PACIFIC SALMON
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TRENDS IN SIZE-AT-AGE, SEX RATIOS, AND AGE-AT-RETURN IN HATCHERY AND WILD CHINOOK SALMON ACROSS BC

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EXECUTIVE SUMMARY

Since 1977, the Salmonid Enhancement Program (SEP) "aims to rebuild vulnerable salmon stocks, provide harvest opportunities, work with Indigenous and coastal communities in economic development, and improve fish habitat to sustain salmon populations"[1]. However, hatcheries may also pose important risks to wild salmon that may undermine these objectives.

Hatcheries, along with a number of other factors, have been linked to declines in the age and size of Pacific salmon. In this study we examined trends in size-at-age, and sex and age proportions in Chinook salmon populations across British Columbia (BC). Due to limitations in data availability for both unenhanced (wild) populations and other species of salmon, this initial exploration is focused on Chinook salmon, largely from enhanced populations.

We were provided with individual fish-based biological data (biodata)[2] and enumerations by Fisheries and Oceans Canada (DFO), spanning the time periods of 1996-2018 and 1972-2018 respectively. These were used to construct indices of mean size, size-at-age, mean age, age composition, and female composition for BC Chinook salmon populations. These data represented the most complete record of biodata and enumerations for BC Chinook salmon. However, a number of data limitations had to be addressed before we could assess biological trends: these are described in this report, together with the solutions implemented to address them.

Alternative sources of hatchery specific or historical biodata were identified and data were procured from hatcheries directly and from SEP staff. These data were standardized and combined with the Stock Assessment Biodatabase into a single database of biosamples. Details of the standardizations conducted are outlined in an accompanying data report (Maharaj et al. 2022).

BIOLOGICAL TRENDS

Annual change in mean age, age composition, mean size, size-at-age and female composition were estimated within each population using linear regressions and age-specific patterns across populations and geographical regions.

The clearest trends observed were in mean size and size-at-age. Both showed declines across most populations with statistical significance. Declines varied in magnitude across populations and age classes.

Mean age showed variable, yet statistically significant declines across most stocks, and appeared to be driven by reductions in the relative proportion of the oldest (ocean-4) and increases in the youngest age classes (ocean-2). Low-enhancement stocks (stocks with mean pHOS < 10%) showed mixed trends in mean age and age composition.

The proportion of females showed variable declines across populations, of which only a small proportion were significant. There was no consistent pattern for the few wild and low-enhancement populations.

Our study shows that the size and age of BC Chinook salmon have declined since the 1970s. Declines such as these may be caused by fishing, predation, competition and hatchery enhancement, however in this review we did not explore quantitative models that incorporate these factors. Simple analyses show some evidence for the effect of hatchery enhancement on declining mean size and size-at-age, with some populations showing increases in size for the youngest age class but declines for the oldest.

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1. www.pac.dfo-mpo.gc.ca/sep-pmvs/index-eng.html
2. Colloquially, 'biodata' refers to data on biological characteristics including traits such as sex ratio, body size-at-age, ages at maturity, fecundity, etc. In Pacific salmon, biodata may refer to data collected from fishing mortalities and/or mature fish returning to reproduce, either at a hatchery or in proximal natural streams.

SOLUTIONS TO DATA LIMITATIONS

Our study identified a number of data limitations that prevent a thorough assessment of hatchery effects, and we present means to address these.

Short-term

High-quality annual biodata must be a higher priority. This requires greater support for the collection, standardization, quality control and review, and incorporation of biodata into modern and accessible database structures. It would also be beneficial to include outstanding historical data, biodata from non-EnPro hatcheries, biodata from other species, and increase capacity dedicated to improving computing systems for more seamless data sharing.

Though the Regional Mark Information System (RMIS) system and data are quite intuitive and accessible, internal datasets such as those from DFO marked recovery program (MRP) should be more readily available. A centralized data centre would be useful to locate useful pre-existing datasets, such as MRP, facilitate data access, and improve assessment capacity.

Medium-term

Wild stocks and minimally enhanced stocks were underrepresented in our study and prevented analytical comparison of trends with their enhanced counterparts. Therefore, wild indicator stocks need to be associated with each major facility and annually monitored. This information would be extremely useful in examining the causal mechanisms for declines with respect to hatchery influence.

Long-term

Many biodata records had to be discarded in our analyses due to our inability to clearly identify the stock from which they originated. Implementing tools for Genetic Stock Identification (GSI) such as Parentage Based Tagging (PBT) and Single Nucleotide Polymorphisms (SNPs) as cost-effective alternatives to broader CWT implementation (Beacham et al., 2018) that can additionally provide researchers the information needed to differentiate among family variations in stock specific responses to the marine environment, fisheries, and hatchery practices. Another cost-effective means to identify hatchery-origin fish is otolith marking, which would be invaluable to accurately identify first-generation hatchery fish in a spawning population.

In conclusion, while trends in size and age of Chinook salmon across BC are concerning, SEP stands to play an important role in furthering our understanding of these trends. Strategic planning and targeted investment of resources and expertise are required to improve data for assessment to truly understand hatchery-wild salmon interactions.

Photo by: Eiko Jones

ACKNOWLEDGEMENTS

Photo by: Eiko Jones

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INTRODUCTION

While hatcheries can provide abundant salmon, they can also have negative impacts on wild salmon. These include negative effects on the genetics of wild populations, overharvesting of wild salmon comigrating alongside hatchery salmon, and competition for food and habitat. While the **Salmonid Enhancement Program (SEP)** has developed frameworks and has best practices in place for addressing risk, the interactions between hatchery and wild salmon, and ultimately the effectiveness of hatcheries, remain uncertain. Therefore, as our government continues to invest in salmon hatcheries, it is important we understand the factors that influence the survival of hatchery fish and their interactions with wild salmon.

Building upon previous research into hatchery survivals conducted during the Salish Sea Marine Survival Project (www.marinesurvivalproject.com), the Pacific Salmon Foundation (PSF) initiated a province-wide, science-based, and independent hatchery review. This review was funded by the BC Salmon Restoration and Innovation Fund in 2019 until spring 2023. The three main objectives of this work are to:

1. **Identify scientific advancements and cutting-edge genetics tools that could improve hatchery performance**

2. **Evaluate how hatcheries release their salmon and what bearing that has on their survival**

3. **Conduct a thorough analysis of the effectiveness of hatcheries and their impacts on wild salmon**

Component 3 has been further broken down into 5 sections:

1. **Systematic literature review**
2. **Role of community hatcheries**
3. **Trends in biological traits**
4. **Hatchery effectiveness**
5. **Hatchery-wild interactions**

Since 1977, the Salmonid Enhancement Program (SEP) has used hatcheries as a tool to support fisheries, conservation and assessment for a number of salmon species. According to the Fisheries and Oceans (DFO) Wild Salmon Policy (DFO, 2005), SEP uses hatcheries to rebuild vulnerable salmon stocks, provide harvest opportunities, improve fish habitat to sustain salmon populations, support Indigenous and coastal communities in economic development, and engage British Columbians in salmon rebuilding and stewardship activities. However, hatchery enhancement poses a number of important risks to wild salmon. Increased overall production may lead to the overexploitation of wild stocks, which may be unable to sustain greater fishing pressure (Gardner et al., 2004). In addition, hatchery salmon or mating practices may pass on certain traits, such as smaller size and younger age at maturity, that may lead to declines in the overall productivity of stocks through reduced capacity for egg production in females (Ohlberger et al., 2020; Oke et al., 2020). Indeed, hatchery practices have been implicated as a driver of declining Chinook body size (Hankin et al., 2009; Johnson and Friesen, 2013). Predation is also a major concern for wild fish in enhanced streams as large pulses of hatchery releases may attract larger than normal numbers of salmon predators, effectively increasing natural mortality on wild fish. Increasing the number of releases may also increase competition between wild and hatchery fish for habitat and food resources, particularly in the marine environment (Bigler et al., 1996; Gardner et al., 2004).

In the Pacific Northwest (PNW), the mean size of Chinook salmon has declined (Bigler et al., 1996; Oke et al., 2020), with older age classes showing larger declines than younger ones (Lewis et al., 2015; Ohlberger et al., 2018). Size declines can also be linked to shifts in age structure (Oke et al., 2020), as the proportion of larger, older age classes has also decreased (Lewis et al., 2015; Ohlberger et al., 2018). The fecundity (eggs per female) of Washington State Chinook has also declined (Malick et al., 2023), with the majority of changes being attributed to annual variation in mean length. In addition, size-selective fishing and predation can cause declines in both size and age structure of Chinook salmon populations (Nelson et al., 2019; Ohlberger et al., 2019; Ricker, 1981).

Given the potential effects on the productivity of salmon populations, fisheries and ecosystems, well-managed hatchery programs should aim to reduce the risks of these impacts. Assessments of hatchery-based enhancement should thus compare trends in size and age between enhanced and wild (control) salmon populations and determine the impact of hatchery enhancement relative to other known causal factors.

