PACIFIC SALMON
FOUNDATION

REVIEW OF PACIFIC SALMON HATCHERIES IN BRITISH COLUMBIA, CANADA, AND INTERACTIONS WITH NATURAL POPULATIONS.

A SYNTHESIS OF THE PACIFIC SALMON FOUNDATION'S HATCHERY EFFECTIVENESS PROJECT

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Cover photos by: top, Eiko Jones, left, Sam James, centre, Braela Kwan and right, Mitch Miller

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ABSTRACT

Hatchery production of Pacific salmon (all species) across the North Pacific region annually releases about 5 billion juveniles. In Canada, the Salmonid Enhancement Program (SEP) is responsible for Pacific salmon hatcheries and presently releases ~250 million juveniles (all species) annually in British Columbia. Diminished abundance of Pacific salmon and recent reductions in BC fisheries suggested a review of hatchery effectiveness was needed for conservation, rebuilding, and harvest of Pacific salmon. To address this, the Pacific Salmon Foundation conducted a review of SEP's hatchery effectiveness and evidence of interactions with Pacific salmon that are produced naturally. In total, this review produced 14 reports and provided the first such review since 1994. Beyond the estimation of hatchery salmon contributing to catches and spawning escapements, there is limited ability to assess effectiveness and the biological costs and benefits to Pacific salmon production in BC. Both negative and positive interactions with natural populations were evident but limitations due to data availability significantly limits this evaluation. Future evaluations of hatcheries and Pacific salmon production requires integration of hatchery and wild salmon analyses, commitments to comparative studies and improved data availability, and more thorough reporting. But new scientific methodologies in genetics and genomics offer future opportunities to understand effects of hatchery technologies and to learn from interactions of hatchery and wild Pacific salmon populations.

Photo by: Eiko Jones

INTRODUCTION

Canada's Salmonid Enhancement Program currently releases about 250 million juvenile salmonids annually into waters of British Columbia (BC). This is a tiny portion of the total release of salmonids into the North Pacific Ocean (<5%, https://npafc.org/statistics/) but is a substantial investment of effort and funds in Canada. Regrettably, there are very few evaluations of SEP since its beginnings in 1977 and of modern hatcheries in BC in 1963. Following from the Salish Sea Marine Survival Program (www.marinesurvivalproject.com), the Pacific Salmon Foundation undertook an extensive review of salmon hatchery programs in Canada's Salmonid Enhancement Program (SEP). The *Hatchery Effectiveness Review* (HER) was stimulated by a comparison between natural and hatchery-produced Chinook salmon in the Cowichan River, BC. Naturally produced Chinook salmon survived at three times the rate of hatchery Chinook (Supplemental data in this report). The goal of the HER was to assess the efficiency of hatcheries in BC to support the production of Pacific salmon, sustain fisheries, and contribute to a sustainable future for wild Pacific salmon. Unfortunately, without better data on hatchery and wild salmon interactions including more critical study, this goal was only partially achieved.

This report synthesizes outcomes from 14 reports in the HER including three literature reviews, an assessment of the community hatchery program, an evaluation of trends in biological traits of Chinook salmon (other species could not be included), an extensive review of hatchery release strategies for Chinook and coho salmon, and evaluations of the contribution of hatchery salmon to harvest, rebuilding of natural populations, and interactions between hatchery and wild salmon. All reports are openly available on the Pacific Salmon Foundation's Marine Science website: https://marinescience.psf.ca/hatchery-effectiveness/.

Photo by: Nicole Christiansen

BACKGROUND

The modern era of hatchery culture of Pacific salmon in BC began 60 years ago with the Big Qualicum River Hatchery (use of spawning channels began a decade earlier in the Fraser River) and then expanded significantly with the development of the SEP in 1977 (DFO 1978). The SEP relied extensively on hatchery technology to increase salmon production and sustain Pacific salmon fisheries in BC, as these original quotations suggest:

> "*Proven salmonid enhancement techniques, such as hatcheries, spawning channels and fishways, are available for widespread application. A number of developing techniques offer great promise of improved production at reduced costs.*
>
> *The biological potential, in both fresh and salt water, exists to double the present salmon production from 25 to 50 million fish per year.*" (pg. 31, DFO 1978)[1]

> "*and Whereas Canada and British Columbia agree that salmonid enhancement technology has been developed and refined in recent years to the state where it can now be applied with confidence;*"[2]

Today the SEP includes 16 large hatcheries, seven spawning channels, and 20 community development (smaller scale) hatcheries; plus, programs in habitat restoration, community involvement to engage citizens in enhancement and educational programs, and SEP maintains a data management and assessment unit (https://www.pac.dfo-mpo.gc.ca/sep-pmvs/index-eng.html). However, as some foresaw and many have subsequently commented, the production of Pacific salmon is not just about producing juveniles for release to the natural environment.

> "*It might seem quaint to a non-biologist to question whether producing more salmon is good for the salmon, but natural systems being what they are, there is always a good chance that our best efforts will turn out to do more harm than good.*" (pg. 1441, Larkin 1974)

Photo by: Benjamin Fortini

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[1] The reference to production in DFO (1978) refers to increased catch in millions of fish.

[2] Federal-Provincial Agreement, Salmonid Enhancement Program, signed Feb. 1979, BC Order in Council. https://www.bclaws.gov.bc.ca/civix/document/id/oic/arc_oic/0468_1979

Figure 1 provides an overview of the historical releases from BC hatcheries and provides the percentage (%) of the annual releases composed of Chinook and coho salmon smolts. Chinook and coho salmon were not the original target species of SEP but became more important to address conservation concerns and issues raised by recreational fishers. The bottom figure presents the historical catches of Pacific salmonids (all species, and includes all fisheries that have available data) in BC, and is smoothed as a 4-point moving average to account for cycles in Fraser River sockeye and pink salmon catches every four years. Over the full-time span, total catches have not been sustained but in the early period of SEP releases, the trend in total catch was favourable until 1991. Following 1991, catch declined steadily until 2001 and then again since 2016. These declines, however, can not be solely attributed to hatcheries and impacts on natural populations as there were numerous changes in the marine environment, international agreements, and in fisheries and conservation policy.

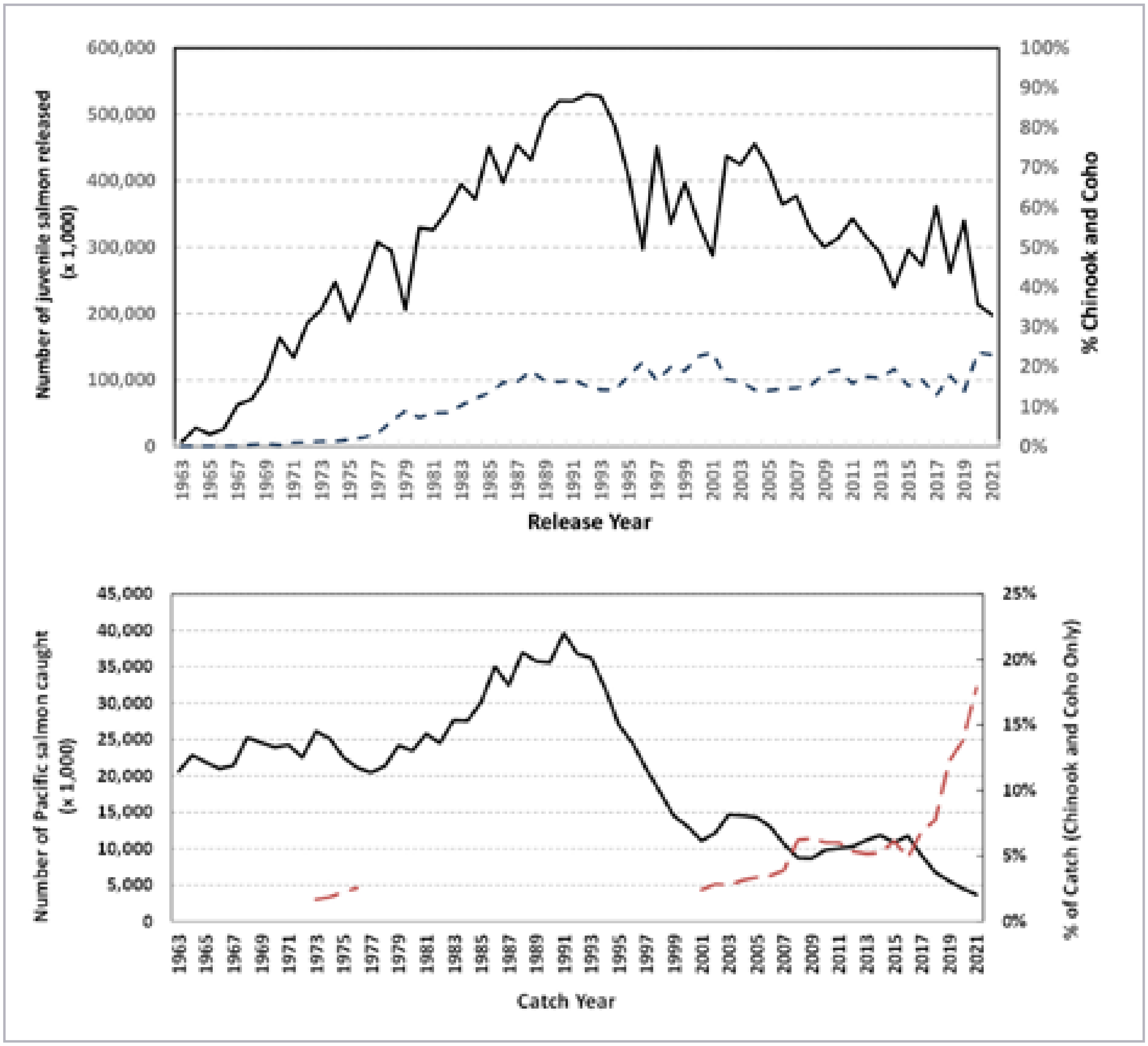

Figure 1: Top figure: SEP annual total releases of release of juvenile salmon (3-pt smoothing) and % Chinook and coho of the total each year (top figure). **Bottom figure:** Total B.C. catch (includes commercial, sport, and subsistence) and % Chinook and coho of the total each year (bottom figure). All data from NPAFC website (https://npafc.org/statistics/). NPAFC statistics do not include estimates of smolts produced through Lake Enrichment Projects.

The early 1990s was also a period of retrospection about the net benefit of intensive fish culture to supplement natural populations and sustain fisheries. Numerous authors identified potential risks to natural populations due to over-harvest, genetic changes in hatchery fish, and ecological impacts via competition, predation, and disease. In 1994, a comprehensive review of the Salmonid Enhancement Program (Pearse 1994) for the Department of Fisheries and Oceans, Internal Audit and Evaluation Branch noted:

- Over 17 years, $526 million was invested in enhancement activities.
- A substantial enhancement capability consisting of more than 300 facilities[3] is in place.
- Enhanced production has fallen significantly short of original expectations.
- The economic achievements have been disappointing.
- Some basic premises on which the Salmonid Enhancement Program was based have proven to be faulty. One was that salmon production could not be restored through better management of wild stocks; improvements in managing fisheries have since increased catches of wild salmon by more than the increase in enhanced production.
- And another premise was that technology of enhancement was proven; it has since been revealed as uncertain and risky.

Since the mid-1990s, evaluations of SEP production and associated costs have been rare (Hilborn and Winton 1993). However, in the United States, there have been extensive studies of hatchery production and interactions with natural salmon populations (e.g., HSRG 2015[4], Anderson et al. 2020[5]). And many literature reviews summarize risks to natural populations associated with production from major salmon hatcheries (Riddell 1993a,b, Waples and Drake 2004, Naish et al. 2007, Araki and Schmid 2010, Flagg 2015, Kitada 2020, Claussen and Philipp 2022). But, as Trushenski et al. (2018) remind us, there are multiple objectives associated with the use of major hatcheries.

Another important development since the early 1970s has been the application of coded-wire tags (CWT, Jefferts et al. 1963) to monitor distribution, annual survival rates, and fishing impacts on hatchery-produced Chinook and coho salmon. Since 1975, a coastwide agreement between the United States and Canada has provided invaluable assessments of Chinook and coho salmon and fishing impacts. These data are available for most Chinook and coho salmon released from production hatcheries in BC and provide insight into the highs and lows of hatchery production.


Photo by: Benjamin Fortini

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[3] Pearse refers to facilities but there have never been 300 facilities. Pearse is referring to projects within the SEP defined by location, species, and activity.

[4] https://www.streamnet.org/app/hsrg/docs/HSRG_Report-to-Congress_2015[1].pdf

[5] https://wdfw.wa.gov/publications/02121

As one example, Figure 2 provides the total production of adult Chinook salmon resulting from juveniles released from Robertson Creek Hatchery since the 1973 spawning year (Brood Year, BY) and accounts for catches in Southeast Alaska, coastal BC, in terminal areas (mostly Barkley Sound and Somass River), and in the spawning escapement in the Somass River. Robertson Creek hatchery is Canada's largest Chinook salmon hatchery and since 1973, has produced, on average, 100,000 adult Chinook per year. But from any one BY, the total production has varied from 1,000 adult Chinook (1992 BY) to 400,000 (1988 BY); a 400-fold variation in annual production. Survival rates over time were not stable and changed very suddenly. Notably, most of the poor survival rates in Figure 2 are associated with strong to very strong El Niño events along the west coast of North America (see https://ggweather.com/enso/oni.htm).

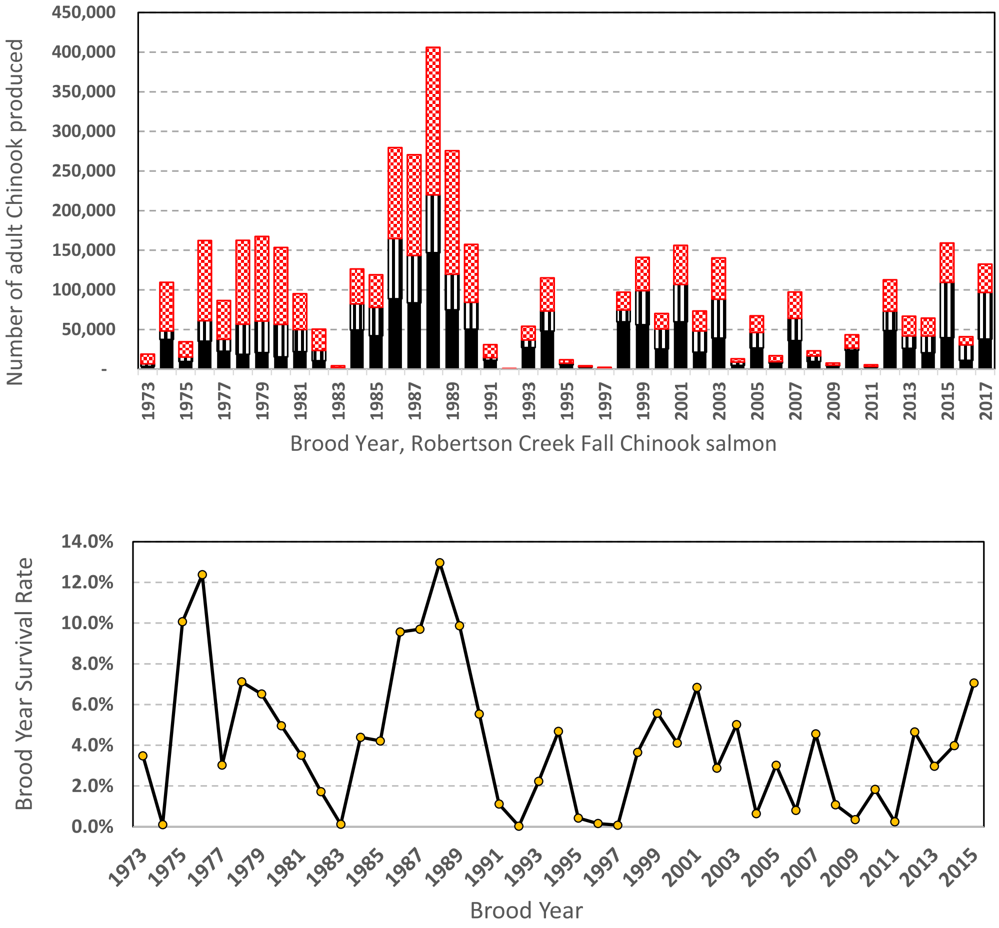

Figure 2: Annual production by Brood Year (BY 1973-2015) for Fall Chinook salmon released from Robertson Creek Hatchery, Port Alberni, BC, Canada. **Top figure** presents the total adult production estimated from coded-wire tags recovered in ocean fisheries (red crosshatch), terminal fisheries (Black vertical lines), and spawning escapement (black bar). **Bottom figure** presents the marine survival rate based on CWT smolts released (release year is BY+1) and estimated cohort abundance at Age-2 Pre-fishery (based on PSC CTC Chinook analyses). Both estimates account for total mortality in fisheries and returns are expressed in Adult Equivalent Mortality to account for mortalities of immature Chinook salmon. https://www.psc.org/publications/technical-reports/technical-committee-reports/chinook/

