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Evaluation framework for assessing potential Pacific Salmon Commission reference points for population status and associated allowable exploitation rates for Strait of Georgia and Fraser River Coho Salmon Management Units

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Foreword

This series documents the scientific basis for the evaluation of aquatic resources and ecosystems in Canada. As such, it addresses the issues of the day in the time frames required and the documents it contains are not intended as definitive statements on the subjects addressed but rather as progress reports on ongoing investigations.

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ABSTRACT

The work presented here continues the development and implementation of a bilaterally-reviewed methodology to establish reference points and associated allowable exploitation rates for Coho Salmon management units detailed in the Pacific Salmon Treaty (PST) Southern Coho Agreement (Annex IV, Chapter 5). Marine survival has been identified as a major factor influencing escapement. However, accurate escapement estimates for many Coho Salmon populations in British Columbia are limited. This project therefore focuses on evaluating effects of exploitation rate across a range of marine survival rates that can be used to define PST abundance classes. We fit a variety of stock-recruitment models with a hatchery-based smolt-adult marine survival covariate to data from the five conservation units (CUs) in the Interior Fraser Coho Salmon management unit (IFC MU) (brood years 1998-2012), and to Black Creek (1986-2012), the sole monitored population representing the Strait of Georgia (SOG) MU. We used a simulation framework based on posterior distributions of stock-recruit parameters to determine the probability of meeting previously established conservation benchmarks over a range of exploitation and smolt-adult marine survival rates.

Based on best fit Ricker models, productivity (adult recruits/spawner at low stock size) of IFC CU's ranged from about 2.2-2.6 recruits/spawner at the geometric mean hatchery smolt-adult marine survival rate since 1998 (1.1%). Exploitation rates that maximized yield (Umsy) at these productivities ranged from 0.36 to 0.42. The range in Umsy declined to 0.27-0.32 based on a Ricker model with an assumed higher carrying capacity, which eliminated overcompensatory dynamics over the range of stock sizes, but reduced stock productivity. Productivity of Black Creek based on the average smolt-adult marine survival for the SOG hatchery indicator stock since 1998 (0.84%) was 2.3 recruits/spawner, resulting in a Umsy of 0.37, and these values declined to 2.0 and 0.32, when using a Ricker model with higher carrying capacity, respectively.

A retrospective simulation analysis of IFC stock-recruit data demonstrated that the majority of variation in escapement to IFC CUs since 1998 has been driven by variation in smolt-adult marine survival rate. Historical simulations indicated that increasing exploitation from 10% (geometric average since 1998 was 11%) to 30% decreased the probability of achieving the short-term MU conservation benchmark (20,000 spawners) from 71% to 43%. However a fixed exploitation rate of 20% resulted in a 50% probability of exceeding the short-term benchmark, which was similar to the observed probability when hatchery-origin fish are not included in the conservation statistic. The modest effects of slight increases in exploitation rate occurred because the increase in escapement associated with lower exploitation did not produce a proportional increase in recruitment in the next generation owing to density-dependence. Forward simulations quantified conservation performance over a wide range of exploitation and smolt-adult marine survival rates and included effects of harvest rate implementation error. This information can be used by decision-makers to set exploitation rates for the IFC MU for marine-survival based PST status categories. However, there is not sufficient information to make these determinations for SOG and lower Fraser River (LFR) MUs.

INTRODUCTION

The objective of the bilateral Canada/US Coho Salmon management plan is to optimize total fishery exploitation to enable MUs to produce Maximum Sustainable Yields (MSY) over the long term, while maintaining the genetic and ecological diversity of the component populations and to improve long-term prospects for sustaining healthy fisheries in both countries. Stock productivity and escapement vary over time, largely due to variation in marine survival rate. During periods when marine survival rate is high, stocks will be more productive and abundant and can withstand greater exploitation compared to when marine survival rates are low. In addition, stock productivity can vary among component populations within each MU, which under the Wild Salmon Policy (WSP), are termed Conservation Units (CUs). Exploitation rates that maximize yield for some CUs may too high for less productive ones and could result in escapements to the weak CU that are so low that the persistence of the population is threatened. Thus, exploitation rates intended to meet fishery and conservation objectives need to account for differences in productivity among CUs and over time; for fisheries that harvest fish coming from more than one MU, variation in productivity among populations in different MUs must also be considered.

The work presented here continues the development and implementation of a bilaterally-reviewed methodology to establish reference points and associated allowable exploitation rates for Canadian Coho MUs detailed in Annex IV, Chapter 5 of the PST: Interior Fraser Coho (IFC), Strait of Georgia (SOG; which merges the two previously-recognized Strait of Georgia MUs), and Lower Fraser River (LFR). The current agreement requires the development of escapement goals and exploitation rates that achieve maximum sustainable yield (MSY) for three status categories (Low, Moderate and Abundant) for each MU. Marine survival has been identified as a major factor influencing adult returns. Accurate estimates of escapement for many Coho Salmon populations in British Columbia are limited. This project therefore focuses on an approach to establishing reference points using marine survival rather than measures of absolute abundance such as escapement.

The objectives of the work presented here are to:

1. recommend metrics for assessing conservation and harvest performance that account for variation in marine survival;
2. develop models to assess impacts of different exploitation rates and reference points on conservation objectives given variation in marine survival and error in harvest implementation;
3. discuss uncertainties and risks associated with use of marine survival for establishment of allowable exploitation rates;
4. suggest potential methods for identifying reference points based on marine productivity to distinguish categorical status zones as described the PST for Canadian Coho MUs; and
5. recommend priority areas for improvements in Coho assessment programs to support implementation of marine survival-based approaches for status determination.

The extent of information available for South Coast Coho Salmon MUs is variable and influences the degree to which we can achieve these objectives. The IFC MU has relatively reliable stock-recruitment data for all of its CUs, a hatchery-based index of marine survival, and previously-defined conservation benchmarks that are grounded in population genetic and demographic data and arguments (IFCRT 2006). Hence, we can develop stock-recruit models that account for variation in marine survival, and use simulation to evaluate how the probability

of attaining conservation benchmarks (conservation performance) is affected by changes in exploitation rates and marine survival. These results can be used by managers to set exploitation rates for each PST status category. The SOG MU has reliable stock-recruit data for only one of many populations and a hatchery-based index of marine survival. As the MU does not have any established conservation benchmarks, it is not possible to use simulation to determine how conservation performance varies with exploitation rates for each status category. However, by comparing the productivity of the SOG index population with those from the IFC MU, it is at least possible to evaluate whether exploitation rates for the IFC MU will have negative effects on the population representing the SOG MU. Finally, the LFR MU only has a hatchery-based marine survival index. There is no recent stock-recruitment data or established conservation benchmarks for this MU. In this case, there is no useful information to evaluate the effects of alternate exploitation rates. Given data availability, the majority of our analysis focuses on the IFC MU. We do present results from a SOG stock-recruitment analysis and compare productivities with those from IFC populations.

METHODS

DATA SOURCES AND UNCERTAINTIES

Our analysis for the Interior Fraser Coho (IFC) MU is based on escapement, recruitment, age structure, and marine survival and exploitation rate data (Table 1) updated from those used in recent assessments (Decker et al. 2014; C. Parken pers. Comm.).The 2014 analysis (C. Parken pers. Comm.) was based on information available through 2013, while our analysis includes stock-recruit data through 2016.

Interior Fraser Coho Salmon are predominately 3_2 fish, with juveniles spending one winter in freshwater and one winter at sea. About 10% of returning adults are age 4_3 resulting from 2-winter smolts. Scales from returning adults are sampled during spawning ground surveys and are compiled by Conservation Unit and year. The scale sampling is incomplete as there are years without any scales, others with small sample sizes, and limited spatial representation within CUs. Previous analyses have varied in the way the age structure has been dealt with. In most cases, age structure has been ignored (IFCRT 2006; Decker and Irvine 2013). The exception is the 2014 analysis (C. Parken pers. Comm) in whichthe average distribution of age-3 and age-4 fish in the returns for each CU was computed, and the proportions were applied to the total returning fish each year to derive the number of 3- and 4-year old fish by return year. Fish were then assigned to their brood year to allow the calculation of recruitment for each brood year.

Ideally, age structure is best dealt with by having sufficient age information for all years to allow the construction of a brood table. If age data must be imputed using averages or modelled values, there are two approaches that differ in their assumptions.

The 2014 method based on the assumption that the age distribution of returning fish remains approximately constant (C. Parken, pers. comm), was the first approach used. This assumption is valid when the production of smolts by age group is similar across years, and variation in abundance is driven by smolt survival. Because virtually all Coho spend one winter in the ocean, for each return year, they share the same ocean residence period, which then synchronizes the variation in abundance across age classes within a return year. However, if return abundance is affected by parent spawner abundance and the early freshwater period, then a strong brood year will generate a larger proportion of age-4s in the following year, causing variation in the age structure by return years. Of concern is that, by assuming a constant age structure by return year, the production of age-3 recruits in small year classes will

be overestimated because the abundance of age-4s from the preceding brood will be underestimated for those years when a small year is preceded by a larger one. This bias will affect stock-recruitment parameter estimates.

The second approach for modelling age structure assumes that the age distribution of brood years is constant, rather than return years. This assumption may be more justifiable in the freshwater phase as smolt age composition by brood may be determined by habitat conditions in freshwater. However, the age composition of adult returns by brood will depend on the relative smolt survivals of the two age groups as they enter the ocean in different years. Survival variation will generate variability in age structure by brood year.

In this analysis, we use the second approach to reconstruct recruitment with a modification to account for differences in age composition resulting from the differential ocean survival of the two smolt ages. We found that smolt age, by brood, was positively related to overall abundance of the cohort. In effect, for broods where the survival of the numerically dominant age-1 smolts was good, there were relatively fewer adults returning from age-2 smolts. We used this predictable correlation between the brood year-based age composition and cohort size to generate annual age composition data for each CU. This approach will minimize some of the variability and potential bias associated with using a fixed average age composition. Details of the approach are summarized in Appendix A.

For some CUs in some years, there is significant hatchery production. For the stock-recruit analysis, we included hatchery-origin fish that spawned in the wild in the determination of the annual escapement, under the assumption that they were able to reproduce successfully in the wild. Estimates of hatchery-origin fish were removed from the returns so that recruitment represented natural-origin fish only.

Consistent with the 2014 analysis (C. Parken, pers. comm), we used the IFC MU smolt-adult marine survival rate of hatchery releases to index survival for naturally produced Coho in the stock-recruitment analysis. Only data from brood years 1998-2012 were used in the stock-recruitment analysis, as earlier data was considered unreliable for this purpose. As described below, smolt-adult marine survival and recruitment estimates for the entire time series (1984-2016, Table 2) were only used to provide preliminary definitions of status categories and to re-examine the 20,000 and 40,000 MU benchmarks.

Our analysis for the Strait of Georgia (SOG) MU is based on data from Black Creek from 1986 through 2015 (Table 3). Recruitment for each brood year from 1986 to 2012 was calculated by expanding annual escapements by annual estimates of exploitation rate for Black Creek (Table 2). Escapement associated with each recruitment estimate for the stock-recruit analysis was simply the escapement three years earlier given that Black Creek is composed almost entirely of age 3 returns. We used the SOG hatchery (SOG_H) index of smolt-adult marine survival as the covariate in the stock-recruitment analysis (Table 4). This index is based on the average smolt-adult marine survival rates from Big Qualicum and Quinsam hatcheries in each year (Big Qualicum estimates excluded for return years 1986-1989). We did not use the Black Creek smolt-adult marine survival rate time series in the stock-recruit analysis because of uncertain funding and concerns about the modelled exploitation rate component of the time series (see Table 5b), and it is much more likely that the smolt-adult marine survival index from Big Qualicum and Quinsam hatcheries will be available in the future. As there was no wild indicator stock for the Lower Fraser MU, we were not able to conduct a stock-recruitment analysis and therefore define exploitation rates for each marine survival/abundance status category. However, we compare the trend in the Inch Creek hatchery smolt-adult marine survival data with SOG_H and IFC data.

As spawner and adult recruit data for the SOG MU was limited to a single population (Black Creek) we were concerned about whether this population is representative of other populations in the SOG MU. Korman and Tompkins (2014) estimated spawner-smolt stock-recruit parameters for 16 coastal Coho populations in Oregon, Washington, and BC (which includes Black Creek), an extension of data first compiled and analyzed by Bradford (2000). There would be more support for using Black Creek to represent the SOG MU if its spawner-smolt parameters were similar to the average across the 16 coastal Coho populations. We used the posterior distributions of Beverton-Holt spawner-smolt stock-recruitment parameters from Korman and Tompkins for this assessment. They examined the fit of Beverton-Holt, Ricker, logistic hockey stick, and depensatory Beverton-Holt models, and found greatest statistical support for the Beverton-Holt model, so that is the set of model results reviewed here. Their hierarchical modelling approach estimated spawner-smolt parameters for each population as well as an average relationship for all 16 coastal populations.

The uncertainties in the data are detailed in Tables 5a and b.

STOCK-RECRUITMENT ANALYSIS

We evaluated the fit of Ricker, Deriso, and power relationships to stock-recruitment data for each IFC CU and from Black Creek. We evaluated models that included a hatchery smolt-adult marine survival rate index (HSASI).

The form of the Ricker model we fit is,

$$\hat{R}_{i,a,t} = p_{i,a,t-a} \cdot S_{i,t-a} \cdot e^{\alpha_i + \gamma \cdot \log(M_{t-1}) - \beta_i \cdot S_{i,t-a}} \qquad \text{Equation 1.}$$

where $p_{i,a,t-a}$ is the proportion of recruitment produced from the same spawning cohort returning at age *a* (*a*=3,4) in CU i (determined based on methods in appendix A), S is the number of spawners returning to CU i in previous year *t-a*, R is the number of natural recruits returning in year *t* of age *a* produced from the escapement in brood year *t-a*, α is a term reflecting maximum survival when there are no density-dependent effects (S→0) and when the smolt-adult marine survival rate (M_t, Table 2) is 1, β is a density-dependent term describing the rate of decrease in log-survival with increasing spawner abundance, and γ is the smolt-adult marine survival coefficient. Note that the smolt-adult marine survival rate used in the prediction is one year prior to recruitment (*t*-1), thus we assume all Coho spend one year at sea. Recruitment from a given brood will therefore depend on smolt-adult marine survival rates two and three years after spawning for age-3 and -4 year fish, respectively. Total recruitment from a brood is calculated as the sum of age-3 and -4 year recruits in consecutive years according to,

$$R_{i,bt} = R_{i,a=3,bt} + R_{i,a=4,bt+1} \qquad \text{Equation 2.}$$

where $R_{i,bt}$ denotes the total recruitment returning to CU i from brood year *bt*.

Maximum productivity, which occurs when spawner stock size is low, changes each year with the smolt-adult marine survival rate index according to,

$$\alpha_{i,t}' = \alpha_i + \gamma \cdot \log(M_t) \qquad \text{Equation 3.}$$

where $\alpha'_{i,t}$ is the year-specific maximum productivity value for CU i. This model assumes that smolt-adult marine survival effects productivity at low stock size only, and has no effect on the density-dependence parameter (β). This is consistent with the long-held view that the majority of density dependence for salmon and steelhead occurs during their freshwater rearing phase. Furthermore, the model structure allows calculation of maximum productivity for a particular

historical period or for a future period by replacing log(M_t) in Equation 1. with $\overline{M}$, that represents the mean smolt-adult marine survival for the historical or future period.

The second model we considered was a Ricker model with depensatory mortality,

$$\hat{R}_{i,a,t} = \frac{S_{i,t-a}}{S_{i,t-a} + \delta} \cdot p_{i,a,t-a} \cdot S_{i,t-a} \cdot e^{\alpha_i + \gamma \cdot \log(M_{t-1}) - \beta_i \cdot S_{i,t-a}} \qquad \text{Equation 4.}$$

where δ is the escapement where recruitment is reduced to 50% of the value it would have been in the absence of depensatory mortality.

The third model we considered was the Deriso model,

$$\hat{R}_{i,a,t} = p_{i,a,t-a} \cdot S_{i,t-a} \cdot e^{\alpha_i + \gamma \cdot \log(M_{t-1})} \cdot (1 - \chi \cdot \beta \cdot S_{i,t-a})^{\frac{1}{\chi}} \qquad \text{Equation 5.}$$

where χ determines the degree of overcompensatory mortality (downward bending of stock-recruitment curve at larger stock size). This model takes on a Beverton-Holt asymptotic shape (no overcompensation) as χ approaches -1, and a Ricker shape as χ approaches 0. We set χ at -0.9 to force the Deriso model to take on an asymptotic shape and avoid overcompensatory mortality.

The fourth model we considered was a power model of the form,

$$\hat{R}_{i,a,t} = e^{\alpha_i + \gamma \cdot \log(M_{t-1})} \cdot p_{i,a,t-a} \cdot S_{i,t-a}^{\beta} \qquad \text{Equation 6.}$$

This model allows a continuous but reducing increase in recruitment with increasing stock size compared to the Deriso model, and does not allow overcompensatory dynamics.

We also considered Ricker models without a survival covariate effect,

$$\hat{R}_{i,a,t} = p_{i,a,t-a} \cdot S_{i,t-a} \cdot e^{\alpha_i - \beta_i \cdot S_{i,t}} \qquad \text{Equation 7.}$$

and a stock-recruitment model without a survival covariate effect or density dependence,

$$\hat{R}_{i,a,t} = p_{i,a,t-a} \cdot S_{i,t-a} \cdot e^{\alpha_i} \qquad \text{Equation 8.}$$

The latter two models were compared to the base Ricker model to evaluate the extent of evidence for a smolt-adult marine survival effect on recruitment, and the effect of density-dependence on recruitment, respectively.

For all models, parameter estimates for α, β and γ was obtained by through Bayesian estimation and assumed that observations of log(R/S) were normally-distributed random variables (~norm) with means predicted by recruitment models described above,

$$\log(\frac{R_{i,bt}}{S_{i,bt}}) \sim norm(\log(\frac{\hat{R}_{i,bt}}{S_{i,bt}}), \tau_i) \qquad \text{Equation 9.}$$

where (τ_i) is the estimated precision (inverse of variance).

When populations share common demographic parameters, hierarchical Bayesian modeling (HBM) enables information to be shared among populations which leads to less uncertainty in stock-recruitment parameters. In our hierarchical stock-recruitment model, stock-recruit data for all CUs in the IFC MU are used simultaneously to estimate parameters for individual CUs as well parameters that define the hyper-distribution from which CU-specific values of productivity

arise. To do this, parameter estimates α_i for each CU were drawn from a normal hyper-distribution,

$$\alpha_i \sim norm(mu_\alpha, tau_\alpha) \qquad \text{Equation 10.}$$

where mu_α and tau_α represent the mean and precision of the normal hyper-distribution describing the variation in log-productivity among CUs. These hyper-parameters are estimated during model fitting. Estimates of τ_i and β_i for each CU were assumed to be independent and γ was estimated as a single common parameter across CUs. For comparative purpose we also fit the base Ricker model (Equation 1.) assuming the α_i's were independent to evaluate the effect of the HBM structure.

The SOG stock-recruitment analysis was based on Black Creek data for brood years 1986-2012 (Table 3) and based on smolt-adult marine survival rates for the SOG_H hatchery indicator stock (Table 4). The correlation between Black Creek and SOG hatchery indicator marine survival for return years 1986-2015 is 0.90. As there is only data for one population for the SOG MU, we did not need to estimate hyper-distribution parameters and simply estimated α, β, γ and τ.

Selecting the appropriate stock-recruitment function could have influence on the effects of exploitation rate and smolt-adult marine survival rate on conservation performance. The Ricker model leads to better defined and more conservative (lower) estimates of productivity, and hence potentially lower exploitation rates at a given smolt-adult marine survival rate compared to other models. C. Parken (pers. comm) provided the following rationale for the use of a Ricker model for an earlier analysis of IFC data:

> "First, as part of a previous risk analysis Folkes et al. (2005) compared model fit among the hockey stick, Beverton-Holt (BH), and Ricker functions using spawner-smolt recruitment data for IFC and found that the hockey stick model had the lowest fit, whereas the BH and Ricker had similar, better measures of fit. Recently, Walters (2009) examined the productivity patterns for 487 Southern BC Coho Salmon stocks and used simulation to compare the performance of the BH and Ricker functions when fit to data generated by the alternate model. When errors in variables and large time series effects existed, the BH overestimated productivity whether or not it was the correct function. Walters found that the Ricker function underestimated productivity when the true model was the BH function. The Ricker function also produces higher estimates of S_{MSY} than the BH model. Thus, the Ricker function provides more biologically conservative estimates of abundance-based benchmarks than the BH function. Additionally, the basic Ricker function described the adult recruitment patterns for IFC better than the (BH) function during the recent low productivity period (Decker et al. 2014)."

These arguments are reasonable, but a Ricker model is not consistent with the shape of reliable spawner-smolt relationships for 16 coastal Coho populations, which showed no evidence for overcompensation (Korman and Tompkins 2014). Assuming the majority of density-dependence occurs in freshwater, these data suggest spawner-adult recruit data should be modelled using a function form that does not allow overcompensation. In this analysis, we attempted to fit alternate models that do not exhibit overcompensation including Beverton-Holt, logistic hockey stick, Deriso, and power models. Unfortunately there were a number of problems when we fit these models the IFC stock-recruit data owing to the fact that:

1. they allow much more independence between productivity (initial slope) and carrying capacity (asymptote); and
2. there is limited information about productivity in the stock-recruit data.

As a result, productivity estimates from Beverton-Holt and hockey stick models were very high and showed almost no variation among CUs. In addition, the effect of smolt-adult marine survival on productivity was estimated to be near-zero or negative due to the challenge of estimating productivity with uninformative data using these more flexible models. This resulted in the unlikely inference that IFC stocks are highly productive and that productivity is not influenced by smolt-adult marine survival rate. Fits of Deriso (Figure B1) and power (Figure B2) models were better but still resulted in very high and unlikely productivities that would make populations unrealistically resilient to poor smolt-adult marine survival conditions, and exhibit very high exploitation rates at maximum yield.

Due to problems with Deriso and power stock-recruit models forms fit to the IFC data, we used three alternative Ricker models to represent a range of alternate hypotheses about the effects of escapement on recruitment:

Ricker: As shown below, the Ricker model without informative priors on carrying capacity or depensatory mortality fit the data best and therefore represents the relationship in the absence of considering additional information about the nature of the stock-recruit relationship. However this relationship does show overcompensation in recruitment at higher stock size.

Ricker – PriorCap: To minimize over-compensatory dynamics, we fit Ricker models (Equation 1.) with highly informative priors on carrying capacity ($1/\beta_i$) with means that were 1.5-fold larger than the carrying capacities from the base Ricker model (**Ricker**). The 1.5-fold adjustment was the minimum adjustment needed to eliminate overcompensation dynamics over the range of escapements that have been observed since 1998.

Ricker – Dep: To simulate potential depensatory mortality at low stock size, we used the depensatory Ricker model (Equation 5.). As there was no evidence of depensatory mortality in the IFC stock-recruitment data, we did not attempt to estimate δ and instead fixed it at 1,000 spawners per CU. Including this level of depensatory mortality required the use of highly informative priors on carrying capacity ($1/\beta_i$) with means that were 1.75-fold larger than the carrying capacities relative to estimates from the base Ricker model (to eliminate overcompensation dynamics over the range of escapements observed since 1998).

Models were fit using WinBUGS (source code provided in Appendix B.1). Vague priors were used for model parameters except for Ricker – PriorCap and Ricker – Dep cases described above. To fit the Ricker models, we ran the Markov Chain Monte Carlo (MCMC) for 45,000 iterations, discarded the first 25,000 to remove any "burn-in" effects and stored every 10th iteration to reduce autocorrelation. Three chains were initialized from different randomly determined starting points. Convergence of the chains were visually assessed by monitoring trace plots of Markov chains for each parameter, as well as by examining the Gelman-Rubin convergence diagnostics (all Rhat values <1.01).

We computed a number of derived parameters based on the mean estimates of stock-recruit parameters. This included the escapement needed to maximize sustainable yield, (Smsy), the escapement needed to reach Smsy in one generation (Sgen), the equilibrium escapement in the absence of harvest (Seq), and the exploitation rate at maximum sustainable yield (Umsy). These derived parameters were computed by nonlinear search using the ‘optim’ function in the statistical package R (R Core Team 2016).

SIMULATION ANALYSIS

Historical Reconstruction (Retrospective Analysis)

We used estimated stock-recruit parameters and residuals to drive a simulation model that estimated escapement for each CU between 2002 and 2015 for the IFC MU. The objective of this historical simulation was to determine what the historical pattern in escapement to each CU would have looked like under different exploitation histories. The model was initialized with observed escapements (both natural and hatchery-origin fish) to each CU from 1998 to 2001. Recruitment in later years was predicted using the mean values of stock-recruit parameters from posterior distributions for each CU, annual hatchery smolt-adult marine survival rates (common to all CUs), the modelled age proportions (appendix A), and also included in-river losses (e.g., First Nations harvest, brood take, losses at traps). Predicted recruitment for each CU and year was then adjusted based on the CU- and year-specific residuals estimated from the stock-recruit analysis. The predicted recruitment was then harvested to predict escapement to each CU by year, which then was the input to the stock-recruit model to predict recruitment for the next generation. We modelled natural recruitment only and did not simulate the contribution of hatchery-origin fish that spawn in the wild to later recruitment. We compared our predictions to observed escapements that excluded hatchery-origin fish.

We first applied the historical exploitation rates to the recruitment predictions to calculate escapement to verify that the simulation could accurately reflect the historical pattern. We then repeated the simulation under constant exploitation rates of 10%, 20%, and 30% to represent conditions where exploitation was constant at a value close to the historical average for this period (12%), and approximately two- and three-fold higher than the historical average. This retrospective analysis simulates what the escapement pattern would have looked like under historical conditions but with alternate exploitation histories. As we did not simulate or include hatchery production, our evaluation is conservative in the sense that it does not account for the hatchery-origin fish spawning in the wild that contribute to natural recruitment in the next generation. Our analysis assumes that the specified exploitation rates would be accurately achieved in each year (i.e., it does not consider implementation error as the forward simulations do). Source code for the historical simulation is provided in Appendix B.2.

Forward Simulation Analysis

We evaluate the effects of alternate exploitation rates and future hatchery smolt-adult marine survival rates on escapement to each IFC CU and the MU as a whole using a 54-year forward simulation. The model was initialized using observed escapements for each CU from 2013 through 2016 and run for an additional 50 years (2017-2066) over which conservation performance was calculated. We used the average age-at-return proportions for each CU (Appendix A) to determine the fraction of recruitment from each brood returning 3 and 4 years later. For each simulation trial, recruitment was predicting based on a random draw from the joint posterior distribution of stock-recruit parameter values and simulated CU- and year-specific deviates. Simulated deviates reflected the magnitude of interannual deviations for each CU, as well as the extent of covariation in deviates for each CU with the common trend among CUs. In each year of the simulation on a given trial, 3-year geometric mean escapements from each IFC CU and the sum of escapements across CUs were compared to conservation benchmarks to determine the frequency of years in which conservation objectives were reached (also called “conservation performance”). The analysis was repeated over 500 simulation trials and we summarized mean conservation performance as well as the 10% and 90% credible intervals. We simulated smolt-adult marine survival rates ranging from 0.0025 to 0.1 and exploitation rates ranging from 0 to 0.7.The simulations assumed lognormal error in exploitation rates. The extent

of exploitation rate implementation error was estimated based on a comparison of historical annual exploitation rate targets and estimated exploitation rates. The source code for the forward simulation analysis is provided in Appendix B.3.

The conservation benchmarks used in the simulations were previously identified by the IFC Recovery Team (IFCRT 2006):

1. ConObj1: the escapement to each CU that leads to a 95% probability that the 3-year geometric mean escapement to at least half the subpopulations will meet or exceed 1,000 spawners.
2. ConObj2: the escapement to each CU that leads to a 95% probability that the 3-year geometric mean escapement to all subpopulations will meet or exceed 1,000 spawners.

ConObj1 and ConObj2 values for each CU were computed by logistic regression using the same approach as Decker et al. (2014), except that our analysis was CU-specific rather than done for the MU as a whole. Escapement data from brood years 1984-2015 for each CU was assigned a “0” value if the objective was not met in that year (e.g., half or more the subpopulations did not have estimated escapements at or above 1,000 spawners for ConObj1) or assigned a “1” if the objective was met. Logistic regression models were then used to compute the probability that ConObj1 or ConOb2 was met as a function of the total escapement to the CU. The logistic regression coefficients were then used to predict the CU escapement that resulted in a 95% probability of meeting ConObj1 or ConObj2 objectives. These were the CU-specific benchmarks against which the simulated annual geometric mean escapements were compared to determine the probability of achieving each conservation objective.

The short- and one of the long-term recovery objectives for the IFC MU were previously computed to be 20,000 and 40,000 spawners, respectively (IFCRT 2006). These values were based on escapement data from 1974-2003. We repeated the logistic regression analysis used above at the MU-level to determine the total escapement to the MU to achieve a 95% probability that half or all of the sub-populations in each CU would meet or exceed 1,000 spawners. Our analysis was based on data from 1984-2015 and included original estimates of escapement from 1984-1997 for the Fraser Canyon CU used by IFCRT (2006).We did not use these values as benchmarks in the forward simulations, but used the revised short-term MU statistics to interpret results based on the 20,000 spawners benchmark.

In the simulations, 3-year geometric mean escapements from 2017-2066 were compared to ConObj1 and ConObj2 statistics for each CU as well as to the 20,000 (MU-low) and 40,000 (MU-high) short- and long-term objectives, respectively. We also computed an additional MU based aggregate conservation statistic across IFC CUs in the simulations, which was the proportion of years where ConObj1 was achieved simultaneously (i.e., in the same year) in all CUs (ConObj1.5). ConObj1.5 and MU-low metrics therefore represent the same objective, but the former is more internally consistent.

RESULTS

IFC STOCK-RECRUITMENT

Ricker stock-recruitment models without informative priors fit the IFC CU data relatively well (Figure 1). This 'base' Ricker model, which included a hierarchical structure for αi and a hatchery smolt-adult marine survival index (HSASI) covariate, explained between 41% and 68% of the variation in log(R/S) across CUs, compared to 23% to 40% of the variation based on the same model without the survival covariate (Table 6, Model 1 vs. Model 2). The Deviance Information Criteria (DIC) value for this Ricker model was 18 points lower than the model without a covariate effect, indicating strong support for the model that included a HSASI covariate effect. The base Ricker model estimates a total of 18 parameters (5 CUs $\cdot$ (α, β, τ) + γ + 2 hyper-parameters for α). There was modest shrinkage in αi estimates due to the hyper-distribution, as the number of effective parameters (pD) was 14.2 (pD would have been ~18 had there been limited shrinkage). Modest shrinkage occurred because there was somewhat limited information for most CUs about the values of αi, so CU-specific values were influenced by the hyper-distribution. The DIC for the base Ricker model with the hierarchical structure was lower than the DIC from the model where we assumed the α's for each CU were independent (Model 1 vs. Model 3). There was strong support for including density-dependence in the model as the DIC for the base model without HSASI covariate effects was 25 points lower than the same model without density-dependent effects (Model 2 vs. Model 6). The Ricker model with a strong prior on a larger carrying capacity did not fit the data as well compared to the base model, as indicated by its DIC value which was 16 points higher (Model 1 vs. Model 4, Figure 2). Including depensatory mortality (Figure 3) led to a further reduction in fit as seen by the slightly higher DIC (Model 5 vs Model 4). The models with a strong prior on a higher carrying capacity (Ricker – PriorCap) and that also included depensatory mortality (Ricker – Dep) virtually eliminated any overcompensatory effects relative to the base model (Ricker), and depensation was apparent in the latter model (Figure 4). However, as there is no indication in the data of depensatory dynamics, this parameter was fixed at an assumed level of 1,000 spawners for all CUs. Thus predictions based on these models depend completely on this highly uncertain assumption. The aggregate stock-recruitment relationships, computed by summing CU-specific predictions over a range of stock sizes, provided reasonable fits to the noisy aggregate spawner-recruit data (Figure 5).

The mean value of the HSASI covariate coefficient (γ) for the base Ricker model (uninformative priors) was 0.52, indicating that maximum productivity increases with the index (Table 7). Although there was some uncertainty in this estimate (95% confidence interval 0.31-0.75), the minimum value of the posterior distribution (0.12) was well above zero. The γ parameter distribution is consistent with the DIC result which supported the HSASI covariate model. Mean γ was 0.16 and 0.13 for Ricker models with higher carrying capacity and depensatory mortality, respectively. These lower values relative to the base Ricker model indicate a decreasing effect of smolt-adult marine survival rates on productivity, which seems unlikely. This dynamic, combined with the poorer fit, suggest that these models are less likely than the base model, and their results should be used with caution.

Exploitation rates which maximized yield (Umsy), which are solely dependent on α' (Equation 3.), ranged from 0.36 (South Thompson) to 0.42 (Fraser Canyon and North Thompson). The carrying capacity for smolts was computed by dividing the maximum adult recruits from the estimated stock-recruitment relationship by the product of the smolt-adult marine survival rate and the number of kilometers of accessible stream that could potentially be Coho habitat. Smolt capacities ranged from 215/km for the Middle Fraser CU to 2,852/km for the Fraser Canyon CU.

Values for Thompson River CUs ranged from 925-1,305 smolts/km which were close to the estimate of 1,500 smolts/km from the Korman and Tompkins (2014) meta-analysis of data from 16 coastal Coho Salmon populations.

As intended, the Ricker model with informative priors for larger carrying capacity (Ricker – PriorCap) led to carrying capacity estimates that were close to 1.5-fold higher than those from the base Ricker model ("Seq" in Table 7). This in turn led to substantively lower productivity and Umsy estimates. The latter ranged from 0.26-0.34 compared to 0.36-0.42 from the base model (Ricker). The depensatory model had even higher carrying capacities and lower Umsy values owing to the higher informative prior on carrying capacity in conjunction with the depensatory assumption. Note that productivity is near zero at 1 recruits spawner owing to the depensation term ($\delta = 1/(1+1000) \approx 0$).

Residuals from the stock-recruitment curve represent the amount of variation in log(R/S) that cannot be explained by the model (Figure 6, Table 8). Because the model includes a smolt-adult marine survival covariate effect, this residual variation reflects the extent of variation in freshwater survival as well as smolt-adult marine survival variation not represented by the IFC MU survival index. The extent of residual variation can be visualized by comparing the distance between the stock-recruitment data points and predictions of their values as represented by the vertical lines in Figure 1-Figure 3. Positive residuals around the curve (points above the stock-recruitment curve) with vertical lines extending towards those points represent years when the HSASI covariate value was higher than average. In these cases, the model makes the correct prediction that recruitment would also be higher than average given the brood escapement. Cases where data points are above the curve but where vertical lines do not extend in a positive direction, or extend in a negative direction, indicate that freshwater survival for the brood was much higher than average, or that the smolt-adult marine survival index was relatively too low compared to the change in survival for naturally-produced smolts. Assuming the IFC MU smolt-adult marine survival index accurately represents interannual variation in survival rates, this visual analysis indicates that there can be substantive variation in freshwater survival rates. There was no long-term trend in residuals from the stock-recruitment curves with the exception of the Lower Thompson CU.

