# CASE STUDY 1: INTERIOR FRASER COHO SALMON

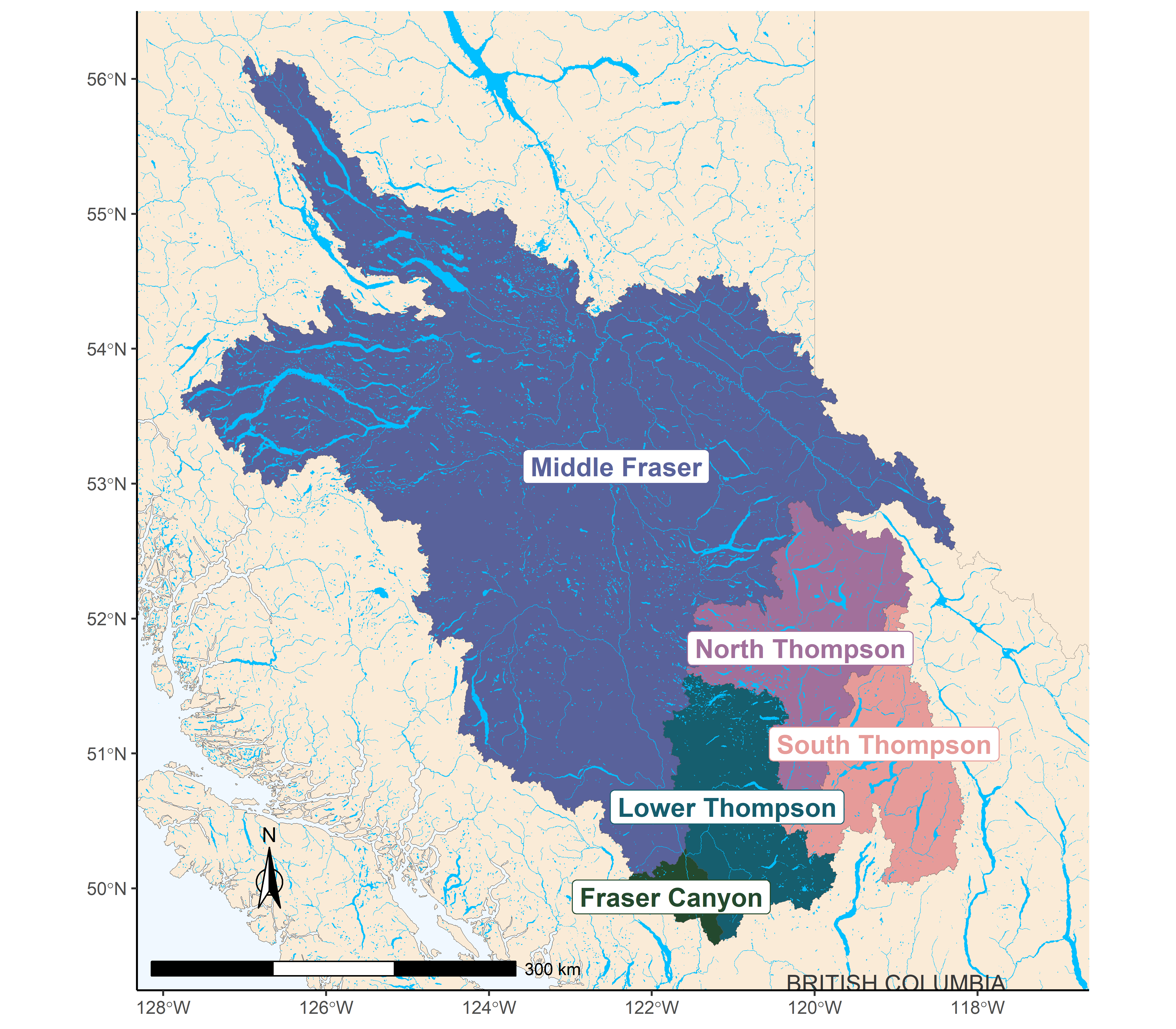
## CONTEXTE

L’UGS du saumon coho du Fraser intérieur convient bien pour illustrer les PRL fondés sur l’abondance agrégée en raison de la longue histoire d’utilisation des cibles de rétablissement fondées sur l’abondance agrégée et des points de référence des pêches à l’échelle de l’UGS. Ceux-ci reposent sur une relation sous-jacente entre l’abondance agrégée et la répartition de l’abondance entre les sous-populations et les UC. De plus, il s’agit d’une UGS relativement riche en données avec des séries chronologiques sur la relation géniteurs-recrutement qui sont disponibles pour toutes les UC à compter de 1998.

Cette UGS comprend les saumons cohos qui fraient dans le fleuve Fraser et ses affluents en amont de Hells Gate dans le canyon du Fraser. Comme la plupart des saumons cohos, ceux du Fraser intérieur passent au moins une année complète en eau douce comme alevins avant de migrer vers l’océan comme smolts [@arbeiderInteriorFraserCoho2020]. La plupart (88 %) des saumons cohos du Fraser intérieur ont un cycle biologique de trois ans au cours duquel ils quittent l’eau douce lors de leur deuxième année et passent 18 mois en mer avant de retourner à leur réseau hydrographique natal pour frayer. Les 12 % restants ont un cycle biologique de quatre ans au cours duquel ils passent une année supplémentaire en eau douce avant de migrer en tant que smolts lors de leur troisième année. Les saumons ayant un cycle biologique de trois et de quatre ans passent 18 mois en mer. On croit que moins de 1 % des saumons cohos du Fraser intérieur reviennent à la frayère sous forme d’unibermarins (mâles matures précoces qui ne passent que six mois en mer) ou à une âge supérieur à quatre ans [@arbeiderInteriorFraserCoho2020].

Cinq UC selon la PSS ont été recensées pour le saumon coho du Fraser intérieur en fonction de la génétique et de la séparation géographique, soit celles du moyen Fraser, du canyon du Fraser, de la Thompson inférieure, de la Thompson Nord et de la Thompson Sud (figure @ref(fig:coho-map)) [@dfoWildSalmonPolicy2015]. Les travaux antérieurs de l’équipe de rétablissement du saumon coho du Fraser intérieur ont permis de recenser 11 sous-populations nichant dans ces cinq UC et d’élaborer des objectifs de rétablissement fondés sur le maintien de l’abondance au-dessus d’un seuil de 1 000 géniteurs dans chacune de ces sous-populations [@ifcrtConservationStrategyCoho2006, tableau \@ref(tab:cohoCU2SP)]. Les délimitations des sous-populations étaient fondées sur plusieurs facteurs, notamment la présence d’obstacles naturels, l’influence de grands lacs sur les régimes de débit en aval et les régimes thermiques, les observations de regroupements de géniteurs dans des conditions de débit différentes et la différenciation génétique. Les 11 sous-populations sont décrites en détail par le @ifcrtConservationStrategyCoho2006.

Seule la partie supérieure de l’aire de répartition de l’UC du canyon du Fraser (en amont de Hells Gate sur le fleuve Fraser) est incluse dans notre délimitation du saumon coho du Fraser intérieur. Cette délimitation est conforme aux analyses précédentes pour cette UGS (p. ex., @arbeiderInteriorFraserCoho2020). Par conséquent, Nahatlatch est la seule sous-population incluse dans notre description de l’UC du canyon du Fraser. Le ruisseau Kawkawa, situé au sud du canyon du Fraser près de Hope, en Colombie-Britannique, n’est pas inclus dans les données que nous utilisons.



Aire de répartition de l’UGS du saumon coho du Fraser intérieur, y compris les cinq UC qui composent l’UGS. Seule la partie supérieure de l’UC du canyon du Fraser (en amont de Hells Gate) est illustrée ici pour correspondre à l’échelle spatiale des données qui ont été utilisées pour les analyses.

(#tab:cohoCU2SP) Interior Fraser Coho Conservation Units (CUs) and associated sub-populations. Note that the definition of these sub-populations, including mapped boundaries, are provided in @ifcrtConservationStrategyCoho2006.

| Conservation Unit | Sub-populations |
| --- | --- |
| Middle Fraser | * Lower Middle Fraser * Upper Middle Fraser |
| Fraser Canyon | * Nahatlatch |
| Lower Thompson | * Lower Thompson * Nicola |
| North Thompson | * Lower North Thompson * Middle Thompson * Upper North Thompson |
| South Thompson | * Adams Drainage * Lower and Middle Shuswap River * Shuswap Lake Tributaries |

Hatchery enhancement has occurred, and continues to occur, in some parts of the Interior Fraser Coho SMU. Two CUs are currently considered wild populations based on the criteria developed by @withlerGeneticallyBasedTargets2018 (i.e., do not have hatchery programs; strays from out-of-basin hatchery production are limited to <3% per year), while the other three are considered integrated-wild populations (i.e., with Proportionate Natural Influence (PNI) values most likely 0.72; M. Arbeider, pers. comm.). Within integrated-wild populations, most fish are considered ‘wild’ under the WSP with parents who were born in the natural environment. The Lower Thompson CU had higher levels of hatchery enhancement between 1998 and 2005, so would likely have been considered an integrated-transition population (0.5 PNI < 0.72) during this period.

The five Interior Fraser Coho CUs have historically shown relatively high levels of covariation in escapement among CUs, with an average correlation in spawner abundances among CUs of 0.56. Similarity among CU responses to environmental and anthropogenic drivers is further supported by application of the four criteria proposed by @holtGuidelinesDefiningLimitInpress to evaluate the extent to which status of data deficient CUs can be inferred from CUs with data. A summary of our consideration of these criteria for Interior Fraser Coho are provided in Appendix @ref(app:coho-appendix). Results showed that Interior Fraser Coho CUs have many shared characteristics. We found few significant indicators that would have prevented us from inferring CU status for one CU from neighboring CUs prior to our case study analyses.

Interior Fraser Coho is included in the first batch of major stocks proposed for regulation under the Fish Stocks provisions of the revised *Fisheries Act*, necessitating the development of LRPs for this SMU.

### Previous assessments

Declines in Interior Fraser Coho spawner abundance throughout the 1990’s led to a suite of management actions to promote recovery, including significant fishery restrictions starting in 1998 [@deckerAssessmentInteriorFraser2014]. Evidence of a new, lower productivity regime starting in return year 1994 has been well documented, coinciding with declines in spawner abundances [@deckerAssessmentInteriorFraser2014]. In 2002, the Interior Fraser Coho stock management unit was designated ‘endangered’ by the Committee on the Status of Endangered Wildlife in Canada (COSEWIC) based on the stock unit being assessed as a single ‘Designatable Unit’ (DU).

Subsequent work by the Interior Fraser Coho Recovery Team (IFCRT) led to a conservation strategy outlining short-term and long-term recovery objectives for the management unit [@ifcrtConservationStrategyCoho2006]. In 2014, Decker et al. assessed status relative to the 2006 IFCRT objectives, and concluded that Interior Fraser Coho had been above the short-term recovery target in every year since 2008, and above the long-term recovery target in the most recent two return years (2012 and 2013). Also in 2014, Interior Fraser Coho were assessed under the framework of DFO’s Wild Salmon Policy (WSP). The WSP Integrated Status Assessment classified three of these CUs as being Amber status (Middle Fraser, Fraser Canyon, South Thompson) and the remaining two CUs as Amber/Green status [Lower Thompson, North Thompson, @dfoWildSalmonPolicy2015]. As part of the WSP assessment, Sgen and SMSY were estimated for each CU and used along with other benchmarks when assigning integrated CU status. A subsequent COSEWIC assessment in 2016 upgraded the status assessment for the Interior Fraser Coho DU from ‘endangered’ to ‘threatened’ [@cosewicCOSEWICAssessmentStatus2016]. In 2018, DFO undertook a Recovery Potential Assessment (RPA) for Interior Fraser Coho that described status, habitat, threats, limiting factors to recovery, candidate recovery targets, and abundance projections for the DU, as well as recommendations regarding mitigation and allowable harm [@arbeiderInteriorFraserCoho2020].

### History of aggregate-abundance based reference points

Interior Fraser Coho show a strong positive relationship between their spatial distribution and overall abundance, which has been used as a basis for identifying aggregate abundance recovery targets and reference points for the stock group. Starting in 2006, the IFCRT identified a recovery goal of one or more viable sub-populations in each of the five ‘populations’, where their definition of populations aligns with CUs under the WSP [@ifcrtConservationStrategyCoho2006]. Note that from this point on, we use the term CU instead of population when describing IFCRT recovery goals to be consistent with the WSP. The IFCRT identified a short-term recovery objective that the 3-year average escapement in at least half of the sub-populations within each of the five CUs was to exceed 1,000 natural-origin spawning Coho Salmon, excluding hatchery fish spawning in the wild. Based on analysis of the relationship between aggregate abundance and the number of CUs that met this objective based on historical data, the IFCRT identified an abundance short-term recovery target of 20,000 spawners as the level required to meet their distributional objective. In addition, the IFCRT identified a long-term recovery target of 40,000 spawners, which represented a level that was expected to maintain 1,000 or more wild Coho Salmon in all 11 sub-populations. @deckerAssessmentInteriorFraser2014 updated the IFCRT’s original analysis using a longer time series of escapement data. They also quantified the relationship between aggregate abundance and distribution by using a logistic regression to estimate the probability of meeting short-term and long-term recovery objectives as a function of aggregate abundance. They concluded that aggregate spawner abundance levels of 20,000 and 40,000 spawners would result in near 100% probability that the IFCRT’s short-term objective and long-term recovery objectives would be met, respectively.

@kormanEvaluationFrameworkAssessing2019 also used logistic regressions of the relationship between the IFCRT’s distributional objectives and aggregate abundance when evaluating how exploitation and smolt-to-adult survival rates affected the ability of Interior Fraser Coho to meet conservation targets. Their approach was similar to that of @deckerAssessmentInteriorFraser2014, except they applied logistic regressions at the CU-level instead of the SMU-level. Using this approach, they calculated the probability that IFCRT sub-population objectives were met as a function of total escapement to the CU within their simulation evaluation. When evaluating how well conservation targets were met at the SMU-level, they chose to rely on the previous values of 20,000 and 40,000 identified by the IFCRT instead of updating these values. Finally, the 2018 RPA used an updated logistic regression to identify a long-term recovery target for Interior Fraser Coho that met the long-term IFCRT objective of 1000 spawners in all sub-populations [@arbeiderInteriorFraserCoho2020]. As a result, @arbeiderInteriorFraserCoho2020 recommended that the long-term recovery target for Interior Fraser Coho should be a 3-year geometric mean abundance of 35,935 natural-origin spawners.