SOCKEYE AND PINK SALMON ENHANCEMENT

The HER involves chum, coho, and Chinook salmon, but a large portion of the SEP annual releases of salmon are sockeye and pink salmon from spawning channels, lake enrichment projects, and hatcheries. The first efforts in artificial culture of Pacific salmon in BC involved these species; first with the Cultus Lake sockeye hatchery and then the first spawning channel at Jones Creek (Fraser R. basin) for pink salmon. The sockeye hatchery project was closed in 1938 following studies that concluded "artificial propagation, as commonly practised, provided no advantage over natural spawning, as a means of maintaining the run." (Foerster 1938). But spawning channels were extensively expanded during the SEP. Recognizing the importance of spawning channels in the SEP, the HER included a historical review of spawning channels in BC (West 2023) that provides an overview of each channel but does not examine evidence for interactions. Interactions with local natural populations have certainly been documented particularly in the Babine Lake Development Program (BLDP, Shortreed and Morton 2000, Price et al. 2019, Price et al. 2021, Wood 2008) and in mixed-stock fishery interactions between Weaver Creek channel sockeye and Cultus Lake sockeye (Schubert et al. 2002). Following the production of Weaver Creek sockeye salmon (1969 return), harvest rates on Cultus Lake sockeye during the sub-dominant Fraser sockeye returns (2 of 4 years) increased by 25-45% until addressed by managers (Schubert et al. 2002). Freshwater competition and transmission of pathogens have been a concern in the BLDP but neither competition (Price and Connors 2014) nor pathogens (Traxler et al. 1998) has been linked to these channels. The SEP also benefited from sockeye salmon produced through the development of lake enrichment projects (Lebrasseur et al. 1978, 1979; Stockner and MacIssac 1996). Enrichment involved the addition of nutrients to lakes that reared sockeye salmon. However, lake enrichment is no longer a major SEP program. It was potentially effective in enhancing juvenile growth and survival within sockeye-rearing lakes but was variable in its success depending on competition with zooplankton or fish (well described in Hyatt et al. 2004).

Photo by: Nicole Christiansen

METHODS

The Hatchery Effectiveness Review consisted of three sections:

(1) Evaluation of hatchery release strategies based on a review of published materials, an assessment of SEP release experiments, and a new analysis using all coded-wire tag releases for Chinook and coho salmon from major BC hatcheries (1972 through 2017).

(2) Assessing the effectiveness of SEP hatcheries and their interactions with wild Pacific salmon populations in BC. This section involved multiple assessments including a literature review restricted to interactions between hatchery and wild salmon, a review of the Community Involvement Program (which includes small-scale hatcheries), new analyses of hatchery contributions to harvest and to rebuilding of natural Chinook salmon populations, spatial covariation of major hatcheries and proximal natural populations, effects on salmon productivity of natural populations, and changes in biological traits in Chinook salmon.

(3) A review of new opportunities in genomics to study hatchery salmon and means to apply new technologies to study hatchery effects and interactions.


Photo by:Nicole Christiansen

SECTION 1: EVALUATION OF HATCHERY RELEASE STRATEGIES

(summarized in James et al. 2021)

(1A) **LITERATURE SEARCH**

The literature search involved peer-reviewed and grey literature published between 1970 and 2020 and was conducted in January 2021 (James 2021a). Keywords were searched using two search engines, Web of Science Core Collection and Aquatic Sciences and Fisheries Abstracts. The Fisheries and Oceans Canada (DFO) Library and the Google Scholar search engine were used to search grey literature. Each title and abstract were screened for eligibility and only research at American or Canadian facilities that examined the effects of release strategies on survival, catch, age at recovery, adult size, and sex ratios were included, and only references with statistical analyses were included. For each eligible report, full texts were read and their literature lists screened for any additional literature that may have been missed.

(1B) **SEP HATCHERY EXPERIMENTS**

Records of experiments conducted by SEP were collated from conversations with SEP staff, interviews with hatchery managers, and by manually searching regional databases for multiple release groups in the same brood year (James 2021b). In total, 25 experiments were identified: seven facilities with releases of multiple life stages of Chinook salmon, four on the weight and date of release of Chinook, eight on the weight and date of release of coho salmon, and six on the effects of sea-pen releases of Chinook. To examine strategies that may be most applicable today, analyses were focused on experiments conducted over the last 20 years, with the exception of experiments conducted pre-2000 at the Chilliwack and Cowichan River hatcheries. The Cowichan River Hatchery is one of few community-based facilities with a long-time series of marked (CWT) releases and has applied a variety of release strategies since 1981. Hatcheries were grouped into five regions based on where the hatchery releases entered the marine environment: Strait of Georgia, West Coast Vancouver Island, Northeast Vancouver Island, Central Coast, and North Coast. For each experiment, the objectives were described, and raw data presented including historical trends in marine survival. Where sufficient data were available, statistical analyses were conducted to determine whether experimental groups differed in production outcomes: mean survival rates, exploitation rates, and return ages were compared between regular and experimental production using t-tests or non-parametric equivalents depending on the distribution of the data. Linear mixed effects models were used to determine which elements of the experiment were the strongest predictors of survival.

(1C) **OVERALL REVIEW: A NEW MODELLING APPROACH USING ALL CWT DATA**

Expanding beyond these 25 experiments, this analysis utilized all release and recovery data available for coded-wire tagged Chinook and coho salmon in BC since CWT releases began in 1972 (James et al. 2023). The analysis began with linear mixed effects models specific to each life stage and hatchery to assess how release strategies influenced survival rates and age-at-maturity. The modelling approaches and models are fully described in James et al. (2023). Juvenile-to-adult survival data were collated for 21 Chinook and 16 coho salmon hatcheries and for releases from 1971 to 2015 brood (spawning) years. This extensive dataset enabled development of single-hatchery and hierarchical multi-hatchery models to evaluate release strategies (weight-at-release, day-at-release, life stage, stock, and release site) that potentially affect smolt-to-adult survival rate and age-at-return.

SECTION 2: ASSESSING THE EFFECTIVENESS OF SEP HATCHERIES AND INTERACTION WITH WILD PACIFIC SALMON.

(2A) **THE LITERATURE REVIEW**

The literature review (Giles 2022) included Atlantic (*Salmo salar*) and Pacific (*Oncorhynchus* spp.) salmon, from all regions of the world where these species were released from hatcheries. Any publication detailing interactions of any type between wild-origin salmon and hatchery-origin salmon was included. Searches were conducted in May of 2021. Four databases were searched: Web of Science, ASFA (Aquatic Sciences and Fisheries Abstracts), DFO Waves, and Google Scholar. All search results from the first three databases were accepted, while only the first 200 results were taken from Google Scholar. The combined list of citations (n=7805) was imported into Covidence, a software package for systematic literature reviews, for removal of duplicates. The final pool of literature was 4974 citations and titles and abstracts of all were screened for inclusion. After screening, the final number of studies for analysis was 112, but upon closer assessment, 27 reports were too broad in scope to be categorized into an interaction type or determine a conclusion. Consequently, the final number of reports included in this analysis was 85. Appendix 2, in Giles (2022), details the screening of all 85 reports.

(2B) **COMMUNITY HATCHERIES**

In parallel with SEP's large production hatcheries, SEP also manages a Community Involvement Program (CIP) that includes smaller community-based hatcheries in two programs: the Community Economic Development Program (CEDP) and the Public Involvement Program (PIP). These community projects are supported by a staff of Community Advisors (CA) that provide advice in fish culture, data management, and planning. This component of the HER was conducted through interviews with CA's (14 of 15) and 32 representatives from community hatcheries. The number of projects involved is a reasonable sample of the CIP hatchery projects. Interviews included 79% of individual CEDP projects and 36% of the PIP projects (these values excluded the many small school/educational projects) based on the 2021 release summary from SEP, Vancouver, BC. The interviewees and interview questions are provided in Appendix B1 and B2 of Fortini (2023). To minimize interview biases, standardized questions were presented consistently to all participants, and all discussions were audio-recorded to ensure accuracy of data extracted (~80 hours of interviews were processed). To provide a better perspective of the role and scale of CIP projects, eight in-person visits were conducted in November 2021. Two of the sites visited had not been included in the interview process and were subsequently included in these analyses.

(2C) **EFFECTIVENESS OF HATCHERY PRODUCTION AND THEIR INTERACTION WITH WILD SALMON.**

Reports for this part involved substantial data collation and the development of analytical methods to assess the contribution of BC hatcheries to salmon fisheries (U.S. and Canadian), their contribution to rebuilding the abundance of naturally-spawning populations, examination of spatial covariation with natural populations in proximity to major hatcheries, the development of models to examine the productivity of natural populations potentially influenced by hatchery releases and/or strays, and changes in biological traits of Chinook salmon.

The effectiveness of SEP hatchery production was assessed by estimation of contributions to U.S. and Canadian fisheries (Harvest) and in rebuilding depressed Chinook salmon populations. Numerous data sources were involved (Table 1), and documentation is provided in each report. In brief, all release data were provided by the SEP staff (Vancouver, BC), catch and CWT data provided by DFO Statistics Branch, Vancouver, BC, and escapement data for hatchery and natural populations from the Pacific Salmon Foundation's Pacific Explorer database (https://data.salmonwatersheds.ca/data-library/). The annual monitoring of salmon returns to rivers/streams across British Columbia is a daunting task and the quality of data varies greatly between systems and over time. Limitations of catch and escapement data are described for each analysis.

Table 1. Years of data included by species and considered in James and Rosenberger (2023). Chum salmon data were provided by Lynch et al. (2020) for net fisheries only and years 1980-2018. SEP releases Steelhead trout in collaboration with the Province of BC but they were not included in this review.

Species (*Oncorhynchus spp.*)	Hatchery/channel releases	Catch/Escapement data
Sockeye	1964-2020	Not included
Pink	1956-2020	Not included
Chum	1956-2020	1980-2020
Coho	1968-2020	1975-2020
Chinook	1968-2020	1975-2020

The assessment of SEP hatchery contributions to harvest (James and Rosenberger 2023) was based on CWT and catch data for 1975-2020, and spawning escapement data for Chinook and coho salmon. Some catch records were not available for this review; for example, North and Central Coast recreational catch data were only available for 2013-2021, and southern BC recreational catches from 1981. James (2023, Harvest Supplemental Data) provides an extensive appendix of data and figures used to summarize harvest. James (2023) summarized catch by year, gear type (troll, net, recreational), and four geographic regions (North Coast, NCST; Central Coast, CCST; West Coast Vancouver Island, WCVI; Interior South Coast, ICS). Data compiled and presented in James (2023) includes:

A. Hatchery releases by species, year, and region, including expanded coded-wire tag (CWT) release plus releases not associated with a CWT group.

B. Total catch by year within each geographic region, summed over gears, and the estimated total contribution from BC hatcheries. NOTE: due to data limitations for NCST and CCST recreational fisheries, total catch in these regions is only present for 2013 to 2020; in WCVI and ISC, the catch data is presented for 1980 to 2020.

C. Estimated hatchery contributions to spawning escapements by year and region.

D. Distribution of expanded CWT from BC hatcheries by species across fisheries and years.

E. Estimated CWT catch per 1,000 CWT released by region, year, and production objectives for Chinook and coho salmon.

To assess rebuilding of natural populations through hatchery releases (James and Rosenberger 2023), historical escapement data were collated for 45 Chinook salmon populations. These populations were determined from a review of the 2014-2021 SEP production plans to identify projects with a stated objective of "Rebuilding". From these, the analysis documented the availability of data over time periods of pre- and post-supplementation (beginning of hatchery releases) and estimates of hatchery contribution by year where available. Full documentation for each of the 45 Chinook populations is provided in Rebuilding Appendix A (James and Rosenberger, 2023).

To assess rebuilding, metrics were developed for expected change of hatchery and wild-origin salmon by generation. These methods were necessary to account for the unknown parentage of spawners after the first-generation of 'marked' hatchery fish in a spawning population. For each Chinook system, the spawner time-series was broken into periods to capture changes over time. For example, in the Sarita River the first year of enhancement was 1985 (1984 Brood year). Sarita River Chinook are an ocean-type Chinook population that tends to return with the dominant age-class as 4-year-old fish. This means that the first significant enhanced returns would have occurred in 1988. This time series of data was separated into 6 segments as described in Table 2. If available, the enhanced contributions (pHOS, Withler et al. 2018) were applied to the total spawner abundance to estimate natural-origin and wild spawners. For summary figures, geometric means were used since spawner abundance is typically log-normal distributed where spawners $_{i,period}$ are the annual ($_{i}$) spawner estimates in that time($_{period}$):

$$geomean_{period} = \exp(mean(\log(spawner_{i,period})))$$

Table 2. Example of designated time periods of spawner abundance in the Sarita River Chinook (WCVI).

Time-Period	Year Range
1. Historical	All years up to and including 1976
2. 2-generations pre-enhancement	1977-1985
First year of releases/enhancement	**1985**
3. First generation post-enhancement	1986-1989
4. Second generation post-enhancement	1990-1993
5. Third generation post-enhancement	1994-1997
6. All years after the 3rd gen post-enhancement	1998 and >

In this analysis, **total spawners** refers to the total number of adults reported on the spawning grounds comprised of both hatchery-origin salmon (e.g., spawned from captured brood stock and released as juveniles, which may or may not be marked with either a CWT, and adipose fin clip, or a thermal mark), and natural-origin salmon. The latter are spawners that are unmarked but whose parents may be of hatchery origin.

The enhanced contributions (pHOS) for Chinook were used to estimate natural-origin spawners (pNOS = (1-pHOS)) in each year and system where the information is available. Estimates of pHOS are based on estimates of hatchery-origin fish that have been marked and identified as such in brood stock collections or sampling the escapement in river systems. For Chinook, estimates of pHOS based on thermal marks were used preferentially, and then CWT information if needed.

Wild fish, as defined by Canada's Wild Salmon Policy (DFO 2005), are fish that:

> "*have spent their entire life cycle in the wild and originate from parents that were also produced by natural spawning and continuously lived in the wild.*" (DFO 2005)[6]

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[6] Online at: https://www.pac.dfo-mpo.gc.ca/fm-gp/salmon-saumon/wsp-pss/policy-politique-eng.html

For this assessment, the metric $pNOS^2$ was applied as a proxy for wild fish, as it is impossible to identify second-generation wild salmon. The application of $pNOS^2$ reflects the probability that 2 natural-origin parents mated in the previous generation (pNOS x pNOS), and was recommended by DFO Science (Carrie Holt, DFO Science, personal communication, 2021). For details on pHOS and the Proportionate Natural Influence (PNI), see Withler et al. (2018). Systems where enhancement was discontinuous were examined for insights into what happens when enhancement is stopped and how sensitive spawner abundance is to hatchery releases.