We computed the mean of residuals across CUs for each year to provide an aggregate index of deviations (thick black line in bottom right plot of Figure 6, IFC column in Table 8). The trend of the aggregate residuals was well correlated with CU-specific residual patterns, with Pearson 'r' values ranging from 0.57 (Lower Thompson) to 0.96 (North Thompson). This covariation is likely driven in part by common effects of weather or hydrology on freshwater survival rates or common variation in the extent of departure between the actual smolt-adult marine survival rates for wild Coho from each CU and the IFC hatchery survival index. The lag-1 autocorrelation among residuals, which indexes the extent of any temporal trends, were low, with values of 0.08, 0.34, 0.59, 0.01 and -0.02 for Middle Fraser, Fraser Canyon, Lower Thompson, North Thompson, and South Thompson CUs, respectively, and with an overall mean of 0.2. This result is expected because the HSASI covariate model removes autocorrelation caused by long-term patterns in smolt-adult marine survival. The higher autocorrelation for the Lower Thompson reflects the low-to-high pattern observed in the residuals (Figure 6).

To demonstrate the effect of the smolt-adult marine survival rate index on the stock-recruitment relationship, we plotted the relationship for the Middle Fraser CU assuming rates of 1% and 5% (Figure 7). As the covariate only affects maximum productivity, higher survival results in an increase in the initial slope of the relationship, but not the stock size that maximizes recruitment ($1/\beta$). However, as the equilibrium escapement (where the curve crosses the 1:1 line) and the stock size that maximizes yield (Smsy) depend on both α and β (see equations in notes for

Table 7), these derived quantities are greater under higher survival rates. Sgen actually declines with increases in smolt-adult marine survival because productivity is higher.

Logistic regression was used to determine the escapement to each CU that ensured that half (ConObj1) or all (ConObj2) of the subpopulations in the CU have an escapement of at least 1,000 fish (Figure 8). In the case of the short-term recovery objective (ConObj1), conservation limits ranged from 1,000 (Fraser Canyon, where only one subpopulation is present) to 3,670 (North Thompson, where 3 subpopulations are present, Table 9). Note that for the North Thompson CU, escapement has been greater than 1,000 spawners for two of three subpopulations in all years since 1984. In this case, it was not possible to estimate logistic regression parameters because there were no occurrences of 0 (years when there were less than 1,000 spawners in 2 of 3 subpopulations). Here we used the minimum escapement to the CU since 1984 for ConObj1. Long-term recovery objectives (ConObj2) were much larger than short-term objectives, and exceeded estimates of equilibrium escapement from the base Ricker model at the historical (1998-2015) hatchery smolt-adult marine survival rate for Lower, North, and South Thompson CUs. This indicates that under the current low survival rate conditions, the long-term recovery objectives cannot be met even in the absence of any exploitation.

Logistic regression-based estimates of escapement to the IFC MU to achieve a 95% probability of meeting short- and long-term objectives were 28,000 and 91,000 spawners, respectively (Figure 9). The former value is a bit higher than the 20,000-25,000 range from the recovery team (IFRCT 2006). The difference is caused by differences in the data and time period analyzed (1973-2003 for IFRCT values vs. 1984-2015 data used here) as well as our use of logistic regression compared to the less formal approach in IFCRT (2006). The IFCRT estimate is based on the observation that the minimum escapement where one of the long-term objectives has been met is approximately 40,000. Our forward simulation analysis uses an escapement of 20,000 to the MU as a whole as a short-term conservation benchmark rather than our new estimate of 28,000. This provides a measure of performance relative to a previously accepted value. Performance based on our ConObj1.5 measure provides an alternative measure that is more consistent with the short-term recovery objective.

The exploitation rate that maximizes yield (Umsy) increases with smolt-adult marine survival rate owing to the increase in stock productivity via α' (Equation 3., Figure 10). Uncertainty around the isopleth was considerable owing to uncertainty in α and γ estimates which determine uncertainty in α', and hence, Umsy. The annual combinations of survival rate and exploitation rate (points on Figure 10) show that the IFC MU was exploited at near optimal rates until brood year 1988. Exploitation rates exceeded Umsy in most brood years between 1989 and 1993 because they were too high given the sudden decline in marine survival (see Figure 13). Since the fishery closure in 1998, exploitation rates have generally been well below the estimates of Umsy.

IFC SIMULATIONS

The historical simulation accurately predicted the observed escapement when driven by historical exploitation rates (Figure 11). In CUs with hatchery contributions, and most noticeably in the Lower Thompson where hatchery contributions are greatest, observed escapements (excluding hatchery returns) were greater than predictions. This occurred because the stock-recruit model only predicts natural production. Hence hatchery-origin fish which spawn in the wild do not contribute to recruitment in the model. The discrepancy was low for the first three years of predictions (2002-2004) because the escapements used to initialize the model (for brood years 1998-2001) do include hatchery-origin fish. Thus the difference between the dashed and sold lines in Figure 11 represents the contribution of hatchery-origin fish to natural recruitment in the next generation. The probability of exceeding short-term conservation

objectives (ConObj1) for each CU and for the MU as a whole predicted by the historical simulation was very close to observed values (Table 10).

We then replaced the historical exploitation rates used in the historical simulation with assumed values of 10%, 20%, and 30% (Figure 12). As expected increasing the exploitation rate resulted in lower escapements. There was a reduction in conservation performance (ConObj 1) from 71% to 50% when moving from a 10% to 20% exploitation rate, and a further reduction to 43% when the exploitation rate was increased to 30% (Table 10). Increased exploitation in any year caused a decline in escapement in that year, but the effect on the next generation was reduced due to compensatory mortality (i.e., density-dependent mortality). In the final generation of the simulation the average MU escapement was estimated to be 31,016, 26,849, and 22,176 for scenarios of 10, 20, and 30% exploitation respectively. The historic simulation indicates that stock status as defined by the IFCRT (2006) short-term conservation objective (20,000 spawners) would have been very similar over the last 15 years had the IFC MU been fished at an exploitation rate of 20% compared to the historical average of 12%. This is not surprising given the productivity estimates from the 1998-2012 stock-recruit analysis (Table 7). The historical simulation also demonstrates that the vast majority of variation in escapement since 1998 has been driven by variation in smolt-adult marine survival and unexplained variation around the stock-recruitment curves. Variation in escapement across the range of simulated exploitation rates was very modest relative to these other sources.

Smolt-adult marine survival rates from four index populations or aggregates showed substantial declines between the early 1980s and the early 1990s (Figure 13). Survival was lower in the mid-1990s but the averages were higher than averages after 1998. Eighty percent of the variation in the smolt-adult marine survival rate for wild Coho from Black Creek could be explained by the SOG_H hatchery index. This suggests that hatchery survival indices, while lower than for wild stocks, are useful for explaining variation in wild recruitment (as also supported by our stock-recruitment analysis). It is important to note that underestimation of the smolt-adult marine survival rate for wild fish based on the hatchery index will not result in a bias in productivity estimates, because the bias is absorbed by the constant (α) in Equation 2. Total recruitment to the IFC MU varied with the hatchery smolt-adult marine survival rate with recruitments over 100,000 usually occurring when the survival rate was greater than 4% (Figure 14). The pattern in this plot would support using breakpoints of 2% and 4% to separate low, moderate, and abundant status categories. Representative survivals for low, moderate, and abundant status categories would logically then be set at 1%, 3%, and 5%, respectively.

Forward simulations require estimates of harvest implementation error to simulate uncertainty about attaining target exploitation rates. (Target) ER objectives for the IFC MU were 13% from 2001-2013, and between 15 and 26% between 2014 and 2016 (Figure 15). Realized ERs as computed by the FRAM model ranged from 6.2 to 13.9% from 2001-2013, and 13-31.8% from 2014-2016. There was no evidence that there is a tendency to overexploit when ER objectives were higher, at least over the ranges experienced since 2001. Discrepancies between target and realized exploitation rates for the IFC MU were quite limited and ranged from -7 to 6% (top left histogram in Figure 16). Assuming lognormal error in exploitation rate implementation, a standard deviation of 0.2 provided sufficient variation in realized exploitation rates to cover the range of discrepancies seen in the historical data (Figure 16, SD=0.2). However, as there is uncertainty in estimated exploitation rates, we also conducted a sensitivity analysis of implementation error on predictions of conservation statistics (see results below).

Our approach to modelling deviation from stock-recruitment relationships for the forward simulations (Appendix B.3) accurately modelled temporal variation as well as the extent of correlation of residuals from each CU with the aggregate trend (Table 8). As expected, forward simulations demonstrated that the probability of attaining conservation objectives declines as

smolt-adult marine survival decreases, or as exploitation rate increases (Figure 17a). Variation in performance among CUs was driven by small differences in productivity as well as larger differences in the conservation limits relative to estimated carrying capacities ("Seq/ConObj1" row, Table 7). The steepness of the contour surface depends largely on the productivity of each CU. Conservation performance will be lower as the benchmark approaches the equilibrium stock size. For example, the long-term recovery objective for the South Thompson CU is about 16,000 spawners, which is about 2-fold larger than the predicted escapement in the absence of exploitation ("Seq" row, Table 7). As a result this CU had the lowest probabilities of meeting the ConObj2 objective (Figure 17b).

The conservation performance for the IFC MU was assessed as a whole based on recovery objectives of 20,000 and 40,000 spawners (IFCRT 2006) by summing the CU-specific simulated escapements (Figure 17c). Under the historical average exploitation and smolt-adult marine survival rates (black point in Figure 17c), the lower conservation limit is achieved about 85% of the time, and declined to 35% under an exploitation rate of 30%. The historical conservation performance for this benchmark excluding returns of hatchery-origin fish (57%, Table 10) was much lower than the value from the forward simulations, but most of the failures in the historical data were very close to the 20,000 threshold (Figure 11) so this difference is not concerning. The upper IFC MU limit of 40,000 was more challenging to achieve, requiring a combination of high smolt-adult marine survival and low exploitation (Figure 17c). Conservation performance for the ConObj1.5 objective, which is the probability that escapement to each CU is sufficient for at least half of the subpopulations to have at least 1,000 spawners (with a 95% probability) in the same year, was slightly lower than values based on the 20,000 spawner objective. ConObj1.5 probabilities are similar to statistics based on an MU threshold of about 25,000 (results not shown for brevity). Note our logistic regression analysis indicated that an MU escapement of about 28,000 is required to meet that short-term objective (Figure 9).

At a given survival rate, lower exploitation rates are required to achieve increasing probabilities of meeting a conservation benchmark (Figure 18). For example, at a smolt-adult marine survival rate of 1%, exploitation rates that result in a 0.25, 0.5, and 0.75 probability of obtaining the ConObj1.5 benchmark were about 0.35, 0.25, and 0.15, respectively. Tabular results for all the data used for the MU>20,000, ConObj1.5, and MU>40,000 benchmarks are provided in Table 11, Table 12, and Table 13, respectively. Conservation performance based on the Ricker model with higher carrying capacity (Ricker-PriorCap) was lower than for the base model, and conservation performance based on the model with assumed depensation (Ricker-Dep) was even lower (Figure 19).

There was considerable uncertainty in predicted conservation performance due to uncertainty in estimates of stock productivity (Figure 20). The extent of uncertainty was highly variable among CU's. Uncertainty was generally low at low (<0.2) and high (>0.6) exploitation rates, but quite large at intermediate levels. In the simulations, each trial was based on a random draw of stock-recruit parameters from the posterior distribution. In cases where the uncertainty in productivity is relatively modest (e.g. Lower Thompson; Figure 1), the uncertainty in conservation performance is also modest (Figure 20), while the opposite is true when uncertainty in productivity is high (e.g. Fraser Canyon). The extent of uncertainty in productivity is determined by the number of stock-recruit points at low stock size and the pattern in those points. The Lower Thompson CU has a number of low stock size observations and the lowest escapements also have low recruitment, which leads to more certainty in productivity. In contrast, the Fraser Canyon CU shows a horizontal scatter of stock-recruit points so there is little information about productivity in this case.

The sensitivity of conservation performance to harvest implementation error was modest and depended on smolt-adult marine survival rate (Figure 21). When survival rate was low, there

was little effect of harvest implementation error because predicted escapements are, on average, close to the short-term recovery objective. Under these circumstances, the effect of lower harvest rates resulting from under-harvesting (relative to the objective ER) on conservation performance is balanced by over-harvesting effects. However, when productivity increased under higher smolt-adult marine survival, average escapements become much higher than the short-term conservation objectives. Under these conditions and with higher exploitation rates, increasing the frequency of over-exploitation at higher levels of harvest implementation error results in poorer conservation performance because it is not balanced by under-exploitation effects.

SOG STOCK-RECRUITMENT

Korman and Tompkins (2014) estimated that maximum productivity for Black Creek was about 74 smolts/spawner which was very close to the average across 16 coastal populations of 71 smolts/spawner (Table 14). Black Creek therefore appears to have a pretty typical productivity and it is reasonable to assume it is representative of the mean for populations in the SOG MU. However, the capacity of Black Creek to produce smolts at high stock size (3,081 smolts/km) was about two-fold higher than the average across the 16 populations.

The Ricker-marine survival covariate model fit Black Creek data reasonably well as it explained 49% of the variation in log recruits/spawner (log(R/S); Table 15; Figure 22). The SOG_H smolt-adult marine survival rate was a useful predictor as the base Ricker model without a hatchery smolt-adult marine survival index (HSASI) covariate explained only 27% of the variation. This model has a DIC of 68.4 compared to 62.4 for the model with the HSASI covariate. Ricker models with higher carrying capacity fit the data almost as well as the base Ricker model (r^2 = 47%, DIC=63.2). However, the fit of the Ricker model with larger carrying capacity and depensatory mortality was poor (r^2 = 13%, DIC=75.2). Deriso and power models fit the data marginally better than the base Ricker model. They explained a bit more than 50% of the variation in log(R/S) and had the lowest DIC values.

Although Deriso and power models fit the data best, they generated productivity estimates of 4 and 77 recruits/spawner, respectively. They also predicted Smsy values that were 0.56-, 0.37-, and 0.26-fold lower than values from the Ricker, Ricker-PriorCap, and Ricker-Dep models, respectively. This occurred because of their higher productivities combined with their much lower estimates of carrying capacity compared to the Ricker models. All models had adequate patterns in residuals, showing no temporal trends (Figure 23) and predicted a substantive effect of increased smolt-adult marine survival on the stock-recruitment relationship (Figure 24).

The productivity and Umsy estimates for the Ricker and Ricker PriorCap models (productivity=2.9, 2.5; Usmy=0.46, 0.40 respectively; Table 15) was based on the geometric average smolt-adult marine survival rate of 1.42% over the Black Creek stock-recruit record (brood years 1986-2012). Using survival data for only brood years 1998-2012, for comparability with the IFC analysis, results in a geometric average survival rate of 0.84%, a productivity of 2.3 and 2.0 recruits/spawner and a Umsy of 0.37 and 0.32 for the Ricker and Ricker PriorCap models respectively.

DISCUSSION

MU PRODUCTIVITY

Based on the base Ricker model without informative priors, our estimates of productivity at low stock size for IFC CUs for brood years 1998-2012 ranged from 2.2 – 2.6 recruits per spawner. These productivities result in optimal exploitation rates (Umsy) ranging from 36% to 42%. This

result is surprising as the IFC stock-recruit analysis was limited to a period of low marine productivity (geometric average smolt-adult marine survival rate of 1.1%). Black Creek productivity and Umsy based on the Ricker model without informative priors was estimated to be 2.9 recruits/spawner and 46%, respectively. However, these values were based on data from brood years 1986-2012 and included years with high smolt-adult marine survival (geometric average =1.43%). Using productivity estimates based on the geometric average SOG_H smolt-adult marine survival from brood years 1998-2012 (0.84%) for comparability with the IFC analysis lowered productivity and Umsy to 2.3 recruits/spawner and 37%, respectively. IFC and the SOG indicator therefore have similar productivity and will respond similarly to a common exploitation rate. Both IFC and Black Creek stock-recruit analyses indicate that exploitation rates that achieve MSY are about two-fold higher than those that have occurred since the 1998 fisheries closure. This result seems counterintuitive given the low smolt-adult marine survival estimates since 1998, and we therefore discuss potential biases and explanations for this result in the following paragraphs.

Assuming the IFC MU survival rate index provides an unbiased estimate of survival for naturally produced smolts, our range of maximum adult recruits/spawner translates to about 200 (2.2/0.011) to 240 (1.6/0.011) smolts/spawner. These values seem unlikely and imply egg-smolt survival rates of about 30% given fecundities of approximately 1500 eggs/female (equivalent to about 750 eggs/spawner; Irvine et al. 1999). Korman and Tompkins (2014) meta-analysis of 16 coastal Coho Salmon populations (with well-determined escapement and smolt production data) estimated a mean productivity of approximately 50 and 70 smolts/spawner based on Ricker and Beverton-Holt models, respectively. Thus, our back-calculated estimates of freshwater productivity for IFC are about 4-fold higher than what has been observed for coastal populations. Back-calculated smolt production for Black Creek was also much higher than observed maximum values. Given these discrepancies, we conclude that we have either overestimated productivity for IFC CUs and Black Creek based on the adult spawner-recruit data, or more likely, that hatchery-based smolt-adult marine survival indices substantially underestimate survival rates for naturally produced fish. The latter is supported by Zimmerman et al. (2015) who found in their analysis of Coho marine survival in the Salish Sea, that "…*across all regions, annual smolt survival was consistently higher for wild than hatchery Coho Salmon*.

Our moderate estimates of productivity (in spite of low smolt-adult marine survival) are not caused by errors in our stock-recruit analysis, and are not unique to this analysis. Estimates of productivity for IFC CUs based on the HBM smolt-adult marine survival covariate model were very similar to those based on the much simpler model presented here, where parameters were estimated independently for each CU without or without a marine survival covariate. This latter result was also seen in the Black Creek analysis. Thus our conclusions about productivity are not an artefact of using a hierarchical model or including a smolt-adult marine survival covariate. Our results for IFC productivity are lower than those from recent efforts (Decker et al. 2014), largely because recruitment estimates used in our fitting accounted for the varying age-4 component in the escapement and excluded hatchery-origin fish.

The next logical question is whether recruitment estimates have been overestimated, leading to an overestimate of productivity in our stock recruitment analysis as well as others (Decker et al. 2014; C. Parken pers. comm.). Recruitment is calculated based on the sum of escapement and estimated catch (and does not include mortality due to catch-and-release in mark-select fisheries). Escapement data for IFC collected since 1998 are considered relatively robust as are data from Black Creek for the period of record. However, there is considerable uncertainty in estimates of exploitation rates used to calculate catch and hence recruitment (C. Parken pers. comm.). Overestimation of historical exploitation rates would lead to overestimates of

recruitment and hence overestimation of productivity. However the extent of such a bias would be relatively small in the case of South Coast Coho Salmon given that the average historical exploitation rate since 1998 has been very low (11.8% for IFC, 4.4% for Black Creek). Under low exploitation, recruitment is largely determined by escapement since catch contributes a small proportion to the overall recruitment. As a result, overestimation of the exploitation rate results in only a small positive bias in productivity. For example, if the true historical exploitation rate had been 5% but had been estimated to be 12%, recruits/spawner would have been overestimated by less than 7%. Hence, error in exploitation rate estimates since 1998 could not have led to a major positive bias in productivity and Umsy estimates.

The only remaining cause for moderate productivity under the current low smolt-adult marine survival rates for hatchery indicator stocks, is a potential bias in these survival rates relative to those for wild populations. The historical geometric average for wild Coho from Black Creek (3.4%) was two-fold higher than the SOG_H hatchery rates (1.7%). In addition, the expansions of coded wire tag (CWT) recoveries on the spawning grounds or in the catch could be too low, which would also result in an underestimation of smolt-adult marine survival rates for both hatchery and wild populations. It may be more than coincidence that there is a substantive and permanent drop in marine survival rates in the same year the IFC fishery closures were implemented (Figure 13). If CWT recoveries in the sport fishery are underreported relative to those in the commercial fisheries, reducing commercial catch due to the 1998 commercial fishery closures would have led to an increase in overall underreporting which in turn would have led to lower marine survival estimates. Note that a consistent bias in smolt-adult marine survival rates over time does not lead to a bias in the stock-recruitment parameters or benchmarks presented here. For example, if survival rates were scaled-up to more accurately reflect those for naturally produced smolts or to account for reporting rate issues, α and γ values in Equation 1 would change but lead to identical values of α' relative to those estimated with the existing marine survival rates. That is, estimates of α_i absorb bias in smolt-adult marine survival rates. Thus, the likely bias in the magnitude of smolt-adult marine survival rates does not affect the stock-recruit parameters or the productivity or Umsy estimates presented here. However, when using these parameters to make predictions about effects of alternate exploitation rates to be applied in the future, it is essential to use the same survival index used in the fitting when predicting future survival rates that are input to the model. And if changes to the fishery are made that result in a false impression that survival rates have increased (due to a reduction in reporting bias), this could lead to the incorrect decision to increase exploitation rates. Additional work on reporting bias in smolt-adult marine survival rate estimation is therefore highly warranted.

RETROSPECTIVE ANALYSIS OF INTERIOR FRASER MU

The retrospective analysis for the IFC CUs demonstrated that the current target exploitation rate of about 12% has led to a 6% and 21%increase in escapements relative to what would have occurred under higher exploitation rates of 20% and 30%, respectively). The majority of variation in escapement since 1998 has been driven by variation in smolt-adult marine survival rates or other residual variation. This is an important and potentially controversial result as it implies that similar conservation performance could have been achieved with an exploitation rate of 20%. Limited increases in spawner abundance despite decreasing exploitation are caused by the modeled density-dependent survival in the freshwater nursery phase that is nearly always observed in Coho Salmon populations. In the long-term, escapement will not increase linearly with a decrease in exploitation rate because the immediate increase in escapement due to lower exploitation will be countered by increased density-dependent mortality causing smolt production to be limited, even at the modest escapements observed beginning in 1998.

Our simulation analysis quantifies the relationship between the frequency of meeting conservation objectives and smolt-adult marine survival and exploitation rates. Once decision-makers define a minimum conservation performance target (e.g., a 75% chance of meeting the target), the exploitation rate that meets that objective can be determined at a projected smolt-adult marine survival rate. We provided conservation statistics for a number of benchmarks, but recommend using those for ConObj1.5. This metric is consistent with the short-term objective for the IFC MU from the IFC Recovery Team (2006). In their 2006 report, they provided a short-term benchmark of 20,000 which had slightly lower conservation performance compared to ConObj1.5. Differences in conservation performance between the two benchmarks occurred because 20,000 spawners is not sufficient to meet the short-term conservation objectives 95% of the time as shown by our logistic regression analysis.

VARIATION IN PERFORMANCE AMONG ALTERNATIVE RICKER MODELS

There was considerable variation in conservation performance among alternate Ricker models. For example, at 1% smolt-adult marine survival, exploitation rates that result in a 50% probability of meeting the ConObj1.5 objective were about 25% and 5% for Ricker and Ricker-PriorCap models, respectively, and were not attainable for the Ricker-Dep model. The Ricker-PriorCap and depensatory models did not fit the data as well as the Ricker model without informative priors, and are not consistent with the fact that IFC escapements have not declined over the last 20 years under an exploitation rate averaging 12%. In addition, Bradford and Irvine (2000) concluded the decline in IFC productivity was not due to density-dependant mortality in fresh water. However, Chen et al (2002) found their Allee effect parameter, indicating depensation, was significant for the 1975 to 1999 North Thompson coho data. The fact that juvenile Coho Salmon produced in tributaries disperse into larger mainstem environments does not imply that overcompensation is not possible, as such effects could manifest during spawning and emergence when densities can be high in localized areas. From a statistical perspective, we therefore recommend that decision-makers use results based on the Ricker model without informative priors.

STRAIT OF GEORGIA AND LOWER FRASER MU DATA DEFICIENCIES

Decision-makers must also face the challenge of setting exploitation rates for SOG and LFR MUs without the benefit of a simulation exercise describing how exploitation and smolt-adult marine survival affects conservation performance. Such simulations were not possible for these MUs owing to the lack of conservation benchmarks and stock-recruitment data from a sufficient number of populations in each component CU. Our analysis suggests that Black Creek may represent the mean for intensively studied coastal populations (given that it was close to the mean for 16 coastal populations), but there are no data describing the variation in productivity across populations in the SOG MU and how well Black Creek represents these SoG populations. The only defensible conclusion to be drawn from this analysis regarding the SOG MU is that exploitation rates of 30% or lower at the average smolt-adult marine survival rate since 1998 are unlikely to cause harm to Black Creek. Black Creek productivity was similar to that for IFC MUs, indicating that a common approach to exploitation rate management may be appropriate. All that can be said for the LFR MU is that the trend in smolt-adult marine survival rate for the hatchery indicator stock is similar to those for SOG and IFC. However, without any stock-recruitment data for the LFR MU, no statements can be made about the effect of various exploitation rates on conservation.

STOCK RECRUITMENT VS CONSERVATION BIOLOGY

Our work identifies a major difference in predictions about effects of exploitation rate on South Coast Coho Salmon populations based on stock-recruitment data and theory versus conservation biology data and theory. The stock-recruitment analyses indicate that IFC and SOG populations are sustainable at exploitation rates of about 40% under the low smolt-adult marine survival rates that have persisted since the mid-1990's. There is no evidence of depensatory mortality in the stock-recruitment data collected over this period and hence no empirical rationale from these data that low stock size reduces the viability of the populations. However, stock-recruitment analysis assumes that each CU is a single panmictic population of uniform productivity and there are no consequences to population diversity associated with declines in abundance. In contrast, much lower exploitation rates are required to meet conservation benchmarks defined by conservation biology arguments made by the IFCRT (2006) as these benchmarks were designed to minimize risks to population diversity within each CU. In a population dynamics context, these benchmarks should identify potential depensation points on the stock-recruitment curve below which CU recovery, in terms of total abundance and diversity, is much reduced. There are a few stock-recruit points at or just above short-term recovery objective values and there is no evidence of depensation at these escapement levels. Further, an explicit indicator of within-CU diversity has not been developed. Thus, exploitation rates set based on a desired frequency of attaining short- or long-term conservation objectives require that decision makers implicitly acknowledge the relation between those objectives and maintenance of genetic and ecological diversity as set out by the PST and Wild Salmon Policy (WSP). Further analysis of the relation between measures of within-CU diversity and the stock-recruit relation may help to resolve differences between approaches to setting benchmarks. For the SOG MU, benchmarks comparable to the IFCRT conservation benchmarks have not been developed. Stock-recruitment derived parameters were calculated for Black Creek (Table 15) and could be used as described in Holt et al 2009 but the applicability of the Black Creek derived parameters to the SOG MU is unknown.

IMPLEMENTATION CONSIDERATIONS

The work presented here does not address challenges associated with implementing exploitation rates higher than what has occurred since 1998. The forward simulations included implementation error in exploitation rate, but the post-season estimates of exploitation used to define that error are highly suspect. Simulation results identified a challenge associated with using three population status levels to set exploitation rates. For example, there were large differences in conservation performance within the range of survivals for our example "low" status category (0-2%). Alternative status class breakpoints might consider the shape of the exploitation-survival rate isopleths to minimize variation in conservation performance within each class. Another challenge is determining the status category for an MU each year. As there are no reliable models predicting those survival rates, decision-makers will likely have to rely on a time-series model or simpler assessments, such as moving averages. The performance of alternate status categories and methods to assign status class each year could be investigated by simulation and would build on the work presented here.

The research document provides a robust framework for evaluating the conservation performance of alternative benchmarks given uncertainties about population dynamics (i.e., alternative stock-recruitment model forms), smolt-adult marine survival rates and exploitation rates. Examples are provided to illustrate how the results from this framework could be used to inform the development of PST reference points for low, moderate and abundant status; however, the paper does *not* provide a formal recommendation on reference points to use for management purposes. The selection of management reference points will need to consider

input from government, First Nations and stakeholders on what will be considered “acceptable” probabilities of achieving conservation outcomes given the uncertainties.

CONCLUSIONS AND ADVICE

This analysis is intended to evaluate potential management implications of alternative approaches for setting management reference points to establish low, moderate and abundant status zones under the PST and associated allowable fishery exploitation rates.

The S-R and simulation-based methods described in this assessment provide a useful means to inform decision makers of the relationships between productivity, exploitation rates, and ability to meet policy-driven objectives for fishery management for the IFC MU. Given limitations of the available data, the methods are sufficiently robust to examine effects of uncertainty and produce information to help evaluate implications for consideration of alternative fishery exploitation rates and risks to achieving conservation objectives. At this time, no analytically derived method to define smolt-to-adult survival rate management reference points to demarcate low, moderate and abundant PST status categories has been established, although visually the data suggest breakpoints of 2% and 4% to demarcate the three status levels.

The likelihood of achieving a suite of conservation objectives across a range of smolt-to-adult survivals and fishery exploitation rates for IFC has been provided through a series of tables (Tables 11-14, one table for each combination of assumed S-R dynamics and conservation objective), It is critical to note that this assessment of conservation performance is particularly sensitive to changes in exploitation rate at low smolt-to-adult survival rates, and that the inherent data uncertainties are likely too large to fully discern these sensitivities at this time.

Given the uncertainties associated with the S-R data, there are several S-R model forms that might be used to represent true underlying Coho Salmon population dynamics (Figure 5, Figure 22). In the context of this analysis, the choice of S-R model influences the estimation of exploitation and smolt-to-adult survival rates, as well as the resulting forward simulations of potential conservation performance. As a result, determination of management reference points and allowable fishery exploitation rates cannot be determined solely from the scientific advice provided here.

Ultimately, the choice of management reference points and associated allowable fishery exploitation rates will require input from government, First Nations and stakeholders on acceptable probabilities of achieving conservation outcomes given the known data gaps and uncertainties.

At this time, it is not possible to use the forward simulation tool on data-limited MUs (e.g., SOG and LFR MUs), and it would take a considerable investment of time and program funds to re-instate or establish suitable indicator stocks and smolt-to-adult survival indices. In the short term, additional work is recommended to investigate the extent to which IFC CUs with similar productivities could be used to represent the data-limited MUs. Further, a comprehensive sensitivity analysis is recommended to better understand how sensitive the S-R parameters are to changes in the underlying population dynamics.

A number of data limitations and assumptions were identified (Tables 5a and b). Key sources of uncertainty and bias include:

- Exploitation rates: uncertainty about how representative the base period is to the current period given substantial changes in fisheries (e.g., from Coho-directed fisheries to release of wild fish in most areas); unreported catch, drop-off and release mortality not fully accounted for.

- Escapement data: survey qualities vary over time and space; only relative measures of abundance (rather than true abundance) are available for some streams.
- Hatchery smolt-to-adult survival: sample size of recovered marked fish is insufficient to give accurate estimates of the proportion of hatchery fish present; potential for hatchery fish to stray to unenhanced streams; representativeness of hatchery smolt-to- adult survival indices for wild stocks; uncertain numbers of coded wire tags (CWTs) released, due to predation after tagging but prior to release.
- Stock-recruit relationship: biases in escapement and exploitation rate time series carry forward to the S-R analysis, affecting the ability to fit and select a suitable model.

These sources of uncertainty are also suspected to vary in direction and magnitude between populations and across years. As such, it is recommended that the assumptions and findings of this assessment be re-evaluated as new research becomes available, in particular with respect to estimation of in-river and marine exploitation rates and smolt-to-adult survival indices.

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TABLES

Table 1. Stock-Recruit data for Interior Fraser Coho (IFC) Conservation Units and other information used in the stock-recruit and retrospective analyses. Byr, Esc, Rec_t, Rec_A3, and RecA4 denote brood year, escapement, total recruitment from that brood, and recruitment for age-3 and -4 year returns, respectively. S_ and ER_ denote age-specific, hatchery-based smolt-adult marine survival indices (the IFC marine survival index) and the age-specific exploitation rate, respectively. These vary by age-at-return because these fish enter the ocean as smolts and return in different years.