## DATA

Data for this case study cover return years 1998-2020. Data prior to 1998 were not used due to inconsistent assessment methods and data quality. All Interior Fraser Coho data were provided by DFO’s Fraser River Stock Assessment Unit (M. Arbeider, DFO, Kamploops, BC, pers. comm.). These data included: (i) annual spawner abundance by CU (1998-2020), (ii) annual natural origin recruits-at-age by CU (brood years 1998 - 2016), (iii) a hatchery-based smolt-to-adult survival rate index, (iv) annual exploitation rates, and (v) annual spawner abundances for 11 sub-populations nested within the 5 CUs.

Two types of spawner abundance series were provided: total spawners and natural-origin returns to the spawning grounds (sometimes called ‘natural returns’). The first type, total spawners, includes both natural-origin spawners and spawners that originated from hatcheries but returned to spawn naturally, but excludes fish removed from the river for hatchery brood stock. When modelling spawner-recruit dynamics, total spawners was paired with natural-origin recruitment so that estimated productivity from all spawners was fully captured. The second type of spawner abundance series, natural-origin spawning returns, included only natural-origin fish that returned to spawn, with hatchery brood stock included. Natural-origin spawning returns were used when comparing spawning abundance to CU benchmarks or SMU-level LPRs in order to estimate CU or SMU status.

Data were similar to those previously described in @arbeiderInteriorFraserCoho2020; data treatments, assumptions, infilling, and data quality are described in detail in that document. More recent updates that are not described in @arbeiderInteriorFraserCoho2020 include the incorporation of three additional years of data (return years 2018-2020; brood years 2014-2016), updates to the SMU smolt-to-adult survival rate index to use a weighted average by release size, and increased data quality screening of scale ages used to calculate the proportion of recruits at age (M. Arbeider, DFO, Kamploops, BC, pers. comm.).

The exploitation rate time series is a large source of uncertainty for Interior Fraser Coho. Exploitation rates are only available at the SMU-level, so are assumed identical among all CUs. This assumption is unlikely to be true because of known differences in freshwater fisheries among CUs. Furthermore, models used to reconstruct exploitation rates require a large number of assumptions that are expected to be incorrect [@arbeiderInteriorFraserCoho2020]. Because exploitation rate time series are used to reconstruct recruitment time series, errors in exploitation rates will propagate through to estimates of stock-recruitment parameters, relative abundance benchmarks such as Sgen, and covariation in recruitment residuals. Additional sources of uncertainty in Interior Fraser Coho data sets include observation errors in spawner abundance estimates and estimates of age-at-escapement. Spawner abundance estimates are largely derived from visual surveys, for which observer efficiency is not estimated and survey life is difficult to estimate accurately. Scale sampling to determine age structure is incomplete at the CU-level with small sample sizes, missing data, and limited spatial representation within CUs in some years [@kormanEvaluationFrameworkAssessing2019].

## CU STATUS ESTIMATION

We use three alternative ways to characterize CU status when developing LRPs for Interior Fraser Coho: 1) multidimensional status estimates derived from the Pacific Salmon Status Scanner, 2) CU-level abundance relative to Sgen as a lower benchmark on abundance, and 3) distribution of spawning abundance relative to distributional targets developed by the IFCRT.

The first approach, which uses the Salmon Scanner tool developed by the State of the Salmon program (Section @ref(rapidToolMethods)), is consistent with Canada’s WSP. The other two approaches are primarily used to develop aggregate abundance LRPs in this case study, as well as for a point of comparison with the Salmon Scanner tool.

The second approach is based on comparing the current abundance of each CU to its CU-specific estimate of Sgen, where CU status is considered Red when abundance drops below Sgen. The value of Sgen represents the number of spawners required to recover to SMSY (spawners at maximum sustainable yield) within one generation, under equilibrium conditions in the absence of fishing [@holtIndicatorsStatusBenchmarks2009]. Sgen is one of several benchmarks available for assigning multidimensional CU status in WSP Integrated Status Assessments and the Salmon Scanner; it represents a lower benchmark between Red and Amber status zones and was used as part of the 2014 Integrated Status Assessment for Interior Fraser Coho [@dfoWildSalmonPolicy2015]. While estimates of CU status relative to Sgen are readily available outputs from the Salmon Scanner tool, we calculated this metric external to the tool for our case study.

The third approach is based on the distribution of spawning escapement among sub-populations nested within CUs (Table @ref(tab:cohoCU2SP)). We apply this approach for Interior Fraser Coho to maintain consistency with previous recovery planning processes for this SMU [@ifcrtConservationStrategyCoho2006; @arbeiderInteriorFraserCoho2020]. Since the distributional target we use was initially developed by the Interior Fraser Coho Recovery Team in 2006, we refer to it as “IFCRT distributional”. Specifically, we use the IFCRT’s short-term recovery objective that the 3-year geometric average escapement in at least half of the sub-populations within each of the five CUs is to exceed 1,000 wild-origin spawners, excluding hatchery fish spawning in the wild. We selected the short-term recovery target as a proxy for the lower benchmark in our case study because, as noted by @arbeiderInteriorFraserCoho2020, the short-term target was designed as an immediate target when the population was endangered. As such, it was interpreted as a level expected to prevent extinction or loss of genetic diversity. We have included this third approach to defining CU status to demonstrate the range of approaches and metrics that can be used, and to demonstrate sensitivity of the LRP to choice of metrics for assigning CU-status. Future iterations of the Pacific Salmon Status Scanner approach could include distributional metrics such as those used in the IFCRT approach.

### Estimation of Sgen

Estimates of Sgen are required when assessing CU status using both the multidimensional algorithm within the Pacific Salmon Status Scanner and the comparison of current CU-level abundance to Sgen. While the application of the Salmon Scanner to Interior Fraser Coho CUs in Pestal et al. (in prep) relies on peer-reviewed estimates of Sgen from the WSP Integrated Status Assessment [@dfoWildSalmonPolicy2015], we re-estimate Sgen here using data updated to 2020. In addition, we explore alternative stock-recruitment model formulations to better understand how model assumptions at the CU-level affect resulting LRP estimates.

Two different formulations of stock-recruitment model were used to estimate Sgen: (i) a base Ricker model, which includes a smolt-to-adult survival covariate, and (ii) an alternative form of the Ricker model in which an informative prior distribution is used to increase SREP compared to the base model, labelled ‘Ricker\_priorCap’. SREP is the spawner abundance level at which the stock replaces itself; the relationship between SREP and Ricker stock-recruitment model parameters is shown below (Equation @ref(eq:beta-Srep)). Both of these models have been previously developed and applied to Interior Fraser Coho CUs. The smolt-to-adult survival covariate used when fitting both models is a hatchery-based smolt-to-adult survival rate index. The index is not CU-specific; the same index is applied to all CUs. A third Ricker model, in which both an informative prior on SREP and depensatory mortality were included, was also used by @kormanEvaluationFrameworkAssessing2019 and @arbeiderInteriorFraserCoho2020; however, we did not include it in our case study for simplicity. As noted by @kormanEvaluationFrameworkAssessing2019, there is no indication in available data of depensatory dynamics, and the SR model fit with depensatory mortality required a highly uncertain assumption about the escapement level at which depensation occurs. Furthermore, formal model selection criteria showed that adding depensatory mortality into models lead to a reduction in model fit [@kormanEvaluationFrameworkAssessing2019].

@kormanEvaluationFrameworkAssessing2019 and @arbeiderInteriorFraserCoho2020 used a hierarchical model structure for both the base Ricker and Ricker\_priorCap models that assumed CU-level productivity parameters were sampled from a common, normal distribution shared by all CUs. Using formal model selection criteria (i.e., DIC), @kormanEvaluationFrameworkAssessing2019 found higher support for the hierarchical structure than when productivity parameters were assumed independent among CUs. However, our initial examination of the hierarchical approach applied to the updated data set lead us to select the independent CU approach for our evaluation. Firstly, we found that LRP estimates were sensitive to the assumed standard deviation on the hyper-distribution prior for the productivity parameter. Using the individual model approach removed prior influence on model results. Secondly, a logistic regression fit to status estimates obtained using the hierarchical model was unable to converge on a solution in several years between 2015 and 2020, including the most recent year (2020).

Future stock-recruitment analyses for Interior Fraser Coho may wish to re-visit the hierarchical approach to modelling productivity. Bayesian posterior distributions of the productivity parameter from our individual model fits show some differences in productivity among CUs (particularly for the Fraser Canyon CU; Appendix @ref(app:coho-appendix)). However, there was substantial overlap in CU-level distributions for all other CUs. We do not expect our decision to apply an individual-stock modelling approach here will affect our general conclusions. In preliminary analyses, LRPs were similar between individual and hierarchical modelling approaches.

The formulations for the two stock-recruitment models are described below.

***Model 1: Ricker***

The base Ricker stock-recruit model formulation was:

where,

= the predicted number of natural origin recruits from CU of age returning in year (i.e., recruits that were produced by escapement in brood year )

= the proportion of recruitment from CU returning at age from brood year

= spawners from CU in brood year

= productivity parameter for CU

= smolt-to-adult survival co-efficient shared among CUs

= hatchery smolt-to-adult survival index shared among CUs for sea entry in year t-1

= density dependent term describing the rate of decrease in density dependent survival for CU with increasing spawner abundance

= standard deviation of process error on recruitment deviations

Total recruitment from a brood year, , was calculated as the sum of age 3 and age 4 recruits in consecutive years,

Observations of were assumed to be normally-distributed random variables with a standard deviation of .

This model formulation is similar to the Ricker model used in @arbeiderInteriorFraserCoho2020, but without a hierarchical structure imposed on . We placed the following non-informative constraints on the likelihood function to replicate the Bayesian model fitting routine of @arbeiderInteriorFraserCoho2020:

***Model 2: Ricker\_priorCap***

To maintain consistency with this previous work on Interior Fraser Coho, we also consider a version of the Ricker model that uses an informative prior distribution on SREP to increase carrying capacity. @kormanEvaluationFrameworkAssessing2019 suggested that the Ricker model with a smolt-to-adult survival co-variate (Model 1) over-estimated compensatory dynamics at high spawner abundances when applied only to data from 1998 onwards. They noted that spawner abundances since 1998 have been much lower than historic levels. Given that sparse data at high spawner abundances makes it difficult to estimate carrying capacity, base Ricker estimates of carrying capacity may be unreliable [@kormanEvaluationFrameworkAssessing2019]. Furthermore, they observed that one brood line had persisted at a relatively higher and more stable spawner abundance than the other two brood lines, which they viewed as evidence for a higher capacity than the base Ricker model estimates. Based on these concerns, @kormanEvaluationFrameworkAssessing2019 proposed an alternative Ricker model that used an informative prior distribution to increase carrying capacity (represented as the spawner abundance at which the stock replaces itself, SREP). @arbeiderInteriorFraserCoho2020 followed the approach of @kormanEvaluationFrameworkAssessing2019 by considering both the base Ricker model and a version of the Ricker model with an informative prior distribution on SREP to be plausible when providing management advice.

@arbeiderInteriorFraserCoho2020 and @kormanEvaluationFrameworkAssessing2019 set at 1.5 times the SREP value estimated from the base model fit without a prior on SREP. For our model fits (described in Section @ref(logistic)), we found that we needed to constrain at no more than 1.4 times the SREP value to achieve model convergence, so we used the 1.4 times expansion instead. We set at spawners, which is the same value used by @arbeiderInteriorFraserCoho2020. Note that the “” term is used to correct for scaling spawner abundance by 1/1000 when fitting models. The effect of adding the prior on SREP when fitting individual models to available data is shown in Figure @ref(fig:coho-SR-fit).

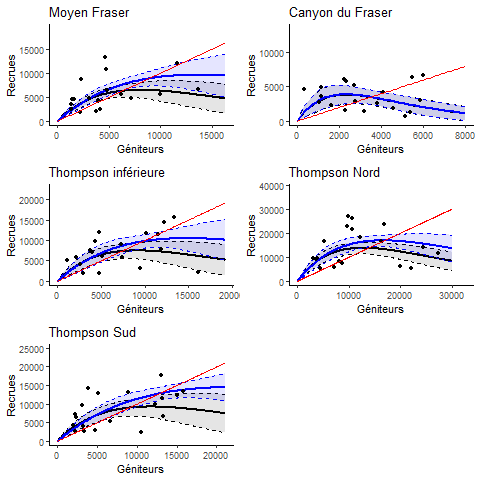
***Calculation of Sgen***

The inclusion of a smolt-to-adult survival co-variate in both stock-recruit models means that the realized productivity changes from year to year with changing survival. We incorporated this adjustment into our calculations of Sgen by first calculating the effective productivity for each CU as:

where, is the average smolt-to-adult survival rate over the available time series.

SMSY was calculated as a function of log() and using:

where, represents the Lambert W function [@scheuerellExplicitSolutionCalculating2016]. Sgen was then calculated numerically by solving the following equation:



Spawner-recruitment curves fit to spawner and recruitment data using individual models for each CU. Solid black lines shows the MLE fit for the base Ricker model while solid blue lines shows the MLE fit for the Ricker\_priorCap model. Associated black and blue shaded regions show the 95 percent confidence intervals on respective model fits using the average long-term smolt-to-adult survival rate from the available time series. The red lines show the replacement line.

