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PRE-SEASON RUN SIZE FORECASTS FOR FRASER RIVER SOCKEYE (*ONCORHYNCHUS NERKA*) AND PINK (*ONCORHYNCHUS GORBUSCHA*) SALMON IN 2021

Context

Fraser River Sockeye stocks have been experiencing historically low productivity in recent years, making quantitative forecasting challenging. Forecasts for these stocks have been prepared with Bayesian models and presented as probability distributions, in order to capture some of this uncertainty. These distributions generally represent the range of survival the stocks have exhibited historically, although we have used environmental covariates for several stocks, in an attempt to capture recent declines in productivity. Environmental drivers are incorporated into forecast models for 13 out of 19 major Sockeye stocks. In addition, we have employed the use of sibling models for nine stocks; using productivity observed in 2020 returns to inform 2021 returns of older age-classes from the same cohort. For five major stocks, including Chilko, we identified a significant disconnect between the productivity implied by forecasting models, and productivity observed in recent generations, which has declined significantly, relative to earlier generations. For these stocks we use a naïve model that applies average productivity (recruits-per-spawner) from the last two generations to brood year spawners.

The Fraser River Sockeye total return is forecast to be 1.33 million fish, at the median level (80% prediction interval:313,000 - 5,496,000). The forecast is dominated by Summer Run stocks, which are forecast to contribute 1.05 million fish to this forecast. Returns are expected to be dominated by age-4 fish, making up 91% of expected returns (Table 3). Across all run-timing groups, 78% of the forecast return is made up of stocks that spawn above the Big Bar landslide. In addition to the quantitative forecast for 2021, we have compiled supplementary freshwater and marine data to provide some qualitative context to the forecast. These indicators provide mixed signals, with freshwater conditions appearing marginally better for the primary cohort returning in 2021 (except for Quesnel; the stock forecast to contribute the most fish to the 2021 return). Marine conditions have remained very warm, which are generally unfavourable for Fraser Sockeye prey quality. If Fraser Sockeye productivity stays within the range observed in the previous generation (2017-2020 returns), then returns should fall closer to the level seen at the 0.25 posterior quantile (P25), of 624,000 fish.

Fraser Pink Salmon represented a forecasting challenge in 2021, since the juvenile data from 2020, which would have generally been used to run the forecast, was not available due to the COVID-19 pandemic. Therefore, a new set of models were considered using retrospective analysis. The chosen model incorporated the effects of temperature, Fraser discharge during outmigration, and sea-surface salinity on productivity. All three environmental covariates are consistent with lower-than-average productivity, and our chosen forecast model for 2021 is predicting productivity near historically observed lows. The forecast return of Fraser Pink salmon in 2021 is 3.01 million (80% prediction interval: 1,701,000 - 5,375,000). This forecast should be used with caution, since it is based on an escapement time-series that spans several different enumeration methodologies.

This Science Response results from the Regional Science Response Process of December 18, 2020 and January 22, 2021 on the Pre-season abundance forecast for Fraser River Sockeye and Pink Salmon returns in 2021.

Background

Fraser Sockeye Salmon

Fraser River Sockeye salmon (*Oncorhynchus nerka*) have historically supported an important commercial fishery in British Columbia, and are an ongoing major contributor to First Nations food, social, ceremonial fisheries, and recreational activities (Cohen 2013). Although declines in productivity appear to have begun around 1990 (Figure 1), productivity since about 2009 has become highly variable, leading to both the highest (2010) and lowest (2020) returns in recorded history (Figure 1, Table 5).

Since approximately the mid-1990's Fraser River Sockeye have been generally returning at lower rates than predicted based on long-term (brood year 1950-2016) average survival (Figure 1). Widespread declines in productivity across Fraser Sockeye stocks have been observed, and have persisted into current times, when stock-recruit models with time-varying productivity have been fit (Figure 2; Dorner et al. 2008, Peterman and Dorner 2012, DFO 2020b). Environmental volatility and warming associated with climate change are associated with low survival of Fraser Sockeye salmon populations (Mueter et al. 2002; Connors et al. 2020). Several environmental covariates are used as part of the quantitative forecasts, and for the 2021 return, are showing warmer than average conditions for both Pine Island and Entrance Island sea-surface temperature (SST; Figure 3). The Pacific Decadal Oscillation (PDO) was also warmer than the long-term average in 2019. In addition to the quantitative inclusion of environmental covariates, there is an ongoing effort to document changes to freshwater and marine ecosystems and environmental conditions faced by Fraser River Sockeye. This additional information is not yet incorporated into the forecast in a quantitative way. Detailed information on the environmental conditions experienced at specific life history stages are usually compiled by Fisheries and Oceans Canada's (DFO's) State of the Salmon program through an annual meeting and report, and generally points to the need for caution when applying the forecast returns for fisheries planning (DFO 2014b, DFO 2015b, DFO 2016b, MacDonald et al. 2018, MacDonald et al. 2019, MacDonald et al. 2020). For 2021, due to program constraints, this meeting did not take place, and a report will not be published. To provide environmental context for the 2021 return, we have gathered and summarized a subset of the information usually gathered in this process, and these data have been included as an appendix in this document (see Appendix 5). The outlook for 2021 is mixed; freshwater conditions and early life-history indicators seem better for the 2021 return, compared to the 2020 return (with the exception of the Quesnel stock, which is forecast to be the largest contributing stock to 2021 returns). In the marine environment, heat-wave conditions persisted through 2019 and 2020. In the Strait of Georgia, overall zooplankton biomass was high in 2019, but on the West Coast of Vancouver Island and further offshore, zooplankton communities continue to show signs of a shift from larger, more northern zooplankton species, to smaller, warm-water associated species, that are a relatively poor food source for Sockeye Salmon. Total Pink salmon densities across the entire North Pacific have been linked to poor Fraser Sockeye productivity (Connors et al. 2020). Pink salmon density hit historically high levels in recent years, but returned to more average levels in 2020, a potentially promising indicator for 2021 sockeye returns. An in-depth discussion of the environmental conditions faced by the primary cohort of Fraser Sockeye that will return in 2021 (2017 brood year) can be found in Appendix 5.

In 2017, a Wild Salmon Policy (WSP) status evaluation, and a Committee on the Status of Endangered Wildlife in Canada (COSEWIC) status report both identified persistent declining trends in abundance of Conservation Units (CU) and Designatable Units (DU); the discrete and evolutionary distinct constituent populations of the Fraser River Sockeye aggregate. While CUs and DUs generally align, there are some differences between our forecast stock groupings and CU/DU groupings (see Table 5A of Grant et al. 2020). The most recent WSP process identified seven of the 23 assessed CUs (representing five major forecast stocks, and two miscellaneous stocks) as being in a state of significant conservation concern (i.e., red status; Grant et al. 2020). The COSEWIC status report recommended that eight of the 23 Fraser Sockeye DUs assessed (which generally align with CUs) be listed as Endangered, while characterizing two more as Threatened (Grant et al. 2020, COSEWIC 2017). Recovery potential was assessed quantitatively for nine Fraser Sockeye DUs (Cultus Lake was assessed separately) in 2019, and analyses for three additional stocks assessed as Special Concern with stock-recruitment data were added to the assessment (DFO 2020b). A technical report updating the Recovery Potential Assessment (RPA) results is being prepared to support a Canadian Science Advisory Secretariat (CSAS) Regional peer Review (RPR) of the remaining RPA elements in March 2021 (Ann-Marie Huang, DFO, Vancouver, BC, pers. comm.). Widespread evidence of declines in productivity was found in both the 2019 analysis, and recently updated analysis, using models with time-varying productivity, across stocks designated as Special Concern, Threatened, and Endangered (DFO 2020b). Based on current productivity, two DUs (representing the Early Stuart and Bowron forecast stocks) were deemed unlikely to very unlikely to reach their recovery target; six DUs were considered as likely as not to reach their recovery target (Upper Barrier, Weaver, Raft, Late Stuart, and Birkenhead), and two DUs were likely or very likely to reach their target, at low mortality rates (Quesnel and Stellako; DFO 2020b). In the RPA process, the Cultus Lake DU, which was assessed as Endangered by COSEWIC, was deemed unlikely to reach either recovery or survival targets without mitigation measures (DFO 2020a). No allowable harm was identified for the Cultus Lake stock (DFO 2020a).

Most recently, 2019 and 2020 consecutively broke records for the lowest recorded Fraser Sockeye return; signaling a continued decline in productivity. Furthermore, a large landslide in the Fraser Canyon near Big Bar, BC, hampered the migration of adult Sockeye to Northern spawning grounds in 2019 and 2020. Although improvements at the slide site have been made over each subsequent winter, and fish transportation mitigation measures have been employed during migration, effects are expected to persist through the 2021 migration. Approximately 80% of our forecast return in 2021 is attributed to stocks that spawn above the Big Bar landslide.

Changes to the management of fisheries and declines in productivity across most stocks have resulted in reduced fishing opportunities for all sectors. Because of the difficulties associated with in-season management of mixed stock fisheries, Fraser River Sockeye are managed in four aggregates or stock management units (SMUs) based upon shared return timing to the Fraser River. Escapement and harvest plans are made at the run-timing aggregate level, so aggregate forecasts are presented in addition to stock-specific return forecasts.

Fraser Pink salmon

Fraser River Pink Salmon *(O. gorbuscha)* are the largest run of Pink Salmon in BC and exhibit a two year life history. Adults spawn in the fall, fry emerge in the spring and migrate immediately to sea. Adults return a year later to spawn two years after the eggs from which they hatched were deposited. Fraser River Pink salmon have a strong bi-annual pattern with significant returns of adult Pink Salmon occurring only in odd years.

The returns seen in the last three cohorts of Fraser Pink Salmon (2015, 2017, 2019) have been below the long-term average of 11.5 million fish. Generally, fry (which could also be referred to as sub-yearling smolts) are enumerated during their downstream migration, and those values are used to forecast the following year's return. Unfortunately, due to the COVID-19 pandemic, the fry enumeration program did not run in the spring of 2020. Therefore, we do not have fry data available to forecast 2021 returns, and must rely on a highly uncertain escapement time-series to forecast 2021 returns. The fry time-series has been favoured for forecasting because the escapement time-series is considered less consistent through time than the fry data set, due to substantial changes in methodology over time (Figure 6). Estimated escapement in 2019 (8.3 million) were above the long-term average (6.2 million), although these escapement estimates span several different enumeration approaches (Grant et al. 2014).

Forecasting

Forecasting salmon returns has been an area of study for generations of fisheries scientists (see Haeseker et al. 2008 for an overview of salmon forecasting methods). Although forecast methods have not changed dramatically over time, there have been innovations both in the modeling frameworks applied, and the sophistication of the computation (e.g. Cass et al 2006, Grant et al. 2010, MacDonald and Grant 2012). For 2021, the forecasting methods developed in previous years will continue to be used for Sockeye, with some modifications detailed in the methods section below. The exceptional circumstances presented by the COVID-19 pandemic in the Spring of 2020, preventing the enumeration of out-migrating Pink fry, required the use of models that had not yet been tested retrospectively. Rather than follow the exact conventions of MadDonald and Grant (2012) some improvements were made to the breadth of models considered, and the retrospective approach was changed to improve our ability to capture predictive ability of candidate models. Since the Chilliwack Sockeye stock has never had a retrospective analysis carried out, these same approach developed for the pink forecast were tested out for this stock (Appendix 3).

The importance of Fraser River Sockeye salmon to commercial, recreational, and First Nations fisheries means that a quantitative forecast of abundance is required, both to inform pre-season planning of fisheries and assessment, and to serve as informative priors for the in-season run-size assessment programs. The forecast informs planning decisions of the bilateral Fraser Panel, which are used to inform advice to DFO regarding in-season harvest management of Sockeye salmon (Pacific Salmon Treaty 1985).

Analysis and Response

1. Data

1.1 Sockeye Data

Escapement is enumerated by DFO staff using a variety of methods. In general, higher precision methods (hydroacoustic counting sites, counting weirs, complete dead-pitch censuses in spawning channels or mark-recapture studies) are used to enumerate large populations with escapements expected to exceed 75,000 spawners, while lower precision methods (peak count method applied to ground- or aerial-based visual surveys; carcass recovery surveys) are used to enumerate populations with expected escapements less than 75,000 (Scott Decker, DFO, Kamloops, BC, , pers. comm.). The specifics of the escapement programs as well as the escapement estimates are documented by the stock assessment program in annual summary reports and are the primary driver of the forecasts. Brood year effective female spawner (EFS) values for relevant brood years can be found in Table 1B.

Fraser Sockeye data used in the forecast process includes the following:

Spawners

- Effective Female Spawners (EFS) data are used up to the 2017 brood year for all stocks except Harrison (2018 brood year).
- Brood year EFS values are presented in Table 1B. In general, the major stocks EFS are below average for their primary age cohort returning in 2021. For cyclic stocks (Early Stuart, Late Stuart and Late Shuswap), brood year EFS (2017) are below cycle-line average. For non-cyclic major stocks (non-misc.), all stocks except Upper Pitt have brood year EFS values that are below average. For Harrison, both brood year 2017 and 2018 EFS are below historical average.

Juveniles

- Fry data for the 2017 brood year are available for Nadina, Weaver, and Gates stocks. each of these stocks typically has a large proportion of fry production originating from a spawning channel with a monitoring program in place. Due to inconsistencies in data collection methods over time, juvenile data are not used to produce forecasts for Gates. Historically, fry data were available for both the channels and the natural rivers/creeks for these three stocks. In recent years, only channel fry data have been available for Nadina and Weaver, while both channel and creek fry data are available for Gates. Fry data gaps in the historic time series were infilled using the average historical fry/EFS production by stream multiplied by the relevant brood year EFS. This infilling approach is consistent with the previous model settings (Grant et al. 2010; MacDonald and Grant 2012).
- Juvenile smolt abundance data corresponding to the 2017 brood year are available for Cultus and Chilko.

Recruitment

- The most recent brood year for which full recruitment data (four- and five-year-olds) are available for the 2021 forecast (generally 2015 brood year; 2016 for Harrison) is included in the dataset, although values are considered preliminary. In an attempt to capture recent low productivity, and because age-5 returns in 2021 are expected to be very low, we also "completed" the 2016 brood year cohort (2017 for Harrison) using younger age-class data only (generally age-4; age-3 for Harrison. This method was tested in sensitivity analyses and generally resulted in differences of less than 5%.
- A number of recruitment estimates for 2020 were flagged because they were lower than the stock's escapement estimate. All of these flagged stocks had medium and high certainty in escapement estimates (3/5 included sonar estimation). For these stocks, because age-4 estimates can be very important for sibling model estimates, preliminary escapement numbers, with age-proportions from 2020 return estimates applied, were substituted for return values. For the Late Stuart stock, a sibling model was not considered, due to high uncertainty associated with the 2020 return estimate, possibly caused by issues with genetic stock identification (GSI) resolution between Late Stuart and Stellako.
- The time series (by brood year) of EFS, juveniles, and recruitment data used to run the models are from 1948-2017 for all stocks except for Nadina (1973-2017), Gates (1968-2017), Scotch (1980-2017), Fennell (1967-2017), Weaver (1966-2017) and Portage (1953-2017). Additionally, since 2016 a stock-recruit relationship has been used to forecast Chilliwack, although this time-series is quite short -- beginning in brood year 2001 (2001-2017; see Appendix 4).

1.2 Pink Data

Adult returns are estimated by the Pacific Salmon Commission (PSC), while juvenile abundance data are usually collected by Fisheries and Oceans Canada (DFO). In spring 2020, however, the downstream smolt enumeration program at Mission was cancelled, due to the COVID-19 pandemic. This cancellation created a gap in a 26-year time-series of fry abundance (odd years, since 1967 brood-year; Figure 6). The fry time-series had been favoured over an escapement time-series for forecasting returns because of more consistent collection methodology over time (Grant et al. 2014). Escapement methodology has varied considerably since quantitative enumeration began in 1957. From 1957-1991 stream-specific estimates were generated using a variety of enumeration methods. From 1993-2001 a system-wide mark-recapture program was used to estimate total watershed escapement. From 2003-2007 system-wide escapement was estimated indirectly using a CPUE-based test fishery index. Since 2009, a system-wide hydroacoustic estimate has been produced by the Pacific Salmon Commission based on data collected at the Mission hydroacoustic site. As a result, both escapement (and consequently, return) time-series may not be comparable over time, as no calibration work has been completed to account for differences in methodology. Similarly, catch estimation methods have varied over time, owing to differences in run-reconstruction methods between 1959-1977 and 1979-1985, differences in genetic stock identification methods between 1987-2005 and 2007-present (Grant et al. 2014, Steve Latham, Pacific Salmon Commission, Vancouver, BC, pers. comm.). Due to the extraordinary circumstances presented for the 2021 forecast, in the absence of juvenile data from the 2020 outmigration, the inconsistent escapement time-series (1957-2019 brood years) was used for forecasting.

1.3 Environmental Data

In addition to stock-recruitment data, several biological models incorporate the following environmental data (see MacDonald and Grant 2012 for further details):

- Pacific Decadal Oscillation (PDO) in the winter preceding outmigration (November to March) (Zhang et al. 1997, Mantua et al. 1997; data available online; Figure 3)
- Average of monthly sea surface temperature (SST) from Entrance Island lighthouse (Ei; Strait of Georgia, near Nanaimo, B.C.) from April to June, and Pine Island (Pi; Northeast corner of Vancouver Island) from April to July (data available online; Figure 3) of the year of outmigration. The Entrance Island SST for 2018 ocean entry year hadn’t passed the QA/QC protocol at the time of analysis and was substituted with the Departure Bay SST (Peter Chandler, DFO, per. comm.). Departure Bay is geographically close to Entrance Island (the distance is 10.6km) and Departure Bay monthly SST is correlated with Entrance Island monthly SST historically (R^2=0.66 for average April-June monthly SST from 1950-2019).
- Peak Fraser Discharge (FrD-peak) and average Fraser Discharge (FrD-average) from April to June of the outmigration year measured at Hope, BC (David Patterson, DFO, Vancouver, BC, pers. comm.; Figure 4).
- For the Pink forecast, the above data are used, as well as sea surface salinity (SSS) during the summer of the outmigration year (2020 for 2019 brood year). Values were averaged across two lighthouses; Amphitrite Point and Race Rocks. Values were averaged across either July-September, or July-August, both of which have been used in previous Pink forecasts (Figure 5).

2. Forecasting Methods

2.1 Fraser Sockeye Forecast Method

The 2021 Fraser Sockeye forecasts follow a similar approach as recent forecasts (MacDonald and Grant 2012; DFO 2013; DFO 2014a; DFO 2015a; DFO 2016a, DFO 2017, DFO 2018, Hawkshaw et al. 2020a, Hawkshaw et al. 2020b), which were adapted from methods used in earlier forecasts (Cass et al. 2006).

For 19 major stocks, forecasts are based on a model selected from a shortlist of top-ranked models, by consensus of a group of experts. Table 4 lists the full suite of candidate models. For most miscellaneous stocks (which generally do not have recruitment data), forecasts are based on brood year escapements and long-term observed survival rates for proxy stocks. The exception is Chilliwack, which is still designated as a miscellaneous stock, and was forecast using this approach until recently (DFO 2016a), but is now forecast using a stock-recruit relationship (see Appendix D of Hawkshaw et al. 2020b). For the 2021 forecast, a retrospective analysis was carried out to guide model selection for Chilliwack, the details of which are outlined in Appendix 4.

Model performance, ranking, and the primary model selection process for Fraser Sockeye Salmon are based on the jack-knife retrospective analyses conducted in 2012 (MacDonald and Grant 2012). Given the environmental conditions and poor productivity observed in recent years, an additional criterion was added during the 2017 model selection process where under certain conditions, environmental covariate models would be favoured over biological models (i.e., stock-recruit models) without environmental covariates (DFO 2017). Further attempts in recent years to capture historically poor productivity have led model selection to become more of an expert-driven process, that hasn’t fit neatly into the model selection criteria laid out in previous years. In an attempt for improved transparency, model selection criteria were revisited this year, and the conventions re-written to reflect this expert-driven process. Appendix 1 outlines the approach taken for model selection for 2021.

For many stocks, top-ranked models without climate-driven covariates, tended to provide forecast estimates at productivity levels far higher than those observed recently (Table 2). In many cases, the only models that provided forecast values near recently observed productivity levels were either forecast models with climate-driven covariates, or naïve models based on recent recruit-per-spawner (RS) estimates (such as RS4yr and RS8yr). In general, the expert group did not favour these naïve models, even when they had high rankings (see Appendix 1 for further explanation), and favoured biological models that could better capture density-dependent dynamics, and allow for the incorporation of potential environmental drivers of low productivity. An exception to this convention was made in extreme cases, where the productivity implied by all candidate biological models far exceeded recent observed productivity. This exception was flagged for a number of stocks by comparing the recent generational average productivity (see Table 2) to the productivities implied at the various forecast probability levels (from 0.1 to 0.9 posterior quantiles; described as P10-P90 in this document). A convention was adopted that if the last generation’s average productivity was below the productivity implied at the P10 forecast level for the top-candidate biological model, then it was deemed that none of the biological models were able to adequately capture recent productivity dynamics. In these cases, an RS8yr model was considered. The forecast productivity from the P10-P90 level using the RS8yr model was also compared to the variability observed in the last few generations, and was only used if it captured the substantial variability in productivity observed in recent years. As a result, RS8yr models were used for five stocks, including the Chilko stock; lowering the forecast substantially. Details on stock-specific model choice rationales can be found in Appendix 3.

For the last several years, sibling models have been used to attempt to inform older age-class productivity, using return data from their brood-year mates that returned the year before. A description of the sibling model can be found in the 2019 forecast document (Hawkshaw et al. 2020a), and a description of the recently updated sibling model selection criteria can be found in the 2020 forecast document (Hawkshaw et al. 2020b). In the context of 2021, the goal of using sibling models is to forecast older age class fish at productivity levels in line with recent, low, productivity. Therefore, an additional criterion was added to the selection of sibling models such that they are not applied when they moved the forecast productivity further away from recently observed productivity. Since in most cases, the biological models tend to provide forecasts implying productivity above recently observed levels (and more in line with historic averages), the application of this criterion generally meant that sibling models were rejected when they increased the forecast return. As a result, sibling models were not used for four stocks that would have used them based on model fit criteria, but since these were all very small stocks, it had a minimal effect on overall forecast returns (Table 8).

For 2021, the sibling model code was re-written so that it produces prediction intervals, rather than credible intervals. Sibling models used in the past had estimated P10-P90 levels using credible intervals, which estimate within-sample uncertainty, although a more appropriate measure of uncertainty for an out-of-sample uncertainty would have been a prediction interval (which takes into account the uncertainty associated with the likelihood function; and is the approach taken for other forecast models used here). This change resulted in wider uncertainties (lower P10 and P25 values, higher P75 and P90 values) but had no effect on median (P50) estimates.

Sibling models were used to forecast upper age-class returns for eight major stocks in 2021 (Upper Barrier (Fennell), Nadina, Pitt, Scotch, Stallako, Harrison, Raft, Cultus; Table 8). The comparisons of coefficient of determination (R^2) values for the major models and sibling models are summarized in Table 8.

The Chilliwack (misc.) stock has been forecast using a Ricker model since it was decided that the stock-recruit time-series was long enough to facilitate the use of stock-recruit models in 2017. A Ricker model was chosen somewhat arbitrarily, and a retrospective analysis of candidate models has never been carried out. Therefore, for 2021, a retrospective analysis of candidate models for Chilliwack was carried out, following the same modelling approach used this year to determine the forecasting model for Pink salmon. Details of this analysis can be found in Appendix 4. The final chosen model was a Power model for age-4's, combined with a sibling model for age-5's.

For miscellaneous stocks (except Chilliwack) for which stock-recruitment data are not available, recruits-per-spawner estimated from proxy stocks are used to forecast returns. Proxy stocks used for each miscellaneous stock can be found in Appendix 2.

2.2 Fraser Pink Salmon Forecast Methods

In order to identify the model to be used for the 2021 forecast, a suite of candidate models were proposed and compared using retrospective analysis. For biological models, both Ricker and Power models were assessed, while non-biological (naïve) models based on previously observed recruits-per-spawner were applied as well. In order to identify candidate models to be tested retrospectively, sequential multiple linear regressions were carried out using both Ricker and Power relationships to identify potential environmental covariates. The same suite of environmental covariates considered for Sockeye stocks (metrics of Fraser River discharge, sea surface temperature, PDO) as well as the two metrics of sea-surface salinity used in previous Pink forecasts, were tested as potential covariates. In Sockeye forecasts, average monthly sea-surface temperature (SST) at Pine Island and Entrance Island lighthouses, and monthly Fraser discharge data were averaged across applicable months to create a single index. For this analysis we considered these monthly environmental variables on their own (for example, May Pine Island SST, April Fraser Discharge), and also in their summarized forms (averaged over months) used in the Sockeye forecasts. Simple linear models were fit in R (R Core Team, 2020) and covariates with the highest p-values were removed sequentially, until all covariates were significant at the $p \leq 0.05$ level.

When considering monthly average Fraser discharge and SST variables separately, several covariates were highly correlated. Therefore, before sequential elimination of covariates was carried out, an assessment of the correlation structure between covariates was carried out. In cases where high correlation was observed (correlation coefficient >0.75), one of the highly correlated covariates was eliminated. For example, average June discharge and peak discharge were highly correlated (correlation coefficient = 0.89) so peak discharge was retained, and June discharge eliminated to start. In addition, all of the Pine island SST's were highly correlated with each other, so May SST was used, as it wasn't highly correlated with any of the Entrance island SST's (and could therefore be considered together in models without concerns about collinearity).

Once a set of models with statistically significant environmental covariates was reached, the final set of candidate models, which would be tested retrospectively, were identified using the Akaike information criterion (AIC; Akaike 1974). If a covariate from a highly correlated pair of covariates was present in a final model (with all covariates significant at the $p \leq 0.05$ level), the other covariate in that pair would be substituted back into the model and tested for goodness of fit as well. First, a "best" model was identified using AIC, and any models within three delta-AIC units of the best model were assessed using retrospective analysis. Various combinations of interaction terms were tested on the set of best models, but never found to be statistically significant (at the $p \leq 0.05$ level). Following initial model review by model selection meeting participants, there was a desire to include some simpler models (with single environmental covariates) to better understand the individual effects of certain covariates. Following this feedback, additional models were added, that may have not been within 3 AIC units of the best model, but had statistically significant single covariates (models 14-19).

1. Power model with no covariates (Power);
2. Power model with April Fraser discharge, June Entrance Island SST, average SSS from July to August (Power_AprFrD_JunEi_JulAugSSS);
3. Power model with average Entrance Island SST, average SSS from July to August (Power_Ei_JulAugSSS);
4. Ricker model with no covariates (Ricker);
5. Ricker model with average June Fraser discharge, May Pine Island SST (Ricker_JunFrD_MayPi);
6. Ricker model with peak Fraser discharge, May Pine Island SST, average sea-surface salinity from July to September (Ricker_FrDpeak_MayPi_JulSeptSSS);
7. Ricker model with average Pine Island SST, average sea-surface salinity from July to August (Ricker_Pi_JulAugSSS);
8. Ricker model with peak Fraser discharge, average Pine Island SST. (Ricker_FrDpeak_Pi);
9. Ricker model with peak Fraser discharge, May Pine Island SST (Ricker_FrDpeak_MayPi);

10. MRS_log – historical average mean log-recruits-per-spawner applied to brood year escapement, using a log-normal distribution;
11. MRS – historical average mean recruits-per-spawner applied to brood year escapement;
12. RS1 – Previous run's recruits-per-spawner applied to brood year escapement;
13. RS2 – Average of two previous run's recruits-per-spawner applied to brood year escapement;
14. Ricker with July-August SSS (Ricker_JulAugSSS);
15. Power with July-August SSS (Power_JulAugSSS);
16. Ricker with May Pine Island SST (Ricker_MayPi);
17. Ricker with June Pine Island SST (Ricker_JunPi);
18. Ricker with July Pine Island SST (Ricker_JulPi); and
19. Ricker with Avg. Pine Island SST (Ricker_Pi).

In order to assess forecasting performance of each of these models, a one-step-ahead retrospective analysis was used. This approach was favoured over the previously used jack-knife approach as it better captures predictive ability. A jack-knife approach does not truly assess predictive ability, since it uses data *after* the prediction period for model fit – it is more generally used as a metric of model fit. One-step ahead analysis simulates the reality of forecasting, since it only uses data that would have been available leading up to a given year, in order to produce that year's forecast. Using a one-step ahead retrospective approach is a much more common convention in fisheries science to assess the performance of forecasting models than using a jack-knife approach, including Puget Sound salmon forecasts (Dr. Mickey Agha, Washington Department of Fish and Wildlife, Olympia, WA, USA, pers. comm.) and the Bristol Bay Sockeye forecast (Dr. Curry Cunningham, University of Alaska Fairbanks, Juneau, AK, USA, pers. comm.; also see Haeseker et al. 2005, 2007, 2008; Ward et al. 2014; Brooks and Legault 2015; Thorson 2018).

Initially, this retrospective analysis was carried out for return years 2011-2019 (brood years 2009-2017). These years were chosen because return and escapement enumeration methods changed between return years 2007 and 2009, and there was a desire to focus on years with estimates made during the most recent enumeration "regime". Following feedback on this approach, the retrospective analysis was expanded to include the last 15 return years (1989-2019). Results for both were considered in the model selection process.

Performance was measured using a series of forecasting error metrics:

1. Mean absolute error (MAE);
2. Mean Percent error (MPE);
3. Root-mean-square error (RMSE);
4. Mean absolute percent error (MAPE);
5. Mean arctangent absolute error (MAAPE); and
6. Mean absolute scaled error (MASE).

The first three error metrics have been used in previous Fraser Sockeye retrospective analyses (see MacDonald and Grant 2012), but the latter three have not been previously used:
MAPE:

$$\frac{1}{N}\sum|\frac{A_t - F_t}{A_t}|$$

Where A_t is the actual value, and F_t is the forecast value in year t, and N is the number of forecast years. MAPE is a widely used measure of forecast accuracy, in a similar way to RMSE, except errors are scaled by actual values, to reduce the relative weight of abundant years compared to less abundance years (i.e., it is scale-free). Mean Proportional error also uses scaled observations, but since it isn't in absolute terms, it is measuring bias, rather than accuracy.

MAAPE:

$$\frac{1}{N}\sum \arctan|\frac{A_t - F_t}{A_t}|$$

MAAPE was developed in 2016, as a more robust alternative to MAPE (Kim and Kim 2016). MAPE has the weakness that it becomes unstable when true values (A_t) approach 0, MAPE approaches infinity. MAAPE has very similar properties to MAPE, but avoids this pitfall, and is more robust as true values approach 0.

MASE:

$$\frac{\frac{1}{N}\sum A_t - F_t}{\frac{1}{N-1}\sum_{t=2}^{N} A_t - A_{t-1}}$$

MASE is a scale-free accuracy measure, like MAPE and MAAPE, and near-zero true values will not cause instability, as is the case with MAPE. MASE has the desirable property that it is symmetrical – meaning that it penalizes over- and under-forecasting equally, whereas all other metrics will penalize over-forecasting more than under-forecasting.

Mean raw error was excluded from this analysis due to the potential for large overestimates and large underestimates "cancelling each other out" and resulting in a misleading metric of performance. MPE has been left so that there is one metric that would flag any substantial bias.

In addition to the candidate models applied retrospectively, the actual historical forecasts (pulled from past forecast documents) were included for comparison for the five-year retrospective analysis (forecast values going back as far as 1989 were difficult to source).

Following the retrospective analysis, we provided 2021 estimates for all biological models (no naïve models performed well in retrospective analysis, so these were not included in output tables and figures, for brevity). Unfortunately, estimates from the Entrance Island lighthouse for Spring 2020 were not yet available at the time of analysis, and so biological models using Entrance Island covariates could not be considered for the 2021 forecast. We attempted to use Departure Bay lighthouse data in the place of Entrance Island, but could not replicate the statistically significant relationships found using Entrance Island data.

As a further diagnostic, we identified a year with similar conditions faced by the cohort returning in 2021 (2019 brood), and compared performance of each model in that year. To identify the most similar years we simply calculated percent absolute deviates from 2020 ocean entry values across all environmantal covariates present in our top models as:

$$Deviate_i = (Y_i - Y_{2020})/Y_{2020}$$

Where Y_i is any one of the candidate environemental covariates, in year i. Then, across all environmental covariates, took an average of these deviates for each year. This allowed us to identify 1974, 1986, and 2014 as the most similar years, in terms of environmental conditions, to

2020 ocean entry. 1974 and 1986 didn't provide useful comparisons because they are quite early in the time series, and therefore were not included in the retrospective analysis, and also didn't show higher-than-average temperatures and Pine Island, which is a predominant feature of 2020 ocean entry. 2014 was identified as the best candidate for comparison, since it has all the same qualitative attributes of 2020 (above average Pine Island SST, above average June and Peak Fraser Discharge, below average SSS). Escapement estimates were also similar between the 2013 and 2019 cohorts, at 9.3 and 8.3 million, retrospectively, so any density-dependant affects on productivity wouldn't be expected to be significantly different for these cohorts. Although 2014 has the same directional differences in these key environmental variables, none of the environmental conditions were as extreme in 2014 as they were in 2020.

3. Results

3.1 Fraser Sockeye 2021 Forecast

The total Fraser River Sockeye return in 2021 is forecast to be 1.33 million fish (80% PI:313,000-5,496,000). Stock-specific forecasts are presented in Table 1A and Appendix 2. This return forecast is well below the cycle average return (7.4 million), and lower than the all-cycle average return (8.3 million; Table 1B). Abundance is dominated by the summer run management group; contributing 79% of the forecast return in 2021. The forecast return is dominated by age-4 fish (91%; Table 3), and fish that spawn above the Big Bar landslide (80%), at the P50 level. The Late Stuart, Chilko, and Quesnel stocks are forecast to be the primary contributors to this year's return, contributing 23, 25, and 26%, respectively, at the P50 level (Table 6).

The Early Stuart aggregate is composed of a single stock and the median (P50) forecast return is 18,000 fish (80% PI:8,000- 47,000). This forecast is based on a Ricker model with the Pine Island sea surface temperature as an environmental covariate. The low forecast return is driven mostly by a combination of low escapements in 2016 and 2017 (Table 1B), and high sea surface temperature at Pine Island for the forecast period (Figure 3).

The Early Summer Sockeye aggregate is composed of eleven stocks, representing nine CUs (see Grant et al. 2020 for detailed descriptions of the CUs), which are divided into seven major stocks and four miscellaneous stocks, although one "miscellaneous" stock, Chilliwack, is now modelled using a stock-recruit relationship (see Appendix 4 for details). The median forecast for this management group is 108,000 fish (80% PI: 33,000-375,000). The individual forecasts within the management group are made with a variety of models (Table 1A). The lower-than-average forecast for this aggregate's returns are driven by a combination of lower-than-average escapement for most stocks (exceptions being Nadina 2016, and Upper Pitt 2016/2017; Table 1B), and warm environmental conditions (five stocks have sea-surface-temperature covariates; Figure 3). For five stocks in the early summer aggregate (Upper Barrier, Nadina, Pitt, Scotch, Seymour, and Chilliwack), sibling models are used in order to take advantage of the relationship between age 4_2 returns in 2020 and age 5_2 returns in 2021. Further details on individual stock model selection rationales can be found in Appendix 3.

The Summer Sockeye aggregate is composed of six major stocks and three miscellaneous stocks, comprising seven CUs (see Grant et al. 2020 for detailed descriptions of the CUs). The median forecast for this management group is 1,046,000 fish (80% PI: 232,000-4,502,000). The lower-than-average forecast returns in this aggregate are driven by generally lower-than-average escapements (Table 1B), warm environmental conditions (four major stocks use SST covariates; Figure 3), and the use of sibling models (for Stellako, Harrison, and Raft).

For Chilko Sockeye, in recent years, a Larkin model has been used. Initially this model was chosen for 2021, as it is top-ranked, and provides the lowest forecast, better reflecting recent historically low productivity observed for this stock (see Figure 2). However, this stock was identified as a case in which none of the candidate biological models captured recent productivity, even at the P10 level, since last generation's average productivity has been the lowest on record, at 0.67 age-4-recruits-per-EFS. This fell well below the implied productivity at the P10 level for the Larkin model (1.51 age-4-recruits-per-EFS). Therefore, an RS8yr model was used for Chilko, as it was found to better capture the range of productivity observed in the last several generations. The use of the RS8yr model for Chilko had a considerable impact on the overall forecast; reducing it by approximately 600,000 fish relative to the Lakrin model.

Another large contributing stock that presented a difficult forecasting scenario for 2021 is the Quesnel stock. The Quesnel stock is highly cyclic, but seemed to "skip" a dominant year for brood year 2005, with a small dominant year occurring for brood year 2006 instead, and occurring in four-year intervals since then (2010, 2014, 2018 brood years). This event coincided with a significant decline in productivity from values seen historically, which appears to have started in the early 1990's. Although peaks in productivity more in line with historical values were observed for the 2010 and 2011 brood years, productivity has remained low in the last four observed brood years (recent generational average productivity observed at 1.35 age-4-recruits-per-EFS; Table 2). None of the candidate biological models were able to capture this recent, extremely low, productivity observed at Quesnel (Table 2; Appendix 2 – Table A2-22). Based on our new naïve model criteria, an RS8yr model wouldn't have been considered for this stock, since the recent generational average productivity is just above the productivity implied at the P10 level by the top candidate model, at 1.14 age-4-recruits-per-spawners (Table 2). Because there have been two peaks in productivity in the last eight years, the RS8yr model would have produced a higher forecast than most other candidate biological models and so it would not have been a viable option to capture the recent low productivity state. Therefore, a Ricker model with Entrance Island SST as a covariate was chosen, despite concerns that it may be over-forecasting for this stock. At the P50 level, the forecast implies 5.55 age-4-recruits-per-EFS; significantly higher than the estimated value for the last generation (1.35). Additionally, concerns have been flagged about freshwater conditions faced by the 2017 brood year at Quesnel. This system is especially prone to warm temperatures, and warm Fraser temperatures observed during the summer run could have posed problems for this stock. Both gamete viability and lipid content metrics for this stock are below thresholds normally used to identify poor spawning success and smolt viability, respectively, for the 2017 brood year (see Appendix 5 for further details). These potential issues with freshwater productivity and survival are especially relevant for the 2021 forecast, given that Quesnel is forecast to be the top-contributing stock in 2021, making up 25% of the forecast at the P50 level. If this stock returns at productivity levels in line with observed productivity in the last four years, then the forecast in its current form will be a large over-estimate at the stock-scale for Quesnel, but also at the aggregate scale for the Summer run, and even for Fraser Sockeye overall.

The Late Sockeye aggregate is composed of six CUs represented in the forecast by five forecast stocks and one miscellaneous stock (see Grant et al. 2020 for detailed descriptions of the CUs). The median forecast for this management group is 159,000 fish (80% PI: 40,000-572,000). Forecasts for individual stocks within the management group are made with a variety of models (Table 1A). The lower-than-average forecast returns in this aggregate are driven by lower-than-average escapements (Table 1B) and recent significant declines in productivity observed for Portage, Weaver, and Birkenhead for which RS8yr models were used to attempt to capture these recent, significant declines. The remaining two forecast stocks (Cultus and Late Shuswap) were modelled using SST covariates, which further reduced forecast returns.

3.2 Fraser Pink 2021 Forecast

In general, model fits were moderate-to-poor, without any one model explaining more than 49% of the variation seen in recruitment (Figure 7; R^2 values in Table 10). Model fits appear to be quite poor in the 1985-2005 period, but seem to have improved in recent years (Figure 7). For the five-year retrospective, across all performance metrics, the top-ranked model was a Ricker model with the environmental covariates of average June Fraser discharge and average May Pine Island SST (Ricker_JunFrD_MayPi; Table 9; Figures 7 and 8). Interestingly, several models out-performed the historical forecast values, which are based on a juvenile-Power model with average July-September sea-surface salinity as a covariate (Power-Juv-SSS), which ranked 11th in the five-year retrospective analysis (Table 9; Figure 8).

As a further exploration, the same retrospective analysis was carried out for 15 years (1987-2017 brood years) to determine the sensitivity of the results to varying time-frames (Figure 9). Our top-ranked model from the five-year retrospective, a Ricker with June discharge and May Pine Island SST covariates (Ricker_JunFrD_MayPi) did not perform as well in the 15-year retrospective, falling into 12th place, when averaging ranks across metrics. A Ricker model with Peak discharge, May Pine Island SST, and July-Sept SSS as covariates (Ricker_FrDpeak_MayPi_JulSeptSSS) came out as the top model in the 15-year retrospective, and a close second in the five-year retrospective. This model also had the highest R^2 value of all models available for use in 2021 when fitted to the entire time series (Table 10). Two other models had higher R^2 values, but could not be considered for 2021 due to missing data for Entrance Island, however, these models weren't ranked as high in either the five-year or 15-year retrospectives.

For the 2015 return year, which had similar (although less extreme) environmental signals to 2021, all of our candidate biological models for 2021 would have over-estimated returns (Table 11). The best performing model in 2015 would have been a Ricker model with peak Fraser discharge, May Pine Island SST, and July-September SSS as covariates (Ricker_FrDpeak_MayPi_JulSeptSSS). The actual forecast published in 2015 using the Juvenile-SSS model was 14,455,000 – far overestimating the true return of just under 6 million (DFO 2015a).

The environmental indicators for 2021 returns (2020 outmigration) are all unfavourable. All discharge and temperature indicators are high and associated with lower returns. Higher salinity indicators were associated with higher returns, and 2020 values were very low, likely indicating poor upwelling and marine productivity. The combinations of environmental covariates "pulled" forecasts down to varying levels, compared to basic Ricker and Power model results.