The third assessment of interactions (Rosenberger and Bottoms 2023) examined whether the potential mixing of hatchery and wild salmon populations through straying or deliberate releases alters the spatial covariation between local streams, the productivity of local populations, and whether this could be detected statistically. While previous studies of spatial coherence between salmon populations have been conducted at large spatial scales (>100 – 700 km), this analysis examined inlet-scale distances (<10 – 100 km) typical of the large BC coastal inlets. The aim of this study was to relate stream-level metrics of salmon escapement and productivity against the distance from nearby enhanced systems to test the hypothesis that an enhanced signal could be detected in local streams/populations. While the intention was to examine Chinook, coho, and chum salmon, the availability of escapement data and scope of this work made this untenable. Instead, the study examined three large BC inlets involved with large-scale chum salmon hatcheries: Area 25, Nootka Sound/Esperanza Inlet (West Coast Vancouver Island, Conuma Hatchery), Area 8 Bella Coola (Central BC, Bella Coola and McLoughlin Creek hatcheries), and Area 6 Douglas/Gardner Channels (Northern BC, Kitimat Hatchery). Following examination of various metrics to compare spawning escapements over time and between streams, this report focused on log(escapement, ESC) and log(recruits per spawner, RPS). For escapement data, streams included had to have data for at least 50% of the years before and after the beginning of hatchery releases. Analyses included cross-correlation matrices within regions, cluster analysis to examine the sensitivity of results to different metrics, tanglegrams to compare dendrograms, and multiple regression analyses to examine distance from enhancement, year, correlation coefficients, and total releases on log(RPS).

A major effort in this study was the estimation of distance between streams. Distance between the enhanced stream(s) mouth(s) and non-enhanced streams was completed in QGIS using a node-based approach, as was the pairwise stream mouth to stream mouth distance. This approach used nodes placed proximate to the hatchery and then nodes at each inlet intersection point, and finally nodes at the mouth of each stream. Between nodes, lines down the length of the inlet, and then distance to each stream was measured perpendicular from the inlet center line to the mouth of the stream. For inlets with multiple entries and/or connections, a subjective decision was made to consider the shortest water-only route. Maps of each study area and nodes used in these analyses are provided in Rosenberger and Bottoms (2023) and detailed appendices (map, data, analyses) are provided for each inlet.

The fourth assessment of interactions (Doherty et al. 2023) applied a Bayesian hierarchical approach for comparing the performance of multi-population spawner-recruitment (S/R) models that included hatchery production, predation, and/or environmental conditions as potential covariates on the productivity of wild Chinook, coho, and chum populations. Wild salmon S/R relationships with multiple covariates were assessed using multi-population Ricker models fit with spawner-recruit time series data from 1954-2015 for 23 coho conservations units[7] (CUs), 1986-2013 for 24 Chinook populations (8 stocks, 16 CUs), and 1973-2013 for 28 chum CUs. A Bayesian multi-population approach allows for improved statistical power relative to single population models, which can have the dual effect of reducing uncertainty in estimated productivity relationships between covariates and reducing the chance of identifying spurious relationships. The use of a hierarchical approach allows information sharing across different populations in BC to estimate common hatchery, predation, and environmental effects across populations, while allowing for population-specific hatchery effects where data are informative. Doherty et al. (2023) includes a description of the full models examined and application of correlation analyses to identify covariates that best explain variation in wild salmon productivity/survival.

Briefly, this analysis proceeded from single-population Ricker models to a multi-population Bayesian model. Stock-recruitment data for Chinook, coho, and chum salmon were collated for wild populations in their respective conservation units from the Pacific Salmon Explorer (PSE) database (Pacific Salmon Foundation (PSF), www.salmonexplorer.ca, accessed August 2021) and from Inner South Coast chum run reconstructions (unpublished data, Pieter Van Will, DFO). Plus, eight stock-specific spawner recruit datasets for Chinook stocks in the Strait of Georgia provided by Nelson et al. (2019) were included. Using the single-population model, several hatchery activities that could affect wild salmon productivity were assessed as potential hatchery covariates. Pearson correlations between residuals from single-stock Ricker models and hatchery activities were estimated and three hatchery covariates selected:

- **A.** species-specific hatchery releases per wild smolt by CU,
- **B.** species-specific hatchery releases per wild smolt by ocean entry region, and
- **C.** cumulative release sites by CU.

Pearson correlations for pHOS with residuals from single population Chinook Ricker models were included but pHOS data were only available for 11 Chinook populations. To include pHOS, two sets of Chinook models were assessed: a 24-Chinook population model without a pHOS covariate and an 11-Chinook population model with pHOS. Predation effects were represented by regional harbour seal abundance and environmental condition was represented by sea-surface temperature during ocean-entry year in six marine regions as described in Doherty et al. (2023). Predation and temperature covariates were also included in the 11 population Chinook model. The various models were assessed using the Leave-One-Out Cross-validation Information Criterion (LOOIC, Vehtari et al. 2017) to compare predictive performance of Bayesian models and avoid over-fitting. A lower LOOIC value indicates better predictive performance.

The final evaluation of interactions was Maharaj et al. (2023), who considered biological trends in size-at-age and age-at-maturity in hatchery and wild Chinook salmon populations. However, interactions between them could not be addressed as data for wild (non-enhanced or minimally enhanced) Chinook salmon populations were very limited. Similar analyses for coho and chum salmon were intended but the data were not available.

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[7] Conservation Units are geographic groups of the same species under Canada's Wild Salmon Policy (2005) and as developed by Holtby and Ciruna (2007).

Trends in size (postorbital-hypural length or POHL[8]) of Chinook salmon across age classes, sexes, and stocks were compared using records of biological data on individual fish. Data were collated from two databases maintained by the Department of Fisheries and Oceans, Vancouver, BC and described in Maharaj (2023a,b). Trends in mean age and size were assessed by comparing rates of change of these biological traits between populations. For inclusion, a stock must contain at least five years of data with ten or more records per year (following previous studies by Ohlberger et al. 2018; Xu et al. 2020). Sampling of ocean age-1 males (Jacks) is frequently a fixed sample size, as such, this age class was excluded from comparisons for mean age analyses. The limited number of years of sampling conducted in different populations was a common problem. Since this may affect the comparability of trends, each population was differentiated by the range of years in the full dataset. The length of the time series for each sample was categorized as shown below based on the longest time-series over all systems for each indicator:

$$\text{Long time-series: } R > \frac{2}{3} R_{\text{max}}$$

$$\text{Medium time-series: } \frac{2}{3} R_{\text{max}} > R > \frac{1}{3} R_{\text{max}}$$

$$\text{Shor-time series: } R < \frac{1}{3} R_{\text{max}}$$

Where R is the time series range of a given stock and R_{max} is the largest value of R across all stocks.

Rates of change across all sampled Chinook populations were compared by regressions on time series of these indicators, extracting slopes from these regressions and grouping them geographically.
For all indicators, only the most consistently represented age classes (ocean-2, ocean-3, and ocean-4) were used to maximize the number of stocks compared.

Photo by: Eiko Jones

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[8] See: Shaw, W. 1994. Can. Tech. Rep. Aquatic Sci. 1998. Page 63, Figure 22.

SECTION 3: GENOMICS AND APPLICATION TO HATCHERY PRODUCTION

A review of four 'omics' technologies (genomics, transcriptomics, proteomics, and metabolomics) was included to consider how they may be applied to understanding hatchery production (EDI 2020). A scientific literature search of the past 10 years was conducted with key words (i.e., genetics, genomics, transcriptomics, proteomics, and metabolomics) and selected by key words (i.e., parentage-based tagging, transcription, gene expression, qPCR, eDNA, eRNA, and environmental). Two search engines were used: the Web of Science and Google Scholar databases. These authors also address the role of epigenetics in the expression of traits and identify knowledge gaps to be addressed. A second report (Vandersteen 2022) further addressed the application of new genomic technologies to SEP hatchery programs. The intent of this report was to provide a 'user-focused' manual to highlight genomic applications and how they could complement current hatchery operations and assist learning. Details on each genomic approach are provided including the types of questions each could addressed. Considerations are also provided for the sampling and storage of tissues, and the level of readiness of each technique for implementation.

Photo by: Benjamin Fortini

RESULTS

SECTION 1: EVALUATION OF HATCHERY RELEASE STRATEGIES

Fundamental to a hatchery being effective is the survivorship of the juvenile salmon released. Overall, release strategies applied by SEP were based on limited research programs but have proved robust to extensive environmental variation and declining trends in marine survival through the time period studied.

The literature search returned a total of 1,123 unique references, of these, 76 met the screening criteria, covering a broad range of release strategies from California north to Alaska (James 2021a). The following summarizes key findings:

A. Hatchery rearing and release strategies have had demonstrable though variable effects on survival and biological traits.

B. Studies revealed increased or no change in survival of smolts released at a larger size for all species. There were no reports of larger sized smolts having lower survival for either Chinook or steelhead but there was one report of this for coho salmon. Releases of larger smolts decreased the age at return in 47% of Chinook studies and 92% for coho salmon.

C. Chinook and coho responded differently to the timing of release. Coho released later had higher survivals in 46% of the studies, while later Chinook releases had lower survivals in 43% of the studies. Late-released coho had higher catch in fisheries but returned as smaller adults; for Chinook, mixed or no relationships were reported for age and size at return.

D. The most reported (43%) relationship between rearing density and survival was negative.

E. Of the four studies on semi-natural rearing, one in BC reported increased returns from the semi-natural treatment, while those in Washington reported mixed, negative, or no effects.

F. Acclimation prior to release showed mixed results across species, however sea-pens had consistently positive outcomes for survival in Alaska. Sea pen-reared coho in Alaska returned as larger adults, but there was no reported effect on Chinook size at return.

G. Releasing smolts volitionally, rather than forced, yielded similar or lower returns.

H. The release of older life stages (i.e., smolts versus fry, or yearling smolts versus sub-yearling smolts) consistently resulted in higher survival.

It was also worth noting that much of the literature for BC and Alaska is more than 30 years old and that half of the studies had only one to three years of data; also, publications on release strategies in SEP are very limited. To assess strategies applied by SEP and their effectiveness, 25 release experiments conducted in BC over the past 20 years were examined (James 2021b). Many of these experimental releases have been exploratory in design, involving only a few years. Given the considerable interannual environmental variability, it is likely that the limited data associated with some of these experiments lacked the power to differentiate between release groups. Consequently, a new hierarchical multi-hatchery Bayesian model was developed to address data limitations between hatcheries and species, assess shared environmental effects, but allow for possible hatchery-specific effects (James et al. 2023). The authors concluded that “higher survival rates were associated with increasing weight-at-release, earlier releases of Chinook salmon, and later releases of coho salmon”, and that “optimizing release practices” could increase returns by 6%-245% for Chinook (mostly Fall Chinook) and 5%-160% for coho salmon. In the absence of stated production objectives for these hatcheries, the posterior estimates of “optimal” practices provide a metric of effectiveness and implies that the release practices applied have been robust to significant annual variability and declining survival rates over time.

These results suggest that SEP release strategies for Chinook and coho salmon have been "effective" in production of adult Chinook and coho salmon, *if assessed only against production of hatchery adults*. Figure 5 in James et al. (2023) presents the decline in the estimated mean posterior marine survival across hatcheries (and 95% intervals) for sub-yearling Chinook smolts and yearling coho smolts but inter-annual variation by hatcheries have also been assessed (Appendix E, Doherty and Cox, 2021). The mean proportion of variance in average annual logit-survival that is explained by random year effects ranged from 13-91% and 10-80% between hatcheries for Chinook and coho, respectively (Tables E.1-E.2, Figures E.1-E.4; Doherty and Cox, 2021). However, these ranges are affected by the numbers of years of data included per hatchery (Figure 3). For hatcheries with 10+ years of data, the range of variance accounted for by random year effects becomes more limited (Chinook sub-yearlings, 30-70%; coho smolts, 20-40%) but still demonstrates extensive environmental variability between years.

Section 1 of the HER was summarized in James et al. (2021), and supplemental data provided (James 2022); data have been archived at the Strait of Georgia Data Centre.

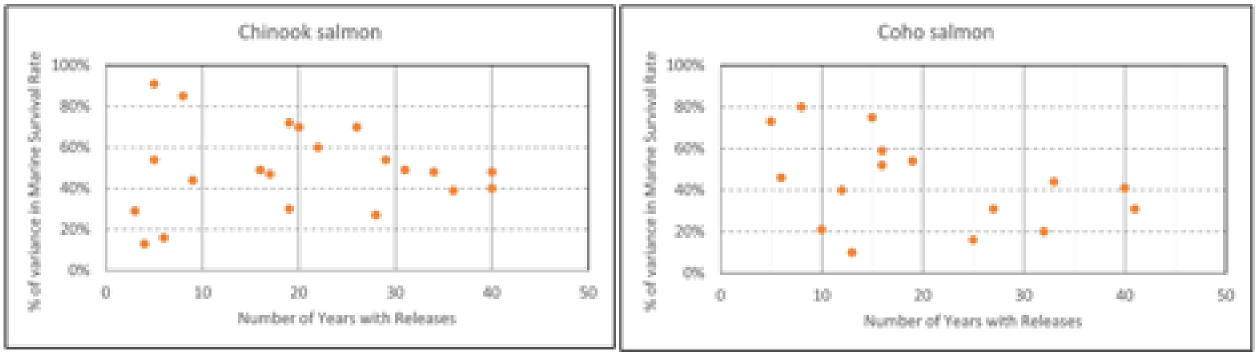

Figure 3: Proportion of variance in average Chinook and coho annual logit-survival rates that is explained by the random year effects. Each data point represents one hatchery included in the multi-hatchery model presented by Doherty and Cox (2021).

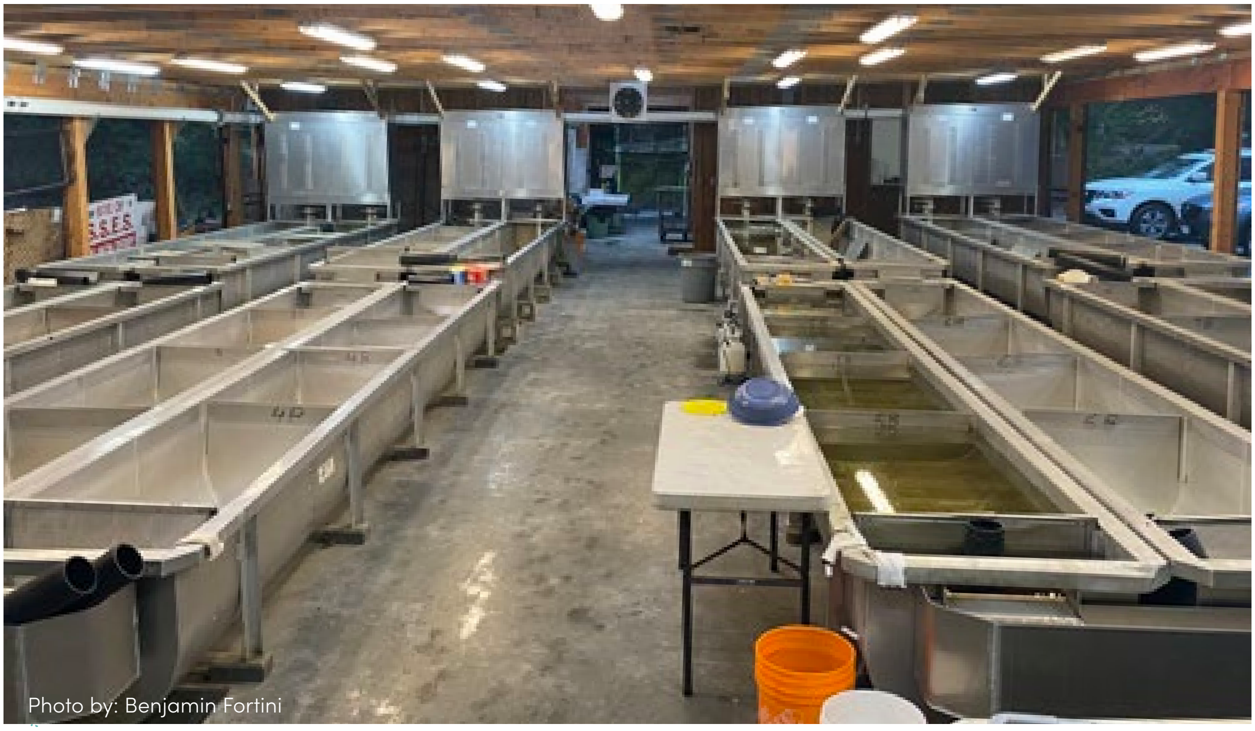

Photo by: Benjamin Fortini

SECTION 2: ASSESSING THE EFFECTIVENESS OF SEP HATCHERIES AND INTERACTION WITH WILD PACIFIC SALMON

Evaluating effects of interactions between hatchery-produced Chinook, coho, and chum salmon with naturally produced conspecifics began with a literature review (studies of interactions only, Giles 2022) and a review of the Community Involvement Program of SEP (Fortini 2023). The latter was an original objective in the SEP to fully engage BC citizens in the conservation and enhancement of Pacific salmon across the province.

