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Review of Hatchery Release Strategies in British Columbia
Final Report

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EXECUTIVE SUMMARY

This review of hatchery release strategies was undertaken by the Pacific Salmon Foundation as part of a larger Hatchery Effectiveness Review funded by the British Columbia Salmon Restoration and Innovation Fund (BCSRIF-2019-136). The objectives of the release strategies review were to evaluate the outcomes of different strategies used by salmon hatcheries throughout British Columbia (BC) and inform how they could be adapted to improve survivals and meet production objectives moving forward. We conducted three separate analyses to this end:

1. a systematic review of the literature on release strategies from BC and the western United States,
2. an evaluation of hatchery experimental releases of coded wire tagged (CWT) Chinook and Coho salmon throughout the province since 2000, and
3. a comprehensive analysis of rearing strategy effects on survival and return ages of CWT Chinook and Coho in BC from 1972 to present.

In synthesizing what we already know, the literature review laid a foundation upon which to build our BC analyses. It also highlighted the fact that very little has been published on release strategies in BC. While there are carefully planned strategies and protocols in place for each hatchery, some have also experimented with alternate release strategies. However, few of them have been rigorously evaluated or published. Outcomes of the literature review are reported separately.

We examined 25 hatchery release experiments conducted in BC over the past 20 years. We found that where facilities released multiple life stages[1] or life history types,[2] the older stages often had higher survival rates. Two experiments looked explicitly at size[3] at release and were unable to detect any difference in production outcomes between release weights. However, several studies have combined release weight and timing[4] by releasing larger-sized fish later in the season. While many of these experiments are still awaiting recovery data, preliminary results suggest that this strategy could be effective in increasing survival rates for both species at select hatcheries. In the few experiments focused only on the day of release, most found no relationship between release day and survival, with the exception of the later released Chinook at Cowichan River Hatchery, which have shown higher survivals than the early releases. Seapen releases also saw similar survival rates to their hatchery-released counterparts, however their exploitation rates were higher for both Quinsam River and Robertson Creek Chinook. Return ages also differed between seapen and hatchery releases at Quinsam and Cowichan River.

Many of these experimental releases have been exploratory in design, running for only a few years and providing the Salmonid Enhancement Program (SEP) with just enough information to guide program management. Resources have not always been available to design and conduct the experiments in a way that allows for detailed statistical analyses. Given the considerable interannual variation attributed to random year effects, it is likely that the limited datasets associated with some of these experiments lacked the power to measure effects of release strategies.

Therefore, in the third and final part of our release strategies review we used all release and recovery information available for all facilities releasing CWT'd Chinook and Coho since 1972, including both experimental and conventional release strategies. With this extensive dataset we developed single-hatchery and hierarchical multi-hatchery models to evaluate how different hatchery release strategies (weight-at-release, day-at-release, life stage, stock, and release site) potentially affect smolt-to-adult survival rates and return ages of Chinook and Coho for 25 hatcheries in BC. We found that the expected survival of hatchery releases was greater for larger weights at-release compared to the historical average release weights for the dominant life stage released at all of the 21 hatcheries releasing Chinook and a majority of the hatcheries releasing Coho (11 out 16). In addition, higher survivals were generally associated with earlier releases of subyearling Chinook and later releases of yearling Coho, relative to the historical release timing, with some exceptions. Increasing the weight at release, specifically, is expected to yield greater improvements to survival than changes to the date of release alone at most hatcheries. Hatchery-specific release weights and dates are provided along with expected changes to survival rates and returns under various release strategy scenarios. This information allows SEP management to evaluate whether the predicted improvements warrant modifications to release strategies or testing in future experiments.

Additional factors such as total annual biomass of hatchery fish released, river migration distance, and environmental conditions also contributed to survival rates. Most hatcheries did not show strong evidence for river migration or release biomass effects on Chinook or Coho survival, which may mean these do not strongly influence survival at a majority of hatcheries or could be related to low statistical power. Sea surface temperature of the early marine environment, the Pacific Decadal Oscillation, and marine mammal predator abundance (Harbour Seals, Killer Whales), were also included in models to evaluate their effects on Chinook and Coho survival. While each of these environmental covariates had significant negative correlations to Chinook and Coho survival, their inclusion in models did not improve model predictive performance relative to models that accounted for interannual sources of variability using year effects.Therefore, the top models for Coho and Chinook used year effects to account for all environmental effects external to the hatchery release strategies. Accounting for environmental covariates using year effects allowed us to reliably estimate the release strategy effects of interest, without having to model numerous environmental effects independently. However, the amount of variation in survival rates explained by random year effects varied widely across facilities and will be an important consideration for prioritizing locations for modifying release strategies.

This is the first time a comprehensive review of this scale has been conducted on hatchery release strategies in BC. Therefore, we needed to develop methods for accessing, interpreting, analyzing, and reporting data from multiple different sources and have highlighted some of the challenges in doing so. We identify some of the main limitations in conducting the review as areas for consideration when interpreting our results, but also as areas to improve for future analyses of this kind.

Through this process, we have developed a set of recommendations for the use of release strategies as effective tools for hatchery management. In short, these recommendations are to:

1. allocate sufficient resources for routine collection, analysis, and reporting of data on the effectiveness of hatchery practices that allows for rigorous experimental designs and timely analyses and assessment,
2. account for the overwhelming effect of environmental variability by running experiments for longer time periods, exploring differences between facilities with high and low random variation, and collecting and reporting environmental data from the receiving environment,
3. increase investment in data poor regions throughout BC,
4. increase monitoring of wild populations on enhanced systems,
5. exercise an adaptive management approach, and
6. use the hatchery-specific release strategies and their predicted impacts on survival rates provided to make informed decisions and establish future experiments.

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1. Life stage refers to the stage of the life cycle at which the salmon are released. For Chinook, life stages reared and released at hatcheries include fry, subyearling smolts, and yearling smolts. For Coho, life stages reared and released at hatcheries include fry and yearling smolts.
2. Life history refers to how a salmon has evolved to grow, survive, and reproduce. Chinook express two major life history types. Ocean-type Chinook migrate to the ocean shortly after emergence; this is the dominant life history type of coastal populations. Stream-type Chinook spend a full year in the river before migrating to the ocean; this life history is more common in inland populations. Interior Fraser River summer Chinook in the Thompson River migrate as subyearling smolts but enter the Strait of Georgia in mid to late summer.
3. Size at release refers to the weight of the fish at release (measured in grams). In this report, size is described as being small (lighter than normal release weights for that life stage), normal (target release weights for a life stage), or large (heavier than regular release weights for that life stage).
4. Release time refers to the date of release and is categorized in this report as early (earlier in the calendar year than normal releases of that life stage), normal (target release date of the life stage), or late (later in the calendar year than normal releases of that life stage).

BACKGROUND

Since the 1970s, modern-day hatcheries in British Columbia (BC) have been used as a tool to improve the freshwater survival of salmon. The goal behind enhancement is to be able to rebuild and conserve populations at risk, generate recreational, commercial, and Indigenous fishing opportunities, and engage and educate the wider community in salmon stewardship. Hatcheries also play an important role in supporting both domestic stock assessment and international treaty requirements. To meet these goals, hatcheries have developed strategies that are intended to mimic those of wild salmon so that enhancement can supplement wild stocks, rather than replace them, and mitigate risks to wild salmon and their habitats (MacKinlay et al. 2004).

Despite the benefits of hatchery programs there are recognized ecological, genetic and fishery-related risks. In fact, there is a substantial body of literature on the risks of enhancement (e.g. ecological: Daly et al. 2012, Tatara & Berejikian 2012; genetic: Waples 1991, Araki et al. 2008, Thériault et al. 2011; fisheries: Hilborn 1992, Wood 2008). However, the risks of enhancement can vary across species, watersheds, program types, and jurisdictions. In BC, Fisheries and Oceans Canada's Salmonid Enhancement Program (SEP) is a multi-faceted program that contributes to the management, conservation, and restoration of Pacific salmon. To address risk, SEP utilizes planning frameworks that outline production planning (DFO 2018), management of biological risk (DFO 2013), and biological assessment of SEP fish production (DFO 2019). These frameworks are implemented together with the Wild Salmon Policy (DFO 2005), operational guidelines, and best management practices (DFO 2016). Nevertheless, the effectiveness of enhancement in BC and the interactions between hatchery and wild salmon remain uncertain.

In 2020, a comprehensive review of hatchery science in Washington identified a lack of specific studies or research associated with many aspects of hatchery risk and also identified that risks are program and scale specific (Anderson et al 2020). The review also identified key gaps in our understanding of hatcheries and made several recommendations for further study and evaluation of hatchery programs (e.g. links between hatchery performance metrics and operational changes, cumulative impacts).

Therefore, as the government continues to invest in salmon enhancement in BC, it is important that we fill in those gaps, adapt to shifting priorities, and continue to incorporate the best available science into decision-making processes. There has been widespread recognition of the need to evaluate the role of hatcheries. In 2013, an Independent Advisory Panel for Southern BC Chinook Salmon concluded that there was a clear need for a thorough and critical program assessment of BC hatcheries (Riddell et al. 2013). The recent BC Wild Salmon Advisory Council report (2019) also recommended an evaluation of options for salmon enhancement, including considerations of the potential ecological, economic, and social/cultural risks and benefits associated with the production options available. In 2021, Washington State approved a new enhancement policy and identified a need to incorporate both hatchery science and structured decision making to be able to account for the risks and benefits of hatchery programs.

Recognizing the need for evaluation and to support science-based decision making, the Pacific Salmon Foundation (PSF) built upon previous research into hatchery survivals conducted during the Salish Sea Marine Survival Project (www.marinesurvivalproject.com) to design a comprehensive hatchery review. PSF was awarded a grant from the British Columbia Salmon Restoration and Innovation Fund (BCSRIF; Project Number BCSRIF-2019-136) in the summer of 2019 to perform an independent assessment of salmon hatchery programs in BC. The objectives of this project are to examine the effectiveness of current production, identify scientific advancements in recent years that may be applied to increase effectiveness (i.e. the ability to meet production objectives), and ultimately to design and conduct a comprehensive analysis of the joint production of hatchery-based and wild Pacific salmon for BC communities and ecosystems.

To achieve the project objectives, the review consists of three sub-projects:

1. a review of cutting-edge research and molecular tools that may be applied to understand and improve the productivity of hatchery-reared salmon in the future;
2. an evaluation of hatchery release strategies and the resulting marine survival of hatchery-released salmon; and
3. a comprehensive review of hatchery effectiveness and impacts on wild populations.

This report contains the summary and conclusions of sub-project 2, the evaluation of hatchery release strategies.

Release Strategies Review

The strategies hatcheries employ for rearing and releasing fish are critical to meeting their goals and objectives. Hatchery programs face the challenging task of developing strategies that maximize survival while meeting management objectives and minimizing risk to wild populations. These strategies have evolved over time to improve hatchery efficiency and increase post-release survival. Rearing strategies include decisions made about the hatchery environment, such as water source, rearing containers, and density. Release strategies refer to elements such as the size at release, timing of release, nature of release (i.e. forced out all at once or allowed to leave the hatchery volitionally), and the use of acclimation facilities (e.g. seapens) prior to release. This report focuses on release strategies specifically and how they can be used as a management tool to influence production outcomes (i.e., survival, catch, return age). The aim is to determine which release strategies are most effective today at achieving desired outcomes at facilities throughout British Columbia.

The ability to optimize hatchery practices requires an evaluation of past programs and findings to date around release strategies and other experimental programs that DFO has carried out. Thus, the PSF evaluation of release strategies consisted of three parts:

1. **Part I:** a systematic review of the literature on hatchery release strategies of salmonids in BC and the western US states,
2. **Part II:** an evaluation of hatchery experimental releases of coded wire tagged (CWT) Chinook and Coho salmon throughout the province since 2000, and
3. **Part III:** a comprehensive analysis of release strategy effects on survival and return ages of CWT Chinook and Coho in BC from 1972 to present.

The literature review conducted in Part I provides a synthesis of what we know from publications and provides a baseline for comparison of practices and outcomes in BC. Part II provides a detailed analysis of hatchery experiments conducted over the past 20 years to highlight the strategies employed most recently. Part III maximizes the full extent of the available data to estimate release strategy effects on survival and return age outcomes and development of hatchery-specific recommendations for improving the effectiveness of hatchery strategies. The full reports for each part can be found in:

Part I: James, S (2021a) Evaluation of hatchery experiments in British Columbia, 2000-2018. Report prepared for the Pacific Salmon Foundation's Hatchery Effectiveness Review (BCSRIF-2019-136).

Part II: James, S (2021b) Review of Pacific salmon hatchery release strategies in Canada and the United States. Report prepared for the Pacific Salmon Foundation's Hatchery Effectiveness Review (BCSRIF-2019-136).

Part III: Doherty, B, and Cox S.P. (2021). Release strategy effects on survival and return ages for British Columbia Chinook and Coho hatchery releases, 1972-2017. Report prepared for the Pacific Salmon Foundation by Landmark Fisheries Research. 186 p.

This report is intended to provide a summary of findings from the detailed statistical analyses conducted in Parts II and III. Chinook and Coho salmon are the focus of our analyses as they are the two species most commonly reared in hatcheries and many Coho and Chinook releases are marked using CWTs, whereas other species are not. These tags are used to assess joint Canadian and American fisheries impacts as per the agreements made in the Pacific Salmon Treaty and thus provide an extensive dataset of releases and recoveries from which to evaluate release strategies in BC. Enhanced Sockeye and Chum salmon are more frequently cultured in spawning channels and released as fry too small for CWTs (although some tagging has been tried with half size CWT). Chum and Pink have also been cultured in hatcheries but are not included in this analysis.

The results from parts II and III may be used to guide decisions on production strategies but there are a number of other factors, such as operational cost, feasibility, risk, and the natural life history of the population that need to be considered when putting these recommendations into practice. These factors were not considered within the scope of this review. Inter-facility effects, such as cumulative changes to total hatchery biomass released within river systems or ocean regions, were also not accounted for. Furthermore, these results reflect past effects of release strategies, however the past may not be the best predictor of the future. Thus, our findings capture the current state of knowledge and provide a valuable first step towards the improvement of hatchery release strategies. However, release strategies should be evaluated continually as environmental dynamics and the state of wild salmon change. In addition, a more holistic experimental design will be required to capture the full spectrum of change in time, space and place.

METHODS

The Data

Chinook and Coho CWT release and recovery data were obtained from the SEP's Enhancement Planning and Assessment Database in December 2019 (EPAD; data provided by Cheryl Lynch, DFO). The EPAD contains information on release events, such as the number of fish released, the average size (length and weight) at release, and the date of release, as well as age at recovery and estimates of survival rates and exploitation rates based on catch and escapement records. In addition, interviews with hatchery managers/staff were conducted to better understand the conditions specific to each facility. To reduce errors and bias, data were filtered to remove erroneous or incomplete records. Data flagged by SEP in the database as being unsuitable for survival or exploitation estimation were excluded. Releases with different tag codes, but identical release weights and dates of the same stock at the same location were combined and treated as a single group.

Part II: Hatchery Experiments

Hatchery experiments have been conducted by several facilities to investigate the effects of release strategies. These experiments have been intentional, with unique tagcodes applied to release groups reared and/or released under different conditions. We assembled a record of previous hatchery experiments in BC through conversations with various SEP staff, interviews with hatchery managers, and manually searching the EPAD releases for comments indicating an experiment or datasets indicative of multiple different release groups of the same brood year. In total, 25 experiments were identified: seven facilities with releases of multiple life stages of Chinook, four on the weight and date of release of Chinook, eight on the weight and date of release of Coho, and six on the effects of seapen releases of Chinook (Table 1).

Salmon populations, production objectives, and environmental conditions have experienced considerable changes since enhancement began in the 1970s. In order to examine which release strategies are most effective for hatcheries today, we focused our analyses on experiments conducted over the last 20 years rather than using historical experiments from the early years of enhancement. However experiments extending pre-2000 were included for Chilliwack and Cowichan River Hatcheries. Today, Chilliwack River Fall Chinook have the highest survival rates of any other enhanced Chinook stock in the province, therefore additional years of data were included to learn as much as possible about the strategies used for this stock. The Cowichan River Hatchery is one of the few community-led facilities with a long time series of release data and has implemented a number of different release strategies during its operation. We grouped hatcheries into one of 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, we described the objectives, presented the raw data, as well as historical trends in survival, and where sufficient data were available, conducted statistical analyses to determine whether or not the experimental groups exhibited different production outcomes. First, 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. Next, linear mixed effects models were used to tease apart the often confounding effects of release strategies and determine which elements of the experiment were the strongest predictors of survival. Not only are release weight and date confounding, but other factors such as climate-driven environmental trends, predator and prey abundance, as well as the genetics of the stock and where it is released. To account for this, the following model was developed:

$$Y_{ist} = \alpha + \Delta_t + \rho_s + \theta_1 W_i + \theta_2 W_i^2 + \beta_1 D_i + \beta_2 D_i^2 + \varepsilon_i \qquad \textbf{(1)}$$

wherein Y_{ist} is the logit-transformed survival rate for release group i of stock-site combination s in year t, α is the intercept or the hatchery average logit-survival before accounting for other covariates, Δ_t is the random year effect deviation in average survival, ρ_s is a stock and release site-specific deviation from the intercept, θ_1 and θ_2 are coefficients for the continuous covariate release weight (W) and its quadratic term (W_2), β_1 and β_2 are the coefficients for the continuous covariate release day (D) and its quadratic term (D_2), and ε_i is an independent and identically distributed Gaussian residual (i.e., $\varepsilon_i \sim N(0,\sigma^2)$). We assume the annual survival deviations follow a normal distribution $\Delta_t \sim N(0,\tau^2)$.

All analyses were conducted in R version 3.6.3 (R Core Team 2020).

Part III: Modelling release strategy effects on survival and return age for all data

Expanding upon the analyses in Part II, Part III went beyond specific hatchery experiments and utilized all release and recovery data available for CWT'd Chinook and Coho salmon since modern day enhanced releases began in 1972. Analyses began with linear mixed effects models specific to each life stage and hatchery to explore how release strategies influenced survival rates and return ages. The modelling approaches used are described below (See Doherty and Cox 2021 for more details on model development).

The hatchery-specific survival models took the same form as in equation (1) from Part II analyses with one addition:

$$Y_{ist} = \alpha + \Delta_t + \rho_s + \theta_1 W_i + \theta_2 W_i^2 + \beta_1 D_i + \beta_2 D_i^2 + Øt_i + \varepsilon_i \tag{2}$$

wherein $Øt_i$ is the hatchery-specific trend coefficient for the ocean entry year (OEY) since the first release year at the hatchery.

Survival rates may follow a common pattern among release groups due to interannual variation. Thus the proportion of the total variance in logit-survival that is accounted for by the random year-effects was quantified using the intra-class correlation (ICC):

$$ICC = \frac{\tau^2}{\tau^2 + \sigma^2} \tag{3}$$

A similar model structure was used to investigate how hatchery strategies potentially affect return ages. Given that Chinook typically returned as 2-5 year olds (99.5% of the data), the mean age of returns was modelled for Chinook:

$$\bar{\alpha}_{ist} = \alpha + \Delta_t + \rho_s + \theta_1 W_i + \theta_2 W_i^2 + Øt_i + \lambda F_i + \varepsilon_i \tag{4}$$

wherein $\bar{\alpha}_{ist}$ is the mean age of returns for release group i, stock and site s, and year t, and λ is the coefficient or effect size for the continuous predictor for the proportion of females in the returns (F), since females tend to return older than males.

Coho return as 2-3 year olds (99.6% of the data), with most 2 year olds being precocious males, also known as jacks. Therefore Coho return age was modelled as the proportion of jacks in returns:

$$\widehat{logit(J_{ist})} = \alpha + \Delta_t + \rho_s + \theta_1 W_i + \theta_2 W_i^2 + Øt_i + \varepsilon_i \tag{5}$$

where $\widehat{logit(J_{ist})}$ is the logit proportion of Coho jacks (age 2 males) for release group i, stock and site s, and year t.