The Ricker model with Peak discharge, May Pine Island SST, and July-Sept SSS as covariates (Ricker_FrDpeak_MayPi_JulSeptSSS) presented itself as a strong candidate model for 2021, as it performed well in both the five-year and 15-year retrospective and has the highest R^2 value of the available models for 2021 (Table 10). This model provides the lowest forecast return for 2021 (P50=3,009,002; Table 10). This estimate is very similar to the one provided by the top model from the five-year retrospective (Ricker with June discharge and May Pine Island SST covariates; P50 = 3,072,791). The second-ranked model from the 15-year retrospective (Ricker with average Pine Island SST covariate) may not be a good choice for the 2021 forecast, since it performed poorly in the five-year retrospective (ranked 8th) and would have over-predicted returns by more than double in 2015, under similar environmental conditions (Table 11). Following the initial forecast model review meeting, there was a desire to review simpler models with single covariates, to determine the magnitude of the effect of some of the key environmental predictors. Of these models, a Ricker model with May Pine Island SST

(Ricker_MayPi) performed best – ranked 8th in the five-year retrospective and second in the 15-year retrospective (Table 10). However, based on the large discrepancy between the forecast produced by this model, and ones that included discharge and/or SSS indicators, it was concluded that a more complex, better performing model was a better choice because it would not to miss an important environmental signal.

A Ricker model with Fraser peak discharge, May Pine island SST, and July-September SSS was chosen for the final forecast. This choice was driven by a desire to capture the anomalously poor environmental conditions observed during the 2020 outmigration, and was bolstered by the fact that in 2015 this model would have performed best, even though it would have overestimated returns by about two million fish. This model can be considered conservative, as it is predicting productivity near the historical minimum (Figure 10).

Despite this model choice being driven by an up-to-date and rigorous retrospective analysis, the uncertainty of the underlying data should not be overlooked. The uncertainty intervals provided from the P10-P90 level do not capture the full range of uncertainty presented by these models, and their underlying data because we have not incorporated the uncertainty associated with either the escapement or recruitment time series. Doing so in a comprehensive way, accounting for the numerous changes in monitoring programs over the years is a complex statistical exercise that was outside the scope of this analysis. Therefore, it is recommended that managers using these values for 2021 treat this forecast with exceptional caution, and consider that the uncertainty level provided likely does not capture the full range of possible outcomes for this year's return.

4. Discussion

4.1 Recent Performance of Fraser Sockeye Forecast Models Under Environmental Changes

Recent returns have been consistently below the median forecast, and in the last five of six years the aggregate return has been below the P25 value, with 2019 and 2020 returns falling at or below the P10 level (Table 5). These outcomes could be a result of many different factors (see Hilborn and Walters 1992 or Walters and Martell 2002 for a discussion of problems with stock-recruitment models), but points to the need for a re-evaluation of our candidate models, and our model selection process. The current forecasting framework is dependent on model rankings that are at least nine years out of date, and environmental conditions during this time have become increasingly warm and volatile (see Appendix 5 for more context on current environmental conditions).

Given the recent pattern of lower-than-long-term-average productivity, exploration of environmental predictors of marine and freshwater survival (which both contribute to overall productivity) and advice for their use in forecasting salmon returns should be undertaken. Environmental variability or persistent long-term changes in environmental conditions can lead to non-stationarity in stock recruitment parameters (Beamish and Mahnken 2001, Peterman and Dorner 2012). Being able to better relate changes in productivity to environmental indices would likely improve forecasts. With increasing uncertainty in ocean and freshwater environments, there should be a renewed focus on the collection/compilation of relevant indices of ocean conditions, freshwater limnological data, and juvenile Sockeye assessment. Many authors have demonstrated that juvenile rearing habitat and spawning area can be used to establish population capacity estimates for Sockeye and other salmon (Hume et al. 1996, Cox-Rogers et al. 2004). Incorporating additional data sources (for example: juvenile abundance estimates, freshwater abundance indices, additional environmental variables) could reduce uncertainty

(Punt and Hilborn 1997, Maunder 2003, Gelman 2013, Thorson and Cope 2017). Limnological and juvenile data are prerequisites for the types of informative priors that can be used to improve the ability to forecast returns in a Bayesian framework. Given that climate change is expected to drive changes to lake rearing environments, tracking these changes should reduce the lag in detecting both regime shifts or non-stationarity in stock recruitment parameters and improve forecasts (Vert-pre et al. 2013, Perälä 2016). While indices of physical marine conditions are more readily available, choosing appropriate indices and model forms based on a mechanistic understanding of marine dynamics, is a much more complex process. Based on preliminary work by the authors exploring alternative model forms, stock-recruit relationships are still the dominant process for most stocks, and important environmental relationships tend to be non-linear and variable across stocks.

It is recommended that a new retrospective model selection exercise is undertaken to provide advice on the best performing forecast models under current conditions. As part of this retrospective analysis, quantitative comparisons of the performance of models that include sibling information needs to be undertaken. Considerable effort to capture recent declines in productivity have been made in the 2021 forecast, but our suite of simple models that only allow for single environmental covariates to be considered at a time, limited our ability to capture these complex dynamics, and our forecast will likely continue to be overly optimistic as a result. If we were to expect the productivity of the cohort returning in 2021 to be similar to productivity observed in the most recent generation, then we would be more likely to see returns at approximately the P25 level, when looking at the watershed as a whole (Table 2).

Conclusions

Recent returns for Fraser Sockeye have been historically low, with 2019 and 2020 consecutively breaking records for the lowest Fraser Sockeye returns (Figure 1). Forecasts in the last five years have not been able to capture this pattern, and have consistently over-estimated returns (Table 5). Attempts have been made in this year's forecast model selection process to better capture recent declines in productivity. Based on the changes made, it is likely that we have done a better job of capturing these declines for many stocks. However, the most recent generational (four-year) average productivity continues to predict returns closer to the P25 level (624,000), than the P50 level (1,330,000). In 2021, 91% of Sockeye returns are expected to be age-4 fish, and total brood in 2017 was higher than in 2016 (Table 1B). While some freshwater indicators are better for the 2017 brood than they were for the 2016 brood year, especially for the large Chilko stock, another large contributing stock, Quesnel, has shown some indications of poor freshwater productivity and survival for the 2017 brood (Appendix 5). Unfortunately, marine heat wave conditions experienced by Sockeye that returned in 2020 have persisted. These warm conditions are associated with a shift from northern, lipid-rich, zoopklankton, towards smaller, southern zooplankton, which are a poorer food source for salmon (Appendix 5).

Pink salmon presented an especially difficult forecasting scenario for 2021, without the collection of juvenile downstream migration data. Novel methods, using an inconsistent time-series of escapement data were used for the 2021, and therefore caution is urged for managers using this forecast. The uncertainty captured in the forecast ranges presented for Pink Salmon in 2021 do not fully capture the full range of uncertainty present in making this prediction. While the forecast value of 3.009 million Pink Salmon is highly uncertain, it is also likely conservative, given that it implies productivity near historical lows

Tables

Table 1A. The 2021 Fraser River Sockeye forecasts. Forecasts are presented from their 10% to 90% probability levels (probability that returns will be at or below the specified run size). At the mid-point (median value) of the forecast distribution (50% probability level), there is a one in two chance the return will fall above or below the specified forecast value for each stock, based on the historical data. Results above 1,000 have been rounded to the nearest 1,000; between 100 and 1,000 to the nearest 100; and between 10 and 100 to the nearest 10. Model descriptions can be found in Table 4.

Run timing group / Stocks	Forecast Model	Probability that Return will be at/or Below Specified Run Size				
		10%	25%	50%	75%	90%
Early Stuart	*Ricker (Pi)*	8,000	12,000	18,000	30,000	47,000
Early Summer Total		33,000	59,000	108,000	207,000	375,000
Total excluding misc. stocks		26,000	46,000	83,000	158,000	280,000
Bowron	*Ricker (Pi)*	100	200	400	700	1,000
Upper Barriere (Fennell)	*Ricker (Pi)4/Sibling5*	300	500	1,000	3,000	5,000
Gates	*RS8yr*	2,000	4,000	9,000	19,000	39,000
Nadina	*PowerJuvFrD-peak4 /Sibling5*	6,000	10,000	19,000	37,000	68,000
Pitt	*Ricker(Ei)4 /Sibling5*	14,000	23,000	40,000	69,000	108,000
Scotch	*Ricker(Pi)4 /Sibling5*	1,000	3,000	6,000	13,000	28,000
Seymour	*Ricker(Ei)*	3,000	5,000	8,000	16,000	31,000
Misc (EShu)	*R/S*	1,000	3,000	6,000	11,000	19,000
Misc (Taseko)	*R/S*	30	60	100	200	300
Misc (Chilliwack)	*Power4/Sibling5*	4,000	6,000	10,000	21,000	44,000
Misc (Nahatlatch)	*R/S*	2,000	4,000	8,000	17,000	32,000
Summer Total		232,000	474,000	1,046,000	2,225,000	4,502,000
Total excluding misc. stocks		228,000	464,000	1,024,000	2,181,000	4,412,000
Chilko	*RS8yr*	71,000	142,000	311,000	677,000	1,366,000
Late Stuart	*Power (Pi)*	62,000	128,000	285,000	600,000	1,241,000
Quesnel	*Ricker(Ei)*	69,000	147,000	331,000	708,000	1,425,000
Stellako	*Larkin4/Sibling5*	21,000	35,000	68,000	128,000	229,000
Harrison	*Ricker(Ei)Odd3/Sibling4*	3,000	8,000	21,000	52,000	120,000
Raft	*Ricker(Pi)4/Sibling5*	2,000	4,000	8,000	16,000	31,000
Misc (N. Thomp. Tribs)	*R/S*	800	2,000	4,000	9,000	18,000
Misc (N. Thomp River)	*R/S*	3,000	8,000	17,000	34,000	70,000
Misc (Widgeon)	*R/S*	90	300	700	1,000	2,000
Late Total		40,000	79,000	159,000	313,000	572,000
Total excluding misc. stocks		37,000	67,000	134,000	267,000	492,000
Cultus	*PowerJuv (Pi)4/Sibling5*	200	500	900	2,000	4,000
Late Shuswap	*Ricker(Ei)*	8,000	16,000	35,000	78,000	149,000
Portage	*RS8yr*	400	800	2,000	4,000	9,000
Weaver	*RS8yr*	23,000	40,000	74,000	136,000	235,000
Birkenhead	*RS8yr*	5,000	10,000	22,000	47,000	95,000
Misc Harrison/Lillooet	*R/S*	3,000	12,000	25,000	46,000	80,000
TOTAL SOCKEYE SALMON		313,000	624,000	1,330,000	2,775,000	5,496,000
Total Sockeye excluding misc. stocks		299,000	589,000	1,259,000	2,636,000	5,231,000
TOTAL PINK SALMON	*Ricker(FrD-peak _MayPi_JulSepSSS)*	1,701,000	2,229,000	3,009,000	4,051,000	5,375,000

Table 1B. Fraser Sockeye brood year effective female spawners (EFS, except smolts for Cultus) for the four- and five-year-old recruits returning in 2021 (2017 and 2016 brood years). Brood year EFS are colour-coded by comparing to the cycle-line average from the historical time series (start years vary; "Mean EFS, Cyc. Years" column). Fraser Sockeye average run sizes are presented across all years and for the 2021 cycle-line for each stock. Median 2021 forecast returns for non-miscellaneous stocks are compared to cycle averages for colour-coding ("Mean Run Size, Cyc. Years" column). Red, yellow, and green shading represents below, near, and above average, respectively. With the near-average range defined as average +/- 0.5 standard deviation of historical time series. For Harrison, 2018 EFS are presented in the 2016 EFS column. For the Cultus stock we have presented brood year smolts, instead of EFS. For Pink salmon, 2019 escapements and 2021 median forecast returns are presented, and compared to historical averages for colour-coding.

Run Timing Group Stocks	2017 EFS	2016 EFS	Mean EFS		2021 FC Return	Mean Run Size	
			All Years	Cyc. Years		All Years	Cyc. Years
Early Stuart	**7,000**	**4,000**	**40,000**	**99,000**	**18,000**	**273,000**	**710,000**
Early Summer (excl. misc.)	**29,000**	**51,000**	**62,000**	**40,000**	**83,000**	**495,000**	**252,000**
Bowron	100	70	4,000	3,000	400	34,000	22,000
Upper Barriere	400	600	3,000	1,000	1,000	21,000	11,000
Gates	3,000	4,000	4,000	4,000	9,000	49,000	42,000
Nadina	2,000	16,000	9,000	10,000	19,000	82,000	61,000
Pitt	19,000	30,000	14,000	15,000	40,000	68,000	73,000
Scotch	2,000	500	10,000	3,000	6,000	106,000	20,000
Seymour	2,000	200	19,000	4,000	8,000	135,000	24,000
Misc(EShu)	800	100	9,000	600	6,000	-	-
Misc(Taseko)	10	80	1,000	400	100	-	-
Misc(Chilliwack)	3,000	30,000	3,000	1,000	10,000	34,000	10,000
Misc(Nahatlatch)	1,000	800	1,000	900	8,000	-	-
Summer (excl. misc.)	**413,000**	**120,000**	**529,000**	**841,000**	**1,024,000**	**3,607,000**	**6,191,000**
Chilko	213,000	66,000	223,000	157,000	311,000	1,333,000	841,000
Late Stuart	80,000	5,000	67,000	210,000	285,000	492,000	1,485,000
Quesnel	60,000	200	150,000	420,000	331,000	1,223,000	3,516,000
Stellako	49,000	16,000	55,000	32,000	68,000	437,000	232,000
Harrison[c]	8,000	29,000	29,000	17,000	21,000	92,000	92,000
Raft	2,000	4,000	4,000	4,000	8,000	29,000	25,000
Misc(N. Thomp. Tribs)	700	200	300	400	4,000	-	-
Misc (N. Thomp. River)	2,000	2,000	2,000	4,000	17,000	-	-
Misc (Widgeon)	80	90	300	300	700	-	-
Late (excl. misc.)	**33,000**	**14,000**	**397,000**	**56,000**	**134,000**	**2,898,000**	**645,000**
Cultus[d]	300	100	800	100	900	34,000	11,000
Late Shuswap	8,000	20	335,000	9,000	35,000	2,217,000	50,000
Portage	400	20	3,000	3,000	2,000	39,000	44,000
Weaver	14,000	90	18,000	16,000	74,000	304,000	284,000
Birkenhead	10,000	13,000	40,000	28,000	22,000	305,000	255,000
Misc(Non-Shuswap)	4,000	2,000	2,000	2,000	25,000	-	-
Total Sockeye	**482,000**	**189,000**	**1,028,000**	**1,036,000**	**1,259,000**	**7,273,000**	**7,798,000**
Total Pink Salmon	**2019** **8,307,000**	**-**	**Mean Esc.** **6,187,000**	**-**	**3,009,000**	**11,493,000**	**-**

Table 2. Historical productivity (recruits-per-EFS) historical mean, peak generational mean, min. generational mean, recent generational mean (all geometric means, four-year generations) compared to those implied by the 2021 forecast. An age-group is included if is made up 20% or more of the 2021 forecast for each stock or stock aggregate. To provide context for the productivity implied by the 2021 forecast, we provide the approximate posterior quantile of the 2021 forecast productivity where the recent general average falls. Colour-coding is based on comparison with historical average productivity ("Geo. Average R/EFS" column), with the near-average range (yellow) defined as mean +/- 0.5 standard deviation, and green and red values indicating productivity above and below these values, respectively.

Stock	Age	Forecast Age Prop.	Geo. Average R/EFS	Peak Geo. Avg. R/EFS	Min Geo. Avg. R/EFS	Recent Gen. R/EFS	Posterior Quantile of Recent Gen. R/EFS	2021 Forecast R/EFS by Probability Level				
								0.10	0.25	0.50	0.75	0.90
Early Stuart	**4**	**89%**	**5.81**	**24.47**	**1.39**	**1.55**	**0.38**	**0.92**	**1.40**	**2.31**	**3.95**	**6.33**
Early Summer	**4**	**55%**	**-**	**-**	-	**0.90**	**0.38**	**0.48**	**0.84**	**1.62**	**3.18**	**5.93**
	5	**45%**	**-**	**-**	-	**0.29**	**0.25**	**0.17**	**0.29**	**0.51**	**0.95**	**1.70**
Bowron	4	75%	5.91	20.42	0.80	1.13	0.25	0.56	1.14	2.36	4.75	8.68
Upper Barriere	4	60%	5.28	53.49	0.65	0.66	0.21	0.37	0.92	2.24	4.76	10.24
	5	40%	0.40	2.10	0.04	0.04	0.05	0.20	0.35	0.68	1.35	2.46
Gates	4	67%	8.12	41.01	0.99	0.99	0.39	0.43	0.88	1.93	4.25	8.64
	5	33%	0.37	3.71	0.06	0.12	0.08	0.17	0.34	0.74	1.63	3.32
Nadina	4	68%	5.36	13.47	1.35	1.35	0.08	1.69	2.98	5.73	11.59	21.56
	5	32%	0.47	2.65	0.02	0.44	0.59	0.11	0.19	0.34	0.63	1.12
Pitt	4	28%	1.08	7.32	0.08	0.08	0.07	0.15	0.29	0.59	1.16	1.90
	5	72%	3.04	10.38	0.49	0.49	0.21	0.36	0.56	0.91	1.51	2.33
Scotch	4	97%	5.42	21.50	1.16	1.18	0.39	0.49	1.04	2.38	5.26	11.80
Seymour	4	99%	6.64	29.24	1.13	1.71	0.17	1.50	2.62	4.89	9.43	18.52
Chilliwack	4	50%	1.59	5.29	0.75	0.77	0.04	1.15	1.57	2.11	2.79	3.63
	5	50%	0.38	1.64	0.16	0.16	0.50	0.02	0.06	0.17	0.45	1.16
Summer	**4**	**96%**	**-**	**-**	**-**	**1.02**	**0.38**	0.48	1.00	2.23	4.79	9.75
Chilko	4	92%	5.87	25.28	0.67	0.67	0.39	0.30	0.61	1.34	2.91	5.88
Late Stuart	4	96%	8.05	57.25	2.07	4.63	0.58	0.67	1.49	3.42	7.32	15.42
Quesnel	4	100%	7.45	31.38	0.57	1.35	0.18	1.14	2.44	5.55	11.87	23.90
Stellako	4	78%	6.05	16.32	0.71	1.40	0.59	0.32	0.54	1.08	2.07	3.79
	5	22%	0.71	3.32	0.03	0.15	0.05	0.32	0.54	0.92	1.61	2.67
Harrison	4	95%	2.96	19.69	0.45	0.45	0.44	0.11	0.25	0.65	1.64	3.75
Raft	4	63%	4.84	14.31	0.30	0.30	0.07	0.55	1.10	2.20	4.70	9.03
	5	37%	1.21	6.78	0.20	0.20	0.18	0.16	0.33	0.68	1.40	2.76
Late	**4**	**93%**	**-**	**-**	**-**	**0.77**	**0.08**	**1.02**	**1.87**	**3.69**	**7.39**	**13.55**
Cultus (R/smolt)	4	99%	0.033	0.059	0.009	0.009	0.416	0.003	0.007	0.015	0.033	0.066
Late Shuswap	4	100%	4.52	21.23	0.21	1.06	0.18	0.91	1.86	4.09	9.21	17.66
Portage	4	100%	9.52	69.07	0.62	0.62	0.09	0.80	1.72	4.01	9.35	20.02
Weaver	4	100%	9.58	41.81	0.82	4.44	0.46	1.60	2.77	5.10	9.41	16.33
Birkenhead	4	59%	4.11	21.53	0.16	0.16	0.07	0.29	0.58	1.28	2.80	5.66
	5	41%	1.48	6.39	0.37	0.37	0.40	0.15	0.30	0.66	1.45	2.93
Total	**4**	**91%**	**-**	**-**	**-**	**1.04**	**0.25**	**0.52**	**1.05**	**2.29**	**4.85**	**9.72**

Table 3. Four- and five-year-old and total 2021 Fraser Sockeye median (50% probability) forecasts for each stock. The four- and five-year-old proportions of the total median forecast are presented in the final two columns. Values below 1,000 were rounded to the nearest 100, and values below 100 were rounded to the nearest 10, rather than the nearest 1,000, in order to demonstrate age distributions. Harrison three-year-old returns are presented in the five-year-old column.

Sockeye stock/timing group	2021 Fraser Sockeye Forecasts				
	Four-year-old return 50%	Five-year-old Return 50%	Total Return 50%	Four-Year-Old Proportion	Five-Year-Old Proportion
Early Stuart	16,000	2,000	18,000	89%	11%
Early Summer					
Bowron	300	100	400	75%	25%
Upper Barriere	600	400	1,000	60%	40%
Gates	6,000	3,000	9,000	67%	33%
Nadina	13,000	6,000	19,000	68%	32%
Pitt	11,000	29,000	40,000	28%	72%
Scotch	5,800	200	6,000	97%	3%
Seymour	7,900	100	8,000	99%	1%
Misc (EShu)	5,940	60	6,000	99%	1%
Misc (Taseko)	40	60	100	40%	60%
Misc (Chilliwack)	5,000	5,000	10,000	50%	50%
Misc (Nahatlatch)	7,000	1,000	8,000	88%	12%
Summer					
Chilko	285,000	26,000	311,000	92%	8%
Late Stuart	274,000	11,000	285,000	96%	4%
Quesnel	330,800	200	331,000	100%	0%
Stellako	53,000	15,000	68,000	78%	22%
Harrison	20,000	1,000	21,000	95%	5%
Raft	5,000	3,000	8,000	63%	37%
Misc (N. Thomp.	3,500	500	4,000	88%	12%
Misc (N. Thomp	13,000	4,000	17,000	76%	24%
Misc (Widgeon)	400	300	700	57%	43%
Late					
Cultus	890	10	900	99%	1%
Late Shuswap	35,000	0	35,000	100%	0%
Portage	2,000	0	2,000	100%	0%
Weaver	73,900	100	74,000	100%	0%
Birkenhead	13,000	9,000	22,000	59%	41%
Misc(Non-Shuswap)	19,000	6,000	25,000	76%	24%
Total	1,207,000	123,000	1,330,000	91%	9%

Table 4. List of candidate models organized by their two broad categories (non-parametric/naïve and biological) with descriptions. Models are described in detail in Appendices 1 to 3 of Grant et al. (2010). Where applicable, models use effective female spawner data (EFS) as a predictor variable unless otherwise indicated by '(juv)' or '(smolt)' next to the model (Tables 1A), where fry or smolt data are used instead. Note that month-specific flow and SST metrics were only used for new retrospective analyses carried out for Pink salmon and Chilliwack Sockeye.

MODEL CATEGORY	DESCRIPTION
A. Non-Parametric (Naïve) Models	
R1C	Return from 4 years before to forecast year
R2C	Average return from 4 and 8 years before the forecast year
RAC	Average return on the forecast cycle line for all years
TSA	Average return across all years
RS1 (or RJ1)	Product of average survival from 4 years before the forecast year and the forecast brood year EFS (or juv/smolt)
RS2 (or RJ2)	Product of average survival from 4 and 8 years before the forecast year and the forecast brood year EFS (or juv/smolt)
RS4yr (or RJ4yr)	Product of average survival from the last 4 consecutive years and the forecast brood year EFS (or juv/smolt)
RS8yr (or RJ8yr)	Product of average survival from the last consecutive 8 years and the forecast brood year EFS (or juv/smolt)
MRS (or MRJ)	Product of average survival for all years and the forecast brood year EFS (or juv/smolt)
RSC (or RJC)	Product of average cycle-line survival (entire time series) and the forecast brood year EFS (or juv/smolt)
R/S (used for miscellaneous stocks)	Product of average survival on time series for specified stocks and the forecast brood year EFS
B. Biological Models	
power	Bayesian power model, see Appendix 2 of Grant et al. 2010
power-cyc	Same as above, using cycle line data only
Ricker	Bayesian Ricker model, see Appendix 2 of Grant et al. 2010
Ricker-cyc	Same as above, using cycle line data only
Larkin	Bayesian Larkin model, see Appendix 2 of Grant et al. 2010
Sibling model	Bayesian sibling model, see section 2.2.1 of Hawkshaw et al. 2020a
C. Biological Models Covariates (e.g. Power (FrD-mean))	
FrD-mean, AprFrD, MayFrD,JunFrD	Mean Fraser discharge (April - June), Mean April flow, May flow, June flow
Ei, AprEi, MayEi, JunEi, JulEi	Mean Entrance Island spring-summer sea-surface temperature (SST) (April-July), Mean April SST, May SST, June SST, July SST
Pi, MayPi, JunPi, JulPi	Mean Pine Island spring-summer SST (May-July), Mean May SST, June SST, July SST
FrD-peak	Peak Fraser Discharge
PDO	Pacific Decadal Oscillation
Jul-AugSSS, Jul-SepSSS	Mean Sea Surface Salinity (Race Rocks and Amphitrite Point light house stations) from July-August, and July to September

Table 5. Total Fraser Sockeye forecasts for 1998 to 2020 from the 10% to 90% p-levels, where available. The forecast value (or values) that corresponded most closely to the actual return is highlighted. For returns that fell above the 50% p-level, the cells are highlighted green. For returns that fell at the 50% p-level, cells are highlighted yellow. Returns falling below the 50% p-level are highlighted orange, and below the 25% p-level are highlighted red. Returns for 2018-2020 are preliminary based on in-season estimates only at the time of this publication.

Return Year	Forecast Probability Level						Actual Returns
	<10%	10%	25%	50%	75%	90%	
1998	NA	4,391,000	6,040,000	6,822,000	11,218,000	18,801,000	**10,870,000**
1999	NA	3,067,000	4,267,000	4,843,000	8,248,000	14,587,000	**3,640,000**
2000	NA	1,487,000	2,449,000	4,304,000	7,752,000	NA	**5,200,000**
2001	NA	3,869,000	6,797,000	12,864,000	24,660,000	NA	**7,190,000**
2002	NA	4,859,000	7,694,400	12,915,900	22,308,500	NA	**15,130,000**
2003	NA	1,908,000	2,742,000	3,141,000	5,502,000	9,744,000	**4,890,000**
2004	NA	1,858,000	2,615,000	2,980,000	5,139,000	9,107,000	**4,180,000**
2005	NA	5,149,000	8,734,000	16,160,000	30,085,000	53,191,000	**7,020,000**
2006	NA	5,683,000	9,530,000	17,357,000	31,902,000	56,546,000	**12,980,000**
2007	NA	2,242,500	3,602,000	6,247,000	11,257,000	19,706,000	**1,510,000**
2008	NA	1,258,000	1,854,000	2,899,000	4,480,000	7,057,000	**1,740,000**
2009	NA	3,556,000	6,039,000	10,578,000	19,451,000	37,617,000	**1,590,000**
2010	NA	5,360,000	8,351,000	13,989,000	23,541,000	40,924,000	**28,250,000**
2011	NA	1,700,000	2,693,000	4,627,000	9,074,000	15,086,000	**5,110,000**
2012	NA	743,000	1,203,000	2,119,000	3,763,000	6,634,000	**2,050,000**
2013	NA	1,554,000	2,655,000	4,765,000	8,595,000	15,608,000	**4,130,000**
2014	NA	7,237,000	12,788,000	22,854,000	41,121,000	72,014,000	**20,000,000**
2015	NA	2,364,000	3,824,000	6,778,000	12,635,000	23,580,000	**2,120,000**
2016	NA	814,000	1,296,000	2,271,000	4,227,000	8,181,000	**853,000**
2017	NA	1,315,000^{R}	2,338,000	4,432,000	8,873,000	17,633,000	**1,641,000**
2018	NA	5,265,000	8,423,000	13,981,000	22,937,000	36,893,000	10,675,000
2019	NA	1,832,000	2,979,000	5,056,000	9,133,000	15,313,000	564,000
2020	NA	275,000	486,000	924,000	1,834,000	3,573,000	288,000

Table 6. Stock composition of 2015-2017 Brood Years and 2021 median forecast (excluding misc. stocks). The five largest stocks in each column are highlighted in bold font, and the largest stock marked in red.

Stock	2015 EFS	2016 EFS	2017 EFS	2021 Median Forecast Return
Early Stuart	0.6%	1.9%	1.4%	1.5%
Early Summer				
Bowron	0.3%	0.0%	0.0%	0.0%
Upper Barriere (Fennell)	0.1%	0.3%	0.1%	0.1%
Gates	1.5%	1.8%	0.6%	0.7%
Nadina	1.4%	**8.3%**	0.5%	1.5%
Pitt	2.8%	**16.0%**	3.8%	3.1%
Scotch	0.5%	0.2%	0.5%	0.5%
Seymour	0.6%	0.1%	0.3%	0.7%
Summer				
Chilko	**65.3%**	**34.0%**	**42.3%**	**24.7%**
Late Stuart	0.7%	2.4%	**15.9%**	**22.6%**
Quesnel	**3.9%**	0.1%	**11.9%**	**26.3%**
Stellako	**7.2%**	**8.1%**	**9.8%**	**5.4%**
Harrison	**8.9%**	**17.7%**	**5.8%**	1.6%
Raft	1.3%	1.9%	0.5%	0.6%
Late				
Cultus	NA	NA	NA	NA
Late Shuswap	0.5%	0.0%	1.7%	2.7%
Portage	0.0%	0.0%	0.1%	0.1%
Weaver	0.2%	0.0%	2.9%	**5.8%**
Birkenhead	**4.1%**	6.9%	2.0%	1.7%
Total Number	657,000	194,000	503,000	1,259,000

Table 7. Overview of model selections for 2017, 2020 and 2021 forecast. Models that changed from 2020 to 2021 are highlighted. See Appendix 3 for stock-specific model choice rationales.

Stock	2017 Model	2020 Model	2021 Model
Early Stuart	*Ricker(Ei)*	*Ricker(Pi)4/Sibling5*	***Ricker(Pi)***
Early Summer			
Bowron	*Ricker(Pi)*	*Ricker(Pi)*	*Ricker(Pi)*
Upper Barriere (Fennell)	*Power*	*Power4/Sibling5*	***Ricker(Pi)4/Sibling5***
Gates	*Larkin*	*Larkin4/Sibling5*	***RS8yr***
Nadina	*MRJ*	*PowerJuvFRDpeak4 /Sibling5*	*PowerJuvFRDpeak4 /Sibling5*
Pitt	*Larkin*	*Larkin4/Sibling5*	***Ricker(Ei)4/Sibling5***
Scotch	*Larkin*	*Larkin*	***Ricker(Pi)4/Sibilng5***
Seymour	*Larkin*	*Larkin*	***Ricker(Ei)***
Misc (EShu)	*R/S*	*R/S*	*R/S*
Misc (Taseko)	*R/S*	*R/S*	*R/S*
Misc (Chilliwack)	*Ricker*	*Ricker*	***Power4/Sibling5***
Misc (Nahatlatch)	*R/S*	*R/S*	*R/S*
Summer			
Chilko	*Larkin*	*Larkin4/Sibling5*	***RS8yr***
Late Stuart	*Power*	*RickerFRDMn4/Sibling5*	***Power(Pi)***
Quesnel	*Ricker(Ei)*	*Ricker(Ei)4/Sibling5*	***Ricker(Ei)***
Stellako	*Larkin*	*Larkin4/Sibling5*	*Larkin4/Sibling5*
Harrison	*Ricker(Ei)3/Sibling4*	*Ricker(Ei)Even3/Sibling4*	***Ricker(Ei)Odd3/Sibling4***
Raft	*Ricker (PDO)*	*Ricker(PDO)4/Sibling5*	***Ricker(Pi)4/Sibling5***
Misc (N. Thomp. Tribs)	*R/S*	*R/S*	*R/S*
Misc (N. Thomp River)	*R/S*	*R/S*	*R/S*
Misc (Widgeon)	*R/S*	*R/S*	*R/S*
Late			
Cultus	*PowerJuv(Pi)*	*PowerJuv(Pi)4/Sibling5*	*PowerJuv(Pi)4/Sibling5*
Late Shuswap	*Larkin*	*RickerCyc4/Sibling5*	***Ricker(Ei)***
Portage	*Larkin*	*Larkin*	***RS8yr***
Weaver	*PowerJuv(Ei)*	*Ricker(PDO)4/Sibling5*	***RS8yr***
Birkenhead	*Ricker (Ei)*	*Ricker(Ei)4/Sibling5*	***RS8yr***
Misc(Non-Shuswap)	*R/S*	*R/S*	*R/S*

Table 8. Sibling model selection process. Sibling models are applied when the percentage difference (see section 2.2 of Hawkshaw et al. 2020b for equation) between R^2 values for major models and sibling models is less than 0.05 (including when it is negative) and estimate of older age-class fish (R_5; representing age-5's for all stocks except Harrison, for which is represents age-4 returns) by sibling models are smaller than the major models . Although Late Stuart met the criteria for the use of a sibling model, one was not applied due to exceptional uncertainty in the 2020 return estimate (see Appendix 3 for further discussion).

Stock	Major Model	Major Model R^2	Sibling Model R^2	Percent Difference	Major R_5	Sibling R_5	Difference	Difference (%)	Select Sibling Model
Early Stuart	Ricker(Pi)	0.69	0.7	-0.02	2,011	2,119	109	5%	NO
Early Summer									
Bowron	Ricker(Pi)	0.54	0.22	1.45	132	638	507	79%	NO
Upper Barriere (Fennell)	Ricker(Pi)	0.09	0.47	-0.82	935	411	-525	-128%	YES
Gates	RS8yr	-	-	-	-	-	-	-	NO
Nadina	PowerJuvFRDpeak	0.59	0.67	-0.11	14,257	5,536	-8,722	-158%	YES
Pitt	Ricker(Ei)	0.07	0.46	-0.85	46,343	28,421	-17,922	-63%	YES
Scotch	Ricker(Pi)	0.45	0.67	-0.33	626	172	-454	-263%	YES
Seymour	Ricker(Ei)	0.22	0.5	-0.56	122	190	68	36%	NO
Summer									
Chilko	RS8yr	-	-	-	-	-	-	-	NO
Late Stuart	Power(Pi)	0.48	0.69	-0.30	11,096	5,306	-5,789	-109%	NO
Quesnel	Ricker(Ei)	0.34	0.66	-0.49	172	1,126	954	85%	NO
Stellako	Larkin	0.47	0.54	-0.13	34,792	14,550	-20,242	-139%	YES
Harrison	Ricker(Ei) Odd	0.19	0.46	-0.59	51,631	19,097	-32,534	-170%	YES
Raft	Ricker(Pi)	0.18	0.37	-0.52	8,596	2,558	-6,038	-236%	YES
Late									
Cultus	PowerJuv(Pi)	0.50	0.59	-0.16	106	12	-94	-752%	YES
Late Shuswap	Ricker(Ei)	0.55	0.62	-0.11	1	22	21	96%	NO
Portage	RS8yr	-	-	-	-	-	-	-	NO
Weaver	RS8yr	-	-	-	-	-	-	-	NO
Birkenhead	RS8yr	-	-	-	-	-	-	-	NO

Table 9. Five-year retrospective analysis results, with values for mean absolute error, mean percent error, root-mean-square error, mean absolute percent error, mean arctangent absolute error, and mean absolute scaled error. Rankings are given based on average performance across metrics, and coefficient of determination (R^2) are given as an additional metric of model fit. Full fifteen-year retrospective results have been omitted for brevity, but rankings for top models can be found in Table 10.

Model	MAE	MPE	RMSE	MAPE	MAAPE	MASE	Rank
Ricker_JunFrD_MayPi	2,215,329	0.2952	2,600,350	0.3895	0.3335	0.3959	1
Ricker_FrDpeak_MayPi_JulSeptSSS	3,062,383	0.1175	3,382,807	0.4395	0.3815	0.5473	2
Power_AprFrd_JunEi_JulAugSSS	2,754,914	0.3247	3,106,507	0.4629	0.3776	0.4924	3
Ricker_FrDpeak_MayPi	3,685,655	0.1822	3,863,152	0.4679	0.4109	0.6587	4
Ricker_FrDpeak_Pi	3,721,972	0.1869	3,885,342	0.4735	0.4161	0.6652	5
Ricker_Pi_JulAugSSS	3,878,908	0.1610	4,558,768	0.4757	0.4219	0.6933	6
Power_Ei_JulAugSSS	3,793,279	0.2298	4,050,493	0.5433	0.4555	0.6779	7
Ricker_MayPi	4,319,675	0.4328	4,682,326	0.5957	0.4755	0.7720	8
Power	3,910,529	0.6635	5,165,574	0.7356	0.4577	0.6989	9
Ricker_Pi	4,351,807	0.4388	4,730,363	0.6017	0.4778	0.7778	9
Forecast (Power-Juv-SSS)	5,547,643	0.3804	5,904,444	0.7903	0.5833	0.9915	11
Ricker_JunPi	5,343,577	0.5910	5,988,671	0.7931	0.5589	0.9550	12
RS1	6,684,374	0.2414	9,603,573	0.5676	0.4661	1.1947	12
RS2	6,104,493	0.3268	6,630,572	0.6278	0.5384	1.0910	12
Power_JulAugSSS	6,100,027	0.5587	6,704,758	0.9128	0.5783	1.0902	15
Ricker	5,692,290	0.9298	7,115,179	1.0309	0.5501	1.0173	16
Ricker_JulAugSSS	5,981,619	0.9022	7,445,716	1.0637	0.5548	1.0691	17
Ricker_JulPi	6,157,355	0.6438	6,869,699	0.8602	0.6101	1.1005	18
MRS_Log	12,412,767	1.4355	14,025,967	1.4935	0.8208	2.2184	19
MRS	19,156,877	2.2236	21,918,110	2.2236	0.9615	3.4238	20

Table 10. 2021 forecast values for each candidate model, along with rankings from both the five-year and 15-year retrospective analysis rankings and coefficient of determination (R^2), based on model fits using all years of data (same data set used for the 2021 forecast). The highlighted model (Ricker_FrDpeak_MayPi_JulSeptSSS) was chosen for the 2021 forecast.

Model	P10	P25	P50	P75	P90	5-year Rank	15-year Rank	R^2
Ricker_JunFrD_MayPi	1,813,750	2,341,050	3,072,791	4,032,889	5,221,185	1	12	0.36
Ricker_FrDpeak_MayPi_JulSeptSSS	1,701,366	2,228,876	3,009,002	4,050,516	5,374,877	2	1	0.42
Ricker_FrDpeak_MayPi	2,062,315	2,620,661	3,393,834	4,365,215	5,485,414	4	12	0.42
Ricker_FrDpeak_Pi	2,109,988	2,676,259	3,454,490	4,441,571	5,599,103	5	15	0.32
Ricker_Pi_JulAugSSS	3,232,279	4,102,581	5,303,810	6,858,239	8,864,516	6	4	0.37
Ricker_MayPi	5,434,465	6,107,042	6,909,518	7,811,357	8,733,293	8	2	0.35
Power	10,275,696	11,236,281	12,375,142	13,609,317	14,768,093	9	10	0.23
Ricker_Pi	5,358,338	6,075,844	6,875,717	7,749,926	8,646,419	9	3	0.35
Ricker_JunPi	3,840,674	4,603,712	5,564,406	6,720,132	7,955,593	12	7	0.29
Power_JulAugSSS	6,022,042	7,124,191	8,565,230	10,288,742	12,145,423	15	14	0.25
Ricker	13,119,704	14,133,119	15,358,942	16,663,795	17,971,440	16	9	0.21
Ricker_JulAugSSS	13,754,998	15,156,485	16,866,995	18,871,862	20,807,950	17	11	0.20
Ricker_JulPi	3,216,768	3,963,836	4,994,308	6,191,920	7,590,645	18	8	0.26

Table 11. Model performance comparison for 2013 brood/2015 return of Fraser Pink salmon. This year was identified as having similar environmental conditions to those faced by the 2019 brood/2021 return year cohort. The model chosen for the 2021 forecast (Ricker_FrDpeak_MayPi_JulSeptSSS) is highlighted.

