Estimating Aggregate Coho Salmon Terminal Run and Escapement to the Lower Fraser Management Unit

Study Design prepared for:

Pacific Salmon Commission
600-1155 Robson Street, Vancouver BC, V6E 1B5

By:

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February 21st, 2020

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1 Context

The absence of reliable and accurate terminal run and escapement estimates for Lower Fraser Coho (LFC) Salmon represents a critical information gap for Southern Boundary Coho Salmon management. Several factors have contributed to deficiencies in LFC escapement data, including poor access to streams, dissimilar visual escapement program methodologies conducted by multiple agencies, and insufficient and inconsistent funding levels. Current fisheries management of LFC applies exploitation rates (ERs) measured from coded-wire tag (CWT) data for hatchery stocks to make inferences about natural stocks using the Fisheries Regulation Assessment Model (FRAM; see MEW 2008). Accurate estimates of LFC escapement are critical for Coho Salmon management and for the use of the FRAM to estimate ER. Further, the usefulness of FRAM-derived estimates of Interior Fraser Coho (IFC) ER depends on the accuracy of LFC escapement (i.e., underestimates of LFC escapement result in overestimates of IFC ERs in concurrent fisheries and vice versa).

This study aims to address data deficiencies by avoiding the aforementioned problems in LFC data collection by leveraging data from existing fisheries programs, processes, and infrastructure, and by adding key program elements that enable information to be integrated among several LFC sources to estimate escapement. As described in section 2.1, total LFC escapement will be estimated through the expansion of stock composition data gathered randomly from a lower Fraser River assessment fishery (assessment fishery). The forecasted catch of the assessment fishery is described in Section 2.2. The expansion to the entire LFC escapement will be scaled based on estimates of spawning escapement for specific stocks, including adipose-fin-clipped (AFC) and CWT Nicomen Coho, AFC and otolith-marked Chilliwack hatchery Coho, and natural Lillooet River Coho. Nicomen Slough and Lillooet River Coho escapement projects are separately funded through the Southern Boundary Fund (Appendix A and Appendix B), while this project will estimate the Chilliwack hatchery Coho escapement through a passive mark recapture approach, which is described in Section 2.3.

2 Methods

2.1 Distant Fishery Mark-recapture Estimation

The LFC terminal run ($\widehat{N}$) will be estimated using a variation of the two-sample Petersen mark-recapture method (Petersen 1896, Seber 1982, Schwarz and Taylor 1998) in an innovative way that uses a distant fishery and terminal escapements as the different components in Equation 1.

(1) $$\widehat{N} = \frac{(\widehat{M}+1)\times(\hat{C}+1)}{(\hat{R}+1)} - 1$$

This method requires that random, representative samples of the Fraser Coho Salmon run be collected via an assessment fishery conducted during the LFC migration into the Lower Fraser River. The assessment fishery will occur downstream of the confluence with potentially abundant LFC spawning rivers (e.g. Pitt, Coquitlam, and Brunette rivers) in the main channel of the Fraser River where all the LFC migrating to upstream locations can be sampled with equal probability (i.e., in the proximity of New Westminster, B.C.). There are two very minor spawning systems, Musqueam and Byrne creeks, which are not anticipated to be part of the study design population because they enter the North Arm of the Fraser River downstream of New Westminster, BC. Details of the assessment fishery (sample sizes, timing, etc.) are provided in Section 2.2.

For the distant fishery mark-recapture estimation method (Equation 1), the 'catch' ($\hat{C}$) will be the total number of LFC encountered in the assessment fishery, and the 'recaptures' ($\hat{R}$) will be the number of 'marks' encountered in the assessment fishery (see Driver Stock Ratio method in PSCSSC 2018). Note that every Coho Salmon encountered in the assessment fishery will fall into one of seven groups (Table 1, Figure 1), and that specific stock components will be identified through DNA, CWT, or otolith samples. For the purposes of this analysis, 'recaptures' ($\hat{R}$) will include Coho Salmon from the 'clipped Nicoman Slough' ($\hat{R}_{Nicomen,AFC}$ where AFC = adipose fin clipped), 'clipped Chilliwack' ($\hat{R}_{Chilliwack,AFC}$), and 'unclipped Lillooet' ($\hat{R}_{Lilloet,unclipped}$) groups. All other LFC will be considered as unmarked with Coho Salmon identified as Interior Fraser Coho through genetics excluded from the catch. And the total catch ($\hat{C}$) will be the sum of LFC Coho Salmon from five of seven groups (i.e. the total catch ($\hat{C}$) will exclude clipped and unclipped IFC). It is important to note that all AFC Coho will be destructively sampled while adipose present Coho will be released alive.