As such, in this component of the comprehensive review, we aimed to assess the impact of major BC hatcheries by:

1. **Comparing trends in size and age for wild and enhanced Chinook salmon populations in BC since the early 1970s;**

2. **Quantitatively assessing the relationship between these trends and known causal factors.**

However, due to limitations in data availability, discussed later in this document and in the accompanying data report (Maharaj et al., 2022), we had limited ability to assess the relative impact of causal factors. We had some, though limited, ability to compare trends between enhanced and wild salmon populations due to the inclusion of several minimally enhanced (mean pHOS < 10% – Harrison River and Kitsumkalum River) as well as two un-enhanced populations (Nechako River and Stuart River). As such, we:

1. **Estimated trends in size and age for enhanced and minimally/un-enhanced Chinook salmon populations across BC since the early 1970s;**

2. **Discussed the possible role of known causal factors by comparing our results to those of previous studies;**

3. **Highlighted limitations presented by data availability/quality that must be addressed to more fully assess the effect of hatchery and non-hatchery factors on size and age trends.**

We end by providing suggestions and recommendations on how to address key limitations facing the assessment of biological trends for the effect of hatchery enhancement on wild salmon stocks.

Photo by: Eiko Jones

METHODS

Here we provide an overview of the data and methods applied and the issues presented by the available data and how they limited our analyses. See the associated [data report](#) (Maharaj et al., 2022) for more in-depth description.

DATA USED

Trends in size (postorbital-hypural length or POHL[3]) of salmon across age classes, sexes and stocks were compared using records of biological data on individual fish. As stated previously, these data would ideally be available for more wild (unenhanced) stocks than the two included in our analysis, such that trends from wild stocks could act as controls to compare enhanced stocks. SEP and Stock Assessment Division (StAD) provided two main datasets for this study:

> the EnPro and the Stock Assessment Biodatabase

> the EPADS

EnPro and the Stock Assessment Biodatabase

EnPro is a hatchery operations management database and reporting tool where data for individual salmon sampling events are compiled. These include information such as results of adult biosampling, inventory transactions, feeding rates, growth rates, marking and tagging activities, juvenile releases and more. EnPro contains data from just over 70 Chinook salmon stocks in BC and was implemented by the SEP in 1998.

The SEP coordinates the collection of data for EnPro from a number of users, and includes southern BC spawning escapement and broodstock data (from 1996 to 2019). Data are collected through river and hatchery enumeration and sampling, in collaboration with StAD programs, SEP Major Operations, and SEP Community Involvement Programs. The Stock Assessment Biodatabase (henceforth referred to as 'the Biodatabase') is a subset of biodata exported from EnPro, formatted, reviewed and updated for analytical purposes, and currently maintained by South Coast StAD, DFO. These data were thoroughly assessed for their analytical utility in this particular project using metadata on the variables collected and notes on sampling design taken from published reports and DFO interviews with hatchery managers, as well as copies of sampling plans for most hatcheries from recent years. Details are provided below and in the accompanying [data report](#) (Maharaj et al., 2022).

Data limitations and solutions

There were a number of challenges encountered in our analyses. Additional datasets were sourced to supplement the existing database, but assumptions were frequently required. Ultimately, some issues prevented us from being able to compare trends between enhanced and wild salmon populations or to assess the relative impact of causal factors. Table 1 outlines these issues and the solutions proposed and implemented to address them. An accompanying [data report](#) provides further details on these limitations and solutions (Maharaj et al., 2022).

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

Table 1: Limitations presented by the Stock Assessment Biodatabase and solutions proposed and subsequently implemented to address them.

Limitation	Solution proposed	Solution implemented
Data were not available for all species of Pacific salmon	Obtain and standardize unreviewed data for additional species	Focused on biological trends for Chinook salmon as case study for future studies on additional species
Data only collected for hatchery enhanced streams	Obtain data from additional wild populations	Obtained data from Nechako and Stuart Rivers
		Identified low-enhancement streams among those included in the stock assessment Biodatabase (pHOS < 0.1)[4]
Data from non-EnPro hatcheries not included	Identify non-EnPro hatcheries and obtain data for populations they survey	Obtained data from Kitimat and Hirsch rivers from Kitimat River hatchery
Smaller hatcheries collect fewer samples due to limited resources	Incorporate data from additional sources	Obtained additional data from RMIS
Historical (pre-1996) data have not yet been incorporated	Incorporate historical data for populations in study	Incorporated historical data for Robertson Creek and Chilliwack River Chinook stocks
Fisheries samples not included	Identify databases of fisheries samples	Requested data from MRP; Obtained data from RMIS
Not possible to determine Stock of origin for records without CWTs or thermal marks	Discard non-CWT samples for populations with adequate CWT data	Discard non-CWT samples for populations with adequate CWT data
	Otherwise, use Sample site for Stock of origin	Otherwise, use Sample site for Stock of origin
Sampling is often stratified across males, females and jacks (one-year old males)	Used enumerations from EPADS to calculate mean age, age composition and female proportion	Used enumerations from EPADS to calculate mean age, age composition and female proportion

4. pHOS is the proportion of hatchery origin spawners on the spawning grounds – for additional information on pHOS please refer to Withler et al. (2018).

EPADS

The Enhancement and Planning Database System (EPADS) is a regional management system developed to track attributes of salmon populations related to annual salmon assessments including targeted and actual production totals, escapement summaries, sample expansions, and estimates of survival and enhanced contributions. EPADS has adult return data for over 130 stocks including five salmon species.

The EPADS came into service in 2010, integrating several historical databases (Production, Targets, Mark Plan, Escapement and Biostandards) into one system. Because the EPADS reports estimates on returns, it does not contain POHL data for individual fish. However, it provides a much more comprehensive estimate of total returns compared to the Biodatabase, which only contains information on individual samples. The EPADS reports river returns by sex, at different sample locations, and provides estimates for both wild and enhanced returns. In addition, it reports three indices of enhanced returns by sex and age (observed, estimated, and expanded) for CWT recoveries, but not thermal marks.

These data are maintained by the SEP Planning and Assessment Group and were provided by Cheryl Lynch (Planning and Assessment Biologist, SEP, personal communication, 2021). Standardization and analytical advice for these data were provided by Jeffrey Till (DFO, retired) and Cheryl Lynch.

Data limitations and solutions

As in the Biodatabase, returns are generally estimated in enhanced systems or at hatcheries, biasing counts toward hatchery-enhanced stocks. However, unlike the Biodatabase, sampling is conducted for scientific assessment of system or population level indices as opposed to individual biological measurements. As such, while the data meet some of the necessary criteria to be used in our analyses, they still contain limitations that prevent us from answering our main question. These limitations and solutions proposed are summarized in Table 2 below.

Table 2: Limitations presented by enumerations taken from the EPADS and solutions proposed to address them.

Limitation	Solution proposed	Solution implemented
Data were not available for all species of Pacific salmon	Obtain and standardize unreviewed data for additional species	Focused on biological trends for Chinook salmon as case study for future studies on additional species
Sampling is often stratified across males, females and jacks (one-year old males)	Used enumerations from EPADS to calculate mean age, age composition and female proportion	Used enumerations from EPADS to calculate mean age, age composition and female proportion
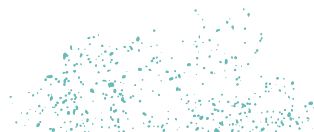
DATA CHECKING AND MANIPULATION

Due to the variety of sources from which our data were taken, a significant data checking and manipulation effort was conducted to standardize all variables for clarity and analyses. A detailed description of these is given in the accompanying data report (Maharaj et al., 2022).

Mean age and size

Trends in mean age and size were assessed by comparing rates of change of these biological traits across stocks using the biodata (Table 3). Trends were only compared for stocks containing at least 5 years of data with 10 or more records per year following previous studies (Ohlberger et al., 2018; Xu et al., 2020). Annual means for these traits were calculated and regressions conducted on these time series using the following formulation:

$$\overline{Y}_i = \beta_0 + \beta_1 X_i + e_i$$

Here $\overline{Y}_i$ represents the annual means of size/age and X_i the respective years. From the resulting regressions, slopes (the β_1 parameter) and p-values were extracted and used to construct summary figures.

Trends in age and sex proportion

Trends in age and sex proportions were compared by using rates of change in class composition extracted from regressions. First, class compositions were estimated:

$$P_{i,a} = \frac{n_{i,a}}{N_i}$$

Here $P_{i,a}$ is the proportion of records for each age/sex class (a) in a given year (i), n_i the number of records from each age/sex class in a given year and N_i the total number of records for all age classes in a given year. Three indices of age composition were calculated using individual sample data from the Observed, Estimated, and Enhanced returns from EPAD. However, only trends from the Estimated returns were reported in the results. The estimated returns were deemed the most complete indicator with the least bias due to expansion uncertainty. The remaining indices are included in the Supplementary Materials for comparison. Only the River Returns from EPAD were used to calculate sex composition as these were the most complete enumerations by sex available (Table 3).

Table 3: A list of the indicators used in our analyses and the datasets used to calculate them

Indicator	Dataset used
Mean age	EPADS – Estimated returns EPADS – Observed returns (supplementary) EPADS – Expanded returns (supplementary)
Age composition	EPADS – Estimated returns EPADS – Observed returns (supplementary) EPADS – Expanded returns (supplementary)
Mean size	Biodatabase
Size-at-age	Biodatabase
Female composition	EPADS – River returns

Trends were only compared in stocks that contained 5 or more years of data for all age/sex classes. Because the number of jacks (male ocean-1 fish) to be sampled is specified for many stocks, this age class is excluded from age compositions. Logistic regressions in class compositions were then conducted using of the following formulation and logit link function:

$$\text{logit}(P_i) = \beta_0 + \beta_1 \text{Year}_i + e_i$$

Where,

$$\text{logit}(P_i) = \frac{P_i}{1 - P_i}$$

Slopes and significance values were extracted from these regressions for rate plots.