Middle Fraser

Byr	Esc	Rec_t	Rec_A3	Rec_A4	S_A3	S_A4	ER_A3	ER_A4
1998	4,851	6,294	5,882	411	0.038	0.037	0.071	0.078
1999	1,652	4,318	3,965	353	0.037	0.010	0.078	0.129
2000	3,920	4,379	4,020	358	0.010	0.012	0.129	0.131
2001	6,162	5,517	5,122	395	0.012	0.008	0.131	0.130
2002	4,170	2,361	2,120	241	0.008	0.003	0.130	0.094
2003	3,809	1,351	1,195	156	0.003	0.012	0.094	0.112
2004	4,760	11,463	11,058	405	0.012	0.006	0.112	0.098
2005	2,189	1,373	1,218	155	0.006	0.011	0.098	0.115
2006	1,301	2,725	2,450	275	0.011	0.010	0.115	0.104
2007	9,958	5,354	4,959	395	0.010	0.014	0.104	0.127
2008	1,464	4,457	4,097	360	0.014	0.013	0.127	0.112
2009	2,306	8,090	7,665	425	0.013	0.009	0.112	0.162
2010	4,689	13,786	13,437	349	0.009	0.021	0.162	0.318
2011	3,920	4,534	4,169	365	0.021	0.008	0.318	0.178
2012	7,127	1,446	1,283	163	0.008	0.011	0.178	0.100

Fraser Canyon

Byr	Esc	Rec_t	Rec_A3	Rec_A4	S_A3	S_A4	ER_A3	ER_A4
1998	5,460	6,542	6,212	331	0.038	0.037	0.071	0.078
1999	4,096	4,083	3,810	273	0.037	0.010	0.078	0.129
2000	2,719	5,262	4,954	308	0.010	0.012	0.129	0.131
2001	5,971	6,781	6,452	329	0.012	0.008	0.131	0.130
2002	3,817	2,478	2,279	199	0.008	0.003	0.130	0.094
2003	4,552	1,726	1,572	153	0.003	0.012	0.094	0.112
2004	5,872	3,172	2,931	241	0.012	0.006	0.112	0.098
2005	2,269	1,127	1,021	106	0.006	0.011	0.098	0.115
2006	1,605	2,720	2,502	219	0.011	0.010	0.115	0.104
2007	2,739	2,468	2,267	201	0.010	0.014	0.104	0.126
2008	1,138	3,709	3,446	263	0.014	0.013	0.126	0.112
2009	2,308	5,837	5,518	319	0.013	0.009	0.112	0.162
2010	2,227	6,449	6,124	325	0.009	0.021	0.162	0.318
2011	3,189	1,333	1,212	122	0.021	0.008	0.318	0.178
2012	5,134	342	306	36	0.008	0.011	0.178	0.100

Lower Thompson

Byr	Esc	Rec_t	Rec_A3	Rec_A4	S_A3	S_A4	ER_A3	ER_A4
1998	2,165	6,002	5,299	703	0.038	0.037	0.128	0.111
1999	3,992	5,306	4,625	681	0.037	0.010	0.111	0.224
2000	4,739	2,339	1,870	469	0.010	0.012	0.224	0.170
2001	9,522	2,869	2,314	555	0.012	0.008	0.170	0.205
2002	16,053	2,235	1,771	464	0.008	0.003	0.205	0.201
2003	2,933	1,152	875	277	0.003	0.012	0.201	0.126
2004	4,304	9,876	9,269	607	0.012	0.006	0.126	0.123
2005	2,614	3,461	2,860	601	0.006	0.011	0.123	0.142
2006	1,082	4,324	3,663	661	0.011	0.010	0.142	0.117
2007	10,169	12,185	11,740	445	0.010	0.014	0.117	0.142
2008	3,800	7,648	6,961	688	0.014	0.013	0.142	0.123
2009	4,768	11,844	11,384	460	0.013	0.009	0.123	0.171
2010	12,217	13,557	13,162	395	0.009	0.021	0.171	0.329
2011	7,289	9,357	8,738	620	0.021	0.008	0.329	0.200
2012	11,559	5,530	4,836	694	0.008	0.011	0.200	0.113

North Thompson

Byr	Esc	Rec_t	Rec_A3	Rec_A4	S_A3	S_A4	ER_A3	ER_A4
1998	9,786	26,351	26,073	277	0.038	0.037	0.086	0.107
1999	10,696	21,497	21,108	390	0.037	0.010	0.107	0.185
2000	8,054	7,678	7,105	573	0.010	0.012	0.185	0.168
2001	27,238	11,935	11,363	572	0.012	0.008	0.168	0.210
2002	22,083	4,933	4,466	467	0.008	0.003	0.210	0.149
2003	7,211	3,972	3,557	415	0.003	0.012	0.149	0.126
2004	10,661	27,312	27,050	262	0.012	0.006	0.126	0.138
2005	4,518	4,221	3,781	440	0.006	0.011	0.138	0.137
2006	3,670	10,742	10,152	589	0.011	0.010	0.137	0.125
2007	24,500	13,289	12,736	553	0.010	0.014	0.125	0.139
2008	3,849	9,720	9,137	584	0.014	0.013	0.139	0.119
2009	9,631	21,794	21,424	370	0.013	0.009	0.119	0.171
2010	12,159	19,016	18,572	445	0.009	0.021	0.171	0.353
2011	8,803	8,077	7,500	577	0.021	0.008	0.353	0.239
2012	20,058	3,713	3,321	392	0.008	0.011	0.239	0.105

South Thompson

Byr	Esc	Rec_t	Rec_A3	Rec_A4	S_A3	S_A4	ER_A3	ER_A4
1998	5,155	12,812	12,177	635	0.038	0.037	0.102	0.125
1999	3,137	10,790	10,167	623	0.037	0.010	0.125	0.151
2000	3,307	3,308	2,956	352	0.010	0.012	0.151	0.158
2001	13,063	18,278	17,721	557	0.012	0.008	0.158	0.266
2002	10,544	2,672	2,372	300	0.008	0.003	0.266	0.111
2003	3,422	2,171	1,913	258	0.003	0.012	0.111	0.133
2004	15,850	13,946	13,313	633	0.012	0.006	0.133	0.153
2005	2,302	6,864	6,312	551	0.006	0.011	0.153	0.159
2006	2,003	4,211	3,790	420	0.011	0.010	0.159	0.138
2007	12,345	10,076	9,445	631	0.010	0.014	0.138	0.205
2008	6,688	4,499	4,062	436	0.014	0.013	0.205	0.136
2009	3,821	15,070	14,462	608	0.013	0.009	0.136	0.177
2010	8,946	14,172	13,562	610	0.009	0.021	0.177	0.355
2011	4,771	1,987	1,753	233	0.021	0.008	0.355	0.276
2012	13,303	2,785	2,467	318	0.008	0.011	0.276	0.111

Table 2. Spawner and natural recruitment data for Interior Fraser Coho (IFC) by calendar year. Conservation Unit data were used to determine CU-specific short-term conservation benchmarks, examine the relationship between hatchery survival rates and recruitment, and to initialize model simulations.

Spawners

Year	Middle Fraser	Fraser Canyon	Lower Thompson	North Thompson	South Thompson
1984	4,726	14,925	6,808	41,396	16,946
1985	5,189	10,084	4,365	17,986	18,294
1986	1,876	11,403	4,002	30,692	16,884
1987	3,529	13,187	5,923	31,262	23,281
1988	7,940	16,060	6,059	35,039	27,552
1989	6,673	11,206	6,519	24,556	18,610
1990	2,593	7,110	8,172	17,551	10,320
1991	2,962	4,674	7,017	12,243	4,612
1992	6,193	7,506	7,976	15,929	13,565
1993	7,624	2,406	15,556	6,552	2,534
1994	1,912	4,348	10,389	14,898	4,918
1995	2,367	3,519	5,345	12,463	4,055
1996	1,183	1,473	1,854	5,923	1,373
1997	1,665	1,964	7,521	8,518	1,420
1998	4,851	5,460	2,165	9,786	5,155
1999	1,652	4,096	3,992	10,696	3,137
2000	3,920	2,719	4,739	8,054	3,307
2001	6,162	5,971	9,522	27,238	13,063
2002	4,170	3,817	16,053	22,083	10,544
2003	3,809	4,552	2,933	7,211	3,422
2004	4,760	5,872	4,304	10,661	15,850
2005	2,189	2,269	2,614	4,518	2,302
2006	1,301	1,605	1,082	3,670	2,003
2007	9,958	2,739	10,169	24,500	12,345
2008	1,464	1,138	3,800	3,849	6,688
2009	2,306	2,308	4,768	9,631	3,821
2010	4,689	2,227	12,217	12,159	8,946
2011	3,920	3,189	7,289	8,803	4,771
2012	7,127	5,134	11,559	20,058	13,303
2013	11,625	5,398	11,887	16,271	13,132
2014	3,081	1,048	7,447	5,244	2,270
2015	1,354	352	5,182	3,030	2,392
2016	14,722	1,160	13,527	15,314	15,023

Recruits

Year	Middle Fraser	Fraser Canyon	Lower Thompson	North Thompson	South Thompson
1984	14,792	46,713	21,595	131,201	53,009
1985	15,917	31,561	14,192	58,140	57,142
1986	5,299	33,258	14,056	93,443	52,034
1987	7,703	28,495	14,080	66,452	40,506
1988	27,908	55,758	17,820	116,235	88,057
1989	18,957	31,582	13,636	67,401	46,288
1990	10,363	26,987	27,474	66,217	38,015
1991	9,019	14,492	20,072	33,124	15,825
1992	33,261	40,498	36,225	80,060	70,838
1993	61,110	19,325	124,674	57,040	21,025
1994	3,373	7,673	8,595	25,954	7,243
1995	5,327	8,026	13,616	29,426	8,063
1996	6,981	8,926	13,200	37,026	8,658
1997	2,780	3,300	11,224	14,252	2,462
1998	5,287	5,874	809	10,297	5,881
1999	1,766	4,502	2,115	11,919	3,922
2000	3,999	2,819	2,976	5,987	3,656
2001	6,241	6,427	5,871	26,586	12,563
2002	4,376	4,141	5,328	21,385	10,802
2003	4,374	5,227	2,551	7,495	3,579
2004	5,480	6,760	2,783	11,936	18,073
2005	2,516	2,608	2,326	5,038	2,929
2006	1,436	1,772	1,339	4,024	2,212
2007	11,214	3,084	9,545	27,464	13,571
2008	1,623	1,262	3,467	4,044	6,945
2009	2,606	2,608	4,264	10,592	4,342
2010	5,234	2,485	12,402	13,325	9,866
2011	4,492	3,647	7,405	9,690	4,693
2012	8,025	5,781	12,072	22,007	14,898
2013	13,862	6,443	13,622	18,942	14,171
2014	4,518	1,537	9,132	7,945	2,363
2015	1,647	428	5,455	3,897	2,700
2016	16,358	1,288	14,049	16,975	15,642

Table 3. Stock-recruit data for Black Creek.

Brood Year	Escapement	Recruitment
1986	4,818	10,816
1987	785	4,306
1988	3,122	11,030
1989	3,272	7,381
1990	1,237	3,672
1991	3,568	4,289
1992	1,720	4,067
1993	959	955
1994	900	2,615
1995	1,760	7,852
1996	284	527
1997	1,200	1,148
1998	7,616	12,683
1999	511	4,593
2000	1,114	2,905
2001	12,100	4,248
2002	4,322	2,352
2003	2,780	591
2004	4,065	5,689
2005	2,248	1,189
2006	565	3,676
2007	5,453	4,332
2008	1,120	1,910
2009	3,536	5,568
2010	4,050	10,814
2011	1,811	7,296
2012	5,317	2,724
2013	10,378	NA
2014	6,800	NA
2015	2,623	NA

Table 4. Estimates of smolt-adult marine survival and exploitation rate for the interior Fraser River Coho Salmon (IFC) hatchery indicator stock, Inch Creek (the Lower Fraser River hatchery indicator stock), SOG_H (the Strait of Georgia hatchery indicator stocks, Quinsam and Big Qualicum), and Black Creek (the SOG wild indicator stock).

Return	Smolt-adult Marine Survival Rate				Exploitation Rate			
Year	IFC	Inch	SOG_H	Black	IFC	Inch	SOG_H	Black
1985	4.4%	-	-	-	68.1%	-	-	-
1986	4.4%	6.7%	9.2%	12.5%	65.7%	79.7%	74.0%	72.7%
1987	3.6%	8.9%	7.8%	11.5%	53.7%	83.4%	79.5%	84.7%
1988	5.5%	20.4%	7.9%	13.4%	71.2%	88.0%	82.1%	67.6%
1989	4.1%	10.9%	10.6%	11.5%	64.5%	67.1%	69.5%	69.7%
1990	6.1%	8.0%	6.0%	12.9%	73.7%	85.9%	77.5%	71.3%
1991	4.0%	7.1%	5.2%	8.0%	67.7%	80.1%	71.4%	67.7%
1992	4.8%	9.7%	5.9%	12.5%	81.5%	75.5%	74.9%	76.7%
1993	4.9%	8.3%	5.1%	5.4%	87.6%	78.8%	76.4%	73.9%
1994	3.5%	6.0%	4.6%	5.9%	43.3%	79.0%	72.4%	79.0%
1995	1.1%	5.5%	2.7%	4.5%	56.2%	76.4%	63.3%	56.7%
1996	2.5%	3.9%	1.5%	3.4%	83.5%	78.5%	58.2%	70.3%
1997	0.9%	1.1%	1.3%	4.9%	40.5%	31.3%	31.4%	54.1%
1998	1.2%	0.5%	0.7%	4.5%	7.0%	4.6%	4.7%	3.0%
1999	2.4%	1.9%	1.0%	1.7%	9.0%	4.4%	4.6%	3.0%
2000	2.7%	1.1%	1.2%	2.2%	3.6%	4.7%	4.1%	3.0%
2001	3.8%	5.8%	1.4%	7.4%	7.1%	7.5%	6.4%	4.6%
2002	3.7%	1.8%	1.2%	4.9%	7.8%	10.3%	9.1%	5.9%
2003	1.0%	1.1%	1.0%	3.0%	12.9%	13.0%	15.5%	4.3%
2004	1.2%	2.9%	1.5%	4.4%	13.1%	24.8%	20.1%	4.3%
2005	0.8%	1.6%	0.3%	1.7%	13.0%	11.9%	19.8%	4.4%
2006	0.3%	1.0%	0.2%	1.4%	9.4%	24.2%	21.1%	4.4%
2007	1.2%	1.4%	0.8%	2.5%	11.2%	25.3%	34.0%	4.2%
2008	0.6%	0.7%	0.6%	0.6%	9.8%	13.4%	9.6%	5.8%
2009	1.1%	1.9%	1.0%	2.5%	11.5%	7.1%	13.3%	3.8%
2010	1.0%	2.5%	0.7%	1.6%	10.4%	4.6%	8.7%	6.5%
2011	1.4%	1.2%	1.0%	1.3%	12.6%	17.5%	18.5%	5.2%
2012	1.3%	4.2%	1.5%	1.4%	11.2%	20.3%	28.8%	4.5%
2013	0.9%	3.2%	1.9%	2.4%	16.5%	37.5%	32.5%	4.0%
2014	2.1%	2.0%	0.8%	1.0%	27.3%	26.5%	18.4%	6.8%
2015	0.8%	0.6%	0.7%	0.3%	12.9%	23.0%	17.6%	3.7%
2016	-	3.8%	2.0%	-	-	10.6%	16.1%	-

Table 5a. Qualitative assessment of uncertainly, bias, and the effect on simulations for Interior Fraser parameters addressed in this document. Table modified from Decker et al. 2014 by L. Ritchie (DFO Stock Assessment, Kamloops)

Interior Fraser

Parameter	Source of Uncertainty	Bias	Effect on Exploitation Rate Simulations
Survival rate	Over or underestimation of the hatchery proportion returning to indicator systems can occur due to bias sampling. Indicator programs are regularly compromised by low or spatially and/or temporally biased carcass recovery and high water events. Mark rate has varied considerably by sampling method. Error in total escapement to indicators may bias CWT returns as well	Magnitude: Medium Direction: Changing	Positive bias will increase calculated marine survival estimates and overestimate productivity of the stock. The opposite will be true with negative bias in CWT return rates and escapement estimates..
	Spawning marked hatchery Coho naturally stray to nearby unenhanced streams but straying is not fully accounted for	Magnitude: Low Direction: Negative	Loss of marked fish will decrease calculated marine survival rates and underestimate productivity of the stock
	Survival series is derived from hatchery smolt releases so freshwater survival of wild juveniles is not incorporated into survival rate series.	Magnitude: Unknown Direction: Unknown	Negative bias will decrease calculated marine survival estimates and underestimate productivity of the stock
Exploitation rate used to reconstruct abundance	Different ER methodologies through time series.	Magnitude: Unknown Direction: Unknown	Error/negative bias in estimates of exploitation rate in previous years (model input) will result in error/positive bias in estimates of total return and productivity, and lead to uncertainty/and overestimation of sustainable ER (model output). However, this may not be of serious consequence if the same methods are used to estimate ER going forward
	Poor sampling in fisheries, incomplete catch estimates, unreported catch, drop-off and release mortality not fully accounted for.	Magnitude: Medium Direction: Negative	
	Unknown relationship of base period data to present with respect to spatial/temporal distribution and encounter rates for Interior Fraser Coho. Unknown relationship between effort and catch.	Magnitude: Medium Direction: Unknown	
	Includes uncertainty in escapement estimates.	See below	-
Escapement estimates	Escapement extrapolated for some streams that went un-surveyed in some years.	Magnitude: Low Direction: Unknown	Uncertainty in 1998-2016 escapements: Errors-in-variables will lead to overestimates of productivity for SR models

Parameter	Source of Uncertainty	Bias	Effect on Exploitation Rate Simulations
	Precise methods (e.g., fence counts, mark-recapture) are used for some streams, though the majority of escapement is determined through visual methods using static calibration factors which could lead to bias in either direction. Changing detection probability as a result of changing visibility conditions are not accounted for in escapement models.	Magnitude: Medium Direction: Changing	Stock recruit errors-in-variables will lead to overestimates of productivity for SR models
	Not all spawning streams are surveyed.	Magnitude: Low /Medium Direction: Negative	Negatively biased-low of aggregate escapement: overestimation of the probability of failing to meet IFCRT short-term and long-term objectives (20,000 and 40,000 spawners, respectively) for a given exploitation rate and productivity level.
Proportion of hatchery fish in wild escapement	Estimated by applying survival to spawning of marked (hatchery) adults observed in carcass recoveries from indicator streams to hatchery smolt releases in unassessed streams were hatchery releases were unmarked; carcass recovery sample sizes are often small or not representative.	Magnitude: Low Direction: Negative	Uncertainty about the proportion of hatchery fish in wild escapement leads to error in estimates of adult recruits and productivity. Negatively biased-low estimates of the proportion of hatchery fish in wild escapement leads to positively biased high estimates of productivity.
Age at Return	It is assumed that 4-year old Coho return to the Interior at a constant rate of approximately 10%, though in practice this number is spatially and temporally variable though not randomly sampled and errors occur in scale reading.	Magnitude: Medium to High Direction: Positive	Assumptions about age at return may overestimate modelled returns on low survival years
Stock-recruitment relationship	The form of the stock recruitment relationship is assumed to be one of several frequently used models.	Magnitude: Low Direction: Positive	The biases in exploitation rates and escapement estimates are expressed in the estimation of the stock recruitment parameters, which can lead to positively biased estimates of productivity. Biases in the data used to select and parameterize the S-R model can lead to biased predictions of stock response to harvest.
	Changing bias in escapement estimates from brood to return may lead to over or underestimate of productivity.	Magnitude: Medium Direction: Changing	

Table 6b. Qualitative assessment of uncertainly, bias, and the effect on simulations for Black Creek parameters addressed in this document. Table modified from Decker et al. 2014 by P. VanWill (DFO Stock Assessment Port Hardy).

Parameter	Uncertainty		Bias			Effect on Exploitation Rate simulations
	Magnitude	Cause	Magnitude	Direction	Cause	
Exploitation rate	High	Unknown relationship of base period (1987-1997) to present with respect to spatial distribution and encounter rates for SOG and Black Creek Coho, and relationship between effort and catch. Black Creek Coho have been CWT tagged but not clipped since around 1998 so marine distribution and harvest not available since that time, hence reliance on based period ER and scaling based on effort	Medium	Negative	Unreported catch, drop-off and release mortality not fully accounted for.	Error/negative bias in estimates of exploitation rate in previous years (model input) will result in error/positive bias in estimates of total return and productivity, and lead to uncertainty/and overestimation of sustainable ER (model output). However, this may not be of serious consequence if the same methods are used to estimate ER going forward (see *Section 3.2*).
Escapement estimates	Low (1984 - present)	Black Creek escapement and juvenile production have been monitored consistently since 1984. Both juvenile and adult enumeration conducted via fence. Adult escapement enumeration is also backed up with a mark recapture program in the event the fence is topped in the fall.	Medium to Low	Positive	Since the inception of the program (and even more significantly in recent years), the proportion of tagged juveniles released does not match the proportion of adults returning indicating: missing a component of the outmigration, differential mortality of tagged and untagged smolts, Increase stray events from other local coho populations such as Oyster River.	Impacts estimate of marine survival for this population which is applied across the board to the other Strait of Georgia populations. Uncertainty about the proportion of native Black Creek fish in escapement leads to error in estimates of adult recruits and productivity. Biased-high estimates of the proportion of non-native coho in escapement leads to biased high estimates of productivity
Proportion of hatchery fish in wild escapement	Low	Currently unknown. Possible issue with strays from other systems with enhancement such as Oyster River. Proportion of unclipped CWT fish in escapement does not match the proportion of released unclipped CWT juveniles at the fence.	Low	Negative	The proportion of hatchery fish (marked and unmarked) is currently assumed to be 0% but hatchery adults do stray at unknown levels to unenhanced streams.	Uncertainty about the proportion of hatchery fish in wild escapement leads to error in estimates of adult recruits and productivity. Biased-low estimates of the proportion of hatchery fish in wild escapement leads to biased high estimates of productivity.
Stock-recruitment relationship	Medium / High	The form of the stock recruitment relationship is assumed to be one of several frequently used models. The model selection is based upon fitting to the ER and escapement time series. Biases in those time series can affect the stock recruitment model fitting and selection.	Low	Positive	Biases in the data used to select and parameterize the S-R model can lead to biased predictions of stock response to harvest.	The three models selected show similar population response at escapements above 10000 so model selection bias should not be a major issue. (Figure 16a and 16b) The biases in exploitation rates and escapement estimates however are expressed in the estimation of the stock

Parameter	Uncertainty		Bias			Effect on Exploitation Rate simulations
	Magnitude	Cause	Magnitude	Direction	Cause	
						recruitment parameters, which can lead to biased high estimates of productivity.

Table 7. Model fit statistics comparing alternate Ricker stock-recruit models for IFC conservation units. The top portion of the table shows the proportion of variation in observed log(R/S) explained by each model. The bottom portion of the table shows the number of parameters that are estimated, the effective number of parameters, and the Deviance Information Criteria (DIC). The model with the lowest DIC score is considered to have the best out of sample predictive power. See text for more detailed descriptions of alternate models.

r^2 Pred vs. Obs log(R/S)

Model Number:	**1 (Figure 1)**	**2**	**3**	**4 (Figure 2)**	**5 (Figure 3)**	**6**
Model Description:	**Base (no informative priors)**	**Base without HSASI covariate**	**Base without hierarchical component**	**Larger capacity**	**Depensation & larger capacity**	**Base without HSASI covariate or density-dependence ($R=S\cdot e^{\alpha}$)**
Middle Fraser	0.49	0.29	0.45	0.49	0.48	0.00
Fraser Canyon	0.41	0.28	0.39	0.40	0.41	0.00
Lower Thompson	0.51	0.40	0.49	0.52	0.51	0.00
North Thompson	0.68	0.45	0.61	0.69	0.69	0.27
South Thompson	0.34	0.23	0.33	0.34	0.34	0.03

Deviance Information Criteria (DIC)

Model Number:	**1 (Figure 1)**	**2**	**3**	**4 (Figure 2)**	**5 (Figure 3)**	**6**
Model Description:	**Base (no informative priors)**	**Base without HSASI covariate**	**Base without hierarchical component**	**Larger capacity**	**Depensation & larger capacity**	**Base without HSASI covariate or density-dependence ($R=S\cdot e^{\alpha}$)**
No. of parameters	18	17	16	18	18	12
pD (No. of effective parameters)	14.2	12.8	19.9	9.3	8.6	8.6
DIC	170.8	188.7	194.3	187.0	190.6	213.9

Table 8. Parameter estimates (mean of posterior distributions) from Ricker models with a hatchery smolt-adult marine survival rate index (HSASI) covariate without informative priors (base Ricker; Figure 1), an informative prior for a larger carrying capacity (Ricker-PriorCap; Figure 2), and informative priors for a larger carrying capacity and depensation (Ricker-Dep; Figure 3). See text for definition of parameter values and footnotes for definition of derived parameters. Sgen, Smsy, and Umsy were computed based on the geometric mean smolt-adult marine survival rate for the IFC MU for brood years 1998-2012, 1.1%.

		Conservation Unit				
		Middle Fraser	**Fraser Canyon**	**Lower Thompson**	**North Thompson**	**South Thompson**
Geometric Mean Escapement (2014-2016)		3,945	753	8,052	6,243	4,337
	ConObj1	1,875	1,000	1,609	3,670	2,213
Model:						
Ricker	**Parameter:**					
	α	3.20	3.27	3.15	3.26	3.11
	β	0.00018	0.00031	0.00013	0.00008	0.00010
	γ	0.52	0.52	0.52	0.52	0.52
	mu_α	3.15	3.15	3.15	3.15	3.15
	Derived Parameters:					
	Productivity	2.43	2.62	2.31	2.60	2.24
	Umsy	0.39	0.42	0.37	0.42	0.36
	Sgen	1,069	618	1,561	2,670	1,977
	Smsy	2,152	1,333	2,970	5,375	3,635
	Seq	4,882	3,061	6,687	12,327	8,140
	SmoltKm	215	2,852	1,025	1,305	925
	Seq/ConObj1	2.60	3.06	4.16	3.36	3.68
Ricker-PriorCap	**Parameter:**					
	α	1.31	1.28	1.49	1.43	1.30
	β	0.00008	0.00012	0.00008	0.00004	0.00005
	γ	0.16	0.16	0.16	0.16	0.16
	mu_α	1.36	1.36	1.36	1.36	1.36
	Derived Parameters:					
	Productivity	1.79	1.74	2.13	2.01	1.77
	Umsy	0.27	0.26	0.34	0.32	0.27
	Sgen	2,248	1,525	2,566	5,161	3,753
	Smsy	3,357	2,226	4,499	8,562	5,566
	Seq	7,265	4,800	9,997	18,855	12,033
	SmoltKm	360	5,162	1,565	2,114	1,523
	Seq/ConObj1	3.87	4.80	6.21	5.14	5.44

Model:						
Ricker-Dep	**Parameter**					
	α	1.54	1.59	1.62	1.38	1.36
	β	0.00011	0.00018	0.00009	0.00004	0.00005
	γ	0.13	0.13	0.13	0.13	0.13
	mu_α	1.49	1.49	1.49	1.49	1.49
	Derived Parameters					
	Productivity	0.00	0.00	0.00	0.00	0.00
	Umsy	0.24	0.19	0.32	0.28	0.23
	Sgen	2,870	2,061	3,380	6,869	4,870
	Smsy	3,975	2,610	5,390	10,275	6,645
	Seq	8,475	4,469	11,663	21,997	14,039
	SmoltKm	335	4,467	1,624	2,311	1,533
	Seq/ConObj1	4.52	4.47	7.25	5.99	6.34

Notes:

1. Average α' over time: $\alpha' = \alpha + \gamma \cdot \log(\overline{M}_t)$
2. Productivity (maximum productivity at low stock size): $e^{\alpha'}$
3. Umsy (exploitation rate at MSY): $0.5 \cdot \alpha' - 0.07 \cdot \alpha'^2$
4. Sgen (escapement level that can reach Smsy in one generation): computed by nonlinear search.
5. Smsy (escapement at MSY): $\frac{\alpha'}{\beta} \cdot (0.5 - 0.07 \cdot \alpha')$
6. Seq (equilibrium escapement with no fishing) $\frac{\alpha + \gamma \cdot \log(\overline{M}_t)}{\beta}$
7. SmoltKm (maximum smolt capacity per km): $\frac{e^{\alpha'-1}}{\beta} \cdot \frac{1}{e^{\log(\overline{M}_t)} \cdot km}$

Average α′ over time can be estimated by (1) for all three Ricker models. Other derived parameters for Ricker and Ricker – PriorCap models can be computed by above formulas but must be estimated by nonlinear search for the Ricker – Dep model. For consistency, we used nonlinear search to estimate these derived parameters for all models.

Table 9. Mean of log(recruits/spawner) residuals by brood year and IFC CU from posterior distributions estimated by the base Ricker model. The right column shows the mean of CU residuals for each brood year representing deviations for the aggregate stock (IFC). The first two rows at the bottom show the estimated mean (μ) of residuals over years and the mean of simulated residuals. The next two rows show the standard deviation (σ) of residuals over years and the standard deviation of simulated residuals. The last two rows show the estimated correlation (ρ) between residuals for each CU with the aggregate residual pattern, and the correlation based on simulated deviates.

	Conservation Unit					
Brood Year	**MF**	**FC**	**LT**	**NT**	**ST**	**IFC MU**
1998	-0.37	0.31	-0.18	0.16	0.00	-0.02
1999	-0.19	-0.26	-0.60	-0.04	0.17	-0.19
2000	0.02	0.62	-0.89	-0.31	-0.39	-0.19
2001	0.13	1.04	-0.82	0.29	0.82	0.29
2002	-0.45	0.03	-0.50	-0.53	-0.88	-0.46
2003	-0.62	0.12	-0.92	-0.38	-0.31	-0.42
2004	0.86	0.28	0.54	0.79	0.64	0.62
2005	-0.64	-0.64	0.06	-0.36	0.85	-0.15
2006	0.13	0.09	0.72	0.44	0.18	0.31
2007	0.37	-0.15	0.70	0.38	0.29	0.32
2008	0.41	0.47	0.24	0.18	-0.62	0.13
2009	0.75	0.63	0.62	0.55	0.91	0.69
2010	1.17	0.90	0.92	0.55	0.66	0.84
2011	-0.30	-1.12	0.04	-0.65	-1.46	-0.70
2012	-1.00	-1.88	0.06	-0.93	-0.86	-0.92
Estimated μ of residuals	0.02	0.03	0.00	0.01	0.00	0.01
Simulated μ of residuals	0.02	0.03	0.01	0.02	0.01	0.02
Estimated σ of residuals	0.68	0.79	0.66	0.54	0.74	0.53
Simulated σ of residuals	0.63	0.79	0.65	0.53	0.75	0.52
Estimated correlation (ρ) between IFC residuals and CU residuals	0.91	0.79	0.52	0.95	0.76	-
Simulated correlation (ρ) between IFC residuals and CU residuals	0.90	0.74	0.57	0.94	0.78	-

Table 10. Summary of conservation limits for each for Interior Fraser River Coho Salmon conservation units (CU). Objectives are the total escapement to each CU that results in a 95% probability of exceeding 1,000 spawners in half (ConObj1, short-term) or all (ConObj2, long-term) of the subpopulations, as computed by logistic regression (see Figure 8).

Conservation Unit	Habitat (km)	Number of subpops	ConObj1, Short Term (1/2 of subpopulations)	ConObj2, Long Term (all subpopulations)
Middle Fraser	1,979	2	1,875	3,637
Fraser Canyon	93	1	1,000	1,000
Lower Thompson	573	2	1,609	11,605
North Thompson	818	3	3,670	14,135
South Thompson	778	3	2,213	16,044
Total	4,240	11	10,367	46,421
MU Objective	-	-	20,000	40,000

Table 11. Comparison of observed probabilities of meeting or exceeding the short-term recovery objective (ConObj1) for each Interior Fraser conservation unit (CU) and for the management unit (MU), and values predicted by the retrospective simulation (for the base Ricker model with uninformative priors).Predicted recruitment depends on the mean of CU-specific stock-recruit parameters, the residuals for each CU and year-age observation, and historical exploitation rates (Historical ER) or fixed exploitation rates of 0.1, 0.2, and 0.3 (Simulated ER).