## LRP ESTIMATION: CU STATUS BASED

### Methods

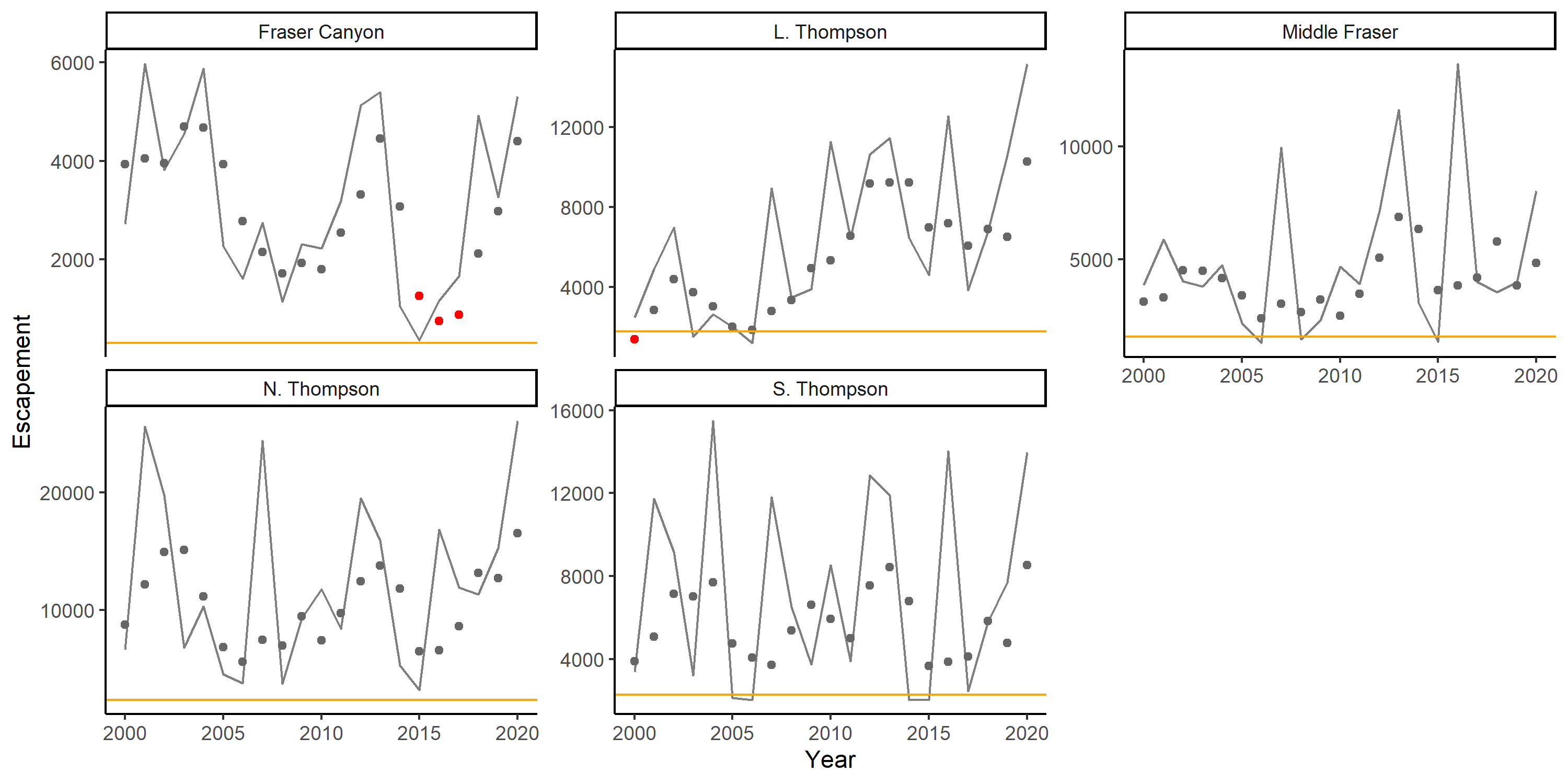
To derive CU status-based LRPs, we calculated the proportion of CUs that had multidimensional statuses from the Pacific Salmon Status Scanner above the Red zone. Status was assessed as being below the LRP in years in which one or more CUs assessed as having Red status. Both Ricker model formulations described above were used to estimate abundance-based benchmarks (lower benchmark = Sgen and upper benchmark = 0.8SMSY) when assessing status with the Pacific Salmon Status Scanner: the base Ricker model and the Ricker\_priorCap model. Estimates of Sgen and SMSY were estimated using all data available up to 2020.

For comparison, we also calculated LRPs from the proportion of CUs that had recent generational average (3-year) spawning abundance greater than Sgen and from the proportion of CUs that failed to meet the IFCRT distributional target of at least half of all sub-populations within each CU having more than 1000 spawners.

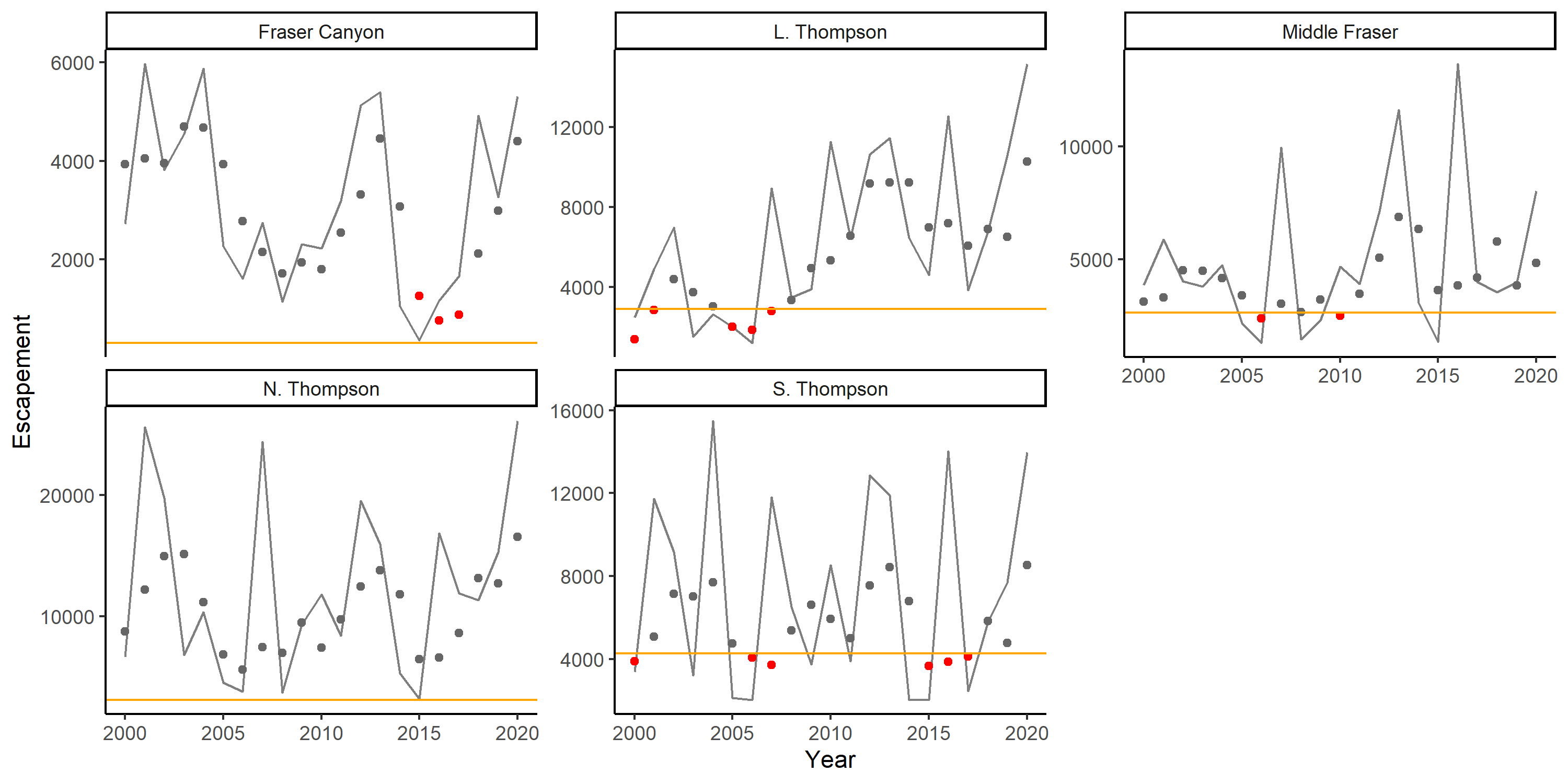
### Results

Estimates of Sgen based on the Ricker\_priorCap model were higher than those based on the base Ricker model for four of the five CUs (Middle Fraser, Lower Thompson, North Thompson, and South Thompson) and were approximately equal for the fifth CU (Fraser Canyon; Appendix @ref(app:coho-appendix)). As a result, generational average spawning abundance was more likely to drop below Sgen when it was estimated using the Ricker\_priorCap model. Under the base Ricker model formulation, generational average spawning abundance remained above Sgen for all years between 2000 and 2020 (Figure @ref(fig:coho-CU-multiDim-Ricker)). In comparison, under the Ricker\_priorCap formulation, generational average abundance dropped below Sgen for 5 of the 21 years between 2000 and 2020. These occurrences included the Lower Thompson CU (2006), the Middle Fraser CU (2006, 2008), and the South Thompson CU (2000, 2006, 2007, 2015; Figure @ref(fig:coho-CU-multiDim-Ricker-Cap)). All five CUs had spawning abundances above Sgen in 2020, regardless of which spawner recruitment model was used, indicating that the stock would be above a CU status-based LRP based on Sgen.

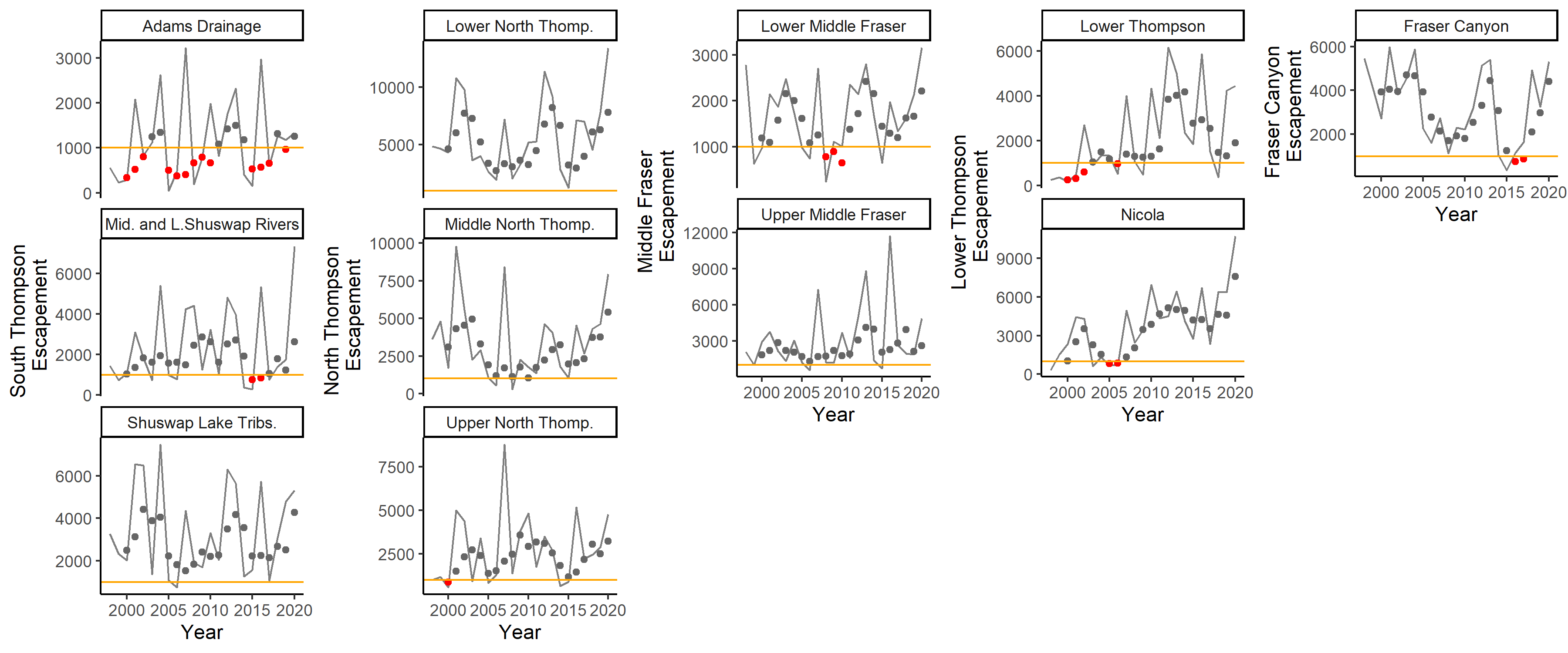
The frequency of years in which the IFCRT distributional target failed to be met for one or more CUs was similar to that observed when Sgen based on the Ricker\_priorCap was used, with distributional targets not met in 4 of the 21 years between 2000 and 2020 (breached in 2006, 2015-2017). Eight of the 11 sub-populations had generational average escapement drop below the 1000 spawner threshold in one or more years (Figure @ref(fig:coho-Subpop-timeseries)). Sub-populations tended to differ in which years they dropped below the 1000 spawner threshold, which meant that the distributional target of at least half of the sub-populations within each CU with greater than 1000 fish was more often met than not. All 11 sub-populations had generational average spawning abundances above 1000 spawners in 2020, indicating that the stock would be well above a CU status-based LRP based on the IFCRT-distributional target (Figure @ref(fig:coho-Subpop-timeseries)).



Escapement time series for Interior Fraser Coho CUs shown as annual escapements (lines) and 3-year geometric mean escapements (dots). First geometric mean includes years 1998-2000. Grey dots indicate years when all CUs had multidimensional Salmon Scanner assessments above Red when S was estimated using the Ricker model, while red dots indicate when one or more CUs had assessments in the Red zone, which would trigger a breach of the LRP. Orange lines show estimated S.



Escapement time series for Interior Fraser Coho CUs shown as annual escapements (lines) and 3-year geometric mean escapements (dots). Grey dots indicate years in which all CUs had multidimensional Salmon Scanner assessments above Red when S was estimated using the Ricker\_priorCap model, while red dots indicate years in which one or more CUs had assessments in the Red zone, which would trigger a breach of the LRP. Orange lines show estimates of S.



Escapement time series for 11 sub-populations of Interior Fraser Coho shown as annual escapements (lines) and 3-year geometric mean escapements (dots). First geometric mean includes years 1998-2000. Grey dots shows years in which the 3-year geometric mean escapement was above the 1000 fish threshold used to assess distributional status, while red dots show years in which the 1000 fish threshold was not met. CUs are represented by columns with labels long the y axis.