Size trends by age and sex

Size trends by age and sex were compared by plotting rates of POHL change across age/sex classes for each stock using the biodata (Table 3). Linear regressions were conducted on POHL time series by age/sex class using the following formulation:

$$\text{POHL}_i = \beta_0 + \beta_1 \text{Year}_i + e_i$$

From the resulting regression statistics, slopes (the β_1 parameter), p-values were extracted and used to construct rate plots. As before, trends are differentiated by the range of time period covered by the raw data.

Size trends were only compared for stocks containing at least 5 or more years and 10 records per year for all age/sex classes. Furthermore, the focus given to sampling jacks (male ocean-1 fish) in sampling plans is reflected in significant bimodality in size data for male fish. As such, this age class is excluded for size trends by sex.

Length of time series

Finally, because variations in the length of time series across stocks may affect the comparability of trends, all trends were differentiated by the range of time periods covered by the raw data. Essentially, the length of the time series for each system was categorized as shown below based on the longest time-series over all systems for each indicator:

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

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

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

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

TRENDS SUMMARIES ACROSS SYSTEMS AND REGIONS

We used biological indicators (size at age, mean age and size, age and female proportion) across BC Chinook salmon populations and compared rates of change by conducting regressions on time series of these indicators, extracting slopes from these regressions and grouping them geographically. For all indicators, only the most consistently represented age classes (ocean-2, ocean-3 and ocean-4) were used to maximize the number of stocks included in our analyses. These were then plotted on scatter plots and box plots to illustrate trends of interest (Figure 1). See the Supplementary Materials (Figures SI 5-10, SI 17, SI 18 & SI 21) for the original time series for these systems. The length of time-series metric indicates in part the amount of certainty we have in a trend. Trends in stocks with short length time series should be interpreted with caution.

Additional information on the data from the report can be found in this biodatabase data report.

$$Y = b_1 + b_0 X$$
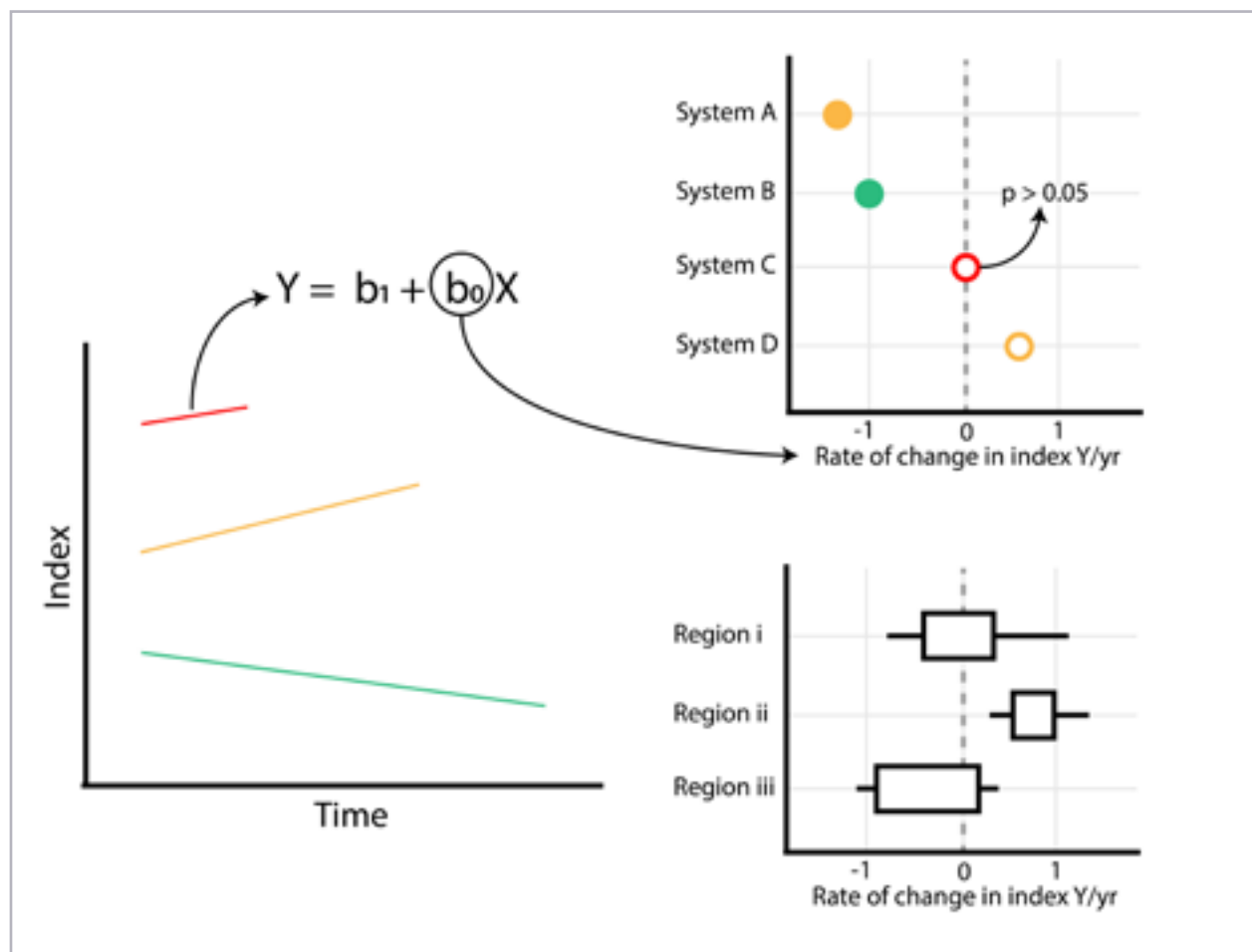
Figure 1: Rate plots are constructed by plotting slope parameters, extracted from regressions on time series of our chosen indicators, by stock. Time series are colour coded by length (short = "Red", medium = "Amber", long = "Green"[5]). Stocks are then grouped by region and geographical patterns illustrated using boxplots.

5 **Short** time series are less than 1/3 the longest time series, **Medium** time series are between 1/3-2/3 the length of the longest time series, **Long** time series are greater than 2/3 the length of the longest time series.

RESULTS

MEAN AGE AND AGE PROPORTIONS

Trends in mean age were variable across the 19 stocks assessed, with significant declines in 9 of 17 hatchery populations, and significant increases in 4 of 17 hatchery populations. (Figure 2). Changes in mean age ranged from -0.025 years/year to 0.018 per year. These were driven by shifts in the relative proportion of the oldest (ocean-4) and youngest (ocean-2) age classes (Figure 3). Of note is the length of time-series, the largest declines and increases were found in stocks with short time series, which highlights the importance of acquiring longer time-series. For the two minimally enhanced systems, there was a significant decline in age-at-maturity of Harrison River Chinook and a small, non-significant decline of Kitsumkalum River Chinook. The two wild systems, Nechako and Stuart Rivers, did not have EPADS data to support mean age analysis.