Model	2015 Return Prediction	Actual 2015 Return	5-year Rank	15-year Rank	R^2
Ricker_JunFrD_MayPi	10,081,281	5,812,085	1	12	0.36
Ricker_FrDpeak_MayPi_JulSeptSSS	7,715,430	5,812,085	2	1	0.42
Power_AprFrD_JunEi_JulAugSSS	10,680,401	5,812,085	3	5	0.56
Ricker_FrDpeak_MayPi	7,960,467	5,812,085	4	12	0.42
Ricker_FrDpeak_Pi	8,143,136	5,812,085	5	15	0.32
Ricker_Pi_JulAugSSS	10,177,072	5,812,085	6	4	0.37
Power_Ei_JulAugSSS	10,854,518	5,812,085	7	6	0.49
Ricker_MayPi	13,173,288	5,812,085	8	2	0.35
Power	14,262,558	5,812,085	9	10	0.23
Ricker_Pi	13,316,455	5,812,085	9	3	0.35
Ricker_JunPi	16,321,999	5,812,085	12	7	0.29

Figures

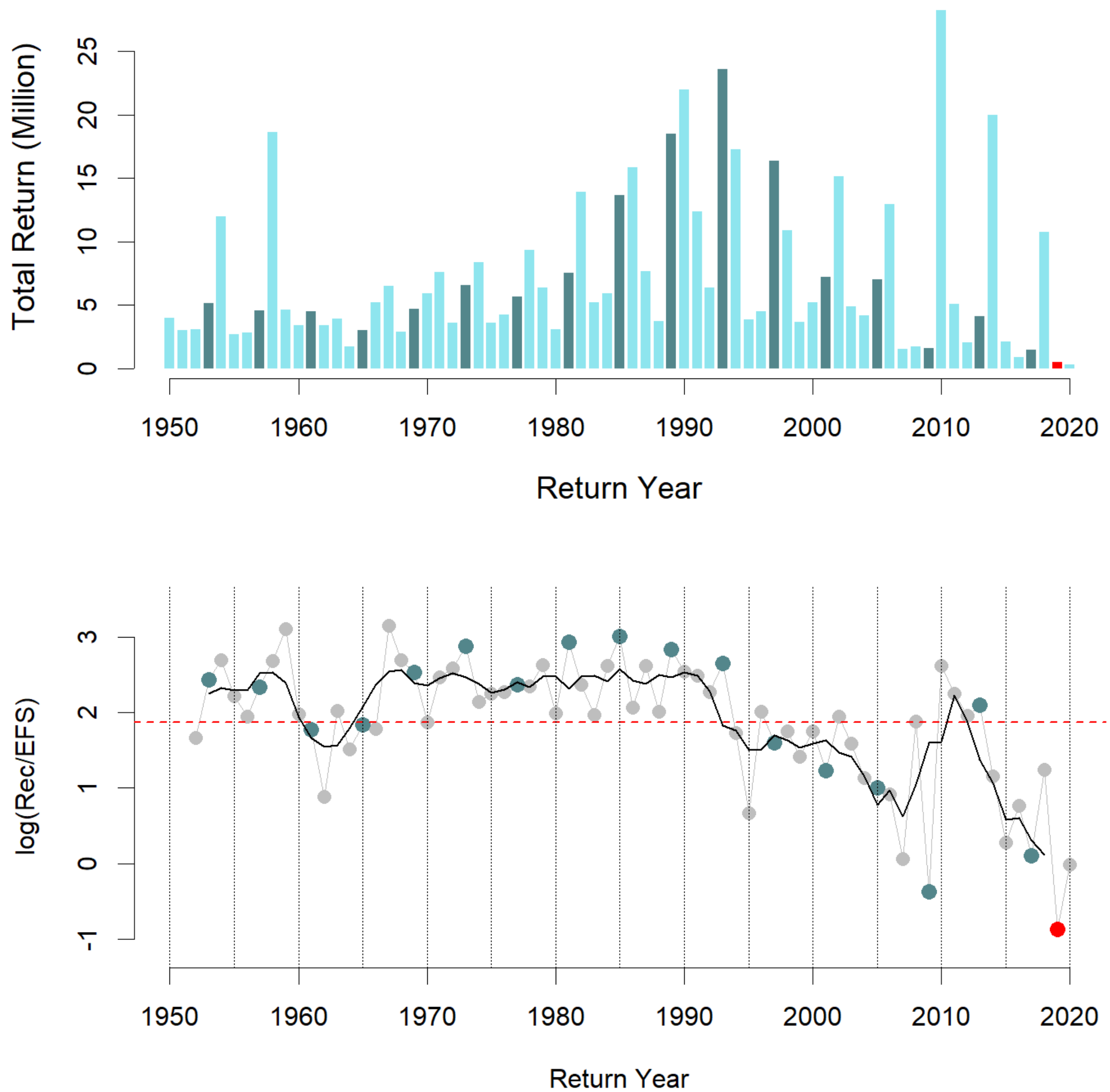

Figure 1. Total returns and overall productivity of Fraser Sockeye Top panel shows total adult annual returns (note that adult returns from 2018-2020 are preliminary). Bottom panel shows overall Fraser Sockeye productivity (loge(recruits / effective female spawners) up to the 2020 return year for the 19 stocks with long time series of spawner and recruit estimates. Points represent annual productivity and the black line represents the smoothed four year running average. The dashed horizontal red line is the time-series average. In both panels, dark blue represents the 2021 cycle line and light blue represents the three other cycles, 2019 returns are highlighted in red as the lowest productivity/survival seen on record.

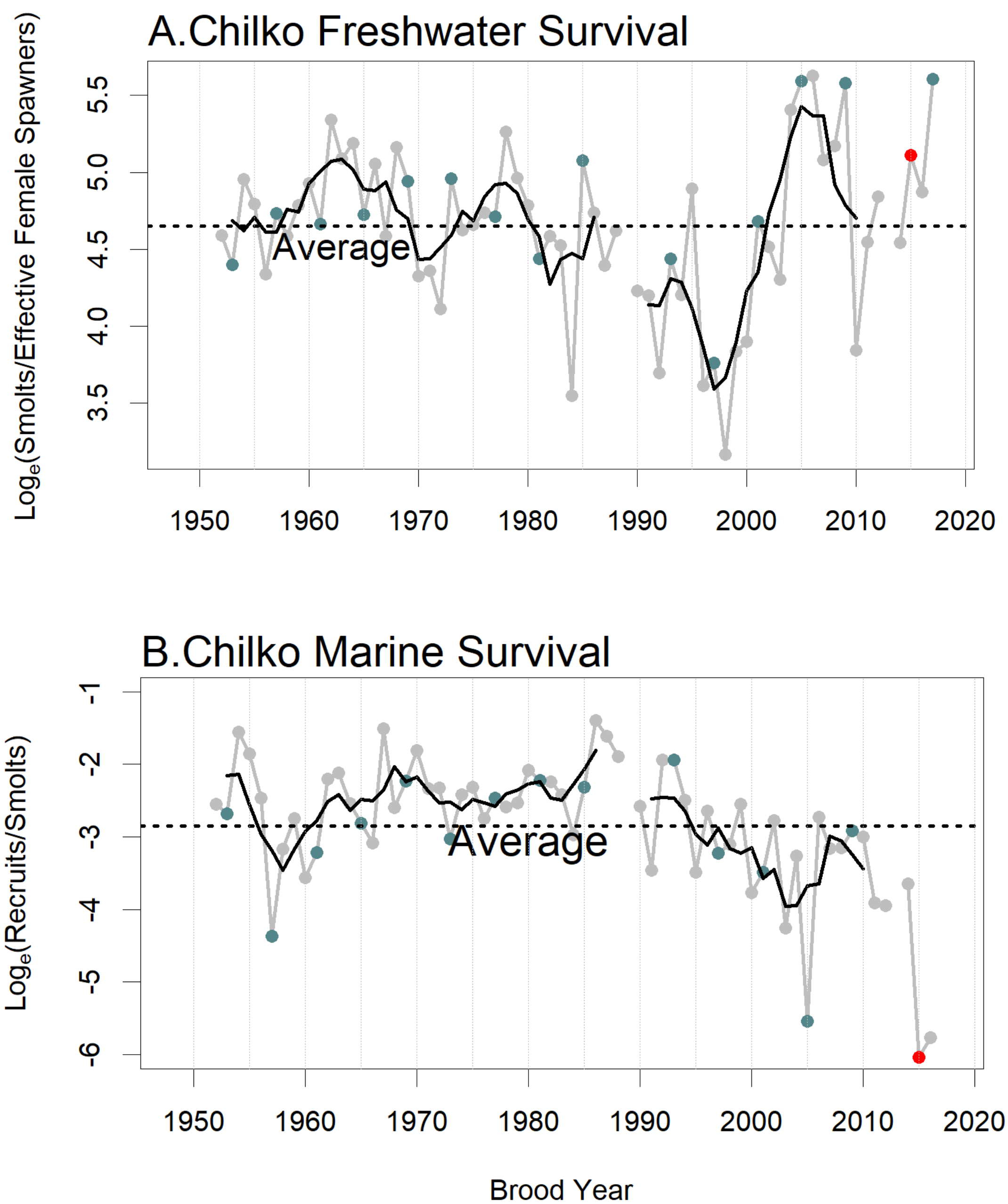

Figure 2. A. Annual freshwater survival (loge smolts/effective female spawners ; filled grey dots and lines); the red filled circle represents the 2015 brood year (2019 returns; historically low productivity/survival across all stocks); dark blue circle represents the 2021 cycle line. The black line represents the smoothed four-year running average survival and the black dashed lines indicate average survival. Note that no smolt assessment was conducted in the 2013 brood year representing a gap. B. Annual 'marine' (loge recruits/smolt) survival (filled grey circles and lines) with the 2015 brood year survival indicated by the red filled circle. 'Marine survival' includes the period of time smolts spend migrating from the outlet of Chilko Lake (where they are enumerated) to when they return as adults and includes their downstream migration in the Fraser River as smolts.

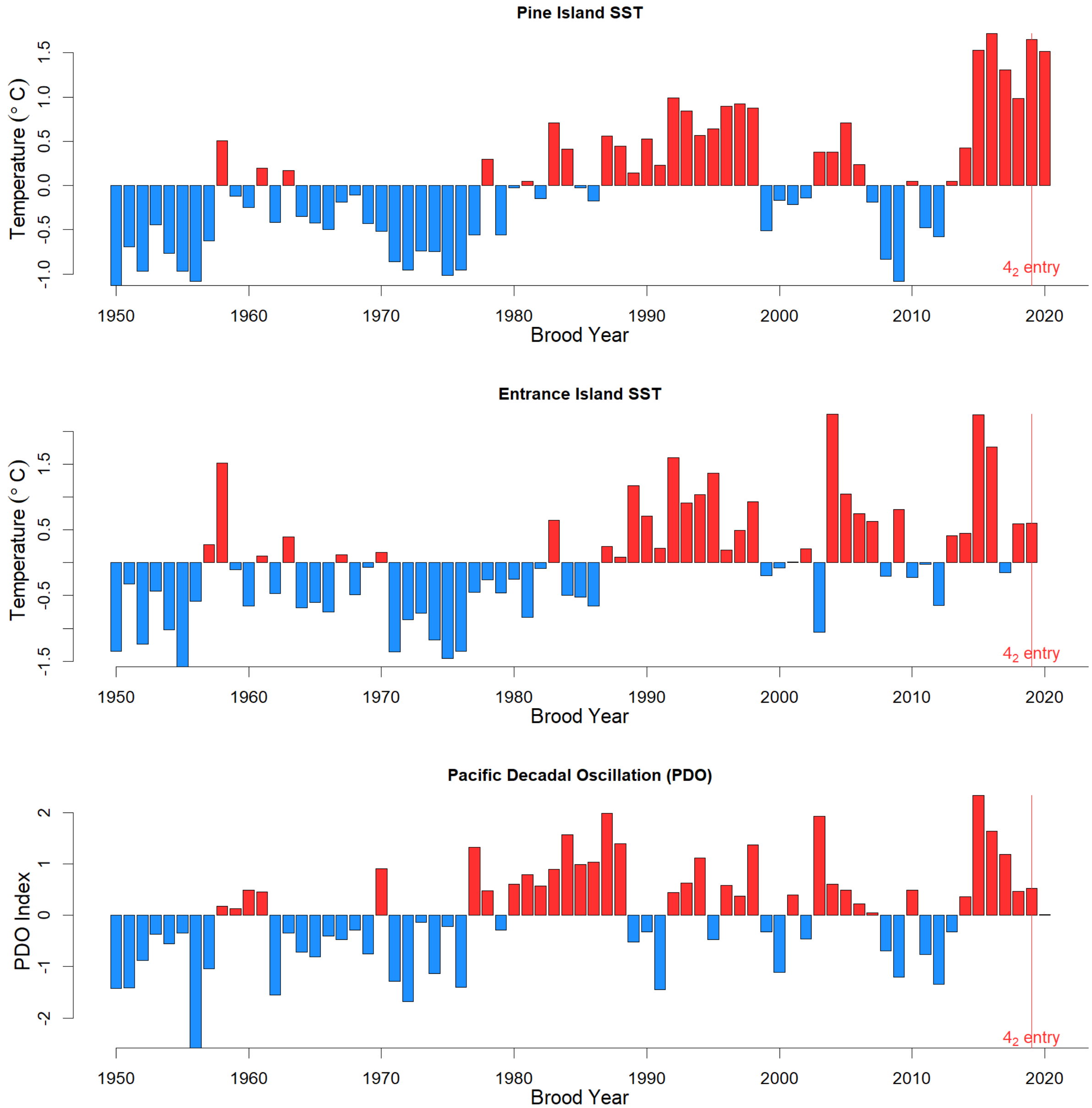

Figure 3. Average April-June sea surface temperature (SST) anomalies (based on 1950-2019 average) measured at Entrance Island (Strait of Georgia) and April-July SST anomalies (based on 1950-2012 average) for Pine Island (Queen Charlotte Strait). Bottom panel shows winter PDO index (Nov.-March). Values are presented as raw deviations from time-series averages. Red bars (positive values) indicate above-average anomalies and blue bars indicate below-average anomalies. Red vertical lines mark 2019 conditions that most Fraser Sockeye returning in 2021 (age 42 Sockeye from 2017 brood year).would have entered into upon outmigration. Note that Pink Salmon returning in 2021 would have entered the ocean a year later in 2020.

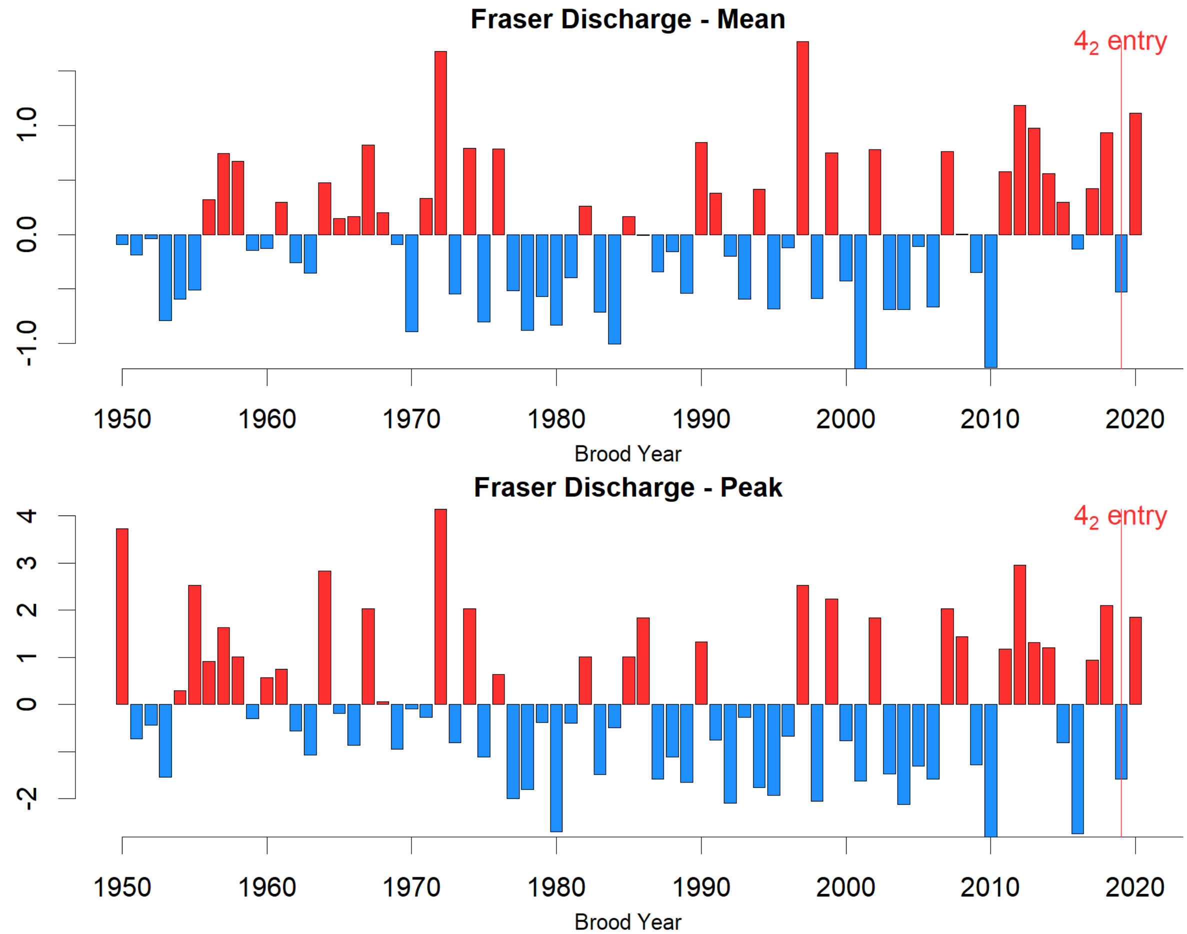

Figure 4. Fraser River discharge shown as April-June means and annual peak discharge. Values are presented as raw deviations from time-series averages (1950-2020). The 2019 ocean entry year, highlighted with a red vertical line, marks the conditions that most Fraser Sockeye from the 2017 brood year entered into upon outmigration as smolts (i.e. a 42 life cycle). Red bars (positive values) indicate above-average flow conditions and blue bars indicate below-average flow conditions. Note that Pink Salmon returning in 2021 would have entered the ocean a year later in 2020.

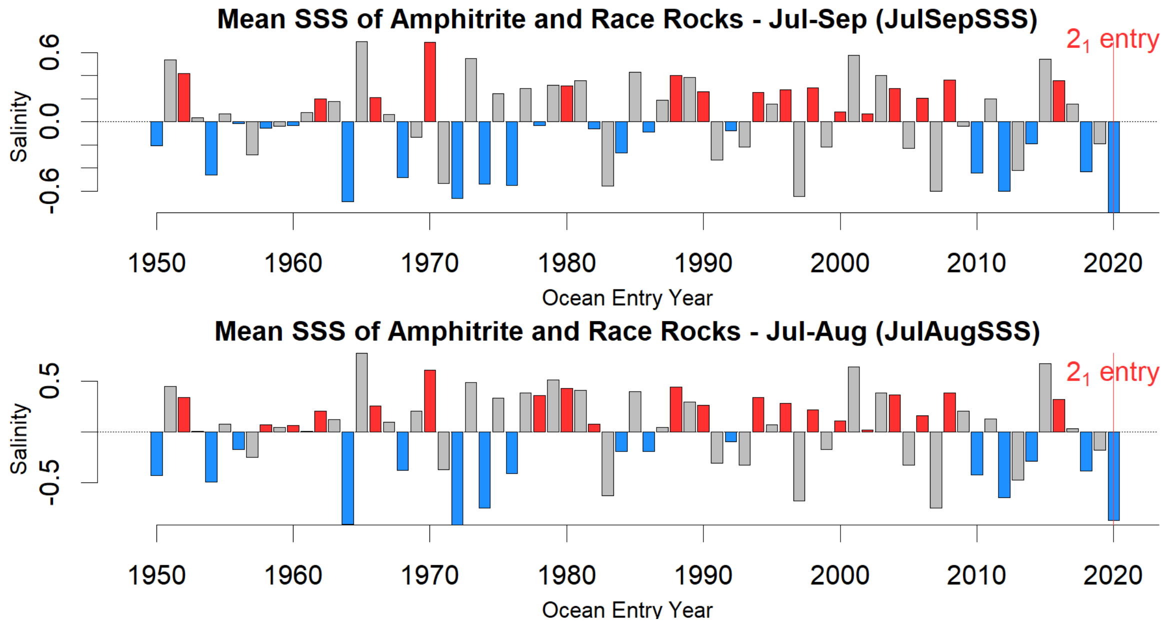

Figure 5. Average sea-surface salinity for July-September and July-August, averaged across Amphitrite Point and Race Rocks lighthouses. Even years are highlighted in either red or blue, indicating above- or below-average salinity conditions faced by outmigrating odd-year smolts. The conditions faced by oumigrating Pink Salmon smolts in 2020 (2_1 fish from 2019 brood year, which will return in 2021) are highlighted with a red vertical line.

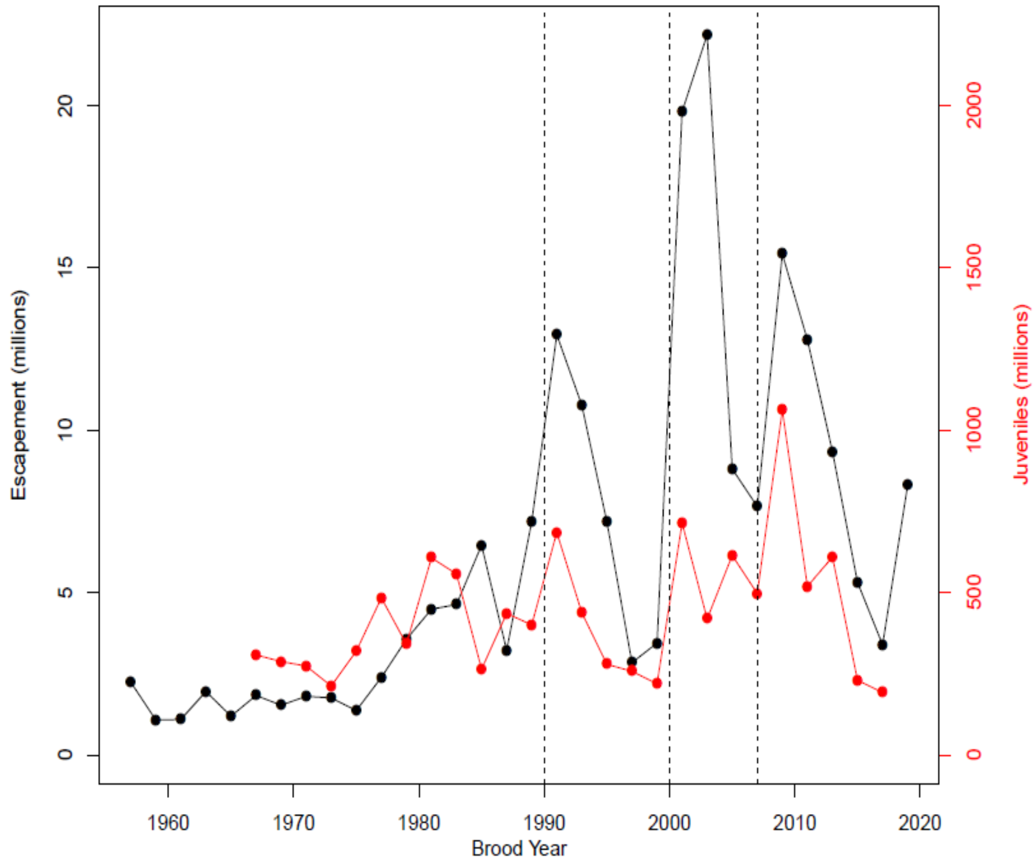

Figure 6. Pink Salmon escapement (black) and juvenile (red) estimates. Dashed lines delineate different estimation regimes that have existed over time: 1957-1991 stream-specific estimates, 1993-2001 system-wide mark-recapture program, 2003-2007 system-wide indirectly-derived test fishery was used, 2009-present system-wide hydroacoustic program.

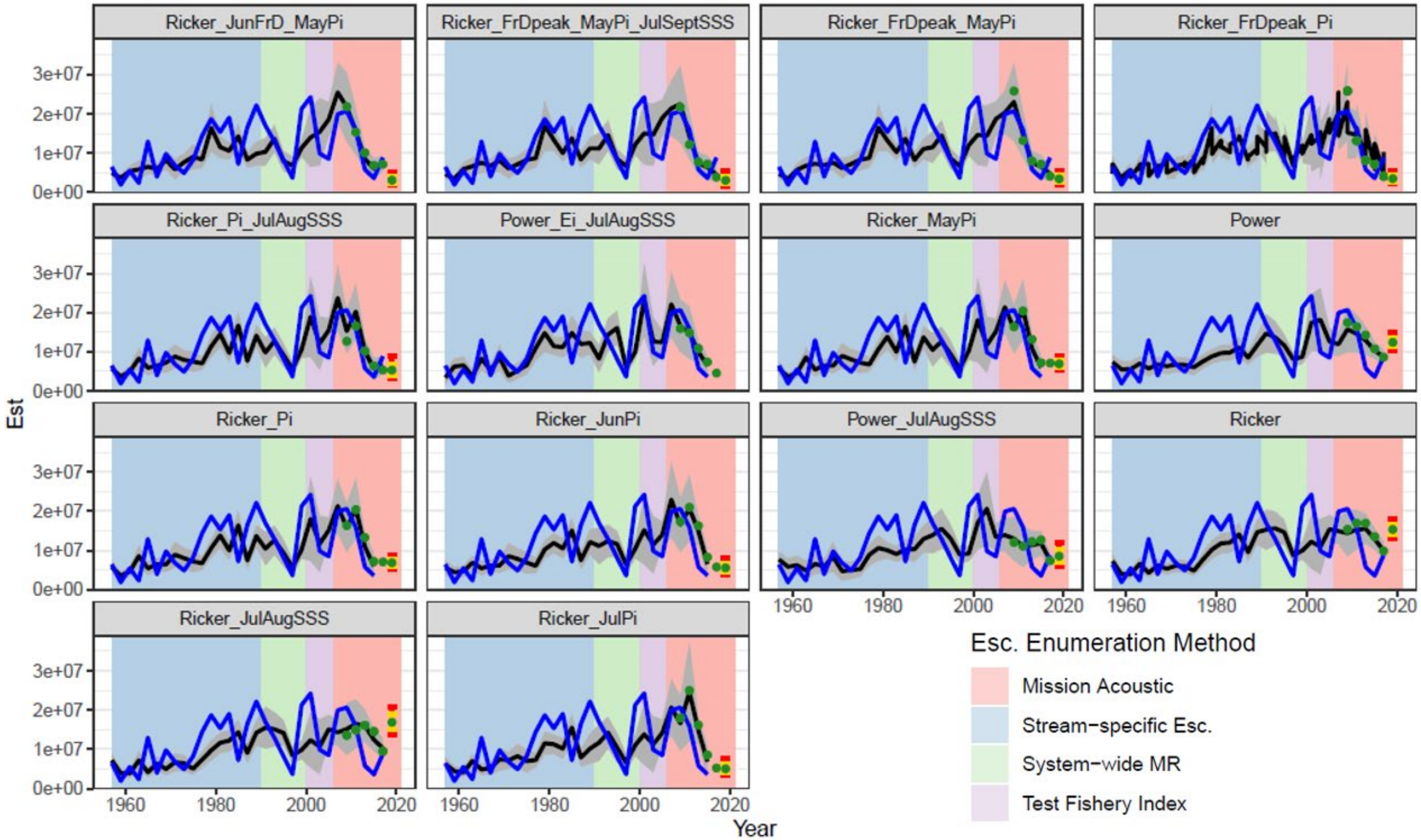

Figure 7. Return time series (blue), and model fits (black with grey error bars), along with 5-year retrospective predictions (green points), and 2021 forecast predictions (green point: P50, yellow bar: P25-P75, red bar P10-P90) for Fraser Pink Salmon. Background colours indicate escapement enumeration method changes over time.

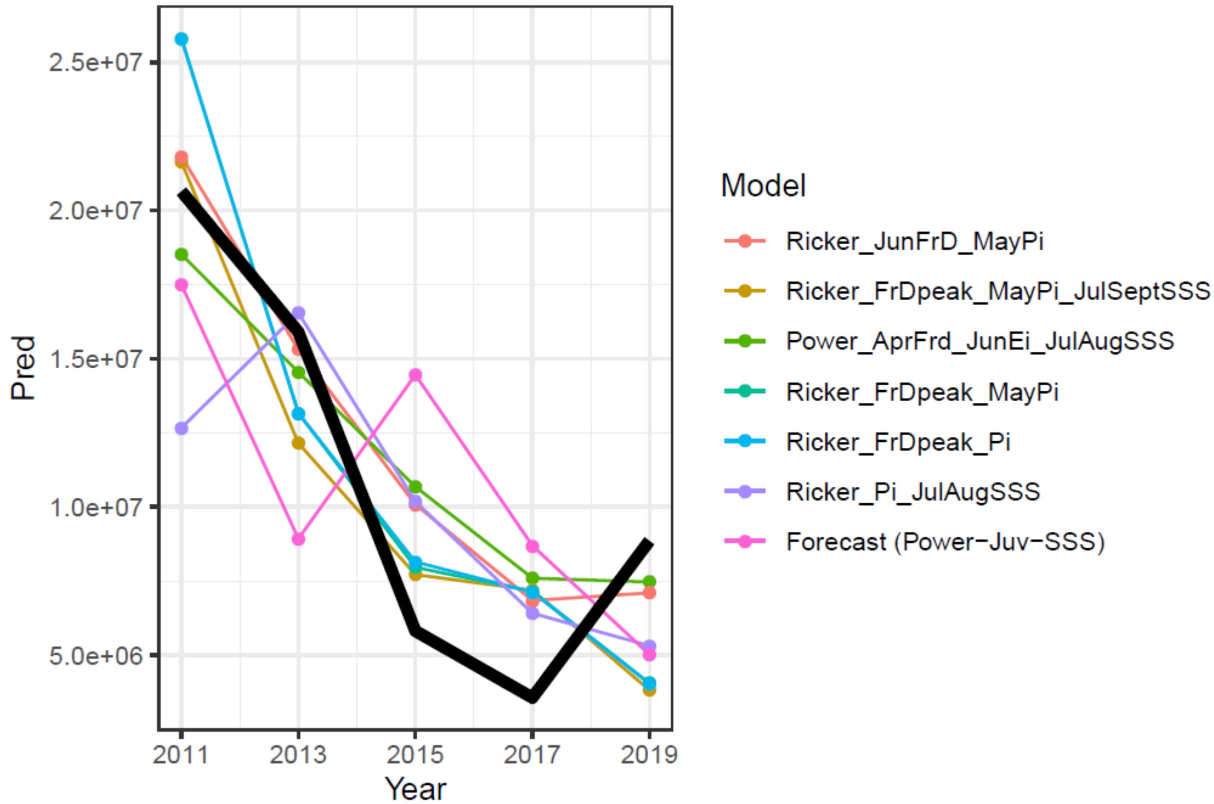

Figure 8. Five-year retrospective results for top-six candidate Fraser pink forecast models, plus actual historical forecast values from the past five brood year (pink; Forecast Power-Juv-SSS), by return year. Black line indicates actual returns, coloured points and lines indicate retrospective forecast estimates for each candidate model (or prior forecast value).

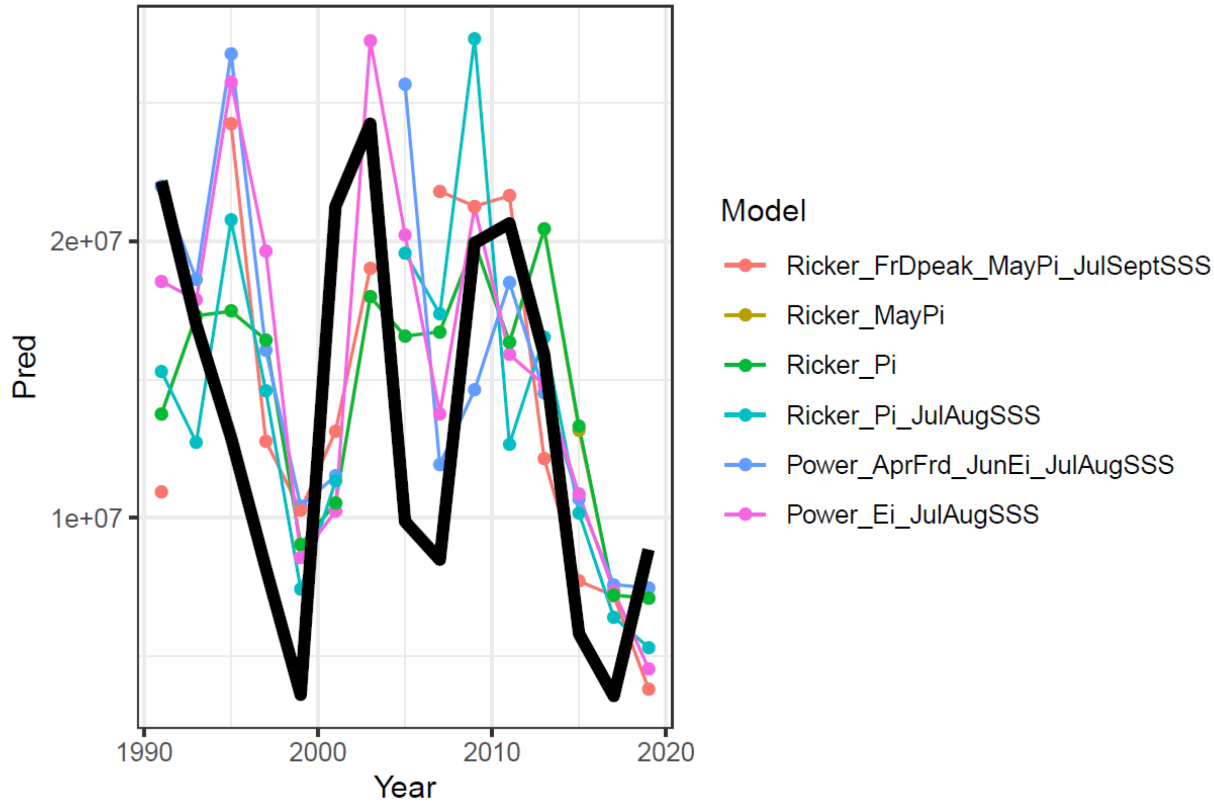

Figure 9. Fifteen-year retrospective (1991-2019 return; odd years) results for top-six candidate Fraser Pink Salmon forecast models, by return year. Missing points indicate that the model did not converge in that year. Black line indicates actual returns, coloured points and lines indicate retrospective forecast estimates for each candidate model.

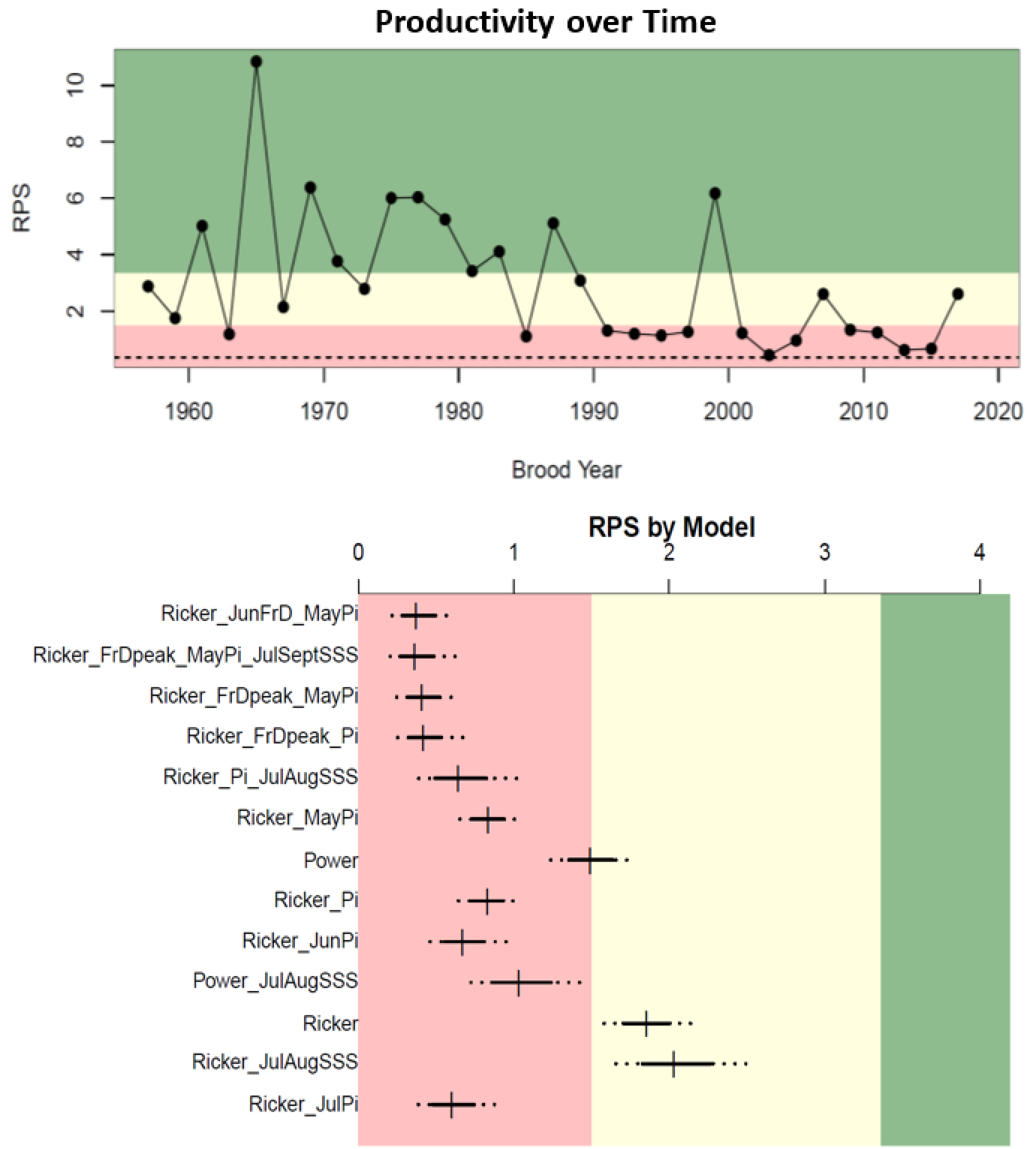

Figure 10. Upper panel: historical recruits-per-spawner for Fraser Pink salmon, based on escapement estimates, with coloured regions delineated by historical mean plus/minus 0.5SD. Dashed line indicates productivity implied by the median 2021 forecast. Lower Panel: productivity implied by candidate models at the median (vertical bar) P25-P75 (solid horizontal bar) and P10-P90 (dotted horizontal lines) levels, overlaid on the same coloured regions as the top panel.

Contributors

Contributor	Affiliation
Aidan Fisher	Lower Fraser Fisheries Alliance
Amy Seiders	Northwest Indian Fisheries Commission
Brian Leaf	Fisheries and Oceans Canada, Pacific
Bronwyn MacDonald	Fisheries and Oceans Canada, Pacific
Brooke Davis	Fisheries and Oceans Canada, Pacific
Catherine Michielsens	Pacific Salmon Commission
David Patterson	Fisheries and Oceans Canada, Pacific
Doug Lofthouse	Fisheries and Oceans Canada, Pacific
Eric Taylor	Pacific Salmon Commission
Fiona Martens	Pacific Salmon Commission
Gottfried Pestal	SOLV Consulting Ltd.
Gordon Rose	Northwest Indian Fisheries Commission
Jamie Scroggie	Fisheries and Oceans Canada, Pacific
Jennifer Nener	Fisheries and Oceans Canada, Pacific
Karen Rickards	Fisheries and Oceans Canada, Pacific
Katie Davidson	Fisheries and Oceans Canada, Pacific
Kelsey Campbell	A-tlegay Fisheries Society
Les Jantz	Fisheries and Oceans Canada, Pacific
Lu Guan	Fisheries and Oceans Canada, Pacific
Lucas Pon	Fisheries and Oceans Canada, Pacific
Matt Mortimer	Fisheries and Oceans Canada, Pacific
Merran Hague	Pacific Salmon Commission
Mickey Agha	Washington Department of Fish and Wildlife
Mike Hawkshaw	Fisheries and Oceans Canada, Pacific
Mike Staley	Fraser River Salmon Management Council
Nicole Frederickson	Island Marine Aquatic Working Group
Peter Chandler	Fisheries and Oceans Canada, Pacific
Robert (Jake) Rice	Washington Department of Fish and Wildlife
Scott Decker	Fisheries and Oceans Canada, Pacific
Steve Latham	Pacific Salmon Commission
Sue Grant	Fisheries and Oceans Canada, Pacific
Tanya Vivian	Fisheries and Oceans Canada, Pacific
Tracy Cone	Fisheries and Oceans Canada, Pacific
Yi Xu	Fisheries and Oceans Canada, Pacific

Approved by

Andrew Thomson
Regional Director
Science Branch, Pacific Region
Fisheries and Oceans Canada

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Sources of Information

Akaike, H. 1974. A new look at the statistical model identification. IEEE Transactions on Automatic Control, 19(6): 716–723.

Beamish, R.J., and Mahnken, C. 2001. A critical size and period hypothesis to explain natural regulation of salmon abundance and the linkage to climate and climate change. Prog. Ocean. 49(1-4): 423–437.

Brooks, E.N., and Legault, C.M. 2015. Retrospective forecasting — evaluating performance of stock projections for New England groundfish stocks. Can. J. Fish. Aquat. Sci. 73: 935–950.

Cass, A., Folkes, M., Parken, C., and Wood, C. 2006. Pre-season run size forecasts for Fraser River Sockeye in 2006. DFO Can. Sci. Advis. Sec. Res. Doc. 2006/060. iii + 72 p. (Accessed April 13, 2021)

Cohen, B.I., 2013. Commission of Inquiry into the Decline of Sockeye Salmon in the Fraser River (Canada) and Cohen, B.I., 2013. The Uncertain Future of Fraser River Sockeye: The Sockeye Fishery. Commission of Inquiry into the Decline of Sockeye Salmon in the Fraser River.

Connors, B., M.J. Malick, G.T. Ruggerone, P. Rand, M. Adkison, J.R. Irvine, R. Campbell, and K. Gorman. 2020. Climate and competition influence Sockeye salmon population dynamics across the Northeast Pacific Ocean. Can. J. Fish. Aquat. Sci. 77(6): 943–949.

COSEWIC. 2017. COSEWIC assessment and status report on the Sockeye Salmon *Oncorhynchus nerka*, 24 Designatable Units in the Fraser River Drainage Basin, in Canada. Committee on the Status of Endangered Wildlife in Canada. Ottawa. xli + 179 pp.