	Middle Fraser	Fraser Canyon	Lower Thompson	North Thompson	South Thompson	IFC MU
ConObj1	1,875	1,000	1,609	3,670	2,213	20,000
Proportion of years when escapement met or exceeded objective:						
Observed	0.78	0.93	0.93	0.79	0.71	0.57
Historical ER	0.79	0.86	0.93	0.79	0.71	0.50
Simulated ER						
0.1	0.79	0.93	0.93	0.86	0.79	0.71
0.2	0.64	0.86	0.93	0.79	0.71	0.50
0.3	0.64	0.79	0.86	0.71	0.64	0.43

Table 12. Probability that escapement to the IFC MU will meet or exceed the short-term recovery objective (20,000) for a range of hatchery smolt-adult marine survival rates and exploitation rates. Results are based on: (a) a Ricker model with uninformative priors; (b) a Ricker model with informative priors on larger carrying capacity; and, (c) a Ricker model with informative priors on larger carrying capacity and depensation. Values represent the mean probability and 80% credible interval (10th and 90th percentiles). Results at a finer resolution and for marine survival rates up to 10% are available upon request from the authors.

a) Ricker - uninformative priors

Exploitation Rate	Hatchery Smolt-adult Marine Survival Rate									
	0.0025	**0.005**	**0.0075**	**0.01**	**0.015**	**0.02**	**0.025**	**0.03**	**0.04**	**0.05**
0	0.06 (0-0.14)	0.36 (0.06-0.74)	0.76 (0.52-0.94)	0.93 (0.84-1)	0.99 (0.96-1)	1 (0.98-1)	1 (1-1)	1 (1-1)	1 (1-1)	1 (1-1)
0.05	0.05 (0-0.1)	0.28 (0.04-0.64)	0.68 (0.38-0.9)	0.89 (0.76-1)	0.98 (0.94-1)	0.99 (0.98-1)	1 (1-1)	1 (1-1)	1 (1-1)	1 (1-1)
0.1	0.04 (0-0.08)	0.2 (0.02-0.5)	0.57 (0.26-0.84)	0.84 (0.66-0.98)	0.97 (0.92-1)	0.99 (0.98-1)	1 (0.98-1)	1 (1-1)	1 (1-1)	1 (1-1)
0.15	0.03 (0-0.04)	0.14 (0.02-0.36)	0.45 (0.14-0.74)	0.75 (0.54-0.92)	0.96 (0.88-1)	0.99 (0.96-1)	0.99 (0.98-1)	1 (0.98-1)	1 (1-1)	1 (1-1)
0.2	0.02 (0-0.04)	0.09 (0-0.24)	0.32 (0.06-0.62)	0.64 (0.38-0.86)	0.92 (0.82-1)	0.98 (0.92-1)	0.99 (0.96-1)	0.99 (0.98-1)	1 (1-1)	1 (1-1)
0.25	0.02 (0-0.04)	0.06 (0-0.14)	0.22 (0.04-0.48)	0.5 (0.2-0.78)	0.86 (0.7-0.98)	0.96 (0.88-1)	0.98 (0.94-1)	0.99 (0.98-1)	1 (0.98-1)	1 (1-1)
0.3	0.01 (0-0.04)	0.04 (0-0.08)	0.13 (0.02-0.32)	0.35 (0.08-0.62)	0.77 (0.54-0.94)	0.92 (0.8-1)	0.97 (0.9-1)	0.98 (0.94-1)	0.99 (0.98-1)	1 (1-1)
0.35	0.01 (0-0.04)	0.03 (0-0.06)	0.08 (0-0.18)	0.22 (0.04-0.46)	0.63 (0.34-0.88)	0.86 (0.68-1)	0.94 (0.82-1)	0.97 (0.9-1)	0.99 (0.96-1)	0.99 (0.98-1)
0.4	0.01 (0-0.02)	0.02 (0-0.04)	0.05 (0-0.1)	0.12 (0.02-0.28)	0.46 (0.16-0.76)	0.74 (0.46-0.96)	0.88 (0.68-1)	0.93 (0.82-1)	0.97 (0.92-1)	0.99 (0.96-1)
0.45	0.01 (0-0.02)	0.01 (0-0.04)	0.03 (0-0.06)	0.06 (0-0.14)	0.28 (0.04-0.56)	0.58 (0.24-0.86)	0.77 (0.5-0.98)	0.87 (0.66-1)	0.95 (0.86-1)	0.97 (0.92-1)
0.5	0 (0-0.02)	0.01 (0-0.04)	0.02 (0-0.04)	0.04 (0-0.08)	0.14 (0.02-0.32)	0.37 (0.08-0.68)	0.6 (0.24-0.9)	0.75 (0.44-0.98)	0.89 (0.68-1)	0.94 (0.82-1)
0.55	0 (0-0.02)	0.01 (0-0.04)	0.01 (0-0.04)	0.02 (0-0.04)	0.06 (0-0.14)	0.19 (0.04-0.4)	0.38 (0.08-0.72)	0.56 (0.16-0.9)	0.77 (0.44-1)	0.87 (0.64-1)
0.6	0 (0-0)	0.01 (0-0.02)	0.01 (0-0.04)	0.02 (0-0.04)	0.03 (0-0.06)	0.08 (0-0.18)	0.19 (0.02-0.46)	0.32 (0.04-0.7)	0.57 (0.14-0.94)	0.73 (0.32-1)
0.65	0 (0-0)	0 (0-0.02)	0.01 (0-0.02)	0.01 (0-0.04)	0.02 (0-0.04)	0.04 (0-0.08)	0.07 (0-0.18)	0.14 (0.02-0.34)	0.32 (0.04-0.72)	0.5 (0.1-0.92)
0.7	0 (0-0)	0 (0-0.02)	0.01 (0-0.02)	0.01 (0-0.04)	0.02 (0-0.04)	0.03 (0-0.06)	0.04 (0-0.08)	0.06 (0-0.12)	0.15 (0.02-0.36)	0.26 (0.02-0.64)

b) Ricker – PriorCap (informative prior on larger carrying capacity)

Exploitation Rate	Hatchery Smolt-adult Marine Survival Rate									
	0.0025	**0.005**	**0.0075**	**0.01**	**0.015**	**0.02**	**0.025**	**0.03**	**0.04**	**0.05**
0	0.4 (0.02-0.98)	0.54 (0.08-0.98)	0.7 (0.36-0.98)	0.81 (0.58-1)	0.89 (0.7-1)	0.91 (0.72-1)	0.92 (0.74-1)	0.92 (0.74-1)	0.92 (0.7-1)	0.92 (0.7-1)
0.05	0.35 (0-0.94)	0.46 (0.04-0.92)	0.59 (0.22-0.94)	0.71 (0.42-0.96)	0.83 (0.58-1)	0.87 (0.62-1)	0.88 (0.62-1)	0.89 (0.62-1)	0.89 (0.6-1)	0.89 (0.58-1)
0.1	0.3 (0-0.88)	0.37 (0.04-0.84)	0.48 (0.1-0.88)	0.59 (0.26-0.92)	0.74 (0.42-0.98)	0.8 (0.48-1)	0.83 (0.48-1)	0.84 (0.5-1)	0.85 (0.44-1)	0.85 (0.44-1)
0.15	0.24 (0-0.8)	0.29 (0.02-0.74)	0.36 (0.04-0.74)	0.45 (0.14-0.8)	0.62 (0.28-0.94)	0.71 (0.34-1)	0.75 (0.34-1)	0.78 (0.32-1)	0.8 (0.32-1)	0.81 (0.3-1)
0.2	0.19 (0-0.68)	0.22 (0.02-0.62)	0.26 (0.04-0.58)	0.32 (0.06-0.62)	0.48 (0.16-0.82)	0.6 (0.2-0.96)	0.66 (0.22-1)	0.69 (0.2-1)	0.73 (0.2-1)	0.75 (0.18-1)
0.25	0.15 (0-0.52)	0.16 (0-0.46)	0.18 (0.02-0.44)	0.22 (0.04-0.48)	0.33 (0.06-0.68)	0.46 (0.12-0.86)	0.54 (0.12-0.96)	0.59 (0.12-0.98)	0.65 (0.1-1)	0.68 (0.1-1)
0.3	0.1 (0-0.34)	0.11 (0-0.3)	0.12 (0-0.28)	0.14 (0.02-0.32)	0.21 (0.04-0.48)	0.31 (0.04-0.68)	0.41 (0.06-0.86)	0.48 (0.06-0.94)	0.56 (0.06-1)	0.6 (0.06-1)
0.35	0.07 (0-0.2)	0.07 (0-0.18)	0.08 (0-0.18)	0.09 (0-0.2)	0.13 (0.02-0.28)	0.19 (0.02-0.48)	0.27 (0.02-0.64)	0.35 (0.04-0.8)	0.45 (0.02-0.96)	0.51 (0.04-1)
0.4	0.05 (0-0.12)	0.05 (0-0.1)	0.05 (0-0.1)	0.06 (0-0.12)	0.08 (0-0.16)	0.11 (0-0.24)	0.16 (0.02-0.4)	0.21 (0.02-0.56)	0.32 (0.02-0.84)	0.4 (0.02-0.94)
0.45	0.04 (0-0.06)	0.03 (0-0.06)	0.04 (0-0.06)	0.04 (0-0.08)	0.05 (0-0.1)	0.07 (0-0.14)	0.09 (0-0.2)	0.12 (0-0.3)	0.2 (0-0.56)	0.27 (0.02-0.78)
0.5	0.02 (0-0.04)	0.03 (0-0.04)	0.03 (0-0.04)	0.03 (0-0.06)	0.03 (0-0.06)	0.04 (0-0.08)	0.05 (0-0.12)	0.07 (0-0.16)	0.11 (0-0.28)	0.16 (0-0.46)
0.55	0.01 (0-0.04)	0.02 (0-0.04)	0.02 (0-0.04)	0.02 (0-0.04)	0.03 (0-0.04)	0.03 (0-0.06)	0.03 (0-0.06)	0.04 (0-0.08)	0.06 (0-0.12)	0.08 (0-0.2)
0.6	0.01 (0-0.04)	0.01 (0-0.04)	0.01 (0-0.04)	0.02 (0-0.04)	0.02 (0-0.04)	0.02 (0-0.04)	0.02 (0-0.04)	0.02 (0-0.04)	0.03 (0-0.06)	0.04 (0-0.1)
0.65	0.01 (0-0.02)	0.01 (0-0.02)	0.01 (0-0.02)	0.01 (0-0.02)	0.02 (0-0.04)	0.01 (0-0.04)	0.02 (0-0.04)	0.02 (0-0.04)	0.02 (0-0.04)	0.03 (0-0.06)
0.7	0.01 (0-0.02)	0.01 (0-0.02)	0.01 (0-0.02)	0.01 (0-0.02)	0.01 (0-0.02)	0.01 (0-0.04)	0.02 (0-0.04)	0.01 (0-0.04)	0.02 (0-0.04)	0.02 (0-0.04)

c) Ricker – Dep (informative prior on larger carrying capacity and depensation)

Exploitation Rate	Hatchery Smolt-adult Marine Survival Rate									
	0.0025	0.005	0.0075	0.01	0.015	0.02	0.025	0.03	0.04	0.05
0	0.35 (0.04-0.82)	0.51 (0.1-0.92)	0.63 (0.24-0.96)	0.72 (0.38-0.98)	0.82 (0.52-1)	0.86 (0.62-1)	0.89 (0.64-1)	0.9 (0.68-1)	0.91 (0.7-1)	0.92 (0.74-1)
0.05	0.27 (0.02-0.68)	0.4 (0.06-0.82)	0.51 (0.12-0.88)	0.61 (0.2-0.94)	0.73 (0.36-0.98)	0.79 (0.44-1)	0.83 (0.5-1)	0.85 (0.54-1)	0.87 (0.62-1)	0.89 (0.62-1)
0.1	0.2 (0.02-0.52)	0.29 (0.04-0.7)	0.39 (0.06-0.78)	0.48 (0.12-0.86)	0.61 (0.18-0.94)	0.69 (0.26-0.98)	0.74 (0.32-1)	0.77 (0.38-1)	0.81 (0.42-1)	0.83 (0.48-1)
0.15	0.14 (0-0.38)	0.2 (0.02-0.5)	0.27 (0.04-0.62)	0.34 (0.06-0.72)	0.47 (0.1-0.86)	0.57 (0.14-0.94)	0.63 (0.18-0.98)	0.67 (0.2-1)	0.72 (0.22-1)	0.75 (0.26-1)
0.2	0.1 (0-0.24)	0.14 (0.02-0.34)	0.18 (0.02-0.42)	0.23 (0.02-0.52)	0.33 (0.04-0.72)	0.43 (0.08-0.84)	0.5 (0.1-0.92)	0.55 (0.1-0.96)	0.62 (0.14-1)	0.66 (0.16-1)
0.25	0.07 (0-0.16)	0.09 (0-0.22)	0.12 (0.02-0.28)	0.15 (0.02-0.36)	0.22 (0.02-0.52)	0.29 (0.04-0.68)	0.36 (0.04-0.8)	0.42 (0.06-0.9)	0.5 (0.06-0.96)	0.55 (0.06-1)
0.3	0.05 (0-0.12)	0.06 (0-0.16)	0.08 (0-0.2)	0.1 (0-0.22)	0.14 (0.02-0.32)	0.19 (0.02-0.48)	0.24 (0.02-0.6)	0.29 (0.02-0.72)	0.37 (0.04-0.9)	0.43 (0.04-0.96)
0.35	0.03 (0-0.08)	0.05 (0-0.1)	0.05 (0-0.12)	0.07 (0-0.16)	0.09 (0-0.2)	0.12 (0.02-0.26)	0.15 (0.02-0.36)	0.18 (0.02-0.5)	0.25 (0.02-0.7)	0.31 (0.02-0.82)
0.4	0.03 (0-0.06)	0.03 (0-0.08)	0.04 (0-0.1)	0.05 (0-0.12)	0.06 (0-0.14)	0.08 (0-0.16)	0.09 (0-0.22)	0.11 (0-0.26)	0.16 (0-0.44)	0.2 (0.02-0.6)
0.45	0.02 (0-0.04)	0.03 (0-0.06)	0.03 (0-0.08)	0.03 (0-0.08)	0.04 (0-0.1)	0.05 (0-0.12)	0.06 (0-0.12)	0.07 (0-0.16)	0.1 (0-0.24)	0.13 (0-0.32)
0.5	0.01 (0-0.04)	0.02 (0-0.04)	0.02 (0-0.04)	0.03 (0-0.06)	0.03 (0-0.08)	0.03 (0-0.08)	0.04 (0-0.1)	0.05 (0-0.1)	0.06 (0-0.14)	0.07 (0-0.16)
0.55	0.01 (0-0.02)	0.01 (0-0.04)	0.01 (0-0.04)	0.02 (0-0.04)	0.02 (0-0.04)	0.02 (0-0.06)	0.03 (0-0.06)	0.03 (0-0.08)	0.04 (0-0.1)	0.04 (0-0.1)
0.6	0.01 (0-0.02)	0.01 (0-0.04)	0.01 (0-0.04)	0.01 (0-0.04)	0.01 (0-0.04)	0.02 (0-0.04)	0.02 (0-0.04)	0.02 (0-0.04)	0.02 (0-0.06)	0.03 (0-0.06)
0.65	0.01 (0-0.02)	0.01 (0-0.02)	0.01 (0-0.02)	0.01 (0-0.02)	0.01 (0-0.02)	0.01 (0-0.04)	0.01 (0-0.04)	0.01 (0-0.04)	0.01 (0-0.04)	0.02 (0-0.04)
0.7	0 (0-0.02)	0 (0-0.02)	0 (0-0.02)	0.01 (0-0.02)	0.01 (0-0.02)	0.01 (0-0.02)	0.01 (0-0.02)	0.01 (0-0.02)	0.01 (0-0.04)	0.01 (0-0.04)

Table 13. Probability that escapement to the IFC MU will be sufficient for half of the sub-populations in each CU to have escapements that meet or exceed 1000 spawners in the same years (ConObj1.5) across a range of hatchery smolt-adult marine survival rates and exploitation rates. Results are based on: (a) a Ricker model with uninformative priors; (b) a Ricker model with informative priors on larger carrying capacity; and (c) a Ricker model with informative priors on larger carrying capacity and depensation. Values represent the mean probability and 80% credible interval (10th and 90th percentiles). Results at a finer resolution and for marine survival rates up to 10% are available upon request from the authors.

a) Ricker - uninformative priors

Exploitation Rate	Hatchery Smolt-adult Marine Survival Rate									
	0.0025	**0.005**	**0.0075**	**0.01**	**0.015**	**0.02**	**0.025**	**0.03**	**0.04**	**0.05**
0	0.06 (0-0.2)	0.42 (0.02-0.84)	0.78 (0.48-0.98)	0.92 (0.8-1)	0.96 (0.92-1)	0.97 (0.94-1)	0.97 (0.94-1)	0.98 (0.94-1)	0.97 (0.92-1)	0.97 (0.92-1)
0.05	0.04 (0-0.12)	0.33 (0-0.78)	0.71 (0.34-0.96)	0.89 (0.74-0.98)	0.96 (0.9-1)	0.97 (0.92-1)	0.97 (0.92-1)	0.97 (0.94-1)	0.97 (0.94-1)	0.97 (0.92-1)
0.1	0.03 (0-0.06)	0.24 (0-0.64)	0.62 (0.18-0.92)	0.84 (0.62-0.98)	0.95 (0.88-1)	0.97 (0.92-1)	0.97 (0.92-1)	0.97 (0.94-1)	0.97 (0.92-1)	0.97 (0.92-1)
0.15	0.02 (0-0.04)	0.17 (0-0.48)	0.51 (0.08-0.86)	0.77 (0.48-0.96)	0.93 (0.84-1)	0.96 (0.92-1)	0.97 (0.92-1)	0.97 (0.92-1)	0.97 (0.92-1)	0.97 (0.92-1)
0.2	0.01 (0-0.04)	0.1 (0-0.32)	0.39 (0.02-0.78)	0.67 (0.28-0.92)	0.91 (0.78-0.98)	0.95 (0.88-1)	0.97 (0.92-1)	0.97 (0.92-1)	0.97 (0.94-1)	0.97 (0.94-1)
0.25	0.01 (0-0.02)	0.06 (0-0.16)	0.27 (0-0.64)	0.55 (0.14-0.86)	0.86 (0.68-0.98)	0.94 (0.84-1)	0.96 (0.9-1)	0.96 (0.92-1)	0.97 (0.92-1)	0.97 (0.92-1)
0.3	0 (0-0.02)	0.03 (0-0.08)	0.16 (0-0.44)	0.41 (0.04-0.78)	0.79 (0.52-0.96)	0.91 (0.78-1)	0.94 (0.88-1)	0.96 (0.9-1)	0.97 (0.92-1)	0.97 (0.92-1)
0.35	0 (0-0)	0.02 (0-0.06)	0.08 (0-0.24)	0.26 (0-0.58)	0.66 (0.28-0.92)	0.85 (0.64-0.98)	0.92 (0.82-1)	0.94 (0.86-1)	0.96 (0.9-1)	0.97 (0.92-1)
0.4	0 (0-0)	0.01 (0-0.04)	0.04 (0-0.12)	0.14 (0-0.38)	0.5 (0.1-0.86)	0.75 (0.42-0.96)	0.86 (0.66-0.98)	0.91 (0.8-1)	0.95 (0.88-1)	0.96 (0.9-1)
0.45	0 (0-0)	0.01 (0-0.02)	0.02 (0-0.06)	0.06 (0-0.18)	0.31 (0.02-0.66)	0.59 (0.18-0.9)	0.77 (0.44-0.96)	0.85 (0.64-0.98)	0.92 (0.82-1)	0.95 (0.88-1)
0.5	0 (0-0)	0 (0-0.02)	0.01 (0-0.04)	0.02 (0-0.08)	0.15 (0-0.38)	0.38 (0.04-0.74)	0.6 (0.18-0.9)	0.73 (0.34-0.96)	0.86 (0.64-0.98)	0.91 (0.8-1)
0.55	0 (0-0)	0 (0-0)	0 (0-0.02)	0.01 (0-0.04)	0.05 (0-0.14)	0.19 (0-0.48)	0.37 (0.02-0.74)	0.52 (0.1-0.88)	0.72 (0.34-0.96)	0.82 (0.56-0.98)
0.6	0 (0-0)	0 (0-0)	0 (0-0.02)	0.01 (0-0.02)	0.02 (0-0.06)	0.05 (0-0.16)	0.15 (0-0.42)	0.27 (0-0.64)	0.49 (0.08-0.86)	0.63 (0.22-0.92)
0.65	0 (0-0)	0 (0-0)	0 (0-0)	0 (0-0.02)	0.01 (0-0.02)	0.02 (0-0.04)	0.04 (0-0.12)	0.08 (0-0.24)	0.22 (0-0.56)	0.35 (0.02-0.72)
0.7	0 (0-0)	0 (0-0)	0 (0-0)	0 (0-0)	0 (0-0.02)	0.01 (0-0.02)	0.01 (0-0.04)	0.02 (0-0.06)	0.06 (0-0.18)	0.12 (0-0.36)

b) Ricker – PriorCap (informative prior on larger carrying capacity)

Exploitation Rate	Hatchery Smolt-adult Marine Survival Rate									
	0.0025	**0.005**	**0.0075**	**0.01**	**0.015**	**0.02**	**0.025**	**0.03**	**0.04**	**0.05**
0	0.27 (0-0.86)	0.36 (0-0.88)	0.48 (0-0.9)	0.58 (0.06-0.94)	0.7 (0.2-0.98)	0.75 (0.24-0.98)	0.77 (0.24-1)	0.78 (0.22-1)	0.79 (0.22-1)	0.79 (0.2-1)
0.05	0.22 (0-0.78)	0.28 (0-0.8)	0.38 (0-0.86)	0.48 (0-0.9)	0.62 (0.06-0.96)	0.68 (0.1-0.98)	0.71 (0.08-1)	0.73 (0.12-1)	0.75 (0.1-1)	0.76 (0.08-1)
0.1	0.17 (0-0.66)	0.21 (0-0.68)	0.28 (0-0.74)	0.37 (0-0.82)	0.52 (0-0.92)	0.6 (0.02-0.96)	0.64 (0.04-0.98)	0.67 (0.04-1)	0.7 (0.04-1)	0.71 (0.02-1)
0.15	0.13 (0-0.52)	0.15 (0-0.52)	0.19 (0-0.58)	0.26 (0-0.66)	0.4 (0-0.84)	0.5 (0-0.92)	0.56 (0-0.96)	0.6 (0-0.98)	0.64 (0-1)	0.66 (0-1)
0.2	0.09 (0-0.38)	0.1 (0-0.34)	0.12 (0-0.4)	0.17 (0-0.48)	0.28 (0-0.7)	0.39 (0-0.86)	0.47 (0-0.92)	0.52 (0-0.96)	0.57 (0-0.98)	0.6 (0-1)
0.25	0.06 (0-0.22)	0.06 (0-0.22)	0.07 (0-0.26)	0.1 (0-0.3)	0.17 (0-0.5)	0.27 (0-0.72)	0.36 (0-0.84)	0.42 (0-0.92)	0.5 (0-0.98)	0.54 (0-0.98)
0.3	0.03 (0-0.08)	0.03 (0-0.1)	0.04 (0-0.14)	0.05 (0-0.16)	0.1 (0-0.3)	0.16 (0-0.5)	0.25 (0-0.68)	0.31 (0-0.82)	0.41 (0-0.94)	0.47 (0-0.96)
0.35	0.02 (0-0.04)	0.02 (0-0.06)	0.02 (0-0.06)	0.03 (0-0.08)	0.05 (0-0.16)	0.08 (0-0.28)	0.14 (0-0.48)	0.2 (0-0.66)	0.3 (0-0.86)	0.37 (0-0.94)
0.4	0.01 (0-0.02)	0.01 (0-0.02)	0.01 (0-0.04)	0.01 (0-0.04)	0.02 (0-0.08)	0.04 (0-0.14)	0.06 (0-0.22)	0.11 (0-0.38)	0.19 (0-0.64)	0.27 (0-0.84)
0.45	0 (0-0)	0.01 (0-0.02)	0.01 (0-0.02)	0.01 (0-0.02)	0.01 (0-0.04)	0.02 (0-0.06)	0.03 (0-0.1)	0.04 (0-0.16)	0.1 (0-0.36)	0.16 (0-0.6)
0.5	0 (0-0)	0 (0-0)	0 (0-0)	0 (0-0)	0.01 (0-0.02)	0.01 (0-0.02)	0.01 (0-0.04)	0.02 (0-0.06)	0.04 (0-0.14)	0.07 (0-0.26)
0.55	0 (0-0)	0 (0-0)	0 (0-0)	0 (0-0)	0 (0-0)	0 (0-0)	0.01 (0-0.02)	0.01 (0-0.02)	0.01 (0-0.06)	0.03 (0-0.1)
0.6	0 (0-0)	0 (0-0)	0 (0-0)	0 (0-0)	0 (0-0)	0 (0-0)	0 (0-0)	0 (0-0)	0.01 (0-0.02)	0.01 (0-0.02)
0.65	0 (0-0)	0 (0-0)	0 (0-0)	0 (0-0)	0 (0-0)	0 (0-0)	0 (0-0)	0 (0-0)	0 (0-0)	0 (0-0)
0.7	0 (0-0)	0 (0-0)	0 (0-0)	0 (0-0)	0 (0-0)	0 (0-0)	0 (0-0)	0 (0-0)	0 (0-0)	0 (0-0)

c) Ricker – Dep (informative prior on larger carrying capacity and depensation)

Exploitation Rate	Hatchery Smolt-adult Marine Survival Rate									
	0.0025	**0.005**	**0.0075**	**0.01**	**0.015**	**0.02**	**0.025**	**0.03**	**0.04**	**0.05**
0	0.05 (0-0.14)	0.09 (0-0.3)	0.12 (0-0.46)	0.16 (0-0.6)	0.23 (0-0.74)	0.3 (0-0.86)	0.35 (0-0.92)	0.4 (0-0.94)	0.47 (0-0.98)	0.52 (0-0.98)
0.05	0.03 (0-0.1)	0.06 (0-0.18)	0.08 (0-0.28)	0.1 (0-0.38)	0.16 (0-0.58)	0.22 (0-0.74)	0.27 (0-0.84)	0.31 (0-0.9)	0.38 (0-0.94)	0.43 (0-0.96)
0.1	0.02 (0-0.06)	0.03 (0-0.12)	0.05 (0-0.16)	0.07 (0-0.24)	0.1 (0-0.34)	0.15 (0-0.5)	0.19 (0-0.7)	0.23 (0-0.8)	0.3 (0-0.9)	0.35 (0-0.94)
0.15	0.01 (0-0.04)	0.02 (0-0.06)	0.03 (0-0.1)	0.04 (0-0.14)	0.06 (0-0.2)	0.09 (0-0.28)	0.12 (0-0.4)	0.16 (0-0.62)	0.22 (0-0.82)	0.26 (0-0.88)
0.2	0.01 (0-0.02)	0.01 (0-0.04)	0.02 (0-0.06)	0.02 (0-0.08)	0.04 (0-0.14)	0.06 (0-0.18)	0.08 (0-0.26)	0.1 (0-0.34)	0.15 (0-0.62)	0.19 (0-0.76)
0.25	0 (0-0)	0.01 (0-0.02)	0.01 (0-0.04)	0.01 (0-0.04)	0.02 (0-0.08)	0.04 (0-0.12)	0.04 (0-0.14)	0.05 (0-0.16)	0.09 (0-0.32)	0.13 (0-0.5)
0.3	0 (0-0)	0 (0-0)	0.01 (0-0.02)	0.01 (0-0.02)	0.01 (0-0.04)	0.02 (0-0.06)	0.03 (0-0.08)	0.03 (0-0.12)	0.05 (0-0.16)	0.08 (0-0.26)
0.35	0 (0-0)	0 (0-0)	0 (0-0)	0 (0-0)	0.01 (0-0.02)	0.01 (0-0.04)	0.01 (0-0.04)	0.02 (0-0.06)	0.03 (0-0.08)	0.04 (0-0.12)
0.4	0 (0-0)	0 (0-0)	0 (0-0)	0 (0-0)	0 (0-0)	0.01 (0-0.02)	0.01 (0-0.02)	0.01 (0-0.02)	0.02 (0-0.04)	0.02 (0-0.06)
0.45	0 (0-0)	0 (0-0)	0 (0-0)	0 (0-0)	0 (0-0)	0 (0-0)	0 (0-0)	0.01 (0-0)	0.01 (0-0.02)	0.01 (0-0.02)
0.5	0 (0-0)	0 (0-0)	0 (0-0)	0 (0-0)	0 (0-0)	0 (0-0)	0 (0-0)	0 (0-0)	0 (0-0)	0.01 (0-0)
0.55	0 (0-0)	0 (0-0)	0 (0-0)	0 (0-0)	0 (0-0)	0 (0-0)	0 (0-0)	0 (0-0)	0 (0-0)	0 (0-0)
0.6	0 (0-0)	0 (0-0)	0 (0-0)	0 (0-0)	0 (0-0)	0 (0-0)	0 (0-0)	0 (0-0)	0 (0-0)	0 (0-0)
0.65	0 (0-0)	0 (0-0)	0 (0-0)	0 (0-0)	0 (0-0)	0 (0-0)	0 (0-0)	0 (0-0)	0 (0-0)	0 (0-0)
0.7	0 (0-0)	0 (0-0)	0 (0-0)	0 (0-0)	0 (0-0)	0 (0-0)	0 (0-0)	0 (0-0)	0 (0-0)	0 (0-0)

Table 14. Probability that escapement to the IFC MU will meet or exceed the long-term recovery objective (40,000) for a range of hatchery smolt-adult marine survival rates and exploitation rates. Results are based on: (a) a Ricker model with uninformative priors; (b) a Ricker model with informative priors on larger carrying capacity; and, (c) a Ricker model with informative priors on larger carrying capacity and depensation. Values represent the mean probability and 80% credible interval (10th and 90th percentiles). Results at a finer resolution and for marine survival rates up to 10% are available upon request from the authors.

a) Ricker - uninformative priors

Exploitation Rate	Hatchery Smolt-adult Marine Survival Rate									
	0.0025	**0.005**	**0.0075**	**0.01**	**0.015**	**0.02**	**0.025**	**0.03**	**0.04**	**0.05**
0	0 (0-0)	0.01 (0-0.02)	0.05 (0-0.14)	0.17 (0.06-0.3)	0.46 (0.26-0.66)	0.64 (0.44-0.84)	0.74 (0.56-0.92)	0.8 (0.64-0.96)	0.87 (0.72-0.98)	0.9 (0.8-0.98)
0.05	0 (0-0)	0 (0-0.02)	0.03 (0-0.08)	0.12 (0.02-0.24)	0.39 (0.22-0.6)	0.58 (0.36-0.8)	0.7 (0.5-0.9)	0.77 (0.58-0.94)	0.85 (0.68-0.98)	0.88 (0.76-0.98)
0.1	0 (0-0)	0 (0-0)	0.02 (0-0.06)	0.08 (0-0.16)	0.31 (0.14-0.52)	0.51 (0.3-0.74)	0.65 (0.42-0.86)	0.73 (0.52-0.92)	0.82 (0.64-0.96)	0.86 (0.7-0.98)
0.15	0 (0-0)	0 (0-0)	0.01 (0-0.04)	0.04 (0-0.1)	0.23 (0.08-0.4)	0.44 (0.22-0.68)	0.58 (0.34-0.82)	0.68 (0.44-0.9)	0.78 (0.58-0.96)	0.84 (0.66-0.98)
0.2	0 (0-0)	0 (0-0)	0 (0-0.02)	0.02 (0-0.06)	0.16 (0.04-0.3)	0.36 (0.16-0.6)	0.51 (0.26-0.76)	0.62 (0.36-0.86)	0.74 (0.52-0.94)	0.81 (0.62-0.96)
0.25	0 (0-0)	0 (0-0)	0 (0-0)	0.01 (0-0.04)	0.1 (0-0.22)	0.27 (0.08-0.5)	0.42 (0.18-0.7)	0.54 (0.26-0.8)	0.69 (0.42-0.92)	0.77 (0.56-0.96)
0.3	0 (0-0)	0 (0-0)	0 (0-0)	0 (0-0.02)	0.05 (0-0.12)	0.18 (0.04-0.36)	0.33 (0.1-0.6)	0.45 (0.18-0.74)	0.62 (0.32-0.88)	0.72 (0.44-0.94)
0.35	0 (0-0)	0 (0-0)	0 (0-0)	0 (0-0)	0.02 (0-0.06)	0.11 (0-0.24)	0.23 (0.06-0.46)	0.36 (0.12-0.64)	0.54 (0.22-0.84)	0.65 (0.36-0.92)
0.4	0 (0-0)	0 (0-0)	0 (0-0)	0 (0-0)	0.01 (0-0.04)	0.06 (0-0.14)	0.15 (0-0.32)	0.25 (0.04-0.5)	0.44 (0.14-0.78)	0.57 (0.24-0.88)
0.45	0 (0-0)	0 (0-0)	0 (0-0)	0 (0-0)	0 (0-0)	0.02 (0-0.06)	0.08 (0-0.2)	0.16 (0-0.34)	0.33 (0.06-0.64)	0.47 (0.14-0.8)
0.5	0 (0-0)	0 (0-0)	0 (0-0)	0 (0-0)	0 (0-0)	0.01 (0-0.02)	0.03 (0-0.1)	0.08 (0-0.22)	0.21 (0.02-0.5)	0.35 (0.06-0.68)
0.55	0 (0-0)	0 (0-0)	0 (0-0)	0 (0-0)	0 (0-0)	0 (0-0)	0.01 (0-0.04)	0.03 (0-0.1)	0.12 (0-0.3)	0.22 (0-0.52)
0.6	0 (0-0)	0 (0-0)	0 (0-0)	0 (0-0)	0 (0-0)	0 (0-0)	0 (0-0)	0.01 (0-0.04)	0.05 (0-0.14)	0.12 (0-0.34)
0.65	0 (0-0)	0 (0-0)	0 (0-0)	0 (0-0)	0 (0-0)	0 (0-0)	0 (0-0)	0 (0-0)	0.02 (0-0.06)	0.05 (0-0.14)
0.7	0 (0-0)	0 (0-0)	0 (0-0)	0 (0-0)	0 (0-0)	0 (0-0)	0 (0-0)	0 (0-0)	0.01 (0-0.04)	0.02 (0-0.06)

b) Ricker – PriorCap (informative prior on larger carrying capacity)

Exploitation Rate	Hatchery Smolt-adult Marine Survival Rate									
	0.0025	**0.005**	**0.0075**	**0.01**	**0.015**	**0.02**	**0.025**	**0.03**	**0.04**	**0.05**
0	0.12 (0-0.4)	0.13 (0-0.4)	0.16 (0-0.42)	0.21 (0-0.5)	0.33 (0.06-0.66)	0.42 (0.08-0.8)	0.48 (0.08-0.86)	0.53 (0.08-0.9)	0.58 (0.08-0.94)	0.61 (0.08-0.96)
0.05	0.1 (0-0.32)	0.1 (0-0.3)	0.12 (0-0.32)	0.15 (0-0.38)	0.24 (0.02-0.54)	0.34 (0.04-0.72)	0.4 (0.04-0.8)	0.45 (0.04-0.84)	0.51 (0.04-0.9)	0.55 (0.04-0.94)
0.1	0.07 (0-0.22)	0.07 (0-0.2)	0.08 (0-0.2)	0.1 (0-0.24)	0.17 (0-0.4)	0.25 (0-0.6)	0.32 (0.02-0.74)	0.37 (0.02-0.8)	0.45 (0.02-0.88)	0.49 (0.02-0.92)
0.15	0.05 (0-0.14)	0.05 (0-0.12)	0.06 (0-0.12)	0.07 (0-0.14)	0.11 (0-0.28)	0.17 (0-0.46)	0.24 (0-0.62)	0.3 (0-0.74)	0.38 (0-0.84)	0.43 (0-0.88)
0.2	0.04 (0-0.06)	0.04 (0-0.06)	0.04 (0-0.06)	0.04 (0-0.08)	0.07 (0-0.16)	0.11 (0-0.3)	0.16 (0-0.46)	0.21 (0-0.62)	0.3 (0-0.76)	0.36 (0-0.84)
0.25	0.03 (0-0.02)	0.03 (0-0.02)	0.03 (0-0.02)	0.03 (0-0.04)	0.04 (0-0.08)	0.06 (0-0.14)	0.1 (0-0.3)	0.14 (0-0.44)	0.22 (0-0.66)	0.29 (0-0.78)
0.3	0.02 (0-0)	0.02 (0-0)	0.02 (0-0)	0.02 (0-0)	0.03 (0-0.04)	0.04 (0-0.06)	0.06 (0-0.16)	0.09 (0-0.26)	0.15 (0-0.52)	0.21 (0-0.7)
0.35	0.01 (0-0)	0.01 (0-0)	0.01 (0-0)	0.02 (0-0)	0.02 (0-0)	0.02 (0-0.02)	0.03 (0-0.04)	0.05 (0-0.12)	0.09 (0-0.28)	0.14 (0-0.46)
0.4	0.01 (0-0)	0.01 (0-0)	0.01 (0-0)	0.01 (0-0)	0.01 (0-0)	0.01 (0-0)	0.02 (0-0.02)	0.02 (0-0.02)	0.04 (0-0.12)	0.08 (0-0.24)
0.45	0.01 (0-0)	0.01 (0-0)	0.01 (0-0)	0.01 (0-0)	0.01 (0-0)	0.01 (0-0)	0.01 (0-0)	0.01 (0-0)	0.02 (0-0.02)	0.04 (0-0.1)
0.5	0.01 (0-0)	0.01 (0-0)	0.01 (0-0)	0.01 (0-0)	0 (0-0)	0.01 (0-0)	0.01 (0-0)	0.01 (0-0)	0.01 (0-0)	0.02 (0-0.02)
0.55	0 (0-0)	0.01 (0-0)	0 (0-0)	0 (0-0)	0 (0-0)	0 (0-0)	0 (0-0)	0.01 (0-0)	0.01 (0-0)	0.01 (0-0)
0.6	0 (0-0)	0 (0-0)	0 (0-0)	0 (0-0)	0 (0-0)	0 (0-0)	0 (0-0)	0 (0-0)	0 (0-0)	0.01 (0-0)
0.65	0 (0-0)	0 (0-0)	0 (0-0)	0 (0-0)	0 (0-0)	0 (0-0)	0 (0-0)	0 (0-0)	0 (0-0)	0.01 (0-0)
0.7	0 (0-0)	0 (0-0)	0 (0-0)	0 (0-0)	0 (0-0)	0 (0-0)	0 (0-0)	0 (0-0)	0.01 (0-0)	0 (0-0)

c) Ricker – Dep (informative prior on larger carrying capacity and depensation)

Exploitation Rate	Hatchery Smolt-adult Marine Survival Rate									
	0.0025	**0.005**	**0.0075**	**0.01**	**0.015**	**0.02**	**0.025**	**0.03**	**0.04**	**0.05**
0	0.05 (0-0.16)	0.09 (0-0.26)	0.13 (0-0.34)	0.18 (0-0.44)	0.28 (0.04-0.58)	0.35 (0.06-0.7)	0.4 (0.08-0.76)	0.44 (0.1-0.8)	0.5 (0.12-0.88)	0.54 (0.14-0.92)
0.05	0.03 (0-0.1)	0.06 (0-0.18)	0.08 (0-0.22)	0.12 (0-0.32)	0.19 (0-0.48)	0.26 (0.02-0.58)	0.32 (0.02-0.68)	0.36 (0.04-0.74)	0.42 (0.06-0.82)	0.47 (0.06-0.88)
0.1	0.02 (0-0.06)	0.03 (0-0.1)	0.05 (0-0.14)	0.07 (0-0.2)	0.13 (0-0.36)	0.18 (0-0.46)	0.23 (0-0.58)	0.28 (0-0.66)	0.34 (0.02-0.76)	0.39 (0.02-0.84)
0.15	0.01 (0-0.02)	0.02 (0-0.06)	0.03 (0-0.08)	0.04 (0-0.12)	0.08 (0-0.2)	0.12 (0-0.32)	0.16 (0-0.44)	0.2 (0-0.52)	0.26 (0-0.68)	0.31 (0-0.76)
0.2	0.01 (0-0)	0.01 (0-0.02)	0.01 (0-0.04)	0.02 (0-0.06)	0.04 (0-0.1)	0.07 (0-0.2)	0.1 (0-0.28)	0.13 (0-0.38)	0.19 (0-0.52)	0.23 (0-0.66)
0.25	0 (0-0)	0 (0-0)	0.01 (0-0.02)	0.01 (0-0.02)	0.02 (0-0.04)	0.03 (0-0.1)	0.05 (0-0.16)	0.07 (0-0.24)	0.12 (0-0.4)	0.16 (0-0.52)
0.3	0 (0-0)	0 (0-0)	0 (0-0)	0 (0-0)	0.01 (0-0.02)	0.02 (0-0.04)	0.03 (0-0.06)	0.04 (0-0.12)	0.07 (0-0.24)	0.1 (0-0.36)
0.35	0 (0-0)	0 (0-0)	0 (0-0)	0 (0-0)	0 (0-0)	0.01 (0-0.02)	0.01 (0-0.02)	0.02 (0-0.04)	0.04 (0-0.1)	0.06 (0-0.18)
0.4	0 (0-0)	0 (0-0)	0 (0-0)	0 (0-0)	0 (0-0)	0 (0-0)	0.01 (0-0)	0.01 (0-0)	0.02 (0-0.04)	0.03 (0-0.06)
0.45	0 (0-0)	0 (0-0)	0 (0-0)	0 (0-0)	0 (0-0)	0 (0-0)	0 (0-0)	0 (0-0)	0.01 (0-0)	0.01 (0-0.02)
0.5	0 (0-0)	0 (0-0)	0 (0-0)	0 (0-0)	0 (0-0)	0 (0-0)	0 (0-0)	0 (0-0)	0 (0-0)	0.01 (0-0)
0.55	0 (0-0)	0 (0-0)	0 (0-0)	0 (0-0)	0 (0-0)	0 (0-0)	0 (0-0)	0 (0-0)	0 (0-0)	0 (0-0)
0.6	0 (0-0)	0 (0-0)	0 (0-0)	0 (0-0)	0 (0-0)	0 (0-0)	0 (0-0)	0 (0-0)	0 (0-0)	0 (0-0)
0.65	0 (0-0)	0 (0-0)	0 (0-0)	0 (0-0)	0 (0-0)	0 (0-0)	0 (0-0)	0 (0-0)	0 (0-0)	0 (0-0)
0.7	0 (0-0)	0 (0-0)	0 (0-0)	0 (0-0)	0 (0-0)	0 (0-0)	0 (0-0)	0 (0-0)	0 (0-0)	0 (0-0)

Table 15. Mean Beverton-Holt tock-recruit parameters from the hierarchical Bayesian spawner-smolt model fit by Korman and Tompkins (2014) to data from 16 populations.Productivity percentiles show the credible interval which contains 80% of the posterior distribution. The final row (mean) shows the mean parameter estimates from the hyper-distribution of productivity and capacity which reflects the mean relationship across populations.