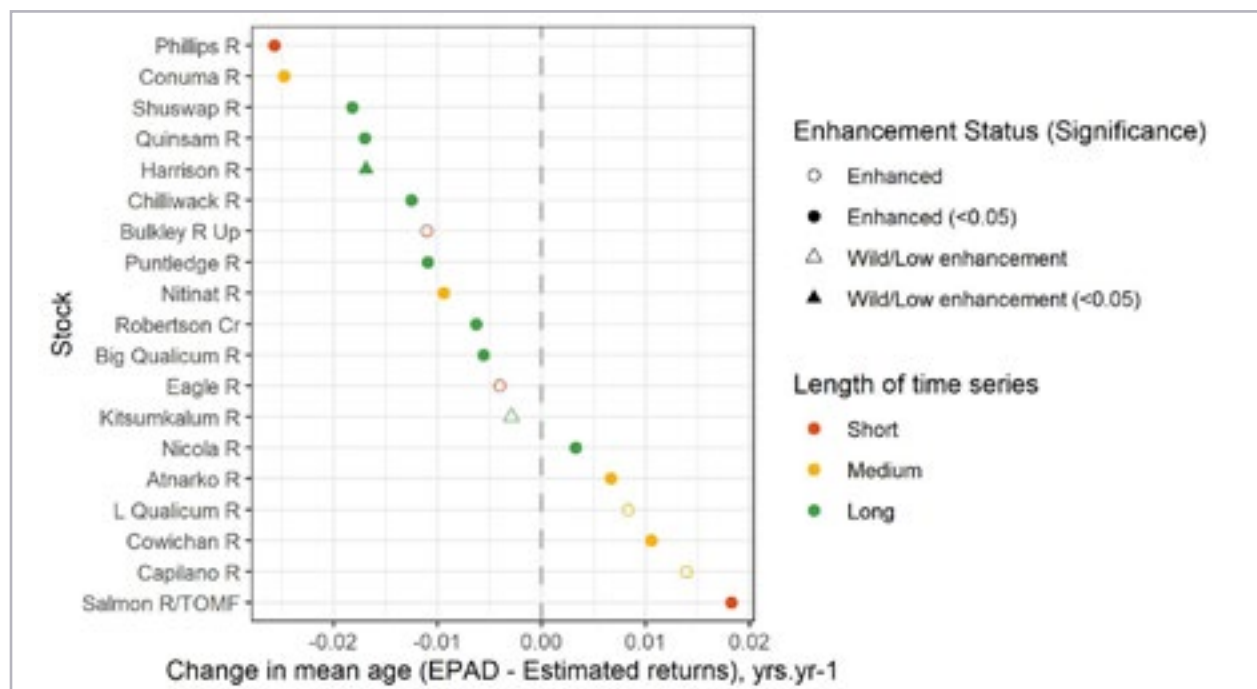**Figure 2:** Rate of change in mean age-at-maturity for Chinook populations assessed (Maharaj et al. 2023). The length of the time series from which trends were calculated is given by coloured circles. Statistically significant trends are represented by filled points. See Figure SI 6 in the Supplementary Materials linked to Maharaj et al. (2023) for time series of annual values.
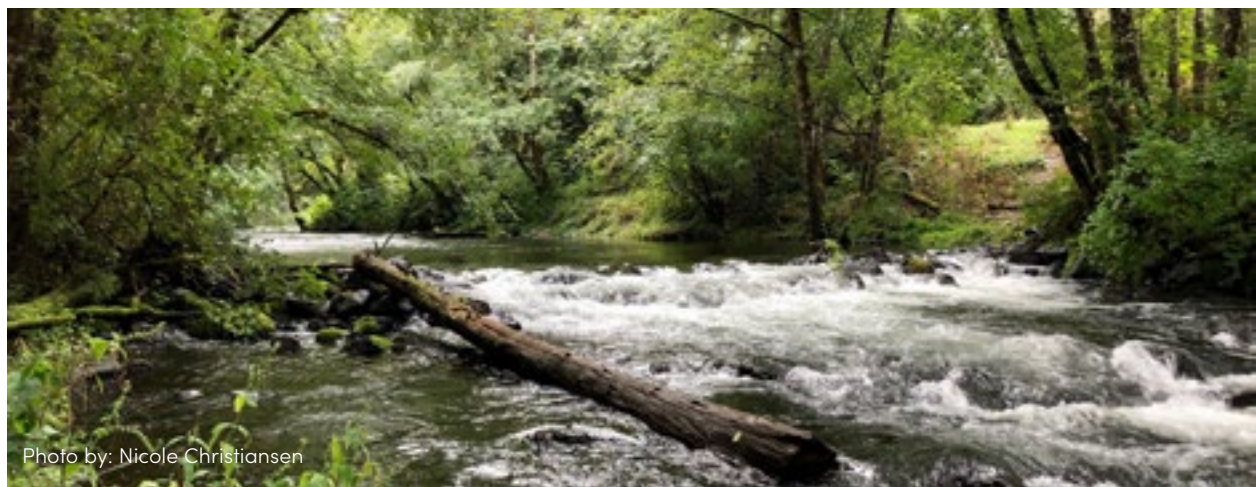
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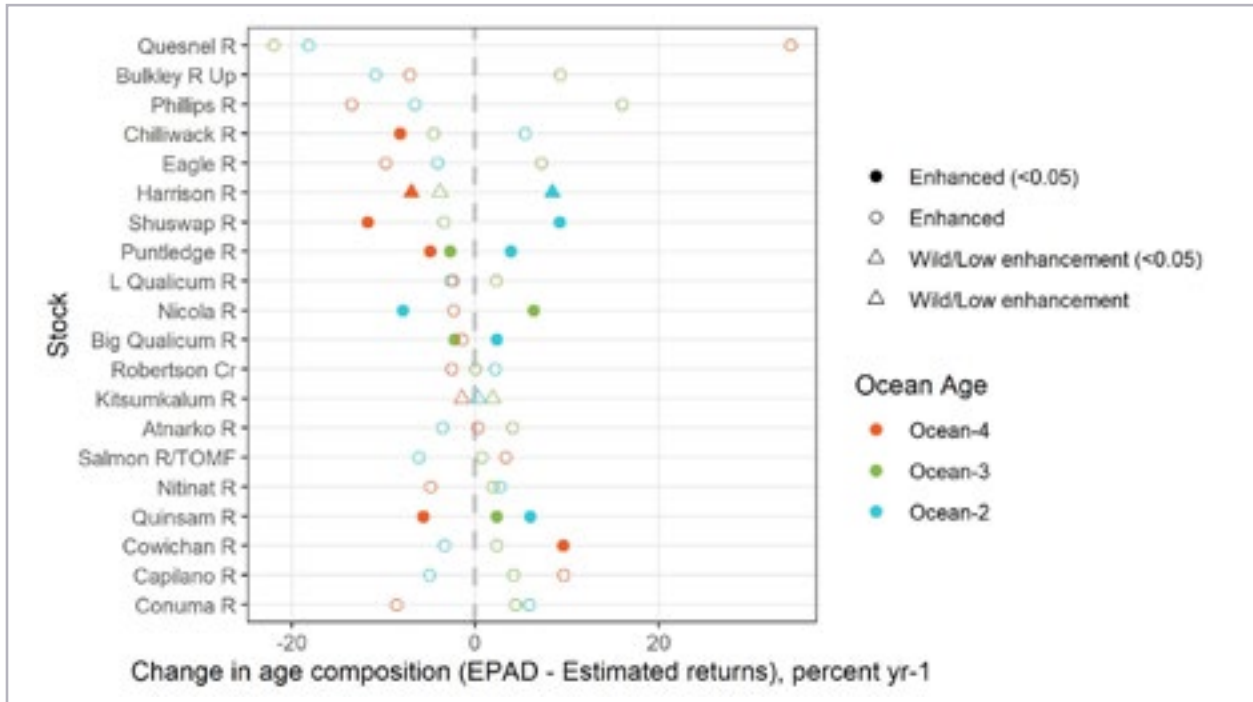
Figure 3: Scatterplot of change in age composition by stock. Age classes given by point colour while statistically significant trends are represented by filled points. See Figure SI 9 in the Supplementary Materials for original timeseries.

Figure 4: Scatterplot of change in mean size by stock. The length of the time series from which trends were calculated is indicated by point colour. Statistically significant trends are represented by filled points. See Figure SI 17 in the Supplementary Materials for original timeseries.