Cox-Rogers, S., Hume, J.M.B. and Shortreed, K.S., 2004. Stock status and lake-based production relationships for wild Skeena River Sockeye salmon. Can. Sci. Advis. Sec. Res. Doc. 2004/010. ii + 56 p. (Accessed April 13, 2021)

DFO. 2013. Pre-season run size forecasts for Fraser River Sockeye and Pink Salmon in 2013. DFO Can. Sci. Advis. Sec. Sci. Advis. Rep. 2012/074 (Accessed April 9, 2021)

DFO. 2014a. Pre-season run size forecasts for Fraser River Sockeye (*Oncorhynchus nerka*) Salmon in 2014. DFO Can. Sci. Advis. Sec. Sci. Resp. 2014/040. (Accessed April 9, 2021)

DFO. 2014b. Supplement to the pre-season return forecasts for Fraser River Sockeye Salmon in 2014. DFO Can. Sci. Advis. Sec. Sci. Resp. 2014/041. (Accessed April 9, 2021)

DFO. 2015a. Pre-Season Run Size Forecasts for Fraser River Sockeye (*Oncorhynchus nerka*) and Pink (*O . gorbuscha*) Salmon in 2015. DFO Can. Sci. Advis. Sec. Sci. Resp. 2015/014 (Accessed April 9, 2021)

DFO. 2015b. Supplement to the pre-season return forecasts for Fraser River Sockeye Salmon in 2015. DFO Can. Sci. Advis. Sec. Sci. Resp. 2015/028: pp. 49. (Accessed April 9, 2021)

DFO. 2016a. Pre-Season run size forecasts for Fraser River Sockeye (*Oncorhynchus nerka*) in 2016. DFO Can. Sci. Advis. Sec. Sci. Resp. 2016/021. (Accessed April 9, 2021)

DFO. 2016b. Supplement to the pre-season run size forecasts for Fraser River Sockeye (*Oncorhynchus nerka*). DFO Can. Sci. Advis. Sec. Sci. Resp. 2016/047. (Accessed April 9, 2021)

DFO. 2017. Pre-Season run size forecasts for Fraser River Sockeye (*Oncorhynchus nerka*) in 2017. DFO Can. Sci. Advis. Sec. Sci. Resp. 2017/016. (Accessed April 9, 2021)

DFO. 2018. Pre-season run size forecasts for Fraser River Sockeye (*Oncorhynchus nerka*) salmon in 2018. DFO Can. Sci. Advis. Sec. Sci. Resp. 2018/034. (Accessed April 9, 2021)

DFO. 2020a. Recovery Potential Assessment – Cultus Lake Sockeye Salmon (*Oncorhynchus nerka*) (2019). DFO Can. Sci. Advis. Sec. Sci. Advis. Rep. 2020/011. (Accessed April 9, 2021)

DFO. 2020b. Recovery potential assessment for Fraser River Sockeye salmon (Oncorhynchus nerka) – nine designatable units – Part 1: Probability of achieving recovery targets. DFO Can. Sci. Advis. Sec. Sci. Advis. Rep. 2020/012. (Accessed April 9, 2021)

Dorner, B, Peterman, R.M., and Haeseker S.L. 2008. Historical trends in productivity of 120 Pacific pink, chum, and Sockeye salmon stocks reconstructed by using a Kalman Filter. Can. J. Fish. Aquat. Sci. 65: 1842-1866.

Gelman, A., Stern, H.S., Carlin, J.B., Dunson, D.B., Vehtari, A. and Rubin, D.B., 2013. Bayesian data analysis. Chapman and Hall/CRC.

Grant, S.C.H., Michielsens, C.G.J., Porszt, E.J., and Cass, A.J. 2010. Pre-season run size forecasts for Fraser River Sockeye salmon (*Oncohrynchus nerka*) in 2010. DFO Can. Sci. Advis. Sec. Res. Doc. 2010/042. vi + 125 p. (Accessed April 9, 2021)

Grant, S.C.H., Townsend, M., White, B., and Lapointe, M. 2014. Fraser River Pink Salmon (Oncorhynchus gorbuscha) data review: Inputs for biological status and escapement goals. Final Project Report to Southern Boundary Restoration and Enhancement Fund. viii + 90. (Accessed April 9, 2021)

Grant, S.C.H., Holt, C.A., Pestal, G., Davis, B.M. and MacDonald, B.L. 2020. The 2017 Fraser Sockeye Salmon (Oncorhynchus nerka) Integrated Biological Status Re-Assessments Under the Wild Salmon Policy Using Standardized Metrics and Expert Judgment. DFO Can. Sci. Advis. Sec. Res. Doc. 2020/038. vii + 211 p. (Accessed April 9, 2021)

Haeseker, S.L., Peterman, R.M., Su, Z., and Wood, C.C. 2005. Retrospective Evaluation of Preseason Forecasting Models for Pink Salmon. N. Am. J. Fish. Manag. 25(1): 897–918.

Haeseker, S.L., Dorner, B., Peterman, R.M., and Su, Z. 2007. An improved sibling model for forecasting chum salmon and Sockeye salmon abundance. N. Am. J. Fish. Manag. 27(2): 634-642.

Haeseker, S.L., Peterman, R.M., Su, Z., and Wood, C.C. 2008. Retrospective evaluation of preseason forecasting models for Sockeye and chum salmon. N. Am. J. Fish. Manag. 28(1): 12–29.

Hawkshaw, M., Xu, Y., and Davis, B. 2020. Pre-season Run Size Forecasts for Fraser River Sockeye (Oncorhynchus nerka) and Pink (Oncorhynchus gorbuscha) Salmon in 2019. Can. Tech. Rep. Fish. Aquat. Sci. 3391: vi + 52 p. (Accessed April 13, 2021)

Hawkshaw, M., Xu, Y., and Davis, B. 2020. Pre-season Run Size Forecasts for Fraser River Sockeye (*Oncorhynchus nerka*) Salmon in 2020. Can. Tech. Rep. Fish. Aquat. Sci. 3392: iv + 56 p. (Accessed April 13, 2021)

Hilborn, R. and Walters, C.J. 1992. Quantitative fisheries stock assessment, choice, dynamics and uncertainty. Chapman and Hall, London, UK.

Hume, J. M. B., Shortreed, K. S., and Morton, K. F. 1996. Juvenile Sockeye rearing capacity of three lakes in the Fraser River system. Can. J. Fish. Aquat. Sci. 53(4): 719–733.

Kim, S., and Kim, H. 2016. A new metric of absolute percentage error for intermittent demand forecasts. Int. J. Forecast. 32: 669-679.

MacDonald, B.L., and Grant, S.C.H. 2012. Pre-season run size forecasts for Fraser River Sockeye salmon (*Oncorhynchus nerka*) in 2012. DFO Can. Sci. Advis. Sec. Res. Doc. 2012/011. v + 64 p. (Accessed April 9, 2021)

MacDonald, B.L., Grant, S.C.H., Patterson, D.A., Robinson, K.A., Boldt, J.L., Benner, K., Neville, C.M., Pon, L., Tadey, J.A., Selbie, D.T. and Winston, M.L. 2018. State of the Salmon: Informing the survival of Fraser Sockeye returning in 2018 through life cycle observations. Can. Tech. Rep. Fish. Aquat. Sci. 3271: 53 + v pp. (Accessed April 9, 2021)

MacDonald, B.L., Grant, S.C.H., Patterson, D.A., Robinson, K.A., Boldt, J.L., Benner, K., King, J, Pon, L., Selbie, D.T, Neville, C.M., and Tadey, J.A. 2019. State of the Salmon: Informing the survival of Fraser Sockeye returning in 2019 through life cycle observations. Can. Tech. Rep. Fish. Aquat. Sci. 3336: 61 + vi pp. (Accessed April 9, 2021)

MacDonald, B.L., Grant, S.C.H., Wilson, N., Patterson, D.A., Robinson, K.A., Boldt, J.L., King, J. Anderson, E., Decker, S., Leaf, B., Pon, L., Xu, Y., Davis, B., and Selbie, D.T. 2020. State of the Salmon: Informing the survival of Fraser Sockeye returning in 2020 through life cycle observations. Can. Tech. Rep. Fish. Aquat. Sci. 3398: v + 76 p. (Accessed April 9, 2021)

Mantua, N.J., Hare, S.R., Zhang, Y., Wallace, J.M., and Francis, R.C. 1997. A Pacific Interdecadal Climate Oscillation with Impacts on Salmon, Bull. Am. Meteorol. Soc., 78(6):1069–1079.

Maunder, M.N. 2003. Paradigm shifts in fisheries stock assessment: from integrated analysis to Bayesian analysis and back again. Nat. Res. Mod. 16:465-475.

Mueter, F.J., Peterman, R.M., and Pyper, B.J. 2002. Opposite effects of ocean temperature on survival rates of 120 stocks of Pacific salmon (*Oncorhynchus spp*.) in northern and southern areas. Can. J. Fish. Aquat. Sci. 59:456-463.

Peterman, R.M., and Dorner, B. 2012. A widespread decrease in productivity of Sockeye salmon (*Oncorhynchus nerka*) populations in western North America. Can. J. Fish. Aquat. Sci. 69(8): 1255–1260.

Perälä, T.A., Swain, D.P. and Kuparinen, A., 2016. Examining nonstationarity in the recruitment dynamics of fishes using Bayesian change point analysis. Can. J. Fish. Aquat. Sci. 74(5), 751-765.

Punt, A.E., and Hilborn, R. 1997. Fisheries stock assessment and decision analysis: the Bayesian approach. Reviews in Fish Biology and Fisheries 7: 35–63.

R Core Team (2020). R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. (Accessed April 13, 2021)

Thorson, J.T., and Cope, J.M., 2017. Uniform, uninformed or misinformed?: The lingering challenge of minimally informative priors in data-limited Bayesian stock assessments. Fish. Res., 194, pp.164-172.

Thorson, J.T. 2018. Forecast skill for predicting distribution shifts: A retrospective experiment for marine fishes in the Eastern Bering Sea Fish and Fisheries 20:159–173.

Treaty between the Government of Canada and the Government of the United States of America concerning Pacific Salmon. 1985. Pacific Salmon Commission. (Accessed April 9, 2021)

Vert-Pre, K.A., Amoroso, R.O., Jensen, O.P. and Hilborn, R. 2013. Frequency and Intensity of Productivity Regime Shifts in Marine Fish Stocks. Proc. Natl. Acad. Sci. U.S.A. 110(5): 1779-1784.

Walters, C.J. and Martell, J.D.M. 2002. Fisheries Ecology and Management. Princeton University Press, Princeton, NJ.

Ward, E.J., Holmes, E.E., Thorson, J.T., and Collen, B. 2014. Complexity is costly: a meta-analysis of parametric and non-parametric methods for short-term population forecasting. Oikos. 123: 652-661.

Zhang Y., Wallace, J.M., and Battisti, D.S. 1997: ENSO-like interdecadal variability: 1900-1993. J. Climate, 10.

Appendix 1. General Model Selection Criteria

Currently, the Fraser River Sockeye and Pink forecast model selection process is an expert-driven process that relies on methods and results summarized in MacDonald and Grant (2012). In recent years, historically low productivity has led to changes in how models are selected. While model rankings from MacDonald and Grant (2012) are still used, choosing a model that reflects recent productivity has become a focus of the process. While there will be deviations from the model selection process described below, the following conventions were generally followed for the 2021 model selection process, which took place over two day-long meetings in December 2020, and January 2021. See Appendix 2 for candidate model selection statistics used, and Appendix 3 for stock-specific model choice rationales.

1. For each stock, models are ranked according to their relative performance on each of four performance measures (MRE, MAE, MPE and RMSE; see Cass et al. 2006 for details). Ranks across the four performance measures are then averaged to generate an average rank for each model evaluated (see Table 5 in MacDonald and Grant 2012).
2. Candidate models (generally a set of top-ranked models) are presented to an expert group along with their rankings based on MacDonald and Grant (2012). The age-specific forecasts, and their corresponding implied productivity rates are presented, and compared to historical time-series of observed productivity (as well as metrics of average, minimum, maximum, and recent average productivity; Table 2 of main document). Since many stocks have shown low productivity in recent generations, efforts are made to choose models that might capture the dynamics of these recent declines in productivity (ie. using environmental covariates). Additionally, alternative models may be proposed (generally with environmental covariates) in an attempt to capture recent dynamics better than those models presented in 2012.
3. a) Generally, biological models are favoured over naïve models, because naive models do not account for density-dependent effects, or rely on any biologically-defensible underlying mechanisms. In cases where the top-ranked models are naïve, they are generally skipped over, especially when these naïve models aren't based on brood year EFS (ie. R1C, R2C, RAC, TSA).

   b) In exceptional cases of significant declines in productivity, where none of the candidate biological models capture recent productivity (identified as recent generational average productivity falling below the P10 level of candidate biological models) an RS8yr model was considered and chosen if it seemed to reflect recent average productivity, and the variation around it in the last few generations, by comparing the productivity implied across the P10-P90 levels, and how it compares to range of values seen recently. An RS8yr model was favoured over an RS4yr model, because only basing the forecast on one generation was viewed as being too narrow of a view, and unlikely to capture a realistic range of uncertainty around potential Recruits-per-spawner values. This is a new criteria for 2021.
4. Due to warm conditions in recent years, driven by climate change, biological models with environmental covariates are generally favoured when they lead to forecasts that better align with recent productivity. For 2021 returns, temperature indicators are similarly poor (ie. warm) as those seen for 2020 returns, and so in an attempt to capture the poor productivity observed in 2020 returns, biological models with SST covariates were heavily favoured in the 2021 forecast. This convention led to the top-ranked biological model with a temperature covariate to be chosen in many cases. This criteria alters the conventions used in previous years.

5. In cases where none of the top-ranked candidate models reflect recent productivity well, a temperature covariate may be added to a top-ranked biological model in an attempt to capture recent low productivity.
6. Recent performance of candidate models is informally considered, although the retrospective analysis is not updated each year. If top-ranked models have over-estimated returns in recent years (under similar environmental conditions) this may be used as motivation for considering alternative models.
7. Sibling models are considered when a biological model is chosen, to estimate the older age-class (generally age-5's, but age-4's for Harrison). Decisions about whether to use a sibling model to forecast the older age-class are made in the following steps:
    a. Sibling models are fit for all major stocks, and model fit is assessed using the coefficient of determination (R^2). The same metric is calculated for the chosen biological model for each stock. Sibling models are considered if the sibling model R^2 value is higher than the corresponding biological model value, or within 5% of it. This convention has not been altered from the approach taken in recent years.
    b. Since we apply sibling models in order to attempt to capture recent productivity, and in recent years, this is generally synonymous with capturing low productivity, in cases where the sibling model produces higher number than the chosen biological model, we do not apply these models. This is a new convention adopted for 2021.

Table A1-1. Model selection criteria used/met are identified for each stock. Generally an X indicates that this selection criteria played a role in model selection. For criteria 7a and 7b, an X indicates whether the given selection criteria was met. This means that a sibling model was only applied if both criteria were met (X's in both columns 7a and 7b; further details on sibling model selection in Table 8 of main document).

Stock	Model Selection Criteria Used/Met								
	1	2	3a	3b	4	5	6	7a	7b
Early Stuart	X	X	-	-	X	-	X	X	-
Bowron	X	X	X	-	X	-	X	-	-
Fennel	X	X	X	-	X	-	-	X	X
Gates	X	X	-	X	-	-	-	-	-
Nadina	X	X	X	-	X	-	-	X	X
Upper Pitt	X	X	X	-	X	-	-	X	X
Scotch	X	X	X	-		X	-	X	X
Seymour	X	X	X	-	X	-	-	X	-
Chilko	X	X	-	X	-	-	-	-	-
Late Stuart	X	X	X	-	-	X	-	-	-
Quesnel	X	X	X	-	X	-	-	X	-
Stellako	X	X	X	-	-	-	-	X	X
Harrison	X[A]	X	-	-	-	-	X	X	X
Raft	X	X	X	-	X	-	X	X	X
Cultus	X	X	X	-	X	-	X	X	X
Late Shuswap	X	X	X	-	X	-	-	X	-
Portage	X	X	-	X	-	-	-	-	-
Weaver	X	X	X[B]	-	-	-	-	-	-
Birkenhead	X	X	-	X	-	-	-	-	-

A. *For Harrison, criteria 1 was used somewhat indirectly, as the chosen model (Ricker-Ei-Odd) is a modification of the top-ranked model (Ricker-Ei).*

B. *For weaver, a naïve model was chosen, despite not meeting criteria 3b, because it was highly ranked, and captured recent productivity dynamics well.*

Appendix 2. Individual stock forecast summaries

For each stock we provide a spawning ground summary with percentage of females observed on the spawning grounds, spawner success, and effective female spawner estimates (EFS) for the applicable brood year returning in 2021 (2017 for four-year-olds, 2016 for five-year-olds), these are compared to historical cycle-line averages (generally 1953-2017 for four-year-olds; 1952-2016 for five-year-olds, unless notes otherwise).

To compare candidate models, tables of forecast values are provided for each stock, along with their rankings from MacDonald and Grant (2012), and their associated age-4 survival (i.e. productivity or recruits-per-EFS). When models were not assessed in MacDonald and Grant (2012), or are showing estimates made by combining a ranked model with a sibling model for the upper age class, they are automatically assigned a ranking of 99. Chosen models are highlighted in grey. See Table 4 for model descriptions.

Horizontal barplots show forecast values for each stock (and associated uncertainty) across candidate models.

Table A2-1. Spawning ground summary - Early Stuart Stock and MU (Takla-Trembleur-Early Stuart CU).

	Four-Year-Olds		Five-Year-Olds	
Spawners	**Cyc. Avg.**	**2017 BY**	**Cyc. Avg.**	**2016 BY**
% Female	54%	55%	52%	54%
Spawner Success	92%	84%	92%	79%
EFS	95,100	7,100	18,300	3,700

Table A2-2. Candidate model forecasts table – Early Stuart Stock and MU (Takla-Trembleur-Early Stuart CU).

		Forecast Return					Forecast Age4 Survival				
Model	**Rank**	**10%**	**25%**	**50%**	**75%**	**90%**	**10%**	**25%**	**50%**	**75%**	**90%**
RickerEi	1	15,000	22,000	35,000	57,000	93,000	1.6	2.6	4.6	7.7	12.9
RickerPi	1	8,000	12,000	18,000	30,000	47,000	0.9	1.4	2.3	3.9	6.3
RickerBasic	3	18,000	28,000	45,000	80,000	137,000	2.1	3.5	5.8	10.5	18.7
RickerPDO	3	16,000	23,000	39,000	66,000	103,000	1.9	2.8	5	8.7	14.1

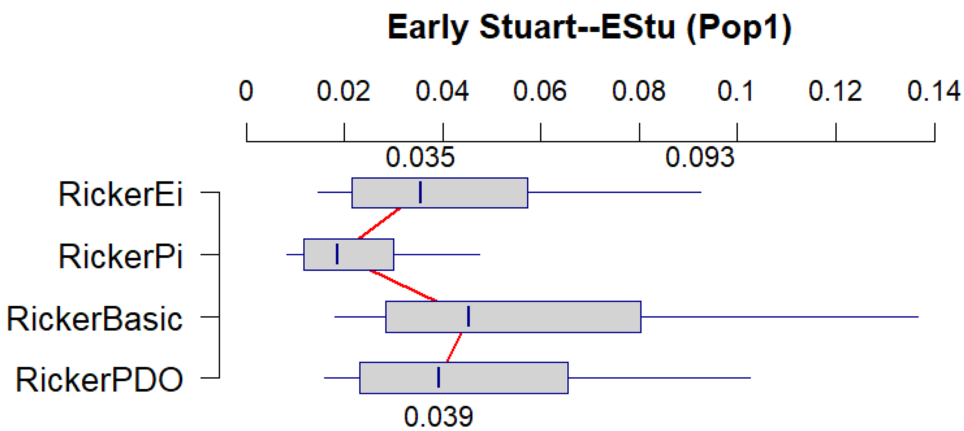


Figure A2-1. Candidate model forecasts (all numbers in millions of fish) – Early Stuart Stock and MU (Takla-Trembleur-Early Stuart CU).

Table A2-3. Spawning ground summary -Bowron (Bowron-ES) – Early Summer Mgmt Unit.

	Four-Year-Olds		Five-Year-Olds	
Spawners	**Cyc. Avg.**	**2017 BY**	**Cyc. Avg.**	**2016 BY**
% Female	53%	50%	53%	50%
Spawner Success	91%	100%	92%	100%
EFS	2,100	100	2,800	100

Table A2-4. Spawning Ground Summary - Bowron (Bowron-ES) – Early Summer Mgmt Unit.

		Forecast Return					Forecast Age4 Survival				
Model	**Rank**	**10%**	**25%**	**50%**	**75%**	**90%**	**10%**	**25%**	**50%**	**75%**	**90%**
MRS	1	200	500	1,000	3,000	7,000	1.6	3.7	9	22.1	49.7
RickerPi	2	100	200	400	700	1,000	0.6	1.1	2.4	4.7	8.7
RickerEi	3	300	400	700	1,000	3,000	1.2	2.3	4.5	9.9	18.7
RickerBasic	11	300	500	1,000	2,000	3,000	1.2	2.9	6.1	12.6	23.3

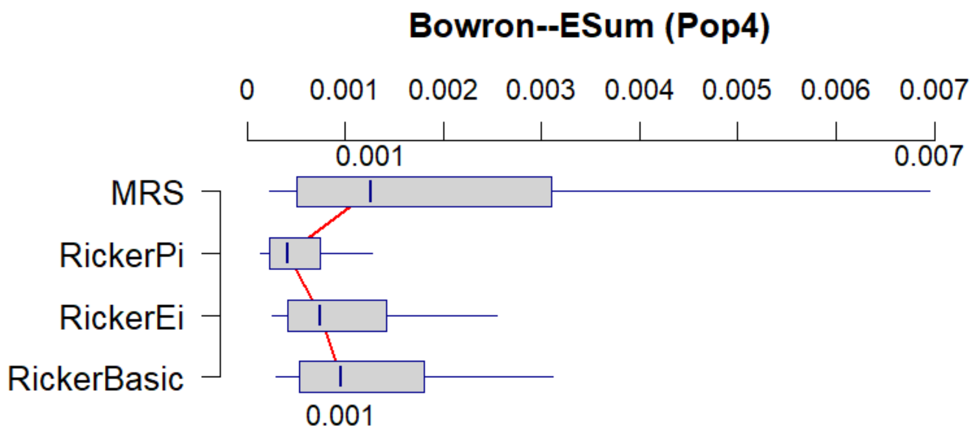


Figure A2-2. Candidate model forecasts (all numbers in millions of fish) – Bowron (Bowron-ES) - Early Summer Mgmt Unit.

Table A2-5. Spawning ground summary Fennell (North Barriere CU) – Early Summer Mgmt Unit.

	Four-Year-Olds		Five-Year-Olds	
Spawners	**Cyc. Avg.**	**2017 BY**	**Cyc. Avg.**	**2016 BY**
% Female	61%	58%	58%	60%
Spawner Success	96%	95%	87%	87%
EFS	1,800	400	4,400	600

Table A2-6. Candidate model forecasts table – Fennell (North Barriere CU) – Early Summer Mgmt Unit.

		Forecast Return					Forecast Age4 Survival				
Model	**Rank**	**10%**	**25%**	**50%**	**75%**	**90%**	**10%**	**25%**	**50%**	**75%**	**90%**
PowerBasic	1	2,000	3,000	6,000	13,000	26,000	2.5	4.8	11.4	24.3	52.4
RAC	2	2,000	4,000	11,000	28,000	67,000	3.4	8.2	21.4	56.2	134
RickerBasic	3	1,000	3,000	6,000	12,000	24,000	1.6	3.6	9.4	22.4	48.1
RickerFrDMn	6	1,000	3,000	6,000	12,000	25,000	1.7	4	9.5	25.4	57.9
RickerPi	6	500	900	2,000	3,000	6,000	0.4	0.9	2.2	4.8	10.2
RickerPi4 Sibling5	99	300	500	1,000	3,000	5,000	0.4	0.9	2.2	4.8	10.2
PowerPi	99	1,000	2,000	3,000	7,000	11,000	1	2.2	5	11.6	24.4

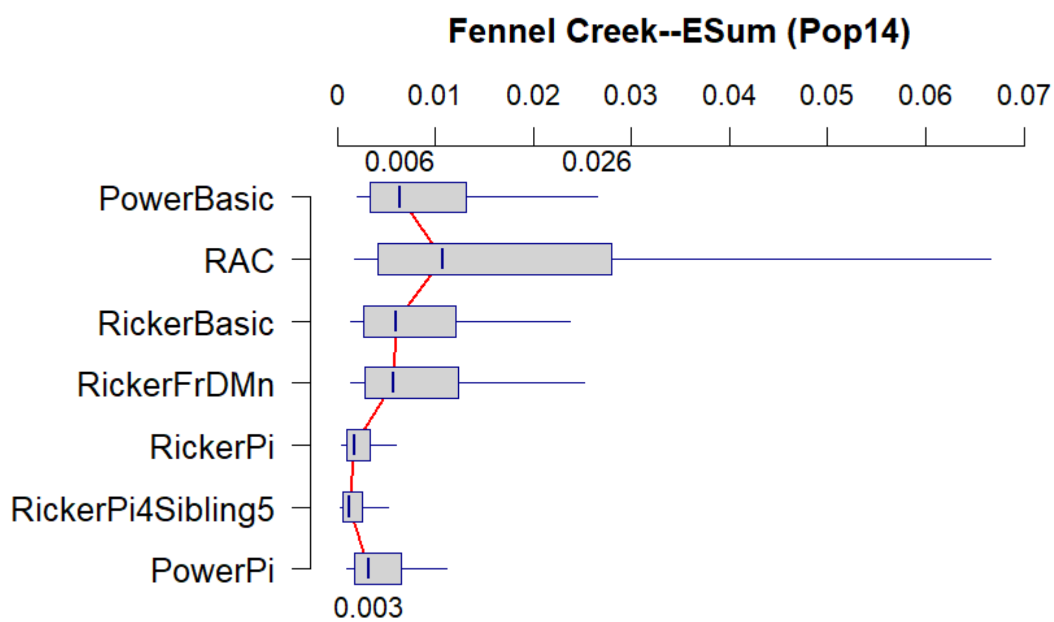


Figure A2-3. Candidate model forecasts (all numbers in millions of fish) – Fennell (North Barriere CU) – Early Summer Mgmt Unit.

Table A2-7. Spawning ground summary - Gates (Anderson-Seton-ES CU) – Early Summer Mgmt Unit.

	Four-Year-Olds		Five-Year-Olds	
Spawners	**Cyc. Avg.**	**2017 BY**	**Cyc. Avg.**	**2016 BY**
% Female	58%	54%	54%	56%
Spawner Success	78%	86%	52%	73%
EFS	5,400	3,200	8,600	3,500

Table A2-8. Candidate model forecasts table – Gates (Anderson-Seton-ES CU) – Early Summer Mgmt Unit.

		Forecast Return					Forecast Age4 Survival				
Model	**Rank**	**10%**	**25%**	**50%**	**75%**	**90%**	**10%**	**25%**	**50%**	**75%**	**90%**
RAC	1	10,000	20,000	42,000	87,000	167,000	2.8	5.3	11	22.9	44
R2C	2	15,000	29,000	61,000	127,000	246,000	4	7.7	16.1	33.5	64.7
LarkinBasic	3	8,000	14,000	25,000	44,000	70,000	2.1	3.7	7.2	12.9	21.2
MRS	3	10,000	23,000	60,000	157,000	372,000	2.5	6	15.6	40.7	96.6
PowerBasic	6	10,000	18,000	31,000	55,000	95,000	2	3.9	7.9	15.3	26
RS4yr	11	1,000	2,000	5,000	9,000	17,000	0.4	0.6	1.3	2.5	4.6
RS8yr	16	2,000	4,000	9,000	19,000	39,000	0.4	0.9	1.9	4.2	8.6
PowerJuv	99	5,000	9,000	18,000	33,000	62,000	1	2.1	4.6	9.5	18.6

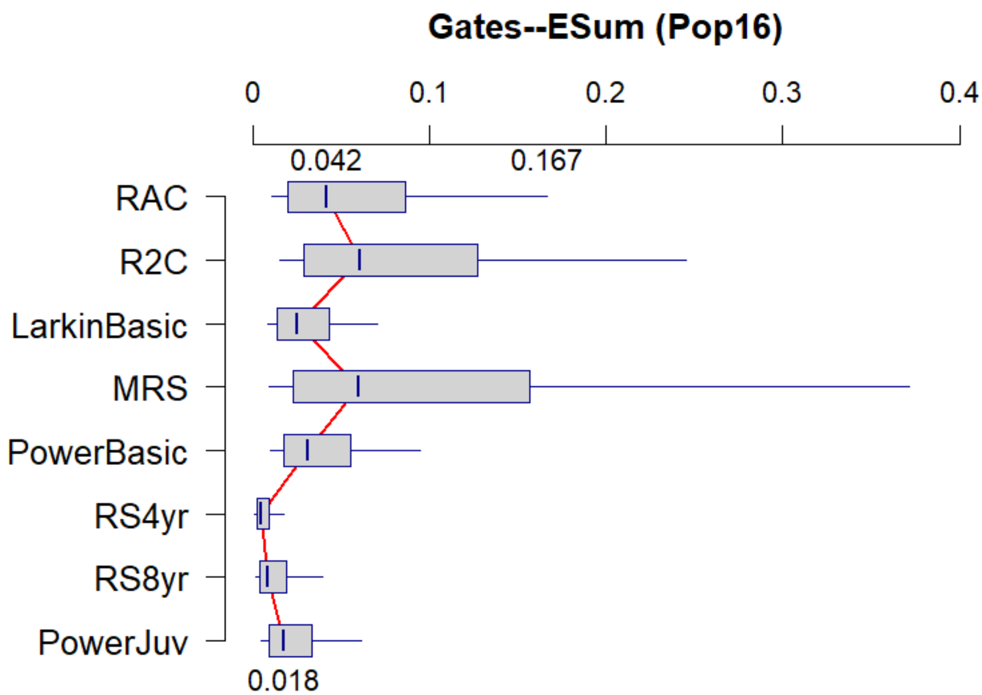


Figure A2-4. Candidate model forecasts (all numbers in millions of fish) – Gates (Anderson-Seton-ES CU) – Early Summer Mgmt Unit

Table A2-9. Spawning ground summary - Nadina (Nadina-Francois-ES CU) – Early Summer Mgmt Unit.

Spawners & Fry	Four-Year-Olds		Five-Year-Olds	
	Cyc. Avg.[a]	2017 BY	Cyc. Avg.[b]	2016 BY
% Female	51%	52%	55%	63%
Spawner Success	88%	89%	68%	96%
EFS	7,500	2,300	14,100	16,100
Freshwater Surv.(fry/EFS)	1,000	1,000	1,300	1,100
Fry Abundance	8M	2M	14M	17M

a. Brood years 1975-2017
b. Brood years 1976-2016

Table A2-10. Candidate model forecasts table – Nadina (Nadina-Francois-ES CU) – Early Summer Mgmt Unit.

Model	Rank	Forecast Return 10%	25%	50%	75%	90%	Forecast Age4 Survival 10%	25%	50%	75%	90%
MRJ	1	7,000	21,000	70,000	233,000	686,000	0.6	1.6	5.4	18	53.1
PowerJuv FRDpeak	2	9,000	15,000	28,000	48,000	85,000	1.7	3	5.7	11.6	21.6
RickerFrDPk	2	11,000	19,000	30,000	51,000	89,000	2.1	3.9	7.3	13.9	23.9
PowerJuv	8	9,000	15,000	25,000	48,000	85,000	1.4	2.3	4.9	9.1	17.2
MRS	12	7,000	22,000	75,000	260,000	796,000	0.6	1.8	6.3	21.8	66.7
RS8yr	14	7,000	18,000	51,000	141,000	356,000	0.6	1.6	4.3	12.1	30.4
RickerEi	16	9,000	15,000	27,000	54,000	98,000	1.5	2.8	5.4	9.7	18.6
RS4yr	24	4,000	12,000	36,000	111,000	307,000	0.4	1.2	3.6	11	30.5
PowerJuv FRDpeak4. Sibling5	99	6,000	10,000	19,000	37,000	68,000	1.7	3	5.7	11.6	21.6

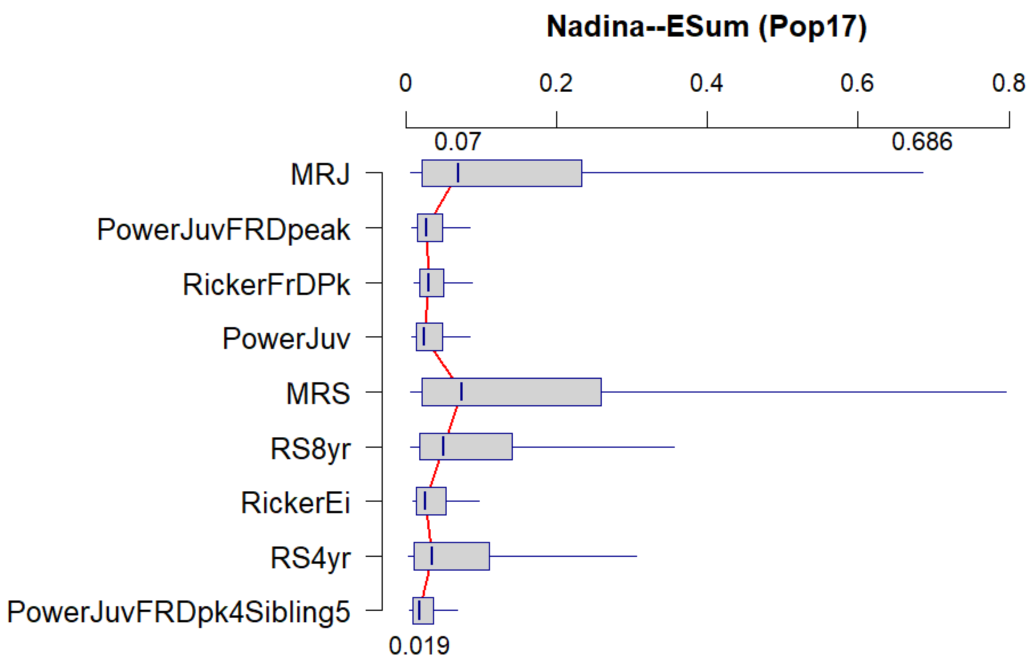


Figure A2-5. Candidate model forecasts (all numbers in millions of fish) – Nadina (Nadina-Francois-ES CU) – Early Summer Mgmt Unit.

Table A2-11. Spawning ground summary - Pitt (Pitt-ES CU) – Early Summer Mgmt Unit.

	Four-Year-Olds		Five-Year-Olds	
Spawners	**Cyc. Avg.[a]**	**2017 BY**	**Cyc. Avg.[b]**	**2016 BY**
% Female	53%	56%	49%	54%
Spawner Success	93%	99%	91%	98%
EFS	15,700	18,900	16,700	31,100

a. Brood years 1949-2017
b. Brood years 1948-2016

Table A2-12. Candidate model forecasts table – Pitt (Pitt-ES CU) – Early Summer Mgmt Unit.

		Forecast Return					Forecast Age4 Survival				
Model	**Rank**	**10%**	**25%**	**50%**	**75%**	**90%**	**10%**	**25%**	**50%**	**75%**	**90%**
LarkinBasic	1	29,000	43,000	72,000	119,000	180,000	0.2	0.3	0.6	1.2	2.1
TSA	2	27,000	43,000	71,000	117,000	185,000	0.2	0.3	0.6	0.9	1.4
RickerPDO	3	26,000	41,000	66,000	107,000	176,000	0.2	0.3	0.7	1.2	2.4
RickerEi	4	24,000	37,000	57,000	93,000	142,000	0.2	0.3	0.6	1.2	1.9
RickerBasic	9	28,000	42,000	71,000	116,000	188,000	0.2	0.3	0.7	1.3	2.5
RS8yr	16	13,000	25,000	53,000	114,000	227,000	0.1	0.1	0.2	0.5	1
RS4yr	17	3,000	6,000	13,000	26,000	50,000	0	0	0	0.1	0.2
RickerEi4. Sibling5	99	14,000	23,000	40,000	69,000	108,000	0.2	0.3	0.6	1.2	1.9

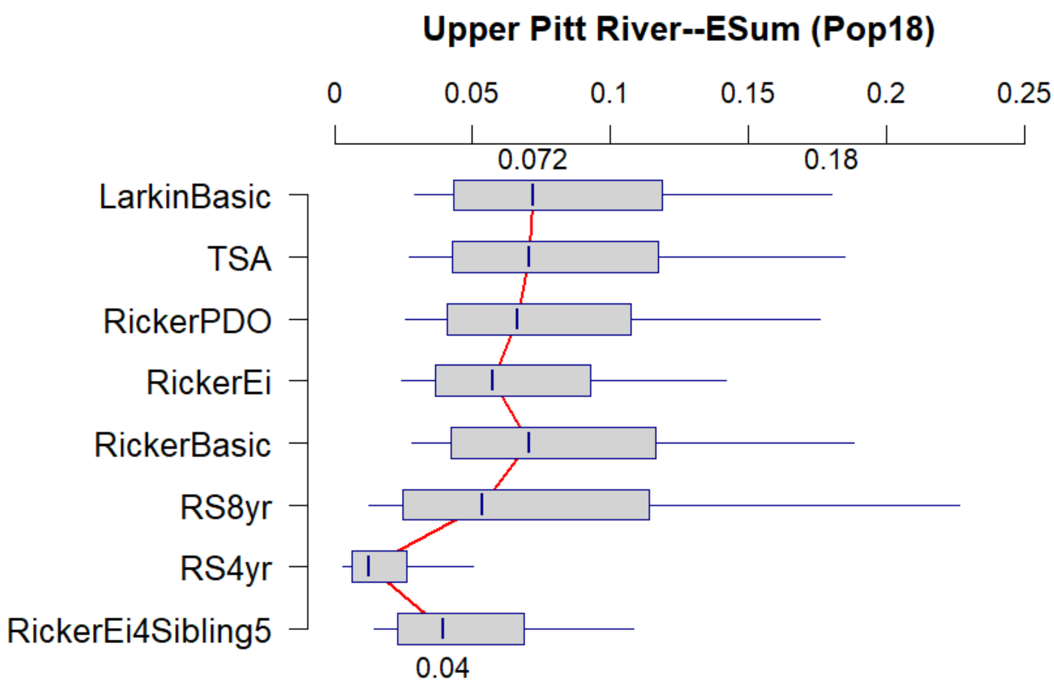


Figure A2-6. Candidate model forecasts (all numbers in millions of fish) – Pitt (Pitt-ES CU) – Early Summer Mgmt Unit.

Table A2-13. Spawning ground summary - Scotch (Part of Shuswap-ES CU) – Early Summer Mgmt Unit.

	Four-Year-Olds		Five-Year-Olds	
Spawners	**Cyc. Avg.**	**2017 BY**	**Cyc. Avg.**	**2016 BY**
% Female	49%	49%	56%	54%
Spawner Success	93%	98%	87%	90%
EFS	3,700	2,400	800	500

Table A2-14. Candidate model forecasts table – Scotch (Part of Shuswap-ES CU) – Early Summer Mgmt Unit.

		Forecast Return					Forecast Age4 Survival				
Model	**Rank**	**10%**	**25%**	**50%**	**75%**	**90%**	**10%**	**25%**	**50%**	**75%**	**90%**
LarkinBasic	1	3,000	5,000	10,000	21,000	42,000	1	1.9	4	8.9	17.8
RickerBasic	2	3,000	7,000	15,000	30,000	63,000	1.1	2.6	6.1	12.5	26.6
RS1	3	8,000	17,000	41,000	100,000	224,000	3.1	7	17.1	41.7	93.2
RickerCyc	11	2,000	4,000	10,000	24,000	58,000	0.7	1.7	4.3	10.4	24.6
RickerPi	16	1,000	3,000	6,000	13,000	28,000	0.5	1	2.4	5.3	11.8
RickerPi4. Sibling5	99	1,000	3,000	6,000	13,000	28,000	0.5	1	2.4	5.3	11.8

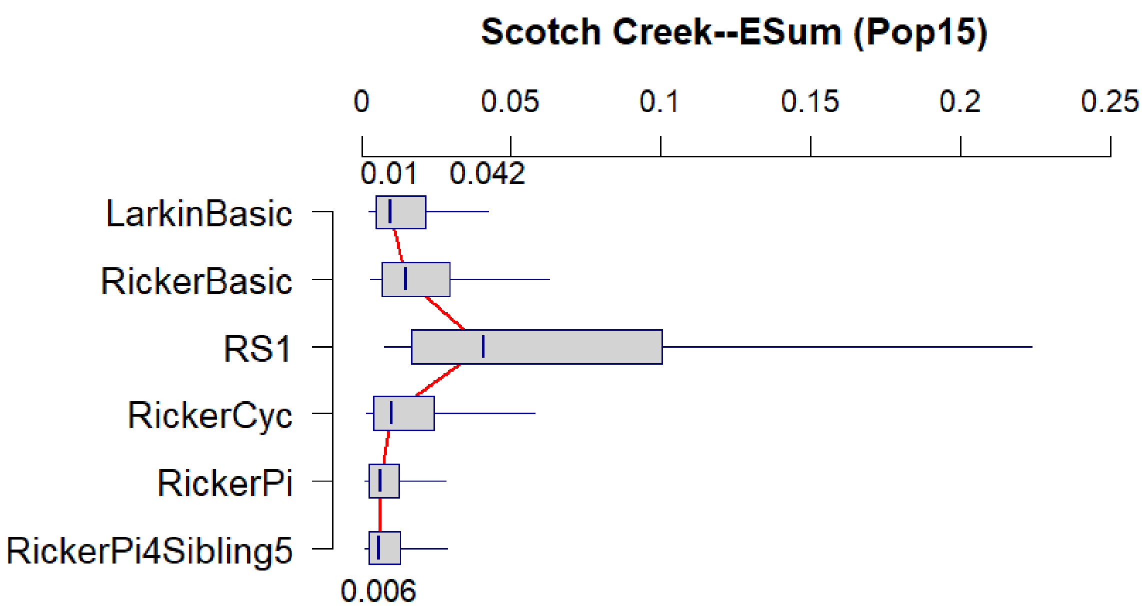


Figure A2-7. Candidate model forecasts (all numbers in millions of fish) – Scotch (Part of Shuswap-ES CU) – Early Summer Mgmt Unit.