Careful accounting of fish in the marked population ($\widehat{M}$) is required to produce a non-biased estimate because any loss of marks between marking and recovery would result in an underestimate of population size. In this design, the number of marked individuals in the population ($\widehat{M}$) will be determined from escapement and sampling of fisheries, as

(2) $$\widehat{M} = \sum_s (\hat{R}_s + \hat{F}_s + \hat{E}_s)$$

Specifically, $\widehat{M}$ will be estimated as the total number of individuals originating from three groups (denoted by subscript s): Chilliwack or Nicomen Slough hatchery-origin, or wild Lillooet Coho. For each group, we will sum the total number of individuals that were caught in the assessment fishery ($\hat{R}_s$) (except Lillooet because they will be live released), returned to each river as escapement ($\hat{E}_s$), or that were harvested in fisheries ($\hat{F}_S$) in the area between the assessment fishery and the escapement location (e.g., the confluence of the Chilliwack and Fraser rivers); and then add them together to calculate $\widehat{M}$ (Equation 2). Catch data from DFO and Aboriginal Fisheries Strategy (AFS) catch monitoring will be used to represent fishery removals between the assessment fishery and spawning tributaries, and stock composition data from these removals will be used to estimate values of $\hat{F}_S$. (i.e., $\hat{F}_{Lilloet,unclipped}$; $\hat{F}_{Chilliwack,AFC}$; $\hat{F}_{Nicomen,AFC}$). Escapement data for Nicomen Slough ($\hat{E}_{Nicomen,AFC}$) and Lillooet River ($\hat{E}_{Lilloet,unclipped}$) Coho will come from separately funded Southern Boundary Fund projects (Appendix A and Appendix B), while this project will estimate the Chilliwack hatchery Coho escapement ($\hat{E}_{Chilliwack,AFC}$) through a passive mark-recapture approach (see section 2.3).

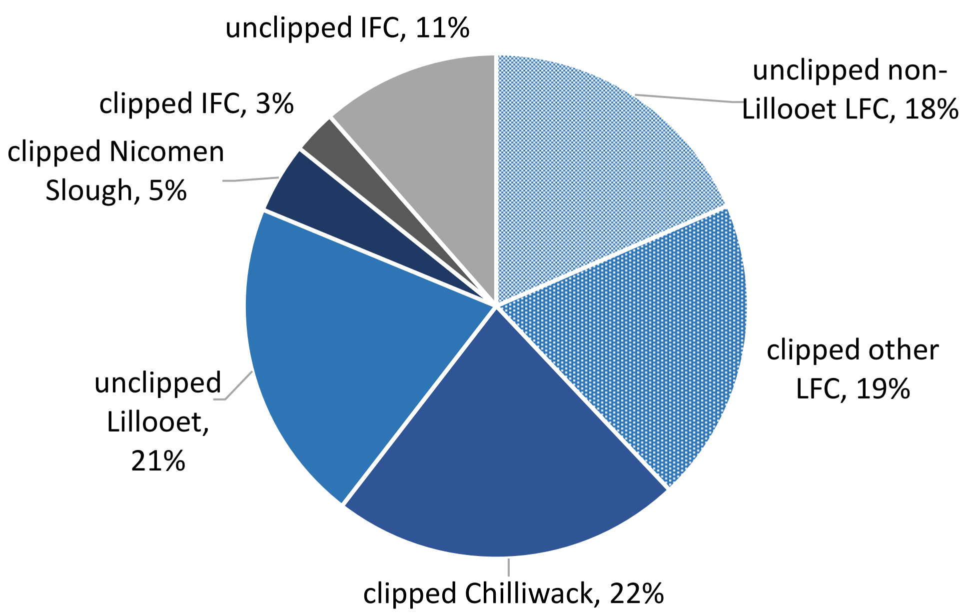


Figure 1. Estimated ratio of Coho Salmon encounters at the proposed Fraser River assessment fishery site. Based on recent Coho Salmon hatchery releases and the Decay Model.

2.1.1 Assumptions

The distant fishery mark-recapture estimation method makes two key assumptions. The first is that the assessment fishery will collect a random sample of the entire LFC run for the year and that the stock components measured in the assessment fishery will be representative of the population components in proportion to their true abundance. Therefore, it is important to have a temporally wide enough sampling window to capture the full run-timing distribution. The second assumption is that the assessment fishery will encounter a stock composition of LFC that is reasonably similar to that depicted in Figure 1, which is based on recent Coho Salmon hatchery releases and the Decay Model (C. Parken, pers. comm. 2020) for stock composition. This second assumption is critical for ensuring that our study design methods are sound and that the assessment fishery will generate adequate sample sizes of our target catch (see Appendix D) to produce a target precision estimate of LFC escapement (see Appendix C).