The literature review accepted 112 studies that directly addressed interactions between wild and hatchery-origin salmon but 27 were assessed as overly broad to assign to categories. For the remaining 85 studies, interactions were assessed as positive, negative, or showed no evidence of effects, and each study was assigned to a category of interaction: genetics, competition, population mixing, fish health, and outcome-based studies. Table 3 summarizes the assessments by category and Giles (2022, Appendix 2) provides reasons for all 85 assessments. However, both studies suggestive of positive outcomes require qualification.

A. The genetic study by Berejikian and Van Doornik (2018) avoided broodstock selection and artificial mating by using naturally produced gametes in a captive breeding program to supplement a small steelhead population. This is a creative means to culture fish for supplementation but not typical of hatchery procedures.

B. The Fish Health study was more of an intervention than an interaction (Ivan et al. 2018). These authors hypothesize that vaccinating a cultured stock could reduce infection in the mixed population over generations, but the concept was not tested.

Given these qualifications, this review did not find any reports that supported positive outcomes for hatchery x wild interactions.

Table 3. Summary of interactions (positive, no effect or unknown, negative) from the literature review by Giles (2022).

Interaction:	Assessment of effect:			Cumulative
	Negative	No Effect Assessed	Positive	Totals
Genetic	**17**	**9**	**1**	**27**
Competition	**9**	**11**	**0**	**47**
Fishery effect	**12**	**0**	**0**	**59**
Fish Health	**1**	**3**	**1**	**64**
Outcome based*	**11**	**10**	**0**	**85**

* Outcomes were considered under productivity impacts, impacts on survival rates, and impacts on biological traits.

The Community Involvement Program (CIP) in SEP involves small-scale hatcheries, habitat restoration projects, and community engagement to promote local stewardship. These projects are more spatially diverse than the large production hatcheries (referred to as Operations) involving communities throughout BC. Table 4 compares the scale of CIP projects versus the Operations hatcheries, comparing releases of Chinook, coho, and chum salmon from all facilities during 2021 (release file provided by SEP, Vancouver, BC). The release file defined each project by hatchery, species, stock origin, and life stage at release. In 2021, 622 projects released a total of 88.1 million juvenile Chinook, coho, and chum salmon. For this release year and these species, community-based projects (CEDP, PIP, and Education) accounted for 64% of projects but only 16% of juveniles released with substantially lower marking incidence (including only 6% of projects with CWT marking for assessments). Sockeye and pink salmon from channels are not included in this total or Table 4.

Table 4. Comparison of 2021 release projects, proportion of the total releases summed for Chinook, coho, and chum salmon, and the portion of the release projects that were marked (coded-wire tags or adipose-only clips).

Program level	# of projects	% of total release	% of projects marked	Comment
Operations	221	84.14%	56.6%	16 major hatcheries
CEDP	147	13.50%	23.2%	20 CEDP hatcheries
PIP	134	2.30%	18.5%	52 PIP facilities
Education	120	0.06%	1.6%	121 schools involved in BC

Photo by: Benjamin Fortini

The PSF review of CIP hatchery-based projects (Fortini 2023) was conducted through an interview process involving 14 of 15 Community Advisors and 32 hatchery/community organizations (15 of 20 CEDP facilities and 17 of 52 PIP programs). Appendices in Fortini (2023) list all hatcheries involved, CA interviews, and provide complete lists of questions asked and responses. The continued commitment of staff and community partners to the CIP was evident in the interviews and projects were largely being conducted consistent with objectives specified by managers within the Pacific Region DFO; and program managers largely followed the Best Management Practices (BMP) provided by SEP (but there were exceptions noted to objectives and operating practices). However, assessing achievement of objectives and compliance with broodstock practices were seriously compromised by the limited marking of salmon within the CIP. To assess the effectiveness of hatchery production, hatchery-produced fish must be identifiable. Based on these releases in 2021 and from the interviewed facilities, only 16% of release groups from PIP facilities and 22% of CEDP facilities applied external marks that would enable identification, *and most of the marking was limited to yearling coho smolts*. Without marking hatchery-produced salmon, hatchery contributions to local spawning populations and compliance with BMPs for broodstock management cannot be assessed. Of note, one hatchery out of the 32 interviewed was using parental-based tagging (PBT, Beacham et al. 2017; Steele et al. 2019) as marks. PBT would enable the evaluation of hatchery contributions once tissues are processed but would not enable broodstock sorting and management without immediate laboratory processing. Most of the hatcheries that did not mark or tag fish cited a lack of funding as the main limitation. Funding was the most common challenge for the interviewed hatcheries with 72% of facilities stating that their level of funding was a significant problem. The other commonly cited challenges included a lack of feedback from data submitted to DFO (44% of respondents), difficulty with water supplies (temperature, amount, etc. 31%), and poor communication with DFO (22%).

Summarizing the contributions of SEP hatcheries to harvest was a challenge given the number of hatcheries, their wide geographic range, and the diversity of fisheries along the BC coast. Plus, catch in a year and fishery also reflects management actions taken for many reasons and may not reflect production from SEP hatcheries. Consequently, catch statistics alone are not an informative measure of hatchery effectiveness but are useful to examine distribution and marine survival rates for numerous tagged hatchery populations. The contribution of BC hatcheries to Canadian salmon fisheries varied widely over time and region. Table 5 summarizes the average contribution (% of total catch) provided in James and Rosenberger (2023), but due to data availability, the years included differ between regions. James and Rosenberger (2023) also examined the efficiency of hatchery contribution to Canadian fisheries by examining the estimated catch per 1,000 juvenile salmon released based on coded-wire tag data (Table 5 in James and Rosenberger 2023). These statistics will be directly affected by species, environmental conditions, and management actions within a region. For example, fishery closures for coho salmon within the Interior South Coast region account for the lower contribution rates for coho salmon in that region. The variability between years is evident in the ranges presented in James and Rosenberger (2023).

Table 5. Estimated % contribution of BC hatchery-produced Pacific salmon (average ± 1 std dev) to Canadian catch (troll, net, recreational, where all the data is available) by geographic regions. Chum catches are for net fisheries only and were provided by Lynch et al. (2020).

Region:	Chinook	Coho	Chum
North BC coast	23 ± 17%	7 ± 3%	16 ± 15%
Central BC coast	26 ± 12%	3 ± 3%	19 ± 16%
Interior Southern BC coast	37 ± 18%	41 ± 19%	43 ± 29%
West coast Vancouver Is.	26 ± 19%	34 ± 22%	25 ± 21%

Augmentation of salmon abundance for harvest has been the most common objective for hatchery production historically but in recent years, the use of hatchery fish to supplement/rebuild spawning abundance in natural systems is an equally common objective (based on 2023 SEP Production Plan, Table 6).

Table 6. Summary of production objectives for Chinook, coho, and chum salmon from the 2023 Production Plan (*SCNC-IFMP-PP-eng.xlsx*) in the Community Involvement Program (CIP) and major production hatcheries (Operations, OPs). Sockeye and pink salmon were excluded.

Objective	Chinook		Coho		Chum	
	CIP	OPs	CIP	OPs	CIP	OPs
Assessment	7	20	1	8	0	0
Conservation	17	11	2	2	0	0
Harvest	20	20	34	21	6	19
Rebuilding	31	21	20	8	34	14
Stewardship	18	0	127	6	88	6
Education	19	0	112	0	64	0

To examine the effectiveness of hatchery-produced salmon for rebuilding of natural salmon populations, James and Rosenberger (2023) identified 45 river systems designated for Chinook salmon rebuilding in the 2014-2021 SEP production plans. Of these, two were excluded from evaluations (Elaho River and Portage Creek) because of inadequate data, and only 36 systems had hatchery contribution data for assessment (pHOS, proportion hatchery-origin fish in the spawning population within a year/stream, Withler et al. 2018). Only 10 systems had sufficiently long time-series of spawner abundance *and* pHOS data. The Rebuilding Appendix in James and Rosenberger (2023) provides a detailed description of each Chinook system (data availability, analyses included, and notes on why or why not they were included) and all data by system/year are presented graphically in a "Dashboard" of supplemental data. The primary question addressed in this analysis was the effectiveness of hatchery releases for rebuilding Chinook abundance in these systems. That is, once a system has been identified as depleted (below carrying capacity), and releases of hatchery-produced juveniles begun, were the releases effective in restoring a larger and sustained natural spawning population?

There were several challenges that limited this assessment, the foremost being data availability, but the data available for 31 Chinook populations utilized in this analysis are presented in Figure 4.

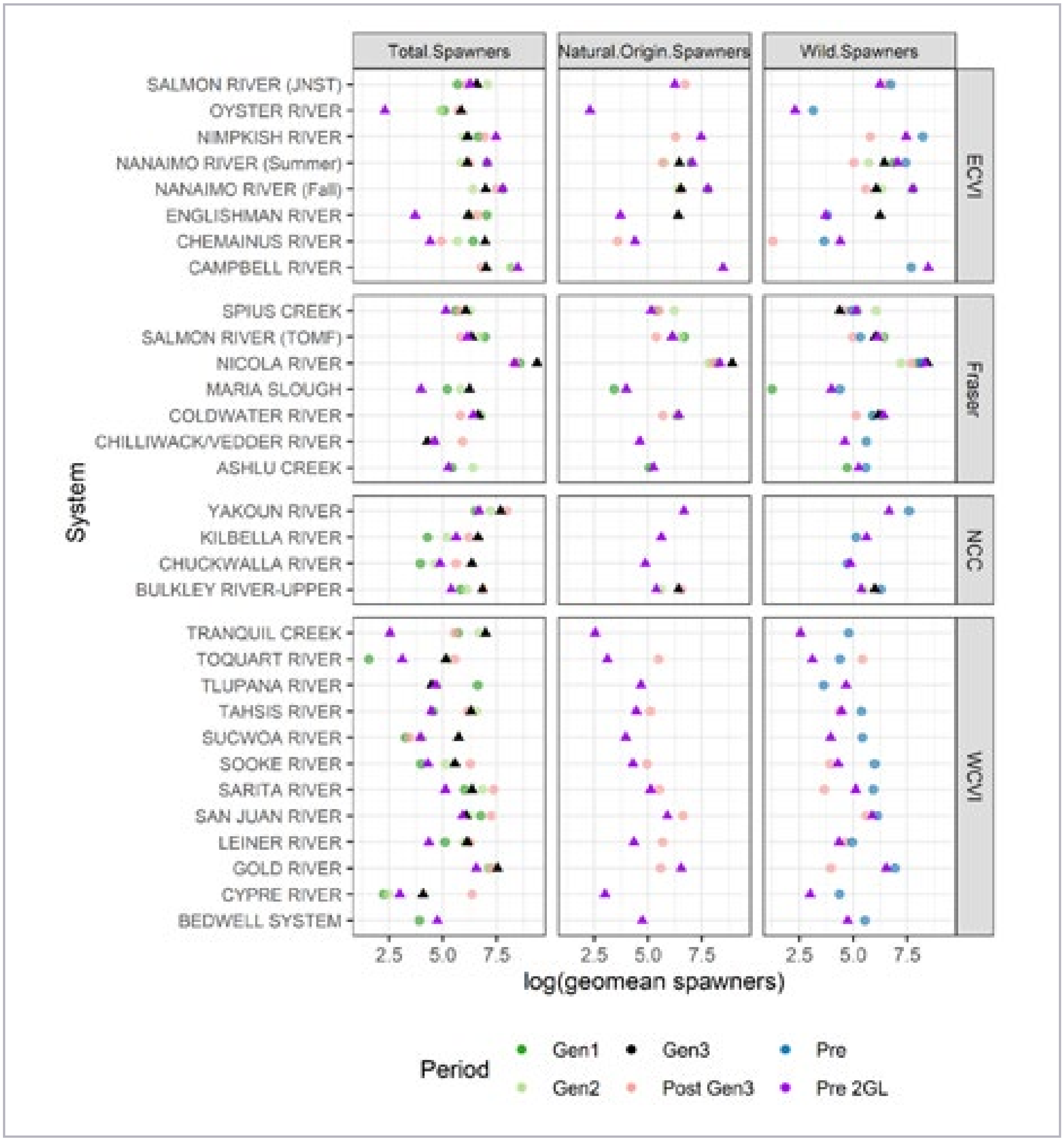

Figure 4: Data availability to assess spawning responses in 31 populations with sufficient data to assess returns **in the 3rd Generation Post-Enhancement** relative to the two generations before commencement of hatchery releases. Triangles represent the geometric mean for these pre- and post-enhancement periods.

In the absence of measurable objectives, this analysis examined changes in spawner abundance before and after enhancement commenced and over generations. If the number of total spawners (independent of origin) is assessed, then 31 of 45 populations can be assessed and 25 (81%) indicate larger populations post enhancement; but only **9 out of the 31** systems had sufficient data to assess natural and wild spawners **in the 3rd generation** post enhancement, and only 4 of 9 resulted in improved wild spawners (Figure 5). These results provide evidence of a 'demographic boost' in total spawners following the beginning of supplementation, however the estimated response of natural-origin and wild spawners was much poorer, implying poor effectiveness when a full assessment could be undertaken.

If Figure 5 was presented for escapements in the **post 3rd generation following enhancement**, then the number of populations assessed for natural and wild-origin spawners increases to 17 and nine of these **systems** (53%) indicate increased returns of natural spawners but only four have evidence for increases of wild-origin spawners. The latter results could be due to a variety of factors including environmental effects on productivity or longer-term consequences of interactions with hatchery-origin fish. As the uncertainty of assessing hatchery associated effects will increase over time, **only the comparison within the 3rd generation post-enhancement** is presented here (Figure 5).