Table A2-15. Spawning ground summary - Seymour (Part of Shuswap-ES CU) – Early Summer Mgmt Unit.

	Four-Year-Olds		Five-Year-Olds	
Spawners	**Cyc. Avg.**	**2017 BY**	**Cyc. Avg.**	**2016 BY**
% Female	56%	53%	51%	54%
Spawner Success	96%	98%	97%	90%
EFS	3,700	1,700	3,800	200

Table A2-16. Candidate model forecasts table – Seymour (Part of Shuswap-ES CU) – Early Summer Mgmt Unit.

		Forecast Return					Forecast Age4 Survival				
Model	**Rank**	**10%**	**25%**	**50%**	**75%**	**90%**	**10%**	**25%**	**50%**	**75%**	**90%**
RickerCyc	1	4,000	7,000	14,000	24,000	41,000	2.1	4.2	8.1	14	24.4
LarkinBasic	2	4,000	6,000	11,000	20,000	37,000	2	3.3	6.3	12.2	21.9
N_R1C	2	1,000	3,000	5,000	9,000	15,000	0.8	1.3	2.5	4.7	8.2
N_RAC	4	9,000	14,000	24,000	42,000	68,000	4.7	7.7	13.1	22.4	36.4
RickerEi	5	3,000	5,000	8,000	16,000	31,000	1.5	2.6	4.9	9.4	18.5
PowerBasic	9	4,000	6,000	13,000	25,000	47,000	1.9	3.6	7.4	15	27.6
RickerBasic	9	3,000	6,000	12,000	23,000	40,000	1.9	3.5	7	13.4	24

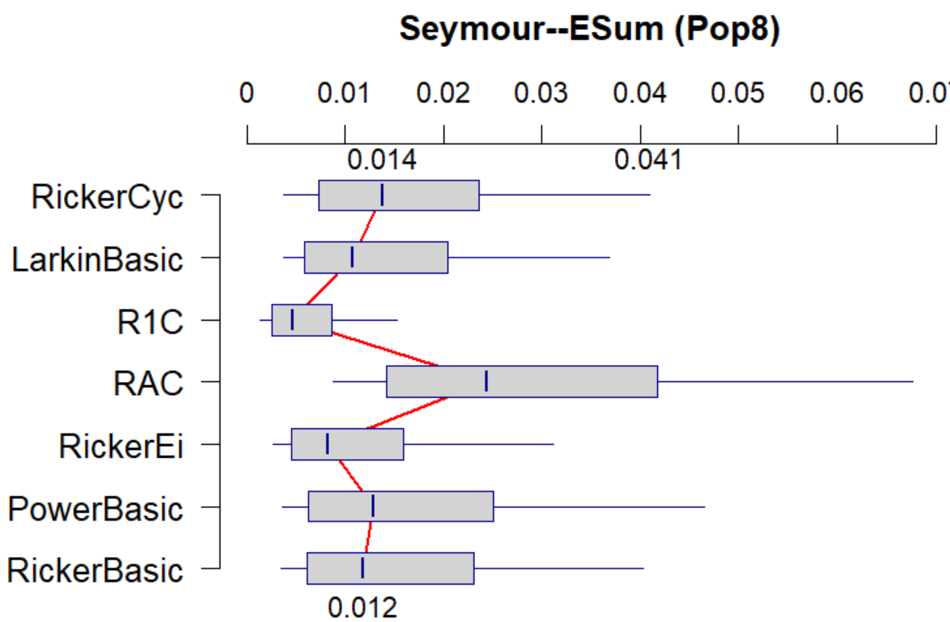


Figure A2-8. Candidate model forecasts (all numbers in millions of fish) – Seymour (Part of Shuswap-ES CU) – Early Summer Mgmt Unit.

Table A2-17. Spawning ground summary - Chilko (Chilko-S CU) – Summer Mgmt Unit. Freshwater survival (fry-per-EFS) are provided, along with fry abundance for each applicable brood year returning in 2021.

Spawners & Fry	Four-Year-Olds Cyc. Avg.[a]	Four-Year-Olds 2017 BY	Five-Year-Olds Cyc. Avg.[b]	Five-Year-Olds 2016 BY
% Female	55%	60%	56%	49%
Spawner Success	97%	96%	92%	87%
EFS	230,100	213,000	227,800	66,000
Fry/EFS	200	300	100	100
Fry Abundance	29M	58M	17M	9M

a. Brood years 1977-2017
b. Brood years 1976-2016

Table A2-18. Candidate model forecasts table – Chilko (Chilko-S CU) – Summer Mgmt Unit.

Model	Rank	Forecast Return 10%	25%	50%	75%	90%	Forecast Age4 Survival 10%	25%	50%	75%	90%
LarkinBasic	1	339,000	524,000	914,000	1,699,000	2,790,000	1.5	2.4	4.2	7.9	13
PowerJuvPi	1	487,000	779,000	1,358,000	2,483,000	4,254,000	1.9	3.3	6.1	11.5	19.8
PowerJuv	3	680,000	1,130,000	2,005,000	3,671,000	6,265,000	2.7	4.9	8.9	17	29.3
PowerJuvFRDpeak	4	721,000	1,285,000	2,263,000	4,111,000	7,088,000	3.1	5.7	10.3	19	33.2
RickerCyc	7	326,000	567,000	1,033,000	1,875,000	3,682,000	1.1	2.2	4.3	8.4	16.9
RickerFrDMn	11	494,000	819,000	1,426,000	2,675,000	4,343,000	2	3.5	6.3	11.9	20
PowerJuvEi	13	651,000	1,087,000	1,923,000	3,537,000	6,075,000	2.7	4.8	8.7	16.1	28.3
RickerBasic	14	482,000	777,000	1,389,000	2,481,000	4,018,000	1.8	3.2	6.1	11.3	18.3
RickerEi	17	404,000	669,000	1,195,000	2,169,000	3,742,000	1.6	2.8	5.3	9.8	17.1
RS8yr	22	71,000	142,000	311,000	677,000	1,366,000	0.3	0.6	1.3	2.9	5.9
RS4yr	30	44,000	92,000	210,000	479,000	1,007,000	0.2	0.4	0.9	2.2	4.5
RickerFrDMn	11	494,000	819,000	1,426,000	2,675,000	4,343,000	2	3.5	6.3	11.9	20

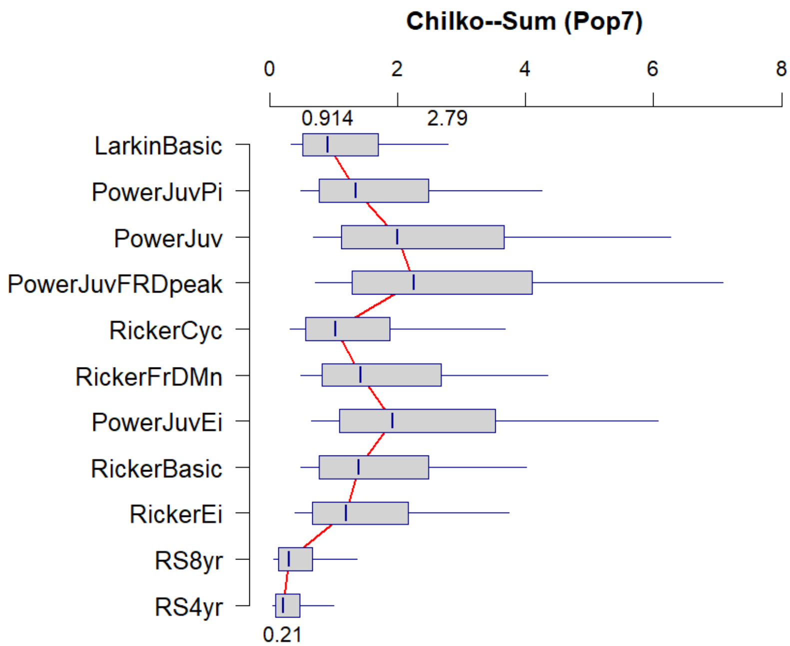


Figure A2-9. Candidate model forecasts (all numbers in millions of fish) – Chilko (Chilko-S CU) – Summer Mgmt Unit

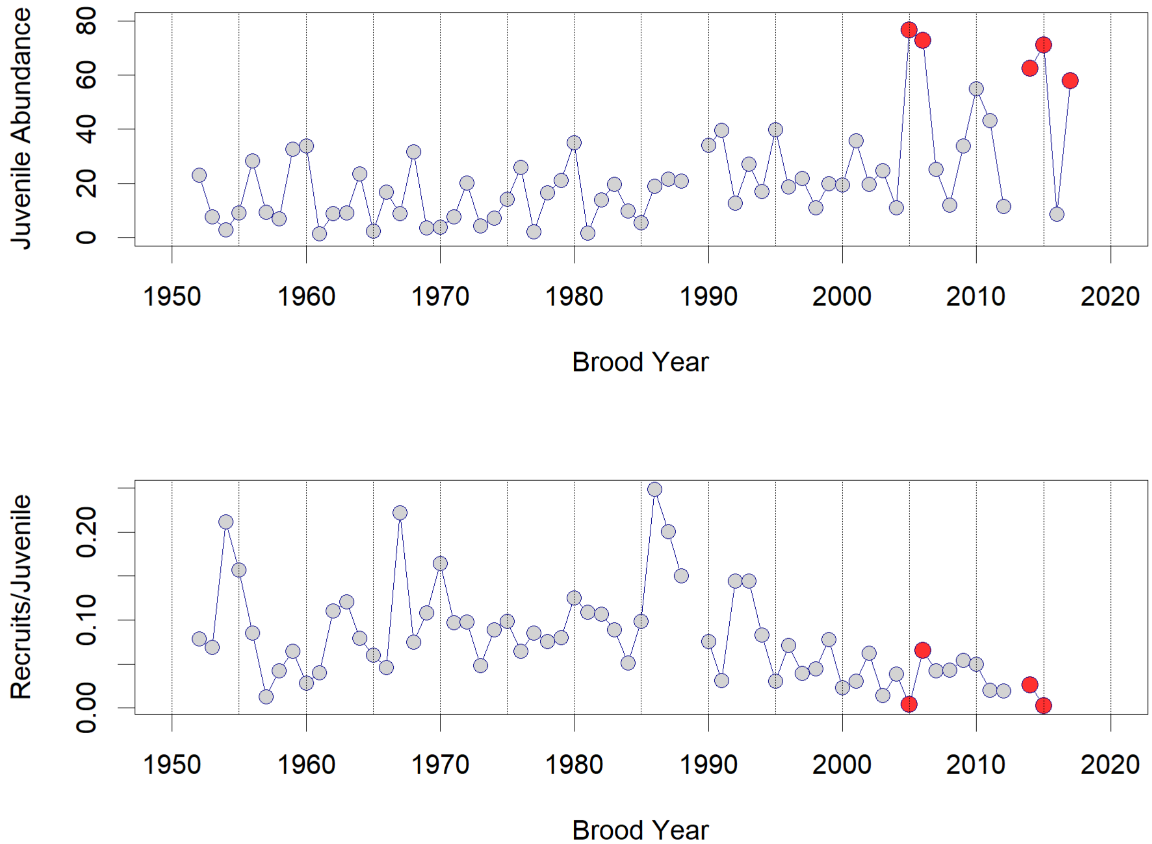


Figure A2-10. Chilko juvenile abundance and productivity plots. The time series of juvenile abundance (in millions) and recruits-per-juvenile (productivity during out-migration and marine stage) of the Chilko stock. Red dots represent brood years of high juvenile abundance (more than 50 million) and corresponding productivity of these brood years, which are relatively low compared to historical records.

Table A2-19. Spawning ground summary - Late Stuart (Takla-Trembleur-S CU) – Summer Mgmt Unit.

	Four-Year-Olds		Five-Year-Olds	
Spawners	**Cyc. Avg.**	**2017 BY**	**Cyc. Avg.**	**2016 BY**
% Female	58%	56%	53%	50%
Spawner Success	93%	97%	90%	100%
EFS	220,400	80,100	24,900	4,700

Table A2-20. Candidate model forecasts table – Late Stuart (Takla-Trembleur-S CU) – Summer Mgmt Unit.

		Forecast Return					Forecast Age4 Survival				
Model	**Rank**	**10%**	**25%**	**50%**	**75%**	**90%**	**10%**	**25%**	**50%**	**75%**	**90%**
R1C	1	89,000	136,000	218,000	350,000	537,000	1.1	1.6	2.6	4.2	6.4
R2C	2	74,000	125,000	222,000	394,000	662,000	0.9	1.5	2.7	4.7	7.9
PowerBasic	3	96,000	172,000	377,000	851,000	1,687,000	1	2	4.4	10.4	21.1
RickerFrDMn	5	129,000	311,000	739,000	1,759,000	4,260,000	1.4	3.7	9.1	21.8	53.2
RickerPi	7	66,000	144,000	381,000	971,000	2,064,000	0.7	1.7	4.6	11.7	25.6
LarkinBasic	8	133,000	298,000	656,000	1,583,000	3,791,000	1.5	3.5	8.1	19.6	46.4
LarkinBasic CycAge	99	139,000	298,000	655,000	1,636,000	3,713,000	1.5	3.6	7.9	20.4	46.3
PowerBasic CycAge	99	95,000	178,000	390,000	858,000	1,731,000	1	2	4.6	10.3	21.5
PowerPi	99	62,000	128,000	285,000	600,000	1,241,000	0.7	1.5	3.4	7.3	15.4

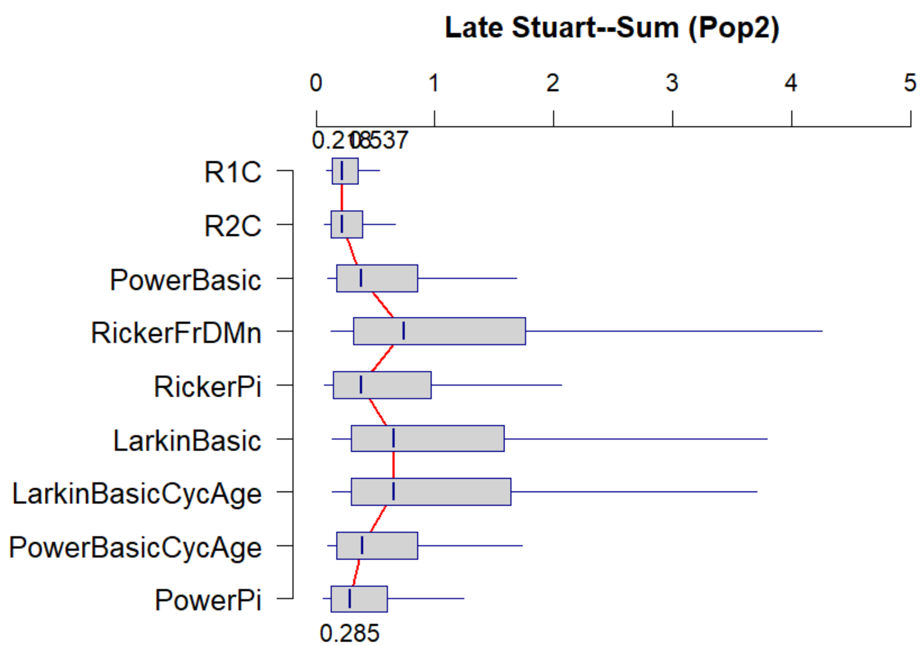


Figure A2-11. Candidate model forecasts (all numbers in millions of fish) – Late Stuart (Takla-Trembleur-S CU) – Summer Mgmt Unit.

Table A2-21. Spawning ground summary - Quesnel (Quesnel-S CU) - Summer Mgmt Unit.

	Four-Year-Olds		Five-Year-Olds	
Spawners	**Cyc. Avg.**	**2017 BY**	**Cyc. Avg.**	**2016 BY**
% Female	55%	56%	58%	58%
Spawner Success	89%	94%	95%	41%
EFS	443,200	59,600	4,500	200

Table A2-22. Candidate model forecasts table – Quesnel (Quesnel-S CU) - Summer Mgmt Unit.

		Forecast Return					Forecast Age4 Survival				
Model	**Rank**	**10%**	**25%**	**50%**	**75%**	**90%**	**10%**	**25%**	**50%**	**75%**	**90%**
R1C	1	49,000	82,000	144,000	252,000	418,000	0.8	1.4	2.4	4.2	7
R2C	2	59,000	110,000	223,000	452,000	852,000	1	1.8	3.7	7.5	14.2
RickerCyc	3	134,000	266,000	549,000	1,202,000	2,484,000	2.2	4.5	9.2	20.2	41.7
LarkinBasic	4	107,000	211,000	448,000	1,007,000	2,097,000	1.8	3.5	7.5	16.9	35.2
RickerEi	5	69,000	147,000	331,000	708,000	1,425,000	1.1	2.4	5.6	11.9	23.9
RickerBasic	6	102,000	211,000	492,000	1,095,000	2,356,000	1.7	3.5	8.3	18.3	39.5
LarkinBasicCycAge	99	125,000	233,000	494,000	1,097,000	2,236,000	2.1	3.9	8.3	18.4	37.5
PowerJuv	99	16,000	47,000	143,000	380,000	1,054,000	0.2	0.6	2	6	16.5

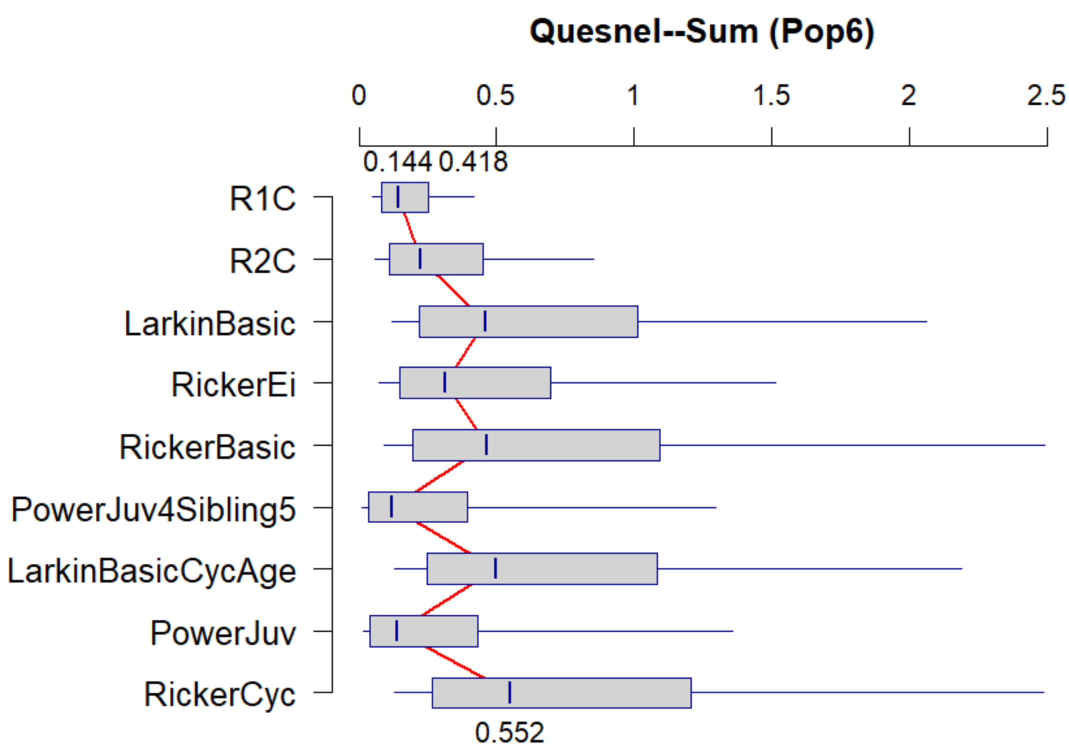


Figure A2-12. Candidate model forecasts (all numbers in millions of fish) – Quesnel (Quesnel-S CU) - Summer Mgmt Unit.

Table A2-23. Spawning ground summary - Stellako (Francois-Fraser-S CU) – Summer Mgmt Unit.

	Four-Year-Olds		Five-Year-Olds	
Spawners	**Cyc. Avg**	**2017 BY**	**Cyc. Avg.**	**2016 BY**
% Female	52%	55%	56%	53%
Spawner Success	95%	98%	89%	99%
EFS	31,100	49,400	61,900	15,800

Table A2-24. Candidate model forecasts table – Stellako (Francois-Fraser-S CU) – Summer Mgmt Unit.

		Forecast Return					Forecast Age4 Survival				
Model	**Rank**	**10%**	**25%**	**50%**	**75%**	**90%**	**10%**	**25%**	**50%**	**75%**	**90%**
R2C	1	62,000	92,000	142,000	218,000	322,000	0.8	1.2	1.9	3	4.4
LarkinBasic	2	34,000	52,000	88,000	146,000	236,000	0.3	0.5	1.1	2.1	3.8
RickerEi	3	95,000	148,000	255,000	465,000	836,000	1.2	2.2	4.2	8.4	16.1
RickerPDO	4	110,000	169,000	294,000	489,000	844,000	1.3	2.5	4.9	8.9	16
RickerPi	6	72,000	110,000	189,000	338,000	591,000	0.8	1.6	3	5.7	10.6
RickerBasic	8	118,000	194,000	334,000	605,000	962,000	1.5	2.8	5.4	11	18.6
RS4yr	15	18,000	31,000	58,000	109,000	192,000	0.3	0.5	1	1.9	3.3
RS8yr	17	41,000	74,000	143,000	276,000	499,000	0.7	1.2	2.4	4.6	8.3
LarkinBasic4. Sibling5	99	21,000	35,000	68,000	128,000	229,000	0.3	0.5	1.1	2.1	3.8

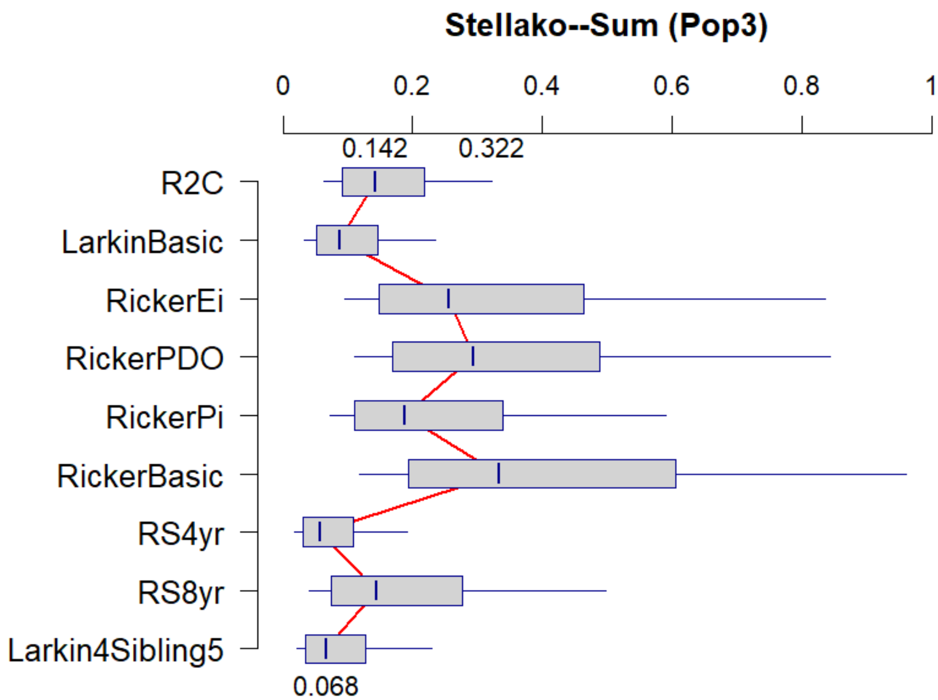


Figure A2-13. Candidate model forecasts (all numbers in millions of fish) – Stellako (Francois-Fraser-S CU) – Summer Mgmt Unit.

Table A2-25. Spawning ground summary - Harrison (Harrison River – River Type CU) – Summer Mgmt Unit. Note that for Harrison, three-year-olds are presented instead of five-year-olds.

	Four-Year-Olds		Three-Year-Olds	
Spawners	**Cyc. Avg.**	**2017 BY**	**Cyc. Avg.**[a]	**2018 BY**
% Female	44%	60%	52%	54%
Spawner Success	97%	98%	99%	99%
EFS	28,600	29,400	7,100	8,200

a. Brood years 1954-2018

Table A2-26. Candidate model forecasts table – Harrison (Harrison River – River Type CU) – Summer Mgmt Unit.

		Forecast Return					Forecast Age4 Survival				
Model	**Rank**	**10%**	**25%**	**50%**	**75%**	**90%**	**10%**	**25%**	**50%**	**75%**	**90%**
RickerEiOdd3 Sibling4	99	3,000	8,000	21,000	52,000	120,000	0.1	0.3	0.6	1.6	3.8
RickerBasic2Step	99	12,000	24,000	57,000	142,000	308,000	0.3	0.7	1.7	4.4	10.2
RickerBasicEven	99	38,000	77,000	170,000	420,000	902,000	0.8	2	4.9	13.4	30
RickerBasicOdd	99	12,000	24,000	57,000	141,000	301,000	0.3	0.7	1.7	4.4	10
RickerEi2Step	99	37,000	79,000	176,000	422,000	1,009,000	0.7	1.8	5.1	13.5	32.6
RickerEiEven	99	38,000	80,000	177,000	423,000	1,045,000	0.7	1.8	5.1	13.5	34.4
RickerEiOdd	99	11,000	22,000	52,000	123,000	267,000	0.2	0.6	1.6	4	8.8

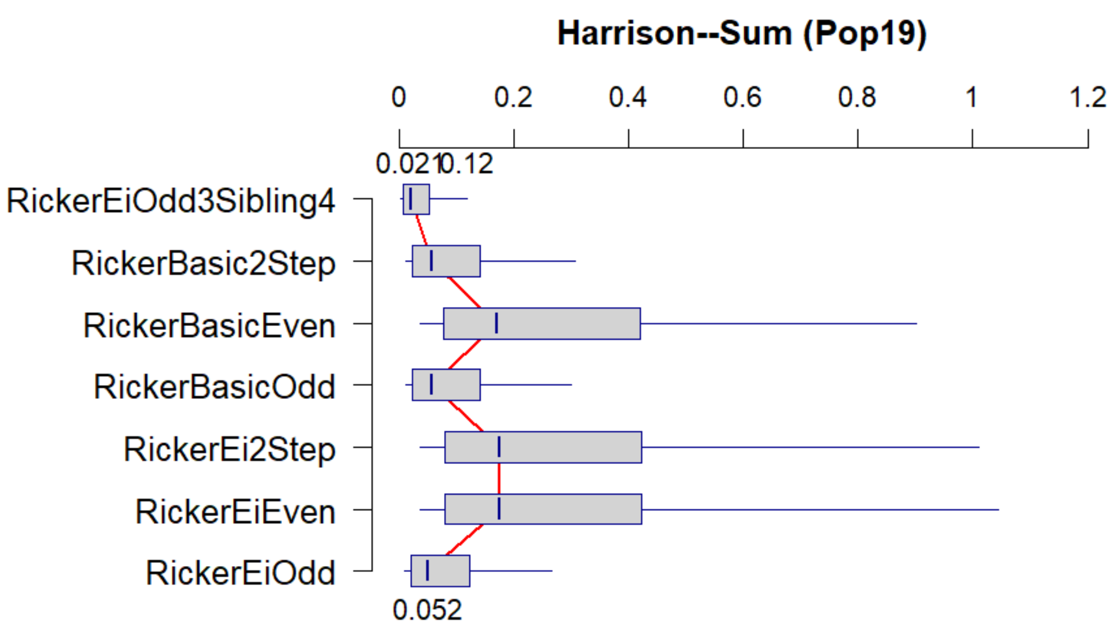


Figure A2-14. Candidate model forecasts (all numbers in millions of fish) – Harrison (Harrison River – River Type CU) – Summer Mgmt Unit.

Table A2-27. Spawning ground summary - Raft (Kamloops-ES CU) – Summer Mgmt Unit.

	Four-Year-Olds		Five-Year-Olds	
Spawners	**Cyc. Avg.**	**2017 BY**	**Cyc. Avg.**	**2016 BY**
% Female	57%	50%	50%	51%
Spawner Success	95%	91%	83%	84%
EFS	4,400	2,300	6,500	3,800

Table A2-28. Candidate model forecasts table – Raft (Kamloops-ES CU) – Summer Mgmt Unit.

		Forecast Return					Forecast Age4 Survival				
Model	**Rank**	**10%**	**25%**	**50%**	**75%**	**90%**	**10%**	**25%**	**50%**	**75%**	**90%**
RickerPDO40k	1	7,000	12,000	20,000	34,000	55,000	1	1.9	4	8.3	14.9
PowerBasic	2	7,000	12,000	22,000	35,000	58,000	1.1	2.1	4.5	9.2	17.5
RickerCyc	2	11,000	17,000	28,000	47,000	76,000	1.5	2.8	5.5	11.4	21.7
RickerPi	4	5,000	8,000	14,000	24,000	40,000	0.6	1.1	2.2	4.7	9
RickerBasic	7	8,000	15,000	26,000	48,000	76,000	1.2	2.3	5	10.4	20.2
N_RS8yr	16	3,000	7,000	15,000	34,000	70,000	0.8	1.7	3.7	8.4	17.2
N_RS4yr	17	400	900	2,000	5,000	11,000	0.1	0.2	0.5	1.3	2.8
RickerPi4. Sibling5	99	2,000	4,000	8,000	16,000	31,000	0.6	1.1	2.2	4.7	9

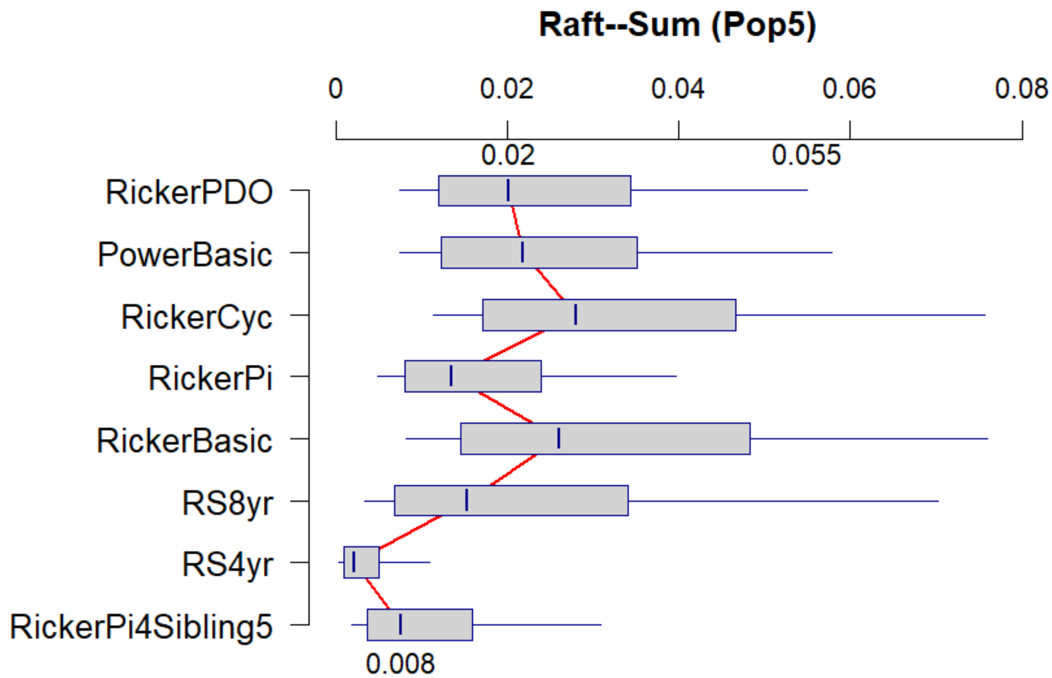


Figure A2-15. Candidate model forecasts (all numbers in millions of fish) – Raft (Kamloops-ES CU) – Summer Mgmt Unit.

Table A2-29. Spawning ground summary - Cultus (Cultus-L CU) – Late Mgmt Unit.

Spawners &	Four-Year-Olds		Five-Year-Olds	
Fry	Cyc. Avg.	2017 BY	Cyc. Avg.	2016 BY
% Female	56%	65%	60%	52%
Spawner Success	6%	63%	3%	11%
EFS	100	300	100	100
Freshwater Surv.(fry/EFS)	700	200	2,800	200
Fry Abundance	235,000	63,000	368,000	32,000

Table A2-30. Candidate model forecasts table – Cultus (Cultus-L CU) – Late Mgmt Unit.

		Forecast Return					Forecast Age4 Survival				
Model	Rank	10%	25%	50%	75%	90%	10%	25%	50%	75%	90%
MRJ	1	300	1,000	4,000	16,000	52,000	1.2	4.1	15.2	56.8	186
PowerJuvFRDpeak	2	400	800	2,000	4,000	7,000	1.2	2.7	5.7	12.3	24.4
PowerJuvPi	3	300	500	1,000	2,000	4,000	0.8	1.6	3.4	7.5	15.1
PowerJuv	9	500	900	2,000	4,000	7,000	1.5	2.8	6	12.6	25.6
PowerJuvPi4. SiblingAge5	99	200	500	900	2,000	4,000	0.8	1.6	3.4	7.5	15.1

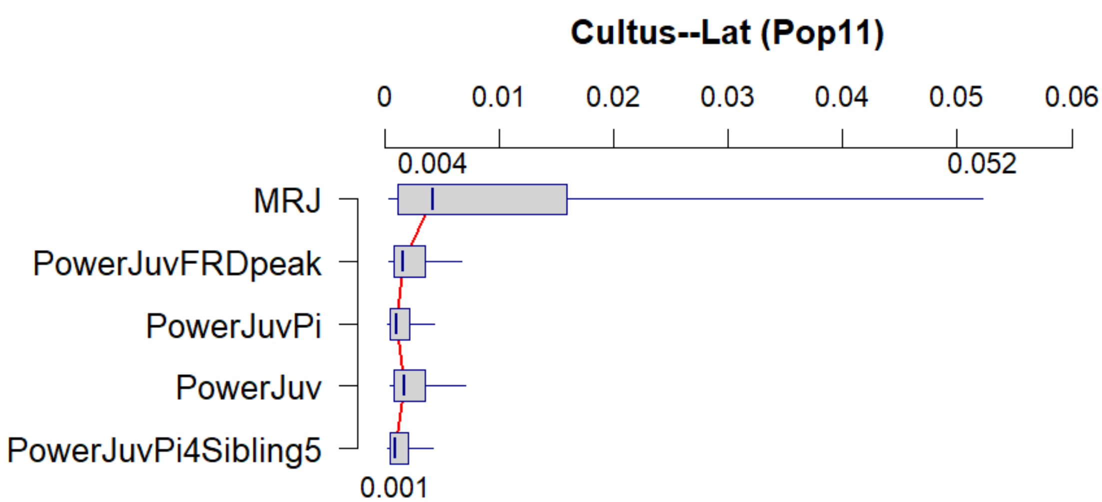


Figure A2-16. Candidate model forecasts (all numbers in millions of fish) – Cultus (Cultus-L CU) – Late Mgmt Unit.

Table A2-31. Spawning ground summary - Late Shuswap (Shuswap-L CU) – Late Mgmt Unit.

	Four-Year-Olds		Five-Year-Olds	
Spawners	**Cyc. Avg.**	**2017 BY**	**Cyc. Avg.**	**2016 BY**
% Female	59%	61%	59%	51%
Spawner Success	97%	91%	97%	100%
EFS	9,200	8,400	2,300	25

Table A2-32. Candidate model forecasts table – Late Shuswap (Shuswap-L CU) – Late Mgmt Unit.

		Forecast Return					Forecast Age4 Survival				
Model	**Rank**	**10%**	**25%**	**50%**	**75%**	**90%**	**10%**	**25%**	**50%**	**75%**	**90%**
R1C	1	4,000	10,000	28,000	80,000	204,000	0.4	1.1	3	8.5	21.8
RickerCyc	2	12,000	29,000	65,000	153,000	319,000	1.4	3.4	7.7	18.1	37.7
RAC	3	11,000	22,000	50,000	114,000	238,000	1.1	2.4	5.4	12.2	25.5
R2C	4	26,000	70,000	211,000	634,000	1,712,000	2.8	7.5	22.6	67.9	183
LarkinBasic	5	18,000	34,000	70,000	159,000	309,000	2.1	4	8.3	18.8	36.6
RickerEi	6	8,000	16,000	35,000	78,000	149,000	0.9	1.9	4.1	9.2	17.7
RickerBasic	7	10,000	21,000	45,000	101,000	228,000	1.1	2.5	5.4	12	27
PowerBasic	11	9,000	18,000	44,000	104,000	217,000	1	2.1	5.2	12.4	25.6
LarkinBasicCycAge	99	19,000	35,000	73,000	162,000	325,000	2.2	4.1	8.6	19.1	38.5
PowerBasicCycAge	99	9,000	19,000	47,000	110,000	220,000	1.1	2.2	5.5	13	26.1

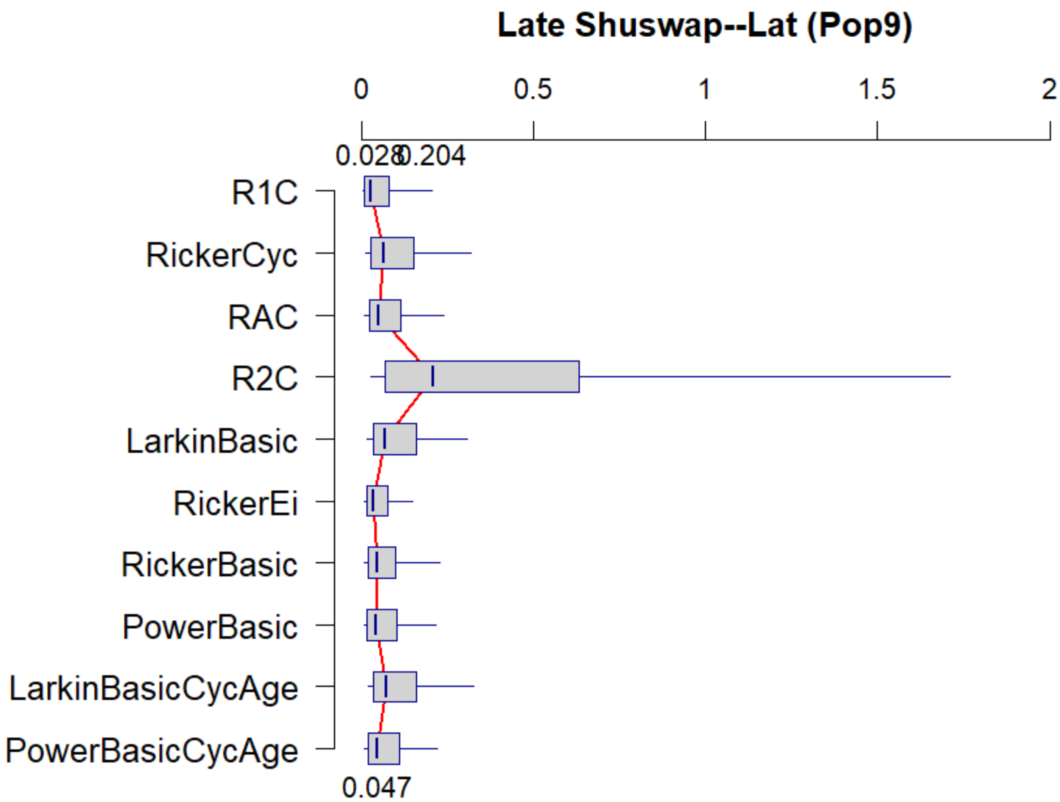


Figure A2-17. Candidate model forecasts (all numbers in millions of fish) – Late Shuswap (Shuswap-L CU) – Late Mgmt Unit.

Table A2-33. Spawning ground summary - Portage (Seton-L CU) – Late Mgmt Unit.

	Four-Year-Olds		Five-Year-Olds	
Spawners	**Cyc. Avg.**	**2017 BY**	**Cyc. Avg.**	**2016 BY**
% Female	57%	43%	59%	51%
Spawner Success	95%	86%	96%	100%
EFS	2,700	400	500	21

Table A2-34. Candidate model forecasts table – Portage (Seton-L CU) – Late Mgmt Unit.