There are also two factors of the distant fishery mark-recapture estimation method that require additional attention. The first factor is that the marked populations may behave differently from each other that results in a different probability of capture at the assessment fishery over the sampling window. We can account for this by using a stratified Petersen estimator (Schwarz and Taylor 1998, Bonner and Schwarz 2011). The stratified Petersen estimator allows for capture probabilities of each marked population to be estimated independently across different temporal periods where we could identify differences in run-timing of each population. Section 2.3, the Chilliwack Passive Mark-Recapture, also uses a stratified Petersen estimator and describes its assumptions and solutions in more detail. The second factor is that the input values that go into the estimator are not certain counts, they are estimates. The current stratified Petersen estimators do not have a way to incorporate variance in their inputs. We account for this variance by using a bootstrap method that creates iterations of the input data based on their individual variances (Appendix C). The bootstrap method propagates the uncertainty of each estimate to the system estimate in a similar way as Bayesian Monte-Carlo algorithms do. However, it was noted (C. Schwarz, pers. comm. 2020) that a full Bayesian framework may be necessary if sample sizes are small or if input value variance is high. Alternative methods are being considered and are under development that utilize Bayesian frameworks where input values have uncertainty (McElreath 2018).

2.1.2 Sampling Logistics

To identify stock components within the assessment fishery for a given year, several types of stock identification methods will be used (Table 1). AFC fish will be sampled for DNA, otolith marks, and examined for a CWT (destructive sampling). Chilliwack and Inch Creek (in Nicomen Slough) hatcheries contribute substantial hatchery production of LFC with Inch Creek Coho being the current CWT indicator stock. Non-lethal DNA samples will be collected for any adipose present (unclipped) Coho Salmon encountered to allow for genetic stock identification (GSI) and to identify fish as IFC, Lillooet-origin LFC or non-Lilloeet LFC. Unclipped Coho Salmon will be placed in an onboard revival tank and released back to the river. Since Chilliwack Coho Salmon will not be CWT'd, they will be identified via parental-base tagging (PBT) for 2021 and by otolith marking from 2022 onward. We expect that the counts of the different stocks in the assessment fishery will have some error associated with them based on CWT loss, clip condition/natural degradation of adipose fins, uncertainty in GSI, and other observation error. Error in the counts will be accounted for in the bootstrap method (Appendix C).

Table 1. Expected Coho Salmon catch composition and sample methods from the proposed Fraser River assessment fishery. Expected Catch Components are also shown in Figure 1. [1]Other refers to populations that are non Chilliwack, Nicomen, or Lillooet origin. [2]IFC = Interior Fraser Coho.

Coho Samples in Catch	Expected Catch Component	Lethal or Non-Lethal Sampling	Detection Method
unclipped non-Lillooet LFC	18%	non-lethal	GSI (Genetic Stock Identification)
unclipped Lillooet River	21%	non-lethal	GSI
clipped other[1] LFC	19%	lethal	clip condition and GSI
clipped Chilliwack River	22%	lethal	clip condition and PBT (2021), otolith (2022 and forward)
clipped Nicomen Slough	5%	lethal	clip condition and CWT
clipped IFC[2]	3%	lethal	clip condition and CWT/GSI
unclipped IFC	11%	non-lethal	GSI

2.1.3 Summary

This study design brings information together from existing escapement programs (Nicomen Slough and Lillooet), infrastructure (hatcheries), and processes (CWT fishery sampling and data management, and otolith marking), and synthesizes them into an overarching objective. Additionally, this method incorporates direct information on natural stocks and mitigates some concerns about hatchery stocks being unrepresentative of natural stocks due to their differences in biological attributes (e.g., migration timing for hatchery fish can vary from natural stocks where hatchery brood collection practices are non-random, such as those that collect brood stock only from the early part of the migration). Details on the various components of the distant fishery mark-recapture method for estimating LFC escapement are found in Section 2.2 and in the appendices of this document.

2.2 Lower Fraser River Assessment Fishery Forecast

Coho Salmon catch for the proposed assessment fishery was forecasted (Figure 2) based on empirical relationships estimated from past test fisheries and studies to assist us in logistical and sample size planning. Data used for the forecast included daily catches per unit effort observed in gillnet and tangle-net test fisheries (historic), genetic stock identification studies, and return rates of clipped fish. Catch forecasts were made for a range of potential fishing effort and sampling durations (herein referred to as the sampling window) based on even effort during the sampling window, with the center of the window focused on the forecasted run-timing peaks. Forecasts also included estimates of uncertainty, based on variability observed in run-timing relative to the predicted run-timing peak, variation in run size, variation in stock composition proportions, and variation in clipping rates observed at Chilliwack hatchery. Full methodological details and results are presented in Appendix D.