Population	Productivity (smolts/spawner)	Productivity Percentiles 10th	90th	Capacity (smolts/km)
Big Beef	73.4	44.3	106.1	2,094
Big Qualicum	105.6	52.3	174.0	3,181
Bingham	107.0	52.0	175.2	1,469
Black	73.6	51.8	99.5	3,081
Carnation	96.9	66.9	131.8	1,536
Deschutes	34.9	25.6	46.0	3,267
Deer	87.1	55.8	125.5	1,812
Flynn	88.5	51.5	133.3	617
Hooknose	107.0	54.1	174.3	1,087
Hunt's	65.2	33.9	100.8	1,134
Needle	67.4	43.2	96.7	415
Nile	88.5	31.8	114.3	1,171
Queets	83.8	54.3	118.8	1,280
Skagit	82.0	41.7	127.9	2,222
Skykomish	102.6	63.4	155.0	3,502
Snow	35.7	27.3	45.4	1,555
Mean	71.2	55.5	89.8	1,564

Table 16. Summary statistics of stock-recruitment parameters and dervided values for Black Creek based on alternate stock-recruitment models. All derived statistics were calculated based on the geometric mean survival for the Strait of Georgia Hatchery indicator stock (SOG_H = 1.4%, brood years 1983-2012). See the caption for Table 7 for additional details.

Variable	Ricker (no informative priors)	Ricker – PriorCap (larger carrying capacity)	Ricker – Dep (larger carrying capacity and depensation)	Deriso	Power
α'	1.06	0.92	1.46	1.38	4.35
β	0.00018	0.00010	0.00012	0.00070	0.49983
γ	0.43	0.40	0.39	0.40	0.42
Productivity	2.90	2.50	0.00	3.99	77.33
Umsy	0.46	0.40	0.47	0.51	0.50
Sgen	1,045	1,914	2,452	440	372
Smsy	2,505	3,855	5,372	1,339	1,490
Seq	5,850	8,785	11,596	3,948	5,963
SmoltKm	12,398	18,652	25,271	9,385	163,197
Geometric Mean (2013-2015)	3,391	3,391	3,391	3,391	3,391
r^2 log(R/S)	0.49	0.47	0.13	0.51	0.52
DIC	62.4	63.2	75.2	60.6	57.8

FIGURES

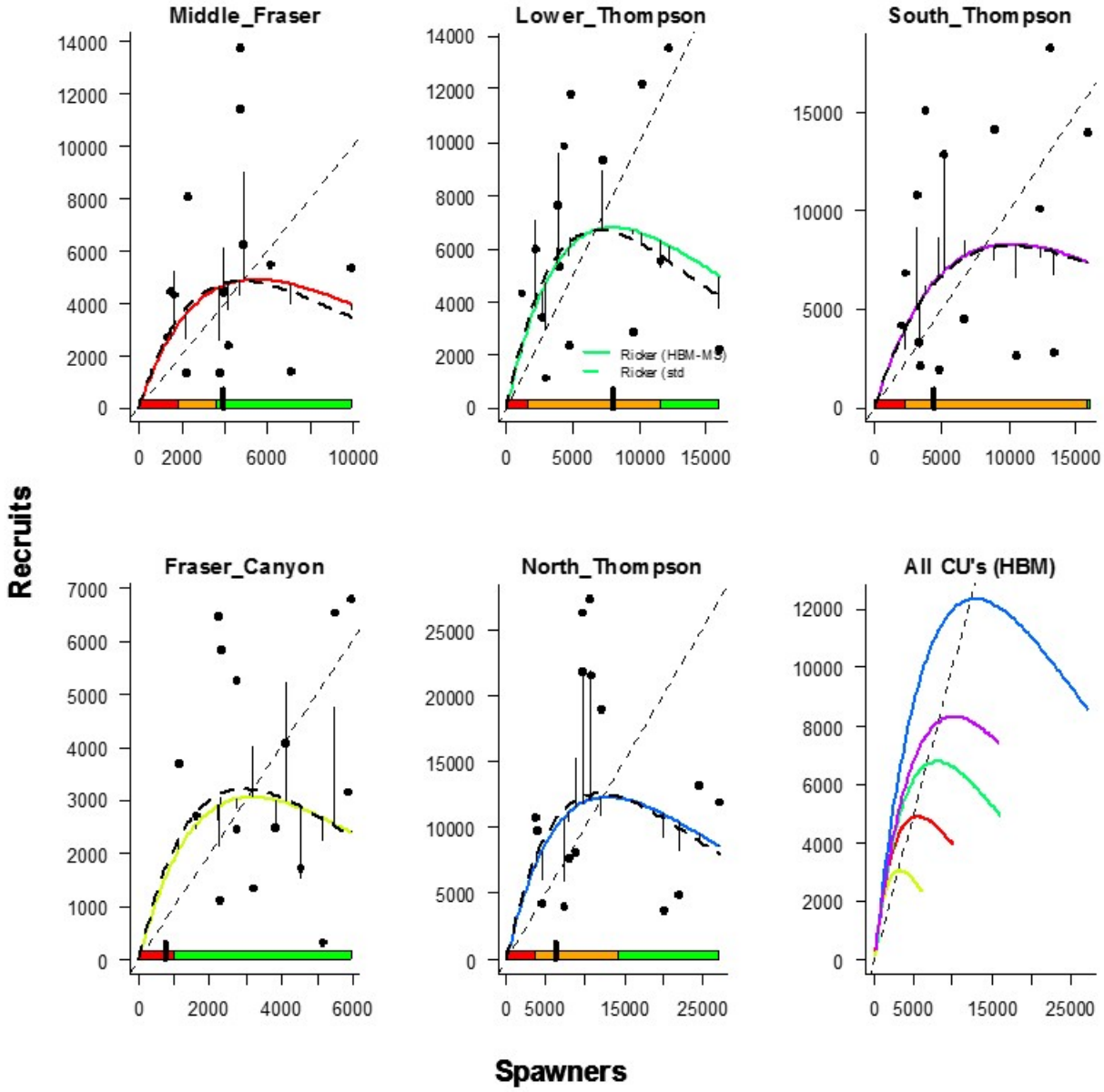


Figure 1. Stock and recruitment data for each IFC conservation unit (CU, points) and best fit Ricker relationships calculated from: 1) the hierarchical Bayesian model with a hatchery smolt-adult marine survival index (HSASI) covariate (colored lines); and 2) the base Ricker model with each CU's parameters estimated independently and no HSASI covariate (heavy black dashed lines). For the former models, the Ricker curve represents the prediction at the average HSASI value for the time series (1.1%) and the vertical lines represent predictions of recruitment in each year based on annual HSASI values. The diagonal dashed line is the replacement line. The benchmarks shown by the colored rectangles at the bottom of each plot are based on conservation limits to each CU that result in a 95% probability that escapement to half (ConObj1, red-orange line break) or all (ConObj2, orange-green line break) of the subpopulations in each CU will meet or exceed 1,000 spawners. The geometric mean escapement for the last generation (2014-2016) is shown by the thick, short black line overlaid on top of the benchmark bars.

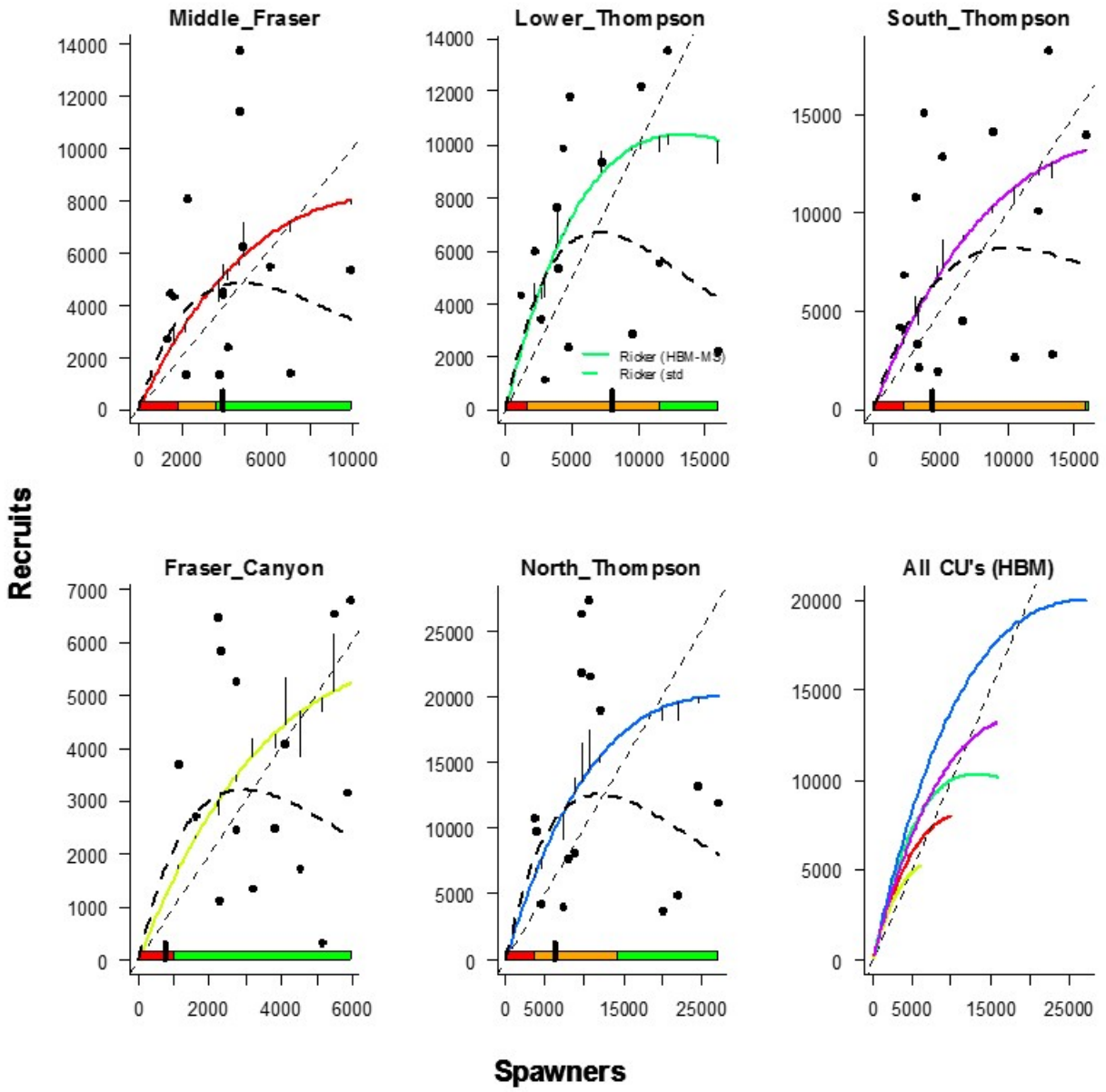


Figure 2. Stock and recruitment data for each IFC conservation unit (CU, points) and best fit Ricker relationships calculated from: 1) the hierarchical Bayesian model with a hatchery smolt-adult marine survival index (HSASI) covariate and with an informative prior on a larger carrying capacity (colored lines); and 2) the base Ricker model with each CU's parameters estimated independently and no HSASI covariate (heavy black dashed lines). See caption for Figure 1 for additional details.

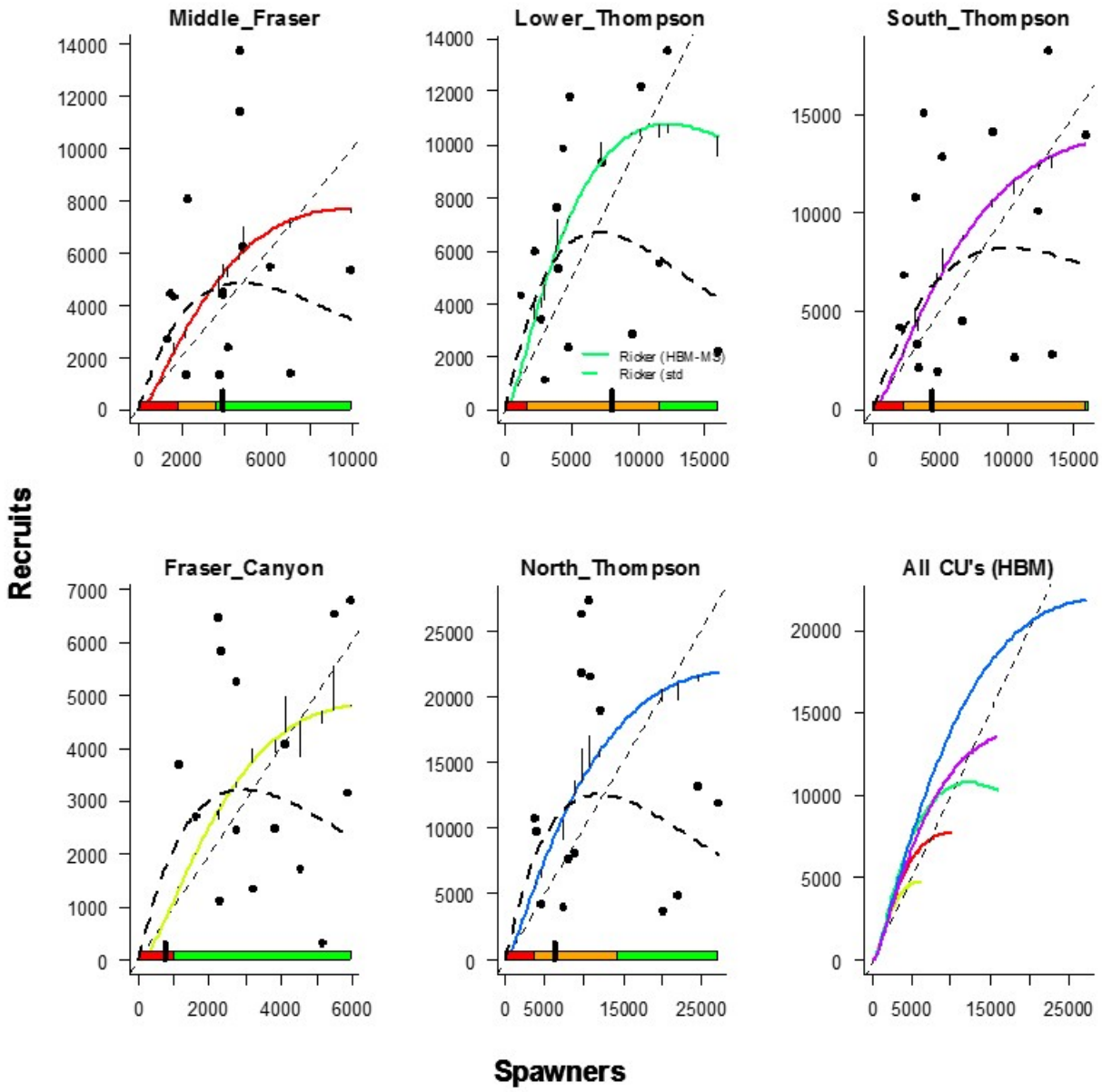


Figure 3. Stock and recruitment data for each IFC conservation unit (CU, points) and best fit Ricker relationships calculated from: 1) the hierarchical Bayesian model with a hatchery smolt-adult marine survival index (HSASI) covariate and with an informative prior on a larger carrying capacity and an assumed depensation value of 1,000 (colored lines); and 2) the base Ricker model with each CU's parameters estimated independently and no HSASI covariate (heavy black dashed lines). See caption for Figure 1 for additional details.

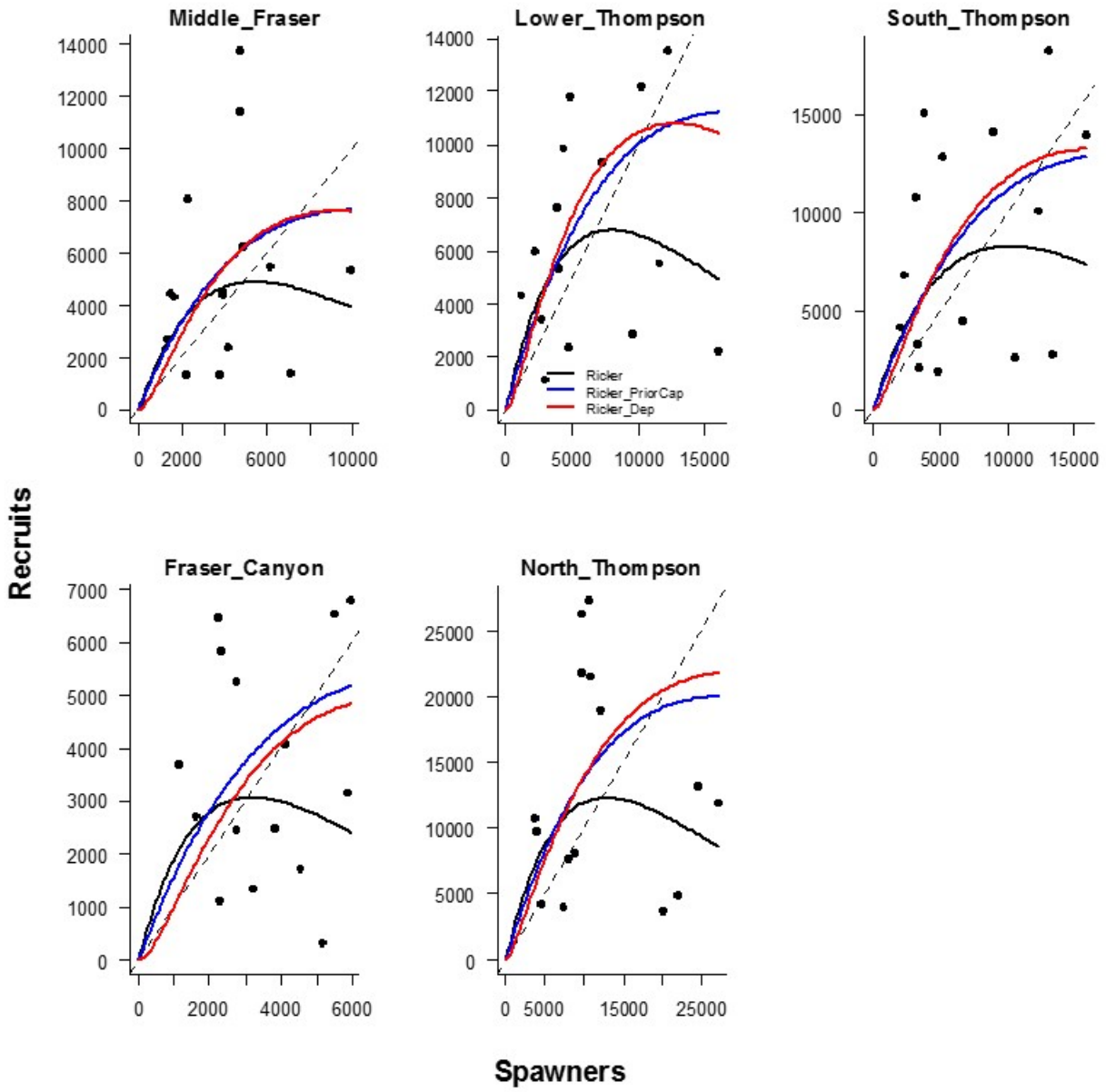


Figure 4. Comparison of three alternate Ricker stock-recruitment models for each IFC conservation unit. All models were based on a hierarchical Bayesian structure with a hatchery smolt-adult marine survival index (HSASI) covariate. The black, blue, and red lines are based on a Ricker model with no informative priors (Ricker, Figure 1), a Ricker model with an informative prior on a larger carrying capacity (Ricker_PriorCap, Figure 2), and a Ricker model with an informative prior on a larger carrying capacity and depensation (Ricker_Dep, Figure 3), respectively. See Figure 1 caption for additional details.

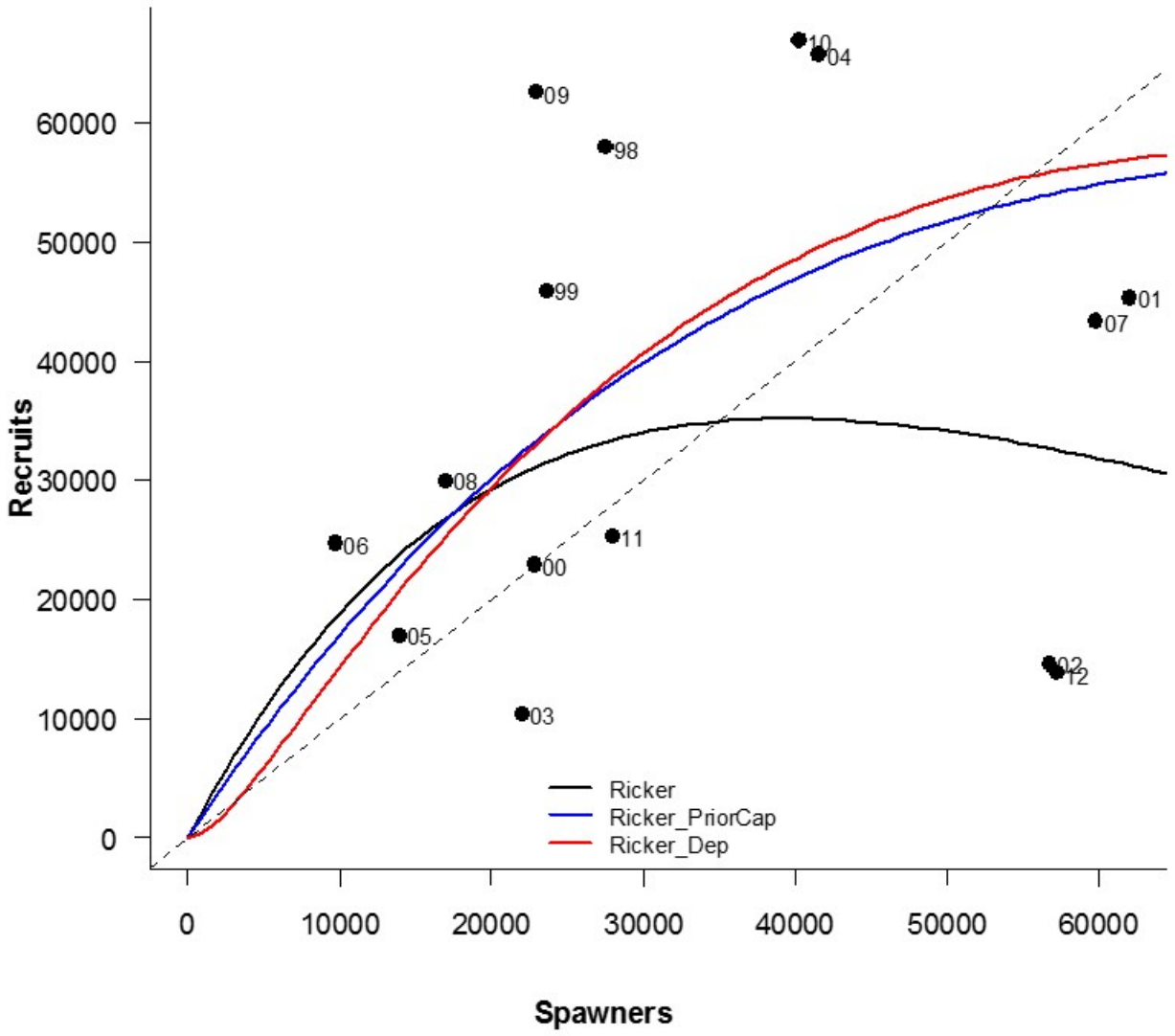


Figure 5. Comparison of three alternate Ricker stock-recruitment models for the IFC MU. All models were based on a hierarchical Bayesian structure with a hatchery smolt-adult marine survival index (HSASI) covariate. The black, blue, and red lines are based on a Ricker model with no informative priors (Ricker, Figure 1), a Ricker model with an informative prior on a larger carrying capacity (Ricker_PriorCap, Figure 2), and a Ricker model with an informative prior on a larger carrying capacity and depensation (Ricker_Dep, Figure 3), respectively. The MU stock-recruit curves were based on summing CU-specific recruitments at each spawning stock size. The text beside each point denotes the brood year. See the caption for Figure 1 for additional details.

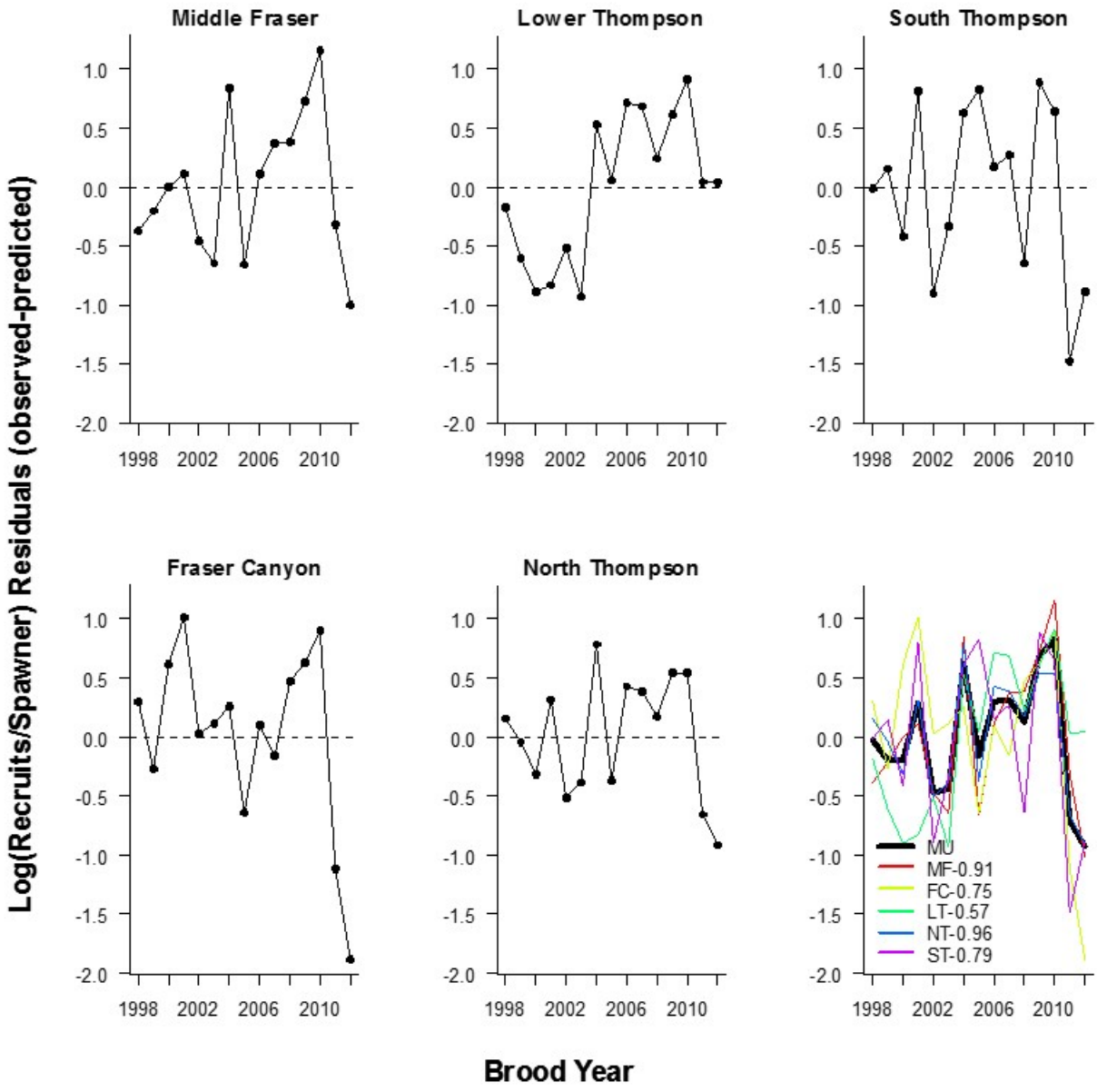


Figure 6. Residuals from the Ricker model with a hatchery smolt-adult marine survival index covariate without informative priors (Figure 1) by brood year for each IFC conservation unit (CU).The lower-right plot shows the mean annual deviations across CUs (thick black line) and CU-specific deviations (colored lines). The values in the legend of the lower-right plot are the correlations (Pearson 'r' values) of residuals between each CU and the aggregate trend.

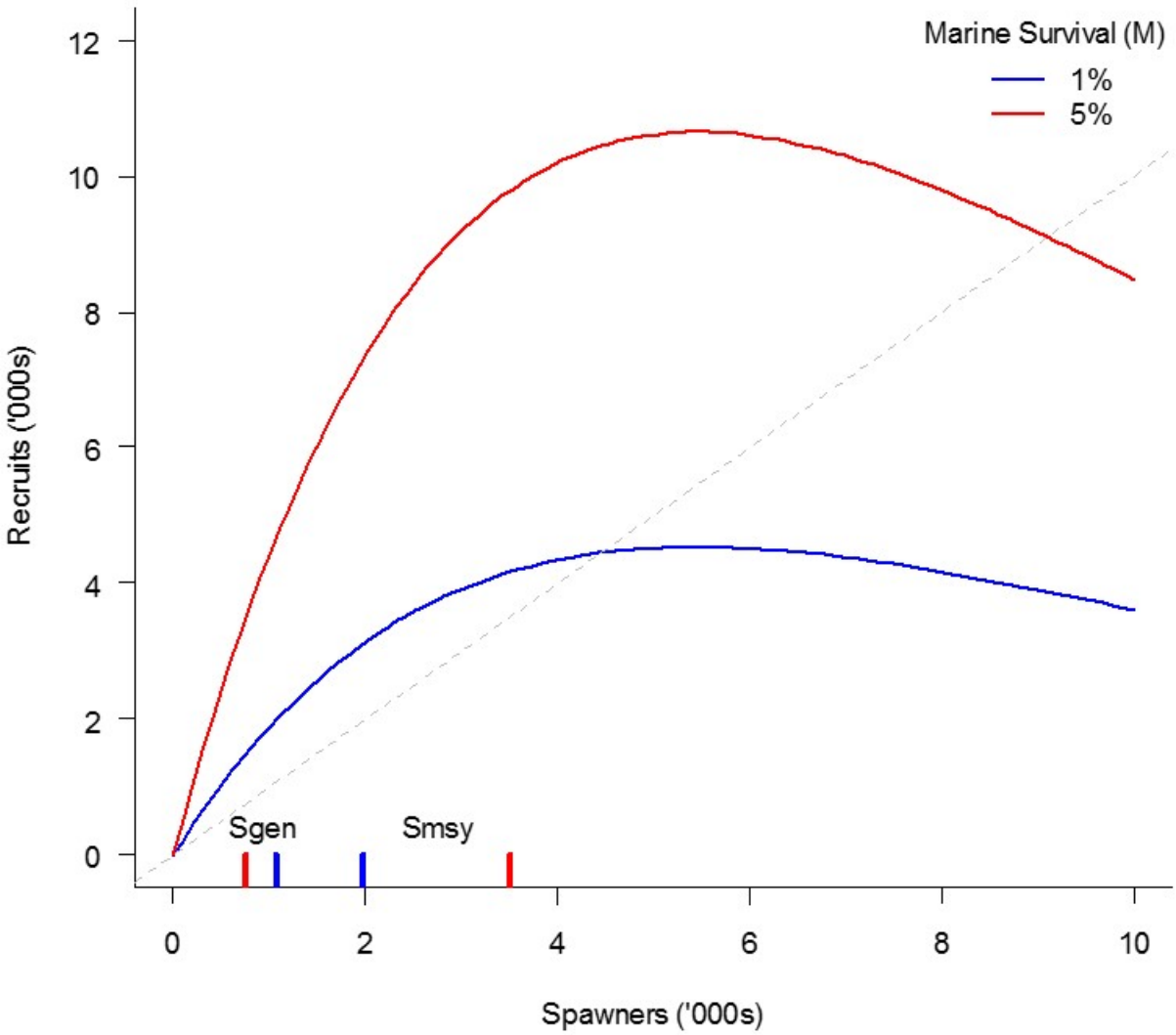


Figure 7. Comparison of stock-recruitment models for the Middle Fraser conservation unit based on smolt-adult marine survival rates of 1% and 5%. The dashed diagonal line is the 1:1 replacement line. Also shown are the escapements required to maximize yield (Smsy) and to attain Smsy in one generation (Sgen) predicted from the stock-recruitment curves. These curves were based on the hierarchical Bayesian Ricker model without informative priors on carrying capacity or depensation.