The release day term was excluded from both return age models since the majority of available data for fitting return age models are from release events that occurred within +/- 15 days of the mean release dates. Thus, there was not a broad enough range in release dates to explore its effects on return ages.

Full models with all possible combinations of fixed effects were fit for survival and return age for each hatchery, on which an all subsets selection procedure was conducted. Model performance was evaluated using the Akaike Information Criterion corrected for small sample size (AICc) as well as the number of predictor terms in the top model. For each hatchery, the model with ΔAICc < 2 and the fewest predictor variables was selected as the top model (as per Burnham & Anderson 2002).

Using the outputs of these initial hatchery-specific models, Bayesian hierarchical multi-hatchery models were developed to further investigate the effects of release strategies on survival with improved estimates. The hierarchical model pools data across hatcheries, generating overall mean effects while also measuring the hatchery-specific deviations from the mean. Statistically, these models have more power than the single-hatchery linear mixed models which reduces uncertainty in the survival response to different release strategies and reduces the chance of finding spurious relationships (Myers & Mertz 1998, Malick et al. 2015). They also accommodate hatcheries with fewer release events that may have been excluded from single-hatchery analyses due to low sample sizes, as data pooling allows information to be shared across all hatcheries (see Figure 1 for list of hatcheries included in hierarchical models). In the multi-hatchery models, the effects of release weight, date, and year were assessed with year as a random effect for annual deviations in the relationships between model parameters. Multi-hatchery models follow a similar structure to the single-hatchery models; however they include parameters for an overall mean effect across all BC hatcheries along with hatchery-specific deviations from the mean:

$$Y_{ih} = \alpha + \alpha_h + \Delta_t + (\theta_1 + \theta_{1h}) W_{ih} + (\theta_2 + \theta_{2h}) W_{ih}^2 + (\theta_3 + \theta_{3h}) D_{ih} + (\theta_4 + \theta_{4h}) D_{ih}^2 + Øt_i + \varepsilon_i \tag{6}$$

where α is the intercept or the mean hatchery average logit-survival before accounting for other covariates in the model, α_h is a hatchery-specific deviation from the mean logit-survival, θ_1 and θ_2 are the overall mean effect across all hatcheries for linear (W) and quadratic (W^2) weight effects, θ_{1h} and θ_{2h} are the respective hatchery deviations from mean hatchery weight effects, θ_3 and θ_4 are the overall mean effect across all hatcheries for linear (D) and quadratic (D^2) release day effects, and θ_{3h} and θ_{4h} are the respective hatchery deviations from mean hatchery day effects.

In addition, we replaced ρ_s from the single hatchery models with site specific conditions in the hierarchical models. Specifically, we included a term for the total biomass (R) of hatchery releases of all species into a given system each year to look for signs of density-dependent effects on survival in the freshwater environment. Higher biomass of enhanced fish released could have a negative effect on survival due to increased competition for food or habitat (Buhle et al. 2009, Scheuerell et al. 2021), but could also have a positive effect through predator swamping (Furey et al. 2016). In addition, the length of the juvenile downstream migration could have positive or negative effects on survival. Thus an additional predictor term was included for freshwater migration distance (M). Freshwater migration distance was measured as the distance (in km) from the release location to the point of salt water entry and thus allowed for comparison between multiple release locations for a given facility. And finally, to account for the releases of multiple life stages, a life stage effect was added to account for any stage-specific differences in survival that are not related to weight or day effects (ω_l). With the addition of these terms to equation **(6)**, we can shorten the notation by including vectors for the mean coefficients ($\theta_j = \theta_1, \theta_2, \theta_3, \theta_4, \theta_5, \theta_6$), hatchery deviations ($\theta_{jh} = \theta_{1h}, \theta_{2h}, \theta_{3h}, \theta_{4h}, \theta_{5h}, \theta_{6h}$), and release strategy predictor variables ($X_{jh} = X_{1ih}, X_{2ih}, X_{3ih}, X_{4ih}, X_{5ih}, X_{6ih} = W_{jh}, W_{ih}^2, D_{ih}, D_{ih}^2, R_{ih}, M_{ih}$), where R_{ih} is the total annual biomass released into the same location as release group i at hatchery h, and M_{ih} is the log freshwater outmigration distance for release group i from hatchery h. The final equation is as follows:

$$Y_{ih} = \alpha + \alpha_h + \Delta_t + \omega_i + \sum_{j=1}^{6}(\theta_j + \theta_{jh})X_{jih} + \O t_i + \varepsilon_i \tag{7}$$

The final step in the hierarchical modelling was to evaluate the role of specific environmental indices on hatchery survival outcomes and to test whether those indices could provide better model fits compared to using random year effects and temporal trends. There are many environmental parameters that likely influence salmon survival through complex and cumulative interactions and it would be challenging to adequately represent them in this analysis, however we looked to include parameters with sufficient data that would represent both large-scale and local conditions, as well as predation. Thus, informed by the literature and limited to parameters with continuous time series data extending to 1972, we fit multi-hatchery models with regional sea surface temperature (SST, Mueter et al. 2002), Pacific Decadal Oscillation (PDO, Mantua 2009), and predator abundance (i.e. harbor seals and killer whales, Chasco et al. 2017) as environmental covariates. The SST data captures regional variability in ocean temperature (100s of kms) while the PDO is an index of ocean climate variability for the North Pacific (1000s of kms). Harbour seals are voracious predators of juvenile salmon, therefore harbour seal numbers in the year of ocean entry were used as one measure of predation. Killer whales prey on adult salmon, therefore their abundance in the return year was used as a second measure of predation.

Monthly SST for 2^o x 2^o grid cells and PDO data were obtained from NOAA's National Centre of Environmental Information (NCEI) and are based on NOAA's extended reconstruction of SST (ERSSTv5, Huang et al. 2017). For each release site, we identified an ocean entry point and delineated an area of early ocean residence that was +/- 40 km in directions perpendicular to the shoreline, and +/- 125 km in directions parallel to the shoreline. Thus, the average monthly SST associated with each release event was calculated using the weighted proportion of grid cells that overlapped with the area of early ocean residence. A 60-day weighted average SST was used to capture the average SST 30 days prior to and after the date of ocean entry. Monthly values were used for the PDO.

Harbour seal abundance estimates for 1970-2020 were estimated from logistic models for the Strait of Georgia and the outer coast of BC (Olesiuk 2010). Thus, Strait of Georgia numbers were used for hatcheries in the Strait of Georgia and outer coast numbers were used to hatcheries in the northeast Vancouver Island, west Vancouver Island, central coast, and north coast regions. For killer whales, both Northern Resident (Chasco et al. 2017, Towers et al. 2020) and Southern Resident (Centre for Whale Research) numbers were used for hatcheries in the Strait of Georgia and around Vancouver Island, while only Northern Resident numbers were used for hatcheries on the north and central coast of BC.

All predictor variables were standardized to have a mean of zero and unit variance by subtracting the mean and dividing by the standard deviation, which facilitates model fitting and comparing effect sizes. Therefore, the coefficient θ_j can be interpreted as the effect size on logit survival from a 1 standard deviation increase in the predictor variable j. All of the hatchery-specific deviation terms (θ_{jh}, α_h) and the year effect deviation (Δ_t) are treated as random effects with assumed normal distributions with mean zero variance $\sigma^2_{\theta j}$,σ^2_{α}, $\sigma^2_{\Delta t}$. We use a gamma prior with shape parameter $\alpha = 2$ and rate parameter $\beta = 0.1$ to constrain the hatchery and year effect deviation variance (Chung et al. 2013).

Leave-one-out cross-validation information criterion (LOOIC) was used to compare predictive performance of Bayesian models (Vehtari et al. 2017) to determine if the life stage, freshwater migration, biomass of releases, and environmental predictors improved model performance. The LOOIC is similar to other information criterion, such as AICc for single hatchery model comparison, where models with the lowest LOOIC have the best predictive performance. We avoided fitting models with covariates that were highly correlated by fitting models with one or the other covariates and using LOOIC to assess model predictive performance.

While the models provide estimates of optimal release strategies for increasing survival at each facility, it can be difficult to know the degree to which survival will be affected, and thus which strategies to prioritize. Costs and benefits need to be considered when adjusting release strategies, and there will likely be a desire to prioritize release strategies that yield the greatest return on investment. In addition, there may be conditions unique to each facility that make adopting certain strategies more or less feasible. Therefore, to further inform decision-making, the top models were used to quantify changes in survival rates at each hatchery under four different release strategy scenarios. The scenarios considered were to release fish at the: 1) mean weight at release and mean day of release, 2) mean weight at release and day for maximum survival, 3) weight for maximum survival and mean day of release, and 4) weight for maximum survival and day for maximum survival. For scenarios 1-3, the mean is calculated from 2000-2015 and 2000-2017 ocean entry years for Chinook and Coho, respectively, to measure the effectiveness of different strategies against current conventional practices. Experimental releases were excluded from these averages, except for Coho releases at Quinsam River where the majority of releases since 2000 have been experimental. The release weight/day for maximum survival are values within the central 95% distribution of historical releases that are expected to maximize survival for the life stage most commonly released at each hatchery, based on the multi-hatchery model fits.

All models were developed using the Template Model Builder package (TMB, Kristensen et al. 2016) within R version 3.6.3 (R Core Team 2020). Posterior distributions of parameter estimates were generated using a Hamiltonian Monte Carlo method in the tmbstan package in R (Monnahan & Kristensen 2018) and LOOIC calculations were done using the loo package in R. All analyses for Part III were conducted by the analytical consultants at Landmark Fisheries Research (Doherty and Cox 2021).


Photos by: Sam James

KEY FINDINGS

Release strategies are often confounding due to inherent relationships between size at release, time of release, and life stage released. Where possible, the experiments/analyses presented below focus on a single release strategy while maintaining the others constant. For instance, size at release experiments and analyses only consider changes in the weight of the fish; life stage released and release date are constant. However, there are also a number of late/large release experiments in which both weight and date of release varied. The following is a synthesis of key findings from both the investigation of hatchery experiments in Part II (James 2021b) and the full dataset modelling in Part III (see Doherty and Cox 2021 for all findings). For the latter, the focus is on the results of the hierarchical multi-hatchery modelling, given their higher statistical power. In total, 25 experimental releases were reviewed: seven on releases of multiple Chinook life stages, four on Chinook release dates and weights, eight on Coho release dates and weights, and six on the effects of seapen releases. In addition, the hierarchical model included release and recovery data from 21 Chinook hatcheries and 16 Coho hatcheries from across BC (Figure 1).

Size at Release

The objectives of size at release experiments conducted in BC over the last 20 years were to evaluate the effects of different release weights on survival rates to inform hatchery practices and update historical information on the effects of release strategies. Altering the weight of Coho being released from hatcheries did not yield any significant differences in survival rates, exploitation rates, or return ages in two 3-year experiments conducted at Quinsam River (t-test; $p = 1.00$, 0.58, and 0.53, respectively; Table 1) and Inch Creek (t-test; $p = 0.45$, $p = 0.23$, and $p = 0.42$, respectively; Table 1). These were the only two experiments in BC over the last 20 years to look at the effects of release weights independent of the day of release. No experiments were conducted on Chinook.

The majority of size experiments conducted in BC in the last 20 years have involved the release of a later group of larger fish 5-7 weeks after the release of their 'normal' production, thus confounding effects of size and time. These releases were exploratory in nature, seeking to understand the effects of this unique strategy on hatchery salmon survival rates, marine distribution, and interactions with wild salmon. For Big Qualicum River Chinook, there were no significant differences in mean survival rates, exploitation rates, or return ages (t-test; $p = 0.27$, 0.84, and 0.28, respectively) between the two release strategies and neither release weight nor date were important predictors of survival for these release groups (Table 2). However, these experiments are ongoing at Big Qualicum and Quinsam River hatcheries and preliminary data from the 2015-2016 late/large release groups have shown higher survivals than normal production at both facilities. For Coho, the late/large strategy has been trialed at Big Qualicum River and Inch Creek hatcheries and is ongoing at Quinsam River Hatchery. Survival rates, exploitation rates, and return ages were all significantly higher for the late/large releases at Quinsam River (Kruskal Wallis; $p = 0.01$, 0.04, and 0.02, respectively), and preliminary data suggests similar results for Big Qualicum Coho. Inch Creek, on the other hand, saw no differences in the late/large releases (t-test; $p = 0.91$, 0.17, and 0.18, for survival, exploitation, and % jacks, respectively) and neither release weight nor release date were important predictors of survival for these releases (Table 2). Therefore, there may be local factors influencing the effectiveness of the late/large strategy in different regions, however additional years of data will be necessary before any conclusions can be drawn.

For our return age models in Part III (Doherty and Cox 2021), adequate data for assessing the effects of release weights on return age were only available for four Chinook hatcheries and seven Coho hatcheries (Tables 3-4). Release weights only influenced Chinook return ages at Puntledge River, where the mean return age decreased as the release weight increased from 3-7 g, but increased as the release weight increased from 7-10 g. For Coho, release weight had an effect on the proportion of jacks in the returns at Big Qualicum River, Puntledge River, and Quinsam River. Specifically, for Big Qualicum River and Quinsam River, the proportion of jacks increased up to a certain release weight (22 g for Big Qualicum and 28 g for Quinsam) and then decreased. Meanwhile at Puntledge River, the larger the yearling release weight, the greater the proportion of jacks, while for fry, larger weights at release produced lower proportions of jacks in returns.

Looking beyond the hatchery experiment data for recent years, hierarchical multi-hatchery survival models using all release data indicate that increasing the weight at release relative to the historical average increases survival rates of both Chinook and Coho across almost all facilities. Specifically, estimated weights for yielding maximum Chinook survivals varied from 3.4 g, 5-16 g, and 14-18 g for fry, subyearling and yearling smolts, respectively and from 2-11 g and 17-33 g for Coho fry and yearling smolts, respectively across facilities (Figure 2). The few exceptions are for Coho reared at McLaughlin Creek, Robertson Creek, and Puntledge River, where smaller releases than their historical average are expected to have higher survival. We found that releasing Chinook and Coho at hatchery-specific estimated weights and dates for maximum survival could generate increases in return rates at many facilities. While increasing the weight at release was more effective than altering the day of release for a majority of hatcheries (13 out of 21 for Chinook, 11 out of 16 for Coho), greater improvements often occur for a combination of the weight and day for maximum survival (Figures 3-6, Tables 5-6). Increases in survival greater than 50% were only predicted for 8 of the 21 Chinook hatcheries and 4 of the 16 Coho hatcheries. Therefore, adjusting or experimenting with release strategies will be of greater value to some facilities than others. The decisions around adjusting release strategies based on these findings will depend on the specific objectives and constraints at each hatchery. The data presented in Figures 3-6 and Tables 5-6 provide information for SEP to evaluate whether the predicted increases in survival rates and returns of Chinook and Coho salmon warrant modifications to release strategies or testing them in new experiments.

It should be noted that these model estimates are based on the weight within the 95% central distribution of historical releases that maximizes survival, rather than the model-based optimums which may extrapolate model predictions beyond the range of observed data at each hatchery. For instance, the model optimal release weight at a facility may be 18 g, however smolts at this facility were historically only released up to 10 g. Therefore the release weight for maximum survival at this facility is considered to be 10 g since we know this release weight is possible at this facility. However, by limiting the release weights within the realm of historical weights we limit the capacity to see changes in survival rates at those facilities where the range of release strategies is limited (e.g., facilities on the lower Fraser). For instance, Inch Creek has historically released subyearling Chinook smolts between 6-7 g while Capilano River releases subyearling Chinook smolts between 3-10 g. Inch Creek will have a smaller difference between the weight for maximum survival and the historical average weight, meaning the potential increase in survival that we have presented will be lower. For these hatcheries with narrow historical release strategies, experimental releases beyond the limited historical ranges will be required to determine whether or not greater improvements could be made from altering release strategies.

Time of Release

There were a number of different objectives behind the time of release experiments conducted in BC over the last 20 years. Hatcheries sought to either mimic the natural life history of the stock, improve survival rates, decrease competition with wild fish, assess the effectiveness of different release days to inform future practices, or to update historical information on release strategies. In addition to the 'later and larger' experimental releases described in the previous section, there were five experiments in BC on release timing specifically, which yielded mixed results (Tables 1-2). Although data were limiting in a mid-1990s Chilliwack River Chinook experiment, survival rates of later releases appeared to be lower. Interestingly, more recent late/large releases of Chilliwack River Chinook using parentage-based tagging have also seen lower survival rates than regular production (Esther Guimond (DFO), personal communication). In contrast, later releases of Cowichan River Chinook had slightly higher survivals than the early release group (Wilcoxon rank sum test; $W = 199$, $p = 0.05$, $n = 49$) and release weight, day, and location were all found to be important predictors of survival (Table 2). For Coho, early releases (late April) at Inch Creek had lower survival rates than normal production (mid-May) (Kruskal Wallis; $p = 0.03$). At Quinsam River, there was no difference between the mean survival rates, exploitation rates, or proportion of jacks between early (April 20-May 5), normal (May 5-19), and late (May 16-27) release groups over a 10 year period. However, release day and release year were important predictors of survival (Table 2), with an increase in survival rates observed over the course of the experiment and earlier releases having lower survival after 2005.

As described in the 'Size at Release' section above, most recent experiments on release timing have been investigating the effects of a combined late/large release strategy. The outcomes of these experiments are described above.

The date of release was not an important predictor of return age for any of the Chinook or Coho single hatchery models (Tables 3-4).

Hierarchical multi-hatchery survival modelling using all available release data found maximum survivals of Chinook salmon subyearling smolts for releases 6-27 days *earlier* than hatchery averages for most (13/17) facilities (Figure 7).

This may seem counter-intuitive given that larger smolts (which produced higher survival rates) typically require longer to rear in the hatchery. However, when we control for release weight, earlier releases had higher survival rates. There are a few exceptions: Quinsam River had higher survival rates for releases approximately 12 days *later* and three facilities (Cowichan River, Inch Creek, and Eagle River) had maximum survivals for releases made within three days of the average. We did not investigate why some facilities were exceptions, however future research may want to explore whether certain characteristics led some facilities to diverge from the more common outcome.

In contrast, overall maximum survivals of Coho across almost all (12/13) hatcheries are expected for releases later than the historical average, ranging from 8-33 days *later* for yearlings depending on the facility (Figure 7). The only exception was Capilano River Coho, where the historical mean release date is also the model-estimated date yielding maximal survivals.

Model results indicated that releasing Chinook and Coho at the release day for maximum survival but at the average release weight was less effective at improving survival rates than releasing them using both the release day and weight for maximum survival (Figures 3-6, Tables 5-6). Therefore, it is important that release dates and weights be jointly considered. Adjusting release dates alone was predicted to increase returns by more than 50% at only 2 of 21 Chinook hatcheries and was not predicted to increase returns by more than 20% at any Coho hatchery. However, as described in the previous section, even for releases with both the day and weight for maximum survival, only 8 of 21 Chinook hatcheries and 4 of 16 Coho hatcheries were predicted to see an increase in returns of more than 50% (Figures 3-6, Tables 5-6). Here, the day of release for maximum survival is the day within the 95% central distribution of historical releases that maximizes survival, rather than the modelled optimum which extrapolates beyond the range of observed data at each hatchery. Thus, those facilities with a narrower range of release dates may be shown to have a smaller change in survivals relative to those facilities that have a broader range of release dates, however this is due to the constraints around release strategies at those facilities.

Life Stage

Hatcheries release different life stages with objectives to maintain the natural life history diversity of the stock, encourage spawners to use historical habitats, increase survival rates, or reduce returns of precocious males (i.e. age-1s and age-2s). The seven life stage experiments analyzed were all for Chinook, and although releases designed to mimic the natural life history are not necessarily considered experimental releases, we include these as they provide valuable insight. Where multiple life stages or life history types were released concurrently in the past 20 years, fry had lower, or similar survival rates to other life stages, whereas yearlings had consistently higher survival rates throughout the province (Table 7). Exploitation rates were similar between life stages. Return ages were also similar, with the exception of Atnarko River yearlings which came back older than their smolt counterparts. However, wherever yearling smolts were released with subyearling smolts, it is important not only to consider return age, but also the number of years at sea. With an additional year spent in freshwater yearling releases were found to spend fewer years at sea, thus decreasing their exposure to fisheries.