Overall, for any given level of effort or duration of sampling window, LFC are expected to make up the biggest proportion of the catch, with hatchery Chilliwack, Nicomen Slough, and Lillooet stocks making up a relatively large proportion of the total LFC catch (Figure 1). Higher fishery effort can be expected, on average, to result in higher catch, but higher efforts are also associated with higher uncertainty in the target catch (primarily due to stochasticity in run-timing and run size; Figure 2). Extended sampling windows provide assurance that more of the run can be sampled, but also result in smaller expected catch because a larger proportion of the sampling would be occurring during off-peak times. Despite this expectation, the forecasts predict that the reduction would be fairly small relative to a shorter sampling window. And while catch is expected to be higher for short-duration sampling windows that coincide with peak run-timing, there is also increased risk associated with uncertainty in the run-timing, and some of the Monte Carlo simulation iterations predicted low catches when the run timing window was not aligned with the timing of the peak returns. Additionally, if there is variation in the run-timing across stocks, a short sampling window may not catch a representative sample of the different stocks used in the distant fishery mark-recapture estimator.

Bycatch was also considered as part of assessment, with the majority of tangle net bycatch occurring in the lower portion of the net (Bennet 1999). By restricting the depth of the tangle net, bycatch could be reduced by over 50% without out a negative impact (i.e., the same or small improvement) on total Coho catches (Appendix E).

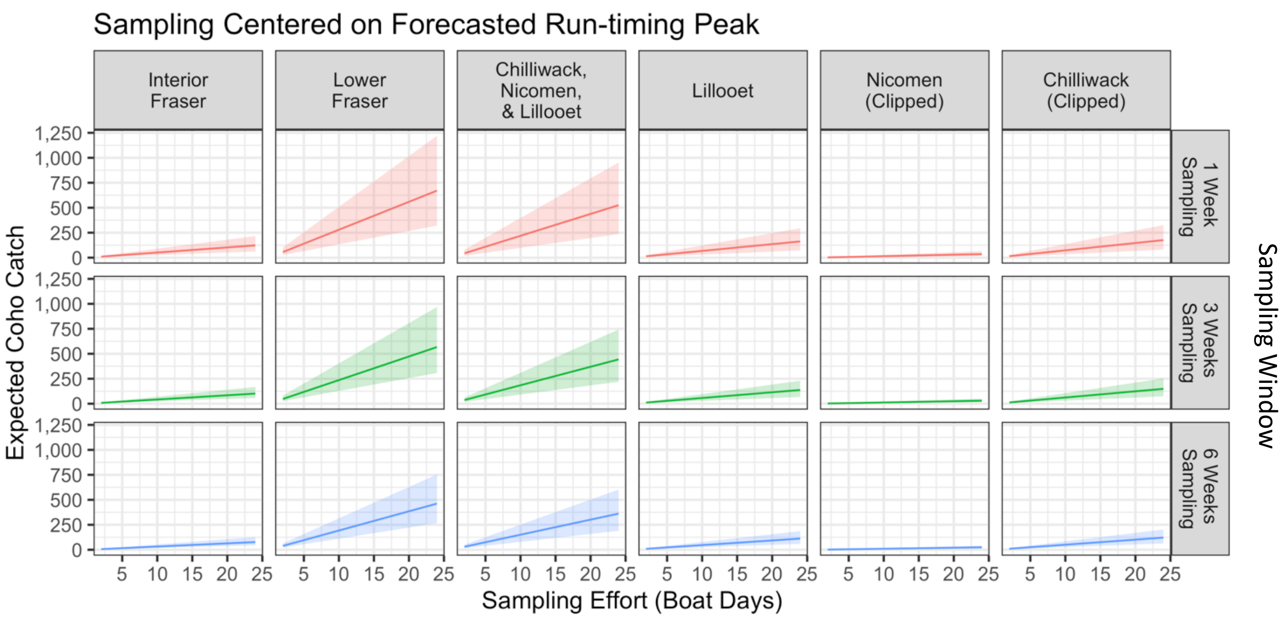


Figure 2. Forecasted assessment fishery Coho Salmon catch, by sampling effort, partitioned across different constituent groups (columns) and for three sampling duration windows (rows). Solid line indicates the mean catch computed across simulation iterations, while shading spans the 2.5% through 97.5% percentiles.

2.3 Chilliwack Passive Mark-Recapture

The general method to estimate the abundance of adipose fin clipped Chilliwack River Coho Salmon returning to the Chilliwack River ($\hat{E}_{Chilliwack,AFC}$) will use a two-sample mark-recapture study design like in section 2.1,

(3) $$\hat{E}_{Chilliwack,AFC} = \frac{(m_{Chilliwack,AFC}+1)\times(c_{Chilliwack,AFC}+1)}{(r_{Chilliwack,AFC}+1)} - 1\ .$$

Other assessment methods were considered (e.g. sonar, area-under-the-curve) but were rejected as impractical for reasons including river size, environmental conditions, concurrent abundance of Chum and Pink salmon, and funding limits.