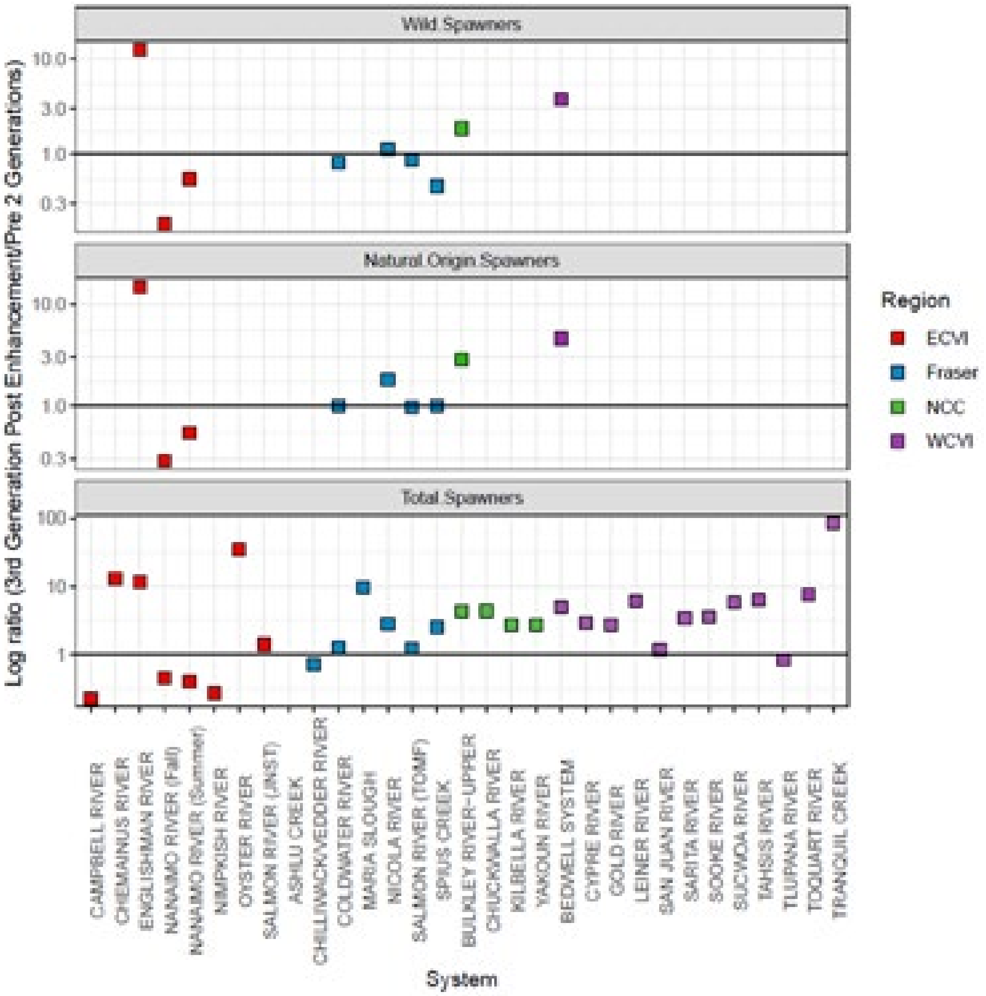

Figure 5: Escapement in 31 populations with sufficient data to assess escapements within the 3rd generation (geometric mean) post-enhancement compared to the two generations pre-enhancement for the total spawners (independent of origin), numbers of natural-origin spawners, and numbers of wild-origin spawners. Data presented as Log Ratio of these returns.

The rebuilding analysis also summarizes data for pHOS and PNI for the Chinook rebuilding systems. These data show that there are only long-time series of hatchery contribution rates for a third of the systems, and that many systems are often below the integrated-wild threshold of 0.72 given in Withler et al. (2018). The data also show that there can be significant differences in PNI estimates using thermal marks (otolith marking) and CWT information (Figure 6). It is understood from discussions with SEP staff that rebuilding systems may start out with low PNI (high hatchery influence), but then should trend towards higher PNI over time (Michael Thom, SEP, personal communication, 2022). This appears to only be the case in two systems (upper Bulkley River and middle Shuswap River Chinook). In the few systems that have long-time series of pHOS information, there are many systems where PNI has remained variable but around the same level, or declined over time, which would contradict the intention of rebuilding.

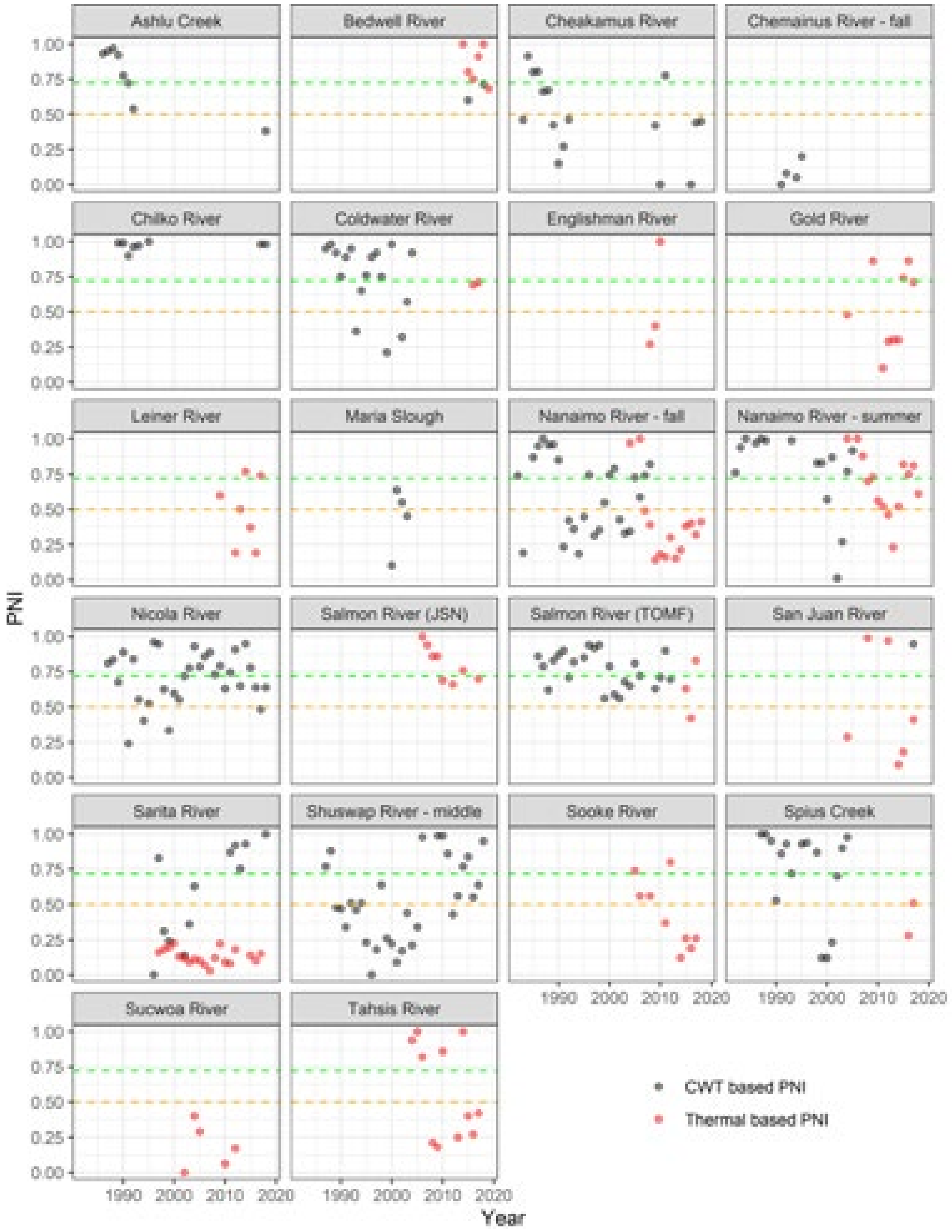

Figure 6: Examples of pHOS sampling for BC Chinook systems using either coded-wire tags and/or otolith thermal marks. (SEP Proportionate Natural Influence Database)

Rosenberger and Bottoms (2023) report on a statistical assessment of spatial coherence in annual spawning escapements within three major BC inlets that included major hatcheries and natural populations. Within each inlet, the coherence of log(ESC) and log(RPS) decreased significantly with increasing distance (Figure 7), but the background variation was substantial. It was notable that within each inlet, the covariation between streams for both metrics were modestly positive (typically in the 0.25 to 0.5 range) and stronger for log(RPS). When assessed amongst streams and within periods, the comparison of RPS in Area 25 indicates a significant decrease over time (Figure 8). The regression analyses supported these observations. In Area 25, total hatchery releases and year had weakly negative but significant correlations with log(RPS). In Area 8, releases (weighted releases from both Snootli and McLoughlin hatcheries), distance, and year had negative effects on log(RPS). And, in Area 6, these analyses indicated that total releases and year had significant but different effects on log(RPS); distance was not statistically significant, releases were negatively related, and year was positively related.

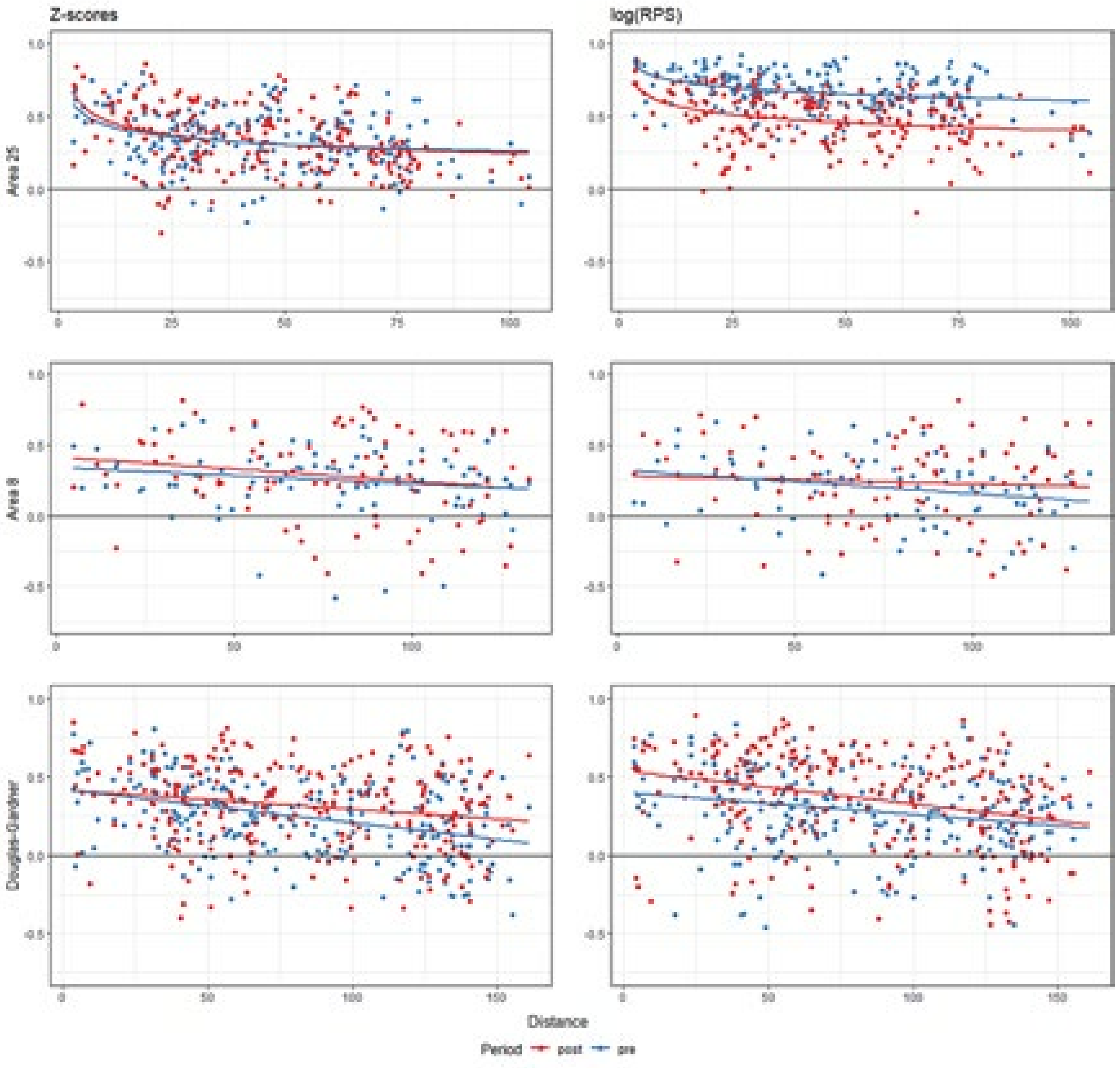

Figure 7: Pairwise stream to stream correlations versus pairwise stream to stream distance for Z-score of log(ESC) and log(RPS) for Area 25, Area 8 and Douglas-Gardner chum. Analysis by Rosenberger and Bottoms (2023).

Overall, Rosenberger and Bottoms (2023) demonstrate significant coherence between chum salmon streams within three large BC inlets, but evidence for interactions between major chum facilities and natural populations was limited to populations in close proximity, and effects tended to decrease with distance. In one of the three inlets assessed, changes in productivity of natural systems decreased significantly between the pre- and post-hatchery periods (Area 25, Figure 7) but confidence in the results for Areas 6 and 8 were limited by the data available.

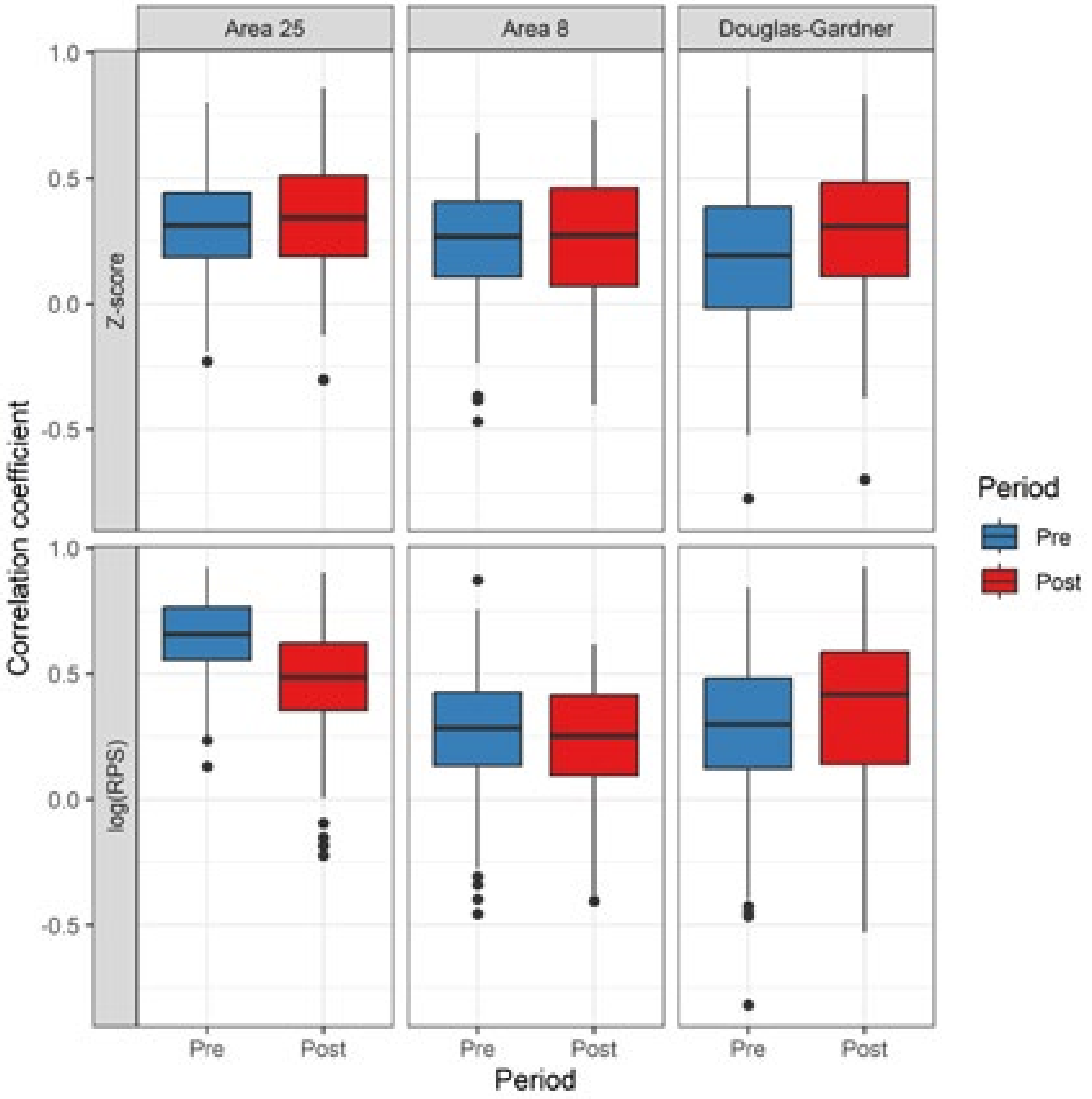

Figure 8: Mean correlation coefficients by area for the pre- and during-enhancement periods for Z-scores (top panel, ESC) and for log(RPS) (bottom panel). Analysis by Rosenberger and Bottoms (2023).

