatchery-reared salmon.

McClelland, E. K., Tobi J Ming, Amy Tabata, Terry D Beacham, Ruth E Withler, and Kristina M Miller. 2013. Patterns of selection and allele diversity of class I and class II major histocompatibility loci across the species range of sockeye salmon (*Oncorhynchus nerka)*. Molecular Ecology 22:4783-4800.

The major histocompatibility complex (MHC), an important component of the vertebrate immune system, provides an important suite of genes to examine the role of genetic diversity at non-neutral loci for population persistence. We contrasted patterns of diversity at the two classical MHC loci in sockeye salmon (*Oncorhynchus nerka*), MHC class I (UBA) and MHC class II (DAB), and neutral microsatellite loci across 70 populations spanning the species range from Washington State to Japan. There was no correlation in allelic richness or heterozygosity between MHC loci or between MHC loci and microsatellites. The two unlinked MHC loci may be responding to different selective pressures; the distribution of FST values for the two loci was uncorrelated, and evidence for both balancing and directional selection on alleles and lineages of DAB and UBA was observed in populations throughout the species range but rarely on both loci within a population. These results suggest that fluctuating selection has resulted in the divergence of MHC loci in contemporary populations.

Moran, P., David A. Teel, Shawn R. Narum, Jon E. Hess, John R. Candy, Colin G. Wallace, Terry D. Beacham, John Carlos Garza, Michael A. Banks, M. Renee Bellinger, Scott M. Blankenship, Lisa W. Seeb, William D. Templin, and Christian T. Smith. 2013. Divergent life-history races do not represent Chinook salmon coast-wide: the importance of scale in Quaternary biogeography. Canadian Journal of Fisheries and Aquatic Sciences 70: 415–435.

The dynamic Quaternary geology of the Pacific Ring of Fire created substantial challenges for biogeography. Fish life history and population genetic variation were shaped by climate change, repeated formation and subsidence of ice sheets, sea-level change, volcanism and tectonics, isostatic rebound, and now human activities. It is widely recognized in Chinook salmon (*Oncorhynchus tshawytscha*) that parallel evolution and phenotypic plasticity have obscured range-wide patterns of life-history segregation with evolutionary lineage, yet the idea of the lineages themselves persists. We employed a large, internationally standardized, microsatellite data set to explore population structure at coast-wide scale and test for two divergent lineages, whether or not related to life history. We found at least 27 distinct lineages. However, relationships among groups were poorly resolved — essentially a star phylogeny. We found pervasive isolation by distance among groups, complicating cluster analysis. Only in the interior

Columbia River (east of the Cascade Mountains) is there a deep genetic bifurcation that supports both the two-lineage hypothesis and the life-history segregation hypothesis. This broad-scale perspective helps reconcile different views of Chinook salmon phylogeography and life-history distribution.

Muttray, A.F., D. Sakhrani, R.E. Withler and Robert H. Devlin. 2015. Low variation in a Y-chromosomal growth hormone pseudogene relative to its functional autosomal progenitor gene in Chinook Salmon. Transactions of the American Fisheries Society 144 (5): 1029-1039. DOI: 10.1080/00028487.2015.1059886.

Most fish species do not have single-chromosome-based sex determination or display cytologically distinguishable sex chromosomes. The selective forces acting on homologous sequences in diploid autosomal versus haploid sex-chromosomal regions are expected to be distinct and thus to differentially influence genetic variation. In Chinook Salmon *Oncorhynchus tshawytscha*, the Y chromosome possesses a growth hormone pseudogene (*ghp*) that is linked to the sex-determination locus and is derived from the functional autosomal growth hormone 2 gene (*gh2*). Thus, examining these two paralogues provides a model with which to study the forces affecting the persistence of genetic variation between sex-linked and autosomal loci among individuals in Chinook Salmon populations. We characterized single-nucleotide polymorphisms in a 1.6-kb contiguous homologous region in *gh2* and *ghp* in 315 individuals from 19 Chinook Salmon populations ranging from Russia to Alaska, British Columbia, and California. The *ghp* sequence was highly similar among individuals and populations, with variant haplotypes being detected in only 5.4% of individuals and restricted to just two populations. In contrast, *gh2* variants from the most common haplotype were found in 46.7% of individuals. We detected more sites of variation in *ghp* (nine positions, five haplotypes) than in *gh2* (three positions, five haplotypes), but these were restricted to just four genotypes for *ghp*, compared with nine for *gh2*. Selection may have caused a single Y chromosome to become fixed among most populations in this species, while the variation at the *gh2* locus is maintained under diploid autosomal conditions. Since the *ghp* locus variants are not likely to be directly associated with strong functions, other linked Y-chromosomal loci may have important functions that, when selected, cause Y chromosomes to either be damaged and rapidly eliminated or to have enhanced fitness and sweep through the species. Whether such loci include the sex-determination locus itself or other functional loci is not yet known.

Raby, G. D., Donaldson, M. R., Hinch, S. G., Clark, T. D., Eliason, E. J., Jeffries, K. M., Cook, K.V., Teffer, A., Bass, A.L., Miller, K.M., Patterson, D.A., Farrell, A.P., & Cooke, S. J. 2015. Fishing for Effective Conservation: Context and Biotic Variation are Keys to Understanding the Survival of Pacific Salmon after Catch-and-Release. Integrative and comparative biology, 55: 554-576.