Multidimensional status derived from the Salmon Scanner is driven by abundance metrics for this SMU. Because absolute abundance data and benchmarks based on Sgen and SMSY were available, the multidimensional algorithm within the Salmon Scanner (Figure @ref(fig:decision-tree)) most often assigned CU status based on this metric (Figures @ref(fig:coho-CU-multiDim-Ricker) and @ref(fig:coho-CU-multiDim-Ricker-Cap)). Though status in some cases was also influenced by absolute abundance relative to the threshold of 1500 spawners. This occurred in the Fraser Canyon CU between 2015 and 2017. In these years, the generational average of absolute spawning abundance was < 1500 spawners and the CU was assigned Red status under the first node of the decision tree even though spawning abundances are above Sgen.

The total number of years in which an LRP would have been breached using the multidimensional approach depended on which Ricker stock-recruitment model was used to estimate Sgen. When status was assessed using abundance-based benchmarks estimated from the base Ricker model, a CU status-based LRP for the SMU would have been breached in 4 of 21 years. For three of these years, the breach was based on Fraser Canyon spawning abundances dropping below 1500 spawners (2015-2017), while for the one additional year (2000) it was due to the Lower Thompson CU having spawning abundance < Sgen (Figure @ref(fig:coho-CU-multiDim-Ricker)). In comparison, when status was assessed using abundance-based benchmarks from the Ricker\_priorCap model, a CU status-based LRP would have been breached in 9 of 21 years (2000-2001, 2005-2007, 2010, 2015-2017; Figure @ref(fig:coho-CU-multiDim-Ricker-Cap)). For both stock-recruitment models, multidimensional status from the Salmon Scanner was above Red for all CUs based on the most recent generational average, indicating that the SMU is currently above a CU status-based LRP, regardless of spawner recruitment model.

## LRP ESTIMATION: AGGREGATE ABUNDANCE, LOGISTIC REGRESSION LRPS

### Methods

We present aggregate abundance LRPs derived using logistic regressions with two of the Interior Fraser Coho benchmarks considered: Sgen and the IFCRT-distributional target. Because two stock-recruitment models were used to estimate Sgen, we distinguish these models as ‘Logistic:Sgen-Ricker’ and ‘Logistic:Sgen-priorCap’ for the Ricker and Ricker\_priorCap models, respectively. We use the label ‘Logistic:IFCRT’ to denote the case in which the IFCRT distributional target was used to develop the aggregate abundance, logistic regression LRP. See Section @ref(logisticMethods) for an overview of the approach used to calculate aggregate abundance LRPs using logistic regression.

When estimating logistic regression LRPs using Sgen, we used an integrated modelling approach in which CU-level Sgen values and the SMU-level LRP were simultaneously estimated. The integrated Sgen-LRP models had two components:

1. Stock-recruitment models fit to each of the 5 CUs to estimate CU-level Sgen (Equation @ref(eq:rickerSurv-IM) and Equations @ref(eq:adjProd) - @ref(eq:Sgen))
2. A logistic regression model fit to aggregated data to estimate the LRP as the aggregate abundance that has historically been associated with a specified probability of all CUs being above Sgen (Equations @ref(eq:logistic) - @ref(eq:logisticLRP))

We initially considered a third version of the logistic regression model, in which we used the multidimensional algorithm within Salmon Scanner to characterize CU status. Preliminary model evaluations led us to exclude this model due to poor fit. The multidimensional algorithm relies on generational mean (smoothed abundances) to assess status of individual CUs against benchmarks, while our logistic regression approach uses raw (unsmoothed) aggregate abundance as a predictor variable. As a result, when logistic regressions were fit to multidimensional CU status estimates, there was a mismatch in the timing of abundance highs and lows. This mismatch led to a weak/nonexistent relationship between SMU status and the raw (unsmoothed) abundances. In addition, using the generational mean of aggregate abundance as the predictor variable in the logistic regression fit, instead of raw annual abundance values, introduced considerable autocorrelation in statuses.

***Retrospective Analysis and Analysis Evaluating Impact of Missing CUs***

We used retrospective analyses to examine the effect of time series length on logistic regression LRP estimates. For each year between 2010 and 2020, we used data only available up to that year to calculate LRPs and associated confidence intervals.

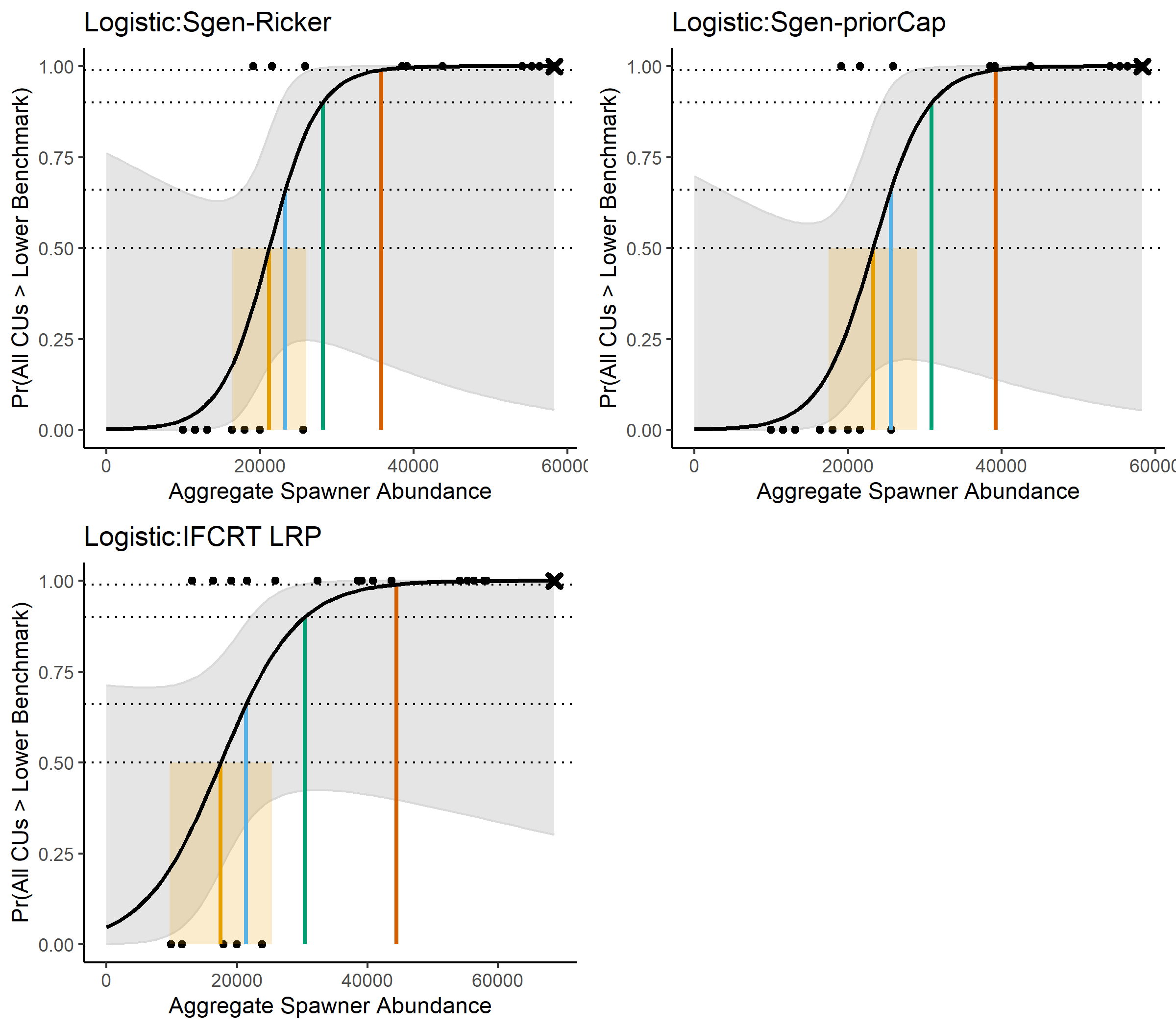
In addition, to examine the effect of missing CUs on retrospective LRP estimates, we calculated LRPs using data from only a subset of the five Interior Fraser Coho CUs. We limited our analysis to missing data from either one or two CUs so that we had at least three CUs of available data when calculating the proportion of CUs above their benchmarks. For each missing data case, we calculated SMU aggregate status as

where is the number of CUs used (3, 4, or 5), is the abundance of natural-origin spawners returning to CU in year (including fish removed for brood), and is the LRP calculated in year using only data from . SMU-level status in a given year was calculated for all possible combinations of CUs available (5 combinations when = 4 and 10 combinations when = 3) to allow examination of the stability of status estimates among available combinations. Estimates of SMU status relative to LRPs were used to compare among missing CU scenarios instead of actual LRP estimates because the magnitude of the LRP will vary with the number and combination of CUs used. Since uncertainty estimates for spawner abundance are not available, confidence intervals on LRP status are based solely on estimated 95% confidence intervals for the LRP.

### Results

***LRP Estimates***

Logistic regression model fits in 2020 from the integrated Logistic:Sgen-Ricker, Logistic:Sgen-priorCap and Logistic:IFCRT models are shown in Figure @ref(fig:coho-IM-logisticFit2020). All three logistic regression LRP methods were able to converge on a solution in 2020. Resulting LRPs for different *p* thresholds are shown on the regression curves, as well as in Table @ref(tab:logisticLRPs2020). There was considerable uncertainty around predicted curves as seen in the large areas of gray shading in Figure @ref(fig:coho-IM-logisticFit2020).



When the Logistic:Sgen-Ricker model was used, aggregate abundance LRPs ranged from 21,190 to 35,737 spawners, depending on whether the required probability of all CUs being above Sgen was moderate (50%) or very likely (99%) (Table @ref(tab:logisticLRPs2020)). LRPs increased across all probability levels when the carrying capacity was assumed higher under the Logistic:Sgen-priorCap model (Table @ref(tab:logisticLRPs2020)). The higher Sgen values for most CUs under the alternative Logistic:Sgen\_priorCap model formulation resulted in more historical years in which < 100% of CUs were above Sgen. The result was a shift of the logistic curve to the right (Figure @ref(fig:coho-IM-logisticFit2020)). LRPs based on the Logistic:Sgen\_priorCap model ranged from 23,245 to 39,200 spawners, depending on whether the required probability of all CUs being above Sgen was moderate (50%) or very likely (99%).

When CU status was based on the IFCRT distributional target, the fit of the logistic curve had a more gradual slope than the two Sgen models due to a greater overlap in ‘successful’ (all CUs > distributional target) and ‘unsuccessful’ (<100% of CUs above distributional target) years at low to moderate aggregate abundances. In 3 of the 6 years with aggregate abundances below 20,000 spawners, the distributional target was not met for all CUs (Figure @ref(fig:coho-IM-logisticFit2020)). LRPs based on this model also became increasingly large at high probability thresholds (Table @ref(tab:logisticLRPs2020)). The LRP based on a 99% probability was 44,403 spawners, with a 95% confidence interval extending from 15,102 - 73,703 spawners.

***Logistic Regression Diagnostics***

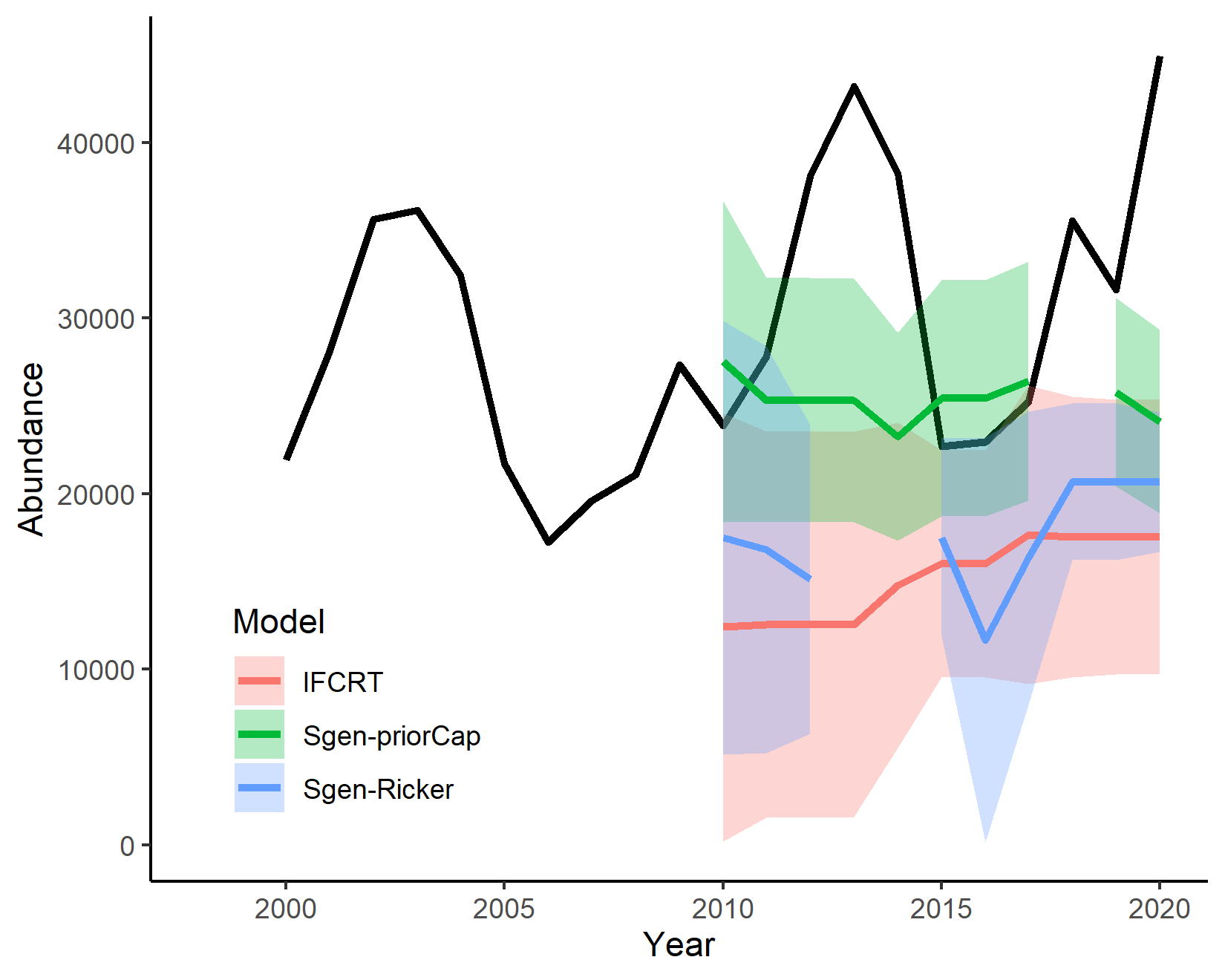
Logistic regression diagnostics showed that key regression assumptions were met, and that model fits were strong enough to support estimation of logistic regression LRPs from all three models (Table @ref(tab:logisticDiagIFC2020)). The assumption of linearity was demonstrated based on the Box-Tidwell test. This test evaluates the significance of adding a non-linear interaction term to the logit regression. We found that this additional interaction term was not significant, supporting the linearity assumption (Table @ref(tab:logisticDiagIFC2020)). An examination of deviance residuals did not show any large outliers, i.e., no residual values were greater than 2 standard deviations away from zero for all three models. Observations were also found to be independent at all year lags examined for all three models based on no significant autocorrelations among residuals.