The two-samples for this mark-recapture study will rely on AFC Chilliwack Coho Salmon that were marked as juveniles with Passive Integrated Transponder (PIT) tags, and two PIT tag interrogation arrays that will detect them as they return as adults. The first sample, the number of individually marked AFC Chilliwack Coho ($m_{Chilliwack,AFC}$), will be determined by detections of the returning PIT-tagged adults at a PIT array near the confluence with the Sumas River (Figure 3). The second sample ($c_{Chilliwack,AFC}$) will be collected at the hatchery, located upstream of the confluence of Slesse Creek and the Chilliwack River. Every AFC Coho that swims into the hatchery is counted and, in the hatchery's fishway, a second PIT array will count the PIT marked AFC Coho that were also detected at the first PIT array near the

Chilliwack-Sumas confluence ($r_{Chilliwack,AFC}$). PIT tags enable the unique identification of individual fish in the first and second samples, thus Coho Salmon will be sampled without replacement.

There are several benefits of marking fish as juveniles that assist in fulfilling several assumptions of the Petersen estimator that accompany mark-recapture methodology. The assumptions are that: (1) either or both of the samples are a simple random sample, i.e., all fish in the population have the same probability of being tagged or all fish have the same probability of being captured in the second sample (i.e. tagged fish mix uniformly with untagged fish); (2) the population is closed; (3) there is no tag loss; (4) the tagging status of each fish (at recovery) is determined without error; and (5) tagging has no effect on the subsequent behavior of the fish (Schwarz and Taylor 1998).

Tagging fish as juveniles with a small (~12.5 mm), internal PIT tag is beneficial for several reasons: i) by the time they are adults there will be a predicted 0 % rate of tag loss between detections (fulfilling assumption 3); ii) the tagging status of each fish in the second sample will be ~100 % (fulfilling assumption 4); and iii) the tags should not affect the behaviour of an adult fish (i.e., no behavioural effect from the time of the initial PIT tag detection to recovery; fulfilling assumption 5).

Violations in assumption 1 can result in considerable bias (Arnason et al. 1996, Schwarz and Taylor 1998); however, there are ways to account for these violations. In a passive mark-recapture experiment, violations of assumption 1 may arise from temporal variation in the probability of detecting PIT tags at the "marking" site (subsequently referred to as *initial* site, detection, or stratum). Temporal changes in detection efficiency may occur due to water level, temperature, conductivity, and air temperature, as well as arrays going offline due to debris dislodging them, vandalism, or theft. There is also a risk that behaviour of returning fish may vary over time, such that fish migrating early in the run do not mix completely with fish later in the run. There will be bias in the Petersen estimator if initial detection efficiencies vary, if fish do not completely mix, or if they behave differently across time. One solution to reduce this bias is to stratify counts of initial and recovery detections by time (or space). There are now general maximum-likelihood and Bayesian semiparametric methods available to compute temporally-stratified-Petersen estimators (Schwarz and Taylor 1998, Bonner and Schwarz 2011).

The statistical stratification methods described by Schwarz and Taylor (1998) also allow a relaxation of assumption 2 (closed population). In spawning escapement surveys, fish may leave the population through either mortality (either natural or from fisheries) or by spawning at sites other than the recovery site. Stratified-Petersen analyses, where the number of recovery strata (t) is greater than or equal to the initial strata (*s*), estimate the population size at the initial strata. Therefore, the number of fish that die or spawn elsewhere is taken into account. Assumption 2, “the population is closed”, is replaced by the assumption that the movement patterns, death, and migration rates for tagged and untagged fish in each initial stratum are equal. Representatively tagging all treatments (i.e., raceways) of hatchery reared juveniles, and assuming that those that survived to adults behave similarly (within a hatchery treatment) will account for this alternative assumption 2.

2.3.1 PIT Tagging Protocol and Array design

Marking of yearling Coho Salmon with PIT tags will occur in January-February at the Chilliwack hatchery (Figure 3). Starting in 2020, 10,000 PIT tags will be applied to hatchery reared juveniles that will also receive a parentage-based tag in 2020 or an otolith mark in every subsequent year in addition to having their adipose fin clipped. PIT tags will be applied representatively across all hatchery treatments (e.g., different raceways) to represent any differences in subsequent survival or behaviour between treatments. Tagging yearlings in the winter will allow them to fully mix with the non-PIT tagged fish and for any initial tagging effects to subside before they are released as smolts in May-June of the same year. The cohort tagged in 2020 will return to the Chilliwack River as age-3 adults during the fall of 2021 (Sep-Dec).