MEAN SIZE AND SIZE-AT-AGE

Mean size of individual fish declined significantly in 73% of the 22 Chinook populations assessed (Figure 4 from the previous page). Changes in mean size ranged from declines of almost 10 mm/year to increases of 4mm/year. Wild fish from the Stuart River and fish from the minimally enhanced, Kitsumkalum River, displayed the smallest declines in mean size of all stocks. Of the six stocks which showed increasing mean size, three had short length time series, and the other three had only medium length time series, whereas only two stocks with significant declines in mean size had short time-series. Mean size is influenced by both changes in size- at-age and age-at-return. As noted above, many stocks showed declining mean age, which may shift the mean length down even if size-at-age is stable. Trends in size-at-age for systems with sufficient information are shown in Figure 5. Those with the largest declines in mean age also showed the largest significant declines in size for the oldest age class (ocean-4). For example, Conuma River Chinook shows a strong decline in mean age as well as a strong decline in both mean size and size at ocean-age 4. For stocks that had enough information to assess trends in ocean age 4 Chinook, 7 out of 9 stocks (78%) showed significant declines in size, with only 2 stocks not having significant size decreases for ocean age 4 Chinook. Approximately 40% of stocks with enough information to assess size at ocean age 2 showed significant increases in the youngest age class (ocean-2) and were among those showing either smaller declines or increases in mean age.
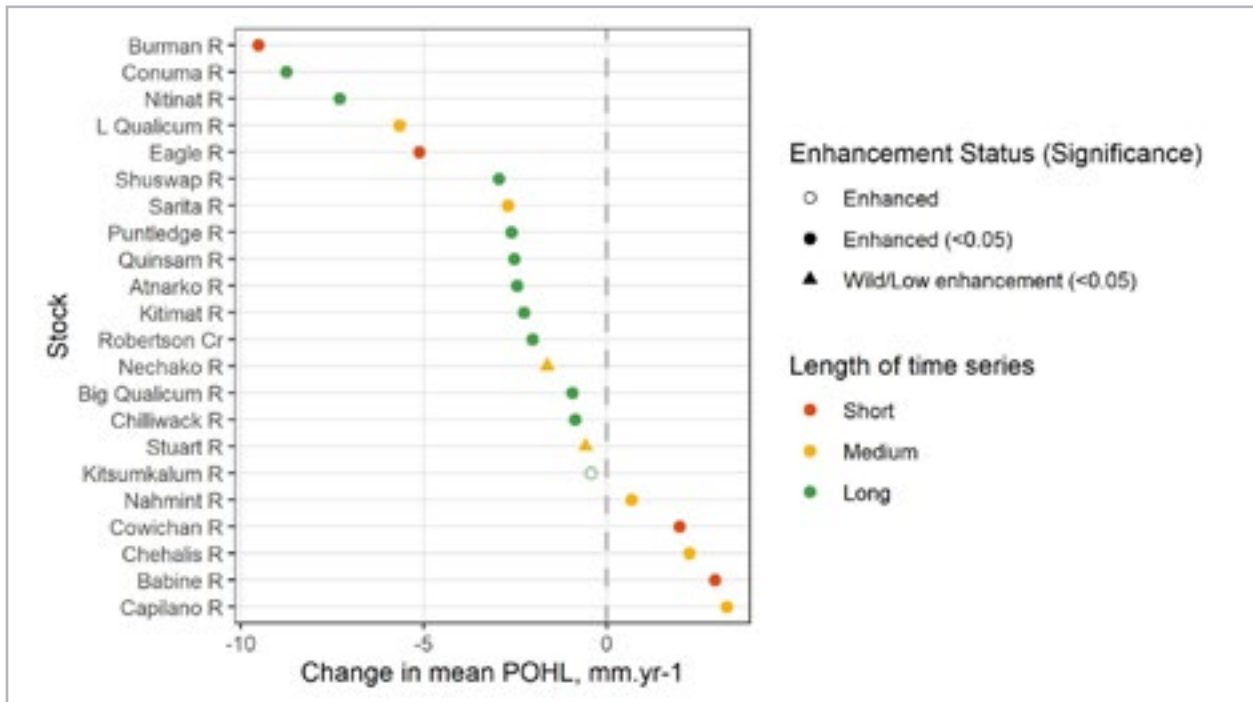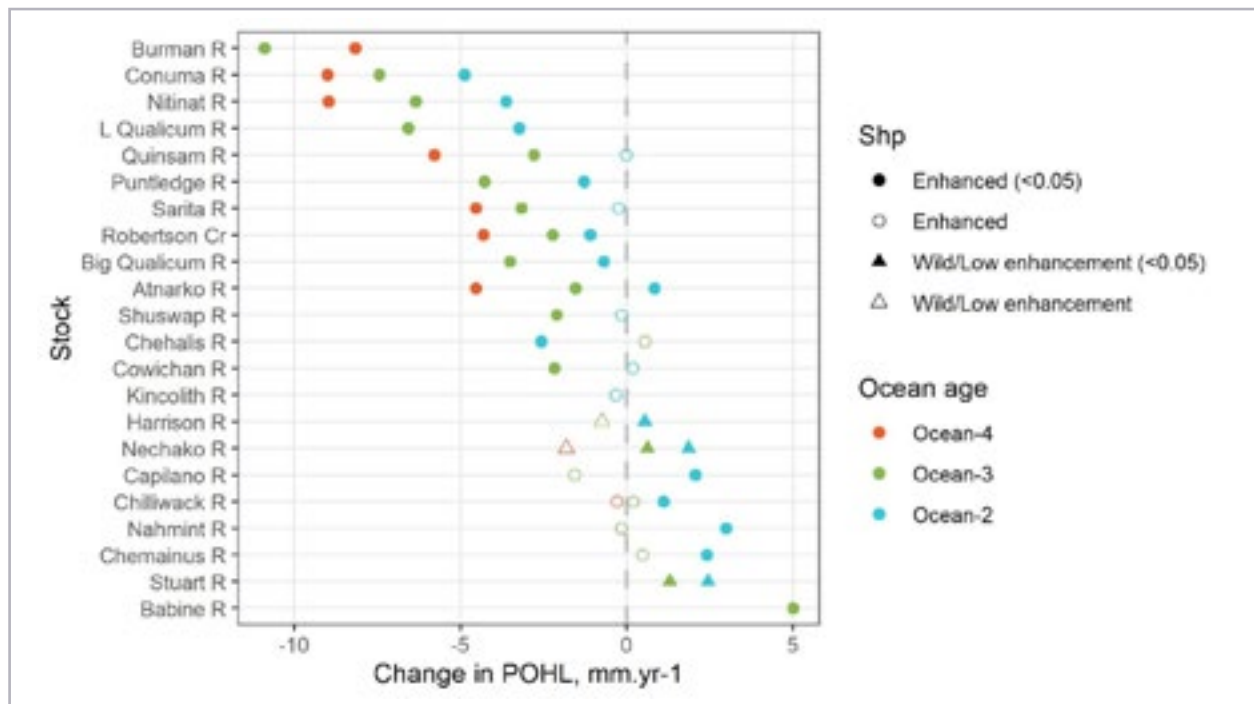

Figure 5: Scatterplot of change in size by age class across stocks. Age classes are shown by point colour while statistically significant trends are represented by filled points. See Figure SI 18 in the Supplementary Materials for original timeseries.

PROPORTION OF FEMALES

Due to the completeness of the river return estimates, the proportion of female fish could be assessed for 84 stocks. Trends in female composition ranged from declines of 37% to increases of 17% per year. Significant declines were only detected in ~17% and increases in ~8% of stocks (Figure 6 on the next page). Trends from systems with very short time series (e.g., Shovelnose Creek, Bonaparte River, Toquart River, Kilbella River, Bridge River) should be interpreted with caution. There was no consistent pattern for the few wild and minimally enhanced stocks included. Wild fish from the Stuart River stock showed a non-significant increase in the proportion of females returning, though this trend was derived from relatively a short time series. The fish from the minimally enhanced Kitsumkalum and Harrison River stocks showed significant increases and declines in female proportion, respectively.

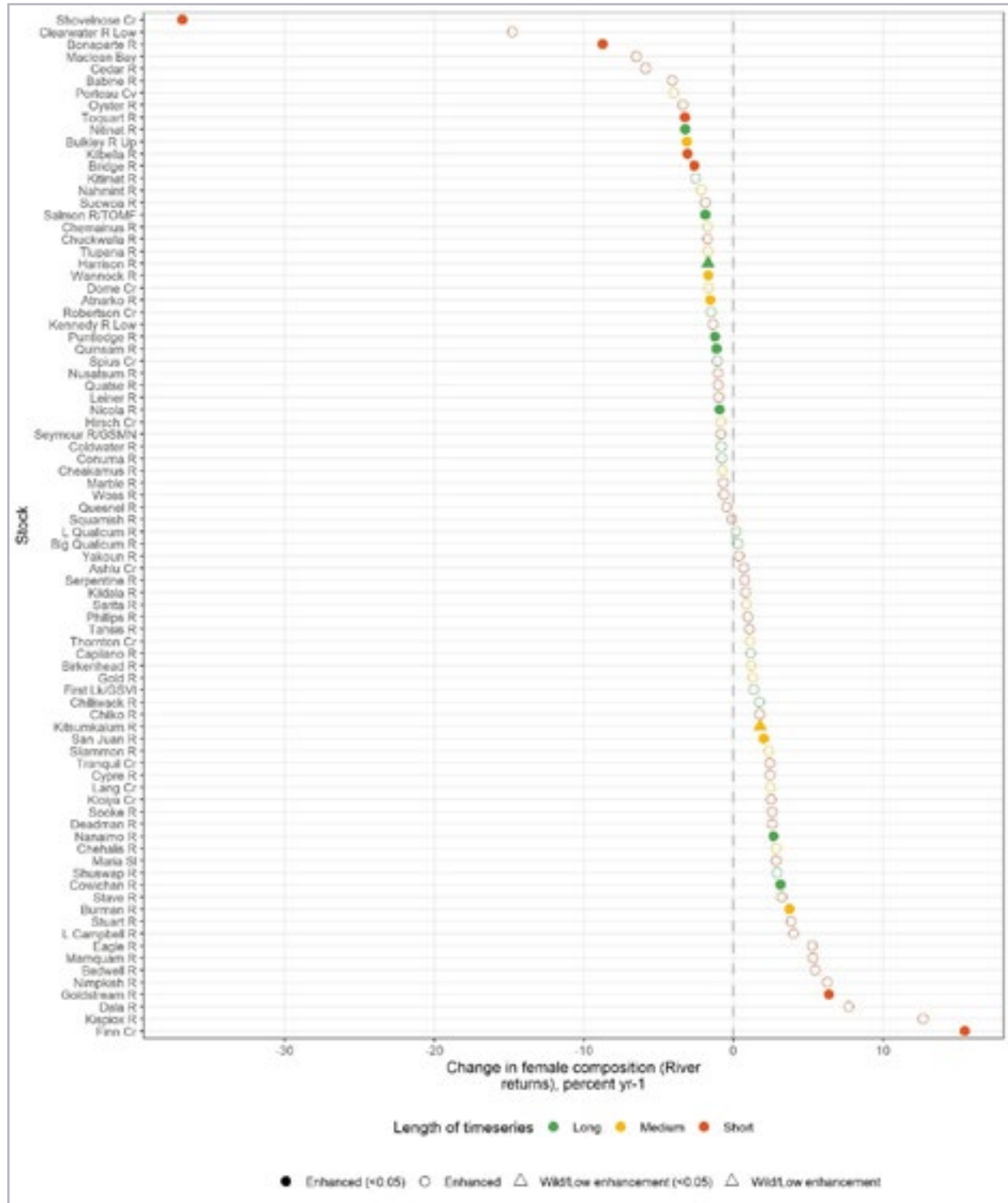Photo by: Nicole Christiansen

Figure 6: Scatterplot of change in the proportion of females by stock. The length of the time series from which trends were calculated is indicated by point colour. Statistically significant trends are represented by filled points. See Figure SI 21 in the Supplementary Materials for original timeseries.

REGIONAL GROUPINGS

Regional groupings were created based on the system location in order to explore large scale patterns in demographic changes. Three region groupings were used (NC/CC DFO management areas 1–10, ISC includes areas 11–20, 28 and 29, and WCVI includes areas 21–27). Trends in mean age were similar across regional groups (n=20 populations, Figure 7) although the WCVI stocks all showed declines. When grouped by region, the change in proportion of each age class was also similar between regions, with most regions showing declines in ocean age 4 Chinook, and mixed trends for ocean age 2 and 3 Chinook (Figure 8). All WCVI systems showed increased size in ocean age 2 Chinook. Trends in the proportion of females also showed no clear regional pattern (Figure 9). However, trends in size showed strong regional grouping and a clear geographical pattern, with larger declines associated with more southern, exposed West Coast of Vancouver Island (WCVI) stocks (Figure 10 and Figure 11), driven by declines in size in ocean age 3 and 4 fish. The smaller sample size associated with North and Central Coast (NC/CC) stocks may confound this observation and more data from North and Central Coast stocks would be informative.