The Wald test showed that the logistic model coefficient for aggregate abundance was marginally significant (p < 0.10). Pseudo- statistics indicated a moderately strong relationship between aggregate abundance and the probability of all CUs being above their lower benchmarks, and the goodness of fit statistics indicated a significant fit of the model with aggregate abundance relative to the null model based on p-values less than 0.01. Finally, ‘out-of-sample’ hit ratios representing classification accuracy as the proportion of successful predictions when one year of data was iteratively left out of the model fit, were relatively high at low probability thresholds, indicating good accuracy. This result was especially true for the Logistic:Sgen-Ricker and Logistic:Sgen-priorCap models which had hit ratios ranging between 0.83 and 0.87 at probability thresholds of 50% and 66%. Classification accuracy was lowest for all models at the 99% probability threshold.

Sample sizes were small due to the short time series available for Interior Fraser Coho; only 23 years of observations were available to fit logistic regression models. @peduzziSimulationStudyNumber1996 recommend a minimum requirement of 10 data points for the least frequent outcome based on their simulation studies in the field of clinical epidemiology. In our case, the least frequent outcome was the failure of all CUs to be above their benchmarks (i.e., 0). We were not able to make this minimum requirement for any of our model fits; we had only 7, 8, and 5 data points at the least frequent outcome for the Logistic:Sgen-Ricker, Logistic:Sgen-priorCap, and Logistic-IFCRT models, respectively. Based on the current ratio of successes and fails in the data, the estimated minimum sample sizes that would be required to meet the criteria of @peduzziSimulationStudyNumber1996 ranged from 26 to 42 years. However, despite small sample sizes, hit ratios are high for all models at p = 50%. As a result, we suggest that logistic regression LRPs may still be useful for this SMU. We proceeded with retrospective analyses in order to examine how sensitive LRPs based on these model fits were to variations in the level of available data.

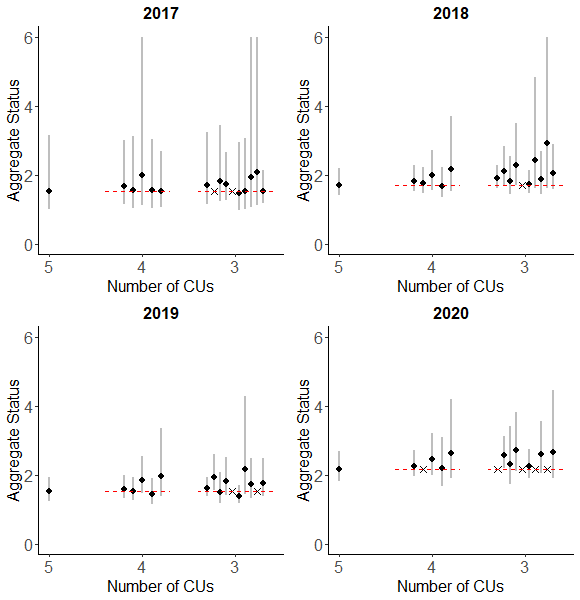
***Retrospective Analysis and Analysis Evaluating Impact of Missing CUs***

We started the retrospective analyses for the three logistic regression models in 2010. Throughout the time series, the Logistic:Sgen-Ricker did not converge when the estimates were truncated to 2013 and 2014. The Logistic:Sgen-priorCap model did not converge on an LRP estimate in 2018. All three models showed some fluctuations in LRP estimates over time (Figure @ref(fig:coho-retroLRPs)). The Logistic:IFCRT model tended to produce the lowest estimates of LRPs over time, followed by the Logistic:Sgen-Ricker and the Logistic:Sgen-priorCap. However there was considerable overlap between the confidence interval of all three LRP estimates (Figure @ref(fig:coho-retroLRPs)).



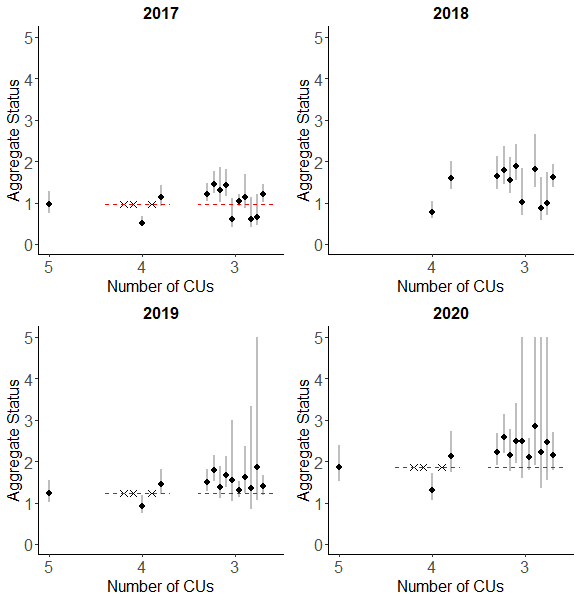
Three-year geometric mean of aggregate spawning abundance for the Interior Fraser Coho SMU (black line) and associated time series of retrospective LRPs from logistic regression estimation methods. LRPs are based on a 50% probability that all CUs will be above their lower benchmarks. Annual LRP estimates are shown as maximum likelihood values (coloured lines) and associated 95% confidence intervals (shaded areas).

When the Logistic:Sgen-Ricker model was applied retrospectively to missing data scenarios with 4 out of the 5 CUs, only a subset of scenarios had LRP estimates that converged on a solution (Figure @ref(fig:coho-IM-missingCUs)). All five possible 4-CU combinations had estimates in 2017-2019, while only four combinations had estimates in 2020. For scenarios in which LRP estimates were possible, estimates of aggregate status (Equation @ref(eq:status)) were often close to the estimate obtained when all 5 CUs were used, and always overlapped with the 95% confidence interval of the full data estimate. The Logistic:Sgen-Ricker model was less likely to converge on a solution when data from only 3 CUs were used. This pattern was especially true for 2020 when only six out of the ten possible combinations had estimates. For 3-CU scenarios that were able to converge, aggregate status estimates tended to be more uncertain than 4- and 5-CU scenarios, and showed larger deviations from estimated status when all CUs were used. One missing data scenario in 2019 had a status estimate that fell outside of the 95% confidence interval of the full data estimate.



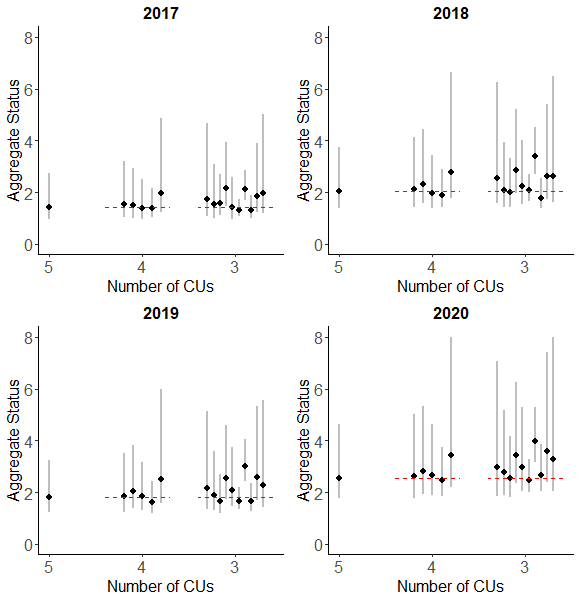
Estimates of SMU status (with 95% confidence intervals) from the Logistic:Sgen-Ricker model under different scenarios about missing CUs, where aggregate status is characterized as the recent generational mean of aggregate abundance / LRP. LRPs are based on a 50% probability that all CUs will be above their lower benchmarks. The set of status estimates associated with each number of CUs on the x-axis represents all possible combinations of CUs created by selecting that number from the 5 available CUs. Red dashed lines show the maximum likelihood estimate when no data is missing (i.e., all 5 CUs) for comparison with the missing data scenarios. Note that the y-axis has been truncated at 6, so the upper limits of some error bars are not shown.

When the Logistic:Sgen-priorCap model was applied to missing data scenarios in which 4 out of 5 CUs had data, LRP estimates were only available for two of the five CU combinations (Figure @ref(fig:coho-IMCap-missingCUs)). For scenarios in which LRP estimates were available, status was poorly estimated with the estimate often falling outside of the 95% confidence interval of the full data estimate. While convergence was more frequent when only 3 CUs were used, estimates had high uncertainty and were variable among scenarios. Several of the status estimates from 3-CU scenarios fell outside of the 95% confidence interval for the full data case. In the year 2018 the model did not converge when all CUs were included, but estimates for missing CU scenarios were available.



Estimates of SMU status (with 95% confidence intervals) from the Logistic:Sgen-priorCap model under different scenarios about missing CUs, where status is characterized as the recent generational mean of aggregate abundance / LRP. LRPs are based on a 50% probability that all CUs will be above their lower benchmarks. The set of status estimates associated with each number of CUs on the x-axis represents all possible combinations of CUs created by selecting that number from the 5 available CUs. Red dashed lines show the maximum likelihood estimate when no data is missing (i.e., all 5 CUs) for comparison with the missing data scenarios. The model with full data (5 CUs) failed to converge in 2018. Note that the y-axis has been truncated at 5, so the upper limits of some error bars are not shown.

LRPs based on the Logistic:IFCRT model could be estimated for all 4-CU data combinations in all years (Figure @ref(fig:coho-distributional-missingCUs)). Resulting estimates of SMU status were similar to the full data estimate for 4 of the 5 CU combinations. Status estimates were highest and most uncertain when the South Thompson CU was dropped from the analysis (i.e., the last of the five 4-CU combinations shown for each year in Figure @ref(fig:coho-distributional-missingCUs)). This pattern is due the 2015 data point for the South Thompson CU, which is an influential observation that has a large impact on the shape of the model fit. The South Thompson CU is the only CU that failed to meet the distributional target in 2015, which meant that its removal leads to a ‘failure’ year (i.e., at least one CU below its lower benchmark) becoming a ‘success’ (all CUs above lower benchmark). This shift results in a lower LRP and a higher status estimate. For missing data scenarios in which only 3 CUs were included, status estimates often had higher uncertainty than the 4-CU or full data scenarios, and showed high variability among scenarios in estimated status.



## LRP ESTIMATION: AGGREGATE ABUNDANCE, PROJECTION LRPS

### Methods

Projections of each of the five CUs within the Interior Fraser Coho SMU were implemented using the samSim modelling tool (Appendix @ref(app:samsim-appendix)). Finer-scale projections at the scale of sub-populations were not possible as spawner-recruitment data series were not available at this scale. As a result, projection LRPs using the IFCRT recovery target was not possible; we were restricted to estimating CU-level status based on Sgen. Parameters characterizing CU-level population dynamics, smolt-to-adult survival rates, and exploitation rates were derived directly from data sets described in Section @ref(cohoData). Base case parameters and alternative parameter values tested in sensitivity analyses are provided in Table @ref(tab:coho-BaseProjectPars). Additional details on key model parameterizations and sensitivity analyses are also described in text below.

Projections were run for 30 years over 20,000 simulation trials, with projections initialized using spawner abundances from the most recent 4 return years, 2016 - 2020. The high number of simulation trials was required to stabilize LRP estimates given the binning of aggregate escapement in 200-fish intervals to identify LRPs based on probability thresholds. The distribution of projected trajectories were near equilibrium after 4 years of projections. During the first 4 years, trajectories depended primarily on the historical time-series (Figures @ref(fig:coho-CUProjections-Ricker) and @ref(fig:coho-CUProjections-Ricker-priorCap)).