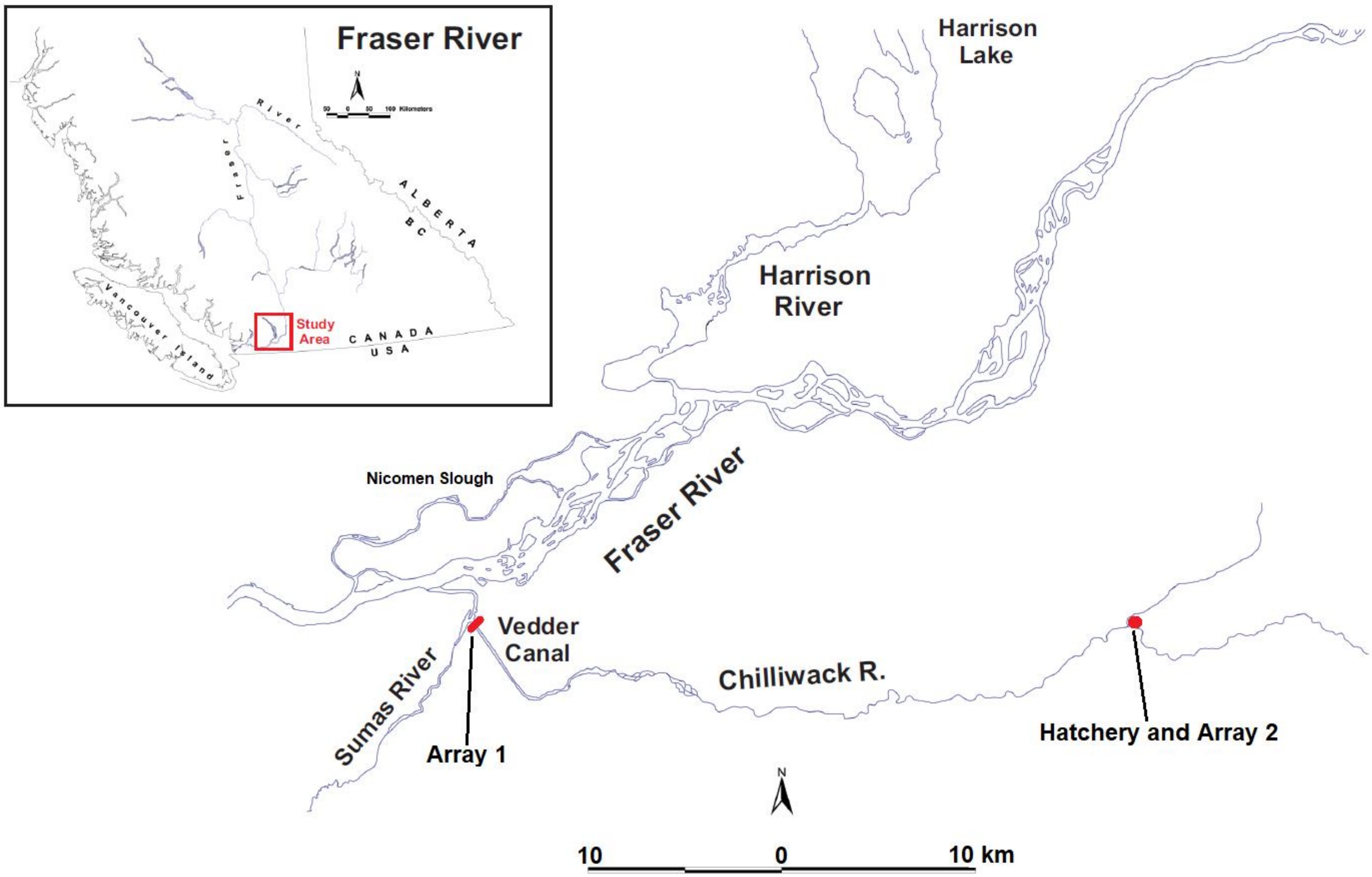
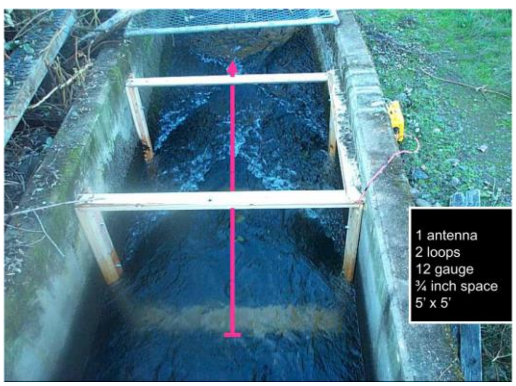


Figure 3. Location of the Chilliwack River, PIT interrogation array sites, and the surrounding area.

As noted above, two PIT tag interrogation array systems will be used in the passive mark-recapture study design during the return. The first array will be located in the Chilliwack River near its confluence with the Sumas River (Figure 3), downstream of any tributaries that could be used by Coho Salmon for spawning, and before the majority of recreational fishery pressure. The second array will be located in the fishway that Coho Salmon use to swim into the Chilliwack River Hatchery (Figure 3). The array located at the hatchery will be a pass-through array because all fish returning to the hatchery swim through a small fishway channel (e.g., Figure 4). One or two relatively small, loop antenna(s) should provide a 100 % detection probability and create an accurate recapture sample (r) of the total return to the hatchery (c). It is integral to have as close to a 100% detection efficiency as possible at the hatchery array; otherwise, the population estimate will be biased high. All Coho Salmon that return to the hatchery are counted and inspected for marks (AFC) by CDFO Salmon Enhancement Program (SEP) staff.