Doherty et al. (2023) examined the potential effect of hatchery and environmental covariates on the productivity of natural salmon populations of Chinook, coho, and chum salmon (Table 7). They emphasized that the use of covariates was necessary to significantly improve explanations of changes in wild salmon productivity over time. For all three species, the ratio of hatchery to wild smolts within marine regions increased productivity whereas the effect of cumulative releases over time was generally negative. However, the statistical significance by covariate and species was not consistent. These analyses indicated positive and negative effects of hatchery covariates within conservation units, but predation and environmental effects had larger combined effects.

Table 7. Covariate effects on recruits per spawner (RPS) models in Doherty et al. (2023), ns indicates effect was not statistically significant.

Covariate	Chinook	Coho	Chum
Hatchery covariates	Full 24 population analysis: Significant positive effects from hatchery releases per wild smolt by CU and ocean entry region. Significant negative effect on average from cumulative release sites.	Co-variates had mixed effects; positive effect from hatchery releases per wild smolt by CU (ns) and for ocean entry region (significant). Significant negative effect on average from cumulative release sites.	By CU's, significant positive effect of hatchery releases per wild smolt and ocean entry region. On average, effects of cumulative release sites covariate were not significant (near zero) but had significant positive effect for populations in the Strait of Georgia (SoG).
Predation	Negative effect (not significant). Larger effects in SoG due to higher seal density.	Significant negative effect. Larger effects in SoG due to higher seal density.	Significant negative effect. Larger effects in SoG due to higher seal density.
Environmental conditions (sea surface temperature SST)	On average, SST had a slight positive effect (ns).	SST by region had significant positive effect on productivity.	Significant negative effect.
Percentage of hatchery origin spawners (pHOS)	For 11-popn. Analysis: inclusion of pHOS covariate had slight positive effect (not significant) with little impact on estimated effects for other covariates.	No data, not assessed.	No data, not assessed.
General Comment	No evidence of model over-fitting. Impact of covariates varied considerably between conservation units.		

Maharaj et al. (2023) collated sufficient data for Chinook salmon to examine changes in age-at-maturity, size-at-age, and %females in spawning escapements but the numbers of populations included in each comparison differed and most populations sampled were of hatchery-origin (Table 8). Maharaj (2023a) provides details of data sources and treatments.

Table 8. Summary of graphic results in Maharaj et al. (2023) for three metrics assessed, number of Chinook populations compared, and trends for each metric including numbers of populations that were statistically non-significant (ns) trend. Annual data for each population and metric are provided in the Supplementary Information (Maharaj 2023b).

Indicator	Units (Rates of change by)	# Populations Sampled (Hatchery/ Wild)	Trend in rate of change	
			Negative (-) trend (# of samples (# ns))	Positive (+) trend (# of samples (# ns))
Mean age at maturity	Year / Year	19 (17/2)	13 (3 ns)	6 (2 ns)
Mean length (POHL)	mm / Year	22 (20/2)	17 (1 ns)	5 (0 ns)
% Female in sample	% change / Year	84	42 (28 ns)	42 (28 ns)

Photo by: Benjamin Fortini

Age-at-Maturity: Change in mean age-at-maturity was assessed in 19 Chinook populations but with only two wild/minimally enhanced populations included (Harrison and Kitsumkalum rivers, Figure 9). For this assessment, minimally enhanced was defined as <5% hatchery composition in total returns. A significant decrease in mean age-at-maturity was observed in nine of 17 hatchery populations and four showed significant increases. Decreases in age-at-maturity were driven by reductions in the proportion of the oldest age class (ocean-4). For the two minimally enhanced systems, there was a significant decline in age-at-maturity of Harrison River Chinook and a small, non-significant decline of Kitsumkalum River Chinook. More detailed changes by age-classes within populations are provided in Maharaj (2023b) but differences in sample sizes and time series confound many comparisons.

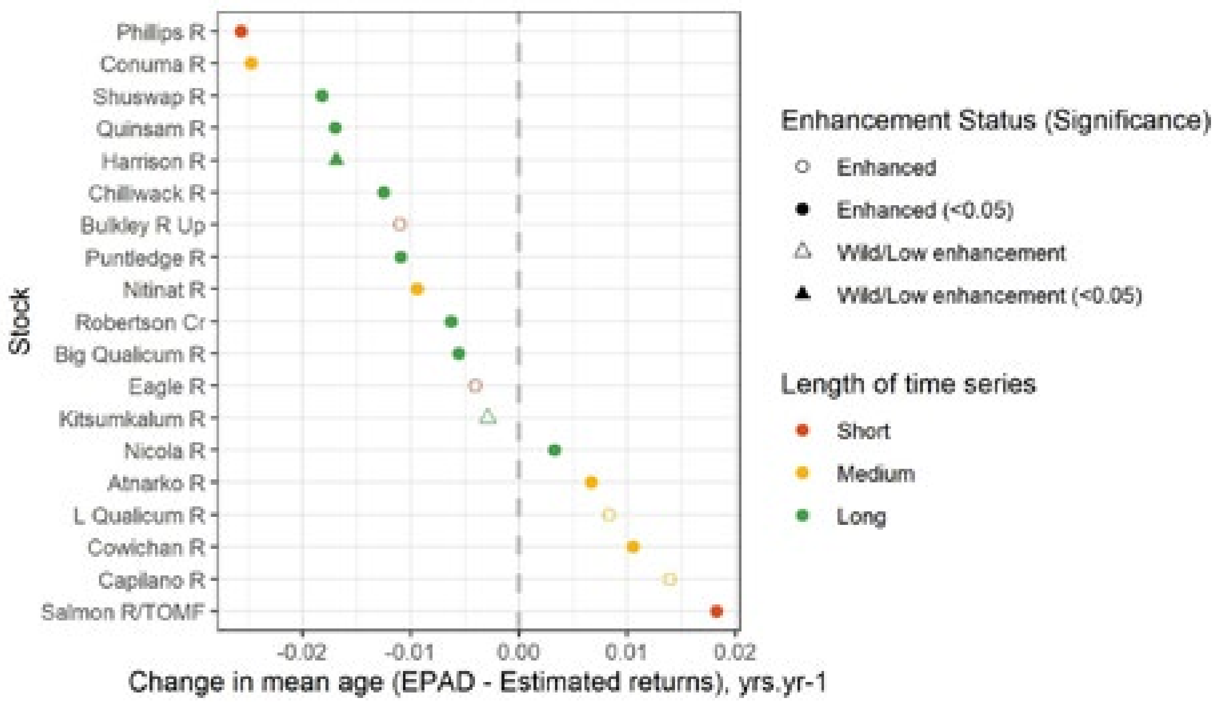

Figure 9: Rate of change in mean age-at-maturity for Chinook populations assessed (Maharaj et al. 2023). The length of the time series from which trends were calculated is given by coloured circles. Statistically significant trends are represented by filled points. See Figure SI 6 in the Supplementary Materials (Maharaj et al. 2023) for time series of annual values.

Mean Size and Size-at-age: Mean size of individual fish declined significantly in 73% of the 22 Chinook populations assessed (Figure 10, see Supplemental data (Maharaj 2023b), Figure SI-17 for full time series by population). Wild Chinook from the Stuart River and fish from the Kitsumkalum River (but see below) displayed the smallest declines in mean size of all stocks.

Mean size is affected by both changes in age and size-at-age in returning Chinook. As noted above, many populations showed declining mean age, consequently mean length will also decrease even if size-at-age was stable. Trends in size-at-age for each system are provided in Maharaj (2023b). Those with the largest declines in mean age also showed the largest significant declines in size for the oldest age class (ocean-4). For populations that had sufficient data to assess size trends in ocean age-4 fish, seven out of nine populations (78%) showed significant declines, about 40% of stocks with sufficient data to assess size at ocean age-2 showed significant increases.

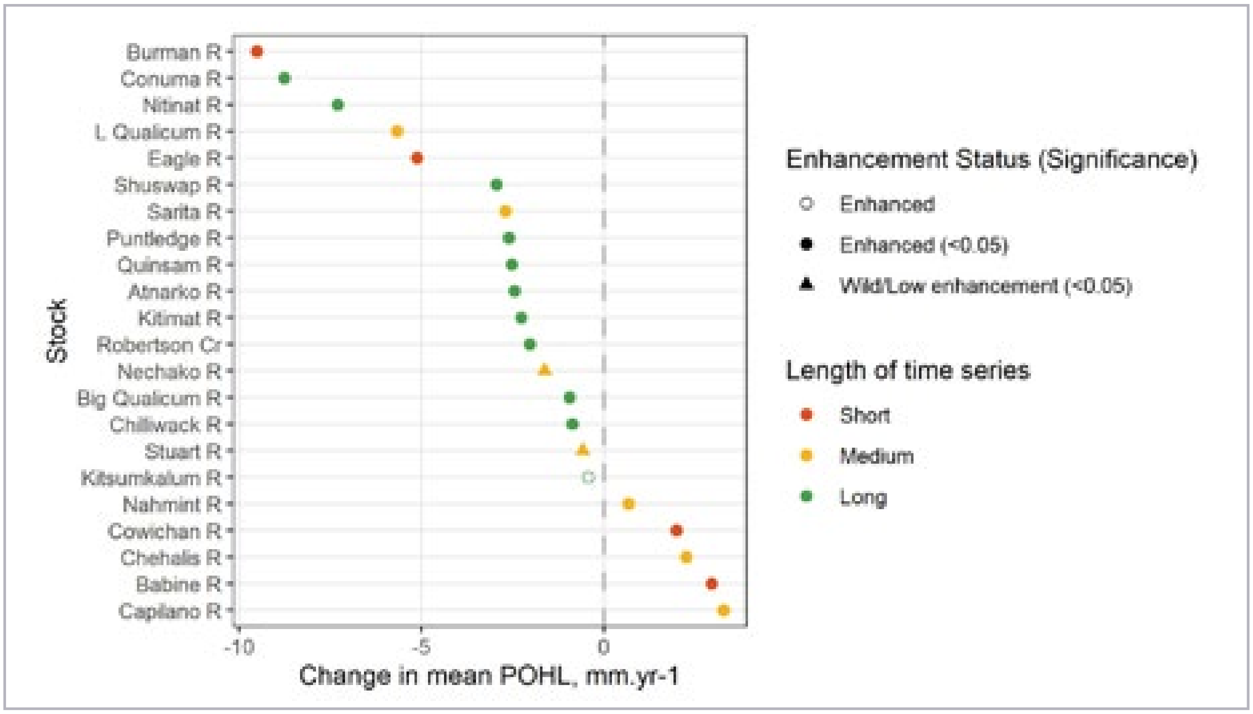

Figure 10: Change in mean size of returning Chinook salmon to these sampled populations.* The length of the time series from which trends were calculated is indicated by point colour. Statistically significant trends are indicated by filled points. See Figure SI 17 in the Supplementary Materials for original data and time series available. See Footnote.

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* Data for the Harrison River Fall chinook (included in Figure 9) were not provided for this report. However, Fraser Fall Chinook in Xi et al. 2020 (Table 1) includes Harrison River and Chilliwack Hatchery Fall Chinook (same genetic stock as Harrison River) showing significantly decreased mean size by age for Ocean Age-3 and Ocean Age-4, 7.23 mm/yr and 9.05 mm/yr respectively over the period 2003-2017. The rates of change for Harrison wild Chinook and Chilliwack Hatchery Chinook were not presented in Xi et al.

Proportion of females: Since monitoring of spawning escapement frequently includes data for per cent females and egg retention, a total of 84 populations could be compared for changes in per cent females over time. However, the change in per cent females is less sensitive than changes by age-class and sex since females are present in all older age classes for Chinook salmon. An index of per cent female in a sample of spawners is then a blend of a few age classes. Trends in female composition ranged from declines of 37% to increases of 17% per year, and significant declines were detected in ~17% and increases in ~8% of stocks (Figure 6 in Maharaj et al. 2023). There was no consistent pattern for the few wild and minimally enhanced stocks included. It is notable though that the largest increases and decreases (both heavily influenced by two populations), are limited by very short and clustered sampling periods. Exclusion of those two extremes results in a limited range of change (within + 10%/yr) and a near balance of positive and negative changes.

NOTE: Since the compilation of data in Maharaj et al. (2023), a comprehensive review of Chinook salmon assessment and monitoring for Kitsumkalum (summer) Chinook has been published by Winther et al. (2021). These authors estimated spawning escapements, hatchery contributions, and age and size-at-maturity for hatchery and naturally produced offspring for the period 1984-2020. Two observations are applicable to the discussion above: the identification of Kitsumkalum Chinook as minimally enhanced (i.e., <5% hatchery contribution in spawners, pHOS) is not an accurate description of the per cent hatchery contribution over time; and changes in both age and size at maturity differs with sex of the fish. The index (pHOS) has increased over time exceeding 5% for ~15 years; and the rate of decrease in mean size at maturity has decreased twice as fast in males than in females. The primary factor leading to the decreased size-at-maturity was the decline in the oldest age-class in the spawning population. Brood years prior to 1991 produced mostly age 6^2 fish (~70% proportion) whereas after 2001 the return of 6^2 decreased to ~20%. The reason for this change was not concluded but these authors document a consistently earlier age-at-maturity for hatchery-produced Chinook that likely contributes to the decline in the overall mature return.

Photo by: Nicole Christiansen

SECTION 3: GENOMICS AND APPLICATION TO HATCHERY PRODUCTION

The report by EDI (2020) includes background information on different objectives for hatcheries, genetics lessons learned, the transition from genetics to genomics, the rise of epigenetics, and an overview of the four 'omics' technologies. A detailed review of each 'omics' technology and their applications to hatcheries is provided in sections 2 to 6, and section 7 addresses knowledge gaps, highlighting experimental designs using the 'omics' technology with the potential to increase our understanding of how to best improve hatchery performance. A last section lists hatchery deliverables and knowledge gaps under hatchery performance, offspring quality, health and condition biomarkers, and hatchery-wild differences; plus, it provides an extensive literature list (142 citations through 2020[9]). Vandersteen (2022) complements the EDI (2020) review by providing a user-focused manual that highlights the genomic applications in terms of how they could benefit current hatchery operation and learning, including flow charts linking genetic or phenotypic questions with genomic approaches to apply. The report provides brief summaries of the SEP's operating frameworks: Biological Risk Management Framework (DFO 2013) and Production Planning Framework (DFO 2018), and then provides examples of genomic technologies that could benefit operational objectives for: **1.** Adult collection, holding, and sorting. **2.** Spawning practices. **3.** Adult carcass management. **4.** Incubation. **5.** Rearing. **6.** Release locations, **7.** Release time, size, condition, **8.** Assessment, and **9.** Spawning channels. *This portion of Vandersteen (2022) is interactive with live links to additional information under each of these objectives.* Vandersteen (2022) concludes with details on: Genotyping and biomarkers, assays for SNPs (Single Nucleotide Polymorphism), gene expression and microarrays, epigenetics, pathogen screening, and environmental-DNA.