Life stage is inherently confounded by several other release characteristics, such as size, timing, and release location. Survival models of each experiment found a mix of life stage and weight at release to be the best predictors of survival (Table 7). Fry are typically smaller than subyearlings, which are smaller than yearlings due to the difference in rearing times of each. Subyearlings are released in the spring after a few months of hatchery rearing, whereas yearlings are released in early spring after just over a year of hatchery rearing. Furthermore, fry are usually released into lakes or upper watersheds to allow more time for freshwater rearing and growth before they reach the marine environment. Without controlling for all other variables, it is difficult to know whether a specific life stage or life history type itself performs differently from others. The outcomes also need to be considered within the context of the natural life history and the possible impacts of introducing a different life history to the system.

In the hierarchical multi-hatchery survival models, the addition of a release stage effect independent of release weight or date did little to improve the model estimates. Thus, differences in the weight and date of release have played a greater role in determining survival than 'life stage' alone.

Seapens

The main objective for releasing salmon from seapens is to produce fish for harvest, although seapens can also be used to avoid poor freshwater rearing conditions and reduce competition with wild outmigrants. Our analyses showed that of the six enhanced stocks with sufficient data on seapen releases, only Quinsam River and Robertson Creek saw higher exploitation rates from seapen releases than from regular hatchery releases (Tables 8-9). Seapen releases were also found to differ in the age structure of their adult returns at both Cowichan River and Quinsam River. Cowichan seapen releases were found to come back older than hatchery releases, while Quinsam River seapen releases come back at younger ages. Seapen releases exhibited similar survival rates to their hatchery-released counterparts.

While no significant differences were measured in mean survival rates between hatchery and seapen releases, models of survival rates for each experiment identified a number of factors influencing overall patterns in survival (Table 8). For instance, release weight was an important predictor of survival for both Cowichan and Quinsam River Chinook, however there was considerable overlap between the release weights of hatchery and seapen fish across facilities. Thus, larger Cowichan River Chinook, regardless of whether they were released from the hatchery or from seapens in the estuary, had higher survival rates. For Quinsam River Chinook, survival rates increased for releases up to approximately 6.5 g and then decreased, regardless of release location. The year of release was important for predicting Cowichan River survivals, with lower survival rates seen in recent years across release types. Release location was also important for both Cowichan River and Robertson Creek Chinook. Cowichan River Chinook have been released at a number of locations throughout the watershed from Cowichan Lake all the way down to the estuary, with releases into Cowichan Lake having lower survival rates than those to the upper Cowichan River. At Robertson Creek, releases from seapens had higher survivals than direct hatchery releases in four of the five years, however the difference in means was not significant.

Where seapens may be more effective is in improving exploitation rates. Both Quinsam River and Robertson Creek Chinook released from seapens had higher exploitation rates than those released directly from the hatchery (Table 8). However, no difference in exploitation rates were observed for Puntledge or Cowichan River Chinook, thus there may be inherent site or stock-specific differences driving the difference in exploitation rates of seapen releases.

Release and Environmental Conditions

The hierarchical multi-hatchery survival models had improved performance when models included covariates for total annual hatchery biomass per release location (Chinook and Coho models) and freshwater migration distance (Chinook models only) (Tables 10-11). In general, total biomass released had a negative relationship and migration distance had a positive relationship with survival (Figures 8-9; Tables 10-11). These relationships were not significant at most hatcheries, however a high biomass of hatchery fish released was related to significantly lower survival rates for Big Qualicum River, Capilano River, and Quinsam River Chinook and Robertson Creek Coho. While effects of freshwater migration distance were observed at Spius Creek, Chilliwack River, Capilano River, Quinsam River, Snootli Creek, and Robertson Creek, there are a number of confounding factors that prevent us from drawing any direct conclusions on the effects of migration distance specifically. In each of these cases, release location is confounded by either seapen releases, releases of different life stages at different locations (e.g. fry in upper watersheds), changing release locations over time, or releases of different stocks at different locations from the same hatchery. For instance, there are only two release locations for Capilano River Chinook salmon: directly from the facility (5.7 km downriver migration) or from seapens in the marine environment. Historical seapen releases of Capilano River fish had slightly lower survival rates than regular hatchery releases, which could explain why a longer migration distance was correlated with higher survival.

Predator abundance (both killer whales and harbour seals), sea surface temperatures, and the Pacific Decadal Oscillation all had significant negative effects on survival rates (Figures 10-11; Tables 12-13). Of these, harbour seal abundance was the strongest predictor of survival. Hatchery-specific estimates for seal predation showed significant negative effects on Chinook survival for 9 of 21 hatcheries (Toboggan Creek, Quinsam River, Robertson Creek, Capilano River, Big Qualicum River, Cowichan River, Nanaimo River, Penny Creek, Eagle River) and on Coho survival for 12 of 16 hatcheries (Quinsam River, Capilano River, Lang Creek, Tenderfoot Creek, Big Qualicum River, Goldstream River, Puntledge River, Chilliwack River, Inch Creek, Spius Creek, Eagle River, Dunn Creek). However, the inclusion of specific environmental covariates in the hierarchical models rather than year effects did not improve model predictive performance (Tables 12-13). Environmental covariates did explain an additional 6-19% and 2-18% of variance in Chinook and Coho survival rates, respectively, compared to the base model without any environmental or year effects. However, instead of modelling these numerous factors independently, the inclusion of fixed and random year effects allowed survival models to account for all environmental effects simultaneously and estimate their net effect on average annual survival. In so doing, we could more reliably estimate the release strategy effects of interest.

Random year effects explained 13-91% (average: 49%) and 10-80% (average: 43%) of the variance in average annual logit-survival rates for Chinook and Coho, respectively. Thus, there are other conditions (such as the environmental covariates we have assessed) influencing survival rates that are beyond the control of hatchery management. Therefore, the weights and dates of release for maximum survival could vary over time depending on large-scale oceanographic features or more local dynamics associated with river conditions, predation, or prey availability (Mathews & Ishida 1989, Nelson et al. 2019). It is important that SEP consider both the potential to increases survival rates (Figures 3 and 5) as well as the strength of random year effects (Figures 12 and 13) when deciding where to implement changes or develop experimental programs. Those facilities where random year effects are low may be ideal locations for measuring the effects of newly adapted release strategies. In addition, future research could investigate what conditions cause some facilities or regions (e.g. lower Fraser River) to experience such high environmental variability.

LIMITATIONS

This is the first time a review of this scale has been conducted on hatchery release strategies in BC. With that comes the challenges of establishing methods for accessing, interpreting, analyzing, and reporting the data from multiple different sources. The following is an overview of the main limitations we faced in conducting our review.

1. **Data accessibility:** While the data are publicly available, they are administered by the Salmonid Enhancement Program (SEP). Formulating data requests could be challenging without prior knowledge of what data were available, highlighting a need for more comprehensive and accessible metadata files. While the back and forth required to request and interpret the data was part of our collaboration process, it was also time consuming for both parties and efforts were sometimes redundant.
2. **Data availability:** Data usability flags within the Enhancement Planning and Assessment Database (EPAD) indicate which releases have quality data for estimating survival and exploitation rates. Several facilities, and a number of hatchery experiments, are flagged as not having quality data for these estimations, and were therefore excluded from our review. One of the major contributors to these flags is a lack of escapement monitoring. In addition, the following data were not always readily available and limited the extent of our analyses:
    - **a)** Release locations and environmental conditions at time of release. These data had to be collated from interviews with hatchery managers and other sources.
    - **b)** Rearing practices (e.g. rearing water type, container type, volitional versus forced releases). Data for recent years was often shared by hatchery staff, but historical records were typically not readily available.
    - **c)** Hatchery releases along the central and north coast. Most releases are not tagged, making it impossible to measure the effects of release strategies.
    - **d)** Thermal mark data. While thermally marked release data were readily available, recoveries of thermally marked fish were not. Thermal marks were therefore excluded from this review.
3. **Retrospective analyses:** No formal record of hatchery experimentation in BC was available. Therefore, considerable 'detective work' was required to piece together the details of past hatchery experiments, often relying on people's memories rather than actual records. The application of 'purpose codes' in EPAD can be inconsistent and so this field could not be used to extract experimental releases. Therefore, some experiments may have been missed.
4. **Experimental design:** Much of the experimentation has been exploratory in nature, leveraging limited resources to improve hatchery practices in the face of changing environmental conditions. Many experiments lacked an experimental design making it difficult to isolate effects of specific release strategies. In addition, experiments have typically run for the minimum number of years necessary to provide SEP with a signal of how release strategies may be affecting production outcomes. However, a considerable amount of the variability in our models was due to random year effects. With only 1-3 years of release data in many cases, it was difficult to detect significant effects of release strategies amidst the background noise of environmental variation. Both the lack of experimental design and the limited time scales of experimentation contributed to poor confidence in the results of some of the experimental analyses.

It is important to note that the results of this review reflect past practices summarized across facilities throughout the province over time. Relationships between hatchery practices and production outcomes likely vary over time as we move through different climate regimes. However, for this initial review of hatchery release strategies we have not assessed changes in these relationships over time; this may be of interest for future studies. In addition, strategies that worked in the past may not work in the future, which is why adaptive management will be critical moving forward. The prescribed release strategies are also independent of one another and it is uncertain how changes to releases at a given hatchery or across an entire region may influence the effectiveness of release strategies elsewhere.

As previously noted, factors such as operational cost, feasibility, and risk were not considered within the scope of this review. We also acknowledge that some release strategies, such as later release, may not be feasible at some facilities due to physiological constraints, such as an increased risk of disease.

RECOMMENDATIONS

The development of optimal release strategies requires a thorough understanding of the complex relationships between genetics, hatchery rearing and release practices, and environmental conditions. As environmental conditions and population dynamics change over time, it is important that we continually re-evaluate our state of knowledge. It also requires that operations and experiments be designed in a way that facilitates assessment, learning, and adaptation. A lack of design has in part limited our ability to draw more concrete conclusions from this review process. This is not a criticism, rather a call for sufficient resources to be allocated to SEP, so that the necessary assessment and adaptive management can occur in the years to come.

First, to address some of the data limitations described in the previous section, we recommend that comprehensive and accessible metadata files be developed to facilitate data requests pertaining to salmonid enhancement in BC. In addition, any concerns around data quality should be shared along with the datasets. We also recommend that data on rearing practices, such as rearing water, container type, and rearing density, be collected and centrally managed.

Through the review process, we have identified the need for a comprehensive, peer-reviewed, experimental design to assess hatchery rearing and release strategies that takes into account the following:

1. A significant amount of variation in survival rates can be attributed to interannual environmental variability. Therefore, experimental trials should have sufficient resources allocated to replicate studies over longer periods of time (> 3 years), improving the ability to detect effects amidst the environmental noise and/or trends. Locations where random year effects are lower and estimated improvements in survival rates and returns are higher could be areas to focus initial efforts. More environmental data could also be collected by hatcheries to improve our understanding of the role the environment in influencing production outcomes. For instance:
    - **a)** Many facilities already record river temperatures and flow rates at the time of release but not all facilities record these environmental data, and the data recorded are not centrally managed. Given the expected impacts of climate change, we recommend that all facilities conduct continual monitoring of freshwater conditions and that these data be centrally managed.
    - **b)** Incorporate environmental data from the marine environment, such as El Niño or La Niña events, sea surface temperature, chlorophyll-a concentrations, or the spring transition date. Collaborations could be made with the relevant scientists to integrate these data into hatchery management. By monitoring these parameters over time and space, we can determine what relationships exist between hatchery production and marine environmental conditions. In the future, these data could be used to proactively adjust hatchery releases to interannual variability in the marine environment.
    - **c)** There are limited data on predator abundances during the downstream migration and early marine residence of hatchery releases. Our survival models indicate that harbour seal predation reduces both Coho and Chinook hatchery survival rates, and hatchery managers and staff have also reported high predation by mink, otters, gulls, and other birds on site and in-river. Therefore predator surveys should be conducted to determine annual abundances of primary predators which can be used to estimate predator density or predation rates for each enhanced system which can then inform release strategies.
2. In order to accurately monitor the effects of release strategies (and ultimately enhancement) at the provincial scale, we recommend that data-poor areas and systems, such as the central and north coast, be prioritized for investment in tagging and assessment. Parentage-based tagging (PBT) or thermal marks are used as alternatives to coded-wire tags in some hatcheries but these marks are not recovered in most fisheries, and contribution and survival rates are therefore incomplete.

3. Release strategies should not put wild populations at risk, however little is known about the impacts of hatchery release timing, size at release, or release location on outmigrating wild salmon. Therefore, we recommend that SEP commit to monitoring the wild populations of enhanced systems to be able to determine which release strategies provide the greatest benefit/least risk to the health of those populations, and to be able to compare the effects of hatchery release strategies to the natural outmigration dynamics.

   a) This could involve concurrent monitoring of the wild salmon downstream migration through the installation and use of rotary traps and fences.

   b) Modern technologies are available to assess the interactions of hatchery and wild salmon, such as PBT and passive integrated transponder (PIT) tags. For instance, tagging studies could compare the outmigrations of wild and hatchery salmon to better understand the mechanisms through which interactions may occur. PSF's Bottlenecks to Survival project is currently expanding the existing PIT array networks along the east coast of Vancouver Island, laying the ground for future PIT tagging work. Expansion of the use of PIT tags and arrays is certainly possible elsewhere.

4. SEP has acknowledged that resources are not always available to design and conduct experiments in a way that produces results with statistical bounds and accuracy. However, effective hatchery management requires that decisions be based on scientific evidence. Therefore, the allocation of resources for the routine collection, analysis, and reporting of data on the effectiveness of hatchery practices needs to be prioritized. With adequate resources available, experiments can then be designed to more effectively estimate rearing/release strategy effects. When allocating resources towards experimentation, the following should also be considered:

   a) What qualifies as appropriate experimental design will depend on whether hatchery objectives are to estimate the effects of a combination of release conditions (e.g., weight and site at release) or a specific strategy (e.g., release weight, release location) on survival outcomes. In order to estimate the effects of a combination of release condition, factorial treatment structures should be used (i.e., all combinations of each factor and levels within the experiment). However, if the objective is to evaluate a single release condition, then an experiment in which all other release variables are kept constant would be required.

   b) It is important to conduct power analyses when designing experiments to determine the necessary sample size for detecting effects on survival and to ensure resources are not wasted with too few or too many release years.

   c) Differences in return age composition among stocks can contribute to differences in average marine survival rates because older fish are exposed to additional years of at-sea mortality, particularly Chinook. One method for addressing this could be to re-scale all adult returns to a single reference age-class, which would require an estimation of ocean mortality rates for each age class. This could improve comparisons of survival outcomes among hatcheries and release strategies by accounting for additional at-sea mortality experienced in the 4TH and 5TH year at sea for the older returns (if the reference was age-3 Chinook).

   d) Greater spatial and temporal replication of experiments to better understand how release strategies can best be developed and implemented throughout the province over time. Given effects of the environment and predators, individual hatchery studies should be conducted within a spatial block design to account for regional covariation between stocks and facilities.

   e) A comprehensive data management system should be developed to support real-time data collection, analysis and reporting of experimental releases. Specifically, there needs to be standards for consistent data entry across facilities and the objectives and timeframes of experiments should be documented.

Therefore, going forward, we recommend an adaptive management approach that establishes clear requirements for the monitoring and adaptation of hatchery rearing and release practices so that these practices can be modified for anticipated climate impacts and can be assessed for effectiveness. This approach should be coordinated across the province to account for local and regional effects of changing production.

Our models prescribe hatchery-specific weights and dates of release within the historical range of observations at each facility that are expected to yield maximum survival rates. Generally speaking, Chinook and Coho could both be reared to larger weights prior to release, while Chinook could be released earlier and Coho released later. How much bigger and how much earlier or later will depend on the facility and has been outlined in Tables 5-6. However, it is important to consider the degree of random year effects at some locations; releasing salmon at the prescribed weights and dates in areas that experience a high amount of random variability may not always yield the highest survival rates or returns. We recommend that SEP management use the information provided within this report to evaluate whether the predicted increases in survival rates justify modifications to release strategies and to develop experimental programs for those facilities. Hatcheries could allocate a proportion of their total production towards experimental releases using the hatchery-specific weight and day of release strategies described in this report. We do recommend that experiments be developed to trial these strategies and improve estimates of hatchery-specific release strategy effects before implementing them on a larger scale. We also recommend that the specific management objectives and constraints at each hatchery be taken into consideration when designing release strategies. And finally, the complex interactions between release strategies, fish health, environmental conditions, and survival rates are likely to change over time. Therefore, the specific release strategies outlined in this report should be adapted over time to reflect such changes.

Outcomes from specific hatchery experiments over the past 20 years suggest beneficial release strategies, however they were not always supported by our broader hierarchical analysis. Thus, we advise against taking successes from a single short-term experiment at a specific hatchery and applying it broadly across other facilities. For instance, previous experiments suggest that seapens have the potential to increase fishing opportunities, and older life stages may have higher survival rates for some facilities. However, we recommend that these experiments be both repeated to increase confidence in the results and be expanded to similar facilities to assess their effectiveness more broadly. As was demonstrated through our hierarchical models, there are consistent spatial and temporal patterns in species responses to release strategies. However, in order to measure regional patterns from a collection of individual experiments, more years of data from more facilities are required.

It is important that release strategies be used to support, but not replace, risk mitigation for both wild and enhanced populations. The goal should be to develop strategies that improve survival rates to the point that fewer hatchery fish need to be released to produce the target number of adults. It will also be important to measure the impacts of these release strategies on other metrics, such as age- and size-at-return. While some release strategies may improve survival rates, they may also result in a higher proportion of jacks or smaller-sized adults in the returns (James 2021a).

Some of these recommendations echo those of the Hatchery Science Reform Group which led comprehensive hatchery reviews in Puget Sound, coastal Washington, and the Columbia River basin. Specifically, they identified the need to use current science in developing strategies, and to continuously monitor, evaluate and adaptively manage hatcheries (HSRG 2009, 2015). Therefore, our review and our recommendations contribute to the widespread and growing evidence that changes can and should be made to improve hatchery effectiveness.

This sub-project of the PSF Hatchery Review provides an evaluation of hatchery release strategies in BC. It is an important first step towards improving our understanding of the complex dynamics of hatchery practices. It also paves the way for additional analyses that were beyond the scope of this initial assessment. For instance, future work could fit models with time-varying release strategies to determine how their effectiveness has changed over time. This could also help to inform the role of release strategy diversity at a given facility in buffering against predators and environmental variability (Irvine et al. 2013, Nelson et al. 2019). In addition, there's more to learn about the effects of total hatchery biomass released and how large changes to production (e.g. reductions to Coho production in the early 2000s) may have influenced the performance of hatchery fish. Future analyses may also want to compare hatchery release weights and dates to the sizes and migration timing of the wild populations.

REFERENCES

Anderson JH, Warheit KI, Craig BE, Seamons TR, Haukenes AH (2020) A review of hatchery reform science in Washington State. Washington Department of Fish and Wildlife.

Araki H, Berejikian BA, Ford MJ, Blouin MS (2008) Fitness of hatchery-reared salmonids in the wild. Evol Appl 1:342–355.

Buhle ER, Holsman KK, Scheuerell MD, Albaugh A (2009) Using an unplanned experiment to evaluate the effects of hatcheries and environmental variation on threatened populations of wild salmon. Biol Conserv 142:2449–2455.

Burnham KP, Anderson DR (2002) Model Selection and Multimodel Inference: A Practical Information-Theoretic Approach (2nd ed). Springer-Verlag, New York.