***Stock-recruitment dynamics***

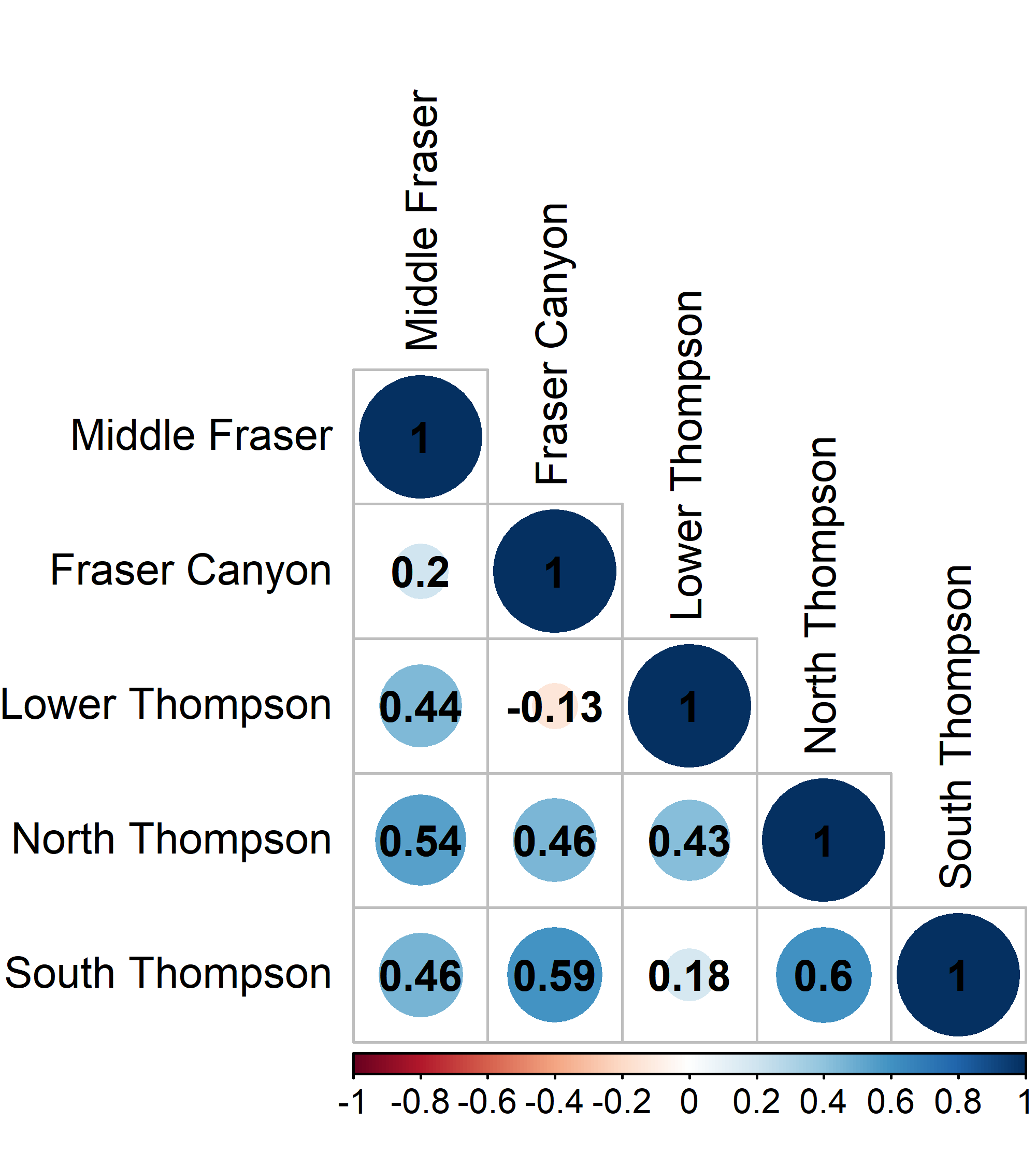
Stock-recruitment parameters for all five CUs were drawn from joint posterior distributions obtained by fitting the two stock-recruit models described in Section @ref(cohoSgen) (Ricker and Ricker\_priorCap) to available spawner-recruit data using Bayesian Markov Chain Monte Carlo (MCMC) estimation. Bayesian estimation was done using ‘tmbStan’ [@kristensenTMBAutomaticDifferentiation2016], which is an R package that allows MCMC samples to be drawn from a TMB model object using ‘rStan’ [@standevelopmentteamRStanInterfaceStan2020]. Three MCMC chains were run for 14,000 iterations, with the first half of each chain excluded from the final posterior sample. Resulting joint posterior distributions included 21,000 samples. Posterior sampling was initiated at the MLE estimates for each model formulation. Neither model showed signs of convergence failure based on our examination of and effective sample size diagnostics, as well as visual inspections of marginal posterior distributions. A summary of marginal posterior distributions for each stock-recruitment parameter (, , , and ) is provided in Appendix @ref(app:coho-appendix).

The two stock-recruitment models, Ricker and Ricker\_priorCap, were treated as two alternative hypotheses about stock-recruitment dynamics, which we compare against each other. We also considered a simple model-averaging approach, in which we equally weighted the two stock-recruit models by combining projections prior to calculating a projection LRP as a demonstration of model averaging. Additional sensitivity analyses described below were applied to the base Ricker model.

***Covariance in recruitment residuals***

We parameterized correlations in recruitment residuals among CUs from MLE predictions of pairwise correlations from stock-recruitment model fits. The correlation matrix from the base Ricker model fit is shown in Figure @ref(fig:coho-recruitResid-Ricker). Correlation values for the Ricker\_priorCap model were similar (not shown).

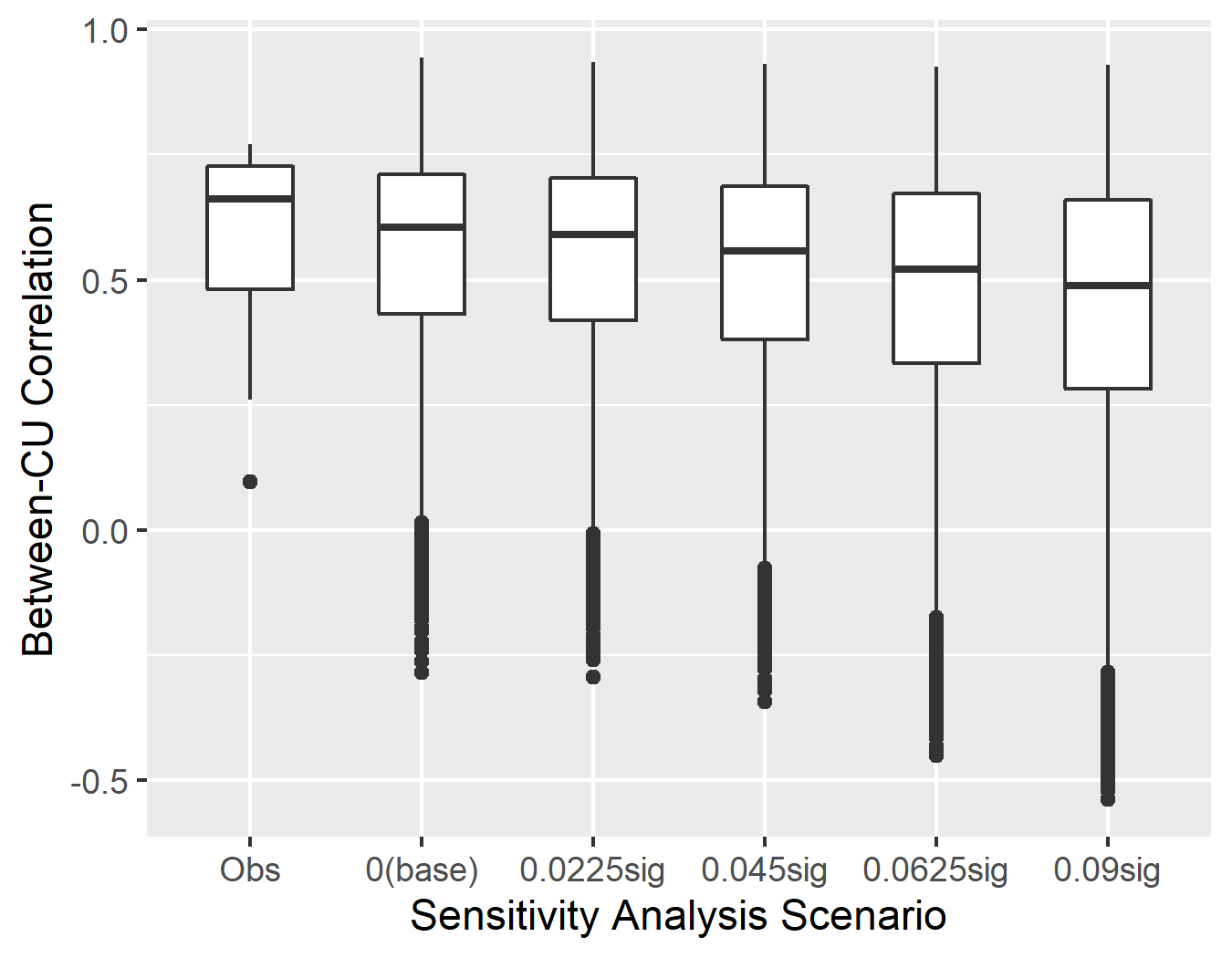
We initially attempted to reduce covariation in spawner abundances among CUs by scaling correlations in recruitment residuals (i.e., scalar < 1). However, we found that scalars had little effect on projected correlations in spawner abundances among CUs due to the shared smolt-to-adult survival rate coefficient dominating among-CU variability in recruitment. We therefore used sensitivity analyses of the level of variability in smolt-to-adult survival coefficients among CUs to drive patterns of covariation in spawner abundance, as described below. This approach differs from that taken for WCVI Chinook (Section @ref(WCVIchinookChapter)).



***Variability in smolt-to-adult survival coefficient among CUs***

When fitting stock-recruit models to data, we followed the approach of @kormanEvaluationFrameworkAssessing2019 and @arbeiderInteriorFraserCoho2020 in assuming that all CUs experienced the same smolt-to-adult survival rate for given sea-entry year, and that the smolt-to-adult survival coefficient, , was constant both among CUs and among years. When projecting CUs forward, we maintained this assumption in our base case by generating a single smolt-to-adult survival rate for each sea entry year and setting = 0, where is the standard deviation of among-CU variability in such that . We used sensitivity analyses on to test the effect of changes in spawner abundance covariation among CUs on projected LRP estimates. Three alternative levels of were used in sensitivity analyses: = 0.045, 0.0675, and 0.09. We selected these levels to cover a range between 0 and 0.09, where 0.09 was the standard deviation of the estimated marginal posterior distribution for from our Ricker stock-recruitment model fit.

The resulting correlations in spawner abundances from the projections are shown in Figure @ref(fig:coho-sigGammaCorrelation). In the forward projections, pairwise correlations in projected spawner abundances among CUs for the base case assumption of = 0 were similar to observed pairwise correlations in spawner abundances among CUs. Increasing resulted in decreased among-CU correlation in projected spawner abundances.

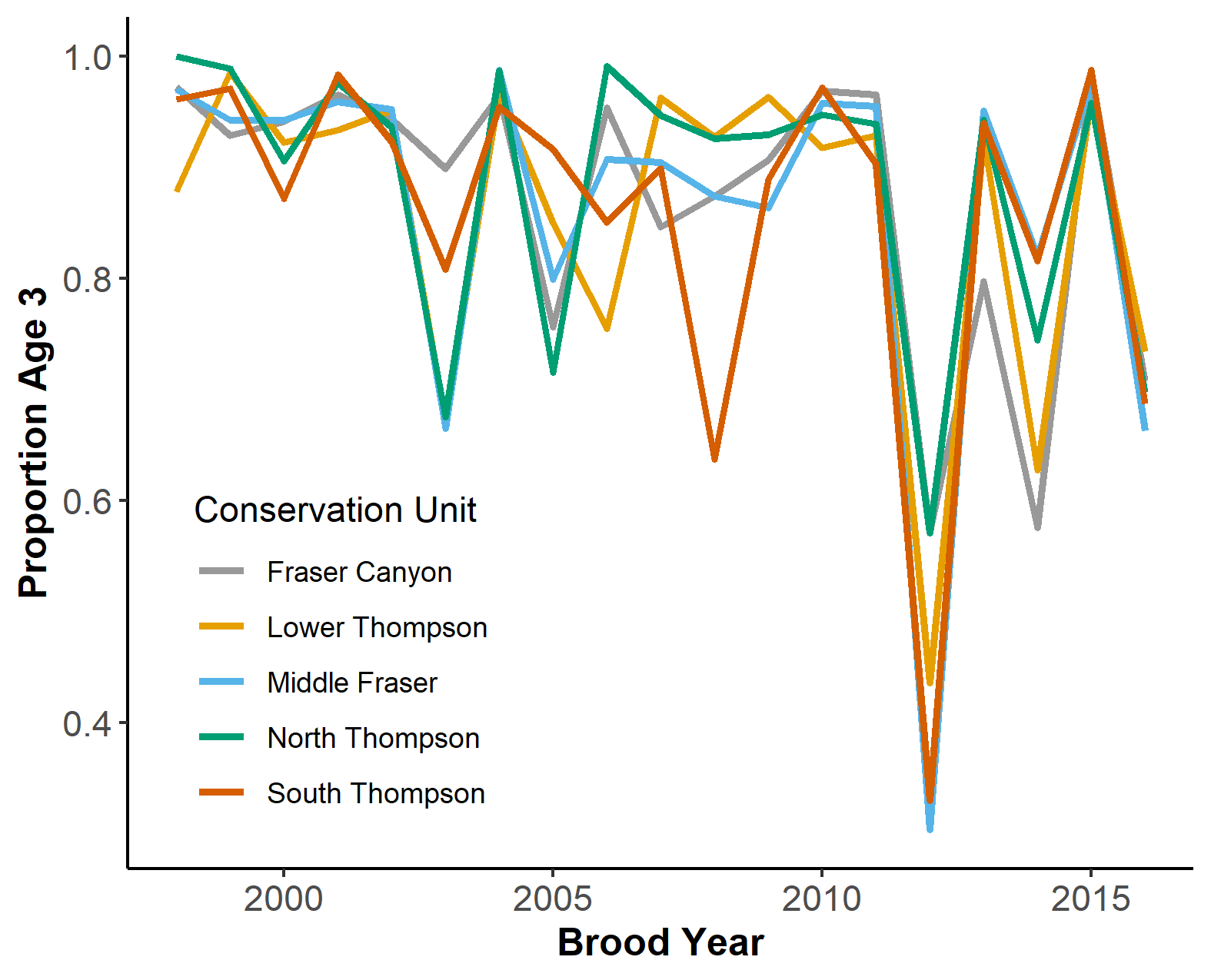


Distribution of correlations of spawner abundances among CUs for observed data between 1998 and 2020 and projected time-series under alternative assumptions about the standard deviation on the smolt-to-adult survival co-efficient among CUs for the base Ricker model formulation.

***Variability in age proportions of recruitments among CUs***

Annual variability in the age structure of returns was generated from a multivariate logistic distribution parameterized using CU-specific time series of proportions at age. The underlying average age structure for each CU was set at the average from the available time series (brood years 1998 - 2016), while annual deviations from underlying age-specific means were drawn from a multivariate logistic distribution. Annual deviations were held constant among all CUs; however, the scale of annual deviations was controlled by the variability parameter , which was estimated individually for each CU. This meant that while all CUs simultaneously experienced increases or decreases in a given year, the magnitude of the increase or decrease was CU-specific. Annual deviations were held constant among CUs to represent the strong covariation in proportions at age seen in available time series for Interior Fraser Coho, especially since 2010 (Figure @ref(fig:coho-ageProp)). When the constraint of constant annual deviations was removed, generated proportion at age data was much more variable than observed data, which was considered to be unrealistic.