Photo by: Nicole Christiansen

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[9] EDI (2020) specifically comments on the potential value of "semi-natural" rearing for salmon, but we are aware of an additional citation to assessment of semi-natural rearing conducted within SEP (Brouwer et al. 2014).

DISCUSSION

While there has been 60 years in a modern era of salmon hatcheries in British Columbia, including Canada's Salmonid Enhancement Program (DFO 1978), there has not been a comprehensive review of the SEP since Pearse (1994). Overall, this review by the PSF demonstrates robust strategies for the production of juvenile Pacific salmon within BC's hatcheries (only Chinook and coho salmon could be included) that were developed against a background of extensive environmental variation and change. This production contributed significantly to Canadian fisheries but an ability to assess the net benefit (the combined production of hatchery and wild Pacific salmon) was limited by insufficient data and lack of comparative studies. Consequently, conclusions can be drawn about the effectiveness of hatchery production only, but can not be drawn about the net benefits of salmon hatcheries in British Columbia. This review was limited by:

A. A lack of SEP objectives to measure effectiveness against.

B. Integrated assessments of hatchery and proximal wild populations have not been established, resulting in very few direct comparisons and a very limited ability to assess the net value of hatchery production and causes of change.

C. Data required for assessments were lacking and availability for analyses was poor.[10]

D. Reporting and analysis within SEP programs have been extremely limited over recent decades, with consequences to limited data availability and completeness, except for the CWT programs.

SEP has also functioned during a period of extensive policy and environmental change. The SEP that began with a goal to double commercial catches and sustain fisheries in BC has evolved into a more complex program with multiple (often conflicting) objectives. Notably the growth of biodiversity and conservation as management objectives (e.g., Canada's Policy for the Conservation of Wild Pacific Salmon, 2005), growing evidence of climate change impacts, changes in allocation, treaties, and user group interests, as well as financial limitations.[11] These factors were not considered in PSF's Hatchery Effectiveness Review.

In the narrowest sense, BC hatcheries included in this assessment were effective in the production of juveniles as assessed by survival rates and release strategies. These analyses indicated that release strategies in SEP's major hatcheries have produced smolts of appropriate size and release time that are robust to extensive change in natural environmental conditions over these years (James et al. 2023). However, James et al. (2023) also noted that "while there are several facilities for which the adaptation of size and timing release practices could serve as a useful management tool for increasing returns, others might require changes to release practices beyond those historically used or may be more susceptible to other factors affecting survival (e.g., predation, SST, etc.). In addition, many of these predictions had a high degree of uncertainty such that no change in salmon returns was also a possible outcome of altering release practices (pg. 715)".

Coupling results of the harvest assessment with the above outcome makes a compelling argument that hatchery effectiveness can not be assessed separately from the marine environmental conditions, the status of natural populations, or other fishery management priorities. The observed catch and marine distribution of hatchery fish is dependent upon the natural migratory pattern of an individual population, interannual variation in environmental conditions, and management priorities of the day. For example, the largest effect on catch (harvest) in BC occurred to conserve Interior Fraser River coho salmon (Irvine and Bradford 2000) resulting in the closure of fisheries in southern BC (as exemplified in Figure 32 of James and Rosenberger 2023). This was despite continued large releases of coho salmon from multiple hatcheries in the Fraser River and Strait of Georgia (Beamish and Neville 2021).

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[10] We emphasize though that regional staff were invaluable in collating fragmented datasets, but this required extensive time and some data could simply not be provided within a workable time period.

[11] The Canadian investment into SEP could not be fully documented as annual and program budget values could not be provided.

Beyond the release of smolts and the accounting in catches (based on coded-wire tag data), the ability to assess effectiveness was seriously constrained by limitations of data quantity and lack of comparative studies. Data limitations were a particularly significant problem for rebuilding and spatial analyses and prohibited any empirical assessment of most Community Involvement Programs. The exceptions in the latter case are two Community Economic Development hatcheries that are "Indicator" stocks representing the distribution of unmarked, local natural populations, although Beacham et al. (2020) suggest caution in such assumptions.

In the analysis of Rebuilding objectives (i.e., restoring production of a population to the sustainable level at the capacity of a habitat/stream) the results indicate that simply supplying local hatchery-produced salmon is seldom successful in restoring a sustained natural population (but only nine of 45 streams identified had sufficient information to undertake this assessment). In the streams with sufficient data, it was apparent that hatchery releases could increase the abundance of salmon returning to a stream, but once the release of hatchery fish was reduced or stopped, then the number of returning salmon declined rapidly to levels observed before rebuilding efforts, and in five of nine comparisons the decline was to levels below the pre-enhancement level.

Other studies that have explored rebuilding in Chinook and coho salmon have reported results similar to James and Rosenberger (2023). Koch et al. (2022) reported that supplementation of Upper Yakima River Chinook increased overall abundance of fish spawning naturally on the spawning grounds, however hatchery-origin Chinook had reduced reproductive success. Venditti et al. (2018) showed a number of key results based on a comparison between supplemented and reference streams in Idaho for Chinook. Supplementation increased abundance at some life stages, but this did not persist into post-supplementation phases; after supplementation ceased, abundance and productivity returned to pre-supplementation relationships, highlighting the importance of addressing limiting factors. Buhle et al. (2009) explored the relationships between hatchery and wild coho along the coast of Washington and found that not only did hatchery-origin coho spawners exhibit stronger density dependence than wild spawners, but productivity of wild salmon decreased as releases of hatchery juveniles increased. But there are also studies documenting demographic boosts to spawner abundance without loss of reproductive success in enhanced populations (Hess et al. 2012, Janowitz-Koch et al. 2019, Courter et al. 2022). These authors found trends towards lower survival of hatchery-origin fish but no reduction in fitness for hatchery-natural-origin crosses, even after two generations, with some evidence of a second-generation boost (e.g., hatchery origin individuals spawning naturally and providing further offspring or grand-offspring to the population). Notably, these programs used 100% natural-origin broodstock, highlighting the importance of natural-origin broodstock in integrated programs, but they did not assess the results after enhancement ceased, or beyond relatively short timeframes.

Overall, studies to date and James and Rosenberger (2023) suggest that supplementation (direct releases of juvenile hatchery salmon) for rebuilding has had limited effectiveness and that short-term supplementation is unlikely to result in increased wild spawners long-term.

Investigations into the cause for the failure of rebuilding efforts in these systems are certainly warranted, as there may be local habitat and/or other limiting factors involved.

In the assessment of spatial interactions, reductions in the productivity of natural chum salmon in proximity to major hatchery facilities were statistically detected but the effects were minor in magnitude and assessed against a large natural variability. However, over a larger geographic scale in Central BC, Atlas et al. (2022) reported a major reduction in chum salmon production (~90% since 1960) despite a major hatchery (Snootli Hatchery in Bella Coola River, completed 1978) that now comprises over 50% of the Central BC chum salmon abundance. These authors note that hatchery production has "buffered" the return of summer chum to the Bella Coola River but variation between years has been large (29-fold variation in the past decade) and hatchery production has not sustained fisheries. They also suggest that large, enhanced populations may have reduced resilience to climate variability and change, as previously proposed by Satterthwaite and Carlson (2015) and Price et al. (2021).

A third study of interactions assessed hatchery covariates and productivity of natural populations of Chinook, coho, and chum salmon within Conservation Units (CU) (Doherty et al. 2023) using Bayesian hierarchical models. These analyses revealed positive and negative interactions between hatchery releases and trends in productivity of salmon populations within CUs. Most notably, inclusion of hatchery and environmental co-variates better explained changes in wild salmon productivity over time than models that excluded covariates.

The final assessment examined changes in biological traits (size and age at maturity) reporting results that are consistent with other studies (Ohlberger et al. 2018, Oke et al. 2020) and are cause for considerable concern. However, the limited ability to compare trends in these traits among hatchery and wild populations severely limits any assessment of hatchery effects. Mean age and size-at-age declined significantly for Chinook populations examined but due to data limitations, this review could not consider other salmon species.

Declines in mean size and age and declines in the proportion and size of fish in the oldest age classes may support the hypothesis of size selective predation and/or fishing. Although some fisheries still apply selective pressures on larger and older Chinook, fishing effort has declined substantially since the 1990s. The ongoing decrease in mean size and age cannot likely be attributed solely to fishing pressure. On the other hand, recent evidence exists for the potential impact of salmon predators on salmon populations (Nelson et al. 2019). Other explanations are also possible including environmental factors such as declining marine productivity, hatchery mating protocols, and climate change in both marine and freshwater environments as likely candidates.

The third section of the HER focused on genomics and the application of new technologies to advance understanding of genetic and environmental effects of hatchery rearing on Pacific salmon, including new insights into epigenetics. Epigenetics may explain why hatchery and wild produced salmon show differences in fitness/performance in the wild despite genetic similarity between the fish studied (i.e., Le Luyer et al. 2017, Christensen et al. 2021, Koch et al. 2022), including the decreased productivity of hatchery salmon in the wild, despite having similar DNA backgrounds as progenitor wild salmon (Fraser 2008, Houston and Macqueen 2018). Epigenetic effects are caused by modification of gene expression rather than changes in the genetic code and can have profound trait or phenotypic effects and may span multiple generations (Best et al. 2018). Specifically, epigenetic programming causes changes in gene expression without changing the underlying DNA sequence. The nature and extent of epigenetic effects has only recently been explored in salmon at the molecular level (Le Luyer et al. 2017, Christensen et al. 2018, Venney et al. 2021, Koch et al. 2022, Waples et al. 2020). Ford et al. (2023) evaluated the genomic divergence between several paired groups of Chinook salmon using whole genome assessments involving millions of SNPs compared to past comparisons using allelic variation (at only 10s of alleles). The key outcome was that "efforts at limiting genetic divergence between captive and natural fish in these populations have successfully kept the average divergence low across the genome, but at a small portion of their genomes, hatchery and natural salmon were as distinct as individuals from different ESU's." Interestingly, the "small portion of their genomes" were on chromosome 28 within a region previously identified and associated with variation in adult run timing in Chinook salmon and steelhead (Hess et al. 2016, Prince et al. 2017, Thompson et al. 2020, Willis et al. 2021, and Waples et al. 2022). The latter result exemplifies the potential importance of genomic tools applied to understanding the phenotypes of Pacific salmon and their conservation in captive and natural environments (e.g., Waters et al. 2018). The potential for shifting from a genetic-only focus (e.g., Devlin et al. 2021) to a broader genomics approach is well described by Bernatchez et al. (2017) and Waples et al. (2022) and exemplified in Meek et al. (2020).

The application of genomic methods in salmon culture and conservation requires special equipment, laboratories, and staff. However, in the Pacific Region, Department of Fisheries and Oceans, these already exist and tools could be applied immediately. The Molecular Genetics Laboratory, Nanaimo, BC has an established record of expertise (Miller et al. 2017, Beacham et al. 2021, 2022, Christensen et al. 2021, Rondeau et al. 2023, Xuereb et al. 2022).

SUMMARY AND RECOMMENDATIONS

Based on the sum of these analyses and using the current production objectives for SEP (SEP Production Planning: A Framework, 2018),[12] a rating of effectiveness is presented in Table 9. Given the diversity of projects within each category and the noted data limitations, the rankings are symbolic as indicated by plus (+) or negative (–) signs and qualified with comments.

Table 9. Effectiveness rating based on PSF's review. Note that there were no reviews conducted that involved sockeye, pink, or steelhead trout. Cn = Chinook, Co = coho, and Ch = chum salmon. Sample sizes (n) are the number of Department of Fisheries and Ocean regional projects with specific objectives in the 2023 Integrated Salmon Management Plan.

Objective	Species	Rank	Comments
Production (overarching need)	Cn, Co	**++**	In the narrowest sense of effective, Operational facilities were assessed to produce juveniles robust to highly variable and changing environments.
Harvest (n=120)	Cn, Co, Ch	**+ to –**	A variety of management factors limit access to salmon produced from hatcheries and limit the utility of harvest assessments in consideration of effectiveness. A significant contribution to past BC fisheries was noted in this review.
Rebuilding (n=128)	Cn	**–**	This review could only assess Chinook salmon and provides little evidence of a lasting effect of hatchery releases to restore wild populations. Data availability (nine analyses in 45 streams) limits confidence in this assessment.
Assessment (n=36)	Cn, Co, Ch	**++ to –**	The use of code-wire tags has been invaluable in monitoring hatchery production and harvest assessment for major hatcheries and indicator stocks. But most CIP hatcheries cannot be assessed as there is inadequate marking for the identification of hatchery-origin salmon.
Conservation (n=32)	NA	**NA**	This objective was not specifically assessed in any of our analyses. Tools to both genetically rear and effectively monitor small populations are available to utilize.
Stewardship and Education (n=440)	Cn, Co, Ch	**++ to ––**	Review of the CIP hatcheries indicate there are issues with communications, funding, and marking. A lack of marking of juveniles prevents assessments and compromises any ability to follow Best Management Practices. However, there remains strong community support for involvement in salmon restoration. DFO's Community Advisors were considered an invaluable link between DFO and BC's salmon community.

++ implies Overall Effective, **+** implies Somewhat Effective, **NA** means Not Assessed,
– implies Somewhat Not Effective, and **––** indicates an assessment of Not Effective.

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[12] https://waves-vagues.dfo-mpo.gc.ca/library-bibliotheque/4074016x.pdf. This document is an up-date of these objectives first described in 2012 and includes a definition of each objective.

> RECOMMENDATION 1: ***Require an integrated management plan for each hatchery*** within Operations and CIP programs including production plans by species and life stage with objectives for each release project, monitoring and evaluation plans and methods, and costing for each program. Each plan should indicate how interactions with local natural salmon populations will be assessed and will designate a responsibility centre. Since regional needs and environmental conditions will change through time, each plan should be continually reviewed and modified as needed. Each plan should involve DFO staff from each Branch, plus local community, and First Nation representatives.

As the literature review and assessment of potential interactions have shown, hatchery-produced salmon are subject to variations of the natural environment and changes in management priorities but can also be a management tool for salmon production (e.g., Fast et al. 2015, Waters et al. 2015). However, this requires a commitment to research, monitoring, and evaluation. The tools (marking and genomic) and staff exist to design and annually conduct these programs. To address the increasingly complex objectives for rebuilding, conservation, and assessment; an analytic team should be assigned to each hatchery management plan.

> RECOMMENDATION 2: ***The Pacific Region must establish a far more effective and timely data management and reporting capability.*** As the need for conservation and rebuilding becomes increasingly prevalent, data must allow managers to assess current conditions in a timely and informed means. Failure to do so is likely to limit successful conservation of salmon populations.

The inability to acquire data during this project resulted in significant time delays, several analyses that could not be undertaken, and significant uncertainty about the strength of conclusions and breadth of issues. These issues pertain more to regional integration of data than to the Salmonid Enhancement Program alone since data by hatchery, species, release groups, and marking were generally available. But data to examine interactions in local natural populations were significantly more problematic. However, there is also a serious lack of reporting of activities and results from the SEP.

> RECOMMENDATION 3: ***The existence of an established and supportive Community Involvement Program across BC is an important asset for the SEP and merits greater support.*** The CIP provides the potential to protect diversity in Pacific salmon and stimulates public support for enhancement and conservation through public inclusion, outreach, and diversity of programs as envisioned originally within the SEP. However, the value of this program for fish production, habitat restoration, and stewardship is limited by inadequate funds, limited technical advice and communications with DFO, and inability to monitor production. Greater investment and support is needed to help ensure the projects follow Best Management Practices stipulated by SEP, undertake marking to evaluate practices and account for fish production, and continued outreach to communities including educational programming.