		Forecast Return					Forecast Age4 Survival				
Model	**Rank**	**10%**	**25%**	**50%**	**75%**	**90%**	**10%**	**25%**	**50%**	**75%**	**90%**
LarkinBasic	1	900	2,000	5,000	13,000	32,000	2	4.2	11.2	29.1	71.8
RickerCyc	2	500	1,000	5,000	15,000	40,000	1.1	3.3	10.7	33.6	91.8
PowerBasic	3	900	2,000	5,000	13,000	31,000	1.8	4.3	10.6	28.9	69.8
RickerEi	6	500	1,000	3,000	8,000	21,000	1.1	2.6	7	19	46.7
RickerBasic	7	700	2,000	5,000	12,000	27,000	1.5	4.1	11.1	28.1	60.4
RickerFrDPk	8	700	2,000	5,000	13,000	32,000	1.5	4.2	11.1	28.6	72
RickerFrDMn	10	800	2,000	5,000	15,000	35,000	1.6	4.4	12.2	34.2	80.3
RickerPi	11	300	700	2,000	5,000	14,000	0.6	1.6	4.6	11.9	32.5
RS8yr	13	400	800	2,000	4,000	9,000	0.8	1.7	4	9.3	20
RickerPDO40k	14	700	2,000	5,000	12,000	29,000	1.5	3.6	10.3	26.1	64.4
RS4yr	18	200	500	1,000	3,000	7,000	0.5	1.1	2.7	6.7	14.9

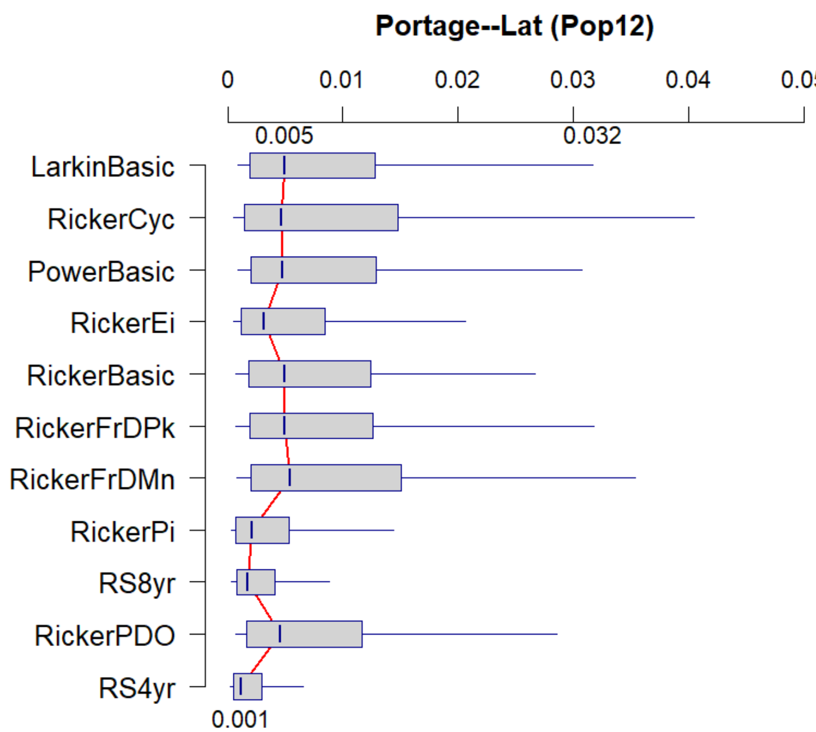


Figure A2-18. Candidate model forecasts (all numbers in millions of fish) – Portage (Seton-L CU) – Late Mgmt Unit.

Table A2-35. Spawning ground summary - Weaver (Harrison (U/S)-L CU) – Late Mgmt Unit.

Spawners & Fry	Four-Year-Olds		Five-Year-Olds	
	Cyc. Avg.	2017 BY	Cyc. Avg.	2016 BY
% Female	54%	50%	57%	42%
Spawner Success	90%	88%	90%	82%
EFS	19,900	14,400	16,900	100
Freshwater Surv.(fry/EFS)	1,600	1,800	1,700	1,500
Fry Abundance	29M	26M	26M	0.14M

Table A2-36. Candidate model forecasts table – Weaver (Harrison (U/S)-L CU) – Late Mgmt Unit.

Model	Rank	Forecast Return					Forecast Age4 Survival				
		10%	25%	50%	75%	90%	10%	25%	50%	75%	90%
RS4yr	1	41,000	66,000	112,000	191,000	308,000	2.8	4.6	7.8	13.3	21.4
MRS	2	65,000	127,000	267,000	559,000	1,090,000	4.5	8.8	18.5	38.8	75.7
RickerPDO	3	22,000	51,000	123,000	312,000	699,000	1.5	3.6	8.5	21.7	48.5
RS8yr	4	23,000	40,000	74,000	136,000	235,000	1.6	2.8	5.1	9.4	16.3
RJC	5	55,000	109,000	232,000	495,000	978,000	3.8	7.5	16.1	34.3	67.9
RSC	6	55,000	105,000	215,000	439,000	834,000	3.8	7.3	14.9	30.4	57.8
PowerJuvFRDpeak	7	35,000	73,000	180,000	438,000	1,059,000	2.3	5	12.5	30.4	73.5
PowerJuvEi	9	28,000	60,000	142,000	316,000	799,000	1.9	4.1	9.8	22	55.4
PowerJuv	14	28,000	61,000	144,000	356,000	771,000	1.9	4.1	9.9	24.7	53.2
RickerBasic	23	25,000	59,000	148,000	324,000	760,000	1.7	4.1	10.2	22.5	52.8

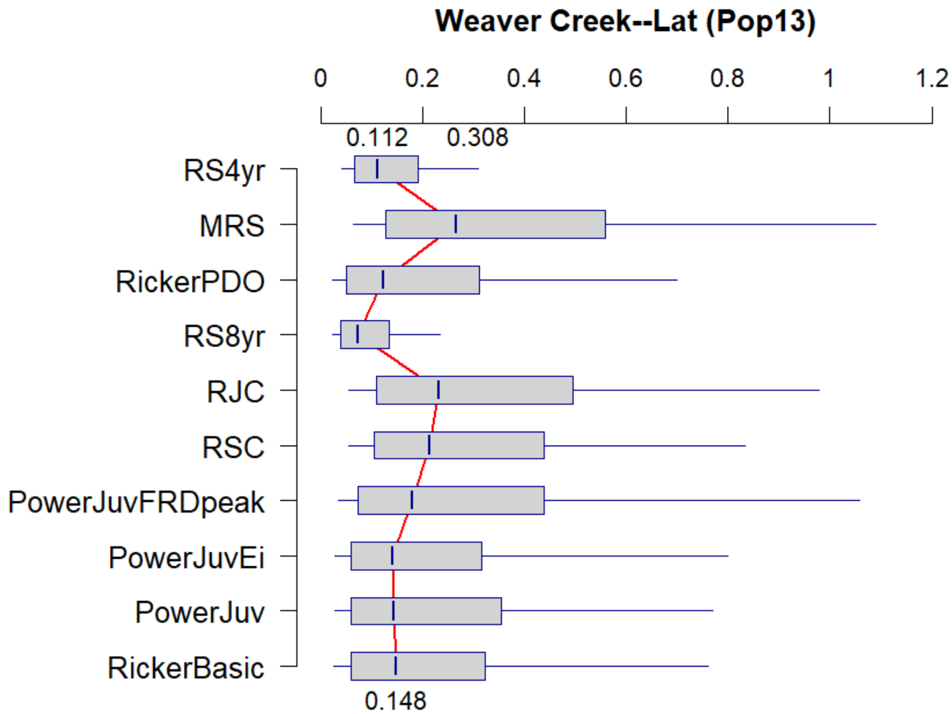


Figure A2-19. Candidate model forecasts (all numbers in millions of fish) – Weaver (Harrison (U/S)-L CU) – Late Mgmt Unit.

Table A2-37. Spawning ground summary - Birkenhead (Lillooet-Harrison-L CU) – Late Mgmt Unit.

	Four-Year-Olds		Five-Year-Olds	
Spawners	**Cyc. Avg.**	**2017 BY**	**Cyc. Avg.**	**2016 BY**
% Female	58%	56%	56%	49%
Spawner Success	93%	95%	86%	76%
EFS	27,600	9,900	29,900	13,500

Table A2-38. Candidate model forecasts table – Birkenhead (Lillooet-Harrison-L CU) – Late Mgmt Unit.

		Forecast Return					Forecast Age4 Survival				
Model	**Rank**	**10%**	**25%**	**50%**	**75%**	**90%**	**10%**	**25%**	**50%**	**75%**	**90%**
RickerEi	1	22,000	40,000	75,000	146,000	257,000	0.6	1.3	3.2	7.2	16.1
RAC	2	54,000	113,000	255,000	574,000	1,193,000	3.8	7.9	17.8	40	83.1
RickerBasic	2	34,000	62,000	126,000	237,000	420,000	0.8	2	5	11.8	25.5
TSA	4	66,000	139,000	318,000	725,000	1,522,000	4.6	9.7	22.1	50.5	106
RickerPi	4	15,000	25,000	46,000	91,000	162,000	0.3	0.7	1.6	4	8.5
RS4yr	16	900	2,000	5,000	14,000	32,000	0	0.1	0.3	0.8	1.8
RS8yr	17	5,000	10,000	22,000	47,000	95,000	0.3	0.6	1.3	2.8	5.7

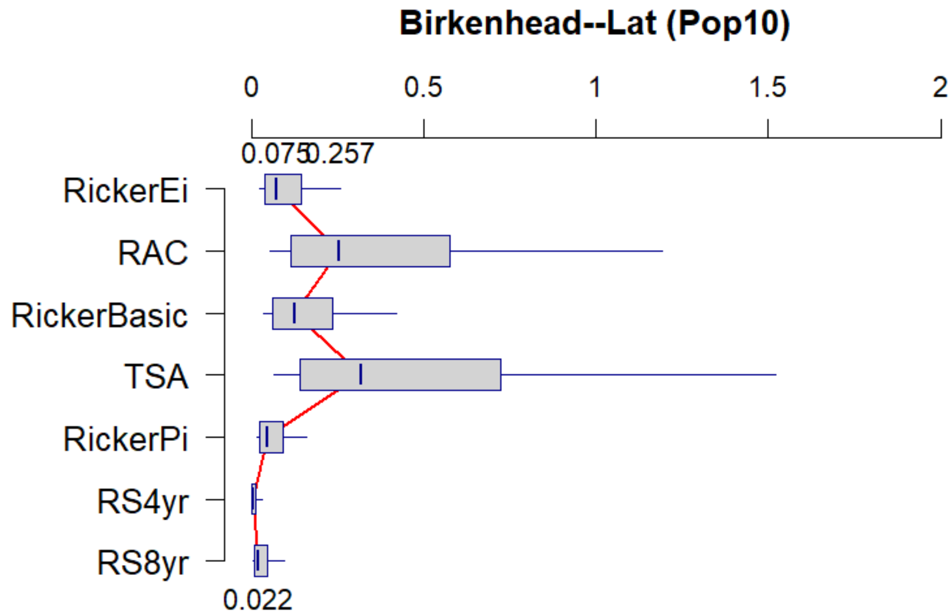


Figure A2-20. Candidate model forecasts (all numbers in millions of fish) – Birkenhead (Lillooet-Harrison-L CU) – Late Mgmt Unit.

Table A2-39. Miscellaneous stock component populations, across all management units.

Forecast Unit	Populations
Early Summer	
EShu	all South Thompson except 4: Scotch Creek, Seymour River, McNomee Creek, and Adams River (upper)
Taseko	Taseko Lake, Taseko River(upper), Yoheta (upper and lower)
Chilliwack	Chilliwack Lake, Chilliwack River, Chilliwack River(upper)
Nahatlatch	Nahatlatch River, Mahatlatch Lake
Summer	
North Thompson Tributaries	Barriere River, Clearwater River, Dunn Creek, Finn Creek, Grouse Creek, Harper Creek, Hemp Creek, Lemieux Creek, Mann Creek, Lion Creek)
North Thompson River	North Thompson River
Widgeon	Widgeon Creek, Widgeon Slough
Late	
Non-Shuswap	Big Silver Creek, Cogburn Creek, Douglas Creek, Green River, Miller Creek, Pemberton Creek, Railroad Creek, Sampson Creek, Tipella Creek

Table A2-40. Forecast total return of miscellaneous stocks and the proxy used for long term productivity.

Forecast Unit	Effective Females 2016	Effective Females 2017	Proxy for long-term Prod.	Forecast total Return 10%	25%	50%	75%	90%
Early Summer								
Misc(EShu)	97	843	Scotch/Seymour	1,221	2,610	5,615	10,995	19,123
Misc(Taseko)	82	10	Chilko	26.1	61	124	231	320
Misc(Chilliwack)	30,138	2,536	NA[a]	3,573	5,780	10,340	20,591	44,299
Misc(Nahatlatch)	808	1,358	All ES Stocks	1,823	4,333	8,457	17,153	32,068
Summer								
Misc(N. Thomp. Tribs)	236	733	Raft/Fennell	754	2,217	4,385	8,841	18,212
Misc (N. Thomp. River)	2,215	2,312	Raft/Fennell	2,879	8,463	16,737	33,746	69,513
Misc (Widgeon)	93	83	Birkenhead	86	330.4	704	1,294	2,264
Late								
Misc (Non-Shuswap)	1,941	3,844	Birkenhead	3,032	11,645	24,816	45,594	79,773

a.See Appendix 4 for details on the analysis used to forecast this stock

Table A2-41. Forecast age-4 return and implied productivity for miscellaneous stocks.

	Forecast Age-4 Return					Forecast Age-4 Productivity				
Forecast Unit	10%	25%	50%	75%	90%	10%	25%	50%	75%	90%
Early Summer										
Misc(EShu)	1,208	2,581	5,552	10,873	18,912	1.4	3.1	6.6	12.9	22.4
Misc(Taseko)	14	33	68	127	175	1.4	3.3	6.8	12.7	17.5
Misc(Chilliwack)	2,912	3,988	5,340	7,070	9,199	1.1	1.6	2.1	2.8	3.6
Misc(Nahatlatch)	1,502	3,571	6,969	14,135	26,426	1.1	2.6	5.1	10.4	19.5
Summer										
Misc(N. Thomp. Tribs)	674	1,981	3,919	7,901	16,275	0.9	2.7	5.3	10.8	22.2
Misc (N. Thomp. River)	2,126	6,249	12,360	24,920	51,333	0.9	2.7	5.3	10.8	22.2
Misc (Widgeon)	49	187	398	731	1,278	0.6	2.2	4.8	8.8	15.4
Late										
Misc(Non-Shuswap)	2,250	8,643	18,419	33,841	59,209	0.2	0.8	1.7	3.1	5.3

Appendix 3. Model choice rationales

Early Stuart

The two top-ranked models for Early Stuart were Ricker models with Entrance Island SST as a covariate, and a Ricker model with Pine Island SST as a covariate. The Ricker model with the Pine Island covariate was chosen because it better reflects recent productivity (Table 2 of main document) and performed well in 2020. For this stock, a sibling model would have been chosen based on model fit criteria, but it resulted in a higher estimate of age-5 return than the main forecast model, further deviating the forecast from recent low productivity, and was therefore excluded. The choice between the sibling model and biological model made a negligible difference (109 fish at the P50 level).

Bowron

For this stock, the second-best-ranked model; Ricker with Pine Island SST covariate was chosen. This model was chosen over the top-rank MRS model because biological models are favoured over naïve models (Appendix 1), it better captures recent productivity (Table 2 of main document), and performed well in 2020. A sibling model was not applied due to poor sibling model fit (Table 8 of main document).

Upper Barriere/Fennell

The top-ranked biological models with an environmental covariate were Ricker models with mean Fraser Discharge as a covariate, and a Ricker model with Pine Island SST as a covariate (both ranked sixth). Between these two models, the Ricker model with Pine Island SST covariate better reflected recent low productivity, and was therefore chosen. A sibling model was used to forecast age-5 returns, based on sibling model selection criteria.

Gates

Originally, a Larkin model was favoured because the two top-ranked models were naïve models that don't take into account spawner abundance. A Juvenile model was considered, but not chosen because it was not tested retrospectively, and there was uncertainty about the applicability of the juvenile data set. This stock was identified as an exceptional case in which our selection of potential models weren't able to capture a recent, significant, decline in productivity. This was identified by comparing the recent generational average age-4 productivity (0.99 recruits-per-EFS) to the productivity implied by the chosen forecast model (a Larkin model). The recent generational average productivity was lower than the productivity implied at the P10 level by the Larkin model. Therefore, an RS8yr naïve model was applied, in an attempt to capture this recent, significant, decline in productivity.

Nadina

The second ranked model; a Power-juvenile model with Fraser River peak discharge as a covariate was chosen. This model was chosen over the first-place naïve model based our general selection criteria, and chosen over the tied-for-second place model because it better reflects recent poor productivity. A sibling model was used to forecast age-5 returns, based on sibling model selection criteria.

Upper Pitt

For this stock, a Ricker model with Entrance Island SST as a covariate, combined with a sibling model for age-5's, was selected. This model was ranked fourth in the 2012 retrospective analysis. This model was favoured over the first and second place models because there was a desire to use a biological model with an environmental covariate, in an attempt to capture recent low productivity. A Ricker model with PDO as a covariate was higher ranked (third place) but the Ricker with the Entrance Island covariate was chosen because the Entrance Island effect was larger than the PDO effect (further reducing forecast returns when compared to the Ricker model with no covariates), and seemed to better reflect recent low productivity.

Scotch

For Scotch, none of the top-ranked models captured recent low productivity well. Since a Ricker model was the highest ranked model that could have a covariate added, a Ricker model with a Pine Island SST covariate was considered, and despite its lower ranking (ranked 16^{th}), it was favoured over other options, because it better captures recent, very low productivity. This model for age-4's was combined with a sibling model for age-5's, based on our sibling model criteria.

Seymour

A Ricker model with an Entrance Island SST covariate was selected, based on it being the highest ranked model with an environmental covariate (ranked fifth). Other higher ranked models did not capture recent productivity well. A sibling model would have increased the number of forecast age-5 returns, further deviating the forecast from recent low productivity, so it was not used (Table 8 of main document).

Chilko

The top-ranked Larkin model was initially chosen, but this stock was identified as an exceptional case in which our selection of potential models weren't able to capture a recent, significant, decline in productivity. This was identified by comparing the recent generational average age-4 productivity (0.67 recruits-per-EFS) to the productivity implied by the chosen forecast model (a Larkin model). The recent generational average productivity was lower than the productivity implied at the P10 level by the Larkin model. Therefore, an RS8yr naïve model was applied, in an attempt to capture this recent, significant, decline in productivity.

Late Stuart

No biological models with climate-related covariates ranked very high for this stock (top-ranked would be Ricker model with Pine Island SST covariate, which was ranked seventh). Therefore, in an attempt to capture recent low productivity, while avoiding the use of naïve models, we proposed a Power model with Pine Island SST as a covariate, since a Power model was the top-ranked biological model (ranked third). This model was chosen because it seemed to reflect recent productivity better than other model choices. A sibling model was not used this year, due to high uncertainty in the 2020 return estimate for this stock. Late Stuart return numbers for 2020 were significantly higher than the escapement estimate, while Stellako escapement numbers were higher than the return estimate. It is suspected that GSI resolution issues between these stocks can lead to Stellako fish being misidentified as Late Stuart fish. This would inflate the Late Stuart return estimate, and cause the Stellako estimate to be biased low.

Quesnel

A Ricker model with Entrance Island SST covariate was chosen because it was the highest ranked biological model with an environmental covariate (ranked fifth). A sibling model was not used to forecast age-5's because it gives a higher estimate of age-5 recruitment (by about 1,000 fish), further deviating the forecast from recent low productivity.

Stellako

A Larkin model was chosen because it was the highest ranked biological model, and it captured recent productivity better than environmental covariate models. A sibling model was used to model age-5 returns, based on our sibling model selection criteria. Harrison

The top-ranked model for Harrison is a Ricker model with Entrance Island SST covariate. Following the retrospective analysis in 2012, models that separate odd and even years have been favoured since 2016. Last year a Ricker model with Entrance Island covariate, fit to even year data for age-3's, with a sibling model for age-4's was used, and true returns came in just above P25, which was viewed as somewhat satisfactory performance; and therefore the same model was used for 2021. Note that since age-4's dominate the forecast return in 2021, the primary driver of this forecast is the sibling model.

Raft

The highest ranked model for Raft was a Ricker model with PDO index as a covariate, but this model does not seem to reflect recent extremely low productivity, and performed very poorly in 2020 (returns came in at P10 level). Therefore, the next highest ranked biological model with a covariate (Ricker model with Pine Island SST; ranked fourth) was favoured. This model was combined with a sibling model for age-5's, based on our sibling model criteria.

Cultus

A Power model fit to juvenile data, with Pine Island SST as a covariate (ranked third) was chosen based on it's acceptable performance last year, and it's reflection of recent very low productivity. Based on our sibling model criteria, this model was combined with a sibling model for age-5's.

Late Shuswap

For this stock, a Ricker model with Entrance Island covariate was chosen, as it is the highest ranked biological model with an environmental covariate. Naïve models made up three of the top-four ranked models, but were not chosen based on our general model selection criteria. The Ricker model with Entrance Island covariate seems to better capture recent low productivity than higher-ranked biological models without covariates (Cyclic Ricker and Larkin). A sibling model was not used for age-5's because it would have resulted in a higher age-5 forecast, although the difference was negligible; approximately 20 fish at the P50 level.

Portage

A Ricker model with Pine Island SST (Ricker-Pi) covariate was initially chosen, in an attempt to capture the observed recent decline in productivity. However, this stock was identified as an exceptional case in which our selection of potential models weren't able to capture a recent, significant, decline in productivity. This was identified by comparing the recent generational average age-4 productivity (0.62 recruits-per-EFS) to the productivity implied by the chosen forecast model (a Ricker-Pi model). The recent generational average productivity was lower than the productivity implied at the P10 level by the Ricker-Pi model. Therefore, an RS8yr naïve model was applied, in an attempt to capture this recent, significant, decline in productivity -- although the associated reduction (from 2,100 to 1,800) is lost when rounding to the nearest 1,000.

Weaver

For Weaver creek, the RS8yr model was considered as a viable option because it was a top-ranked model (ranked 4th) and seemed to capture recent productivity well. It was not identified using convention 3b (Appendix 1), as was the case for other stocks where the RS8yr model was used. This was an exceptional case where a naïve model wasn't skipped over, because it was one that took brood-year spawners into account, and seems to capture the variability in productivity observed in the last 20 years fairly well (when looking at the range from P10-P90).

Birkenhead

A Ricker model with Pine Island SST covariate was initially selected, despite being the second-ranked biological model with an environmental covariate (Ricker model with Entrance Island SST covariate ranked first, Pine Island covariate ranked fourth). This model was chosen because the top-ranked model performed very poorly in 2020 (returns came in below P10 level), and the Pine Island covariate seems to better capture recent low productivity. Upon further review this stock was identified as an exceptional case in which our selection of potential models weren't able to capture a recent, significant, decline in productivity. This was identified by comparing the recent generational average productivity (0.16 and 0.37 recruits-per-EFS for age-4's and age'5, respectively) to the productivities implied by the chosen forecast model (a Ricker-Pi model). The recent generational average productivities were lower than the productivities implied at the P10 level (for both age-4's and age-5's) by the Ricker-Pi model. Therefore, an RS8yr model was applied, in an attempt to capture this recent, significant, decline in productivity.

Chilliwack

Model choice for Chilliwack was based on a new retrospective analysis (Appendix 4). Two models tied for top-ranking; a Power-sibling model, and a Ricker model with Fraser River mean discharge, and PDO index as covariates, combined with a sibling model for age-5's. These models gave quite similar forecasts, with the covariate model giving a slightly higher forecast. To try and capture recent low productivity (0.73 recruits-per-EFS at for age-4's), we did not choose covariate models that increased forecast values. Therefore, the Power model without a covariates, combined with a sibling model was favoured, as it better reflects recent low productivity.

Appendix 4. Chilliwack Retrospective Analysis

Prior to 2016, Chilliwack was forecast as a miscellaneous stock; using the mean recruits-per-spawner values calculated across early summer stocks. In 2016 the decision was made to switch to using a Ricker model, since the dominant brood year returning in 2016 (2012) was one of the largest on record, and there was a desire to include density-dependent affects, and avoid a gross overestimation of recruitment. Despite a Ricker model being implemented since 2016, no retrospective analysis has been carried out to test the performance of this model.

The time series of recruitment data for Chilliwack is short (starting in brood year 1999), and has variable data quality (see Appendix D of Hawkshaw et al. 2020b). Following a sensitivity analysis, the 1999 and 2000 data points have been dropped. These years were based on incomplete visual surveys, and resulted in anomalously high recruits-per-spawner. Chilliwack is a cyclic stock, with returns every four years (called the dominant cycle-line) being significantly higher than the three years in between (off-cycle or sub-dominant years). In recent years, there has been increased focus on Chilliwack, especially in these dominant years, given its relative contribution in the Early Summer run management group (although 2021 is on a sub-dominant cycle-line, with the next dominant cycle-line return expected in 2024). An exploration of applicable models, and potential covariates was carried out to provide more options for 2021, and provide better justification for the chosen model, following the same approach used for Pink Salmon in 2021 (see section 2.2).

Sequential multiple linear regressions were carried out using both Ricker and Power relationships to identify potential environmental covariates. The same suite of environmental covariates considered for Sockeye stocks in the past (various metrics of Fraser River discharge, sea surface temperature, PDO) as well as two metrics of sea-surface salinity used in previous pink forecasts, were tested as potential covariates. The multiple linear regression approach was followed for this stock, as was used for the Pink salmon model, the details of which can be found in section 2.2. Although Larkin models are generally favoured for cyclic stocks, since they allow for interactions between cycle lines (which may be a contributing factor in the occurrence of these cycles), Larkin models were not feasible in this case because they require an extra three years of lead-in data, reducing our number of stock-recruit data pairs from 15 to 12 – not providing enough years to carry out a feasible retrospective analysis.

Based on these linear regressions, for both the power and Ricker models, the combination of average April-June Fraser flow and PDO index came out as a top candidate model, going into the retrospective analysis. In addition, a similar Ricker model, with Peak flow and PDO index as covariates came out as a top-fitting model, based on the linear regression exercise. In addition, each biological model was combined with a sibling model to estimate age-5 returns in retrospective analysis. Naïve models were also applied and tested (models 11-15). Therefore the final set of models tested in retrospective analysis were:

1. Power model with no covariates (Power);
2. Power model with no covariates, sibling model for age-5 recruitment (Power_Sibling);
3. Power model with avg. April-June Fraser flow, PDO index as covariates (Power_FrDmean_pdo);
4. Above model, sibling model for age-5 recruitment (Power_FrDmean_pdo_Sibling);
5. Ricker model with no covariates (Ricker);
6. Ricker model with no covariates, sibling model for age-5 recruitment (Ricker_Sibling);

7. Ricker model with avg. April-June Fraser flow, PDO index as covariates (Ricker_FrDmean_pdo);
8. Above model, sibling model for age-5 recruitment (Ricker_FrDmean_pdo_Sibling);
9. Ricker model with peak Fraser flow, PDO index as covariates (Ricker_FrDpeak_pdo);
10. Above model, sibling model for age-5 recruitment (Ricker_FrDpeak_pdo_Sibling);
11. MRS_log – historical average mean log-recruits-per-spawner applied to brood year escapement, using a log-normal distribution;
12. MRS – historical average mean recruits-per-spawner applied to brood year effective female spawners;
13. RS1 – Previous run's recruits-per-spawner applied to brood year effective female spawners;
14. RS2 – Average of two previous run's recruits-per-spawner applied to brood year effective female spawners; and
15. RSC – Cycle-line recruits-per-spawner applied to brood year effective female spawners.

Retrospective Analysis

Retrospective analysis was carried out in similar manner to the Pink salmon retrospective analysis, described in section 2.2. The only difference being that multiple brood years can contribute to a given year's return, which is not the case for Pink Salmon. In the past, retrospective analysis has been carried out by assessing predictions at the brood-year scale (representing fish that will return across different years). To more accurately reflect the true process of forecasting (which happens on the return year scale) we split brood year returns by age, to create return-year forecasts in our one-step-ahead retrospective. This means that we are comparing forecast returns for a given return year, to true returns in that year.

Since the time-series for this stock is so short (brood years 2001-2015), it was only possible to run a very short retrospective analysis. We chose to run the retrospective analysis for one complete four-year cycle; 2017-2020 return years. In addition, since our capacity to test these models retrospectively is limited, we also provide coefficient of determination (R^2) values for model fits using the entire time series as an alternative measure of model suitability. Performance was measured using a suite of forecasting error metrics used for the Pink Salmon retrospective analysis described in section 2.2. Forecast values were pulled from the last four years of forecast documents and performance of candidate models was compared to the performance of these values ("Forecast" model in Table A4-1).

Retrospective Results

A power model with no covariates, combined with a sibling model for age-5 recruits (Power_Sibling) tied for best performance in the retrospective analysis with a Ricker model with average April-June Fraser flow, and PDO index as covariates, also with a sibling model used for age-5 recruits (Ricker_FrDmean_pdo_Sibling; Table A4-1). The primary difference between these two models is that the power model without covariates tended to be biased high (MPE=0.52), while the Ricker covariate model tended to be biased low (MPE = -0.49; Table A4-1, Figure A4-1). Additionally, the Ricker covariate model had a better model fit overall, with an R^2 value of 0.928, compared to 0.662 for the power model with no covariates, and appears to capture the magnitude of dominant-cycle-line returns better (Figure A4-2). Four of the top-five models used sibling relationships to estimate age-5 recruits, demonstrating that these models are a useful tool for forecasting this stock (Table A4-1). All biological models tested here out-performed the forecast performance in the last four years, although this may not be a totally fair comparison, since preliminary recruitment estimates are often used for forecasts, and can change over time. In general, models using environmental covariates tended to be slightly biased low in the past four years, where biological models without covariates, and especially naïve models, tend to be biased high.

2021 Forecast

Across all models with covariates, high Fraser discharge during outmigration and high PDO indices (associated with warmer temperatures) were associated with poor productivity. During outmigration for the 2017 cohort (which is the component of the population being modelled using the biological model; age-5's are primarily being estimated using a sibling model in our top-ranked models) Fraser Discharge levels were quite far below average (Figure 4 of main document), while PDO index was above average, but not as significant of a deviation from average as discharge (Figure 3 of main document). Since all of our top-ranked biological models include an index of Fraser Discharge, they give higher forecasts for 2021 than models without environmental covariates.

For 2021 returns, the age-5 contribution is expected to be significant because 2016 was a dominant year (EFS = 30,000), while 2017 saw fairly low escapement (EFS=2,500). However, 2017 brood-year migrants faced more favourable conditions, with below-average peak and average flows, and near-average (although slightly above) PDO conditions. 2016 brood-year migrants faced similarly neutral PDO conditions, but significantly higher than average peak and average flow (Figure 4 of main document).

Based on retrospective analysis, and model fits (estimated using R^2 values), the Ricker model with avg. flow and PDO index as covariates appears to be the top candidate model. However, it may not capture recent low productivity well. Age-4 productivity (measured as recruits-per-EFS) have declines significantly since peaking around brood-year 2008 (Figure A4-2) and in the recent generation, were averaging near-historic lows at 0.77 recruits-per-EFS (Table 2, main document). Recent generational average age-5 recruits-per-EFS are estimated at 0.17, but these seem to be better captured in our top-ranked models by the sibling model (Table 2, main document). The top-rated covariate model results in a P50 recruitment forecast of 12,000 fish (P10-P90: 5,000 – 45,000; Table A4-2) implying a productivity of 2.9 age-4-recruits-per-EFS (P10-P90: 1.9-4.4) – much higher than the recently observed generational average of 0.77. The power model with no covariate gives a slightly lower forecast of 10,000 fish at the P50 level (P10-P90: 3,000 – 44,000; Table A4-2); implying a productivity of 2.1 age-4 recruits-per-spawner (P10-P90: 1.15-3.63). During the model selection exercise, the power model with no covariates was favoured for 2021 since it did a slightly better job of capturing recent declines in productivity.

Future Work

The code for this analysis is separate from the existing forecast model code, and can be run easily in future years. Since the time series is so short, each new year of data can have a large impact on outcomes. It is recommended that this analysis be repeated in future years, in order to continue to build our understanding of the dynamics of this stock, and make well-informed decisions in future forecasts.

Tables

Table A4-1. Results of the retrospective analysis, with values for mean absolute error, mean percent error, root-mean-square error, mean absolute percent error, mean arctangent absolute error, and mean absolute scaled error. Rankings are given based on average performance across metrics, and coefficient of determination (R^2) are given as an additional metric of model fit.

Mod	MAE	MPE	RMSE	MAPE	MAAPE	MASE	Retro Rank	R^2
Power_Sibling	3,887	0.524	5,047	0.524	0.429	0.396	1	0.662
Ricker_FrDmean_pdo_Sibling	4,226	-0.490	4,936	0.490	0.438	0.431	1	0.928
Ricker_FrDpeak_pdo_Sibling	5,339	-0.471	7,244	0.471	0.426	0.544	3	0.933
Ricker_FrDmean_pdo	5,017	-0.404	5,545	0.591	0.517	0.512	4	0.907
Power_FrDmean_pdo_Sibling	5,122	-0.530	6,469	0.530	0.472	0.522	5	0.937
Ricker_FrDpeak_pdo	6,507	-0.341	8,012	0.600	0.535	0.663	6	0.912
Power_FrDmean_pdo	7,554	-0.277	8,483	0.800	0.662	0.770	7	0.917
Ricker_Sibling	11,888	0.834	17,687	0.834	0.630	1.212	8	0.674
Power	9,251	1.250	13,494	1.250	0.661	0.943	9	0.327
MRS_Log	15,194	1.173	20,501	1.221	0.726	1.549	10	-
Ricker	16,565	1.537	21,450	1.537	0.847	1.689	11	0.425
Forecast	22,857	2.637	35,020	2.637	0.844	2.331	12	-
RS2	28,131	2.582	44,576	2.955	0.911	2.868	13	-
RS1	38,873	2.747	55,199	3.239	0.850	3.964	14	-
MRS	62,063	5.688	82,377	5.688	1.251	6.328	15	-
RSC	65,258	5.690	84,442	5.690	1.282	6.654	16	-

Table A4-2. Forecast predictions for 2021 for all biological models. Retrospective rankings are provided for reference, as well as R^2 values, and estimated proportions of age-4 recruits expected under each model formulation.

Mod	P10	P25	P50	P75	P90	Retro. Rank	R^2	Prop. Age-4
Power_Sibling	3,573	5,780	10,340	20,591	44,299	1	0.662	0.516
Ricker_FrDmean_pdo_Sibling	4,967	7,172	11,731	21,846	45,196	1	0.928	0.574
Ricker_FrDpeak_pdo_Sibling	5,492	7,685	12,061	21,866	44,777	3	0.933	0.585
Ricker_FrDmean_pdo	7,885	10,081	12,935	16,469	20,508	4	0.907	0.520
Power_FrDmean_pdo_Sibling	5,213	7,624	12,389	22,823	46,627	5	0.937	0.596
Ricker_FrDpeak_pdo	7,762	9,569	11,692	14,156	17,023	6	0.912	0.604
Power_FrDmean_pdo	6,451	8,671	11,688	15,683	20,925	7	0.917	0.632
Ricker_Sibling	3,300	5,393	9,838	19,876	43,258	8	0.674	0.492
Power	6,149	9,187	13,862	20,659	30,801	9	0.327	0.385
Ricker	12,151	16,159	21,432	28,085	36,277	11	0.425	0.226

Figures

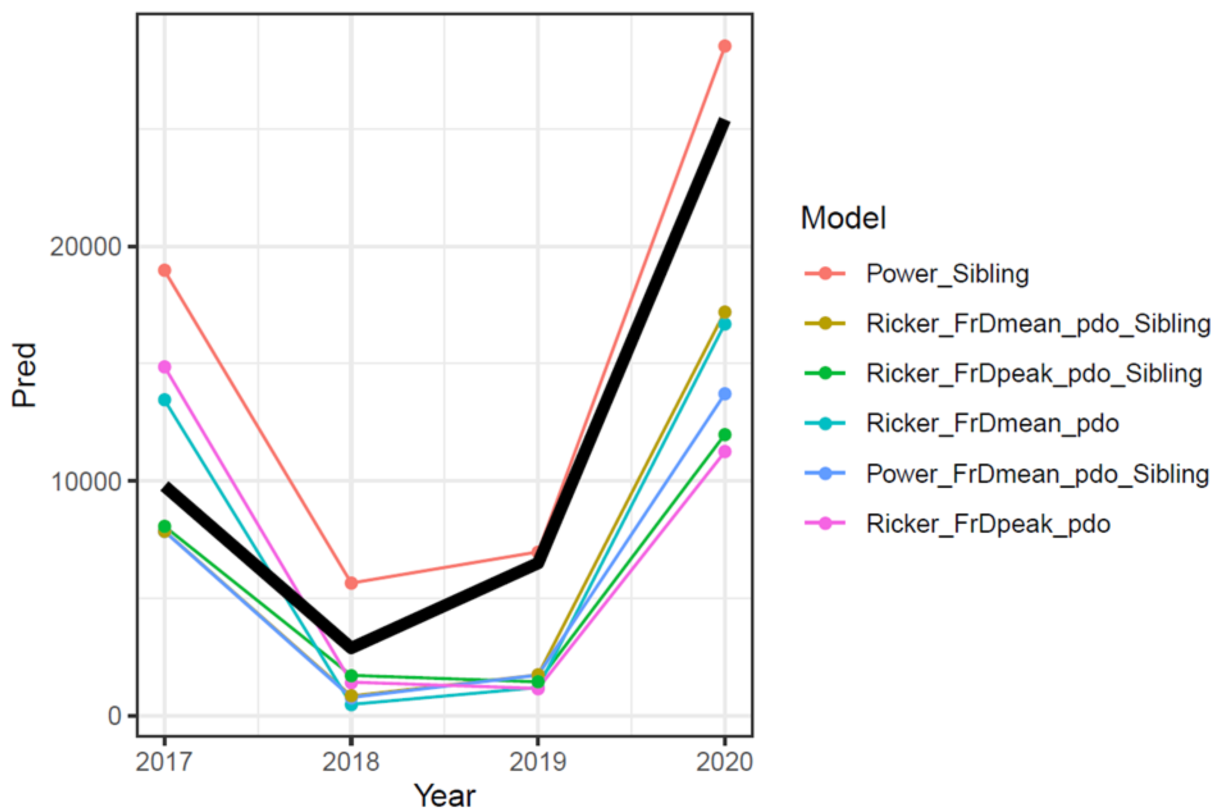


Figure A4-1. Top-6 models (coloured) overlaid on observed returns (by return year; bold black), models are ordered by rank (note that the top-two models are tied).

Figure A4-2. Model fits for total recruitment (black w/grey error bars) with true recruitment overlaid (red), by brood year.

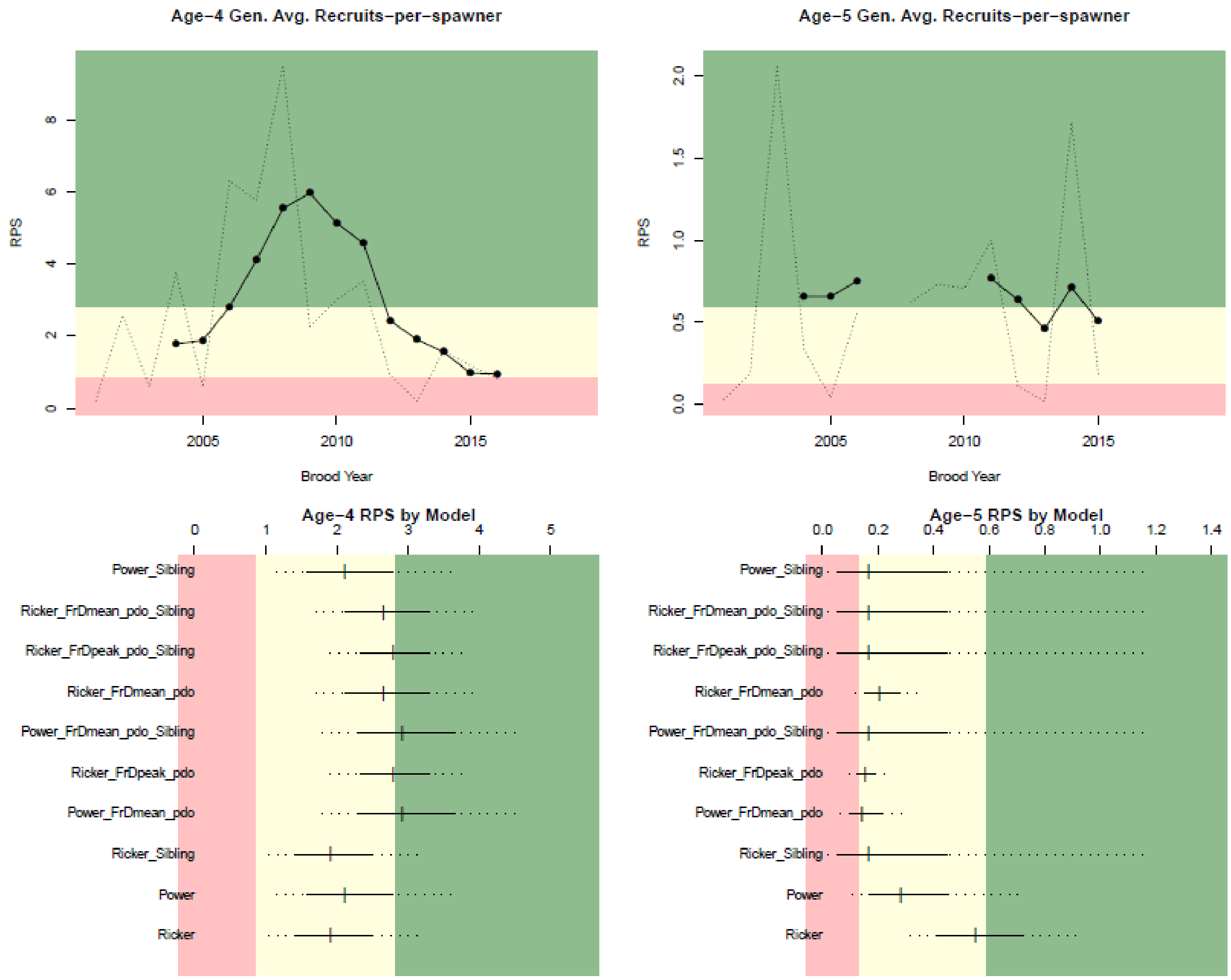


Figure A4-3. Top plots show generational average observed recruits-per spawners over time, with yearly values included for reference (dotted lines). Background colours indicate productivity zones, with yellow indicating average productivity; mean +- ½ standard deviation. For age-5 recruits-per-spawner, there is one highly anomalous year (2007 brood) that saw an estimated 22 age-5 recruits-per spawner. For the purpose of capturing mean values, this year was removed from the figure, and excluded from the calculation of productivity zones, since it increased the standard deviation so much, that the entire plotting region became yellow. Bottom panels show productivity implied by candidate forecast models. Note that all models incorporating sibling models to estimate age-5 returns will show the same values in the bottom-right panel.