Annual variability in the age structure of recruitments has not been included in other recent projection analyses for this SMU. Both @kormanEvaluationFrameworkAssessing2019 and @arbeiderInteriorFraserCoho2020 assumed a constant age structure over time.



Proportion of recruits returning at age 3 for 1998 - 2016 brood years. Only two age classes (age 3 and age 4) are present in the age structure, so the proportion of recruits returning at age 4 will account for the remainder of returns from each brood year.

***Covariance in exploitation***

We assumed an average exploitation rate of 12.5% for all CUs in forward projections based on recent average values, with common interannual variability in exploitation rates due to shared fishery impacts among CUs each year. Interannual variability in exploitation rates was assumed to be Beta distributed (constrained between 0 and 1), with the standard deviation of the Beta distribution parameterized from estimated exploitation rates for 1998 - 2016 brood years. The corresponding coefficient of variation (CV) for interannual variability was 0.44.

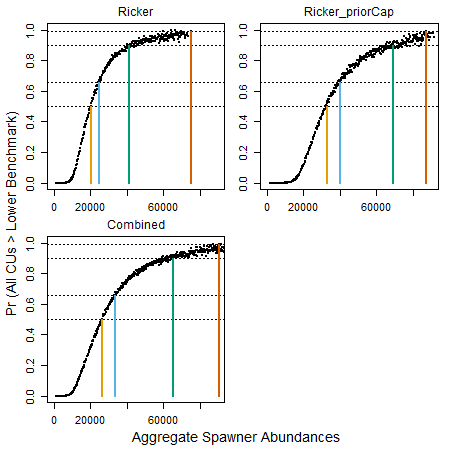
Exploitation rates for Interior Fraser Coho are only available at the SMU-level due to limited coded-wire indicator programs (one to two CUs with indicators / year) that have been available for the Fishery Regulation Assessment Model used by the Pacific Salmon Commission for Coho Salmon [@pacificsalmoncommissionJointCohoTechnical2013]. As a result, empirically-based estimates of among-CU variability in exploitation rates are not available. However, there are reasons to expect exploitation rates to vary among CUs in a given year, including differences in freshwater fisheries. We assumed that CU-specific variability in exploitation rates was half the common (SMU-level) interannual variability (CV=0.22), and varied this in sensitivity analyses from 0 and 0.44 to cover plausible bounds. Varying assumptions about variability in exploitation among CUs between CV = 0 and 0.44 in forward projections did not impact the distribution of correlations in spawner abundances in the projections (results not shown).

### Results

***LRP Estimates***

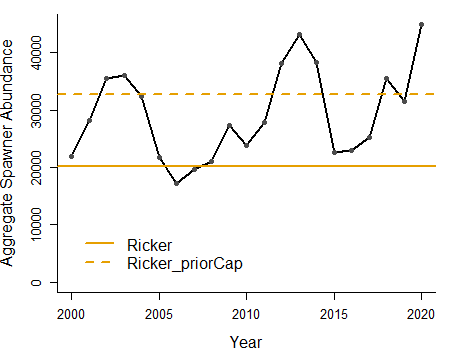
Aggregate abundance LRPs estimated using the Ricker model as a basis for forward projections were lower than those obtained when the Ricker\_priorCap model was used, regardless of which probability threshold was used (Table @ref(tab:projectedLRPs2020); Figure @ref(fig:coho-projLRPCurveByOM)). This result is similar to the logistic regression LRPs, where LRPs derived using Sgen estimates from the Ricker\_priorCap model were higher due to higher Sgen values. The projected curve showing the probability of all CUs being above Sgen had a slope that was more gradual and further from the origin for the Ricker\_priorCap model compared to the base Ricker model (Figure @ref(fig:coho-projLRPCurveByOM)). When projection outputs from both stock-recruitment model formulations were combined prior to binning in order to create a model-averaged scenario (with equal weight assigned to both scenarios), the resulting probability curve was mid-way between the curves from the two individual models. In all cases, projected curves had higher scatter with increasing aggregate abundance, such that LRP estimates at probability thresholds of p = 0.90 and p = 0.99 were unstable.

Projection LRPs were higher than logistic regression LRPs calculated using the same stock recruitment relationship. While we did not explore the underlying cause of this pattern, or whether it was a general result or specific to this case study, it may occur because projection LRPs account for more sources of uncertainty than logistic regression LRPs.



Probability of all CUs being above their lower benchmark of S along a gradient in aggregate abundances within bins of 200 fish for two different stock-recruit model options (Ricker and Ricker\_priorCap) as well as a model averaged case (Combined) in which results from both stock-recruitment models were equally weighted. Results are derived from projections over 30 years and 20,000 MC Trials. Each dot is the proportion of MC trials where all CUs were > lower benchmarks of S. Candidate LRPs at p=0.5 (yellow) and p=0.66 (blue), 0.90 (green), and 0.99 (orange) are highlighted.

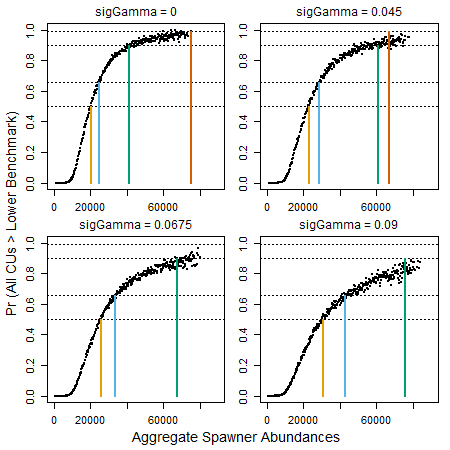
Generational average spawning abundance (based on a 3-year geometric mean) remained above the projection LRP derived using the Ricker model with a probability threshold of p = 0.5 for most years between 2000 and 2020. There were two years when aggregate spawning abundance decreased below the LRP: 2006 and 2007 (Figure @ref(fig:coho-AggEscpSeries-wProjLRP)). In comparison, when projection LRPs were derived using the Ricker\_priorCap model with p = 0.5, aggregate spawning abundance remained below the LRP for 11 out of the 21 years.



Three-year geometric mean of aggregate natural-origin spawning abundance for the Interior Fraser Coho SMU (black line) relative to projection LRP estimates using two different stock-recruitment model formulations, Ricker and Ricker\_priorCap, with a probability threshold of p=0.5. Forward projections used to estimate reference points were parameterized using available 1998-2020 time series under base model assumptions.

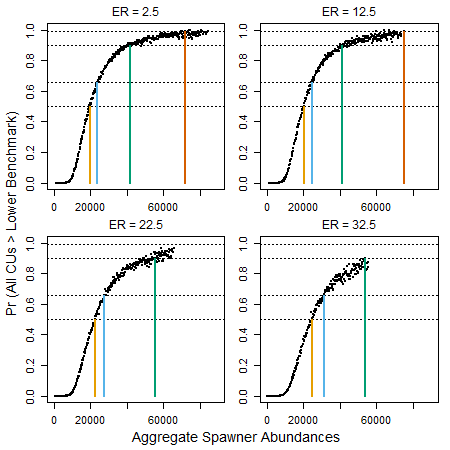
***Sensitivity Analyses***

Increasing , which corresponded with reduced between-CU pairwise correlation in spawner abundances over time (Figure @ref(fig:coho-sigGammaCorrelation)), resulted in a flattening of the projected relationship between aggregate spawner abundances and the probability of all CUs being above their lower benchmarks (Figure @ref(fig:coho-projLRPCurve-bySigGamma), where is labelled ‘sigGamma’). LRP estimates corresponding to a given probability threshold increased as increased due to curves shifting to the right and becoming more gradual (i.e., less steep). For the two highest scenarios examined (=0.0675 and 0.09), a 99% probability of all CUs being above their lower Sgen benchmark was never achieved.



Probability of all CUs being above their lower benchmark of Sgen along a gradient in aggregate abundances (within bins of 200 fish) for alternative scenarios about the value of sigGamma. The baseline value used for forward projections was sigGamma = 0. Results are derived from projections over 30 years and 20,000 MC Trials. Each dot is the proportion of MC trials where all CUs were > S. Candidate LRPs at p=0.5 (yellow) and p=0.66 (blue), 0.90 (green), and 0.99 (orange) are highlighted.

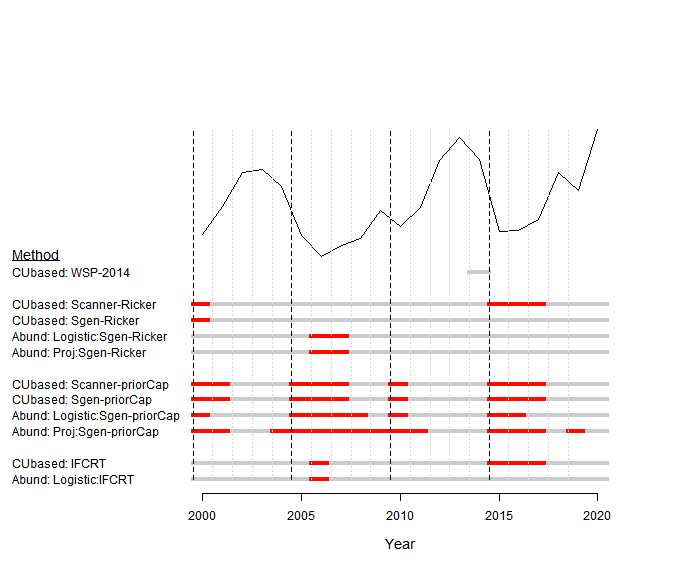
Increasing the average exploitation rate used in forward projections also led to a shift in projected curves to the right; however, the shift was more gradual over the range of exploitation rate scenarios we considered than the effect of increasing (Figure @ref(fig:coho-projLRPCurve-byER)). The effect of increasing exploitation rates was smallest at low probability thresholds. At p = 0.5, the LRP differed by 400 fish between the ER = 2.5% and ER = 12.5% scenarios (range = 19,700 - 21,000), and by < 4000 fish among all four scenarios (range = 19,700 - 24,000). Differences were much larger among the four exploitation rate levels examined for the p = 0.90 threshold. When the average exploitation rate was set at 22.5% or 32.5%, aggregate abundances barely exceeded 60,000 fish, and it was not possible to achieve a 99% probability of all CUs being above their lower Sgen benchmarks.



Probability of all CUs being above their lower benchmark of Sgen along a gradient in aggregate abundances (within bins of 200 fish) for alternative scenarios about average exploitation rates (ER) in forward projections. The baseline value used for forward projections was ER = 12.5%. Results are derived from projections over 30 years and 20,000 MC Trials. Each dot is the proportion of MC trials where all CUs were > S. Candidate LRPs at p=0.5 (yellow) and p=0.66 (blue), 0.90 (green), and 0.99 (orange) are highlighted.

## HISTORICAL EVALUATION OF STATUS ACROSS LRP METHODS

We compared annual estimates of SMU status relative to LRPs for the range of LRP estimation options considered in this case study (Figure @ref(fig:coho-statusPlot-withBars)). For all aggregate abundance LRPs, we illustrate LRPs estimated from a probability threshold of p = 0.5 (i.e., a 50% probability that all CUs would have status above their lower benchmark). We used the following labeling convention when comparing historical status estimates across LRP estimation methods: *“Metric” : “LRP Method” : “CU Status Method”*. ‘Metric’ refers to the choice of whether to base an LRP on the proportion of CUs above Red CU status (CU status-based LRPs; labelled as ‘CUbased’) or on aggregate SMU-level abundance (Abund). The ‘LRP’ method only applies to aggregate-abundance based LRPs, which can be logistic regression (Logistic) or projection (Proj). Finally, the ‘CU Status Method’ can be based on the multidimensional algorithm within the Pacific Salmon Status Scanner in which CU abundance benchmarks are based on one of the two Ricker models (Scanner-Ricker or Scanner-priorCap). Alternatively, when only a single benchmark is used to characterize CU status, it can be based on Sgen estimated from one of the two Ricker models (Sgen-Ricker or Sgen-priorCap) or the IFCRT target (IFCRT). For example, when referring to an aggregate abundance LRP that is estimated via a logistic regression fit to historical CU status, with CU status estimated relative to Sgen from the base Ricker model, it was labelled as “Abund: Logistic: Sgen\_Ricker”. In the future, @ref(fig:coho-statusPlot-withBars) could be expanded to include the number of CUs in the Red zone and / or the names of CUs in the Red zone. This type of information may help inform the development of rebuilding plans by highlighting CUs that are consistently in the Red zone.



We show historical results for three types of CU status-based LRP methods: using the proportion of CUs with Pacific Salmon Status Scanner status > Red (e.g., CUbased: Scanner-Ricker), using the proportion of CUs with abundance > Sgen (e.g., CUbased: Sgen-Ricker), and using the IFCRT distributional target status (CUbased: IFCRT) . @holtGuidelinesDefiningLimitInpress recommend CU statuses be derived from a multidimensional approach such as that used within the Salmon Scanner; however, we show results for the single metric Sgen and IFCRT approaches to demonstrate how these approaches impact SMU status. This comparison is of interest because our aggregate abundance LRPs use status estimates based on a single metric rather than a multidimensional approach.

In addition to the LRP estimation methods presented so far in this case study, we include the full WSP assessment that was conducted in 2014 as an option for estimating CU status for use in a CU status-based LRP. We label this case “CUbased : WSP-2014”. SMU status would have been assessed as being above the LRP at this time as all CUs were assessed as Amber or Amber/Green.

In general, estimated LRP breaches coincided with low points in the aggregate abundance time series (2000, 2005 - 2007 and 2015-2017). However, there were differences among methods in the years that SMU status was estimated to be below the LRP, as well as a couple methods for which status was never estimated to be below the LRP (CUbased: Sgen-Ricker and Abund: Logistic: IFCRT).