The Pacific Salmon Foundation (PSF) has also been engaged in these community salmon programs since 1989 and annually provides millions of dollars in support; but it has been inadequate to maintain facilities and the diversity of projects. Partnerships via the CIP are not being adequately pursued at a time when diversity of salmon populations, habitat restoration, and water management are crucially important under continued economic development and changing climates. How much and how quickly to increase investments could be advised by an independent organization such as the PSF.

> **RECOMMENDATION 4:** Given the problems encountered with data availability and assessments, opportunities for genomics and statistical designs to advance hatchery and wild salmon studies, and the increasingly complex questions anticipated, ***a new Enhancement Science program is strongly recommended within DFO Pacific Region.***

While such a program would have to function regionally, the recommendation for a specific program in the Science Branch is to address limitations noted for lack of studies and limited reporting, the need for statistical/experimental designs to estimate effects with uncertainty, effects of environmental parameters, and identification and application of new technologies and methods. Given the state of Pacific salmon today and the increasing uncertainty attributed to climate change, now is the time for research and critical evaluations. This requires experimental design and creativity to identify key factors limiting salmon survival, and knowledge of modern technologies to advance learning about salmon in their ecosystem. These needs are not new today but have certainly not been acted upon to date. Further, user groups that salmon managers consult do not always agree on plans and procedures. For a complex biological, environmental, and governance issue such as Pacific salmon, a dedicated program based on investigation, analysis, learning, and response is appropriate. These steps begin with good science and effective communication to sustain Pacific salmon for future generations.

Photo by: Nicole Christiansen

CONCLUDING COMMENT

Hatchery effectiveness can not be assessed without stated objectives, marking, and reporting. As hatcheries are more fully integrated into regional production and conservation plans, objectives within a hatchery will become more diversified, including consideration of resilience to adapt to climate change including changes in marine conditions. Managing for diversity and resilience will differ significantly from simple production goals by release group.

As the abundance of Pacific salmon declines, pressures to assist with rebuilding local natural populations, meet community expectations, and minimize effects on local natural populations will increase. The availability of hatcheries may be an opportunity to contribute to salmon returns, but they will also be seen as a source of risks to natural populations. The presence of risks is no longer worthy of debate as differences between hatchery and wild salmon have been repeatedly reported, but to what extent and effect? Particularly when a local population is severely depressed, the risk of supplementing with first generation hatchery fish may be less than leaving the natural populations to its own fate (e.g., Nuetzel et al. 2023). The evaluation of Chinook rebuilding projects in this review provides minimal support for the use of hatchery fish for rebuilding wild salmon populations. Given this, the Pacific Region should more fully evaluate procedures and analyses, and incorporate other programs such as habitat restoration and water management in rebuilding planning. Additionally, the scientific opportunities associated with the application of new genomic tools could greatly increase understanding and ability to protect genetic variation and monitor change in recovering populations. All these objectives argue strongly for the integration of hatchery production in comprehensive management and science plans at localized scales across BC (and the Yukon Territory).

The overarching result of these investigations is that hatchery effectiveness can be examined on multiple levels but beyond the production of hatchery smolts and tracking contributions of identifiable hatchery fish to catches and spawning escapements, DFO/Pacific Region has extremely limited ability to assess effectiveness when based on the net benefit to Pacific salmon production and communities. There already exists an overwhelming literature that salmon from hatcheries differ from those reared in the wild, that they tend to be less productive than wild salmon in natural environments, and that they have effects on wild populations of both Atlantic and Pacific salmon. However, the multi-generational impact of mixing hatchery and wild salmon remains more poorly understood. This is an increasingly important question as natural salmon populations decline in abundance, become more fragmented, and stressed under climate change. This scenario is anticipated to become more common in the near term, and if so, using hatchery production effectively to sustain natural salmon production, provide fishing opportunities, and meet public values will become increasingly complicated as recently portrayed by Terui et al. (2023). Future conservation and use of Pacific salmon in Canada requires integration of resources, better data, and research capitalizing on new technologies and collaboration across the full life cycle of Pacific salmon. And this also likely requires far greater public communications about costs and benefits of hatcheries in sustaining a future for Pacific salmon.

Photo by: Nicole Christiansen

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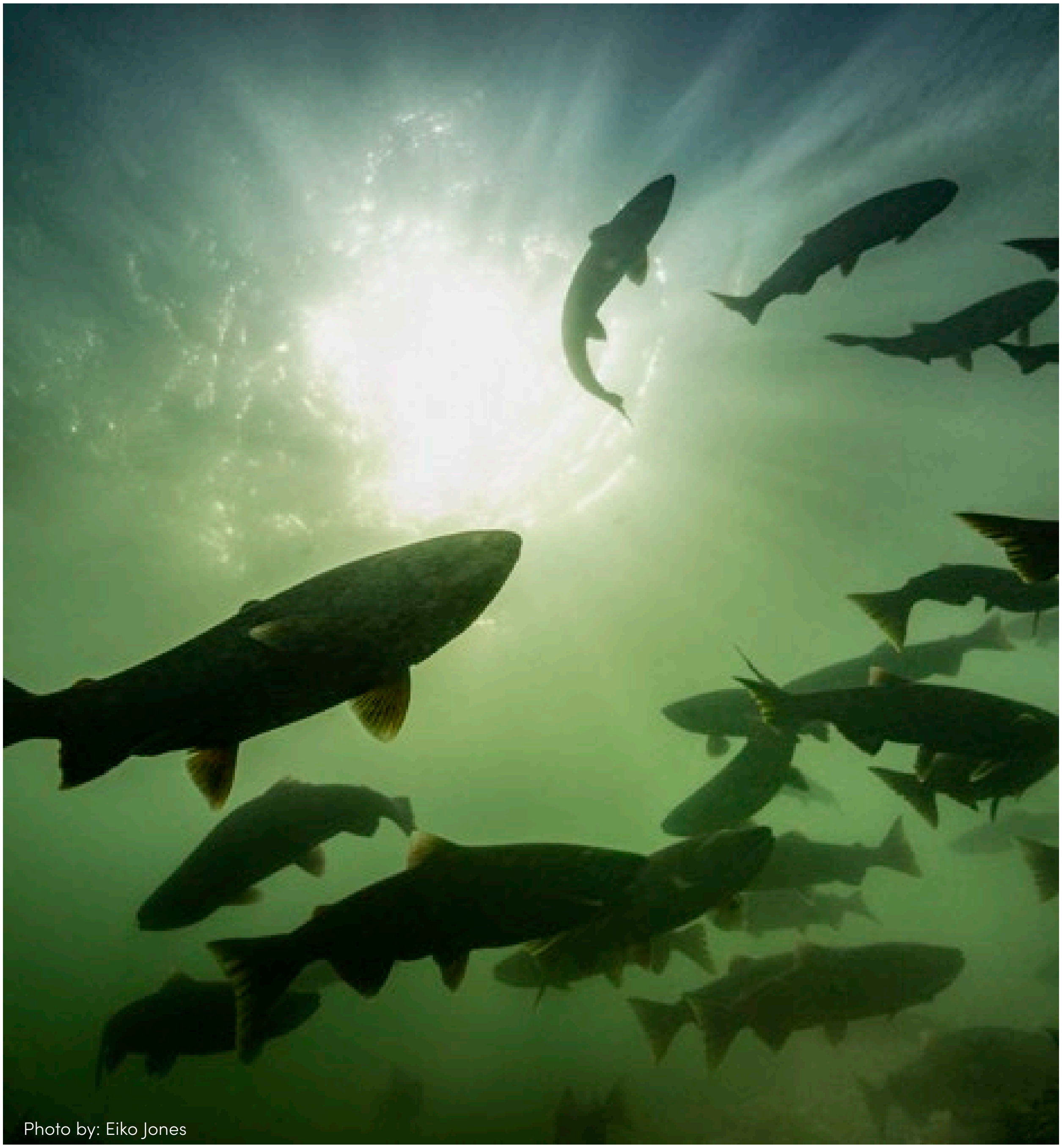

Photo by: Eiko Jones

SUPPLEMENTAL DATA

COWICHAN RIVER CHINOOK SALMON PIT TAG STUDY, 2015 AND 2016

As part of the Salish Sea Marine Survival Program (https://marinesurvivalproject.com/), a comparison of survival rates for naturally-spawned and hatchery-reared Chinook salmon (*Oncorhynchus tshawytscha*) was undertaken in the Cowichan River, BC. PIT tags (12 mm x 2.1 mm Biomark tags) were applied to juvenile Chinook salmon (> 6 cm). Juvenile Chinook were collected using a rotating trap in-river, beach seines in the estuary, a purse seine in Cowichan Bay, and micro-trolling (hook-and-line, Duguid and Juanes 2017) in Sansum Narrows, immediately outside of Cowichan Bay. Sampling for tags in fisheries was not undertaken and distribution and exploitation are assumed to be equal between tagged groups. Comparison between natural and hatchery Chinook were based on PIT tag (www.biomark.com/pit-tags/) detections upon return to the Cowichan River (1-4 years after emigration), from a Biomark PIT-tag array that crossed the Cowichan River at a counting weir at 7 km from the estuary. The data presented below are for the two most intensive tagging years; releases in 2015 (n = 15,274) and in 2016 (n = 22,619). Over both years, the tags allocated to natural Chinook = 23,339 and for hatchery Chinook = 14,554. Hatchery fish were all adipose-clipped and could be unambiguously identified. Tag and recovery data by year and origin are presented below. Tagging continued during 2017 but sampling success was much poorer that year due to very high flows in the river and impacts in local marine waters (no comparisons could be made for 3 of the 4 tagging locations). Based on recoveries to date, survival of naturally produced Chinook salmon was three times that of the hatchery-origin Chinook.

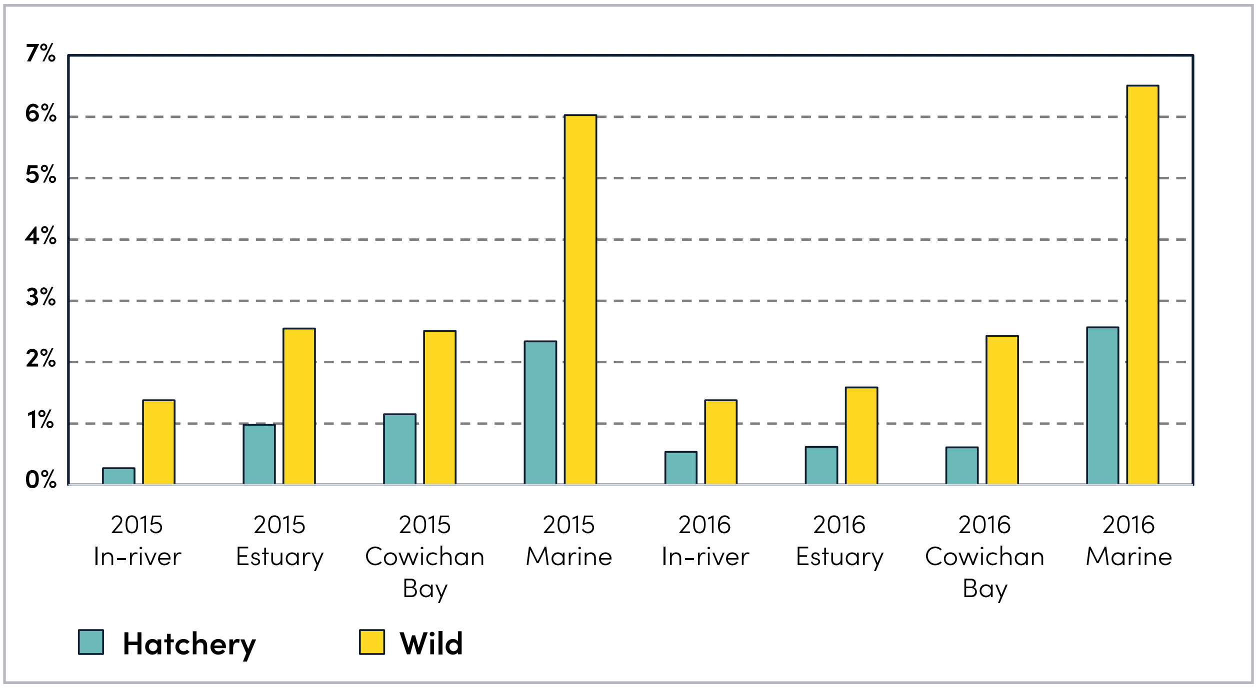

Figure 11: Comparison of Hatchery and natural (Wild) origin juvenile Cowichan River Fall Chinook salmon for two years of tagging (2015 and 2016) and four tagging locations. Comparisons are based on % return of tags detected at a PIT-tag detection array in the Cowichan River.

DATA SUMMARY FOR TAGGING AND RECOVERY

Table 10. Tag releases for **Natural-origin Chinook** salmon for 2015 and 2016, and subsequent detections in the Return Years (2015 through 2019). The natural life history of Cowichan Fall Chinook salmon is for maturity as Age-3 and 4 (Brood Year+3 and BY+4).

Raw Detects		Return Year				
2015	**2015 Tag Year**	**2015**	**2016**	**2017**	**2018**	**2019**
River	1954	0	10	4	10	0
Beach	1745	0	12	9	5	0
Purse	3315	0	40	18	20	0
Micro Troll < 350 mm	730	0	10	3	4	0
Micro Troll > 350 mm	84	3	2	0	0	0

Raw Detects		Return Year				
2016	**2016 Tag Year**	**2016**	**2017**	**2018**	**2019**	**2020**
River	5708	1	45	13	21	0
Beach	1921	0	26	12	11	0
Purse	6410	1	86	37	37	1
Micro Troll < 350 mm	1459	0	28	12	10	0
Micro Troll > 350 mm	13	2	0	0	0	0


Photo by: Sam James

Table 11. Tag releases for **Hatchery-origin Chinook** salmon for 2015 and 2016, and subsequent detections in the Return Years (2015 through 2019). The natural life history of Cowichan Fall Chinook salmon is for maturity as Age-3 and 4 (Brood Year+3 and BY+4).

Raw Detects		Return Year				
2015	**2015 Tag Year**	**2015**	**2016**	**2017**	**2018**	**2019**
River	5008	2	13	10	2	0
Beach	341	0	2	0	0	0
Purse	1681	0	4	4	1	0
Micro Troll < 300 mm	322	1	2	0	2	0
Micro Troll > 300 mm	94	0	0	0	0	0

Raw Detects		Return Year				
2016	**2016 Tag Year**	**2016**	**2017**	**2018**	**2019**	**2020**
River	5092	7	7	7	0	0
Beach	205	1	0	2	0	0
Purse	1476	2	10	2	5	0
Micro Troll < 300 mm	322	1	3	1	0	0
Micro Troll > 300 mm	13	1	0	0	0	0

Table 12. Average Length (Fork length, mm) and one standard deviation for juvenile Chinook salmon that received PIT tags in 2015 and 2016 by tagging location.

Year/Location	Hatchery Origin		Natural Origin (Wild)	
	Average (mm)	**1 Std. Dev. (mm)**	**Average (mm)**	**1 Std. Dev. (mm)**
2015 River	76.1	5.07	68.2	6.39
2015 Estuary	77.0	6.26	73.2	6.08
2015 Bay	88.3	11.35	84.7	10.53
2015 Samson Narrows	194.8	31.89	197.4	32.58
2016 River	77.4	4.68	65.4	6.75
2016 Estuary	80.0	6.77	71.4	6.58
2016 Bay	88.6	13.87	84.7	17.30
2016 Samson Narrows	187.4	22.57	185.8	23.89

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