The most extreme trends were produced by stocks with short time-series. However, many trends from short time-series also fell within the range of those produced by medium and long time-series. As such, patterns including these shorter time-series should be interpreted cautiously.
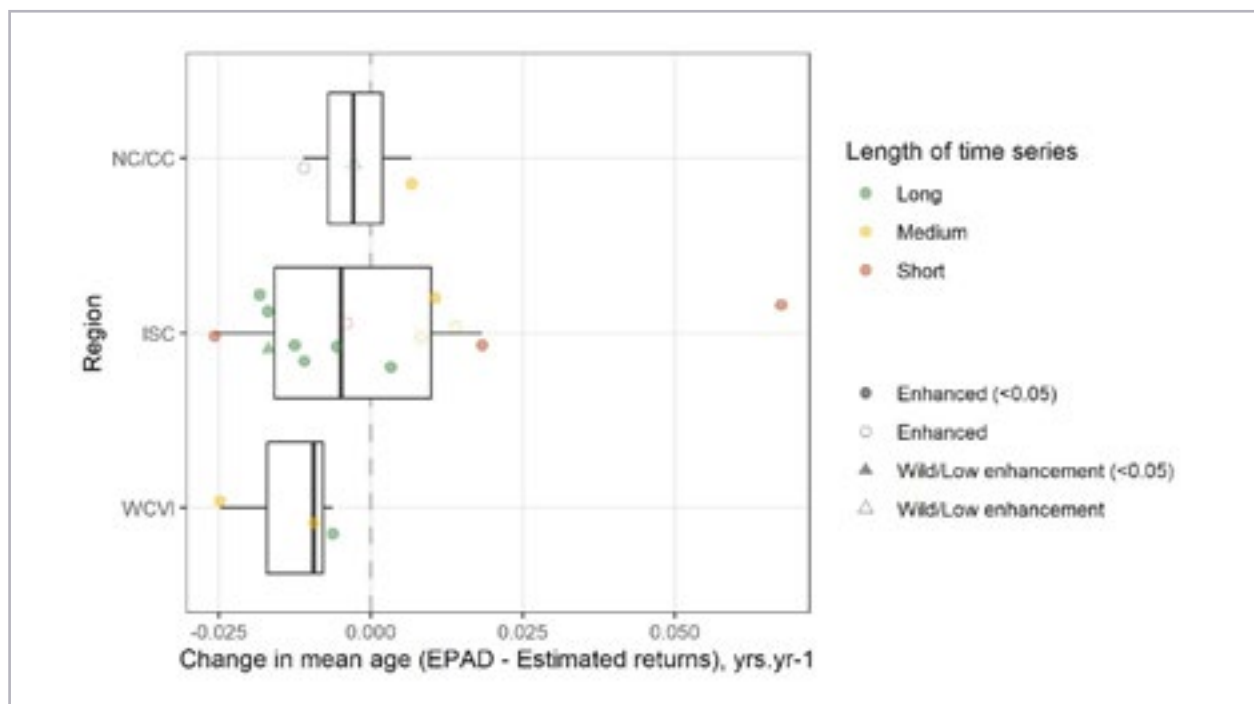
Figure 7: Boxplot of change in mean age, grouped by region. The length of the time series from which trends were calculated is given by point colour. Statistically significant trends are represented by filled points.
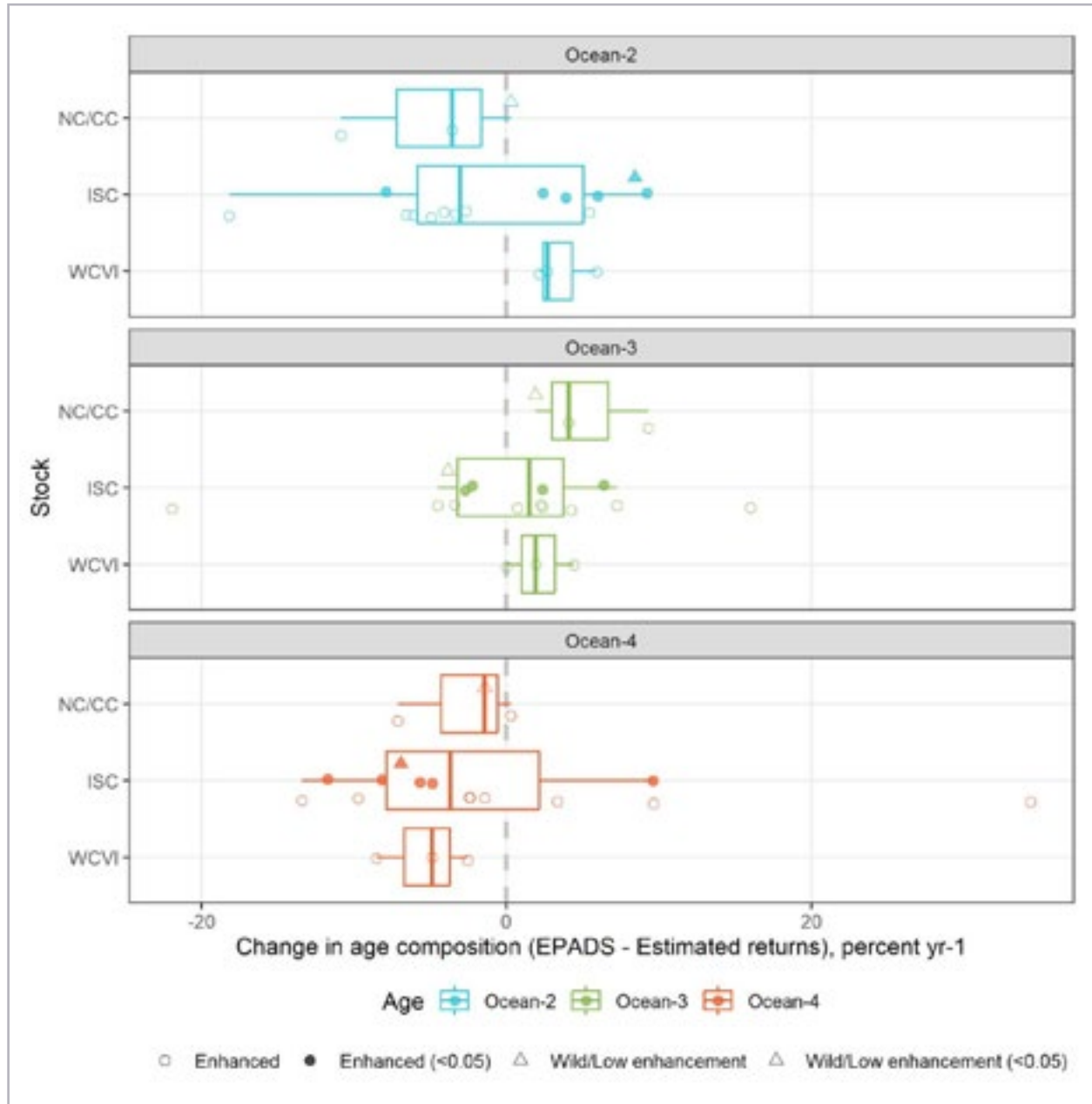
Figure 8: Boxplots of change in the proportion of each age class by geographical groupings. Age class is given by colour, statistically significant trends are represented by larger filled points, while outlier points are represented by smaller filled points.
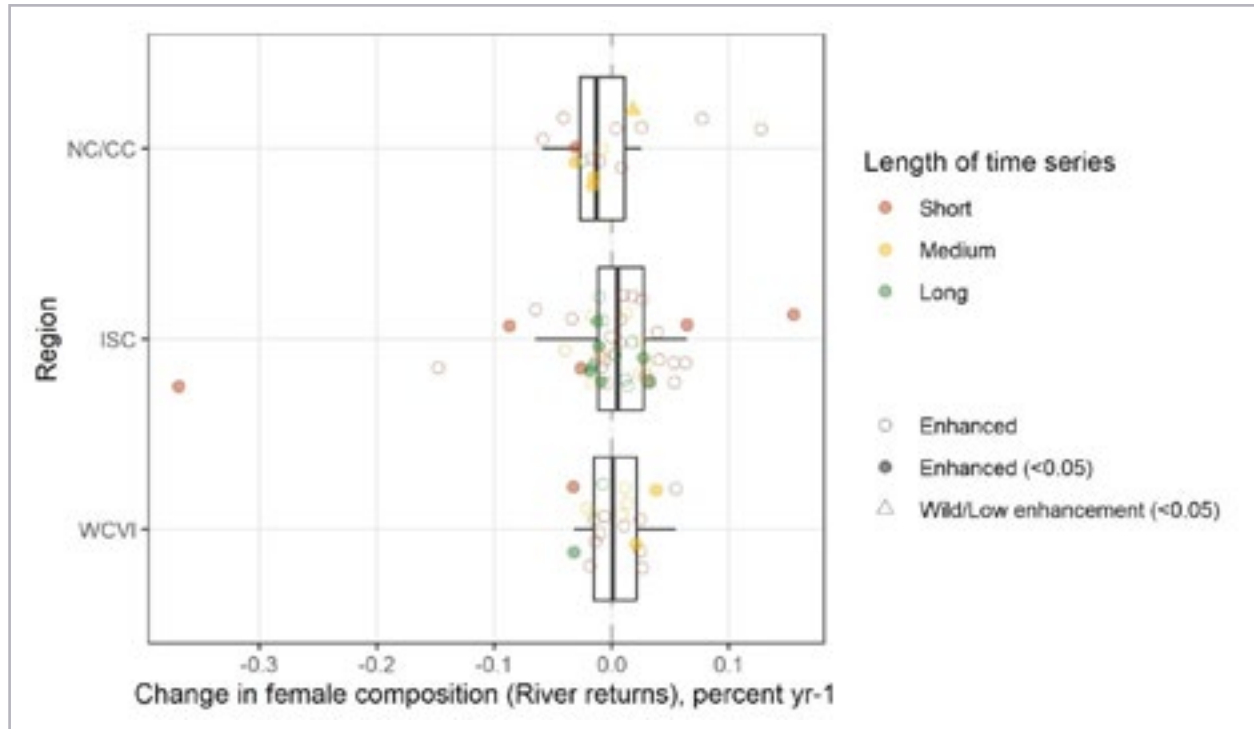
Figure 9: Boxplot of change in the proportion of females. Trends are presented by region to illustrate any geographical grouping. The length of the time series from which trends were calculated is indicated by point colour, while statistically significant trends are represented by filled points.