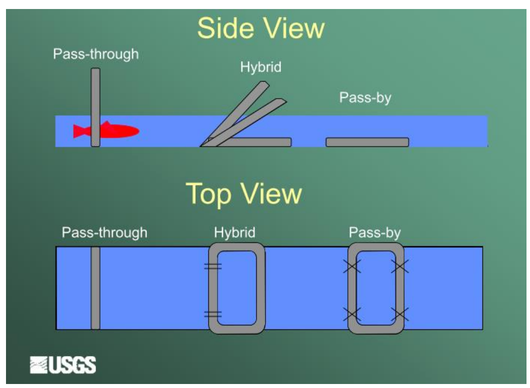


Figure 4. Pass-through array located in an anthropogenic passage in Upper Willamette Basin (left). Side and top views of pass-through, hybrid, and pass-by arrays (right). Original images printed in USFWS 2007*, pages 185 and 228, respectively.*

After consultation with several PIT array specialists, several array designs are under consideration for the first array near the confluence of the Sumas River; however, several hurdles were identified. The wetted width of the Chilliwack/Vedder River channel is large (90-100 m), the discharge fluctuates considerably during October to December (Figure 5), and the channel is deep (1-3 m). Several arrays may be required to increase detectability over different levels of discharge. Some array designs (e.g., hybrid arrays, Figure 4) change with water level; however, there is speculation that salmonids avoid them due to their movement and reduces their detection efficiency (Connolly et al. 2008). An additional challenge with the first array area is that it is highly travelled by anglers, pedestrians, vehicles, and vessels, which increases risk of vandalism and theft. Theoretically, Coho Salmon migration may be concentrated through certain channel cross-sectional areas based on depth and other stream habitat features such as cover. The final location(s) of the array(s) will be chosen to maximize coverage of the majority of the run while minimizing the cost of the array(s), including security and maintenance costs.

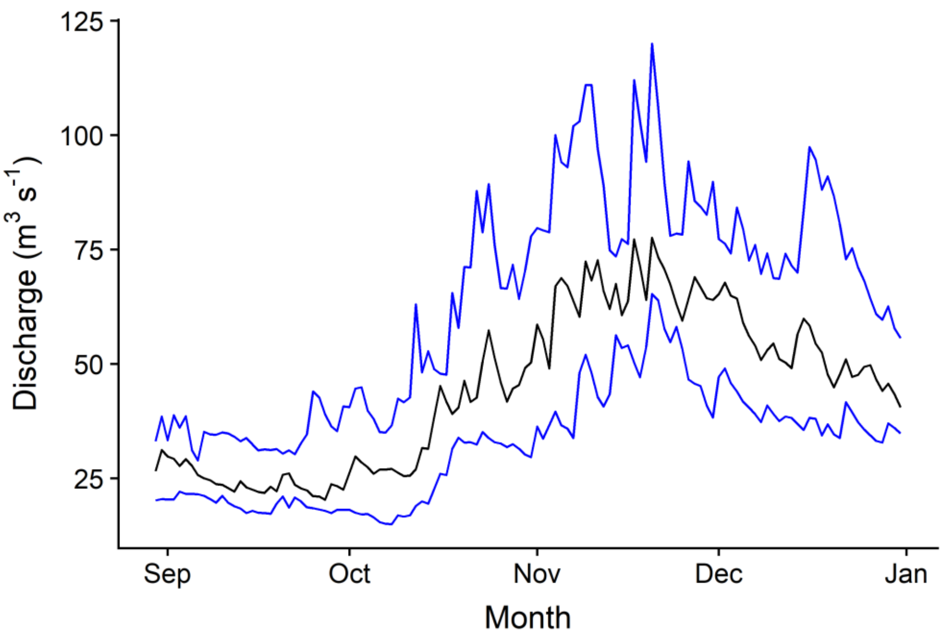


Figure 5. Discharge at Vedder Crossing on the Chilliwack River. Data are from 2000-2016 and are summarized by the median (black line) and upper and lower quartiles (blue lines). Wetted width at Vedder Crossing is approximately 30 m.