Comparison of SMU status estimates over time for all LRP estimation methods that used Sgen from the base Ricker model showed differences in statuses between the CU status-based and aggregate abundance methods (status bars 2-5 in Figure @ref(fig:coho-statusPlot-withBars)). Under the ‘CUbased: Scanner-Ricker’ method, the LRP was breached in years 2000 and 2015-2017, but for the ‘CUbased: Sgen-Ricker’ method, the LRP was only breached in the year 2000. The Salmon Scanner multidimensional algorithm includes a step in which CU status is designated as Red when the generational mean spawning abundance is less than 1500 spawners (Figure @ref(fig:decision-tree)). Because estimated Sgen is less than 1500 spawners for the Fraser Canyon CU, it is possible for the criteria of <1500 spawners in a CU to be breached even though abundance exceeds Sgen. This situation occured for the Fraser Canyon CU in 2015-2017. Therefore, LRP methods that use the multidimensional approah to characterize CU status can be more precautionary than methods that rely on a single Sgen benchmark.

In the years 2005-2006, SMU status for both the ‘Abund: Proj: Sgen-Ricker’ and ‘Abund: Logistic:Sgen-Ricker’ methods fell below the LRP, while the CU status-based methods (labelled ‘CUbased:’) did not. Declines in aggregate SMU abundance in 2005-2006 were driven by declines in the four larger CUs (which, still remained above their individual Sgen estimates). Declines in the abundance of the Fraser Canyon CU were not as drastic. As a result, while SMU-level aggregate abundance dropped below the abundance LRP, the Fraser Canyon CU that triggered Red status in 2015-2017 exceeded 1500 spawners and did not trigger the CUbased: Scanner-Ricker method. The aggregate abundance LRP from the ‘Abund: Proj: Sgen-Ricker’ estimation method was higher than that from the ‘Abund: Logistic: Sgen-Ricker’, so only the former method triggered an LRP breach.

When the Ricker-priorCap model was used to estimate Sgen instead of the base Ricker model, both Sgen and LRP estimates were higher than under the base Ricker model formulation. This in turn resulted in more frequent LRP breaches when the Ricker-priorCap model was used (status bars 6-9 in Figure @ref(fig:coho-statusPlot-withBars)). Among the ‘priorCap’ methods, status was most frequently estimated to be below the LRP when the ‘Abund: Proj:Sgen-priorCap’ method was used; for this method, the LRP was triggered in 14 out of the 21 years between 2000 and 2020. In comparison, the LRP was triggered in 9, 9, and 8 of the 21 years for the ‘CUbased: Scanner-priorCap’, ‘CUbased: Sgen-priorCap’ and ‘Abund: Logistic:Sgen-priorCap’ methods, respectively.

Finally, SMU status was below the LRP in four years (2006, 2015-2017) out of the 21 years for the ‘CUbased: IFCRT’ method, but was only triggered in 2006 under the ‘Abund: Logistic: IFCRT method’ (status bars 10-11 Figure @ref(fig:coho-statusPlot-withBars)). The ‘Abund: Logistic: IFCRT method’ produced the lowest LRP of all logistic methods (Figure @ref(fig:coho-IM-logisticFit2020) and Table @ref(tab:logisticLRPs2020)), therefore the LRP tended to get breached less often.

Despite the differences in status estimates in some years for CU status-based and aggregate abundance LRPs highlighted above, estimated status tended to match in more years than not for CU status-based and aggregate abundance methods. Out of the 21 years available for comparison, the number of years with consistent status estimates for CU status-based and aggregate abundance LRPs ranged from 15 - 18 years (71 - 86% of years), depending on the exact methods being compared. For the Base Ricker models, the proportion of years with consistent status estimates was lowest when comparing the CUbased:Scanner-Ricker method to the Abund:Logistic:Sgen-Ricker and Abund:Proj:Sgen-Ricker methods (15 / 21 years; 72% for both comparisons). These proportions were higher when comparing among the Ricker\_priorCap models (86% and 81% for the same comparisons).

## DISCUSSION

The Interior Fraser Coho SMU is considered a data-rich SMU because it has stock-recruitment time series for all five CUs within the SMU, which allowed for the estimation of stock-recruitment based benchmarks (Sgen). However, time series were restricted to years after 1998, when spawner abundance data were collected with more consistent methodologies and regularity. This period also aligns with the low productivity period [@deckerAssessmentInteriorFraser2014] when the SMU abundance is considered depressed relative to historical levels. Despite the short time series, Interior Fraser Coho are well-suited for looking at the application of aggregate abundance LRPs due to the long history of using aggregate abundance recovery targets and fisheries reference points [@ifcrtConservationStrategyCoho2006; @kormanEvaluationFrameworkAssessing2019; @arbeiderInteriorFraserCoho2020]. While we were able to estimate aggregate abundance LRPs using a suite of CU-level benchmarks and LRP estimation methods (logistic regression and projection), our results highlight variability in status against aggregate abundance LRPs that in some cases deviates from status against CU status-based LRPs. Our results also highlight the sensitivity of logistic regression based LRPs to data availability.

### CU status-based vs. Aggregate Abundance LRP Methods

Comparisons of status between the abundance-based methods and the CU status-based methods yielded mixed results. While there were differences in the years in which CU status-based and aggregate-abundance based methods dropped below LRPs, status tended to match in more years than not. Out of the 21 years available for comparison, the number of years with consistent status estimates for CU status-based and aggregate abundance LRPs ranged from 15 - 18 years (72-86% of years), depending on the exact methods being compared.

Consistency between CU status-based and aggregate abundance LRPs depended on the method used to assess CU status. For methods using the base Ricker model, status tended to drop below CU status-based LRPs when abundance of individual CUs was low (2000-2001, 2015-2017), and drop below aggregate abundance LRPs when aggregate abundances were low (2006-2007). As a result, CU status-based LRPs were breached in years with low abundance in only one CU (e.g, 2000, 2015-2017) whereas the aggregate abundance methods did not. In comparison, status was generally consistent for the scenarios in which the Ricker\_priorCap model was used with LRPs breached in similar years. This result occurred because estimated Sgen and aggregate abundance LRPs were higher under the Ricker\_priorCap model, which resulted in a more frequent occurrence of years with both aggregate abundance below the LRP and individual CUs below benchmarks. Finally, when the IFCRT distributional target was used, the CU status-based LRP was breached for 3 years in which the aggregate abundance was not (2015-2017) due to low abundance in one CU.

When considering CU status-based LRPs, comparisons between using a single metric benchmark to estimate CU status (i.e., Sgen) and using a multidimensional approach yielded similar results. This occurred because the multidimensional algorithm relies on Sgen benchmarks when those are available. Exceptions occur when an estimated Sgen is less than the absolute threshold of 1500 spawners, as occurred for the Fraser Canyon CU.

### Structural Uncertainty in Spawner-Recruitment Dynamics

Most methods evaluated for the Interior Fraser Coho case study relied on the evaluation of CU status relative to Sgen. As a result, the method used to estimate Sgen had a large influence on results. Sgen estimates were higher for the Ricker\_priorCap model compared to the base Ricker model, which meant that LRPs were more frequently triggered under this formulation. This pattern was observed for all four methods that relied on the Ricker\_priorCap Sgen estimates.

We considered two alternative Ricker models for Interior Fraser Coho to represent different assumptions regarding carrying capacity, which in turn affected productivity. This approach has also been used in previous analyses for this SMU. @arbeiderInteriorFraserCoho2020 used a model averaging approach with three SR models equally weighted when assessing recovery potential for the Interior Fraser Coho SMU (the base Ricker and Ricker\_priorCap models we used, as well as a third depensatory mortality version that we did not consider). @kormanEvaluationFrameworkAssessing2019 also considered multiple Ricker model formulations when estimating reference points for the Interior Fraser Coho SMU; however, they opted to focus on results for the base Ricker model instead of using model averaging approaches.

Future analyses to characterize Interior Fraser Coho dynamics and estimate biological reference points could further explore model structure by considering more varied approaches. For example, life-cycle models that partition the life cycle into separate marine and freshwater components allow for more direct representation of smolt abundance and subsequent marine survival than our current approach of using smolt-to-adult survival as a covariate in adult-to-adult spawner recruitment models [@bradfordRiskAssessmentThompson1998]. Treating smolt abundance as a latent variable within a life-cycle model would allow the smolt-to-adult survival rate index to be directly applied to smolt abundance [@ohlbergerDemographicChangesChinook2018]. Modelling frameworks that incorporate hatchery enhancement into spawner-recruitment models while allowing for differential productivity between hatchery- and natural-origin spawners could also be considered in the future [@falcyDetectingEffectsManagement2018].

The consideration of multiple model structures requires a decision on which model, or models, should be used to assess stock status. One approach to accounting for uncertainty in underlying model structure is to integrate estimates of LRP status over alternative structures. We demonstrate this approach when using projection estimates of aggregate abundance LRPs, in which we combine projections under each SR model scenario before calculating the LRP. This approach is basically a model averaging approach in which both scenarios are equally weighted. However, other methods of assigning weights among model are possible, such as weighting based on prediction skill [@kellValidationStockAssessment2021]. When model averaging, it is important to consider the plausibility of various models and the distribution of uncertain parameters (e.g., their variances and biases)[@dormannModelAveragingEcology2018; @millarModelAveragingStreamline2015]. It may be more appropriate to select one model instead of averaging over models when they provide competing hypotheses (i.e., bimodal distributions) with differing management implications [@millarModelAveragingStreamline2015].

### Logisic Regression LRPs

Retrospective analyses of logistic regression LRP options showed that LRPs were sensitive to data availability, with LRP estimates changing over time as more data became available. In addition, relatively small shifts in estimated Sgen over time meant that logistic models based on Sgen were sometimes unable to converge on a solution even with more data. This failure to converge was a result of a lack of overlap between aggregate abundance levels associated with ‘successes’ and ‘failures’, which is a requirement for logistic models. This limitation did not occur for the IFCRT logistic regression approach, in which the absolute threshold used to define CU status was constant over time.

Missing data scenarios, in which 1 or 2 CUs were removed from the data set, further highlighted limitations in the ability of the logistic regression models to converge on a solution given small changes in the pattern of ‘successes’ and ‘failures’. In addition, we found that removing CUs in logistic regression LRPs resulted in an increase in uncertainty of estimated status. However, despite these limitations, the 95% confidence intervals for the missing data scenarios usually overlapped with status based on all CUs being included. This result suggests that our assumption of CU representativeness for stock status within the Interior Fraser Coho SMU, as described in Appendix @ref(app:coho-appendix), may be supported. Future work on this SMU (or, other SMUs wishing to apply these methods) could use retrospective analyses of CU status-based approaches to see whether status estimates remain stable when 1 or 2 CUs are removed from the data set. The extent to which this result can be applied to other SMUs is expected to be dependent on the level of covariation in CU status among CUs within an SMU.

Taken together, these retrospective results highlight that caution should be used when applying logistic regression LRPs. While they did provide similar estimates of SMU status as CU status-based methods for several (but not all) years in the historical comparison, they were sensitive to reductions in data availability. For the specific case of Interior Fraser Coho, retrospective performance may improve in the future as more data become available to improve the statistical power of logistic regression fits.

### Projection LRPs

Projection LRPs have the advantage of being able to incorporate uncertainty about current (and future) population and / or fishery dynamics into LRP estimates, whereas logistic regression LRPs represent conditions that have been previously experienced, which may or may not persist into the future. Projection LRPs also allow key structural uncertainties to be incorporated into LRP estimates through the combination of multiple projection scenarios. For example, in the current application, we chose not to apply a third formulation of the Ricker model with depensatory mortality that has been used previously [@kormanEvaluationFrameworkAssessing2019; @arbeiderInteriorFraserCoho2020]. However, future applications of projection LRP methods for Interior Fraser coho could easily incorporate depensation as an additional scenario in a model-average approach if this was considered a key uncertainty to be represented.

The sensitivity of projection LRPs to exploitation rate means that these LRPs are specific to the management context. In our Interior Fraser Coho projections, we set exploitation rates at the recent average as fishery restrictions since 1998 been stable. In this case, the LRP represents the level of aggregate abundance that would be required to ensure all CUs were above Sgen given that constant exploitation rate. However, Interior Fraser Coho are not managed using a fixed ER policy. While harvest has been relatively constant for several recent years, target harvest rates can vary among years for several reasons, including fishery plans for other species (e.g., Fraser Sockeye Salmon). For years in which target exploitation rates are increased, the LRP would also need be increased accordingly to ensure that the underlying objective of all CUs above Sgen could be achieved. This pattern arises due to variability in productivity among CUs; when higher exploitation rates are applied, some low productivity CUs will require higher spawning abundances to ensure that they remain above Sgen. This effect is demonstrated in Appendix @ref(app:ERsensitivity-appendix). As a result, projection LRPs are not static measures of serious harm, as commonly developed for other stocks and species.

Projection LRPs were also sensitive to the level of covariation in spawner abundances among CUs over time. Reductions in covariation resulted in increased LRP estimates. This pattern will result in higher LRPs as the relationship between aggregate abundance and CU status weakens because random dynamics among CUs will increase the probability of any one CU having Red status. We recommend that possible instabilities in projections be evaluated for this SMU, and other applications for projection LRPs, which could arise due to changes in covariation of spawner abundance among CUs due to CUs with different productivity levels responding differently to exploitation.

### Distributional-based benchmarks

The distribution of spawning abundances among smaller populations or sub-populations within a CU is recognized as an important component of CU status [@dfoCanadaPolicyConservation2005]. We relied on previously established distributional targets for Interior Fraser Coho to demonstrate the development of LRPs based on finer-scale distributional metrics. These metrics were based on a short-term recovery target of of 1000 spawners in at least 50% of sub-populations [@ifcrtConservationStrategyCoho2006]. While these targets were used for recent recovery planning analyses [@arbeiderInteriorFraserCoho2020], they were not considered as part of the 2015 WSP Status Assessment for Interior Fraser Coho [@dfoWildSalmonPolicy2015] and are included in the Pacific Salmon Scanner Tool because formal distributional benchmarks have not been identified under the WSP. We recommend research on the development and evaluation of metrics and benchmarks of distribution of spawning within CUs, as well as the development of guidelines on how to incorporate these into CU-level assessments under the WSP.