Figure 10: Boxplot of change in mean size, presented by region to illustrate geographic groups in trends. The length of the time series from which trends were calculated is indicated by point colour. Statistically significant trends are represented by filled points.

Figure 11: Boxplots showing the geographical distribution of size changes by age class. Age classes are shown by colour while statistically significant trends are represented by filled points.
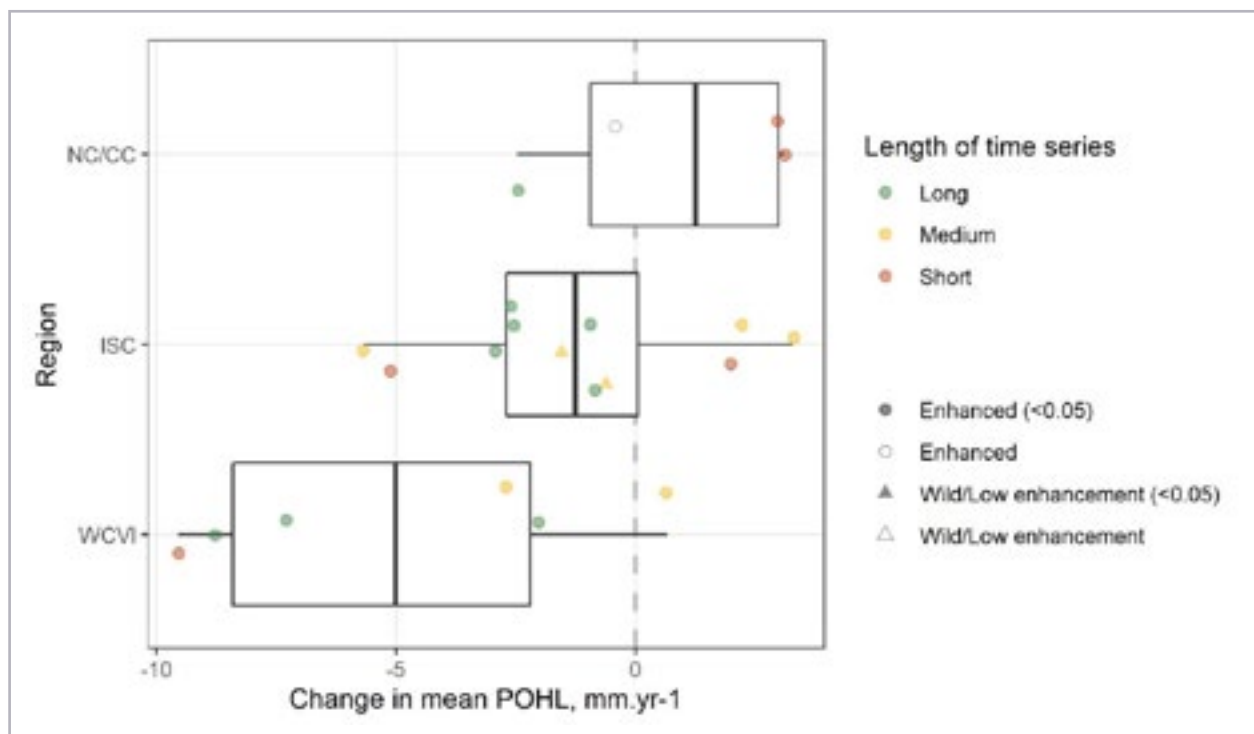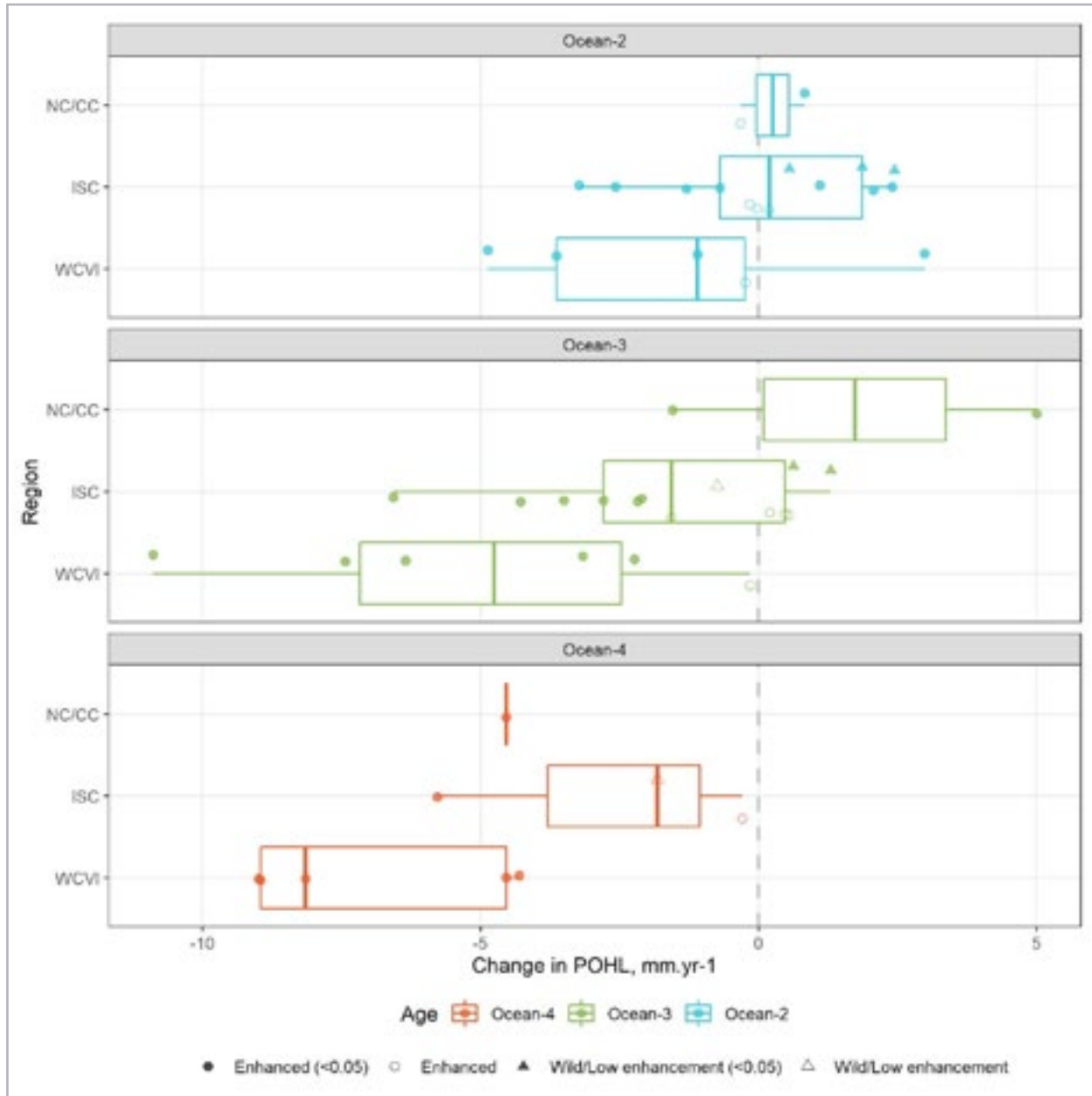
Additional figures and tables are available in a supplementary information document.

DISCUSSION

Here we provide an overview of the data and methods applied and the issues presented by the available data and how they limited our analyses. See the associated data report (Maharaj et al., 2022) for more in-depth description.

Our analyses are largely consistent with other recent studies of size and age of Chinook salmon in the Pacific northwest (e.g. Lewis et al., 2015; Ohlberger et al., 2018; Malick et al., 2023). In particular, we found that mean size and age declined significantly for many of the stocks analyzed, although increases in mean size and age were also observed. We also saw notable shifts in the age composition of some stocks, with significant declines in the oldest age class (ocean-4) relative to the youngest (ocean-2). In addition, we found that size increased significantly for the youngest age class (ocean-2) in some stocks. Approximately half of the stocks showed significant declines in size-at-age for all age classes (ocean age 2, 3 and 4). A recent study on Fraser River Chinook showed that size-at-age varied across population aggregates, but was not necessarily consistently positive or negative (Xu et al., 2020). Fraser River stocks in our study (Harrison River, Shuswap River and Chilliwack River) reflected similar patterns, showing variable patterns in size-at-age which were among the smallest changes compared to the others. However, beyond these stocks, size-at-age trends varied across BC, with more southern stocks showing larger declines.