Chasco BE, Kaplan IC, Thomas AC, Acevedo-Gutiérrez A, Noren DP, Ford MJ, Hanson MB, Scordino JJ, Jeffries SJ, Marshall KN, Shelton AO, Matkin C, Burke BJ, Ward EJ (2017) Competing tradeoffs between increasing marine mammal predation and fisheries harvest of Chinook salmon. Sci Rep 7:1–14.

Chung Y, Rabe-Hesketh S, Dorie V, Gelman A, Liu J (2013) A nondegenerate penalized likelihood estimator for variance parameters in multilevel models. Psychometrika 78:685–709.

Daly EA, Brodeur RD, Fisher JP, Weitkamp LA, Teel DJ, Beckman BR (2012) Spatial and trophic overlap of marked and unmarked Columbia River Basin spring Chinook salmon during early marine residence with implications for competition between hatchery and naturally produced fish. Environ Biol Fishes 94:117–134.

DFO (2005) Canada's policy for conservation of wild Pacific salmon. Vancouver, Canada.

DFO (2013) A biological risk management framework for enhancing salmon in the Pacific region. Salmonid Enhancement Program, Fisheries and Oceans Canada, Pacific Region.

DFO (2016) A compliation of operational and planning guidelines for the Salmonid Enhancement Program. Fisheries and Oceans Canada, Pacific Region.

DFO (2018) SEP production planning: A framework. Salmonid Enhancement Program, Fisheries and Oceans Canada, Pacific Region.

DFO (2019) SEP biological assessment framework. Salmonid Enhancement Program, Fisheries and Oceans Canada, Pacific Region.

Doherty, B, and Cox S.P. (2021). Release strategy effects on survival and return ages for British Columbia Chinook and Coho hatchery releases, 1972-2017. Report prepared for the Pacific Salmon Foundation by Landmark Fisheries Research. 186 p.

Furey NB, Hinch SG, Bass AL, Middleton CT, Minke-Martin V, Lotto AG (2016) Predator swamping reduces predation risk during nocturnal migration of juvenile salmon in a high-mortality landscape. J Anim Ecol 85:948–959.

Hilborn R (1992) Hatcheries and the future of salmon in the Northwest. Fisheries 17:5–8.

HSRG (Hatchery Scientific Review Group) (2009) Columbia River Hatchery Reform System-Wide Report. Paquet P, Appleby A, Barr J, Blankenship L, Campton D, Delarm M, Evelyn T, Fast D, Flagg T, Gislason J, Kline P, Maynard D, Nandor G, Seidel P, Smith S.

HSRG (Hatchery Scientific Review Group) (2015) Annual report to Congress on teh science of hatcheries, 2015: A report on the application of up-to-date science in the management of salmon and steelhead hatcheries in the Pacific Northwest. Campton D, Currens K, Fast D, Flagg T, Kline P, Missildine B, Nandor G, Patterson S, Warheit K:20.

Huang B, Thorne PW, Banzon VF, Boyer T, Chepurin G, Lawrimore JH, Menne MJ, Smith TM, Vose RS, Zhang HM (2017) Extended reconstructed sea surface temperature, Version 5 (ERSSTv5): Upgrades, validations, and intercomparisons. J Clim 30:8179–8205.

Irvine JR, O'Neill M, Godbout L, Schnute J (2013) Effects of smolt release timing and size on the survival of hatchery-origin Coho salmon in the Strait of Georgia. Prog Oceanogr 115:111–118.

James S (2021a) Evaluation of hatchery experiments in British Columbia, 2000-2018. Report prepared for the Pacific Salmon Foundation's Hatchery Effectiveness Review (BCSRIF-2019-136).

James S (2021b) Review of Pacific salmon hatchery release strategies in Canada and the United States. Report prepared for the Pacific Salmon Foundation's Hatchery Effectiveness Review (BCSRIF-2019-136).

Kristensen K, Nielsen A, Berg CW, Skaug H, Bell BM (2016) TMB: Automatic differentiation and Laplace approximation. J Stat Softw 70.

MacKinlay DD, Lehmann S, Bateman J, Cook R (2004) Pacific salmon hatcheries in British Columbia. Am Fish Soc Symp 44:57-75.

Malick MJ, Cox SP, Mueter FJ, Peterman RM (2015) Linking phytoplankton phenology to salmon productivity along a north – south gradient in the Northeast Pacific Ocean. Can J Fish Aquat Sci 72:697–708.

Mantua NJ (2009) Patterns of change in climate and Pacific salmon production. Am Fish Soc Symp 70:1–14.

Mathews SB, Ishida Y (1989) Survival, ocean growth, and ocean distribution of differentially timed releases of hatchery Coho salmon (*Oncorhynchus kisutch*). Can J Fish Aquat Sci 46:1216–1226.

Monnahan CC, Kristensen K (2018) No-U-turn sampling for fast Bayesian inference in ADMB and TMB: Introducing the adnuts and tmbstan R packages. PLoS One 13:1–10.

Mueter FJ, Ware DANM, Peterman RM (2002) Spatial correlation patterns in coastal environmental variables and survival rates of salmon in the north-east Pacific Ocean. 205–218.

Myers RA, Mertz G (1998) Reducing uncertainty in the biological basis of fisheries management by meta-analysis of data from many populations: A synthesis. Fish Res 37:51–60.

Nelson BW, Shelton AO, Anderson JH, Ford MJ, Ward EJ (2019) Ecological implications of changing hatchery practices for Chinook salmon in the Salish Sea. Ecosphere 10:1–19.

Olesiuk PF (2010) An assessment of population trends and abundance of harbour seals (*Phoca vitulina*) in British Columbia. DFO Can Sci Advis Sec Res Doc 2009/105.

Riddell B, Bradford M, Carmichael R, Hankin D, Peterman R, Wertheimer A (2013) Assessment of status and factors for decline of Southern BC Chinook Salmon: Independent panel's report. Prepared with the assistance of DR Marmorek and AW Hall, ESSA Technologies Ltd., Vancouver, B.C. for Fisheries and Oceans Canada (Vancouver, BC) and Fraser River Aboriginal Fisheries Secretariat (Merritt, BC). xxix + 165 pp. + Appendices.

Scheuerell MD, Ruff CP, Anderson JH, Beamer EM (2021) An integrated population model for estimating the relative effects of natural and anthropogenic factors on a threatened population of steelhead trout. J Appl Ecol 58:114–124.

Tatara CP, Berejikian BA (2012) Mechanisms influencing competition between hatchery and wild juvenile anadromous Pacific salmonids in fresh water and their relative competitive abilities. Environ Biol Fishes 94:7–19.

Thériault V, Moyer GR, Jackson LS, Blouin MS, Banks MA (2011) Reduced reproductive success of hatchery Coho salmon in the wild: Insights into most likely mechanisms. Mol Ecol 20:1860–1869.

Towers JR, Pilkington JF, Gisborne B, Wright BM, Ellis GM, Ford JKB, Doniol-Valcroze T (2020) Photo-identification catalogue and status of the Northern Resident Killer Whale population in 2019. Can Tech Rep Fish Aquat Sci 3371:iv + 69p.

Vehtari A, Gelman A, Gabry J (2017) Practical Bayesian model evaluation using leave-one-out cross-validation and WAIC. Stat Comput 27:1413–1432.

Waples RS (1991) Genetic interactions between hatchery and wild salmonids: Lessons from the Pacific Northwest. Can J Fish Aquat Sci 48:124–133.

Wood C (2008) Managing biodiversity of Pacific salmon: Lessons from the Skeena River Sockeye salmon fishery in British Columbia. Am Fish Soc Symp 49:349–364.

Wild Salmon Advisory Council (2019) Recommendations for a made-in-BC wild salmon strategy. Prep for Province of British Columbia.

TABLES

Table 1: Summary of each stock in each region used for each release strategy experiment by ocean entry year (OEY) in BC using CWT'd Chinook and Coho salmon over the past 20 years. Earlier experiments are also shown for Chilliwack and Cowichan River.

Strategy	Region	Stock	Run	Species	OEYs	Experiment
Life Stage*	CC	Atnarko R Low/Up	Summer	CN	2009-2013	smolt vs yearling
	NEVI	Phillips R	Fall	CN	2011, 2012, 2014	smolt vs yearling
		Quinsam R	Fall	CN	2001-2007 2015-2018	release of fed fry to Quinsam Lk vs smolts from hatchery
	SoG	Cheakamus R	Summer	CN	2016-2019	fed fry vs yearlings
		Puntledge R	Summer	CN	2002, 2003, 2005	fed fry (released at multiple locations) vs hatchery smolts
		Shuswap R Mid	Summer	CN	2015-2018	smolt vs yearling
	WCVI	Robertson Cr	Fall	CN	2004-2007 2017-2018	smolts vs yearlings
Size	SoG	Quinsam R	Fall	CO	2010-2012	normal vs large
		Inch Cr	Fall	CO	2012-2014	small vs normal
Time	SoG	Chilliwack R	Fall	CN	1993-1995	early vs late
		Chilliwack R	Fall	CO	1983, 1990-1991, 2000-2001	early vs mid vs late
		Cowichan R	Fall	CN	1990-1995, 1998, 2001-2004, 2006, 2008-2009, 2011-2016	early and late, at two release locations
		Inch Cr	Fall	CO	2006-2008	early vs normal
		Quinsam R	Fall	CO	2002-2012	early vs normal vs late
Time & Size	NEVI	Quinsam R	Fall	CN	2015-2017, 2019	normal vs late/large
		Quinsam R	Fall	CO	2016-2020	normal vs late/large
	SoG	Big Qualicum R	Fall	CN	2011-2013, 2015-2017	normal vs late/large
		Big Qualicum R	Fall	CO	2016-2018	normal vs late/large
		Inch Cr	Fall	CO	2015-2017	normal vs late/large
Seapens	CC	Wannock R	Fall	CN	2010-2011, 2014-2015, 2018-2019	hatchery (freshwater) vs seapen (marine) releases
	NEVI	Quinsam R	Fall	CN	2000-2018	hatchery (freshwater) vs seapen (marine) releases
	WCVI	Robertson Cr	Fall	CN	2002-2004, 2014-2018	hatchery (freshwater) vs seapen (marine) releases
	SoG	Puntledge R	Summer	CN	2000, 2002-2003, 2006-2009	hatchery (freshwater) vs seapen (marine) releases
		Cowichan R	Fall	CN	1992-2004, 2006-2009	hatchery (freshwater) vs seapen (marine) releases
		Chilliwack R	Fall	CN	2014-2017	hatchery (freshwater) vs seapen (marine) releases

*Life stages include fry, subyearling smolts, and yearling smolts. Fry are released shortly after emergence from the gravel, subyearlings are reared for a few months and typically released in the spring of the same year they hatched, and yearlings are reared for a full year and typically released in the early spring of the year after hatching. Life stage is considered within the context of the natural life history of the population.

Table 2: Summary of species, stock, ocean entry year (OEY), and experiment type for time and size at release experiments and effects on survival rates, exploitation rates, and return ages. The experimental strategy is bolded. Green cells show experiments where a significant positive relationship was found between the bolded time/size at release and the production outcome. Red cells represent significant negative relationships, while grey cells represent no significant effect. Rows in orange had insufficient data for conducting statistical analyses. Where survival models were possible, the best release strategies from the top model are provided in the 'Survival' column. Source: James 2021b.

Species	Stock	OEY	Experiment	Survival	Exploitation	Age
CN	Big Qualicum R	2011-2013, 2015-2017	normal vs **late/large**	none		
CN	Chilliwack R	1993-1995	early vs **late**	insufficient data		
CN	Cowichan R	1990-1995, 1998, 2001-2004, 2006, 2008-2009, 2011-2016	early and late, at two release locations	weight, day, release site		
CN	Quinsam R	2015-2017, 2019	normal vs **late/large**	insufficient data		
CO	Big Qualicum R	2016-2018	normal vs **late/large**	insufficient data		
CO	Chilliwack R	1983, 1990-1991, 2000-2001	**early** vs mid vs **late**	insufficient data		
CO	Inch Cr	2006-2008	**early** vs normal	insufficient data		
CO	Inch Cr	2012-2014	**small** vs normal	Insufficient data		
CO	Inch Cr	2015-2017	normal vs **late/large**	none		
CO	Quinsam R	2002-2012	**early** vs normal vs **late**	day, year		
CO	Quinsam R	2010-2012	normal vs **large**	insufficient data		
CO	Quinsam R	2016-2020	normal vs **late/large**	insufficient data		

Table 3: Hatchery-specific model results for Chinook mean return ages from smolt and yearling releases. Predictor terms and estimated coefficients with 95% CIs (,) are shown for fixed effects included in top models selected for Chinook releases at individual hatcheries. None of the 95% CIs for model coefficients include zero, indicating statistically significant effects. Hatcheries are grouped by release site areas (JNST = Johnstone Strait, SWVI = southwest Vancouver Island), GSVI = Strait of Georgia Vancouver Island side).

				Covariate coefficients for fixed effects							
Area	**Hatchery**	**Life Stage**	**Intercept**	**Weight**	**Weight^2**	**Year**	**% Females**	**Stock/ Site**	**ICC**	**n**	**ΔAIC_c**
JNST	Quinsam R	sub-yearling	3.47 (3.35, 3.6)				0.73 (0.44, 1.02)	+	0.24	126	0.72
SWVI	Robertson Cr	sub-yearling	3.51 (3.35, 3.66)				0.61 (0.14, 1.11)		0.66	36	0
GSVI	Big Qualicum R	sub-yearling	3.33 (3.21, 3.46)						0.04	20	0
GSVI	Puntledge R	sub-yearling	3.56 (2.94, 4.14)	-0.25 (-0.43, -0.07)	0.018 (0.003, 0.033)		1.11 (0.53, 1.71)		0.49	38	0

Table 4: Hatchery-specific model results for proportion of Jacks in returns from Coho fry and yearling releases. Predictor terms are on logodds scale and estimated coefficients with 95% CIs (,) are shown for fixed effects included in top models selected for Coho releases at individual hatcheries. Note the top models for Robertson Creek Yearling and Chilliwack R Yearling are intercept-only models with the random year effects. None of the 95% CIs for model coefficients include zero, indicating statistically significant effects. There was no stock or release site effect in any of the top models. Hatcheries are grouped by areas (JNST = Johnstone Strait, SWVI= Southwest Vancouver Island, GSMN = Strait of Georgia Mainland, GSVI = Strait of Georgia Vancouver Island, LWFR = Lower Fraser).

				Covariate coefficients for fixed effects						
Area	**Hatchery**	**Life Stage**	**Intercept**	**Weight**	**Weight^2**	**Year**	**Stock/ Site**	**ICC**	**n**	**ΔAIC_c**
JNST	Quinsam R	yearling	-9.89 (-15.17, -4.55)	0.76 (0.35, 1.16)	-0.014 (-0.021, -0.007)		+	0.67	89	0
SWVI	Robertson Cr	yearling	-2.07 (-2.42, -1.7)					0.41	39	0
GSMN	Capilano R	yearling	-2.57 (-2.94, -2.2)					0.51	26	0
GSVI	Big Qualicum R	yearling	-12.05 (-19.89, -5.42)	0.97 (0.4, 1.64)	-0.022 (-0.036, -0.011)	0.059 (0.032, 0.087)		0.75	25	0
GSVI	Puntledge R	fry	-1.58 (-3.24, 1)	-0.3 (-0.72, 0.09)			+	0.18	36	0
GSVI	Puntledge R	yearling	-4.82 (-5.92, -3.71)	0.17 (0.12, 0.22)				0.89	44	0
LWFR	Chilliwack R	yearling	-2.16 (-2.5, -1.81)					0.50	24	0
LWFR	Inch Cr	yearling	-3.6 (-4.17, -3.03)			0.069 (0.039, 0.099)		0.25	44	0

Table 5: Estimated median posterior and 95% credible intervals for % survival and estimated % increase in average Chinook returns for release weight and day that maximize survival (W_S, D_S) relative to the mean release weight and day ($\overline{W}$, $\overline{D}$) of the most commonly released life stage (F = fry, S = subyearling smolt, Y = yearling smolt) over the last 20 ocean entry years (OEY; specific years used for determining averages shown for each hatchery). Mean release weights and days are calculated from CWT releases without experimental and seapen releases.

			Weight (g) and Julian day at release				Average survival rate (%)				% increase in returns for different release strategies		
Hatchery	**Life Stage**	**OEYs (Historical Avg)**	W_S	$\overline{W}$	D_S	$\overline{D}$	$\overline{W}, \overline{D}$	$\overline{W}, D_S$	$W_S, \overline{D}$	W_S, D_S	$\overline{W}, D_S$	$W_S, \overline{D}$	W_S, D_S
Big Qualicum R	S	2000-2016	13.9	6.3	134	145	0.1 (0.0,0.3)	0.1 (0.0,0.3)	0.4 (0.1,0.9)	0.4 (0.1,1.0)	4 (-9,20)	229 (106,450)	245 (101,518)
Capilano R	S	2013-2016	9.9	7.5	121	145	0.7 (0.3,1.5)	1.2 (0.6,2.6)	1.0 (0.5,2.0)	1.6 (0.7,3.7)	69 (28,123)	35 (11,62)	128 (56,228)
Chehalis R	S	2006-2016	6.6	5.8	145	159	0.6 (0.2,2.1)	0.7 (0.2,2.3)	0.7 (0.2,2.3)	0.7 (0.2,2.5)	7 (-29,51)	11 (-5,24)	18 (-23,69)
Chilliwack R	S	2000-2017	6.3	5.4	122	140	0.9 (0.2,3.0)	1.1 (0.2,3.9)	1.0 (0.3,3.4)	1.2 (0.3,4.5)	18 (-18,77)	14 (-1,30)	35 (-10,107)
Cowichan R	S	2000-2017	10.5	6.3	135	131	0.5 (0.2,1.4)	0.5 (0.2,1.3)	0.6 (0.2,1.8)	0.6 (0.2,1.8)	0 (-3,5)	18 (-26,77)	18 (-24,74)
Eagle R	S	1984-1992	6.8	4.6	139	142	0.1 (0.0,0.6)	0.1 (0.0,0.6)	0.2 (0.0,0.9)	0.2 (0.0,0.9)	0 (-5,5)	47 (20,82)	47 (23,79)
Gillard Pass	S	2010-2016	6.1	4.6	140	144	0.5 (0.2,1.6)	0.5 (0.2,1.7)	0.7 (0.2,2.1)	0.7 (0.2,2.3)	6 (-5,22)	33 (13,58)	42 (19,71)
Inch Cr	S	2000-2002	7.2	7	147	150	0.6 (0.2,2.4)	0.6 (0.2,2.4)	0.6 (0.2,2.4)	0.6 (0.2,2.5)	3 (-5,12)	3 (-1,7)	6 (-2,16)
L Qualicum R	S	2000-2002	8.5	7.7	140	150	0.2 (0.1,0.5)	0.3 (0.1,0.7)	0.3 (0.1,0.6)	0.3 (0.1,0.7)	22 (-5,66)	10 (-2,21)	34 (2,84)
Nanaimo R	S	2000-2010	16.3	5.8	130	141	0.5 (0.2,1.4)	0.5 (0.2,1.5)	1.5 (0.4,6.5)	1.6 (0.3,7.2)	4 (-13,25)	213 (7,796)	224 (2,935)
Penny	Y	2000-2004	14.1	10.3	109	95	0.2 (0.0,0.7)	0.3 (0.1,1.2)	0.2 (0.1,1.0)	0.4 (0.1,1.6)	62 (30,102)	33 (-21,107)	116 (15,269)
Lang Cr	S	1991-1997	11.9	7.3	133	140	0.3 (0.1,1.0)	0.3 (0.1,1.1)	0.5 (0.1,1.7)	0.5 (0.1,1.8)	1 (-17,23)	59 (-23,191)	62 (-23,202)
Puntledge R	S	2000-2010	10.4	6	145	153	0.3 (0.1,0.4)	0.3 (0.2,0.5)	0.5 (0.3,0.9)	0.6 (0.3,1.0)	11 (2,22)	98 (49,167)	120 (61,204)
Quinsam R	S	2000-2017	14.2	6	146	130	0.2 (0.1,0.4)	0.3 (0.2,0.4)	0.5 (0.3,1.0)	0.6 (0.3,1.0)	9 (-5,27)	113 (37,229)	134 (63,230)
Robertson Cr	S	2000-2017	7.5	5.3	137	145	0.2 (0.1,0.3)	0.2 (0.1,0.3)	0.3 (0.2,0.5)	0.3 (0.2,0.5)	10 (1,20)	68 (40,101)	84 (54,122)
Rosewall Cr	S	2011-2017	7.5	5.5	143	149	0.3 (0.1,0.7)	0.3 (0.1,0.8)	0.4 (0.2,1.0)	0.4 (0.2,1.0)	6 (-14,28)	31 (-2,73)	39 (-2,94)
Shuswap R	S	2000-2016	9.1	6.7	130	137	0.7 (0.2,2.5)	0.7 (0.2,2.7)	0.8 (0.2,3.1)	0.9 (0.2,3.4)	8 (-7,28)	27 (-5,62)	37 (1,81)
Snootli Cr	S	2008-2016	5.3	5	156	162	0.4 (0.1,1.1)	0.4 (0.2,1.2)	0.4 (0.1,1.2)	0.5 (0.2,1.3)	12 (-7,37)	7 (3,10)	20 (-1,46)
Spius Cr	Y	2000-2015	18.3	15.5	124	111	1.0 (0.3,5.4)	1.2 (0.3,6.0)	1.1 (0.3,5.7)	1.2 (0.3,6.5)	16 (-8,48)	4 (-17,31)	21 (-13,69)
Deep Cr	F	2000-2015	3.4	2.6	157	150	0.1 (0.0,0.5)	0.1 (0.0,0.5)	0.2 (0.0,0.6)	0.2 (0.0,0.6)	2 (-8,14)	27 (17,38)	29 (12,51)
Toboggan Cr	Y	2000-2015	15.6	13.2	106	125	0.5 (0.1,2.2)	0.7 (0.2,3.1)	0.6 (0.1,2.6)	0.8 (0.2,3.4)	26 (-24,158)	9 (-24,46)	38 (-20,180)

Table 6: Estimated median posterior and 95% credible intervals for % survival and estimated % increase in average Coho returns for release weight and day that maximize survival (W_S, D_S) relative to the mean release weight and day ($\bar{W}$, $\bar{D}$) of the most commonly released life stage (F = fry, Y = yearling smolt) over the last 20 ocean entry years (OEY; specific years used for determining averages shown for each hatchery). Mean release weights and days are calculated from CWT releases without experimental and seapen releases.