ConObj1: Escapement ≥ 1000 for half of subpopulations in each CU

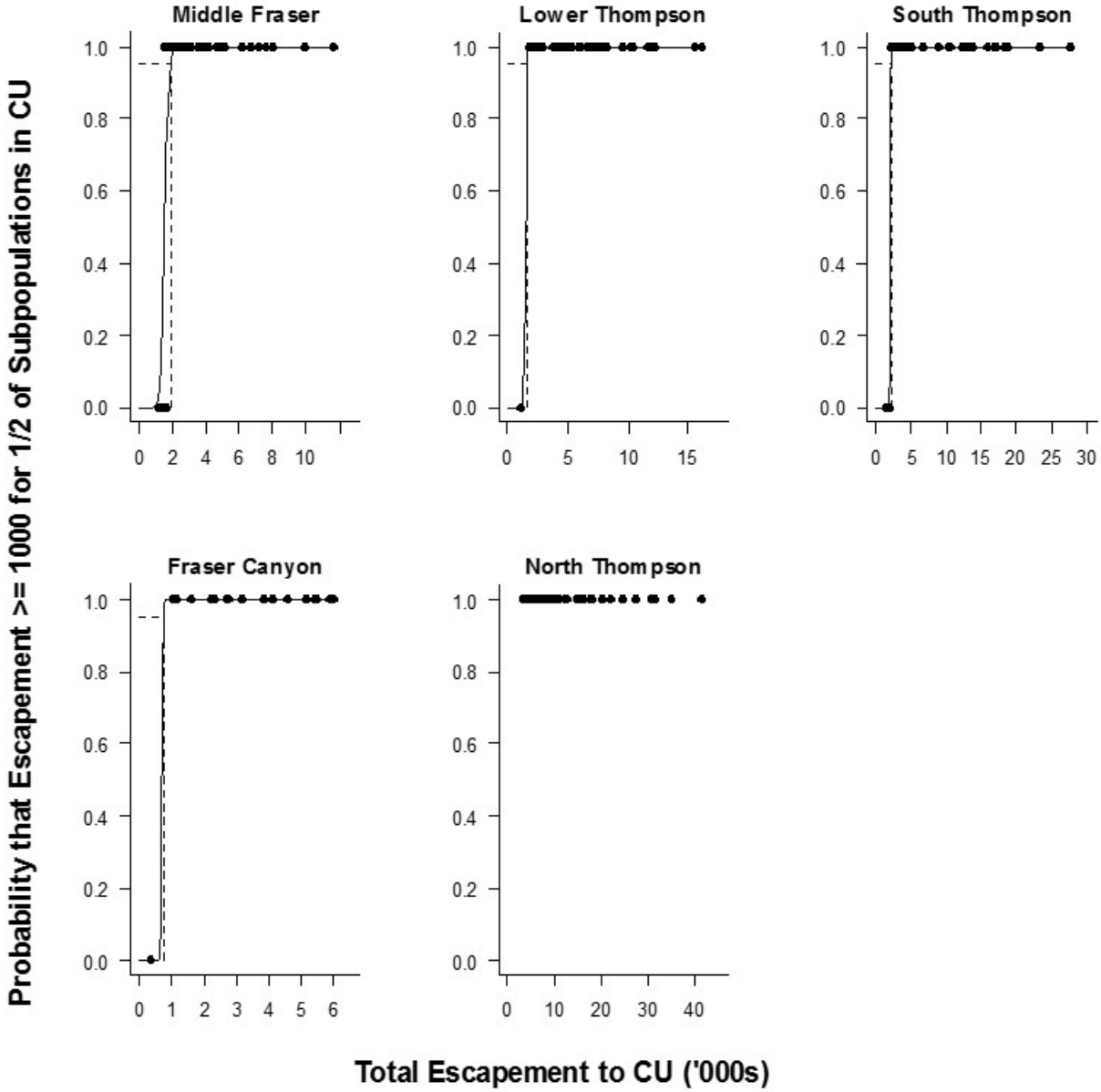


Figure 8. Logistic regression models predicting the probability that escapement will meet or exceed a conservation limit of 1,000 spawners in (a) half, or (b) all, of the subpopulations within a conservation unit (CU) as a function of the total escapement to the CU.The solid lines show predictions from logistic regression models and the points show the observed total escapement to each CU by year and whether 1,000 or more spawners returned to half or all of the subpopulations (0=no, 1=yes). The dashed lines show the total escapement to the CU required to meet or exceed 1,000 spawners in half or all of the subpopulations 95% of the time. Results are based on escapement data from 1984-2015, except for the Fraser Canyon CU where reliable data are only available from 1998-2015.

ConObj2: Escapement at least 1,000 for all subpopulations in each CU

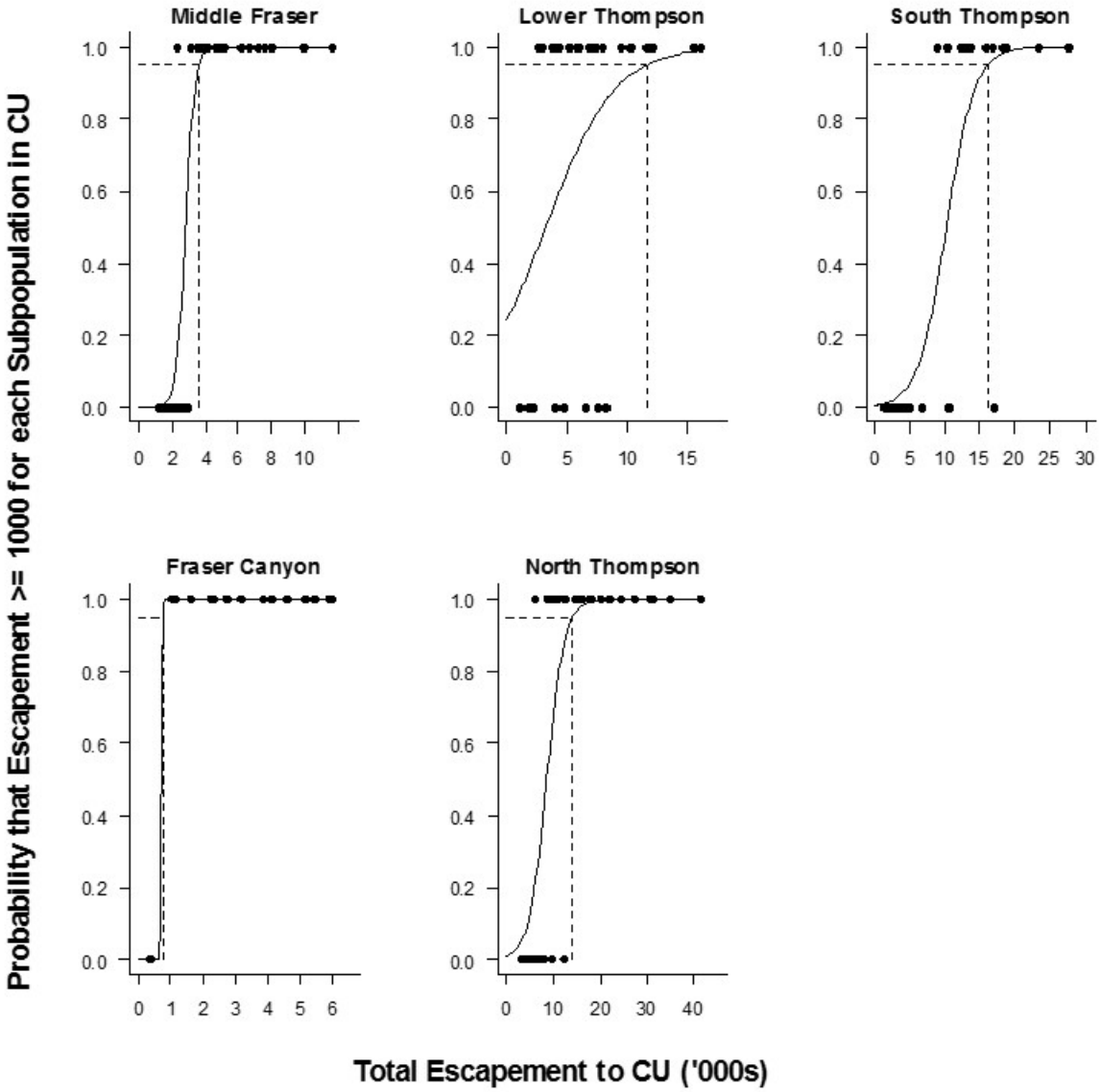


Figure 8. Con't

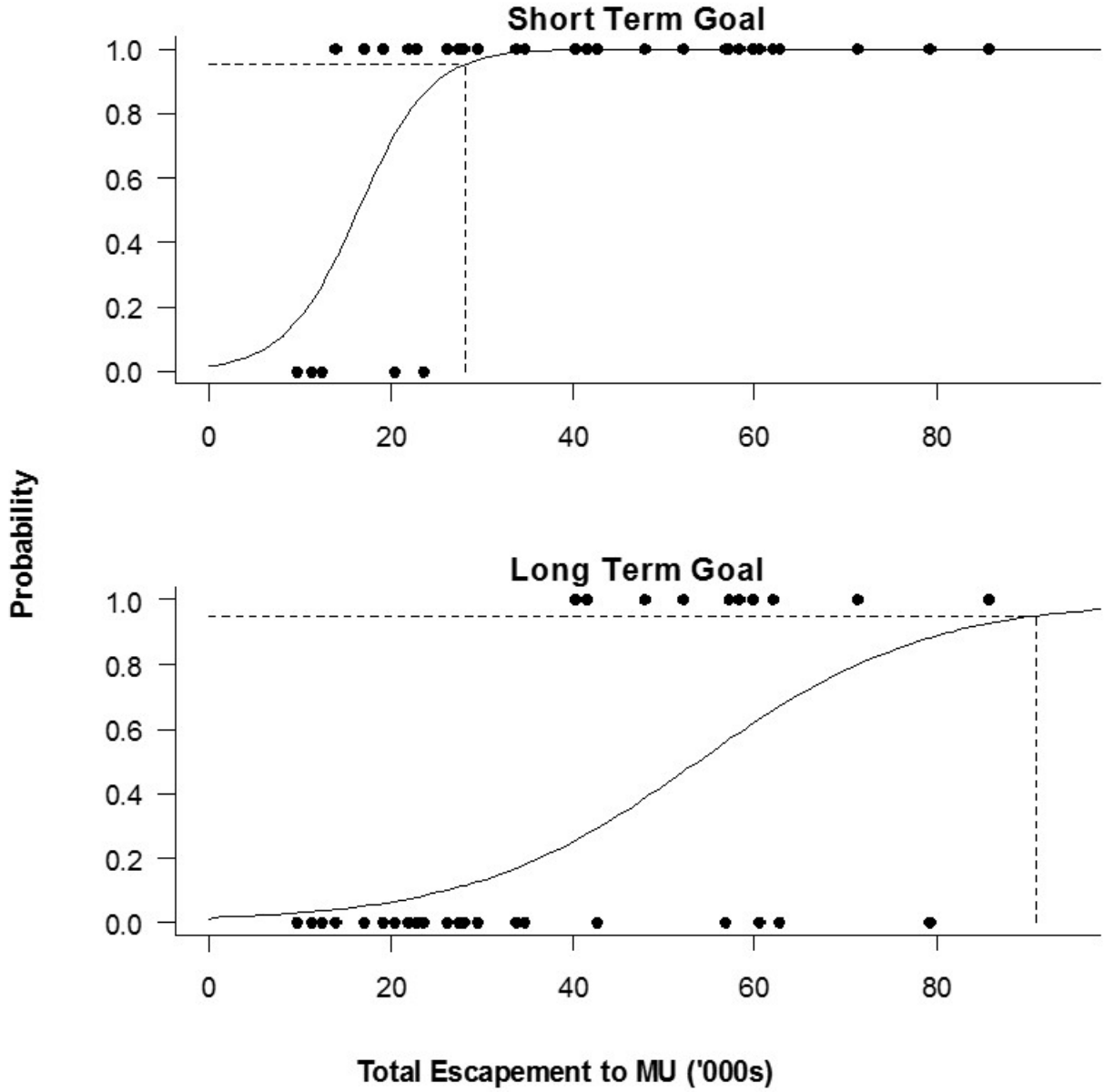


Figure 9. Logistic regression models determining the probability that half (short-term IFCRT goal) or all (long-term IFCRT goal) Interior Fraser Coho (IFC) sub-populations will have escapements of 1,000 or greater in the same year as a function of the total escapement to the IFC management unit (MU). Results are based on escapement data from 1984-2015.

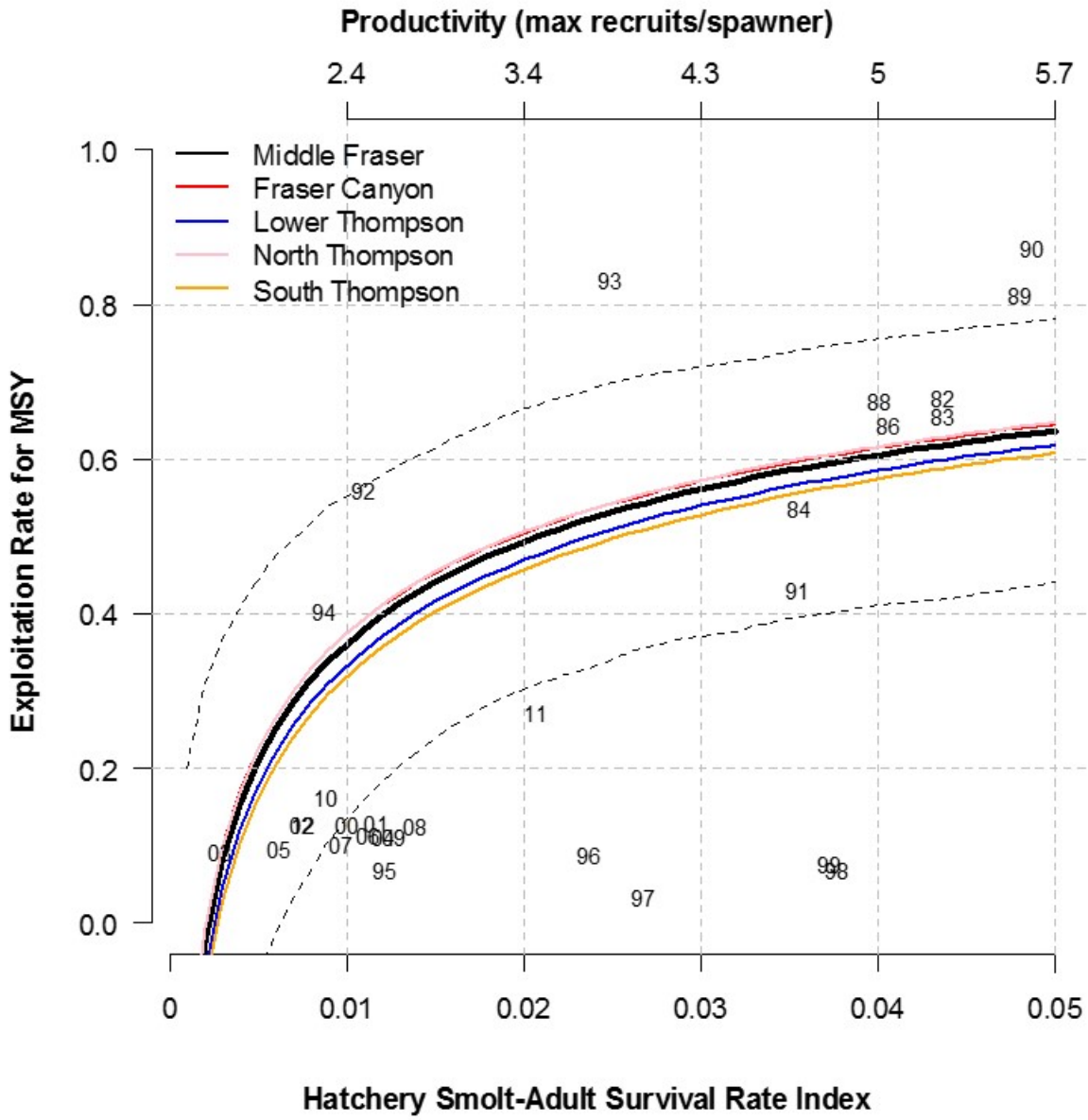


Figure 10. Isopleths describing the relationship between the hatchery smolt-adult marine survival rate index (HSASI) and the exploitation rate to maximize sustainable yield (Umsy).The solid and dashed lines black lines show the mean and 95% credible intervals for the conservation unit (CU) with the lowest productivity (Middle Fraser), respectively. Colored lines show the mean relationship for other interior Fraser River CUs. The isopleths were calculated based on the posterior distribution of parameters from the hierarchical Bayesian HSASI without informative priors (Figure 1) by substituting different values of smolt-adult marine survival into equation 3 to compute α', and then calculating Umsy based on $0.5 \cdot \alpha' - 0.07 \cdot \alpha'^2$. Productivity associated with smolt-adult marine survival values shown on the bottom x-axis were calculated as $e^{\alpha'}$ and are shown in the top x-axis (for the Middle Fraser CU). Points show the smolt-adult marine survival and exploitation rates for each brood year.

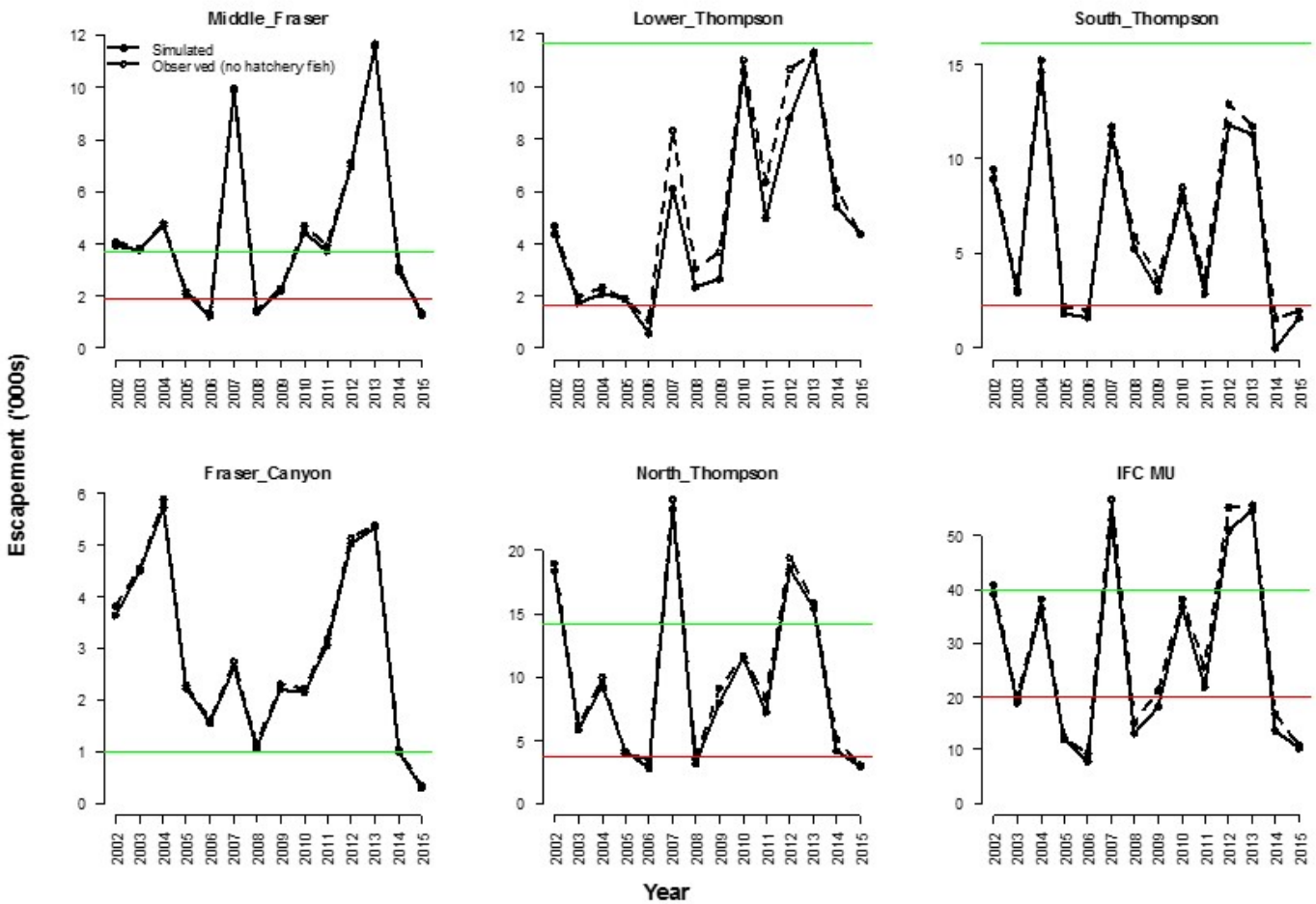


Figure 11. Comparison of simulated and observed naturally-produced escapement for each conservation unit (CU) and the sum of escapements across CUs (IFC MU) based on the base Ricker model (i.e., without informative priors; Figure 1). Simulated escapements are based on the historical values of hatchery smolt to adult survival and exploitation rates (including within river ER) and mean parameters for each CU-specific stock-recruitment relationship, and mean values of residuals for each CU-year-age data point. The horizontal red and green lines show the short-(ConObj1) and long-(ConObj2) term conservation objectives for each CU and MU-specific benchmarks (20,000 and 40,000), respectively.

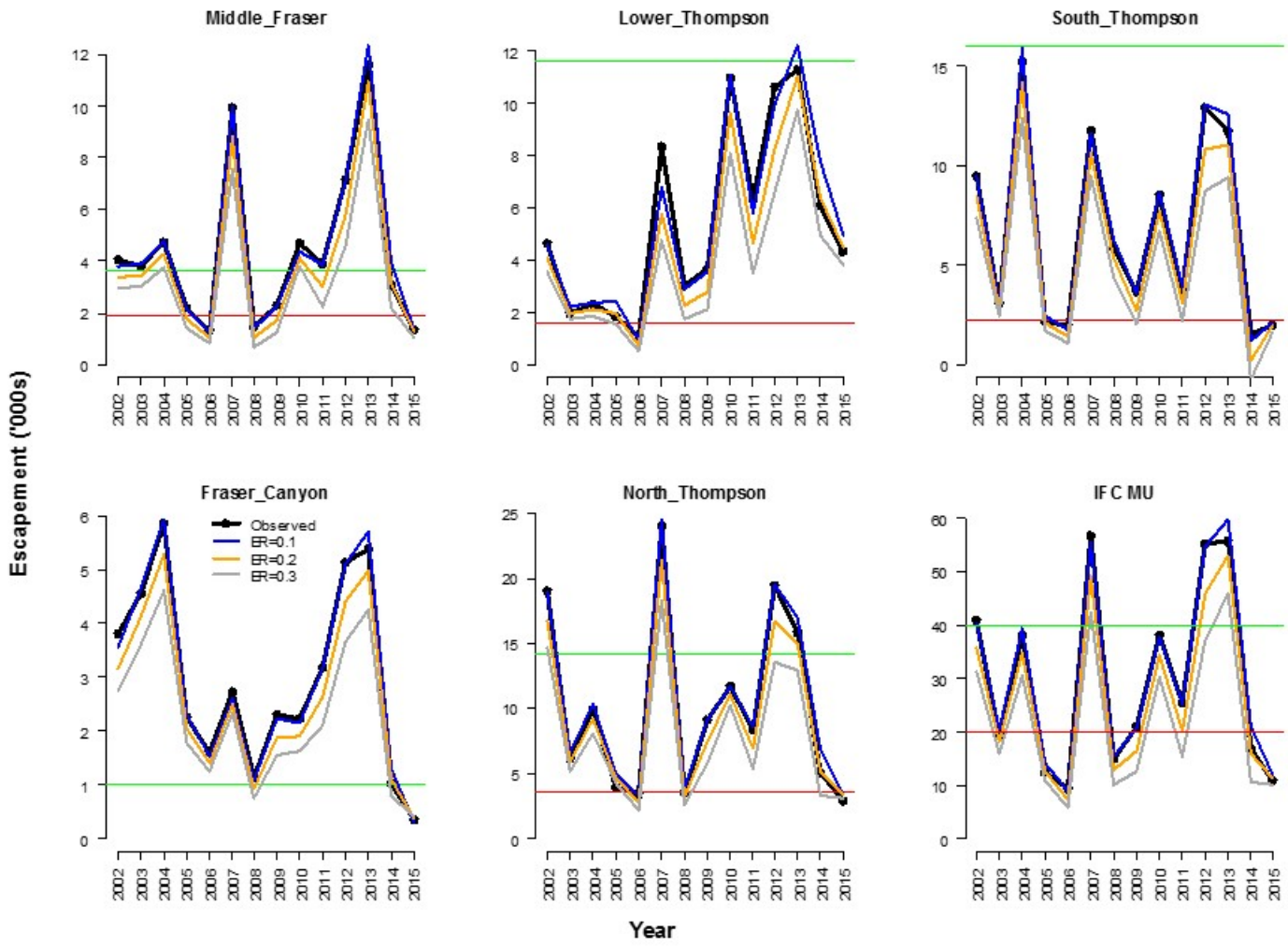


Figure 12. Comparison of simulated and observed escapement for each IFC conservation unit (CU) and for the entire management unit (IFC MU). Simulated escapements are based on the Ricker curve with uninformative priors (Figure 1), mean CU-specific stock-recruit parameters, mean CU- and year- and age-specific residuals, and historical values of smolt-adult hatchery survival. Results are based on constant exploitation rates (ER) of 10%, 20%, and 30%.

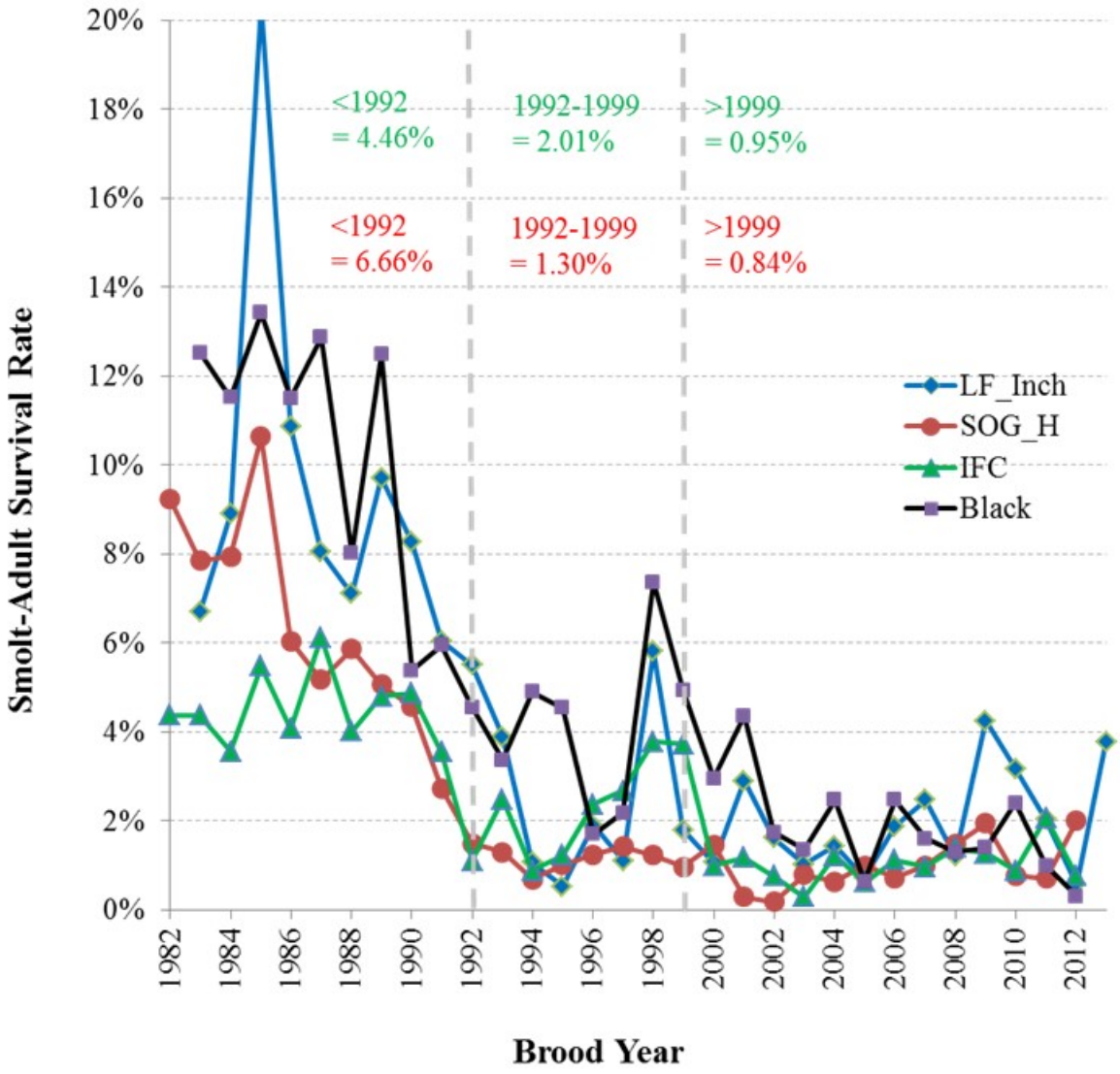


Figure 13. Trends in the smolt-adult marine survival rates for hatchery Coho indicator stocks for Lower Fraser (LFR, Inch Creek hatchery), Strait of Georgia (SOG_H, represented by Qualicum and Quinsam hatcheries), and Interior Fraser Coho (IFC) management units. Also shown is the trend for Black Creek, a wild population in the SOG. Vertical dashed grey lines denote pre-1992, 1992-1999, and post-1999 periods referred to in the text. Green and red text shows the geometric average survival rates for the IFC and SOG_H time series for three periods, respectively.

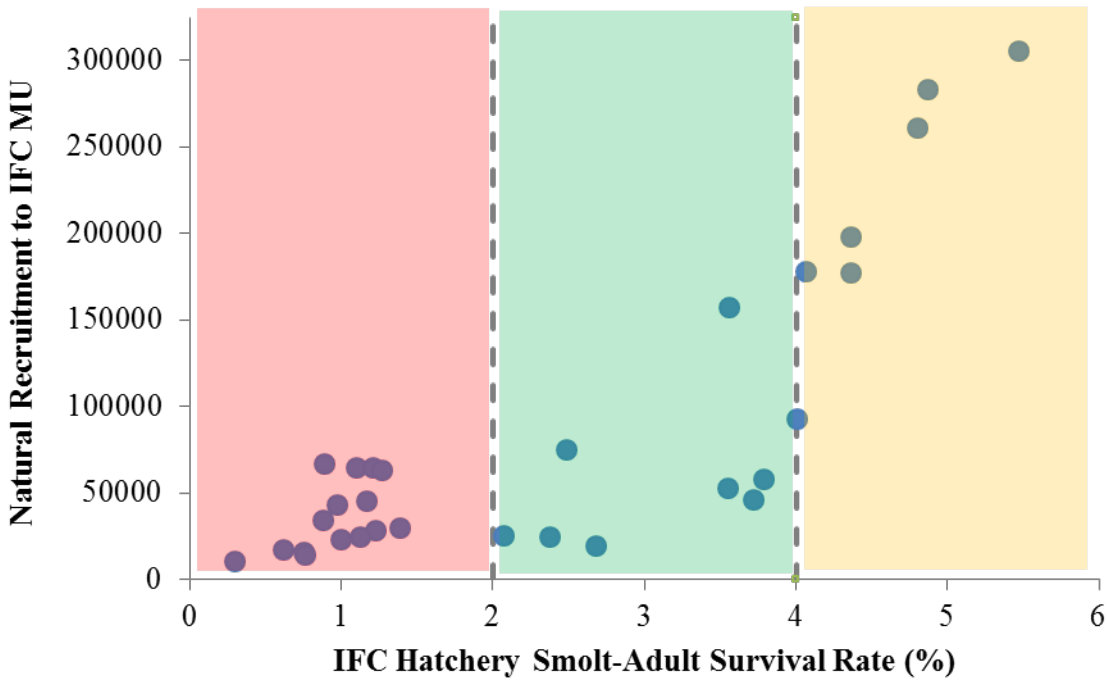


Figure 14. Relationship between the IFC hatchery smolt-adult marine survival rate and total natural recruitment to the IFC MU based on returns from brood years 1982-2012. Dashed vertical lines show 2% and 4% breakpoints used to distinguish low (red), moderate (orange), and abundant (green) status categories.