Appendix 5. Supplemental Environmental Information to Inform the 2021 Fraser Sockeye Forecast

Authors: Brooke Davis, Moira Galbraith, Sue Grant, Roy Hourston, James Irvine, Doug Lofthouse, Bronwyn MacDonald, Clare Ostle, David Patterson, Ian Perry, Lucas Pon, Kendra Robinson, Tetjana Ross, Yi Xu

Background

Since 2015, supplementary environmental information relevant throughout the Fraser Sockeye life-cycle has been compiled yearly to help provide context to the Fraser Sockeye forecast. This information is normally gathered from various research programs during an in-person meeting early in the year, and then synthesized and published as a report (DFO 2015, DFO 2016, MacDonald et al. 2018, MacDonald et al. 2019, MacDonald et al. 2020). Due to program constraints in 2020/2021, this process was unable to proceed in 2021. To capture at least some of the information that would have been presented in that process, we assembled and synthesized relevant environmental information to provide further context to the 2021 forecast. While environmental covariates are used to model 13 of 19 major stocks, we only incorporated one environmental covariate at a time, selected from a limited suite of potential indicators. Models that incorporate multiple environmental covariates at once were considered for Chilliwack (which is still categorized as a “Miscellaneous” stock) for the 2021 forecast (Appendix 4), but none were not chosen for the final forecast model. By taking this more holistic approach, and looking at indicators at every life-stage, a more comprehensive understanding of the overall conditions faced by the primary cohort returning in 2021 (2017 brood year, lake-type life history) can be gleaned.

Upstream Migration

Parental experience of high en route migratory stress associated with high discharge and/or high temperature during upstream migration can have negative impacts on future recruitment. High discharge in the Fraser Canyon has been associated with spawning migration delays (>7,000 m^3/s) and obstruction (>9,000 m^3/s) and has been linked to effects on offspring, such as reduced egg size and egg survival (Macdonald 2000; Patterson et al. 2004; Braun et al. 2013). Fraser basin snow packs were high in the winter of 2017, and low precipitation and warm spring temperatures led to rapid snowmelt. By June 2017, snowpacks in northern latitudes of BC were below average, and in southern latitudes, were closer to average. Fraser discharge measured at Hope were higher than historical median until late June, at which time they dipped below median, and remained there for the duration of the spawning migration (Figure A5-1). Given that flow conditions didn’t reach extreme highs nor extreme lows, adult Sockeye were likely not significantly negatively affected by flows during their upstream migration in 2017.

Adult migrating salmon experiencing warm water temperatures (18°C-20°C and above) have been shown to decrease swimming performance, increase mortality, increase egg retention, reduce gamete viability, and have negative impacts on the condition of juvenile offspring (Macdonald et al. 2000; Tierney et al. 2009, Burt et al. 2011, Eliason et al. 2011, Macdonald et al. 2012; Sopinka et al. 2016). River temperatures were anticipated to be above average for migrating Sockeye in 2017, with the early loss of snowpack reducing cool water inputs into rivers and lakes, paired with below average rainfall. However, extensive and heavy smoke cover due to forest fires mitigated against rising temperatures by reducing sunlight. The outcome was near-average summer water temperatures in the Fraser River in 2017 for the first half of the run (approx. June 1 to August 1), and then increasing to mostly above-average temperatures in the later part of the season (Figure A5-2). Temperatures up until about September 1 were cooler than they were in 2016, signaling slightly better conditions for the 2017 cohort over the 2016 cohort for earlier-timed stocks. Warm temperatures (above 18°C) would have been experienced in the lower river by the majority of summer-run fish (Figure A5-2). The Horsefly River component of the Quesnel stock may have been especially exposed to warm river temperatures. The Horsefly River is not lake-headed, and therefore is less buffered to warm temperatures, and tends to be a more temperature-sensitive system (Macdonald 2000). Therefore, fish from this component of the population may have experienced warm temperatures throughout the extent of their upstream migration and spawning. The majority of the Quesnel stock spawn in the Horsefly River, and the Quesnel stock is forecast to contribute more than any other stock, making up 26% of the total forecast Fraser Sockeye return, at the P50 level.

Spawning

Fertilization success is an integrative measure of adult condition during spawning (Macdonald et al. 2000; Patterson et al. 2004), and can be measured by artificially crossing individual spawners, and then testing gamete viability at the four-cell stage. Fertilization success was measured at Chilko, Gates Creek, Horsefly (Quesnel), Stellako, and Weaver in 2017. Generally, 80% success is considered “normal” (Whitney et al. 2014), and anything below that value may have had poor adult condition, resulting in poor reproductive potential (Figure A5-3). Gates Creek and Horsefly (Quesnel) are the two populations flagged as having potential issues with gamete viability (Figure A5-3). Egg retention estimates were below 20% (ie. “spawn success” of 80% or more) for major stocks in 2017, indicating that there were no significant spawning failures in major stocks.

Incubation

High in-river spawning and incubation temperatures have been linked to negative effects on fertilization success and embryo survival, can affect the timing of hatch (Whitney et al. 2014), emergence (Macdonald et al. 1998), and reduced swimming endurance and impaired swimming behavior of fry (Burt et al. 2012). Temperatures became more variable in Fall 2017, and cooler over winter 2017-2018, which would have presented favourable conditions for egg incubation.

Egg-to-fry survival, which integrates survival from egg deposition to fry emergence, is calculated at the Weaver and Nadina spawning channels. These channel estimates likely reflect some of the best incubation conditions across the Fraser and therefore may not be a good reflection of natural incubation conditions, as their conditions (temperature and flow) are managed. Weaver egg-to-fry survival for 2017 brood year was 65.5% which is above average compared to the last 12 years (60.7%), and higher than 2016 brood (52.0%). Nadina egg-to-fry survival for 2017 brood was 50%, which is below average for the last 12 years (61%), and lower than 2016 brood (63%).

Lake Rearing

Warmer temperatures can improve juvenile growth rates when prey are not limiting (Brett 1971, Edmundson and Mazumder 2001), and also increase the length of the growing season in some areas (Schindler et al. 2005). Higher water levels in lakes can also increase littoral zone habitat available for emerging juvenile fry. The exposure of a salmon population to these various discharge and temperature-related freshwater conditions will vary by system. Water temperatures during the littoral zone freshwater lake rearing period in the spring of 2018 were variable. Early spring air temperatures (which are an assumed proxy of lake temperatures) were below normal until late April. In May, when most Sockeye fry have emerged are inhabiting nearshore lake habitat, maximum air temperature anomalies were 4°C above normal throughout the basin (Pacific Climate Impacts Consortium (PCIC) 2021). The overall summer air temperatures were above normal; September maximum air temperature anomalies were 3°C below normal.

In 2018, hydroacoustic estimates of limnetic juvenile Sockeye salmon abundance in the fall (i.e. fall fry) were conducted for Bowron, Chilliwack, Cultus, Fraser, Quesnel, and Stuart lakes (Table A5-1). Estimates of fall fry-per-effective-female-spawner (EFS) were also calculated based on the near final estimates compiled by DFO's Stock Assessment program and are presented in Table A5-1. Unrealistically high fry-per-EFS (1,863) were estimated for Bowron Lake for the second year in a row. Returns and escapements for Bowron have been exceptionally low in recent years (EFS estimated at 72, 122, 4846 for brood years 2016-2018, respectively) and therefore even small biases in EFS can lead to relatively large variability fry-per-EFS. Given that there was a reasonable trawl catch to genetically distinguish between Sockeye and Kokanee, we speculate there may be an underestimate of the number of EFS in these years. For Cultus, the relatively high fry per EFS may also be attributed to an underestimate of EFS, given the documented challenges of estimating egg retention and spawner numbers for this stock (since they spawn in the lake), or possibly an artifact of limited trawl catch on the representative abundances of hatchery supplemented marked fish, and unmarked fish. In Fraser (Stellako stock), Quesnel, and Stuart lakes, the fry-per-EFS estimates were more consistent with historic ranges. For the 2017 BY, an estimate of 128 fall fry-per-EFS was determined for Quesnel. This was lower than the observed mean in recent years (i.e. BY 2009 to BY 2015; 218 fall fry/EFS), but was more consistent with the full historic survey record dating back to the 1970's for years when Kokanee were less likely to be a confounding factor (126 fall fry/EFS). Fraser and Stuart lakes have limited recent fall fry/EFS data to compare with, though the values observed in 2018 (186 and 228 respectively) were neither abnormally high or low. Chilliwack fall fry/EFS (51) was lower than that observed in other lakes, but was fairly consistent with the recent historic mean for that lake dating back to 2008 (41 fall fry/EFS).

Recognizing that fry size data is highly dependent on the time of year the survey takes place, and can be influenced by the density of fry, the values observed in all lakes surveyed for 2018 (2017 BY offspring) were fairly consistent with recent lake-specific data (Table A5-2).

From the Cultus smolt counts conducted by DFO Stock Assessment (total 11,794 age-1 smolts), an overwinter 'survival' from fall fry to outmigrating smolt was estimated at 8.45%. Recent fry-to-smolt survival estimates have been low for Cultus Lake (DFO 2018, DFO 2020). Invasive smallmouth bass (*Micropterus dolomieu*) were observed in Cultus lake for the first time in 2017 and snorkel surveys have found that they have established a population in the Lake in recent years. While the magnitude of potential impacts on juvenile Sockeye in Cultus Lake is an active area of new research, preliminary stomach content analyses have found that juvenile Sockeye salmon are being preyed upon by smallmouth bass (Wendy Margetts, Thompson Rivers University, Kamloops, BC, pers. comm.).

Small smolt body size and low lipid percentage can indicate poor freshwater conditions (Hume et al. 1996), and can potentially flag subsequent poor early marine survival (Naesje et al. 2006; Wilson et al. 2021). A 2% value is often used as a minimum survival threshold for wild Sockeye salmon smolts (Macdonald et al. 2019), and this was recently confirmed with swimming performance being severely impaired in Chilko smolts with a median lipid value of 1.93% (Wilson et al. 2021). Smolt condition for the Chilko stock leaving natal lake area was better for brood year 2017, at 3.1% (n=48, SD 1.1), than it was for brood year 2016, at 2.1% (n=153; SD 0.48). Body size was also larger for the 2017 brood than it was for 2016 (Figure A5-4). Smolt body size was lower than the historical average (86.0 mm for 1984-2017 brood) for the 2016 brood (83.3 mm), but above average for the 2017 brood (89.9 mm), with a distinct lack of very small body-sized smolts from the 2017 brood, compared to 2016 brood (Figure A5-4). The estimate of smolts-per-EFS at Chilko was also significantly higher for the 2017 brood (272 smolts-per-EFS) than the 2016 brood (130 smolts-per-EFS), indicating that spawning and rearing success was higher in 2017, compared to 2016 for this stock. The only potential indicator of poor freshwater growth conditions exists for Quesnel, which had an average total body lipid percentage of 2.5% (n=23; SD = 1.08). Across other stocks, lipid values were as follows: Cultus lake 4.6% (n=27; SD=1.3), Seton 4.5% (n=70; SD=1.1; combination of Gates and Portage Sockeye), and Nautley 3.7% (n=149; SD=1.1; combination of Nadina and Stellako).

Downstream Migration

The large interannual variation in downstream smolt survival (Clark et al. 2016; Stevenson et al. 2019) is the likely result of changing biological (i.e. size, predators) and environmental factors (i.e. temperature and discharge). Discharge levels can impact predation risk through changes in water clarity and velocities (Gregory and Levings 1998; Ginetz and Larkin 1976), and water temperatures can influence swim performance (Brett 1971) and optimal smoltification window (Bassett 2015). The Fraser basin snow pack was below normal leading into spring freshet in 2019 (British Columbia River Forecast Center 2021). During downstream smolt migration, near normal flow conditions were observed (Environment and Climate Change Canada (ECCC) 2021; Figure A5-5). While the mechanism is poorly understood, for Fraser Sockeye stocks where Fraser discharge during outmigration is used as a covariate in stock-recruit modelling used for forecasting, low flows during outmigration are generally associated with higher productivity (and therefore higher forecast predictions), although this signal is not consistent across all stocks and models (see Appendix 2 for model comparisons). Spring air temperatures were variable in 2019, with a very warm May throughout the Fraser basin (PCIC, 2021). Water temperatures in the lower Fraser River transitioned from average to above average during the outmigration of major stocks (ECCC 2021; Figure A5-6). It should be noted that this was first brood year cohort to travel over the Big Bar landslide during their outmigration, although the impact of downstream migration over the slide are currently unknown.

Marine Migration and Rearing

Upon entering the Strait of Georgia, the majority of lake-type Fraser Sockeye migrate northward and exit the Strait of Georgia via Johnstone Strait, and Hecate Strait (although some head Northwest sooner, travelling along the West Coast of Haida Gwaii) as they head northward towards the Gulf of Alaska (Tucker et al. 2009, Beacham et al. 2014, Clark et al. 2016). Harrison Sockeye have a unique life history in that they are ocean-type (they migrate straight to ocean upon emergence), and also in that a larger proportion of this stock has been found to exit the Strait of Georgia through the strait of Juan de Fuca, and migrate northward along the West Coast of Vancouver Island (Tucker et al. 2009, Beamish et al. 2016). For this supplementary section we are focusing on age-4 lake-type Sockeye returning in 2021 (2017 cohort), but we have included some environmental data from the West Coast of Vancouver Island, since a small number of lake-type Sockeye from the 2017 cohort would have passed through this area, and these conditions may be indicative of wider patterns of Northeast Pacific Ocean conditions.

Sea-Surface Temperatures during Early Marine Rearing

Warm sea surface temperatures near ocean entry points have been linked to negative effects on the productivity of BC and Southeastern Alaska Sockeye populations (signals were different for Gulf of Alaska and Bering Sea stocks; Connors et al. 2020). This is consistent with the stock-recruitment modelling carried out for the forecast, which generally finds negative effects associated with warmer SST along early marine migration routes, resulting in lower forecasts for cohorts that have experienced warm SST's during initial ocean rearing (see Appendix 2 for model comparisons). Surface temperatures in the entire NE Pacific during ocean entry for Fraser Sockeye in 2019 were extremely warm (Figure A5-7). More specifically, nearshore sea surface temperatures in the Strait of Georgia (measured at Entrance Island from April-July 2019) were above normal, and temperatures in Queen Charlotte Strait (measured at Pine Island from May-July 2019) were at historic highs (Figure 3, main document). Consistent with these warm temperature conditions, the Pacific Decadal Oscillation (PDO) index for winter 2019/2020 (November 2019-March 2020) 2019 was above average (Figure 3, main document). These three climate and ocean variables have been included in forecasts for 13 out of 20 stocks for which biological models are used, comprising 57% of the total forecast), but they will not capture the total cumulative effects of warm nearshore and offshore conditions during marine rearing from Spring 2019 through to Spring 2021.

Food Availability During Early Ocean Migration Northward Through the Strait of Georgia

In the Strait of Georgia, total zooplankton biomass anomalies have been increasing since 2005, and since 2015 they have been at or above the long-term (1996-2010) average. From 1996 to 2018, total zooplankton biomass was dominated (76%) by large-sized crustaceans (euphausiids, large and medium size calanoid copepods, and amphipods), many of which are key prey for outmigrating juvenile Sockeye (Perry et al. 2021). This suggests that the food environment for these fish has been improving since about 2005. In the Strait of Georgia, in 2019, zooplankton biomass was above the long-term average, indicating early marine food availability may have been favourable for out-migrating juveniles (Young et al. 2020). Positive biomass anomalies were observed for hyperiid amphipods, decapods, and euphausiids, which are important zooplankton prey for juvenile salmon (Young et al. 2020).

The zooplankton biomass and species composition of the West coast of Vancouver island and Hecate Strait is assessed at several locations (Figure A5-8) and reported annually (ex. Galbraith and Young 2020). Data from 2019 showed that zooplankton continued to exhibit characteristics consistent with warmer ocean temperatures, characterized by high abundances of gelatinous taxa and low abundances of crustaceans, but patterns vary amongst sampling locations (Galbraith and Young 2020). Subarctic and boreal copepods are larger with higher lipid content, making them a better food source for fish growth than southern copepods (which tend to be smaller and have lower lipid contents). The Northern Vancouver Island, and Hecate Strait sites from this survey would be the areas that migrating Sockeye would be most likely to pass through on their northward journey, as they head northwest towards the Gulf of Alaska (Figure A5-8). Both of these locations showed above-average southern copepod anomalies in 2019, although these anomalies were not as high as those seen in recent years (ie. since 2015; Figure A5-9). Boreal copepods at both of these sites have shown a corresponding increase in biomass since about 2015, and in 2019 their biomass was above average (Figure A5-9). Subarctic copepod biomass anomalies off of Northern Vancouver island were below average in 2019, and near average in Hecate Strait (Figure A5-9). These observations show some improvement in potential food quality for migrating Sockeye in 2019, compared to years before, although subarctic copepod biomass remained lower than average (Figure A5-9).

Broader Ocean Conditions During Marine Phase

Marine heatwaves persisted in the Northeast Pacific during 2019 and 2020, with the marine heatwave of 2019 being third largest and longest on record since tracking began in 1982; which lasted 239 days and covered approximately 8.5 million km^2 at its peak (Leising and Bogrod 2020). During this same period, warmer than average subsurface temperatures were again observed at subsurface depths (e.g. about 100 m; Ross and Robert 2020). There were two marine heatwaves in 2020. The second of these peaked in September 2020, and at its maximum size (~9.1 million km^2), was the second largest on record (Leising and Bogrod 2020). This heatwave receded offshore during November-December 2020, about one month later than the recession seen in the 2019 marine heatwave (Leising and Bogrod 2020). Warmer ocean temperatures generally result in poor quality zooplankton prey for Sockeye salmon, whereas cooler conditions are related to better prey quality (Galbraith and Young 2020, Mackas et al. 2004, Mackas et al. 2007).

Wind stress along the Pacific coast is used to estimate the timing and magnitude of oceanic upwelling, which appear to be important indicators of fish productivity and growth during recent years (Xu et al. 2019). Along-shore upwelling-favourable and downwelling-favourable wind stress data at sixteen locations (31-59ºN) near the continental shelf are compiled annually along with other surface ocean data by DFO (Hourston and Thomson 2020). Figure A5-10 shows the timing of the onset of both upwelling (Spring Transition) and downwelling (Fall Transition) based on surface wind stress and ocean currents, as well as the magnitude of upwelling, for a coastal location of the West coast of Vancouver Island (49ºN 126ºW). In 2019, the Spring Transition was near the 1991-2020 average, while the Fall transition was later than average (vertical bar position in Figure A5-10), and upwelling magnitude was above-average (see color of vertical bars in Figure A5-10). However, in early summer, the upwelling-favourable wind stress magnitude was below average from 50-60ºN (the northern migration route for Sockeye, past Pine Island; Hourston and Thomson, 2020), suggesting generally unfavourable conditions for coastal productivity during early marine rearing for this cohort. Both winter 2018/2019, and winter 2019/2020 showed significantly weaker than average downwelling-favourable wind stress, which indicated weaker and/or eastward shifted wind patterns and/or a shorter winter storm season. These ocean conditions are associated with marine heatwaves (Hourston and Thomson, 2020). In winter 2018/2019, at 50ºN, mixing was weaker than the two previous years, returning to conditions more consistent with warm “blob” years as observed from 2013-2015 (Ross and Robert 2020). This return to weak mixing could signal that surface nutrient levels were lower in the spring of 2019, immediately before most age-4 Sockeye from the 2017 cohort entered the ocean (Ross and Robert 2020). During winter 2019/2020 mixing continued to be weak, again suggesting lower surface nutrient levels, but not as low as in 2019 (Tetjana Ross, DFO, Sidney, BC, pers. comm.).

At the furthest-North extents of the information compiled by collaborators (55-60ºN; Coastal Southeastern Alaska) spring transition was late in 2020, and shorter than average, potentially signaling lower ocean productivity conditions (Roy Hourston, DFO, Sidney, BC, pers. comm.). Upwelling-favourable wind stress in the same Northern areas in spring and summer 2020 were about average. These two observations, when combined, indicate that the upwelling season started later than average, was shorter than average in duration, and about average in magnitude; indicating that upwelling-based ocean productivity was worse than average overall in the spring-summer of 2020.

Broader Food Availability Trends During Ocean Rearing

Anomalies for southern copepods were positive along the West coast of Vancouver Island (specifically the Southern Vancouver Island and Line P locations; see Figures A5-8 and A5-9) in 2019 and 2020, although they were lower than peaks in 2015 and 2016 (Figure A5-9; Galbraith and Young 2020). At these same locations 2019 biomass anomalies of boreal copepods were at or above average, whereas subarctic copepods were below average (Figure A5-9). Although not directly applicable to the 2017 brood, the majority of which would have already migrated into the Gulf of Alaska, zooplankton conditions at all surveyed sites (Southern Vancouver Island, Northern Vancouver Island, Hecate Strait, Line P) appear to have been closer to average in 2020. In 2020, lower abundance of gelatinous zooplankton was observed compared to 2014-2019, and subarctic copepod biomass increasing to near-normal levels (Moira Galbraith, DFO, Sidney, BC, pers. comm.). However, total zooplankton biomass was low in 2020, reflecting boreal/subarctic zooplankton communities that were still at below-average levels (Moira Galbraith, DFO, Sidney, BC, pers. comm.).

A separate plankton survey has been conducted for a larger oceanic area off the BC coast (Batten and Ostle 2020). Based on these continuous plankton recorder (CPR) samples taken both on the shelf and in the offshore area surrounding BC (Figure A5-11), mean copepod lengths remained low in 2019 and 2020, consistent with the warm marine conditions persisting since about 2015 (Figure A5-12). On the BC continental shelf, warm-water copepods have been declining towards pre-heatwave conditions since peaking in 2015, but remained elevated (Figure A5-12). Warm water copepod concentrations continued to be elevated offshore, relative to pre-heatwave conditions (Figure A5-12). This indicates that, despite zooplankton remaining abundant overall, food quality at a broader scale could remain poor due to the increasing relative abundance of smaller and warm-water copepods (Batten and Ostle 2020, Clare Ostle, the Marine Biological Association, Plymouth, UK, pers. comm.).

Potential Competition with Pink Salmon

Declines in productivity of Sockeye salmon have been associated with high open-ocean density of Pink salmon competitors in the Sockeye's second ocean rearing year (i.e. 2020 for 2017 brood; Ruggerone and Connors 2015, Ruggerone et al. 2016, Batten et al. 2018, Connors et al. 2020). Pink abundance in the open ocean has been increasing steadily since the 1970's, and reached historic peaks in several odd years since 2009 (Ruggerone and Irvine 2018; updated in Figure A5-13). 2018 was particularly anomalous, with the highest Pink Salmon abundance observed in the time series landing on an even year, seemingly breaking the cycle of higher abundance in odd years (Figure A5-13). Pink salmon density remained near-historic highs in 2019, but in 2020 returned to average even-year levels; a potentially promising indicator for 2021 Fraser Sockeye returns (Jim Irvine, DFO, Nanaimo, BC, pers. comm.).

Summary

Overall, some aspects of freshwater conditions were better for the 2017 brood year than they were for 2016 brood, which showed historically low productivity upon their return in 2020. Indices of smolt size and energetic condition for Chilko are better for the 2017 brood year than they were for the 2016 brood. However, for the 2017 brood year, there are some indications of low energetic status for the Quesnel smolts. Temperatures during upstream migration in 2017 were high for summer stocks (Figure A5-2), and fertilization success was highly variable across stocks, with a notable reduction in success for Horsefly (Quesnel) and Gates populations (Figure A5-3). Additionally, fall fry abundance relative to EFS was lower than recent years for Quesnel (Table A5-1), however, fall fry body size were within the normal range (Table A5-2). Chilko and Quesnel are forecast to be the largest contributors to the 2021 Sockeye return; each contributing about a quarter of the total forecast return.

During early marine migration through the Strait of Georgia in 2019, temperatures were well above average (Figure 3 of main document), which is generally associated with poorer productivity for Fraser Sockeye. However, food availability in the Strait of Georgia has improved over recent years, and may have benefited 2017 brood year Sockeye during their migration northward in 2019. Further North, upon exiting Johnstone Strait either through Queen Charlotte Sound or Hecate Strait, copepod biomass anomalies, although improved from recent years, were still tending towards less nutritious southern copepod species (Figure A5-9).

Although not as severe as during the 2014-2016 heatwave in the northeast Pacific, broader ocean conditions in 2019 and 2020 remained very warm, which has generally been unfavourable for Fraser Sockeye productivity in recent years. Lower productivity would be consistent with the conclusion by Holsman et al. (2018) that, without a concurrent increase in prey quality or quantity, predator growth and productivity is expected to decrease under warming conditions. The data on prey quality we have, although it may not cover the entire extent of the marine migration and rearing of Fraser Sockeye, continue to indicate the continued dominance of less nutritious, southern zooplankton species, which are associated with warm ocean conditions. Our furthest North indicators of upwelling-based productivity signal lower than average productivity for coastal areas of SE Alaska in 2020, potentially indicating poor productivity for Sockeye during their second ocean year rearing in the Gulf of Alaska. One positive indicator for the 2017 brood year was significantly lower Pink salmon abundance in North Pacific in 2020, compared to recent years (Figure A5-13).

Tables

Table A5-1. Summary of juvenile Sockeye Salmon abundance surveys conducted in 2018 (i.e. offspring of 2017 brood year). For Cultus Lake, the abundance estimate included both marked and unmarked Cultus fry. EFS are those counted upon entering the lake and excluding retained broodstock. Fall fry/EFS are limited to unmarked fry-per-lake-spawner.

Lake	Fall survey date	Age-0 Sockeye abundance	95% CI	Density (fish/ha)	2017 EFS estimates	Fall fry/EFS
Bowron	Sept. 10, 2018	227,234	107,725	245.2	122	1,863
Chilliwack	Nov. 1, 2018	128,081	26,479	107.9	2536	51
Cultus*	Nov. 6, 2018	139,543	30,685	221.4	274	354
Fraser	Sept. 11, 2018	9,216,796	1,592,871	1715.2	49,425	186
Quesnel	Oct. 9, 2018	7,664,546	1,321,114	293.8	59,630	129
Stuart	Sept. 13, 2018	15,871,287	5,758,555	467.5	69,697	228

Table A5-2. Summary of size data for fall fry from trawl catch in lakes with adequate fish capture. Data represent lake-wide means and standard deviations.

Lake	Fall survey date	Sample size	Length Mean (mm)	Length SD (mm)	Weight Mean (g)	Weight SD (g)
Bowron	Sept. 10, 2018	64	61.89	8.20	2.89	1.11
Fraser	Sept. 11, 2018	60	71.68	5.39	4.47	1.08
Quesnel	Oct. 9, 2018	81	74.94	6.21	4.58	1.06
Stuart	Sept. 13, 2018	84	68.48	6.69	4.11	1.21

Figures

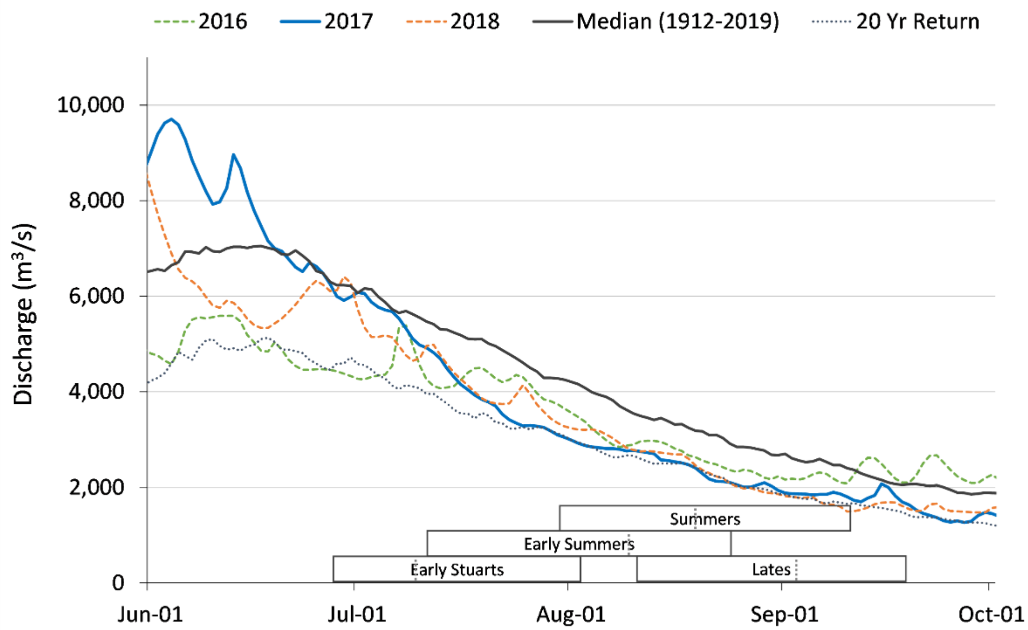


Figure A5-1. Fraser River discharge at Hope, 2016-2018, as well as historical median (1912-2019) and 20-year return period (i.e. 1 in 20 years are expected to be below this value), in cubic meters per second (m^3/s). Each run-timing group block depicts the medial 95% of migrants estimated to have passed the Mission hydroacoustic site in 2017; the associated dotted grey lines depict the 50% migration date for each group. Data is sourced from the Water Survey of Canada (ECCC 2021) and the Pacific salmon Commission.

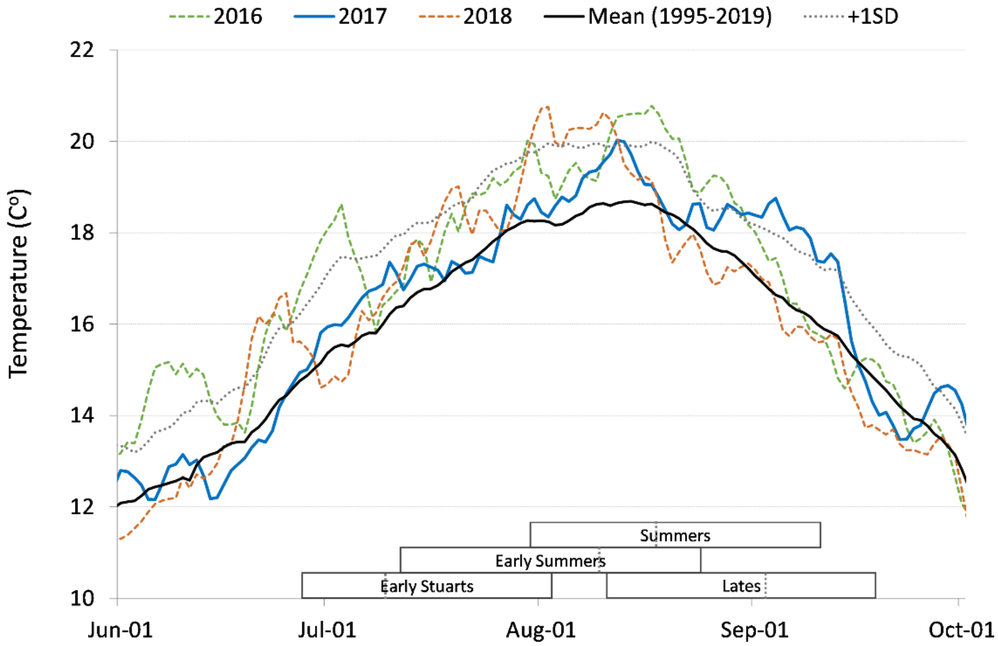


Figure A5-2. Fraser River temperature measured at Qualark during adult upstream migration for 2016-2018, and mean (1995-2019). Each run-timing group block depicts the medial 95% of migrants estimated to have passed the Mission hydroacoustic site in 2017; the associated dotted grey lines depict the 50% migration date for each group. Data is sourced from the DFO Environmental Watch Program and the Pacific salmon Commission.

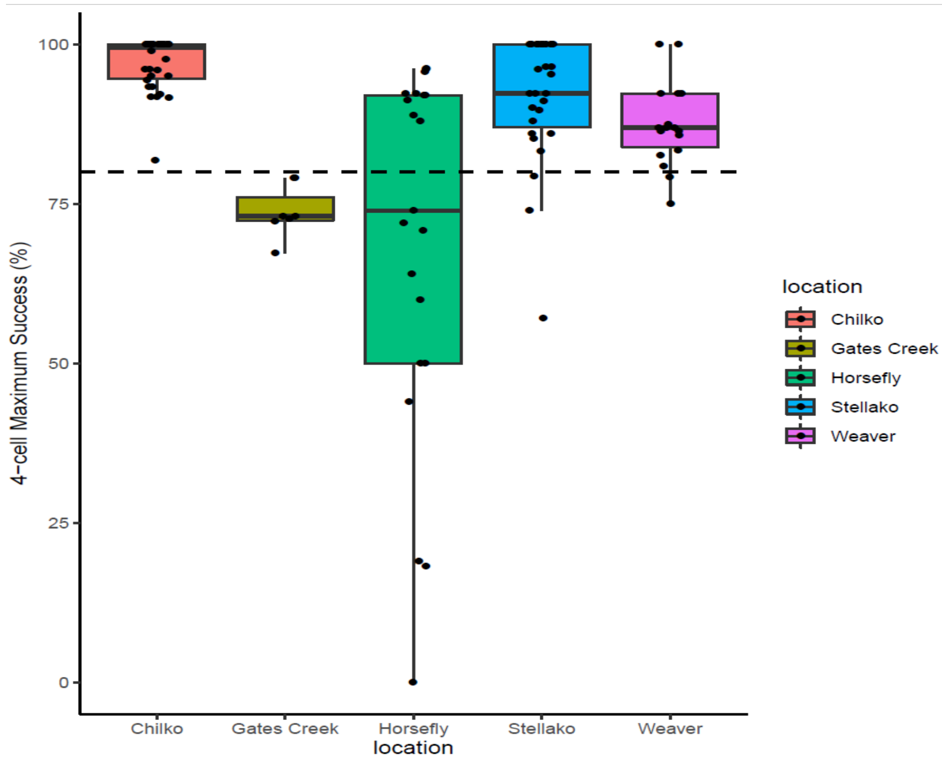
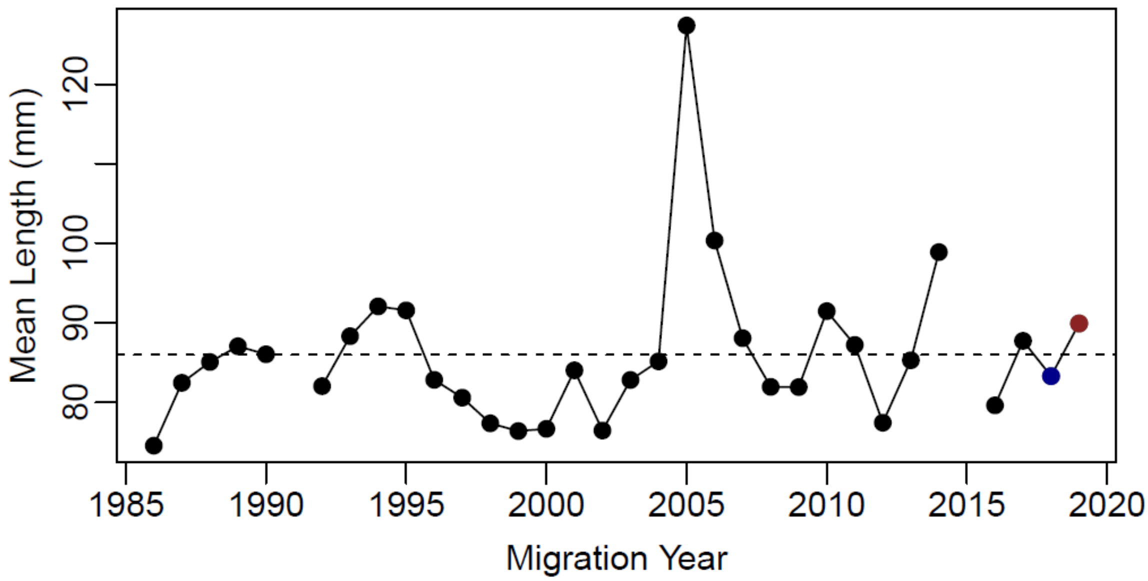


Figure A5-3. Fertilization success across five stocks, in 2017. Each dot represents the maximum fertilization success (4-cell stage) of an individual, male or female, artificially crossed with a minimum of three other unique partners in separate crosses. Generally, 80% success is considered "normal" (dashed horizontal line).



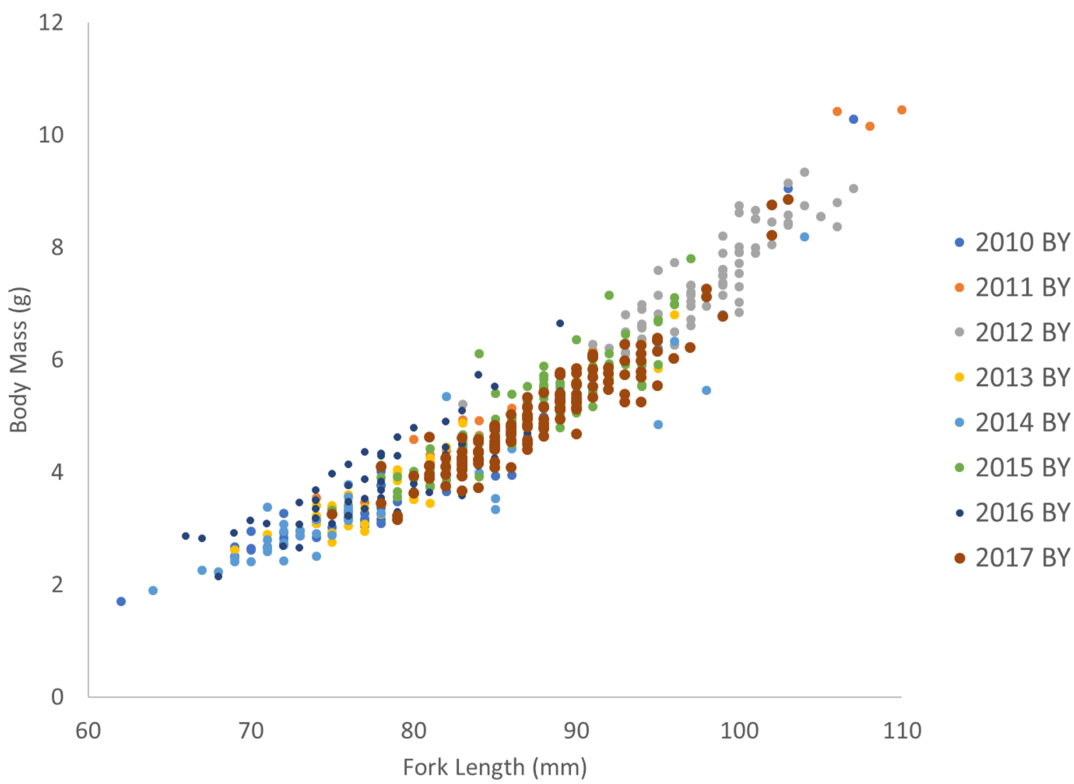


Figure A5-4. Top panel shows mean lengths (mm) of age-1 Chilko smolts leaving their rearing lake, at the Chilko fence, with the dashed line representing the average across years. 2016 brood-year smolts are highlighted in dark blue, and 2017 brood-year smolts highlighted in dark red. Bottom panel shows individual fork lengths (mm) and body mass (g) of Chilko smolts from 2010 to 2017.

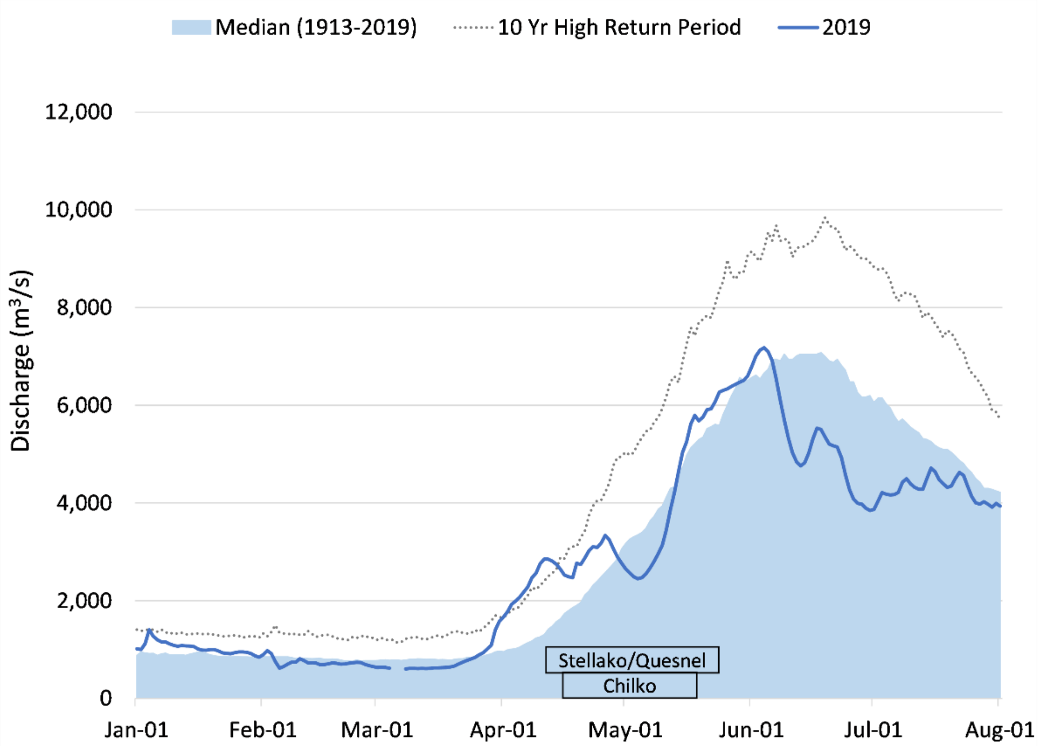


Figure A5-5. Fraser River discharge (m^3/s) at Hope during 2019 smolt outmigration, compared to median (light blue) and 10-year high return period (dotted; meaning that 1 in 10 years are expected to be below this value). Data sourced from the Water Survey of Canada (ECCC 2021).