Most of the stocks with long-term data are hatchery dominated populations. Many of these stocks also showed declines in size at age and mean size, with some discrepancy in changes of size-at-age between age classes. However, we were unable to compare hatchery dominated systems with wild systems due to limitations in data availability – the information available for wild stocks is simply insufficient. This precludes robust comparisons between hatchery and wild stocks, and therefore makes it difficult to examine hatchery effects. Stocks showing an increase in size for the youngest age class and a decrease for the oldest age class may indicate hatchery effects. When compared to wild salmon, hatchery-origin salmon display higher growth rates at younger ages, thus maturing younger and smaller (Gardner et al., 2004). Further, mate selection in the natural environment happens at an individual level based on indicators of fitness, rather than randomized mating at SEP hatcheries. Randomized mating may inadvertently select for the most abundant age class i.e., the younger age classes, leading to a bias in genetic selection for fast growth and younger age-at-maturity. However, our results also showed increases in size for the youngest age class from stocks with little or no enhancement. These types of mating protocols may also circumvent natural mating preferences where large fish mate with large fish, for example. Ultimately, a larger sample size of wild and/or low-enhancement stocks is required to elucidate the effects of hatchery enhancement on changes in biological characteristics.

Photo by: Nicole Christiansen

In this report, we did not explore causal factors for the observed trends, either environmental or hatchery related. The data we procured and compiled may support these types of analyses, however most of the stocks in the Biodatabase with high quality and long-term data are hatchery dominated stocks. For the entire Pacific Region, the only un-enhanced Chinook population that we were able to identify and retrieve data for was from the Nechako River. Nechako River data were collected as part of a special monitoring program for a hydro-power project review, and are no longer being collected annually. Therefore, we can only speculate on the potential drivers of trends. Declines in mean size and age, and declines in the proportion and size of fish in the oldest age classes may support the hypothesis of size selective predation and/or fishing; the removal of individuals with the biological potential to attain the largest sizes renders them unable to pass their genes on to subsequent generations. Although some fisheries still apply selective pressures on larger and older Chinook, fishing effort has slowly declined since the 1990s. Therefore, the ongoing decrease in mean size and age cannot be attributed solely to fishing pressure. On the other hand, recent evidence exists for the potential impact of salmon predators on salmon populations (Nelson et al., 2019). Other explanations are also possible, with environmental factors such as declining marine productivity, hatchery mating protocols, capacity of the North Pacific Ocean, and climate change in both marine and freshwater likely candidates.

Finally, Nelson et al. (2019) found no significant influence of hatchery production on the productivity of BC Chinook populations. However, production may not correlate well with hatchery risk since this depends on the ratio of natural-origin to hatchery-origin spawners used at hatchery facilities. Hatchery influence may thus be better represented by an index of hatchery risk such as the Proportion of Natural Influence (PNI) or the Proportion of Hatchery-Origin Spawners (pHOS).

Ultimately, declines in size-at-age and shifts in age composition toward younger age classes may have important effects on hatchery effectiveness. Smaller and younger female salmon will produce fewer and smaller eggs, which have been linked to lower fisheries and ecosystem productivity (Ohlberger et al., 2020; Oke et al., 2020; Malick et al., 2023). This highlights a need to review escapement targets accounting for reductions in older-aged Chinook salmon and reductions in the fecundity per female.

Photo by: Sam James

RECOMMENDATIONS

These changes in biological traits echo other studies and are cause for considerable concern, and warrant significant future investigation. However, our analyses also highlighted critical data limitations that must be addressed before the nature and causes of these trends can be better understood. Here we suggest a few solutions for these issues.

Short-term solutions

Issue: Lack of high-quality accessible biodata

Acquisition of high-quality annual biodata should be a higher priority. More resources should be dedicated to supporting biodata collection, standardization, quality control, and review. These data should be incorporated into modern and accessible database structures along with outstanding historical data, biodata from non-EnPro hatcheries, and biodata from other species. Additionally, capacity could also be dedicated to improving computing systems for more seamless data sharing.

Issue: Challenges with data acquisition

Fisheries samples in this study were obtained from RMIS; however, these data already exist within the DFO MRP. The MRP captures and stores data from CWT recoveries made by Canadian fisheries, which are subsequently submitted to RMIS. Though the RMIS system and data are quite intuitive and accessible, internal datasets such as those from MRP should be more readily available to reduce the likelihood of process errors. We recommend a centralized data centre that can locate useful pre-existing datasets, such as MRP. This would improve issues with data accessibility and help improve assessment capacity.

Medium-term solutions

Issue: Lack of biodata on wild stocks

Wild indicator stocks need to be associated with each major facility and monitored annually. Wild stocks and minimally enhanced stocks were underrepresented in our study and prevented analytical comparison of trends with their enhanced counterparts. Our analyses detected declines in Chinook age and size in most enhanced stocks, however, it is unknown whether these same trends exist in wild systems. This information would be extremely useful in examining the causal mechanisms for declines with respect to hatchery influence. We recommend as a mid-term goal, an increase in the number of wild stocks consistently sampled. Since they represent natural variability, surveys should be designed to include a sample of 'wild' salmon populations and could be integrated with other regional tasks for annual stock assessments.
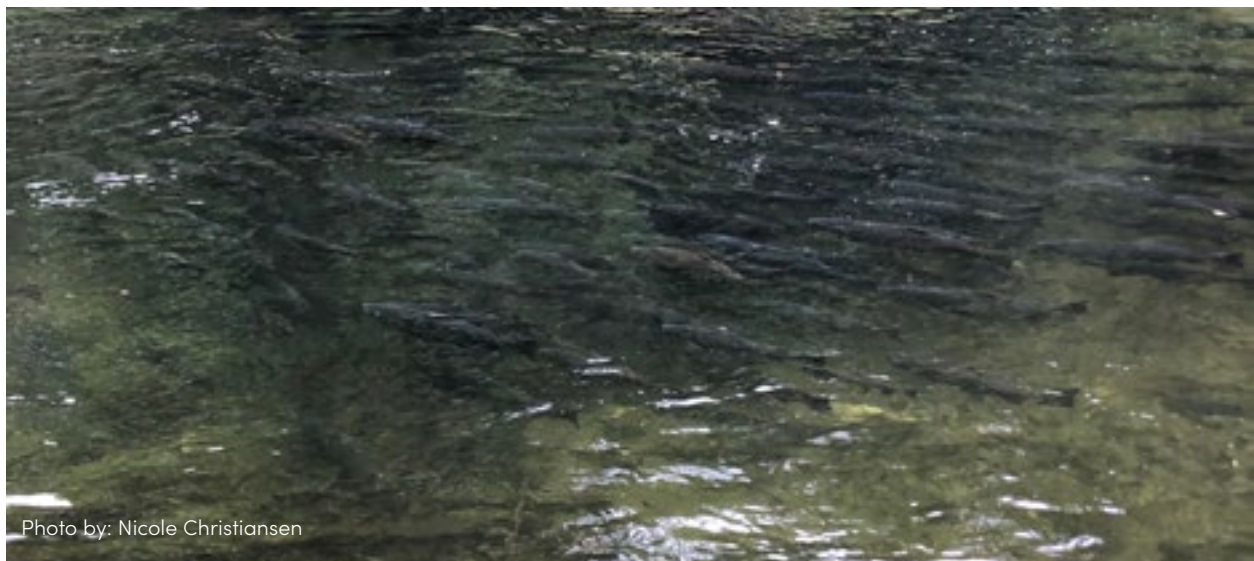

Photo by: Nicole Christiansen

Long-term solutions

Issue: Lack of clear information on stock of origin

Many biodata records had to be discarded in our analyses due to our inability to clearly identify the stock from which they originated. In some cases, specifically for wild stocks and historical escapement data that lack parallel release records, this was unavoidable. Here, we assumed stock of origin is the location where the biodata was collected, potentially introducing uncertainty into our biological trends due to straying. Implementing CWTs widely enough to increase the resolution of stock of origin across samples is expected to be expensive and effort intensive. As such, tools for Genetic Stock Identification (GSI) such as Parentage Based Tagging (PBT) and Single Nucleotide Polymorphisms (SNPs) present cost-effective alternatives to broader CWT implementation (Beacham et al., 2018). Further, genomic tools may help researchers differentiate among family variations in stock-specific responses to the marine environment, fisheries, and hatchery practices. Over the long -term, intergenerational data from such programs may determine the cause of change observed in phenotypic traits such as size-at-age, age-at-maturity, etc. The high up-front costs associated with GSI tools for implementation may be offset by combining them with CWT programs, where fish are first checked for CWT information and only sampled for GSI if no CWT are present. However, the most cost-effective means to identify hatchery-origin fish is otolith marking that would be invaluable to accurately identify first-generation hatchery fish in a spawning population.

In conclusion

While trends in size and age of Chinook salmon across BC are concerning, SEP stands to play an important role in furthering our understanding of these trends. Strategic planning and targeted investment of resources and expertise are required to improve data for assessment in the short- to medium-term, and for longer-term learning to truly understand hatchery-wild salmon interactions.

Photo by: Nicole Christiansen

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