			Weight (g) and Julian day at release				Average survival rate (%)				% increase in returns for different release strategies		
Hatchery	Life Stage	OEYs (Historical Avg)	W_S	$\bar{W}$	D_S	$\bar{D}$	$\bar{W}, \bar{D}$	$\bar{W}, D_S$	$W_S, \bar{D}$	W_S, D_S	$\bar{W}, D_S$	$W_S, \bar{D}$	W_S, D_S
Big Qualicum R	Y	2000-2015	28.3	20.4	155	134	1.2 (0.6,2.2)	1.4 (0.7,2.5)	1.5 (0.6,3.5)	1.6 (0.7,3.8)	9 (1,19)	22 (-27,108)	34 (-20,131)
Capilano R	Y	2000-2000	24.7	18.3	156	147	1.4 }(0.8,2.3)	1.4 (0.8,2.4)	1.5 (0.8,2.6)	1.5 (0.8,2.7)	1 (-2,4)	10 (-6,29)	11 (-5,31)
Chilliwack R	Y	2000-2016	22.8	18.4	142	128	1.1 (0.4,2.3)	1.1 (0.5,2.5)	1.2 (0.4,3.2)	1.3 (0.5,3.4)	8 (-3,21)	13 (-26,84)	22 (-21,102)
Eagle R	F	1983-1993	11.1	3.9	183	181	0.5 (0.2,1.2)	0.5 (0.2,1.2)	0.8 (0.3,2.0)	0.8 (0.3,2.0)	0 (-1,1)	61 (-5,167)	61 (-5,166)
Goldstream R	Y	2000-2011	21.9	19.3	142	129	1.2 (0.5,2.6)	1.3 (0.5,2.9)	1.4 (0.5,3.4)	1.5 (0.6,3.6)	7 (-3,17)	14 (-15,68)	22 (-10,81)
McLaughlin Cr	Y	1990-1994	18.8	17.8	141	116	1.2 (0.5,3.3)	1.5 (0.6,3.8)	1.2 (0.5,3.3)	1.5 (0.6,3.8)	18 (-3,45)	1 (-7,9)	19 (-1,44)
Inch Cr	Y	2000-2016	32.8	20.4	156	133	2.0 (1.0,4.9)	2.2 (1.1,5.4)	3.0 (1.2,7.9)	3.3 (1.4,8.6)	9 (1,17)	48 (-15,153)	61 (-6,174)
Lang Cr	Y	2007-2007	16.7	24	142	115	0.8 (0.3,2.3)	0.9 (0.3,2.4)	1.3 (0.6,2.9)	1.4 (0.7,3.0)	14 (-25,47)	50 (-26,299)	69 (-25,359)
Puntledge R	Y	2000-2002	18	20.7	152	145	1.2 (0.6,2.0)	1.2 (0.7,2.0)	1.2 (0.7,2.0)	1.2 (0.7,2.1)	2 (-1,4)	4 (-7,17)	6 (-6,20)
Quinsam R	Y	2000-2016	NA	24.9	160	132	1.1 (0.6,1.9)	1.2 (0.7,2.1)	NA	NA	9 (-1,20)	NA	NA
Robertson Cr	Y	2000-2016	18.2	19.6	143	130	0.7 (0.4,1.2)	0.8 (0.4,1.3)	0.7 (0.4,1.2)	0.8 (0.4,1.3)	8 (4,13)	1 (-7,10)	10 (-1,21)
Rosewall Cr	F	2011-2016	2.4	2.1	162	150	0.3 (0.1,1.2)	0.3 (0.1,1.3)	0.3 (0.1,1.2)	0.3 (0.1,1.3)	1 (-6,8)	4 (-2,10)	5 (-4,14)
Spius Cr	Y	2000-2016	19.8	15.2	144	136	1.2 (0.5,2.8)	1.2 (0.5,2.9)	1.5 (0.6,3.6)	1.5 (0.7,3.7)	3 (-1,8)	25 (-12,79)	29 (-8,85)
Tenderfoot Cr	Y	1982-1999	25.4	20.8	160	139	1.5 (0.7,3.2)	1.5 (0.7,3.3)	1.5 (0.6,4.1)	1.6 (0.6,4.3)	5 (-3,12)	4 (-35,71)	9 (-32,78)
Dunn Cr	Y	2006-2007	21.9	14.1	170	142	0.9 (0.4,2.3)	1.0 (0.4,2.5)	2.3 (0.9,5.8)	2.4 (0.9,6.3)	8 (-2,18)	141 (34,350)	160 (42,391)
Toboggan Cr	Y	2000-2016	16.9	14.1	NA	136	1.2 (0.5,3.1)	NA	1.4 (0.6,3.4)	NA	NA	12 (-14,47)	NA

Table 7: Summary of the stocks and ocean entry years (OEY) of each experiment and the relationships found between experimental life stage released (bolded) and survival rates, exploitation rates, and return ages. The best release strategies for predicting survival in the top mixed linear effects models for each hatchery are provided in the 'Survival' column. Green cells represent significantly higher outcomes for the experimental release group, red cells represent significantly lower outcomes, and grey cells represent no difference between release groups. Rows in orange had insufficient data for conducting statistical analyses. Source: James 2021b.

Stock	OEY	Experiment	Survival	Exploitation	Age
Atnarko R Low/Up	2009-2013	subyearling vs **yearling**	life stage	▨	🟩
Cheakamus R	2016-2019	fed fry vs yearlings	insufficient data		
Phillips R	2011, 2012, 2014	subyearling vs **yearling**	insufficient data	▨	▨
Puntledge R	2002, 2003, 2005	**fed fry** (released at multiple locations) vs hatchery subyearlings	weight	▨	▨
Quinsam R	2001-2007, 2015-2018	release of **fed fry** to Quinsam Lk vs hatchery subyearlings	weight, life stage	▨	▨
Robertson Cr	2004-2007, 2017-2018	subyearling vs **yearling**	weight	▨	▨
Shuswap R Mid	2015-2018	subyearling vs **yearling**	insufficient data		

Table 8: Summary of relationships found between seapen releases and survival rates, exploitation rates, and return ages relative to a corresponding hatchery release. Where survival models were possible, the best release strategies from the top model are provided in the 'Survival' column. Green cells represent significantly higher outcomes for the seapen release group, red cells represent significantly lower outcomes, and grey cells represent no difference between release groups. Source: James 2021b.

Species	Stock	OEY	Experiment	Survival	Exploitation	Age
CN	Chilliwack R	2014-2017	Sandy Cove seapen	insufficient data		
CN	Cowichan R	1992-2004, 2006-2009	Cowichan estuary seapen	weight, year, release site	▨	🟩
CN	Puntledge	2000, 2002-2003, 2006-2009	Comox Bay seapen	none	▨	▨
CN	Quinsam R	2000-2018	Seapens throughout Discovery Passage	weight, day	🟩	🟥
CN	Robertson Cr	2002-2004, 2014-2018	Harbour Quay seapen (02-04), Alberni Inlet Seapen (14-18)	release type	🟩	▨
CN	Wannock R	2010-2011, 2014-2015, 2018-2019	Wannock Estuary seapen	insufficient data	NA	▨

Photos by: Eiko Jones

Table 9: Overall mean (standard deviation) survival rates, exploitation rates, and return ages for facilities releasing Chinook salmon from both the hatchery and seapens over a set number of years. Source: James 2021b.

Stock	Survival (%)		Exploitation (%)		Age (yrs)		Years
	Hatchery	Seapen	Hatchery	Seapen	Hatchery	Seapen	
Chilliwack R (Capilano)	0.62 (0.37)	1.14 (0.48)	77.65 (4.30)	78.41 (3.67)	2.97 (0.10)	2.95 (0.05)	2
Cowichan R	0.24 (0.12)	0.30 (0.16)	56.81 (14.85)	68.34 (15.83)	2.97 (0.24)	3.13 (0.23)	9
Puntledge R (Summer)	0.24 (0.11)	0.37 (0.21)	24.42 (10.46)	33.41 (11.61)	3.12 (0.18)	3.20 (0.27)	8
Quinsam R	0.26 (0.14)	0.26 (0.16)	39.60 (15.87)	55.6 (18.24)	3.92 (0.35)	3.75 (0.31)	19
Robertson Cr	1.43 (0.68)	2.01 (0.84)	64.68 (6.21)	73.79 (5.11)	3.72 (0.19)	3.72 (0.18)	5
Wannock R	0.18 (0.06)	0.19 (0.11)	NA	NA	4.07 (0.19)	4.10 (0.20)	4

Table 10: Comparison of different Chinook multi-hatchery survival models with all life stages (fry, sub-yearling smolts, yearling smolts, n=1668) using different predictor variables, including linear and quadratic terms for weight and day (W, W^2, D, D^2), life-stage (ω_s), log river migration distance (M), and biomass of hatchery releases at release sites (R). The mean posterior coefficient estimates and 95% credible intervals () are shown for the different models and the full model with all predictor variables is in bold.

Release Strategy Predictors	Intercept	Release Strategy Effects						ΔLOOIC
		Weight	Weight²	Day	Day²	Releases	Migration	
$W, W^2, D, D^2, R, M, \omega_s$	-4.01 (-4.71,-3.32)	0.52 (0.31,0.72)	-0.07 (-0.12,-0.02)	-0.16 (-0.38,0.03)	-0.14 (-0.17,-0.1)	-0.32 (-0.8,0.19)	0.33 (-0.05,0.72)	0.0
W, W^2, D, D^2, R, M	-3.77 (-4.42,-3.13)	0.46 (0.27,0.63)	-0.08 (-0.12,-0.03)	-0.11 (-0.32,0.08)	-0.14 (-0.18,-0.1)	-0.28 (-0.79,0.24)	0.3 (-0.08,0.68)	0.3
W, W^2, D, D^2, M	-3.58 (-4.2,-2.97)	0.42 (0.24,0.57)	-0.06 (-0.1,-0.01)	-0.08 (-0.25,0.09)	-0.14 (-0.17,-0.1)		0.14 (-0.15,0.43)	40.7
W, W^2, D, D^2, R	3.55 (-4.15,-2.95)	0.44 (0.26,0.6)	-0.06 (-0.11,-0.02)	-0.07 (-0.25,0.09)	-0.15 (-0.18,-0.11)	-0.13 (-0.33,0.06)		70.2
W, W^2, D, D^2	-3.47 (-4.06,-2.88)	0.42 (0.24,0.58)	-0.05 (-0.1,-0.01)	-0.08 (-0.25,0.08)	-0.14 (-0.18,-0.11)			76.8

Table 11: Comparison of different Coho multi-hatchery survival models with all life stages (fry, yearling smolts, n=1007) using different predictor variables, including linear and quadratic terms for weight and day (W,W2,D,D2), life-stage (ω_s), log river migration distance (M), and biomass of hatchery releases at release sites (R). The mean posterior coefficient estimates and 95% credible intervals () are shown for the different models and the full model with all predictor variables is in bold.

Release Strategy Predictors	Intercept	Release Strategy Effects						ΔLOOIC
		Weight	Weight^2	Day	Day^2	Releases	Migration	
W, W^2, D, D^2, R	-4.01 (-4.71,-3.32)	0.52 (0.31,0.72)	-0.07 (-0.12,-0.02)	-0.16 (-0.38,0.03)	-0.14 (-0.17,-0.1)	-0.32 (-0.8,0.19)	0.33 (-0.05,0.72)	0.0
$W, W^2, D, D^2, R, M, \omega_s$	-3.77 (-4.42,-3.13)	0.46 (0.27,0.63)	-0.08 (-0.12,-0.03)	-0.11 (-0.32,0.08)	-0.14 (-0.18,-0.1)	-0.28 (-0.79,0.24)	0.3 (-0.08,0.68)	2.1
W, W^2, D, D^2, R, M	-3.58 (-4.2,-2.97)	0.42 (0.24,0.57)	-0.06 (-0.1,-0.01)	-0.08 (-0.25,0.09)	-0.14 (-0.17,-0.1)		0.14 (-0.15,0.43)	3.8
W, W^2, D, D^2, M	3.55 (-4.15,-2.95)	0.44 (0.26,0.6)	-0.06 (-0.11,-0.02)	-0.07 (-0.25,0.09)	-0.15 (-0.18,-0.11)	-0.13 (-0.33,0.06)		27.8
W, W^2, D, D^2	-3.47 (-4.06,-2.88)	0.42 (0.24,0.58)	-0.05 (-0.1,-0.01)	-0.08 (-0.25,0.08)	-0.14 (-0.18,-0.11)			28.1

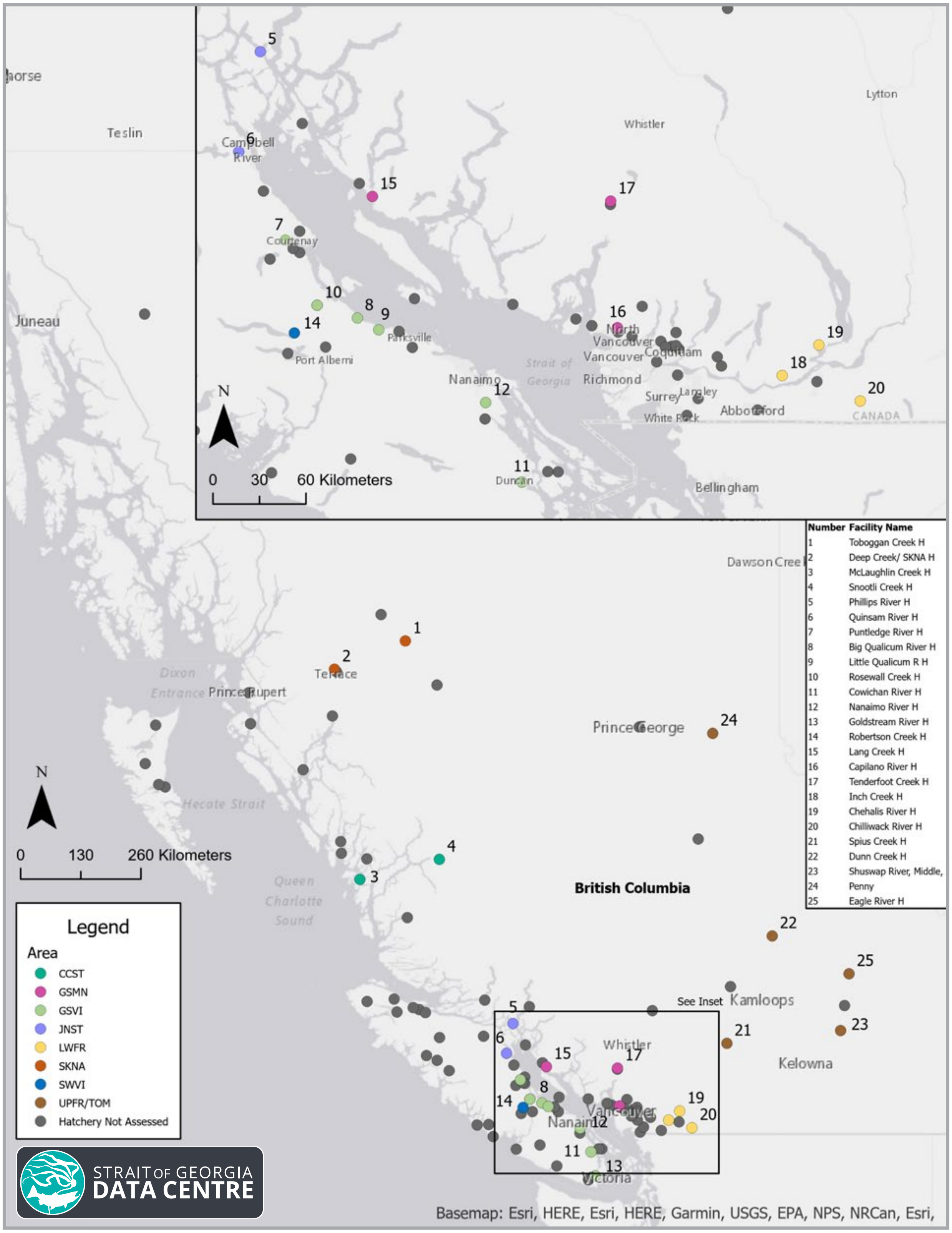
Table 12: Comparison of the full Chinook multi-hatchery survival model with all life stages (fry, sub-yearling smolts, yearling smolts, n=1597) with and without environmental covariates and year effects. The mean posterior coefficient estimates and 95% credible intervals () are shown for weight, day, and environmental covariates. The last row shows a model (M_0) with only weight (W, W^2), day (D, D^2), life-stage (ω_s), release biomass (R), and river migration (M) predictors, without any year or environmental effects. Other rows show models with the inclusion of one of the environmental covariates (H= Harbour Seals, K = Killer Whales, S = Sea Surface Temperature, P = PDO), fixed year effects ($\O_t$), and random year effects (Δ_t). The top row shows the full model with both fixed and random year effects ($\O_t + \Delta_t$), shown in bold in Table 10. MLE values are shown for $R^2_{logit(c)}$ along with $\Delta R^2_{logit(c)}$, which indicates the additional proportion of variance explained by adding the environmental or year effects relative to M_0.