Acute stressors are commonly experienced by wild animals but their effects on fitness rarely are studied in the natural environment. Billions of fish are captured and released annually around the globe across all fishing sectors (e.g., recreational, commercial, subsistence). Whatever the motivation, release often occurs under the assumption of post-release survival. Yet, capture by fisheries (hereafter “fisheries-capture”) is likely the most severe acute stressor experienced in the animal’s lifetime, which makes the problem of physiological recovery and survival of relevance to biology and conservation. Indeed, fisheries managers require accurate estimates of mortality to better account for total mortality from fishing, while fishers desire guidance on strategies for reducing mortality and maintaining the welfare of released fish, to maximize current and future opportunities for fishing. In partnership with stakeholders, our team has extensively studied the effects of catch-and-release on Pacific salmon in both marine and freshwater environments, using biotelemetry and physiological assessments in a combined laboratory-based and field-based approach. The emergent theme is that post-release rates of mortality are consistently context-specific and can be affected by a suite of interacting biotic and abiotic factors. The fishing gear used, location of a fishery, water temperature, and handling techniques employed by fishers each can dramatically affect survival of the salmon they release. Variation among individuals, co-migrating populations, and between sexes all seem to play a role in the response of fish to capture and in their subsequent survival, potentially driven by pre-capture pathogen-load, maturation states, and inter-individual variation in responsiveness to stress. Although some of these findings are fascinating from a biological perspective, they all create unresolved challenges for managers. We summarize our findings by highlighting the patterns that have emerged most consistently, and point to areas of uncertainty that require further research.

Tucker, S., T. D. Beacham, and M. Trudel. 2015. Seasonal distribution of juvenile Vancouver Island Chinook Salmon. NPAFC Document 1603. 15 pp.

We used genetic stock identification to identify and characterize the distribution of juvenile Chinook salmon (n=3,869) originating from west coast Vancouver Island (WCVI) Conservation Units (CUs) caught in fall and winter trawl surveys 1998-2012. These fish were constrained to the shelf waters and inlets of the west coast of Vancouver Island. With few exceptions, fish were generally found in proximity to their origin or further north except individuals from the Northwest Vancouver Island (NWVI) CU which remain within Quatsino Sound and were very rarely caught outside. In fact stock composition was similar between sampling sites within a 90 km distance range. The distribution patterns were stable from fall to winter. Interestingly, a large fraction of fish originating from central and southern CUs used adjacent and northern inner waters of inlets and Sounds of Vancouver Island. In addition, we took advantage of the presence of known-origin CWT fish in our sample to test the accuracy of genetic stock identification to CU (96% accuracy).

Urawa, S., T.D, Beacham, S. Sato, T. Kaga, B. Agler, R. Josephson, and M. Fukuwaka. 2016. Origins and biological status of Chum Salmon in the Gulf of Alaska during winter. NPAFC Research Bulletin 6: 153–160.

Winter is believed to be a critical period for marine salmon survival. In February 2006, a winter research cruise was conducted to examine the stock-specific distribution and biological status of salmon in the central Gulf of Alaska (GOA). By surface trawl, 519 chum salmon (*Oncorhynchus keta*) were caught at seven stations (48–54ºN, 145ºW) where the surface seawater temperature ranged from 5.2ºC (54ºN) to 7.0ºC (48ºN). Ocean age-2 and -3 fish were dominant at all sampling stations, and young fish (ocean age-1) were distributed in the southern stations. The stock composition of chum salmon abundance (CPUE) estimated by microsatellite DNA analysis was 11% western Alaska/Alaska Peninsula, 11% Prince William Sound (PWS), 16% Southeast Alaska (SEAK), 6% northern British Columbia (BC), 17% southern BC, 2% Washington, 17.5% Russian, and 20% Japanese stocks. There was a latitudinal shift in the stock-specific distribution: North American stocks were dominant in northern waters, and Asian stocks were dominant in southern waters. All young fish (ocean age-1) were North American origin (mostly PWS, SEAK and southern BC), while the proportion of Asian (Japan and Russia) stocks increased with ocean age. The samples included 48 otolith-marked fi sh released from hatcheries in PWS (n = 7), SEAK (n = 37), BC (n = 1), and Japan (n = 1). A comparison of CPUEs estimated by genetic stock identification and otolith mark recoveries suggested that the contribution of hatchery fi sh was variable among brood years (0–51%, PWS stock; 19–87%, SEAK stock). Microsatellite and otolith mark analyses confirmed that various stocks of North American and Asian chum salmon inhabit the central GOA during winter. Their winter distribution pattern is different among regional stocks or age groups, maybe reflecting stock- or age-specific preferences for habitat water temperatures to maximize survival.

Withler R.E., D.S. O'Brien, N.M. Watson, and K.J. Supernault. 2014. Maintenance of genetic diversity in natural spawning of captively-reared endangered sockeye salmon, *Oncorhynchus nerka*. Diversity 6: 354-379. doi:10.3390/d6020354

Captive propagation of Pacific salmon is routine, but few captive breeding programs have been conducted to successfully re-establish extirpated wild populations. A captive breeding program for endangered Sakinaw Lake sockeye salmon was established from 84 adults between 2002 and 2005, just prior to extirpation of the wild population. After several years of absence, sockeye salmon released from captivity returned to spawn in Sakinaw Lake in 2010 and in all years thereafter. Freshwater survival rates of released hatchery fry and naturally produced progeny of reintroduced sockeye salmon have not limited abundance of the reintroduced population. In contrast, marine survival rates for Sakinaw sockeye salmon have been <1%, a level that precludes population restoration in the absence of supplementation. Genetic diversity commensurate with the number of parental founders has been maintained in captivity. The 517 adult second-generation captive fish that spawned in Sakinaw Lake in 2011 produced a smolt emigration of almost 28,000 juvenile fish with an effective population size of 132. Allelic richness and gene diversity levels in the smolts were similar to those observed in captivity. This indicates genetic contributions from all or most founding parents have been retained both in captivity and in the nascent reintroduced natural population.