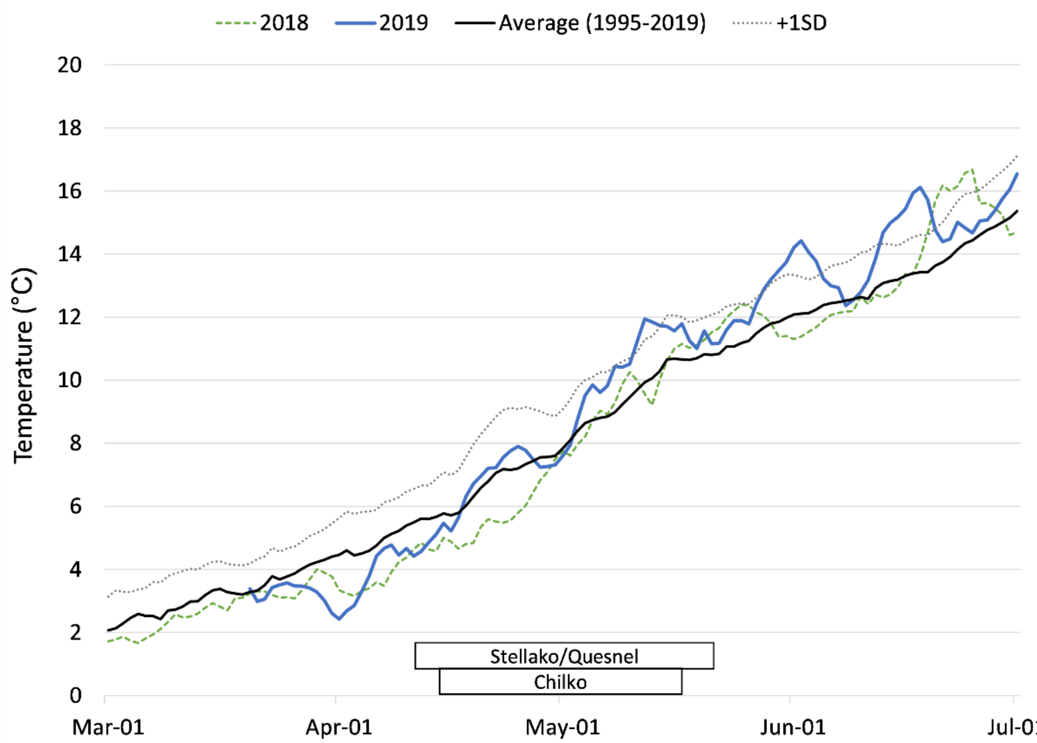


Figure A5-6. Fraser River water temperature measured at Qualark during smolt outmigration period for 2019 (brood year 2017) and 2018 (brood year 2016), as well as 1995-2019 average +1 standard deviation. Approximate timing of passage through this area for smolts from major stocks is indicated with boxes below.

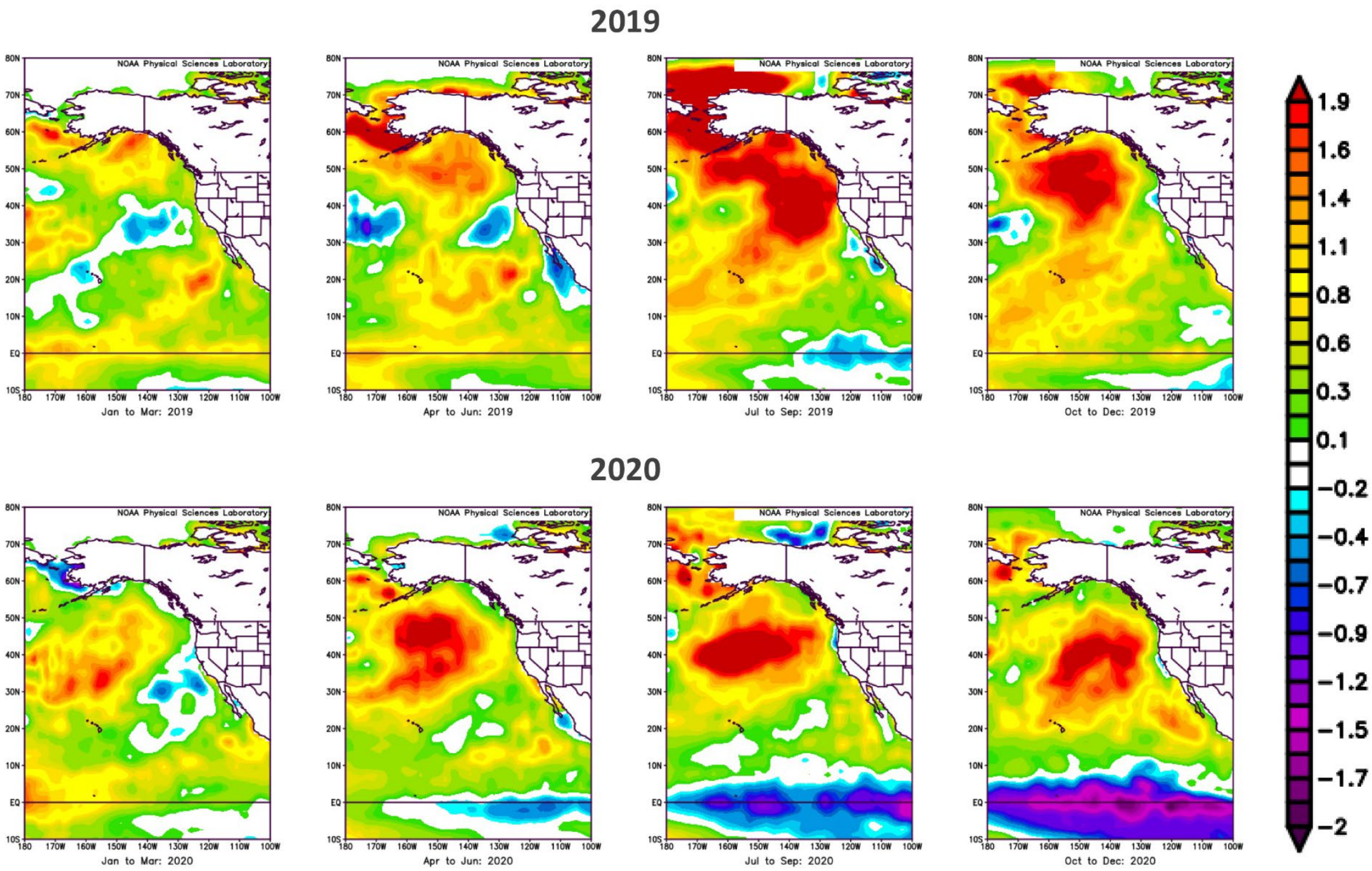


Figure A5-7. Sea surface temperature anomalies, in three-month periods, for the northeast Pacific Ocean as measured from satellites during ocean rearing for the 2017 Sockeye brood year cohort. Data sourced from PCIC (2021).

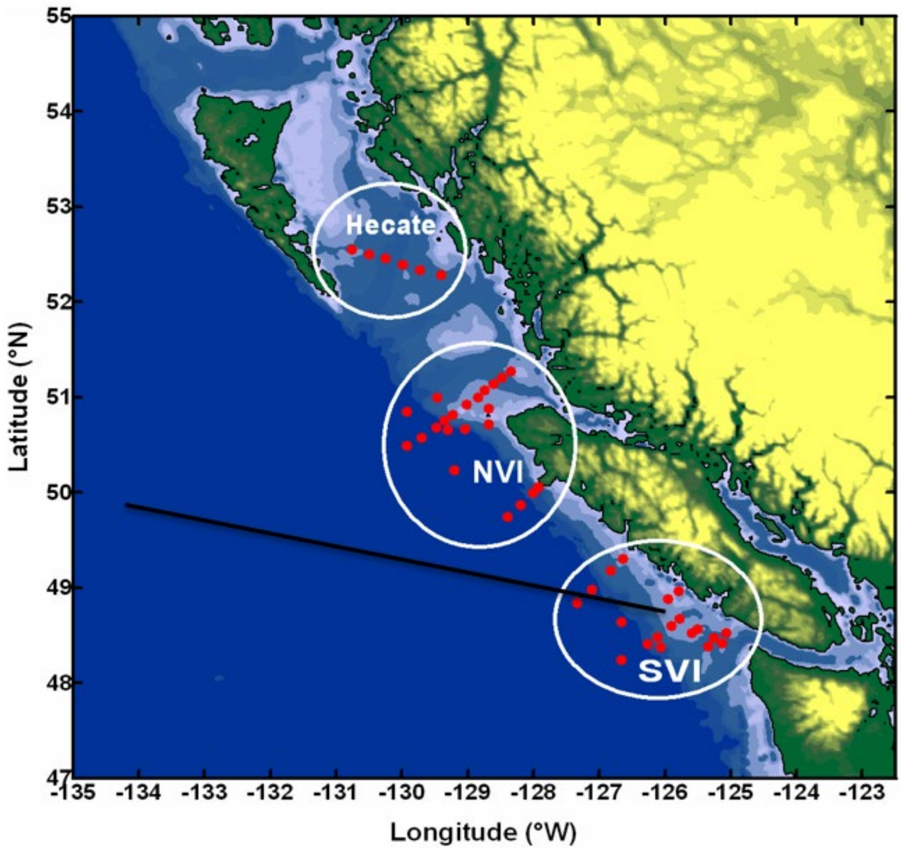


Figure A5-8. Zooplankton time series sampling locations (red dots; Line P – black line) in B.C. marine waters. Source: Moira Galbraith.

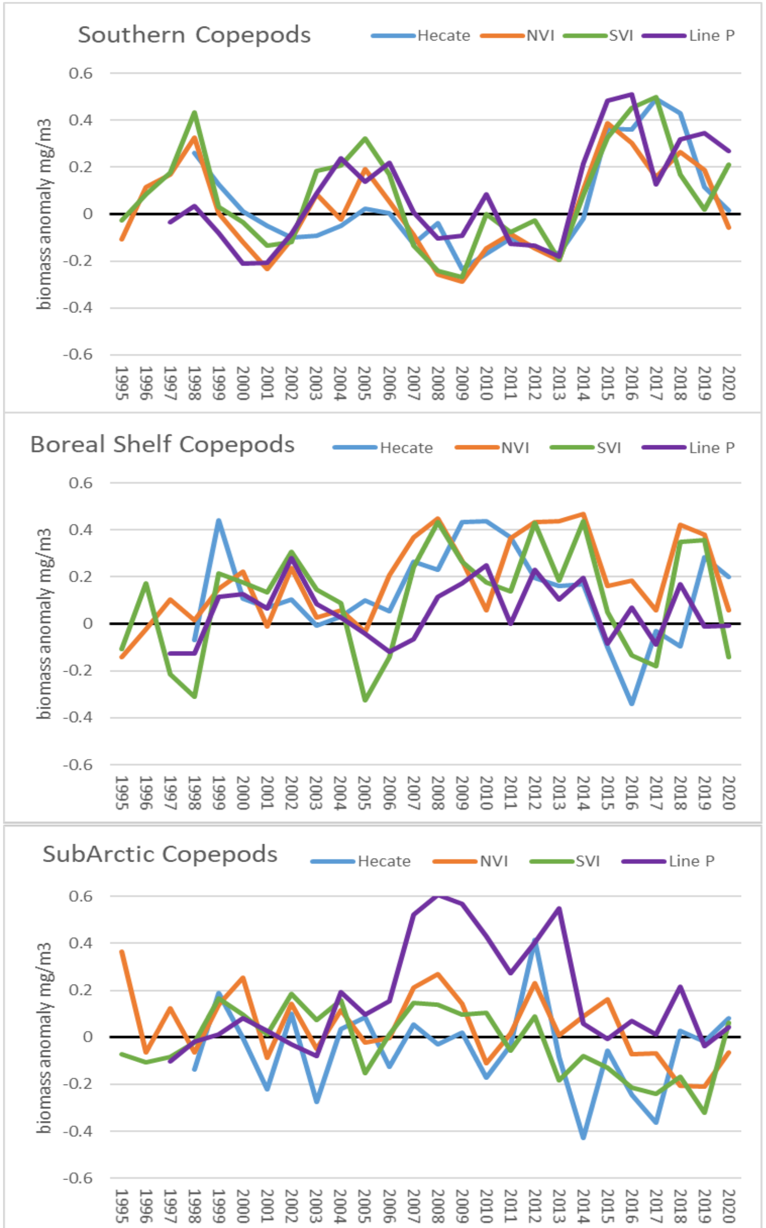


Figure A5-9. Zooplankton species-group anomaly time series for the regions shown in Figure A5-8. Line graphs are annual log scale anomalies. Southern Vancouver Island (SVI) green; Northern Vancouver Island (NVI) orange; Hecate Strait blue; Line P purple - for all graphs. Blank years mean no samples were collected. Source: Moira Galbraith.

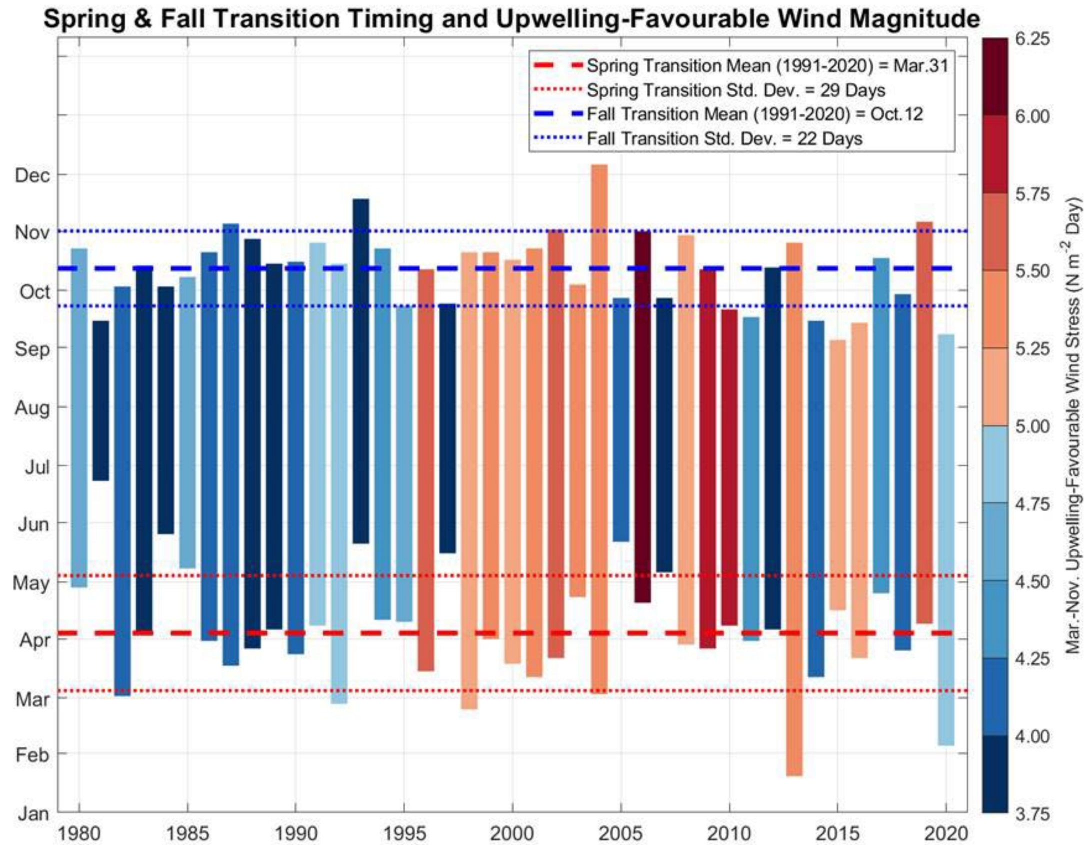


Figure A5-10. The upwelling index for the west coast of British Columbia. Bar plot showing Spring and Fall transitions and upwelling-favourable wind stress magnitude. The length of the bar corresponds to the duration of the upwelling season, coloured by the intensity of the upwelling (red indicates intense upwelling, blue indicates weak upwelling). Bold dashed lines indicate the average spring (red) and fall (blue) transition dates. Light-dashed lines indicate standard deviations of the spring (red) and fall (blue) transition dates. Source: Roy Hourston.

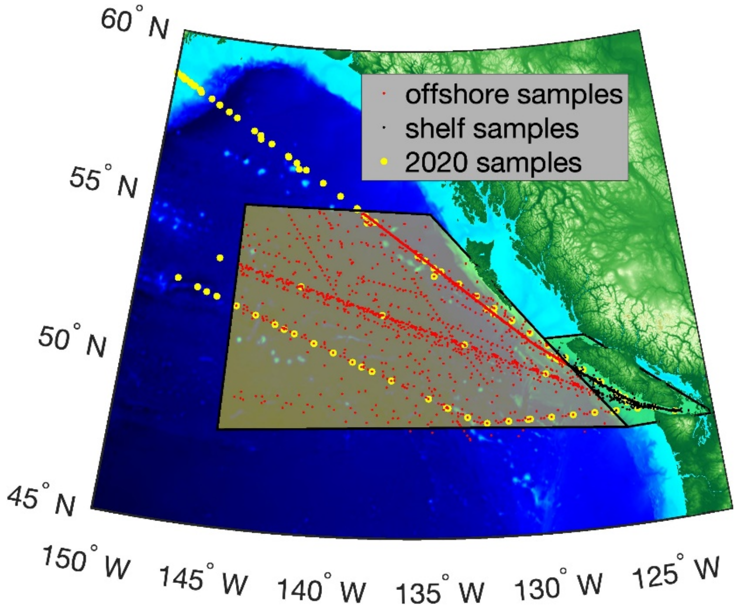
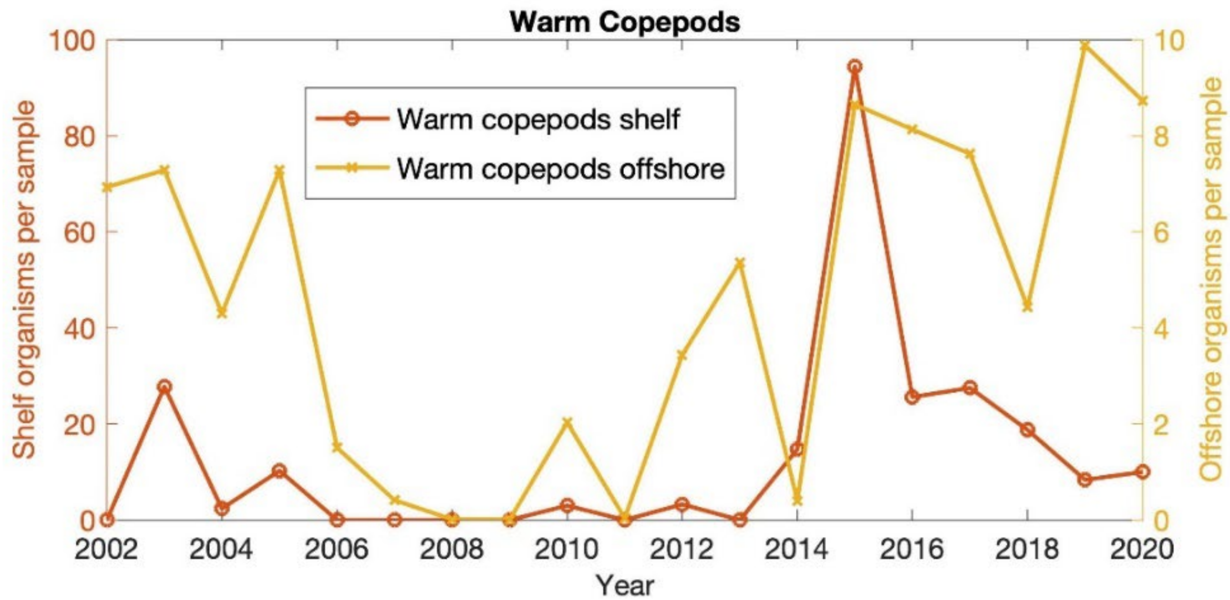


Figure A5-11. Map showing the location of historic CPR samples (2002-2019) red = offshore, black = shelf. Yellow circles are the location of the 2020 samples. Source: Clare Ostle.



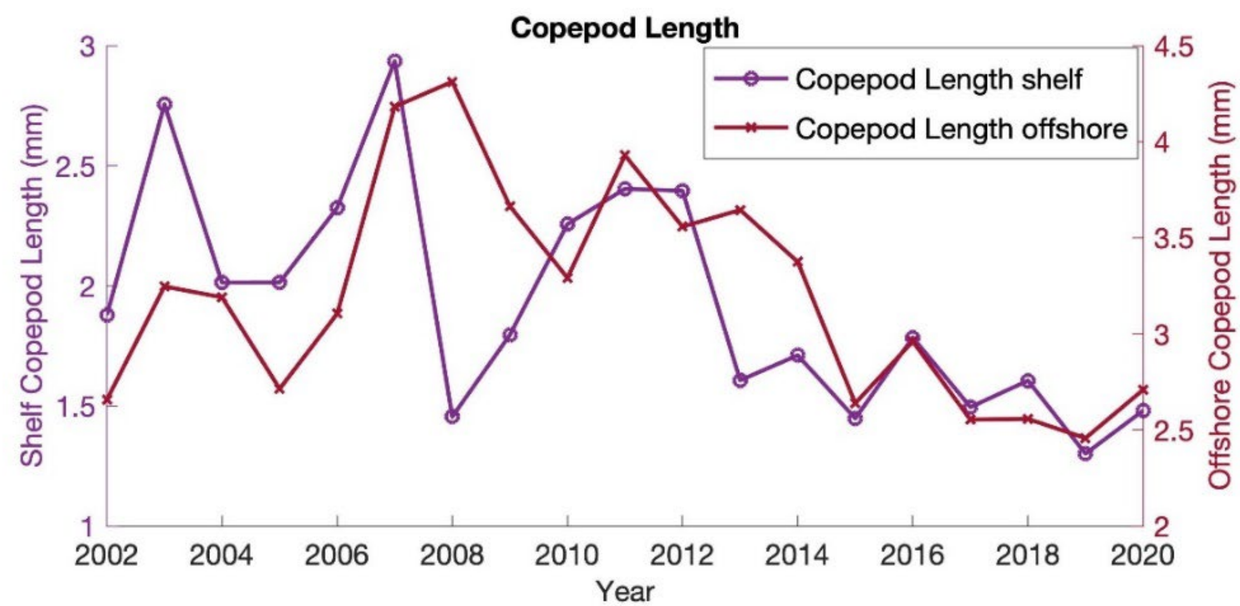


Figure A5-12. The mean annual abundance of warm water copepods (top), copepod length (bottom) for both the shelf (left axis) and offshore (right axis) regions of BC, based on CPR sampling. Source: Clare Ostle.

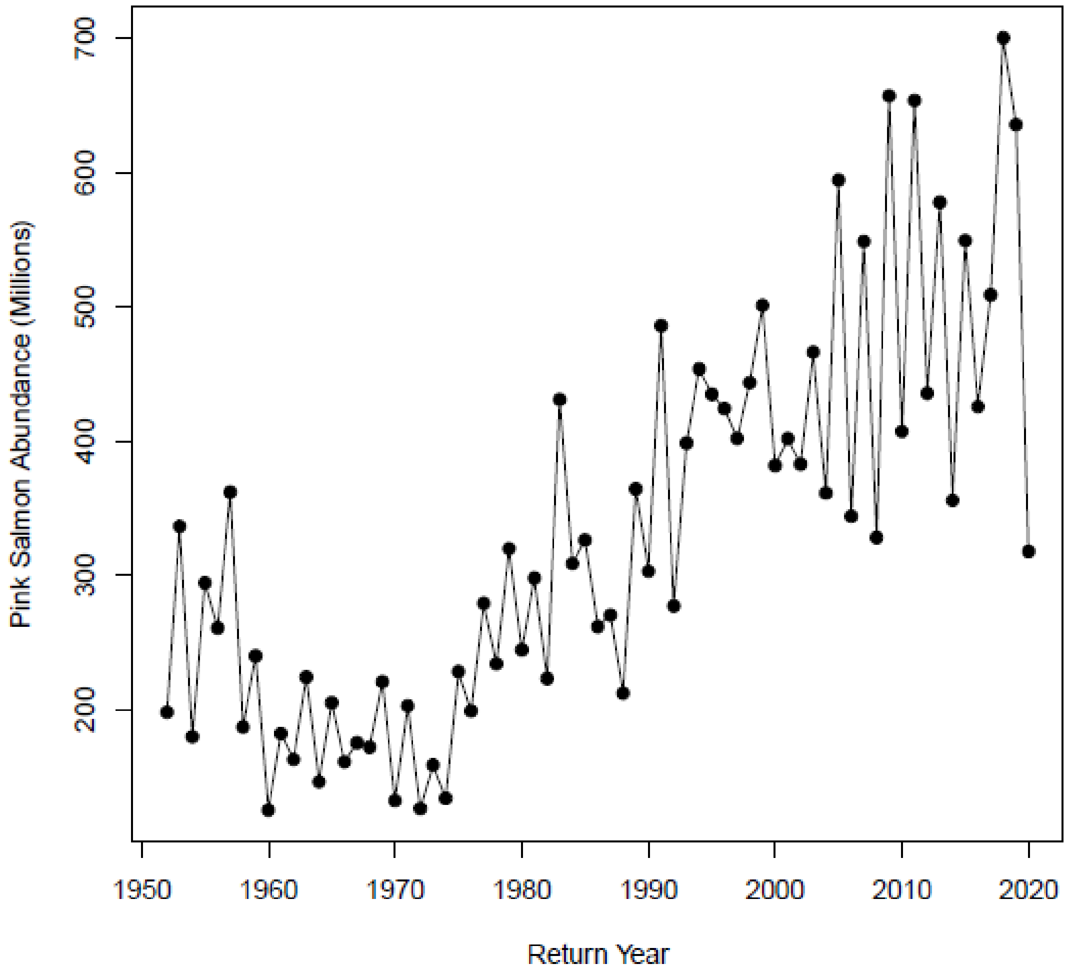


Figure A5-13. Numbers of Pink salmon in the North Pacific Ocean from 1952-2020. Source: James Irvine, updated from Ruggerone and Irvine (2018).

Works Cited

Batten, S., and Ostle, C. 2020. Lower trophic levels in the Northeast Pacific *In* State of the Physical, Biological and Selected Fishery Resources of Pacific Canadian Marine Ecosystems in 2019. Can. Tech. Rep. Fish. Aquat. Sci. 3377. *Edited by* J.L. Boldt, A. Javorski, and P.C. Chandler. (Accessed April 13, 2021)

Bassett, M. C. 2015. Temporal and spatial differences in smolting among Sockeye salmon (*Oncorhynchus nerka*) populations throughout fresh- and seawater migration and the effect of water temperature on the smolt window. UNBC MSc. Thesis. (Accessed May 21, 2021)

Batten, S.D., Ruggerone, G.T., and Ortiz, I. 2018. Pink Salmon induce a trophic cascade in plankton populations around the Aleutian Islands. Fish. Oceanogr. 27:548-559.

Beacham, T.D., Beamish, R.J., Candy, J.R., Wallace, C., Tucker, S., Moss, J.H. and Trudel, M. 2014. Stock-Specific Migration Pathways of Juvenile Sockeye Salmon in British Columbia Waters and in the Gulf of Alaska. Trans. Am. Fish. Soc., 143: 1386-1403.

Braun, D.C., Patterson, D.A., and Reynolds, J.D. 2013. Maternal and environmental influences on egg size and juvenile life-history traits in Pacific salmon. Ecol. Evol. 3(6): 1727–1740.

Brett, J.R. 1971. Energetic responses of salmon to temperature. A study of some thermal relations in the physiology and freshwater ecology of Sockeye salmon (*Oncorhynchus nerka*). Am. Zool. 11(1): 99–113.

British Columbia River Forecast Center. 2021. Snow Conditions and Water Supply Bulletin. Accessed May 11, 2021.

Burt, J.M., Hinch, S.G., and Patterson, D.A. 2011. The importance of parentage in assessing temperature effects on fish early life history: a review of the experimental literature. Rev. Fish Biol. Fish. 21: 377–406.

Burt, J.M., Hinch, S.G., and Patterson, D.A. 2012. Developmental temperature stress and parental identity shape offspring burst swimming performance in Sockeye salmon (*Oncorhynchus nerka*). Ecol. Freshw. Fish 21(2): 176–188.

Clark, T.D., Furey, N.B., Rechisky, E.L., Gale, M.K., Jeffries, K.M., Porter, A.D., Casselman, M.T., Lotto, A.G., Patterson, D.A., Cooke, S.J., Farrell, A.P., Welch, D.W. and Hinch, S.G. 2016. Tracking wild Sockeye salmon smolts to the ocean reveals distinct regions of nocturnal movement and high mortality. Ecol. Appl., 26: 959-978.

Connors, B., Malick, M.J., Ruggerone, G.T., Rand, P., Adkison, M., Irvine, J.R., Campbell, R., and Gorman, K. 2020. Climate and competition influence Sockeye salmon population dynamics across the Northeast Pacific Ocean. Can. J. Fish. Aquat. Sci. 77(6): 943–949.

DFO. 2015. Supplement to the pre-season return forecasts for Fraser River Sockeye Salmon in 2015. Can. Sci. Adv. Sec. Sci. Response 2015/028. (Accessed April 9, 2021)

DFO. 2016. Supplement to the pre-season run size forecasts for Fraser River Sockeye (*Oncorhynchus nerka*). Can. Sci. Adv. Sec. Proc. 2016/047. (Accessed April 9, 2021)

DFO. 2018. Science Response Process of July 18, 2018 on the Review of Science Information to Inform Consideration of Risks to Cultus Lake Sockeye Salmon in 2018. DFO Can. Sci. Advis. Sec. Sci. Resp. 2018/052. (Accessed April 9, 2021)

DFO. 2020. Recovery Potential Assessment - Cultus Lake Sockeye Salmon (*Oncorhynchus nerka*). DFO Can. Sci. Advis. Sec. Sci. Advis. Rep. 2020/011. (Accessed April 9, 2021)

Edmundson, J.A., and Mazumder, A. 2001. Linking growth of juvenile Sockeye salmon to habitat temperature in Alaskan lakes. Trans. Am. Fish. Soc., 130: 644–662.

Eliason, E.J., Clark, T.D., Hague, M.J., Hanson, L.M., Gallagher, Z.S., Jeffries, K.M., Gale, M.K., Patterson, D.A., Hinch, S.G., and Farrell, A.P. 2011. Differences in thermal tolerance among Sockeye salmon populations. Science. 332(6025): 109–112.

Environment and Climate Change Canda. 2021. Water Level and Flow Data. (Accessed May 11, 2021)

Galbraith, M., and Young, K. 2020. West Coast British Columbia zooplankton biomass anomalies 2019. *In* State of the physical, biological and selected fishery resources of Pacific Canadian marine ecosystems in 2019. Can. Tech. Rep. Fish. Aquat. Sci. 3377. *Edited by* J.L. Boldt, L. J, and P.C. Chandler. pp. 64–69. (Accessed April 13, 2021)

Ginetz. R.M. and Larkin, P.A. 1976. Factors Affecting Rainbow Trout (*Salmo gairdneri*) Predation on Migrant Fry of Sockeye Salmon (*Oncorhynchus nerka*). J. Fish. Res. Board Canada. 33(1): 19-24.

Gregory, R.S. and Levings, C.D. 1998 Turbidity Reduces Predation on Migrating Juvenile Pacific Salmon. Trans. Am. Fish. Soc., 127:2, 275-285

Holsman, K., Hollowed, A., Shin-Ichi, I., Bograd, S., Hazen, E., King, J., Mueter, F., and Perry, R.I. 2018. Climate change impacts, vulnerabilities and adaptations: North Pacific and Pacific Arctic marine fisheries. *In* Impacts of climate change on fisheries and aquaculture: synthesis of current knowledge, adaptation and mitigation options. *Edited by* M. Barange, T. Bahri, M.C.M. Beveridge, K.L. Cochrane, S. Funge-Smith, and F. Poulain. FAO Fisheries and Aquaculture Technical Paper, No. 627. FAO, Rome. pp. 113–138. (Accessed April 13, 2021)

Hourston, R., and Thomson, R. 2020. Wind-driven upwelling/downwelling along the Northeast coast of North America: timing and magnitude *In* State of the Physical, Biological and Selected Fishery Resources of Pacific Canadian Marine Ecosystems in 2019. Can. Tech. Rep. Fish. Aquat. Sci. 3377. *Edited by* J.L. Boldt, A. Javorski, and P.C. Chandler. (Accessed April 13, 2021)

Hume, J. M. B., Shortreed, K. S., and Morton, K. F. 1996. Juvenile Sockeye rearing capacity of three lakes in the Fraser River system. Can. J. Fish. Aquat. Sci., 53(4): 719–733.

Leising, J., and Bograd, S.J. 2020. The California Current marine heatwave tracker-an experiemental tool for tracking marine heatwaves: California Current Project. Southwest Fisheries Science Centre. NOAA. (Accessed December 12, 2020)

Macdonald, J.S., Scrivener, J.C., Patterson, D.A., and Dixon-Warren, A. 1998. Temperatures in aquatic habitats: the impacts of forest harvesting and the biological consequences to Sockeye salmon incubation habitats in the interior of B.C. *In* Forest-fish conference: land mananagment practices affecting aquatic ecosystems. Proc. Forest-Fish Conf., May 1-4, 1996, Calgary, AB. *Edited by* M.K. Brewin and D.M.A. Monita. Natural Resources Canada, Edmonton, AB. pp. 313–324.

Macdonald, J.S. 2000. Mortality during the migration of Fraser River Sockeye salmon (*Oncorhynchus nerka*) : a study of the effects of ocean and river environmental conditions in 1997. Can. Tech. Rep. Fish. Aquat. Sci. 2315: 120p. (Accessed May 18, 2021)

Macdonald, J.S., Morrison, J. and Patterson D.A. 2012. The Efficacy of Reservoir Flow Regulation for Cooling Migration Temperature for Sockeye Salmon in the Nechako River Watershed of British Columbia, North American Journal of Fisheries Management, 32:3, 415-427.

MacDonald, B.L., Grant, S.C.H., Patterson, D.A., Robinson, K.A., Boldt, J.L., Benner, K., Neville, C.M., Pon, L., Tadey, J.A., Selbie, D.T. and Winston, M.L. 2018. State of the Salmon: Informing the survival of Fraser Sockeye returning in 2018 through life cycle observations. Can. Tech. Rep. Fish. Aquat. Sci. 3271: 53 + v pp. (Accessed April 9, 2021)

MacDonald, B.L., Grant, S.C.H., Patterson, D.A., Robinson, K.A., Boldt, J.L., Benner, K., King, J, Pon, L., Selbie, D.T, Neville, C.M., and J.A. Tadey. 2019. State of the Salmon: Informing the survival of Fraser Sockeye returning in 2019 through life cycle observations. Can. Tech. Rep. Fish. Aquat. Sci. 3336: 61 + vi pp. (Accessed April 9, 2021)

MacDonald, B.L., Grant, S.C.H., Wilson, N., Patterson, D.A., Robinson, K.A., Boldt, J.L., King, J. Anderson, E., Decker, S., Leaf, B., Pon, L., Xu, Y., Davis, B., and Selbie, D.T. 2020. State of the Salmon: Informing the survival of Fraser Sockeye returning in 2020 through life cycle observations. Can. Tech. Rep. Fish. Aquat. Sci. 3398: v + 76 p. (Accessed April 9, 2021)

Mackas, D.L., Peterson, W.T., and Zamon, J.E. 2004. Comparisons of interannual biomass anomalies of zooplankton communities along the continental margins of British Columbia and Oregon. Deep Sea Res. Part II Top. Stud. Oceanogr. 51(6–9): 875–896.

Mackas, D.L., Batten, S., and Trudel, M. 2007. Effects on zooplankton of a warmer ocean: recent evidence from the Northeast Pacific. Prog. Oceanogr. 75(2): 223–252.

Næsje, T. F., Thorstad, E. B., Forseth, T., Aursand, M., Saksgard, R., and Finstad, A. G. 2006. Lipid class content as an indicator of critical periods for survival in juvenile Atlantic salmon (*Salmo salar*). Ecol. Freshw. Fish, 15(4), 572– 577.

Pacific Climate Impacts Consortium. 2021. Seasonal Anomoly Maps. (Accessed May 11, 2021)

Patterson, D.A., Macdonald, J.S., Hinch, S.G., Healey, M.C. and Farrell, A.P. 2004. The effect of exercise and captivity on energy partitioning, reproductive maturation and fertilization success in adult Sockeye salmon. J. Fish Biol., 64: 1039-1059.

Perry, R.I., Young, K., Galbraith, M., Chandler, P., Velez-Espino, A., Baillie, S. 2021. Zooplankton variability in the Strait of Georgia, Canada, and relationships with the marine survivals of Chinook and Coho salmon. PLoS ONE 16(1): e0245941.

Ross, T., and Robert, M. 2020. Are Marine Heatwaves the New Normal for the Northeast Pacific Ocean? *In* State of the Physical, Biological and Selected Fishery Resources of Pacific Canadian Marine Ecosystems in 2019. Can. Tech. Rep. Fish. Aquat. Sci. 3377. *Edited by* J.L. Boldt, A. Javorski, and P.C. Chandler. (Accessed April 13, 2021)

Ruggerone, G.T., and Connors, B.M. 2015. Productivity and life history of Sockeye salmon in relation to competition with pink and Sockeye salmon in the North Pacific Ocean. Canadian Journal of Fisheries and Aquatic Sciences 72:818-833.

Ruggerone G.T., Agler, B.A., Connors, B., Farley, Jr., E.V., Irvine, J.R., Wilson, L., and Yasumiishi, E.M. 2016. Competition between pink and Sockeye salmon at sea and its influence on Bristol Bay Sockeye salmon forecast error. North Pacific Anadromous Fish Commission Bulletin No. 6:349-361.

Ruggerone G.T., and Irvine, J.R. 2018. Numbers and biomass of natural- and hatchery-origin pink, chum, and Sockeye salmon in the North Pacific Ocean, 1925-2015. Marine and Coastal Fisheries: Dynamics, Management, and Ecosystem Science 10:152-168.

Schindler, D.E., Rogers, D.E., Scheuerell, M.D., and Abrey, C.A. 2005. Effect of changing climate on zooplakton and juvenile Sockeye salmon growth in Southwestern Alaska. Ecology 86(1): 198–209.

Sopinka, N.M., Hinch, S.G., Healy, S.J., Raby, G.D., and Patterson, D.A. 2016. Effects of experimentally elevated egg cortisol on offspring traits in two species of wild Pacific salmon. Environ. Biol. Fish 99, 717–728.

Stevenson, C.F., Hinch, S.G., Porter, A.D., Rechisky, E.L., Welch, D.W., Healy, S.J., Lotto, A.G. and Furey, N.B. 2019, The Influence of Smolt Age on Freshwater and Early Marine Behavior and Survival of Migrating Juvenile Sockeye Salmon. Trans. Am. Fish. Soc., 148: 636-651.

Tierney, K.B., Patterson, D.A., and Kennedy, C.J. 2009. The influence of maternal condition on offspring performance in Sockeye salmon *Oncorhynchus nerka*. J. Fish Biol. 75(6): 1244–1257.

Tucker, S., Trudel, M., Welch, D.W., Candy, J.F.T., Morris, M.E., Thiess, M.E., Wallace, C., Teel, D.J., Crawford, W., Farley Jr., E.V., and Beacham, T.D. 2009. Seasonal stock-specific migrations of juvenile Sockeye salmon along the West Coast of North America: Implications for growth. Trans. Am. Fish. Soc. 138:1458-1480.

Wilson, S.M., Robinson, K.A., Gutzmann, S., Moore, J.W., and Patterson, D.A. 2021. Limits on performance and survival of juvenile Sockeye salmon (*Oncorhynchus nerka*) during food deprivation: a laboratory-based study. *Cons. Phys.* 9(1).

Whitney, C.K., Hinch, S.G., and Patterson, D.A. 2014. Population origin and water temperature affect development timing in embryonic Sockeye salmon. Trans. Am. Fish. Soc. 143(5): 1316–1329.

Xu, Y., Fu, C., Peña, A., Hourston, R., Thomson, R., Robinson, C., Cleary, J., Daniel, K. and Thompson, M. (2019). Variability of Pacific herring (Clupea pallasii) spawn abundance under climate change off the West Coast of Canada over the past six decades. J. Mar. Syst. 200; 103229.

Young, K., Galbraith, M., and Perry I. 2020. Zooplankton status and trends in the cental and nothern Strait of Georgia, 2019. *In* State of the Physical, Biological and Selected Fishery Resources of Pacific Canadian Marine Ecosystems in 2019. Can. Tech. Rep. Fish. Aquat. Sci. 3377. *Edited by* J.L. Boldt, A. Javorski, and P.C. Chandler. (Accessed April 13, 2021)

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