Model	Coefficients for release strategy effects				Coefficients for environmental covariates				ΔLOOIC	$R^2_{logit(c)}$	$\Delta R^2_{logit(c)}$
	Weight	Weight²	Day	Day²	Seals	Killer Whales	PDO	SST			
$M_0 + \O_t + \Delta_t$	0.52 (0.31,0.72)	-0.07 (-0.12,-0.02)	-0.16 (-0.38,0.03)	-0.14 (-0.17,-0.1)					0.0	0.337	0.141
$M_0 + (\Theta_7 + \Theta_{7h})\,H_h$	0.54 (0.34,0.73)	-0.07 (-0.12,-0.02)	-0.15 (-0.35,0.04)	-0.14 (-0.18,-0.1)	-0.68 (-1,-0.37)				278.0	0.386	0.191
$M_0 + y_2\,P$	0.46 (0.25,0.65)	-0.06 (-0.11,-0.01)	-0.1 (-0.31,0.1)	-0.13 (-0.17,-0.09)			-0.27 (-0.32,-0.21)		308.9	0.339	0.144
$M_0 + (\Theta_8 + \Theta_{8h})\,K_h$	0.45 (0.25,0.64)	-0.04 (-0.09,0.02)	-0.1 (-0.29,0.07)	-0.12 (-0.16,-0.08)		-0.44 (-0.69,-0.19)			337.2	0.339	0.143
$M_0 + \O_t$	0.44 (0.23,0.65)	-0.05 (-0.11,0)	-0.08 (-0.29,0.13)	-0.13 (-0.17,-0.09)					405.6	0.341	0.146
$M_0 + y_1\,S$	0.32 (0.1,0.54)	-0.04 (-0.1,0.01)	0.3 (0.07,0.5)	-0.11 (-0.15,-0.07)				-0.35 (-0.45,-0.25)	555.4	0.260	0.065
M_0	0.27 (0.04,0.49)	-0.03 (-0.09,0.02)	0.07 (-0.15,0.26)	-0.09 (-0.14,-0.05)					609.7	0.195	0.000

Table 13: Comparison of the full Coho multi-hatchery survival model with all life stages (fry, yearling smolts, n=1007) with and without environmental covariates and year effects. The mean posterior coefficient estimates and 95% credible intervals () are shown for weight, day, and environmental covariates. The last row shows a model (M_0) with only weight (W, W^2), day (D, D^2), life-stage (ω_s), release biomass (R), and river migration (M) predictors, without any year or environmental effects. Other rows show models with the inclusion of one of the environmental covariates (H= Harbour Seals, K = Killer Whales, S = Sea Surface Temperature, P = PDO), fixed year effects ($\O_t$), and random year effects (Δ_t). The top row shows the full model with both fixed and random year effects ($\O_t + \Delta_t$), shown in bold in Table 11. MLE values are shown for $R^2_{logit(c)}$ along with $\Delta R^2_{logit(c)}$, which indicates the additional proportion of variance explained by adding the environmental or year effects relative to M_0.

Model	Coefficients for release strategy effects				Coefficients for environmental covariates				ΔLOOIC	$R^2_{logit(c)}$	$\Delta R^2_{logit(c)}$
	Weight	Weight²	Day	Day²	Seals	Killer Whales	PDO	SST			
$M_0 + \O_t + \Delta_t$	0.19 (-0.1,0.49)	-0.16 (-0.35,0.02)	0.09 (-0.03,0.2)	-0.11 (-0.23,0)					2.1	0.311	0.046
$M_0 + (\Theta_7 + \Theta_{7h}) H_h$	0.3 (-0.02,0.64)	-0.1 (-0.28,0.07)	0.09 (-0.03,0.19)	-0.09 (-0.19,0)	-1.22 (-1.85,-0.66)				42.9	0.441	0.176
$M_0 + (\Theta_8 + \Theta_{8h}) K_h$	0.26 (-0.07,0.6)	-0.02 (-0.21,0.15)	0.07 (-0.04,0.18)	-0.06 (-0.14,0.01)		-0.89 (-1.34,-0.47)			143.9	0.372	0.107
$M_0 + y_1 S$	0.26 (-0.14,0.67)	-0.06 (-0.27,0.14)	0.36 (0.2,0.51)	-0.14 (-0.23,-0.07)				-0.22 (-0.31,-0.14)	198.7	0.295	0.030
$M_0 + y_2 P$	0.26 (-0.12,0.64)	-0.07 (-0.27,0.12)	0.09 (-0.03,0.21)	0.09 (-0.19,-0.01)			0.05 (-0.11,0)		223.6	0.288	0.022
$M_0 + \O_t$	0.27 (-0.1,0.65)	-0.07 (-0.27,0.12)	0.08 (-0.03,0.2)	-0.09 (-0.2,0)					224.1	0.287	0.022
M_0	0.32 (-0.19,0.85)	0 (-0.23,0.22)	0.17 (0.03,0.32)	-0.23 (-0.73,0.11)					578.9	0.265	0.000

FIGURES



Number	Facility Name
1	Toboggan Creek H
2	Deep Creek/ SKNA H
3	McLaughlin Creek H
4	Snootli Creek H
5	Phillips River H
6	Quinsam River H
7	Puntledge River H
8	Big Qualicum River H
9	Little Qualicum R H
10	Rosewall Creek H
11	Cowichan River H
12	Nanaimo River H
13	Goldstream River H
14	Robertson Creek H
15	Lang Creek H
16	Capilano River H
17	Tenderfoot Creek H
18	Inch Creek H
19	Chehalis River H
20	Chilliwack River H
21	Spius Creek H
22	Dunn Creek H
23	Shuswap River, Middle,
24	Penny
25	Eagle River H

Figure 1. Map of salmon enhancement facilities included in the hierarchical modelling of release strategies by production area. Production areas include: SKNA = Skeena, CC = Central Coast, JNST = Johnstone Strait, SWVI = Southwest Vancouver Island, GSMN = Georgia Strait mainland side, GSVI = Georgia Strait Vancouver Island side, LWFR = lower Fraser River, UPFR/TOMM = upper Fraser River and Thompson River.

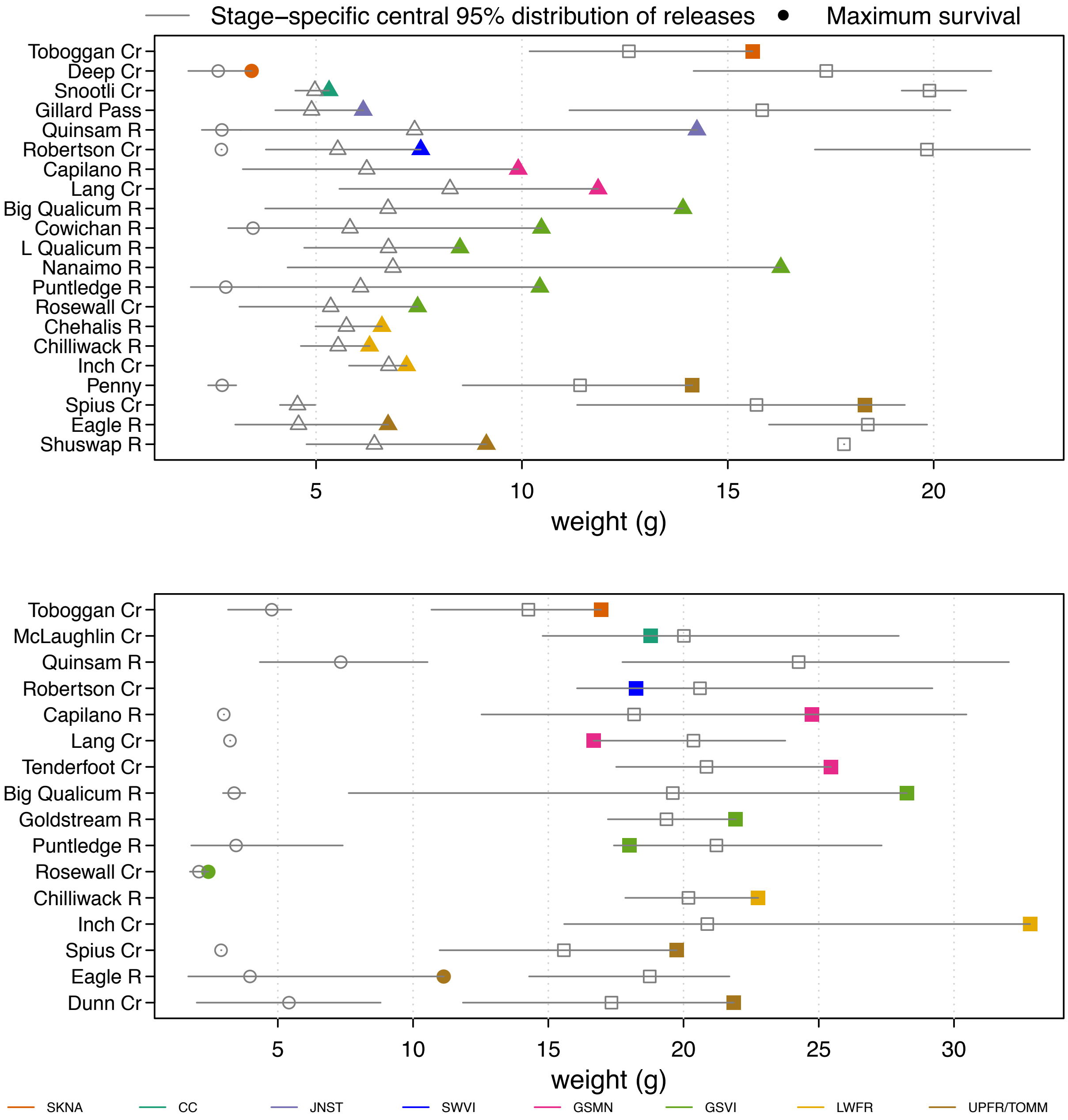


Figure 2. Weights of release for maximum Chinook (top) and Coho (bottom) survival for multi-hatchery model posterior means. For each hatchery, the horizontal lines indicate the central 95% distribution of release weights for each life stage (some of which overlap) with means for fry (○), subyearling (△) and yearling smolts (□). The coloured symbol indicates the release weight within the central 95% distribution of observations (grey line) that is expected to maximize survival for a given hatchery. Colours represent the different production areas (SKNA = Skeena, CC = Central Coast, JNST = Johnstone Strait, SWVI = Southwest Vancouver Island, GSMN = Georgia Strait mainland side, GSVI = Georgia Strait Vancouver Island side, LWFR = lower Fraser River, UPFR/TOMM = upper Fraser River and Thompson River). Source: Part III report, Doherty and Cox 2021.

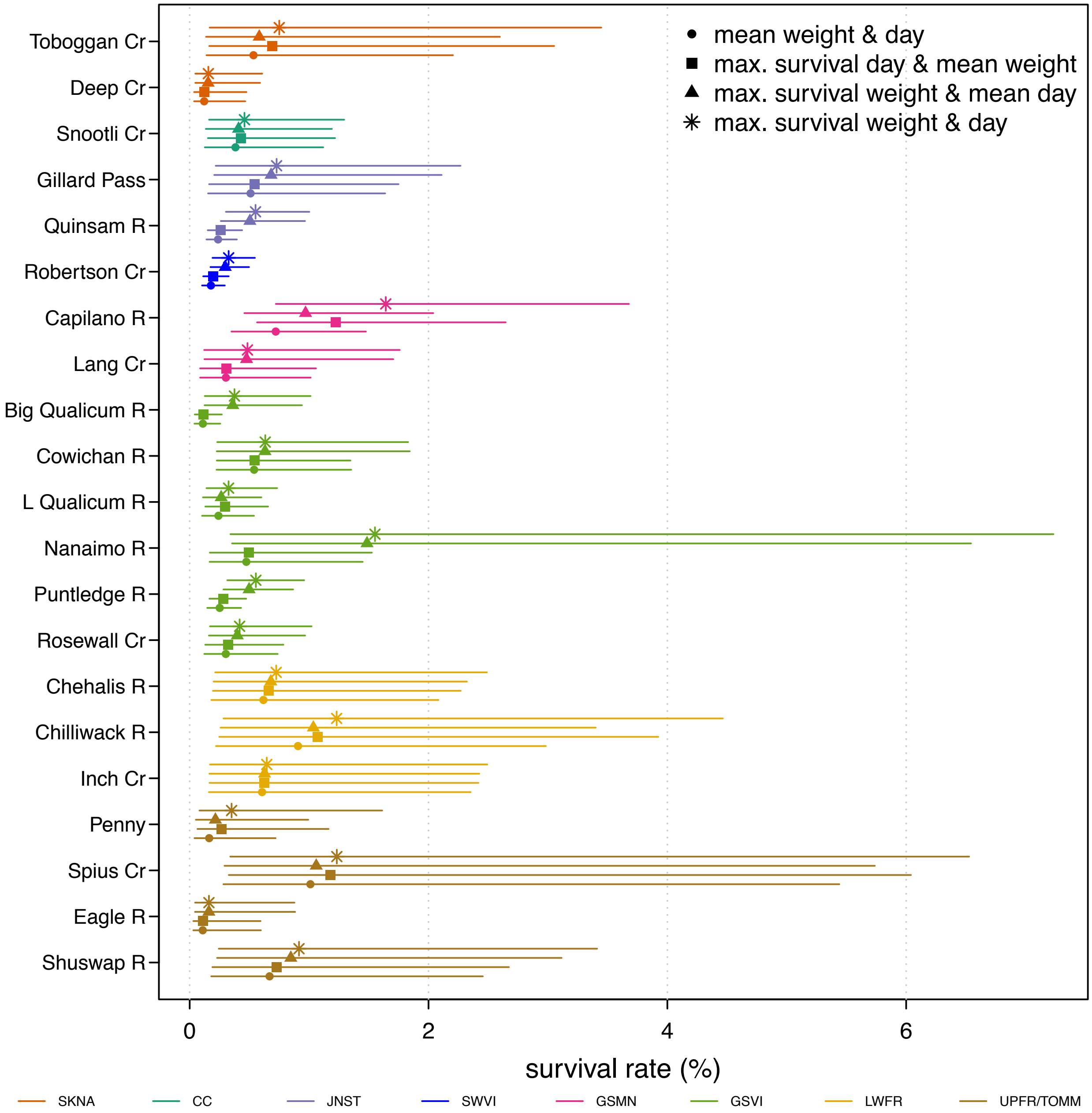


Figure 3. Predicted Chinook smolt-to-adult survival rates for 2000-2015 ocean entry years for different release weights and days relative to the mean release weight and day. For each hatchery, the survival rates are estimated for release weights and/or days within the historical observations that are expected to maximize survival for the life stage most commonly released. Points indicate median posterior estimates, while error bars show 95% credible intervals. Values shown are for fry (Deep Cr), yearling smolts (Penny Creek, Spius Cr, Toboggan Cr) and subyearling smolts (all others). Colours represent the different production areas (SKNA = Skeena, CC = Central Coast, JNST = Johnstone Strait, SWVI = Southwest Vancouver Island, GSMN = Georgia Strait mainland side, GSVI = Georgia Strait Vancouver Island side, LWFR = lower Fraser River, UPFR/TOMM = upper Fraser River and Thompson River). Source: Part III report, Doherty and Cox 2021.

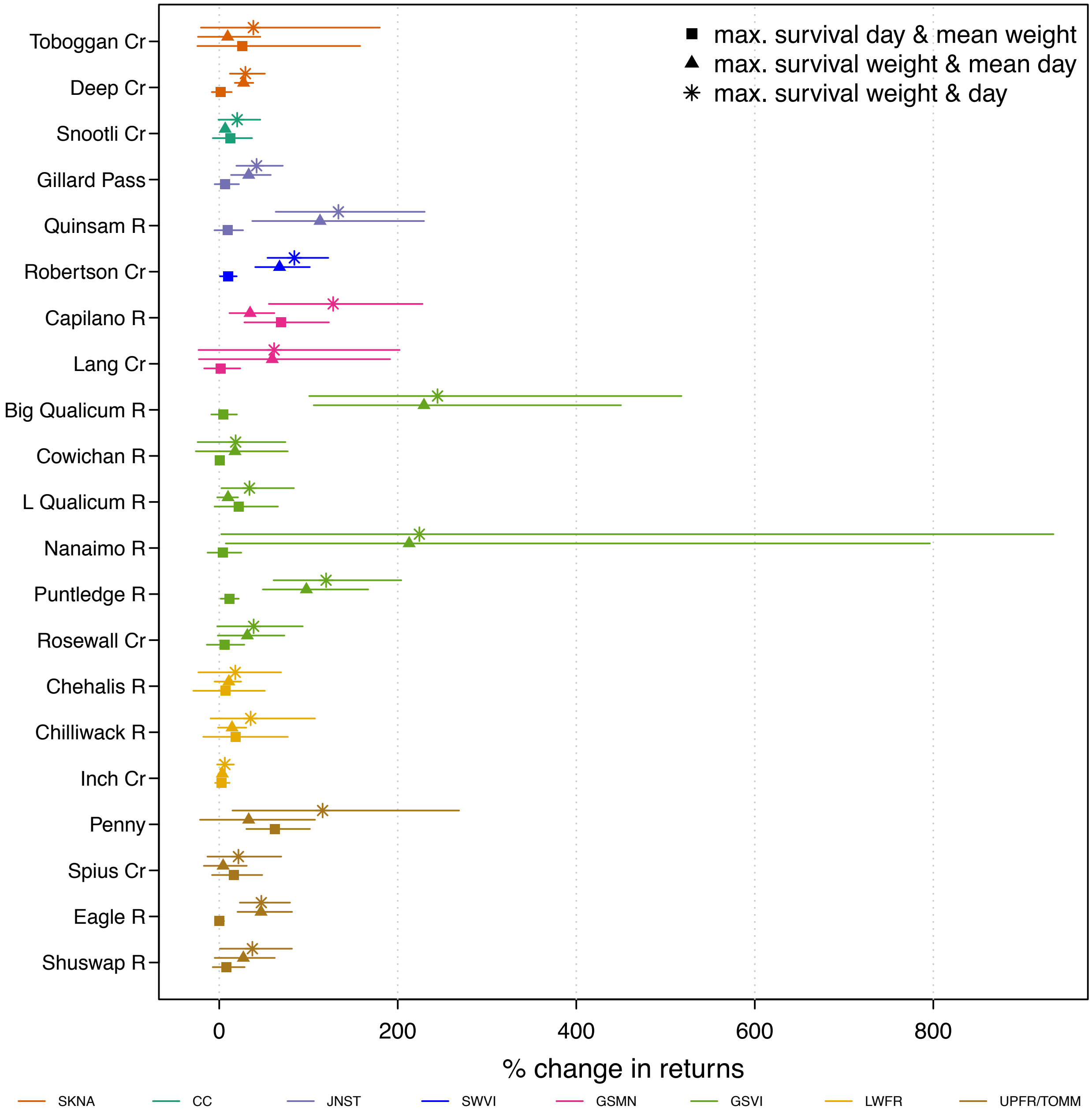


Figure 4. Estimated increase in average Chinook returns (%) for 2000-2015 ocean entry years for different release weights and days relative to the mean release weight and day. For each hatchery, the % change in returns is shown for release weights and/or days within the historical observations that are expected to maximize survival for the life stage most commonly released. Points indicate median posterior estimates, while error bars show 95% credible intervals. Values shown are for fry (Deep Cr), yearling smolts (Penny Creek, Spius Cr, Toboggan Cr) and sub-yearling smolts (all others). Colours represent the different production areas (SKNA = Skeena, CC = Central Coast, JNST = Johnstone Strait, SWVI = Southwest Vancouver Island, GSMN = Georgia Strait mainland side, GSVI = Georgia Strait Vancouver Island side, LWFR = lower Fraser River, UPFR/TOMM = upper Fraser River and Thompson River). Source: Part III report, Doherty and Cox 2021.