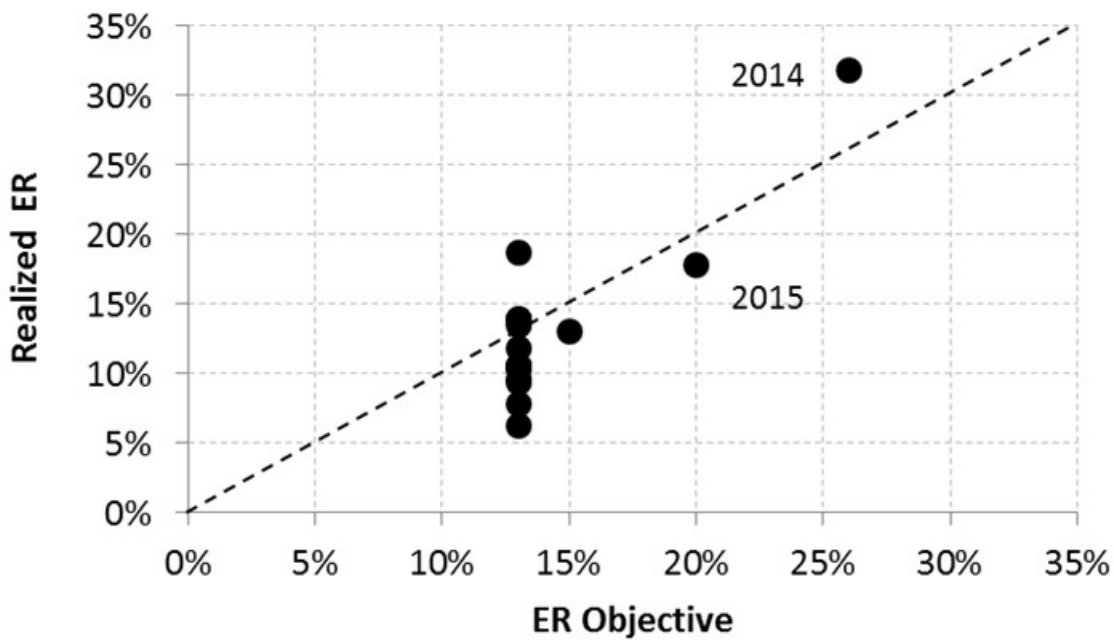


Figure 15. Comparision of estimated Interior Fraser Coho Salmon exploitation rates (Realized ER from FRAM model) and targeted exploitation rates (ER Objective) using data from 2001-2016.

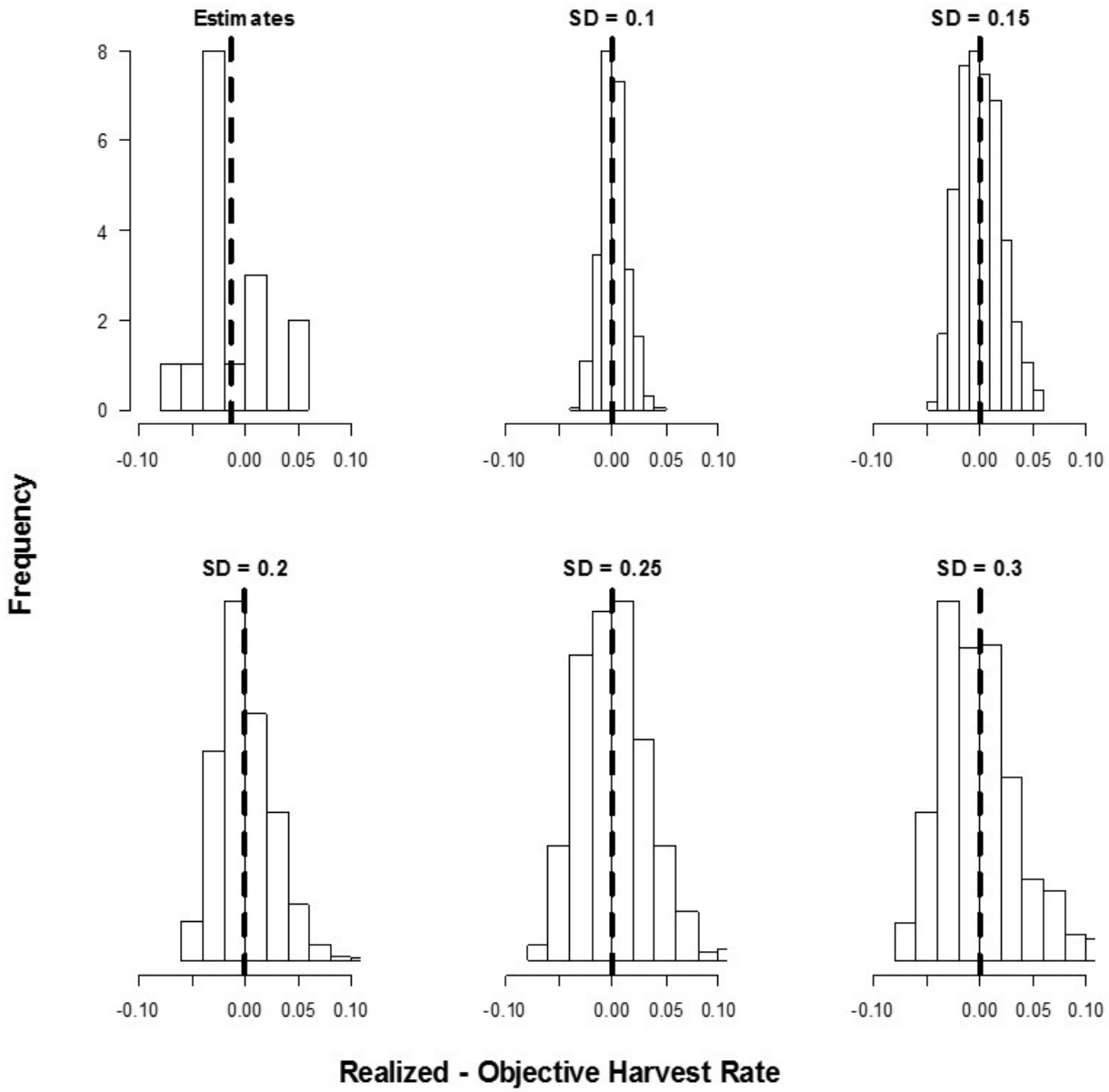
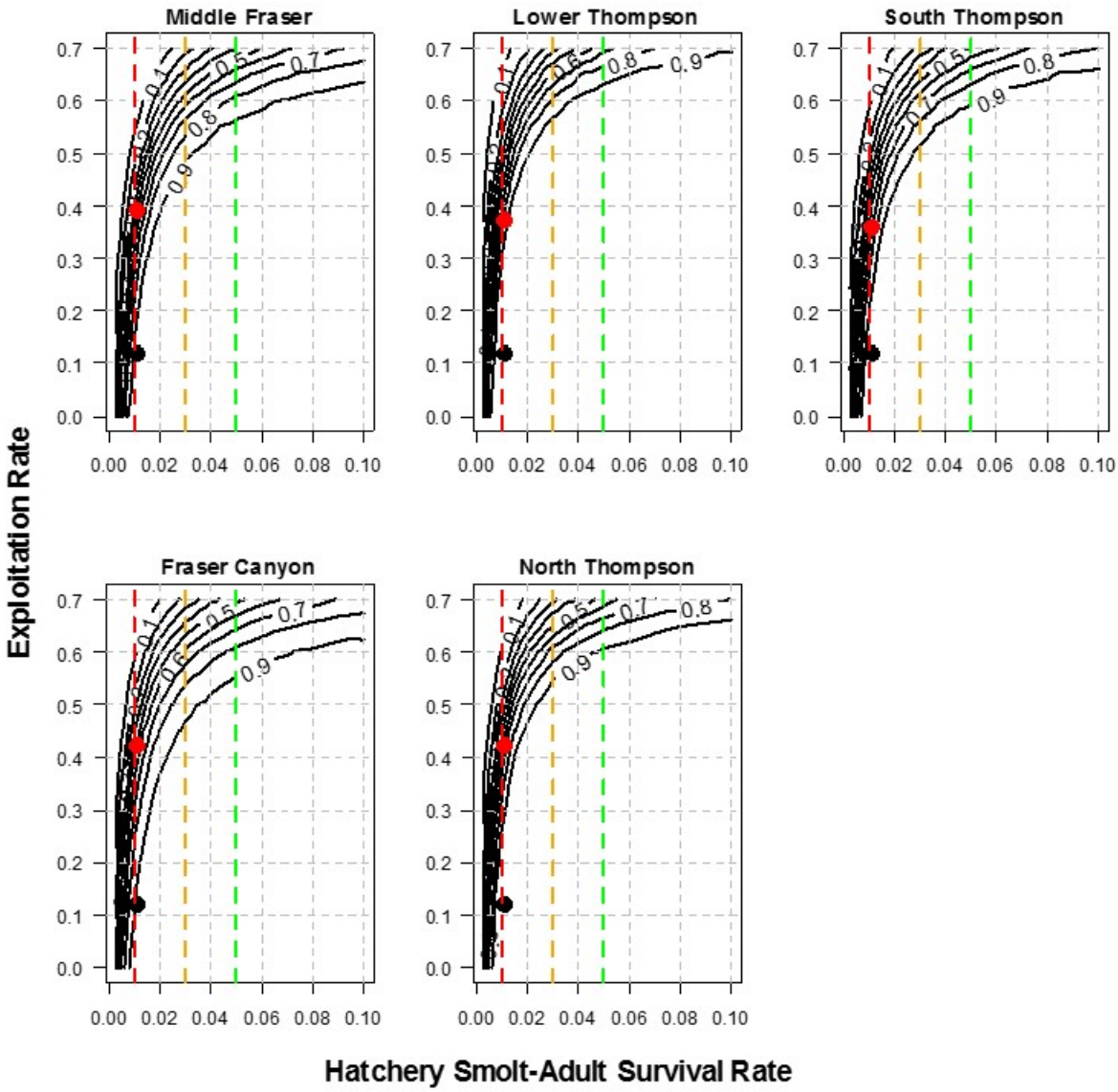
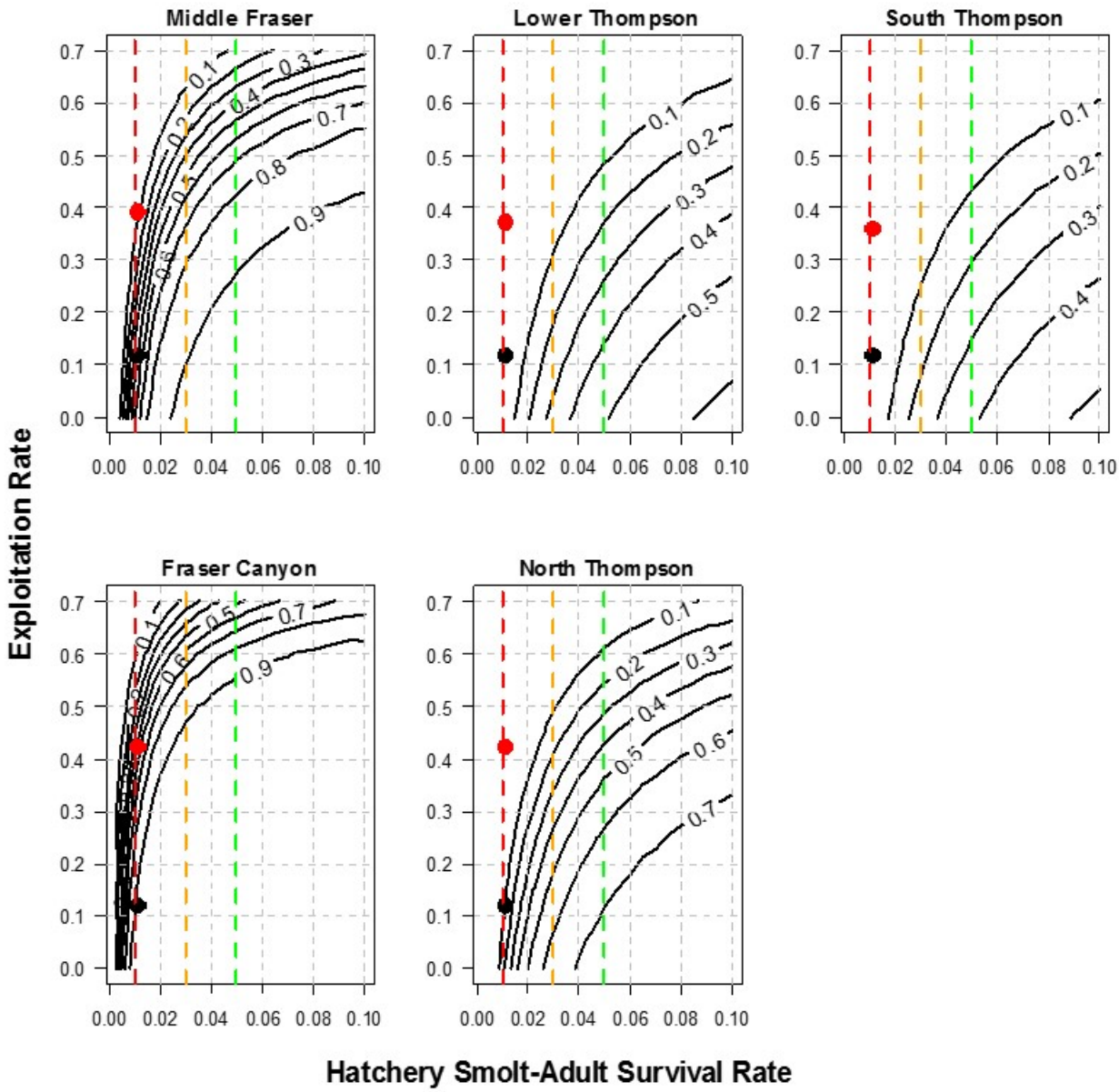


Figure 16. Observed and simulated harvest implementation error. The top-left plot ("Estimates") is a frequency distribution of the difference between the realized exploitation rate and the annual targeted exploitation rate for the IFC MU. The remaining plots show the difference between simulated and targeted exploitation rates under different assumed levels of harvest implementation error. SD denotes the standard deviation used to simulate harvest implementation error.



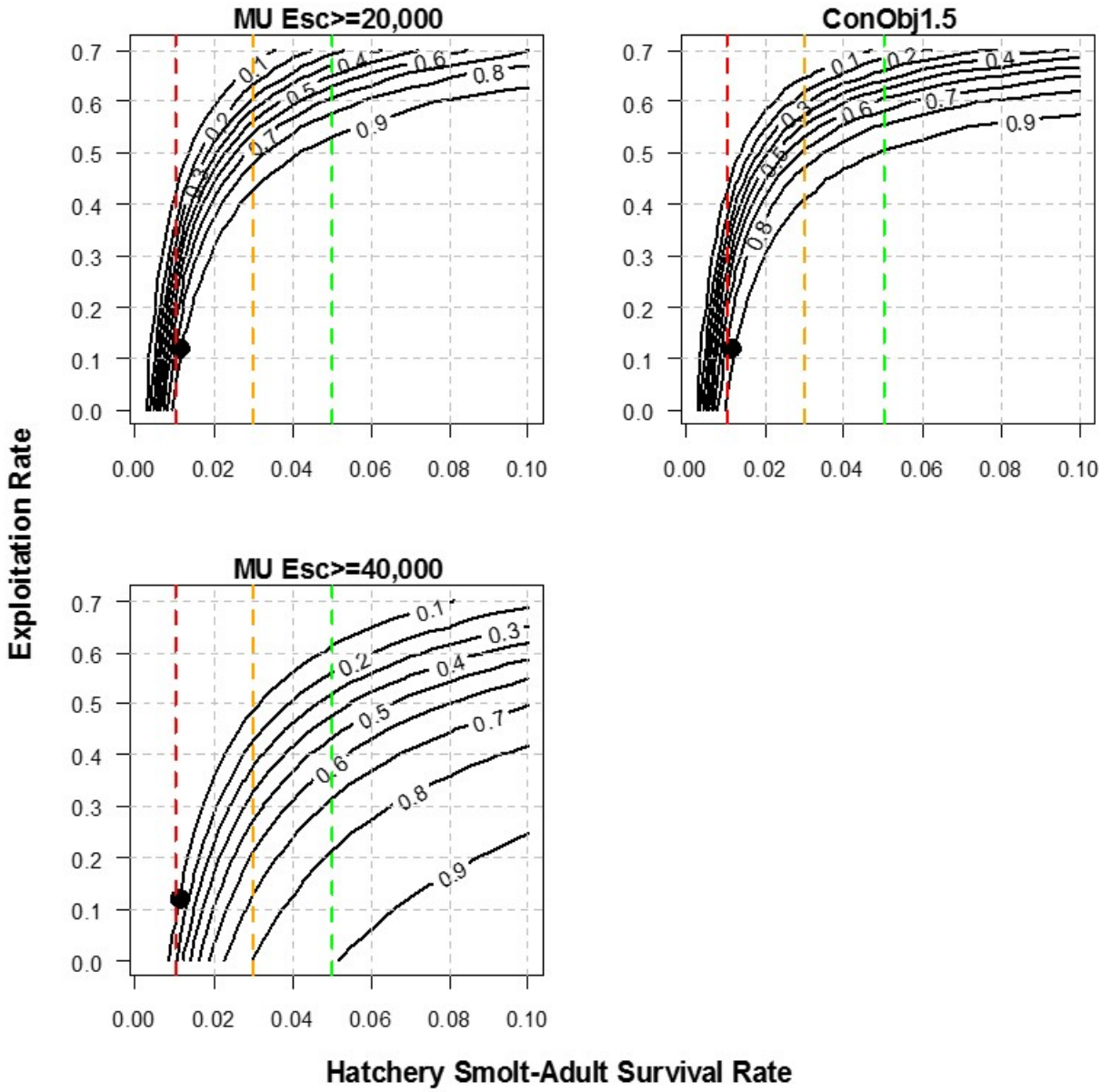
a) ConObj1: Escapement ≥ 1,000 for half of the subpopulations in each CU

Figure 17. Contour plots showing the probability that escapement will exceed: a) the total escapement to each CU that results in a 95% probability that at least half of subpopulations will have escapements of at least 1,000 spawners (ConObj1); b) the total escapement to each CU that results in a 95% probability that all subpopulations in the CU will have escapements of at least 1,000 spawners (ConObj2); c) the total escapement to the IFC MU meets or exceeds 20,000 and 40,000 fish or simultaneously exceeds ConObj1 for all CUs in the same year (ConObj1.5). Results are based on the base Ricker model (i.e., without informative priors on a larger carrying capacity or depensation), and a harvest implementation error rate of SD=0.2. Vertical, red, orange, and green lines show low, moderate, and high status as defined by hatchery smolt-adult marine survival rates of 0.01, 0.03, and 0.05. The black points show the average smolt-adult marine survival and exploitation rates from 1998-2015. Red points show the exploitation rate to produce MSY (Umsy) under the average smolt-adult marine survival rate.



b) ConObj2: Escapement ≥ 1000 for all subpopulations in each CU

Figure 17. Con't.



c) MU targets >=20,000, 40,000, escapement to each CU ≥ 1000 for at least half of all subpopulations in each CU in same year (ConObj1.5, CU Esc>Obj1, all CUs)

Figure 17. Con't.

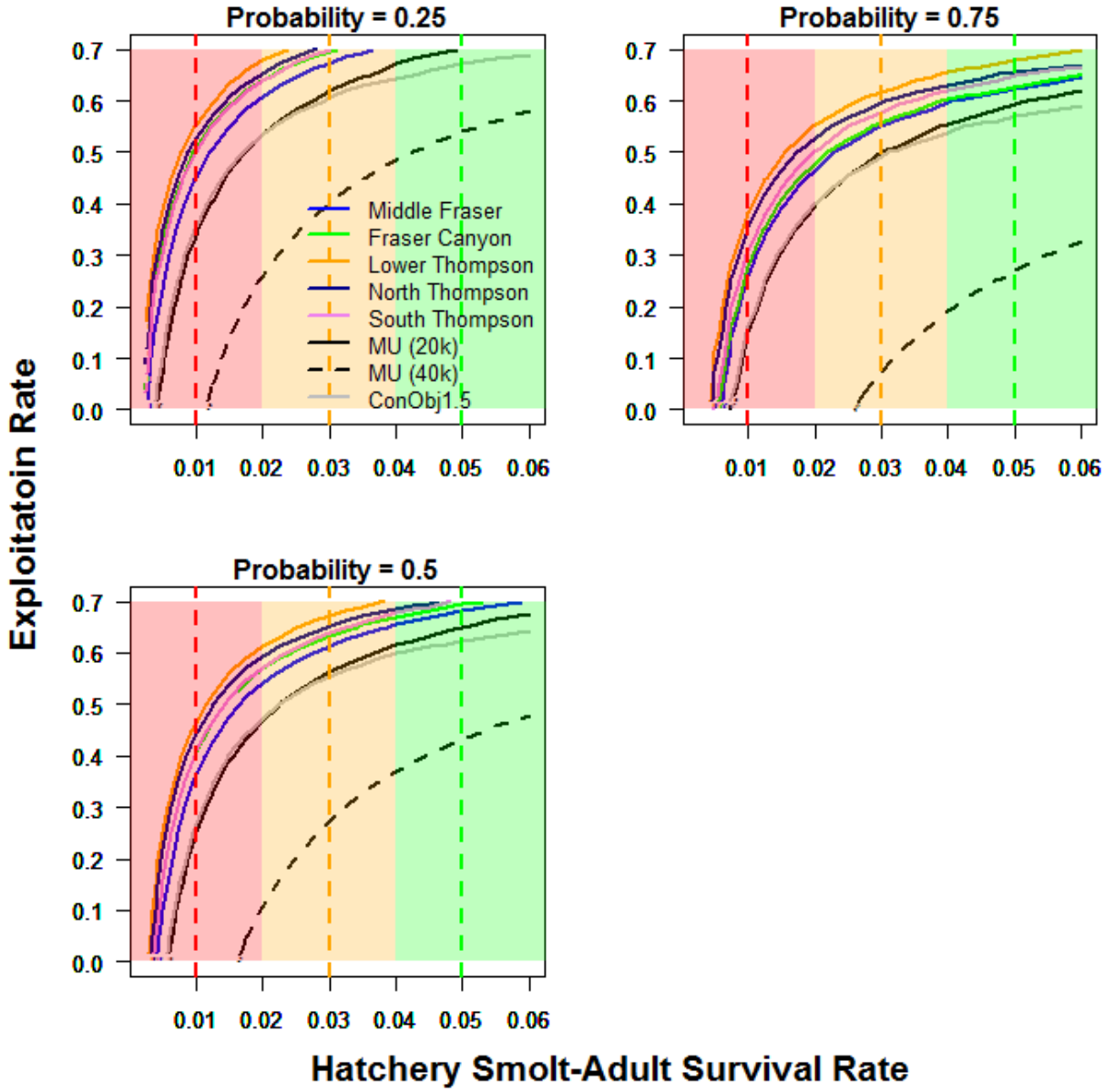


Figure 18. Exploitation and hatchery smolt-adult marine survival rates that result in a 0.25, 0.50, and 0 75 probability of meeting various IFC conservation objectives based on the base Ricker model (i.e., without informative priors on carrying capacity or depensation). See caption for Figure 17 for additional details.

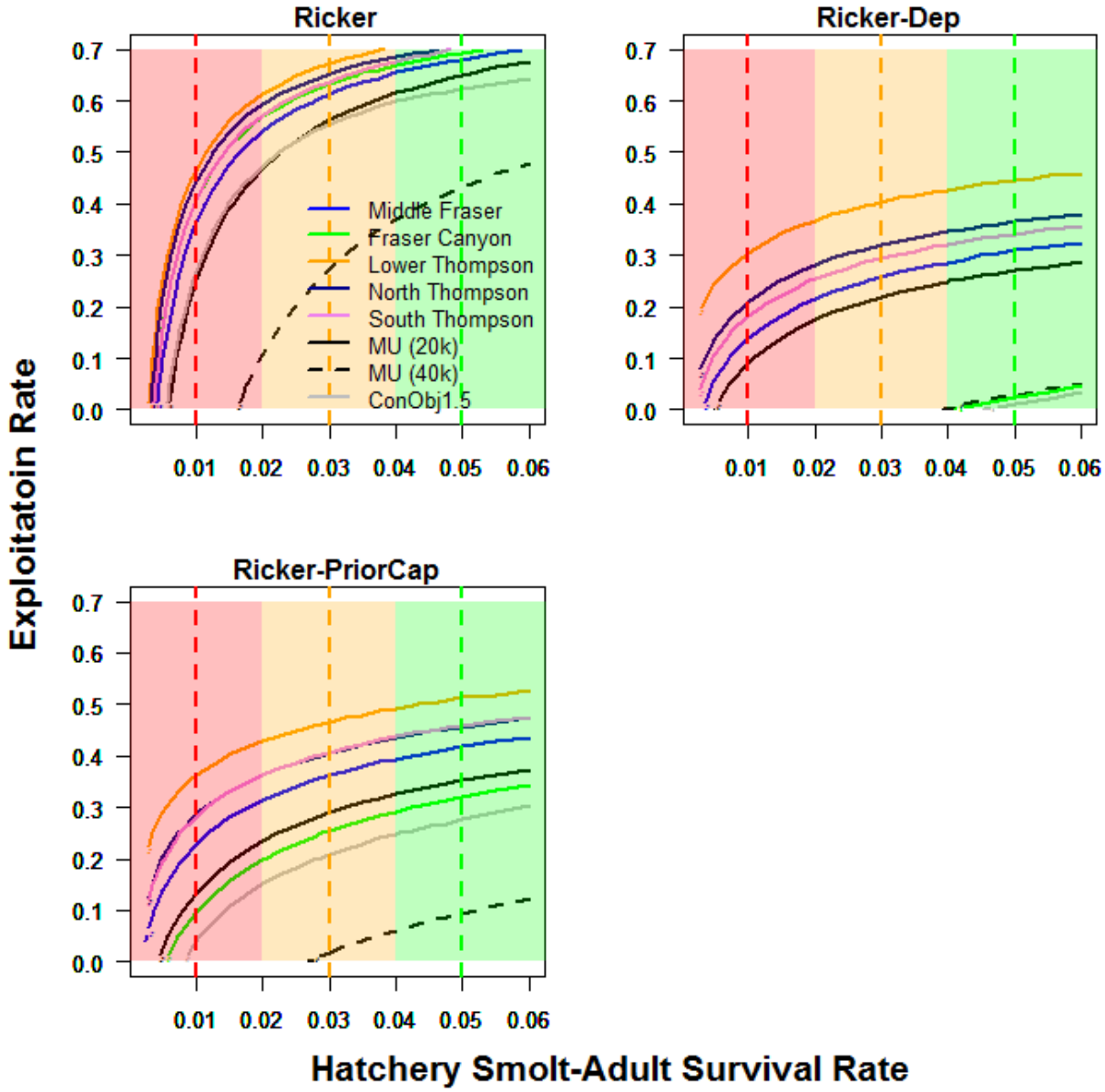


Figure 19. Exploitation and hatchery smolt-adult marine survival rates that result in a 50% probability of attaining a variety of conservation benchmarks for the IFC MU based on three alternative stock-recruitment models. See caption for Figure 17 for additional details.

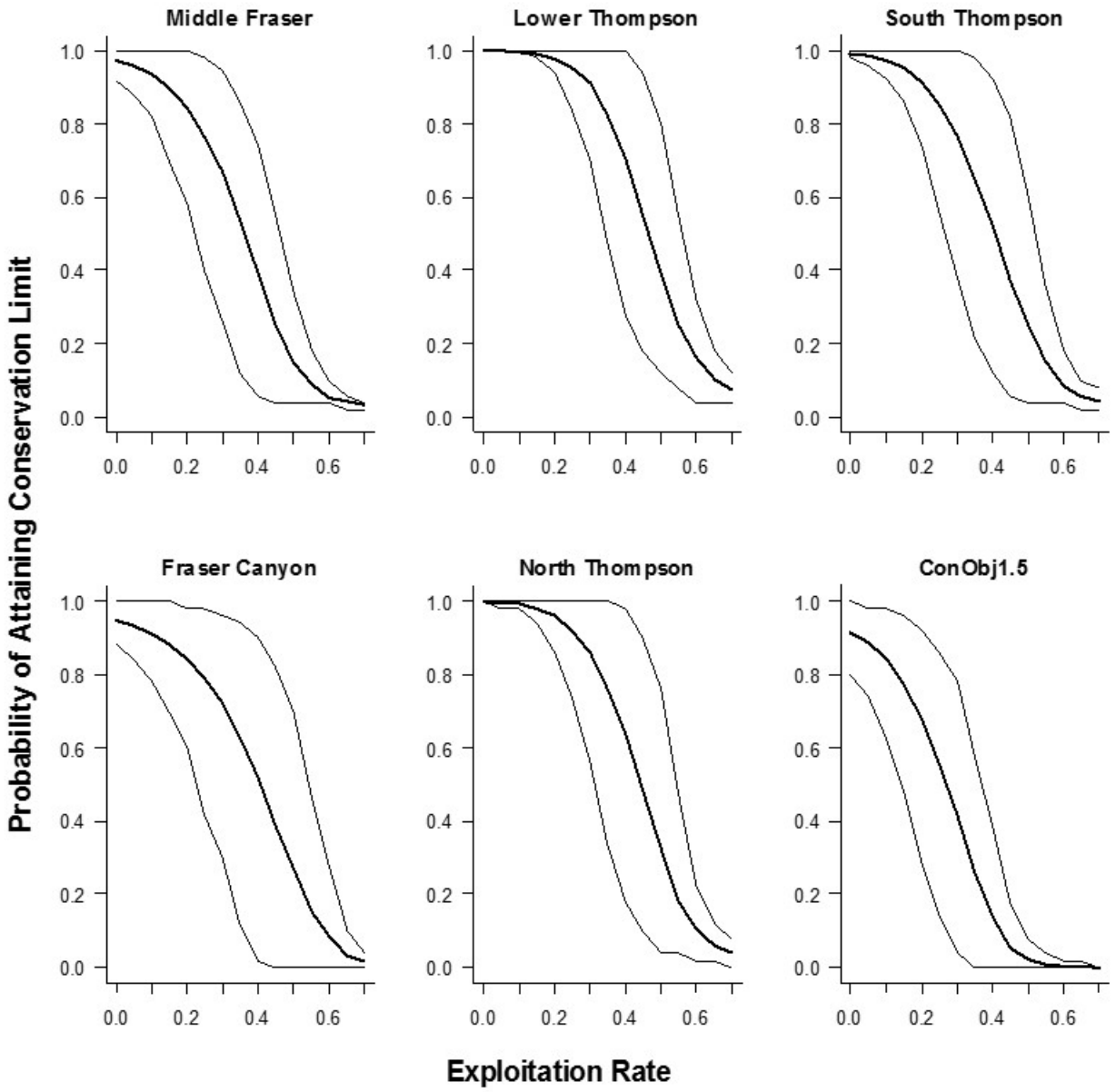


Figure 20. Uncertainty in prediction of the probability of meeting or exceeding the short-term conservation objective (ConObj1) for each Interior Fraser conservation unit (CU) and for all CUs in the same year (ConObj1.5) at a hatchery smolt-adult marine survival rate of 1% and a harvest implementation error rate of SD=0.2.The thick line represents the mean conservation performance among 500 trials and thin lines show the 10% and 90% credible intervals. Results are based on the base Ricker model (i.e., without informative priors on carrying capacity or depensation).

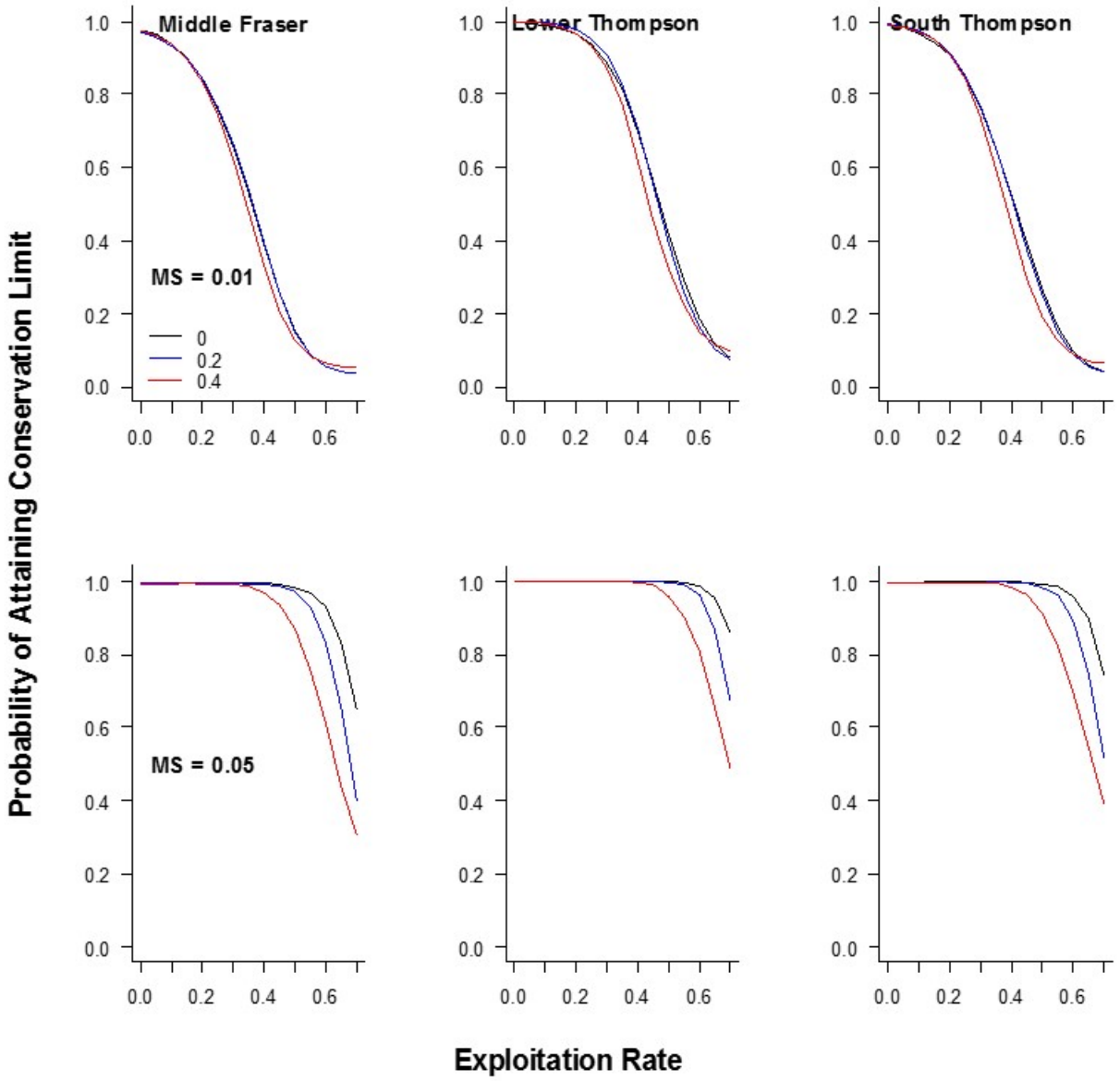


Figure 21. Comparison of probabilities that escapement will exceed the short-term conservation objective (ConObj1) under harvest implementation error rates of SD=0 (black lines), 0.2 (blue lines), and 0.4 (red lines) based on hatchery smolt-adult marine survival rates of 0.01 (top panel) and 0.05 (bottom panel) for three Interior Fraser Coho CUs. Results are based on the base Ricker model (i.e., without informative priors on larger carrying capacity or depensation).