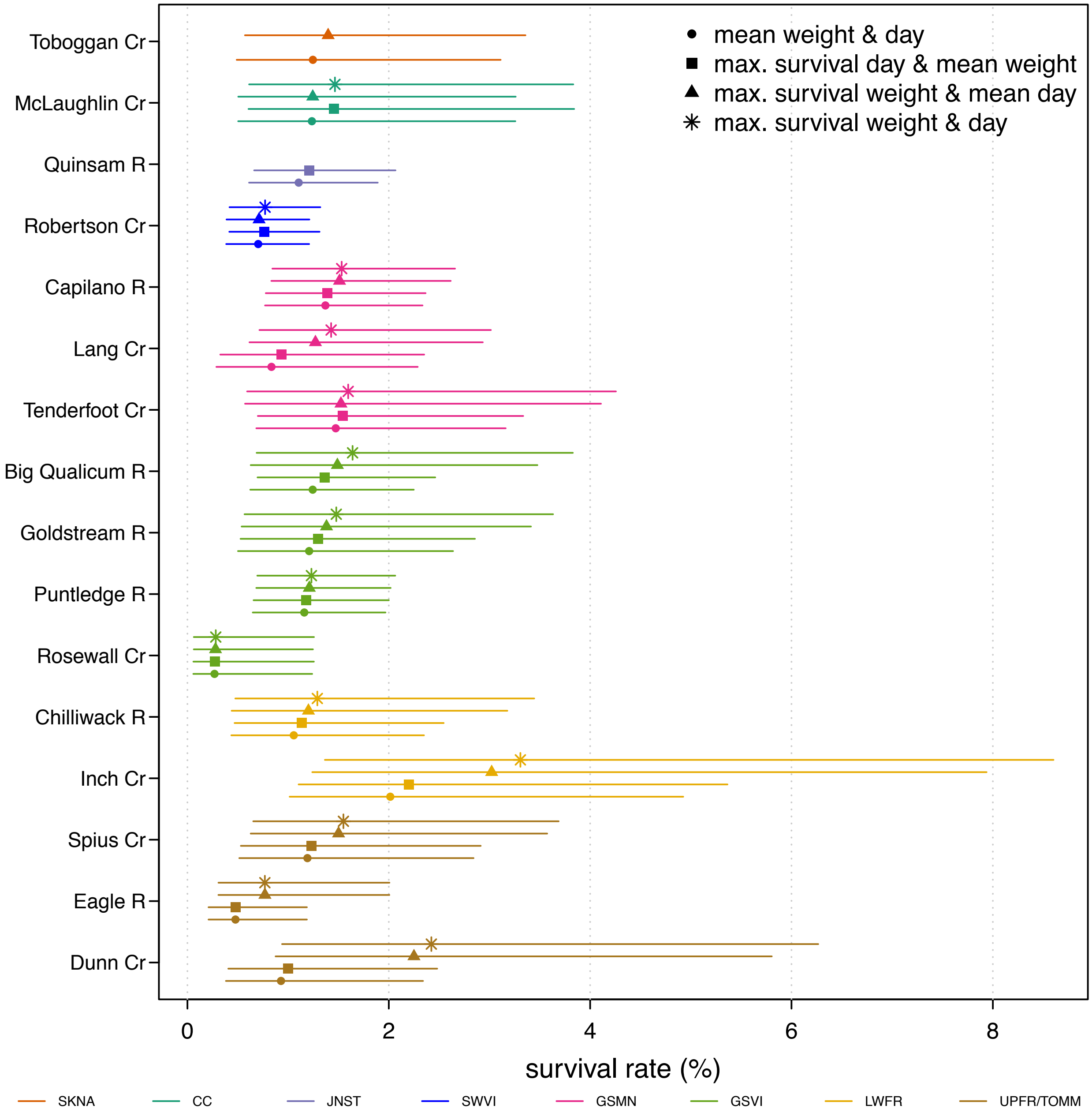


Figure 5. Predicted Coho smolt-to-adult survival rates for 2000-2017 ocean entry years for different release weights and days relative to the mean release weight and day. For each hatchery, the survival rates are estimated for release weights and/or days within the historical observations that are expected to maximize survival for the life stage most commonly released. Points indicate median posterior estimates, while error bars show 95% credible intervals. Values shown are for fry releases at Eagle River and Rosewall Creek, and yearling smolts for all other hatcheries. Colours represent the different production areas (SKNA = Skeena, CC = Central Coast, JNST = Johnstone Strait, SWVI = Southwest Vancouver Island, GSMN = Georgia Strait mainland side, GSVI = Georgia Strait Vancouver Island side, LWFR = lower Fraser River, UPFR/TOMM = upper Fraser River and Thompson River). Source: Part III report, Doherty and Cox 2021.

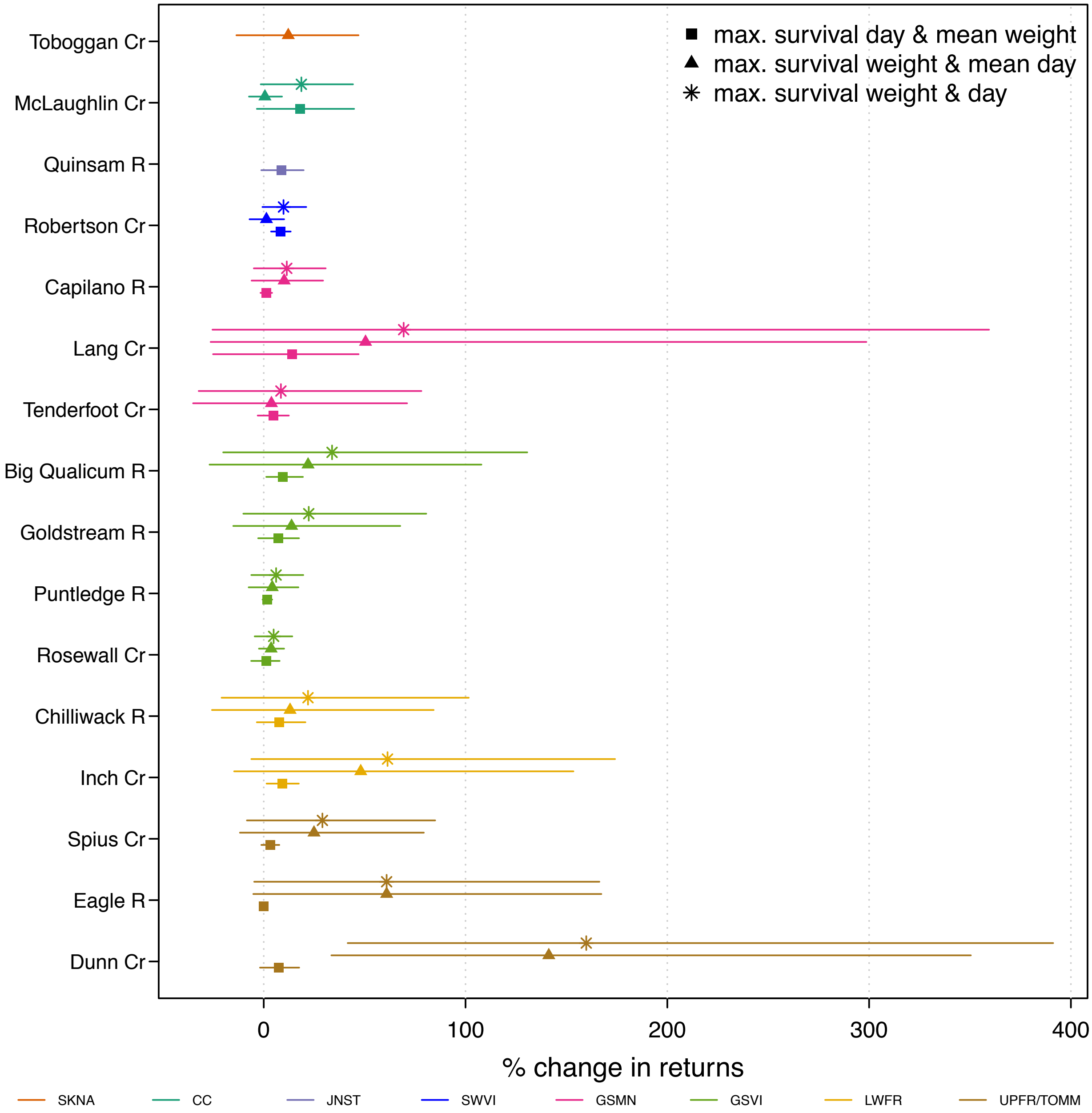


Figure 6. Estimated increase in average Coho returns (%) for 2000-2017 ocean entry years for different release weights and days relative to the mean release weight and day. For each hatchery, the % change in returns is shown for release weights and/or days within the historical observations that are expected to maximize survival for the life stage most commonly released. Points indicate median posterior estimates, while error bars show 95% credible intervals. Values shown are for fry releases at Eagle River and Rosewall Creek, and yearling smolts for all other hatcheries. Colours represent the different production areas (SKNA = Skeena, CC = Central Coast, JNST = Johnstone Strait, SWVI = Southwest Vancouver Island, GSMN = Georgia Strait mainland side, GSVI = Georgia Strait Vancouver Island side, LWFR = lower Fraser River, UPFR/TOMM = upper Fraser River and Thompson River). Source: Part III report, Doherty and Cox 2021.

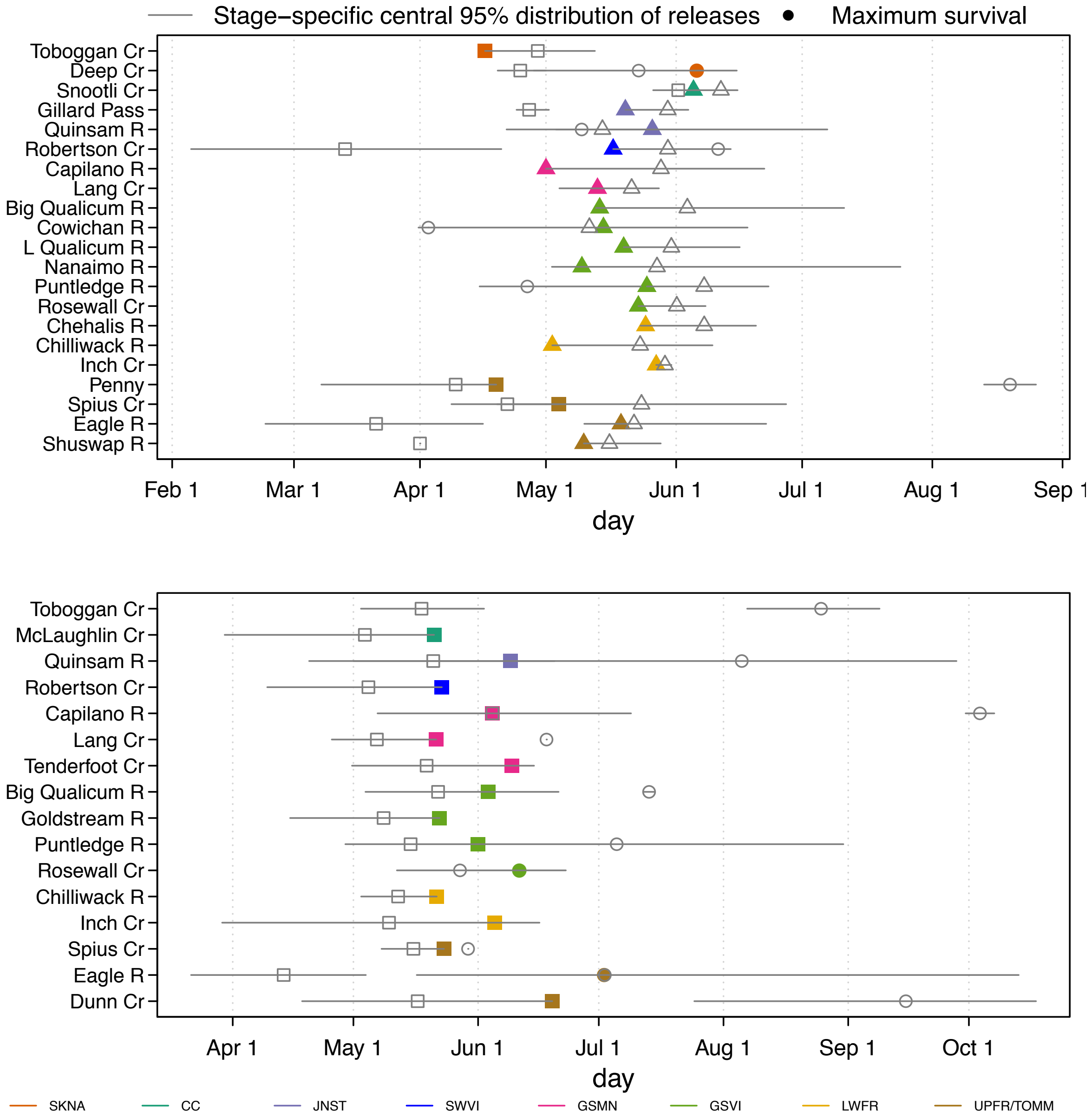
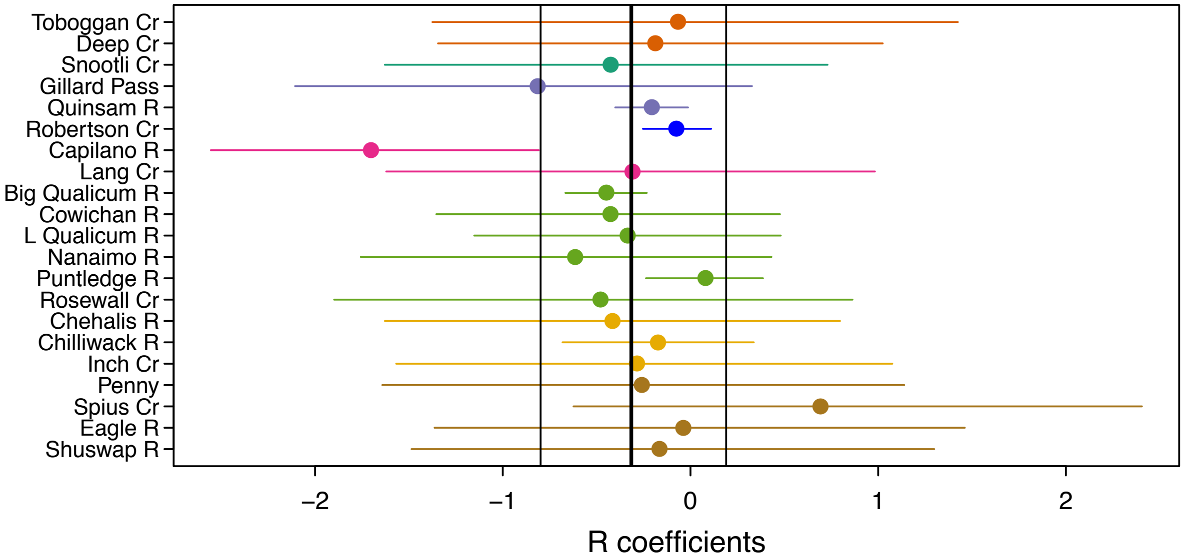


Figure 7. Dates of release for maximum Chinook (top) and Coho (bottom) survival for multi-hatchery model posterior means. For each hatchery, the horizontal lines indicate the central 95% distribution of release dates for each life stage (some of which overlap) with means for fry (○), subyearling (△) and yearling smolts (□). The coloured symbol indicates the release date within the central 95% distribution of observations (grey line) that is expected to maximize survival for a given hatchery. Colours represent the different production areas (SKNA = Skeena, CC = Central Coast, JNST = Johnstone Strait, SWVI = Southwest Vancouver Island, GSMN = Georgia Strait mainland side, GSVI = Georgia Strait Vancouver Island side, LWFR = lower Fraser River, UPFR/TOMM = upper Fraser River and Thompson River). Source: Part III report, Doherty and Cox 2021.



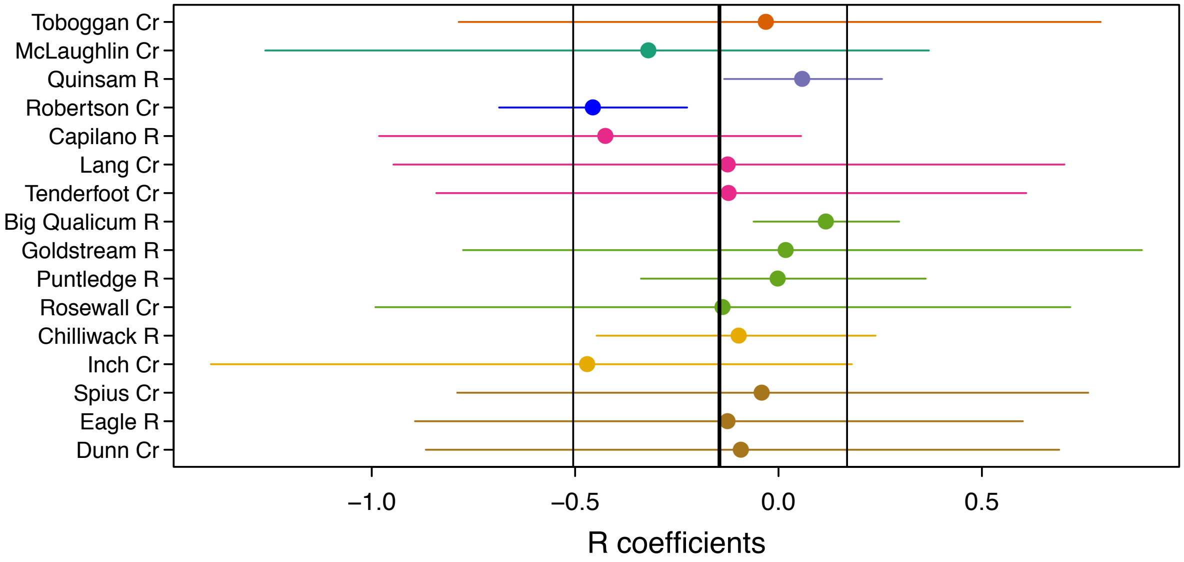


Figure 8. Multi-hatchery Chinook (top) and Coho (bottom) survival model coefficient estimates for the release biomass (*R*) predictor. The circles indicate hatchery specific mean posterior estimates along with 95% credible intervals, while the vertical lines indicate the mean posterior for the average effect across all hatcheries (thick black line) with 95% credible intervals for the posterior distribution (thin black lines). Colours represent the different production areas (SKNA = Skeena, CC = Central Coast, JNST = Johnstone Strait, SWVI = Southwest Vancouver Island, GSMN = Georgia Strait mainland side, GSVI = Georgia Strait Vancouver Island side, LWFR = lower Fraser River, UPFR/TOMM = upper Fraser River and Thompson River). Source: Part III report, Doherty and Cox 2021.