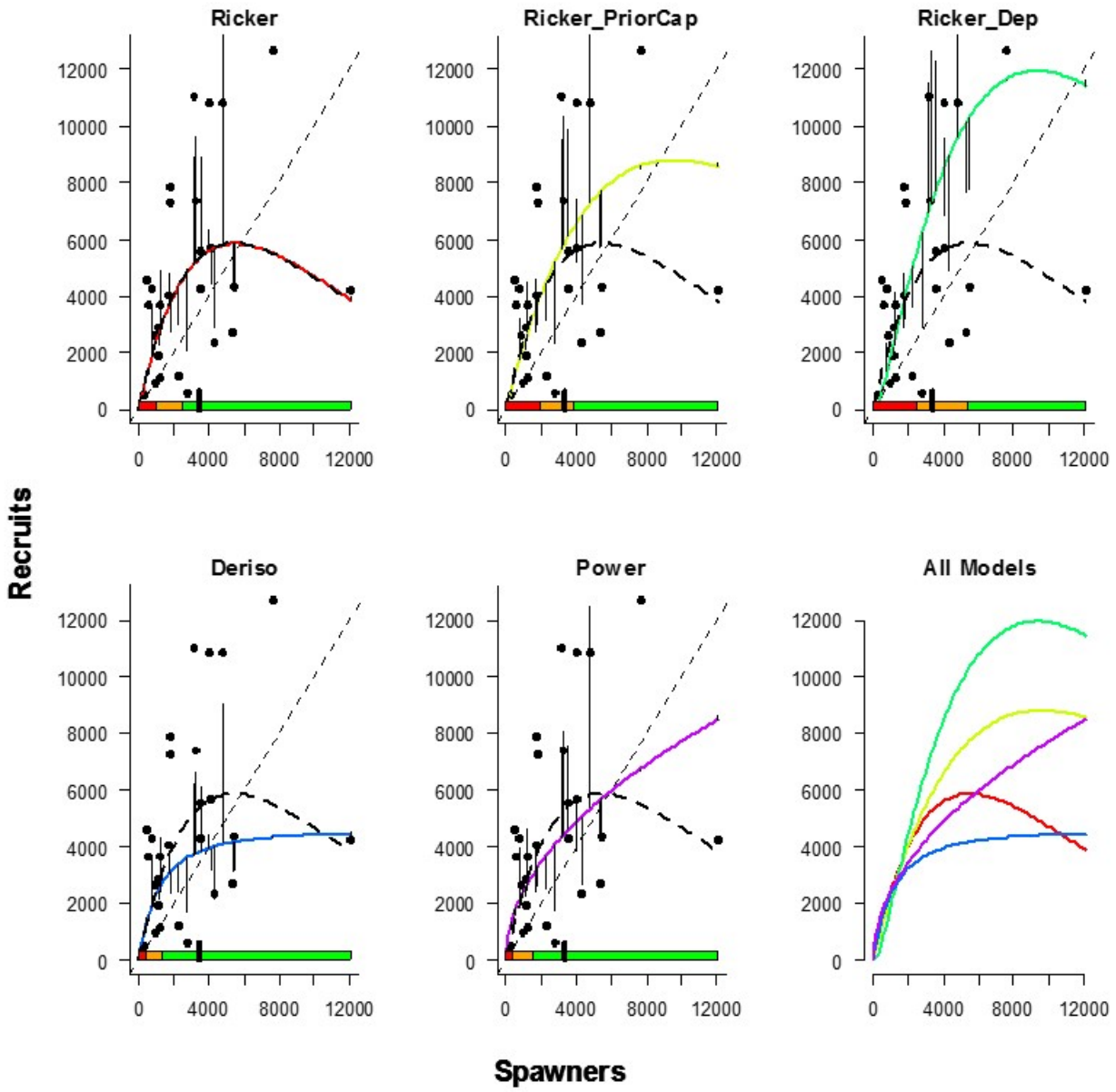


Figure 22. Stock and recruitment data from Black Creek and expected relationship that include smolt-adult marine survival index covariate effects (colored lines) and the standard Ricker model without a survival covariate (heavy black dashed line).For the survival covariate models, the colored lines the predictions at the average survival rate and the vertical lines represent predictions of recruitment in each year based on annual survival values. The diagonal dashed line is the replacement line. The benchmarks shown by the colored rectangles at the bottom of each plot are the escapement required to reach the escapement that maximizes yield in one generation (Sgen, red-orange break), and the escapement that maximizes yield (Smsy, orange-green break). The geometric mean escapement for the last generation (2013-2015) is shown by the thick short black line overlaid on top of the benchmarks.

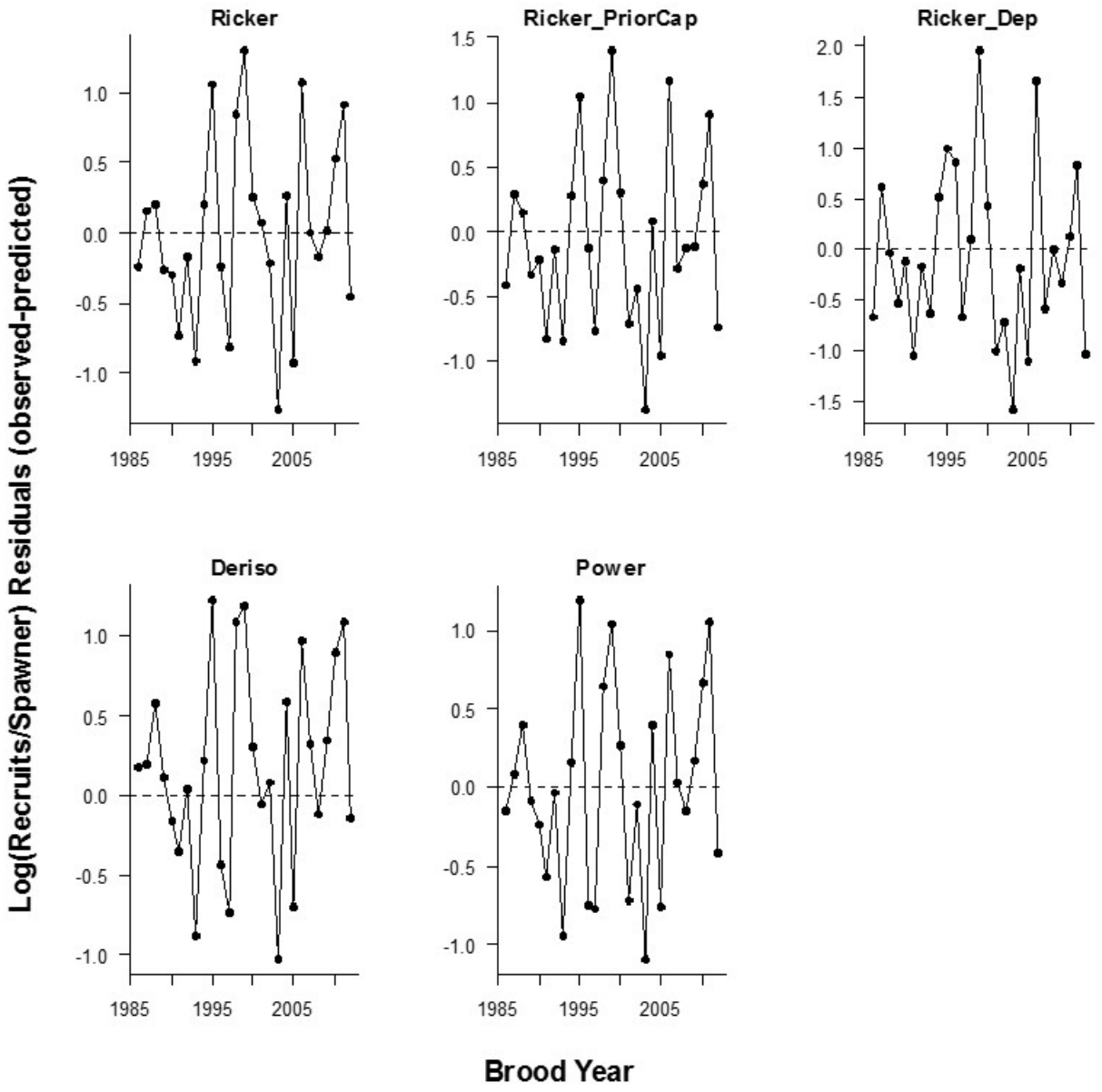


Figure 23. Residuals from stock-recruitment models with smolt-adult marine survival covariate effects. See caption for Figure 22 for additional details.

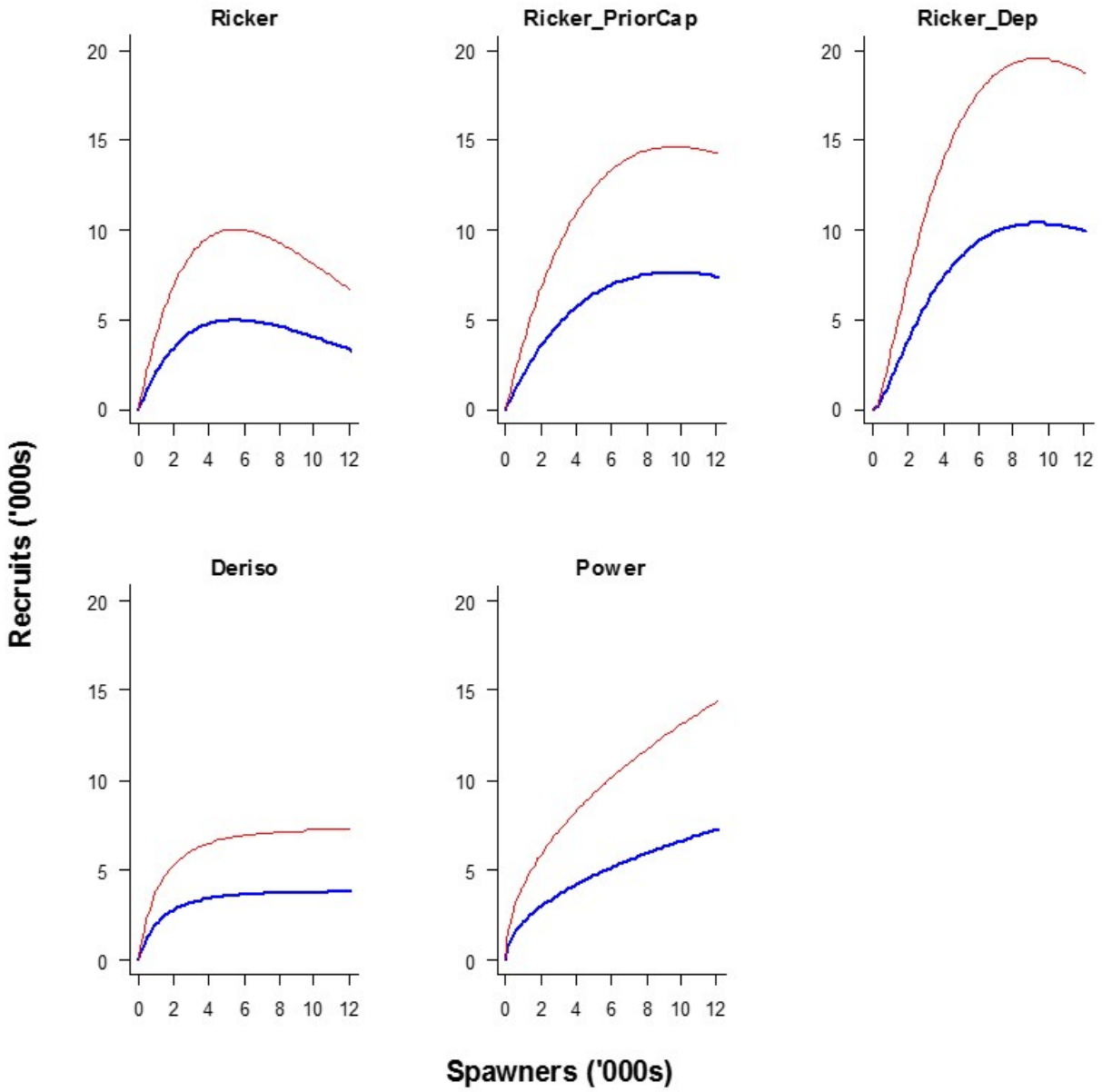


Figure 24. Predicted stock-recruitment models with smolt-adult marine survival covariate values of 1% (blue lines) and 5% (red lines). See caption for Figure 22 for additional details.

APPENDIX A. DETAILS OF INTERIOR FRASER COHO RECRUITMENT RECONSTRUCTION

Age information for Interior Fraser Coho through 2016 was assembled, and known hatchery-origin fish were removed. For each year of sampling the proportion of age-3s in the return year *t* (*pAge3RY*$_t$) was computed. The proportion of age-3 fish in each brood year was calculated as:

$$pAge3BY_t = \frac{pAge3RY_{t+3}RET_{t+3}}{pAge3RY_{t+3}RET_{t+3} + pAge4RY_{t+4}RET_{t+4}} \qquad \text{Equation 11.}$$

where RET refers to the pre-fishery total abundance in year *t*. This equation accounts for the relative abundance in each of the 2 return years (*t+3* and *t+4*) that recruits from a single brood year contribute to.

We observed that *pAge3BY* was related to the size of the cohort (Figure A1). Large cohorts had very high proportions of age-3s whereas that proportion decreased with decreasing brood strength. A similar relation was observed for each of the 3 CUs that had sufficient age data. The proportion of age3s in a brood year also varied with pre-fishery return abundance 3 years later as 3 year olds were dominant in the return year. Because brood year age distribution varied with total abundance, total abundance could be used to predict age composition for each brood year.

The proportion age-3 for brood year *t* was predicted from the returns in year t+3 with logistic model:

$$pAge3BY_t = \frac{e^{s_0+s_1RET_{t+3}}}{1+e^{s_0+s_1RET_{t+3}}} \qquad \text{Equation 12.}$$

The logit transformation was applied to predict and observed values and the parameters s_0 and s_1 were solved by minimizing the least-squares residuals. The mean was subtracted from return data to standardize parameters.

There are 2 CUs with 2 few data to estimate this relation (MF and FC). Instead, parameters for the 3 CUs were averaged to derive a composite relation to predict values for these CUs. For CUs with data, there is the option of using the empirical age composition data and infilling missing data with the predicted values, or only using the predicted values. We chose to use the predicted values to eliminate variation due to small sample sizes or variation in spatial distribution of samples among years.

Total return for each year RET_t can be calculated from the contributions of each brood year as:

$$RET_t = pAge3BY_{t-3}REC_{t-3} + pAge4BY_{t-4}REC_{t-4} \qquad \text{Equation 13.}$$

Where REC is the total recruitment of the 2 contributing brood years that will return in year t. Using matrix methods, this is equivalent to:

$$\boldsymbol{A} \cdot \boldsymbol{REC} = \boldsymbol{RET} \qquad \text{Equation 14.}$$

Where **RET** is a *nx1* vector of returns for *n* years, **REC** is a *n*x1 vector of recruitments, and **A** is *nxn* matrix with the age-3 proportion on the diagonal and the age-4 proportion for the same brood year below it (example for n = 4):

$$\begin{bmatrix} P_3 & 0 & 0 & 0 \\ P_4 & P_3 & 0 & 0 \\ 0 & P_4 & P_3 & 0 \\ 0 & 0 & P_4 & P_3 \end{bmatrix}$$

To reconstruct recruitment for each broodyear from total returns the inverse e of the aging matrix is employed:

$$\boldsymbol{A^{-1} \cdot RET = REC} \qquad \text{Equation 15.}$$

The recruitment vector is then aligned with the vector of total spawners by year to create the stock-recruit dataset for analysis (see Table 1).

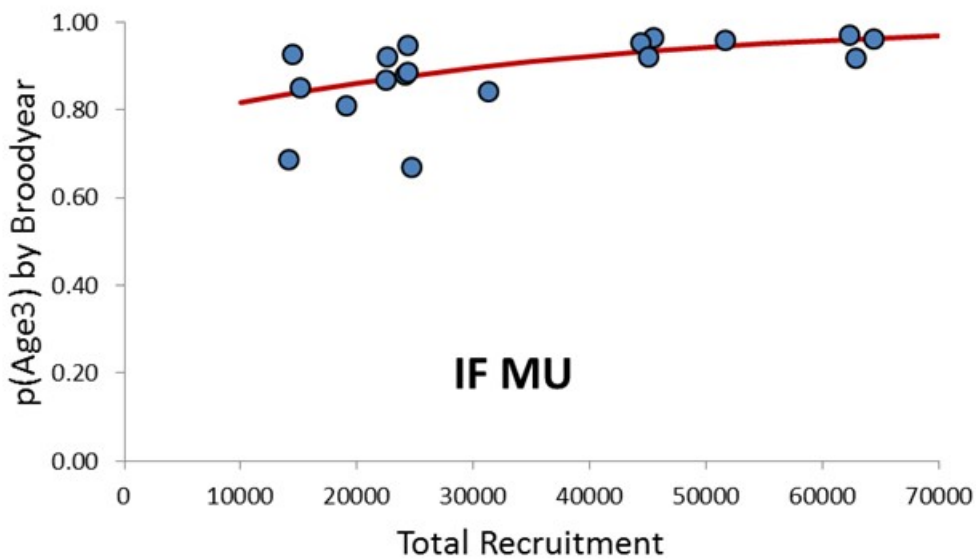


Figure A1. Relation between the average proportion of age-3 fish in each brood year and the total recruitment for the management unit by brood year (1998-2012 broods), and the logistic model fit to the data. Age-4 fish are more common in smaller broods because the survival of the dominant age-3 group is lower.

APPENDIX B. SOURCE CODE FOR STOCK-RECRUIT ANALYSIS AND HISTORICAL AND FORWARD SIMULATIONS

B.1 Stock-Recruit Analysis (WinBUGS model code)

```
mu_alpha~dnorm(1,0.5)          #Prior on mean of hyper-distribution for alpha
tau_alpha~dgamma(0.1,0.1)      #Prior on precision of hyper-distribution for alpha
gamma~dnorm(0,0.01)            #Prior on smolt-adult survival covariate effect

for(i in 1:Ncu){               #Loop across CUs
        alpha[i]~dnorm(mu_alpha,tau_alpha)     #alpha for each CU a draw from hyper-
distribution
        beta[i]~dlnorm(1,1.0E-01)        #uninformative prior on 1/capacity (beta)
        tau[i]~dgamma(0.01,0.01)         #Precision for likelihood on log(R/S) = LRS below
}

for(i in 1:Nrecs){#Loop across all stock-recruit records
        #Predicted log(R/S).
        #Sp is brood year escapement (data) and LSurvAge3 is the log of smolt-adult survival for
        that #brood year for age 3's(observed). CUid is the CU index for current record i
        Pred_RecAge3[i]<-pAge3[i]*Sp[i]*exp(alpha[CUid[i]]+gamma*LSurvAge3[i]-
        beta[CUid[i]]*Sp[i])
        Pred_RecAge4[i]<-(1-pAge3[i])*Sp[i]*exp(alpha[CUid[i]] +gamma*LSurvAge4[i]-
        beta[CUid[i]]*Sp[i])

        #Add age 3 and age 4 recruits and include depensatory effect if Soff>0 (a constant)
        Pred_Rec[i]<-Sp[i]/(Sp[i]+Soff)*(Pred_RecAge3[i]+Pred_RecAge4[i])

        Pred_LRS[i]<-log(Pred_Rec[i]/Sp[i])

        #The likelihood comparing observed log(R/S) = LRS with predicitons (Pred_LRS)
        LRS[i]~dnorm(Pred_LRS[i],tau[CUid[i]])
        Resid[i]<-LRS[i]-Pred_LRS[i]          #The residual for observation i

        #For historical simulations
        Resid3[i]<-Rec_Age3[i]-Pred_RecAge3[i]
        Resid4[i]<-Rec_Age4[i]-Pred_RecAge4[i]
}

for(i in 1:Ncu){ #Some derived parameters
        Smax[i]<-1/beta[i]                          #Escapement that maximizes
recruitment
        prod[i]<-exp(alpha[i] + gamma*muLSurv)      #Productivity
}
```

B.2 Historical (Retrospective) Simulation

```
for (icu in 1:Ncu){        #Loop across CUs

        #Mean stock-recruit parameters for current cu.
        alpha=mean(post[,icola]);b=mean(post[,icolb]);g=mean(post$gamma)

        for(iyr in 1:Nyrs){ #Loop through years (1998-2015)

                #Use observed escapement prior to 2002 or predicted after that for input to SR model.
                #As SR analysis started in 1998 and returns can be up to four years old. First complete
                #predicted recruitment is for brood year 2002.
```

```
		if(Yr[iyr]<=2001){
			Sp=ObsEsc[iyr,icu]
		} else {
			Sp=Esc[iyr,icu]
		}

		if(Yr[iyr]<=2012){		#Last brood year when a residual is available

			#SR model. Note only depensatory if Soff>0. Resid[] is the mean residuals
			across MCMC #simulations for each year and CU.
			Pred_RecAge3=Sp/(Sp+Soff)*pAge3[iyr,icu]*Sp*exp(alpha+g*LSurv3[iyr,icu]-b*Sp)+
	Resid3[iyr,icu]
			Pred_RecAge4=Sp/(Sp+Soff)*(1-pAge3[iyr,icu])*Sp*exp(alpha+g*LSurv4[iyr,icu]-b*Sp)+
	Resid4[iyr,icu]

			#Escapement in each year is based on recruitments from brood years 3 and 4
		yrs earlier
			#and what survival marine and within-river exploitation. ER can be set to a
			constant and #River ER set to 0 to simulate effect of a non-historical regime.
			Esc[iyr+3,icu]=Esc[iyr+3,icu]+ Pred_RecAge3*(1-ER3[iyr,icu])*(1-
	RiverER[iyr+3,icu])		Esc[iyr+4,icu]=Esc[iyr+4,icu]+
	Pred_RecAge4*(1-ER4[iyr,icu])*(1-RiverER[iyr+4,icu])

		}
	}
}
#Sum escapements across CUs for MU escapement predictions
TotEsc=rowSums(Esc)
```

B.3 Forward Simulation

```
#Compute simulated log(R/S) deviates for each simulation trial, year, and CU
for (isim in 1:Ntrials){ #loop through # of trials (500)
	irow=postrecs[isim]	#randomly selected row from posterior (MCMC output)

	k=0				#Read in residual for each selected MCMC trial for each data
point
	for(icu in 1:Ncu){		#Loop across CUs
		j=0
		for(iyr in 1:NByrs){		#Loop across number of brood years from SR analysis
			j=j+1
			k=k+1
			icol=which(names(p)==paste("Resid.",k,sep="")) #determine appropriate col #
			Resid[j,icu]=p[irow,icol]		#residual for year j and CU icu
		}
	}

	MU_mu=mean(rowMeans(Resid))		#mean of residuals for aggregate (MU)
	MU_sd=sd(rowMeans(Resid))	#SD of yr-specific mean residual across CUs (variance over
time)
	MUdev=rnorm(n=Nyrs,mean=MU_mu,sd=MU_sd)		#aggregate residual series across sim
yrs for this trial

	for(icu in 1:Ncu){
		CU_mu=mean(Resid[,icu])		#mean of residuals for this CU
		CU_sd=sd(Resid[,icu])		#SD of yr-specific residuals for this CU
```

```
		CUdev=rnorm(n=Nyrs,mean=CU_mu,sd=CU_sd)		#CU-specific residual series

		#correlation between aggregate residuals and residuals for this CU
		rho=cor(rowMeans(Resid),Resid[,icu])

		#deviation for current sim, year and CU calculated based on aggregate deviation and CU
		#deviation with mix determined by rho
		for (iyr in 1:Nyrs){
			#See Table 5 for test of this calculation. dev[,,icu] will have the same SD
			#as CU_sd, and cor(MUdev,dev[,,icu] will have the same value as rho.

			dev[isim,iyr,icu]= MUdev[iyr]*rho + CUdev[iyr]*sqrt(1-rho^2)
		}
	}
}

#Main forward simulation loop for a given smolt-adult survival (MS) and ER (BaseER).
for(icu in 1:Ncu){
	for(isim in 1:Ntrials){	#loop through # of trials (500)
		irow=postrecs[isim]	#randomly selected row from posterior (MCMC output)

		#Ricker SR parameters for this random MCMC draw
		alpha=p[irow,icol1];	b=p[irow,icol2];  g=p[irow,icol3]

		for(iyr in 1:Nyrs){		#loop through 54 yr simulation (2013 – 2066) but
						compute conservation #statistics from 2017-2066 (50
						yrs)
			if(Yr[iyr]<=2015){
				Sp=IniEsc[iyr]		#initial spawners is observed number
				Esc[isim,iyr,icu]=IniEsc[iyr]	#to compute Geommean for first yrs of
	sim						} else {
				Sp=Esc[isim,iyr,icu]
			}

			if(iyr<=Nyrs-4){
				LSurv=log(MS)  #MS is smolt-adult survival simulated
				Rec=(Sp/(Sp+Soff))* Sp*exp(alpha - b*Sp + g*LSurv + dev[isim,iyr,icu])

				#Base ER is mean exploitation rate simulated. Adjust based on
				lognormal error with bias #correction
				ER=BaseER*exp(rnorm(n=1,mean=0,sd=SDer)-0.5*SDer^2)

				#future escapement is recruitment adjusted for CU age structure and ER
				#This allows escapement to consist of 3 and 4 yr olds based on
				proportion returning at 3 #and 4. Esc will be used for CU conservation
				statistics
				If(Yr[iyr+3]>=fyr)
			Esc[isim,iyr+3,icu]=Esc[isim,iyr+3,icu]+Rec*pAge3[icu]*(1-ER)
				Esc[isim,iyr+4,icu]=Esc[isim,iyr+4,icu]+Rec*(1-pAge3[icu])*(1-ER)
			}
		}#iyr
	}#isim
}#icu

#Accumulate escapement across CUs for MU escapement to be used for MU conservation stats
for(isim in 1:Ntrials){for(iyr in 1:Nyrs){TotEsc[isim,iyr]=sum(Esc[isim,iyr,1:Ncu])}}
```

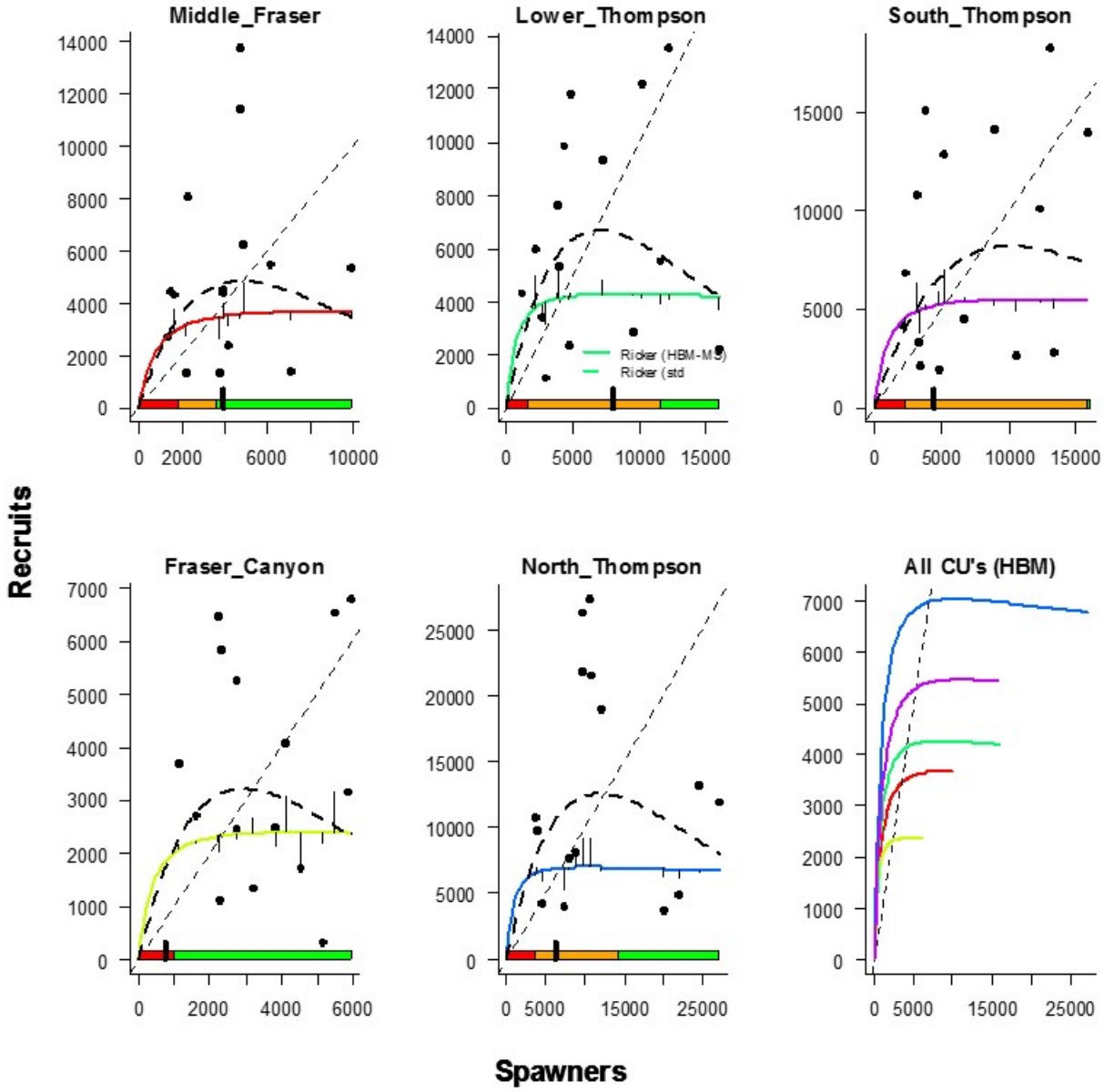


Figure B1. Stock and recruitment data for each IFC conservation unit (CU, points) and best-fit Deriso models ($R=e^{\alpha+\chi\cdot\log(MS)}\cdot S\cdot(1-\chi\cdot\beta\cdot{}^{*}S)^{1/\chi}$ calculated from: 1) the hierarchical Bayesian model with a hatchery smolt-adult marine survival index (HSASI) (colored lines); and 2) the standard Ricker model with each CUs parameters estimated independently. See caption for Figure 1 for additional details. The mean γ estimate was 0.24 (reduced effect of smolt-adult marine survival compared to Ricker fit in Figure 1) and productivities were 5.1, 6.8, 6.6, 8.9, and 6.4 recruits/spawner for Middle Fraser, Fraser Canyon, Lower Thompson, North Thompson, and South Thompson, respectively.

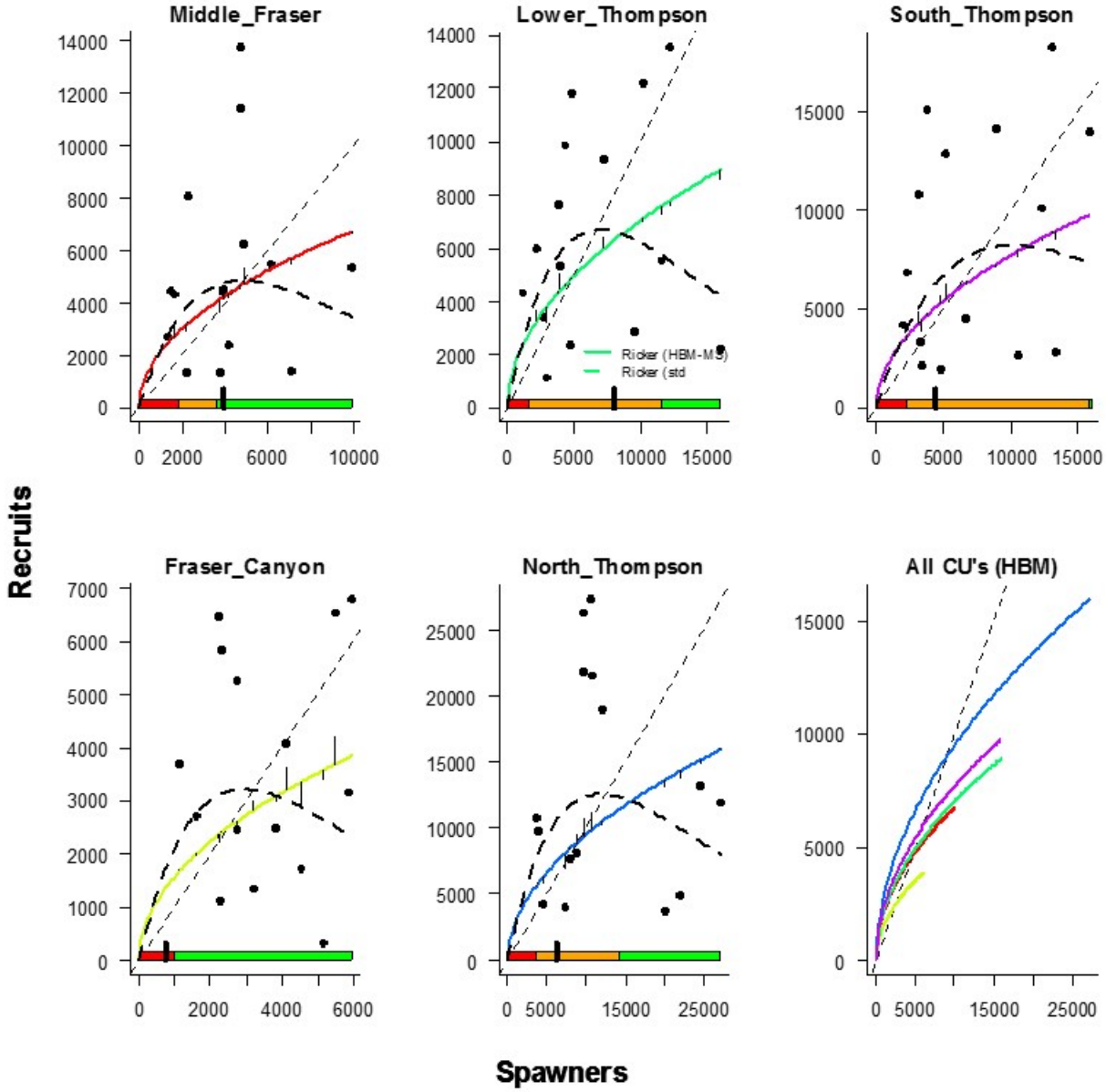


Figure B2. Stock and recruitment data for each IFC conservation unit (CU, points) and best-fit power models ($R=e^{\alpha+\gamma\cdot log(MS)}\cdot S^{\beta}$) models calculated from: 1) the hierarchical Bayesian model with a hatchery smolt-adult marine survival index (HSASI) (colored lines); and 2) the standard Ricker model with each CUs parameters estimated independently. See caption for Figure 1 for additional details. The mean γ estimate was 0.17 (reduced effect of smolt-adult survival compared to Ricker fit in Figure 1) and productivities were 67, 51, 66, 81, and 69 recruits/spawner for Middle Fraser, Fraser Canyon, Lower Thompson, North Thompson, and South Thompson, respectively.