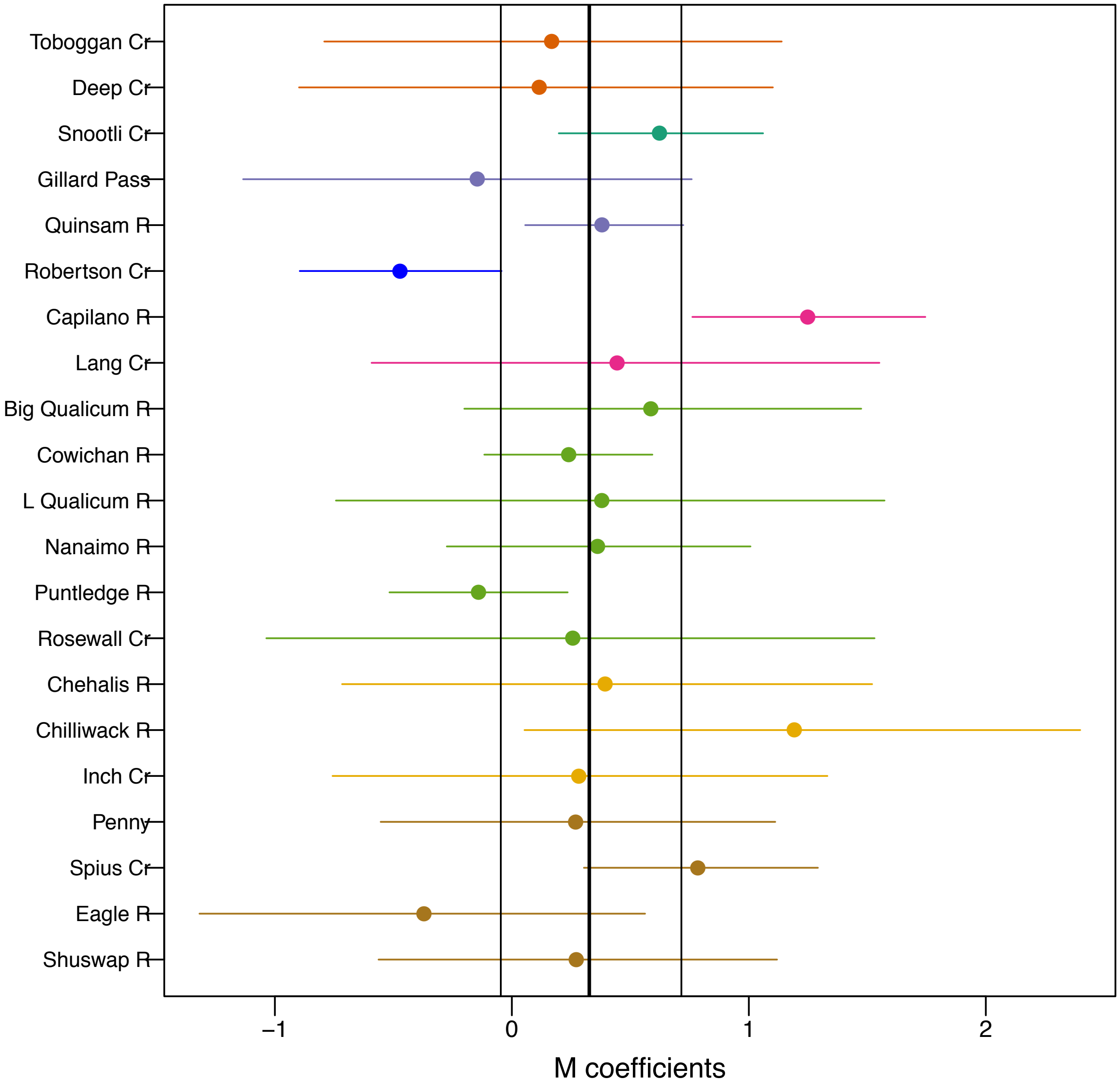


Figure 9. Multi-hatchery Chinook survival model coefficient estimates for the log river outmigration distance (*M*) predictors. The circles indicate hatchery specific mean posterior estimates along with 95% credible intervals, while the vertical lines indicate the mean posterior for the average effect across all hatcheries (thick black line) with 95% credible intervals for the posterior distribution (thin black lines). Colours represent the different production areas (SKNA = Skeena, CC = Central Coast, JNST = Johnstone Strait, SWVI = Southwest Vancouver Island, GSMN = Georgia Strait mainland side, GSVI = Georgia Strait Vancouver Island side, LWFR = lower Fraser River, UPFR/TOMM = upper Fraser River and Thompson River). Source: Part III report, Doherty and Cox 2021.

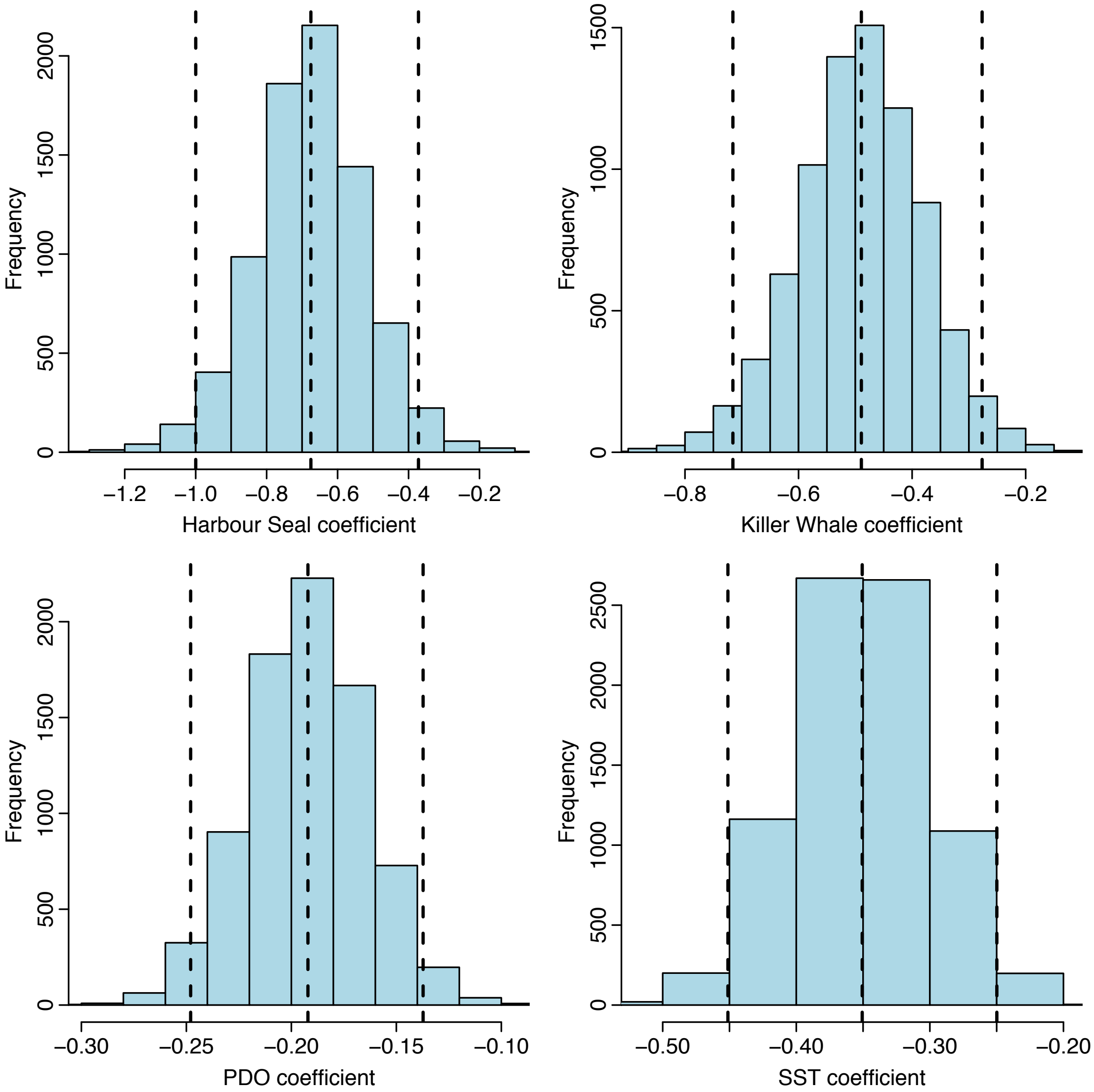


Figure 10. Posterior distribution of coefficient estimates for the four Chinook multi-hatchery survival models that were fit with environmental covariates (Harbour seals, Killer Whales, PDO, SST) instead of year effects. For each distribution the vertical dotted lines indicate the 2.5th, 50th, and 97.5th percentiles. Source: Part III report, Doherty and Cox 2021.

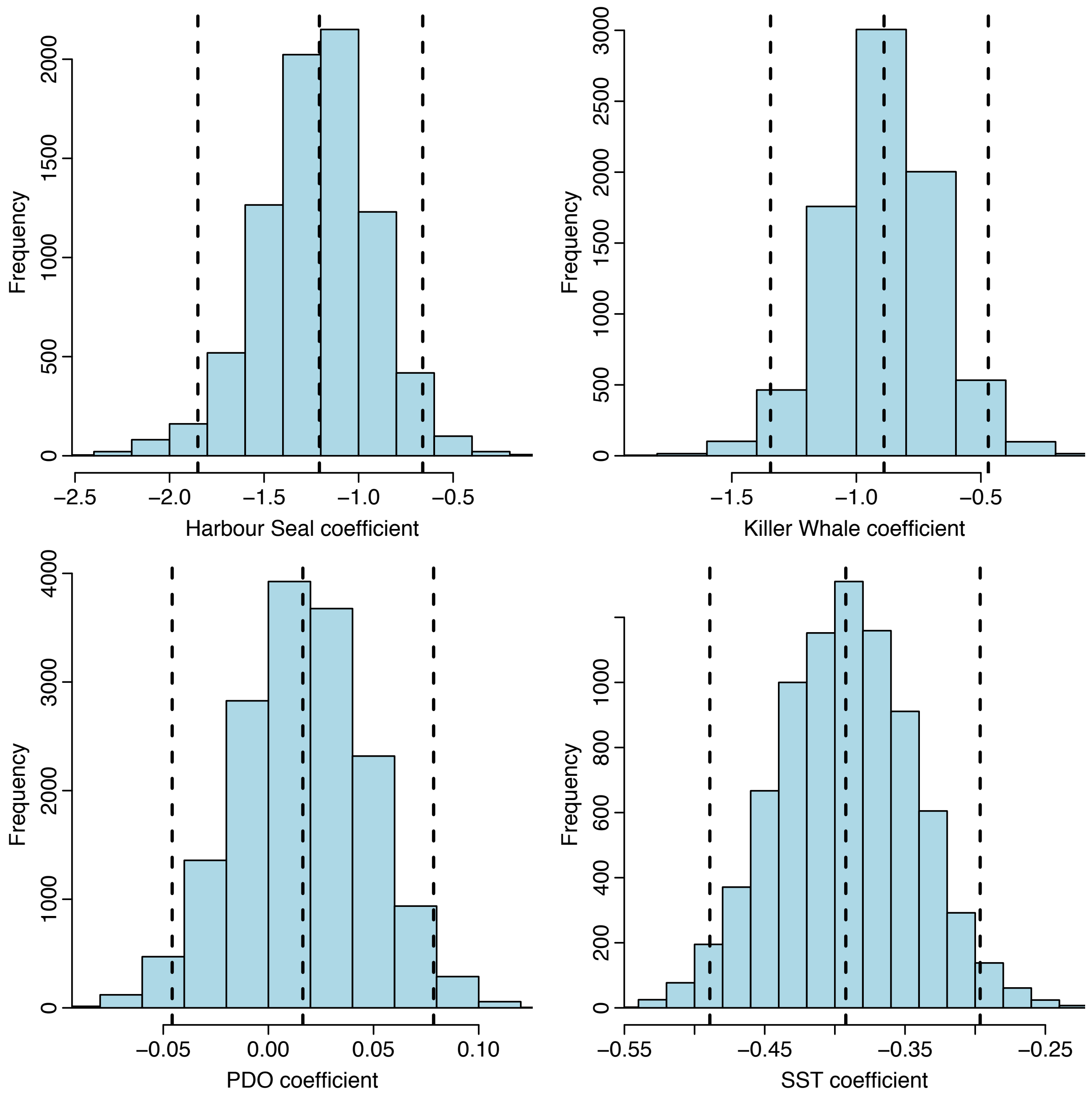


Figure 11. Posterior distribution of coefficient estimates for the four Coho multi-hatchery survival models that were fit with environmental covariates (Harbour seals, Killer Whales, PDO, SST) instead of year effects. For each distribution the vertical dotted lines indicate the 2.5th, 50th, and 97.5th percentiles. Source: Part III report, Doherty and Cox 2021.

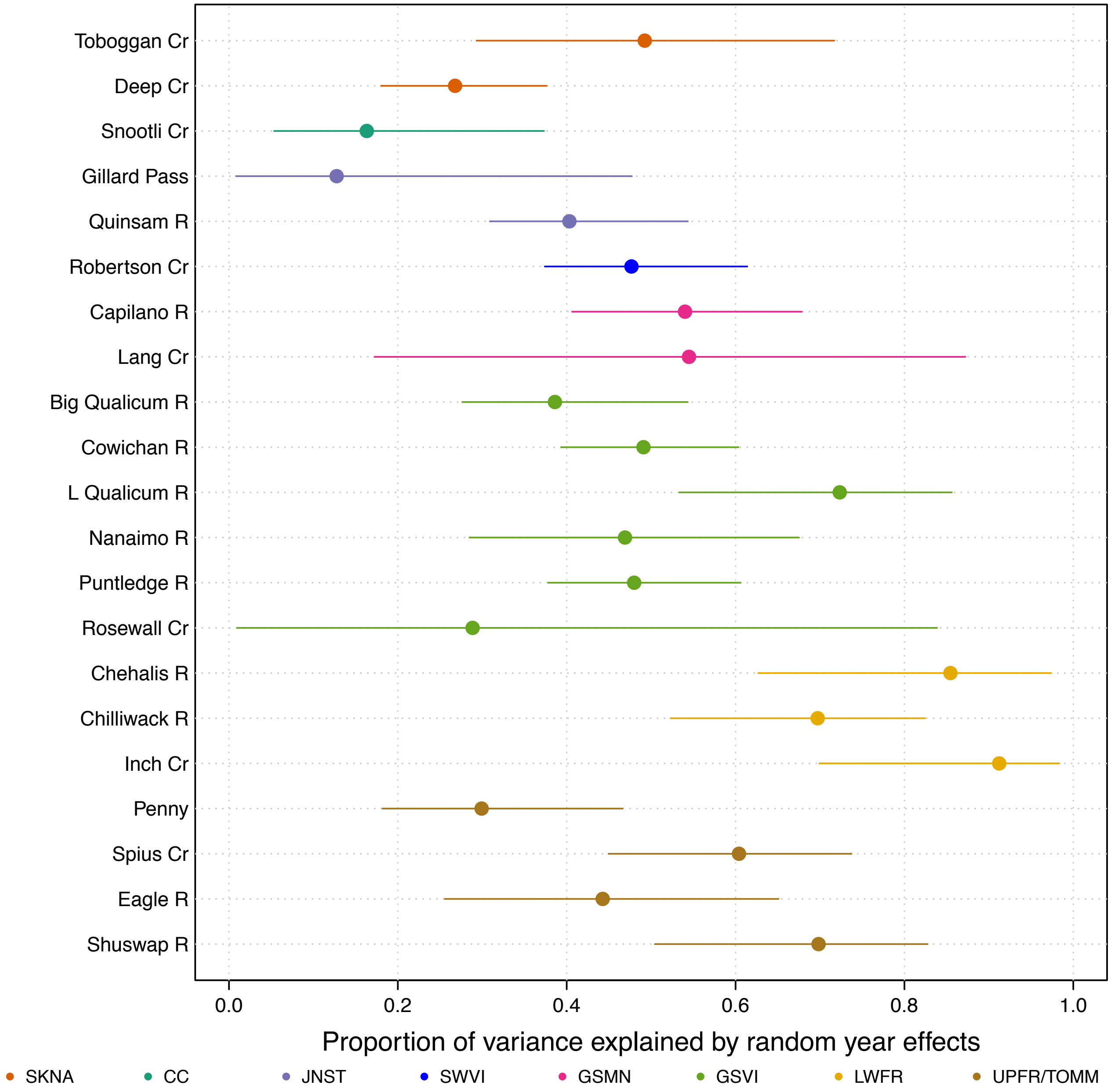


Figure 12. Proportion of variance (ρ_h) in average Chinook annual logit-survival rates that is explained by the random year effects for all ocean entry years (1972-2015). The mean posterior ρh with 95% credible intervals is shown for each hatchery. Facilities are coloured by production area: SKNA = Skeena, CC = Central Coast, JNST = Johnstone Strait, SWVI = Southwest Vancouver Island, GSMN = Georgia Strait mainland side, GSVI = Georgia Strait Vancouver Island side, LWFR = lower Fraser River, UPFR/TOMM = upper Fraser River and Thompson River.

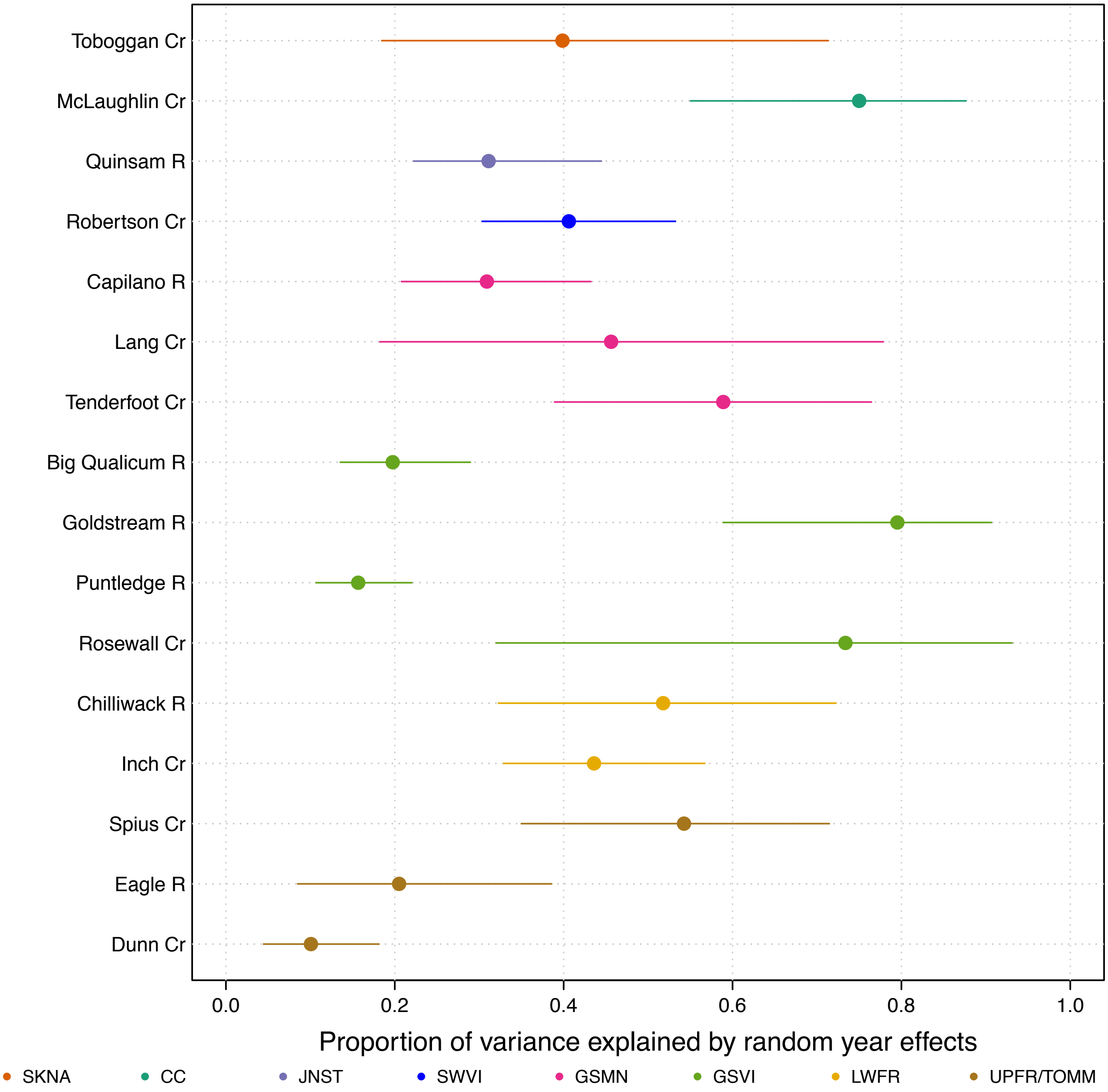


Figure 13. Proportion of variance (ρ_h) in average Coho annual logit-survival rates that is explained by the random year effects for all ocean entry years (1973-2017). The mean posterior ρh with 95% credible intervals is shown for each hatchery. Facilities are coloured by production area: SKNA = Skeena, CC = Central Coast, JNST = Johnstone Strait, SWVI = Southwest Vancouver Island, GSMN = Georgia Strait mainland side, GSVI = Georgia Strait Vancouver Island side, LWFR = lower Fraser River, UPFR/TOMM = upper Fraser River and Thompson River.


Photo by: Eiko Jones

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