2.3.2 Detection Efficiency and Data Standards

The estimate of $\hat{E}_{Chilliwack,AFC}$ needs to be accurate and precise to provide a correspondingly accurate and precise estimate of the LFC system estimate (Appendix C). The previously discussed temporal stratification methods can reduce possible bias in the mark-recapture estimator and increase the accuracy of the population estimate. A 100 % detection efficiency at the second array is also required to have an accurate population estimate. The precision of the estimate, however, depends on the sample size collected at the first array. The variance of a mark-recapture population estimate is influenced most by the number of marks recovered (r), which is bound by the initial number of marks (m). The sample sizes of m and r depend on the total number of adults with PIT tags present in the system *and* the proportion of the tagged fish that are detected at the first array, which will be referred to as *detection efficiency*. The number of marks recovered is affected through recreational exploitation, other pre-spawn mortality causes, and straying to tributaries other than the hatchery. Therefore, the available methods to affect the precision of the results are to change the number of smolts that are PIT tagged (assuming an average smolt-to-adult survival) and the detection efficiency of the first array. To reduce long-term costs of high numbers of PIT tagging smolts, it is important to design, measure, and optimize the detection efficiency of the first PIT tag array. The PSC Chinook Technical Committee (CTC) has a data standard for escapement estimates, which is to have a Coefficient of Variation (CV) of 15% or less when planning escapement estimation studies (CTC 2013). An exploration of different detection efficiencies, sample sizes, and straying rates is presented in Appendix F.

2.3.3 Measuring Array Detection Efficiency

PIT arrays will be purchased and tested in the fall of 2020 to determine their detection efficiency, and to optimize their arrangement before the adult PIT tagged Coho Salmon return in 2021. In 2020, PIT-array detection efficiencies will be determined by fitting adult Coho Salmon that returned to the Chilliwack hatchery with both PIT and radio telemetry tags. These fish will then be trucked back down the river and released downstream of the confluence of the Sumas and below the first Chilliwack PIT tag array. Their movements will be tracked by radio-telemetry to determine when each individual swims past each PIT array. These passage events will be checked against the logged PIT tag detections to determine the PIT array detection efficiencies (see equation 4 below). Understanding PIT tag detection efficiencies under a variety of river discharge conditions will help to determine if any detection array refinements are needed. The detection efficiencies will also be used to plan the optimal number of PIT tagged Coho Salmon that should be released, such that adequate detections of PIT-tagged adult Coho Salmon are collected to generate escapement estimates of acceptable accuracy.

Several fixed-position radio telemetry arrays will be used to estimate the proportion of possible PIT tag detections. A radiotelemetry array (or arrays) will be located just upstream of the first PIT array. Another radiotelemetry array will be located just upstream the first radio-telemetry array and on the opposite riverbank. The radio-telemetry arrays will be staggered to increase their combined detection rates (to provide more accurate estimates of the detection efficiency of the first PIT tag array). A third radiotelemetry array will be located at the hatchery, just upstream of the second PIT tag array within the channel. The third radiotelemetry array should have a high probability of having a 100 % detection efficiency because of the narrow width, shallow depth, and uniform nature of the hatchery fishway. A fourth radiotelemetry array may be located near the confluence of the Sumas and Fraser rivers to identify radio-tagged fish that drop out of the study area.

The detection efficiency of the PIT tag array in the hatchery channel (DE_{hatch}) will be estimated by:

(4) $$DE_{hatch} = D_{h+T3} / (D_{h+T3} + D_{T3})$$

where D_{T3} is the number of double-tagged fish detected by third radiotelemetry array and *not* detected at the hatchery PIT tag array. D_{h+T3} is the number of double-tagged fish that were detected at both the hatchery PIT and the third radio-telemetry arrays. Therefore, the detection efficiency in the hatchery channel is equal to the proportion of fish detected by the radiotelemetry array that were also detected by the PIT array.

The detection efficiency of the PIT tag array in the lower Chilliwack channel (the Vedder Canal) will be estimated using a similar method but can incorporate the detections of any of the PIT or radiotelemetry arrays upstream. This method can be used with the delta method (Seber 1982) to calculate the variance and standard error of the detection efficiencies (Connolly et al. 2008).

2.3.3.1 Sample Sizes

A typical sample size to calculate a proportion with a 5% margin of error is 400 (Browner et al. 2001); however, a larger sample will be required over the span of the return because there is additional variability due to temporal flow changes. The hydrograph in the Chilliwack (Figure 5) generally increases during October, peaks in mid- to late-November, and then slowly decreases throughout December. Ideally, sufficient samples sizes should be used at both the low and high periods of flow (and therefore water level). Possible rearrangements of arrays may also introduce an additional treatment that may need to be accounted for. A tagging and release regime that allows for binning of data over multiple flows or rearrangements of PIT arrays would be optimal to capture this variation, with a target of 400 fish per bin/treatment. Furthermore, some tagged adults may also leave the system before passing the first PIT array due to unpredictable migratory behaviour or various sources of mortality. Therefore, additional fish should also be tagged and transported to act as a buffer against these reductions to our initial sample size. A preliminary sample design of tagging and transporting 100-200 adult Coho Salmon at low, moderate, and high river levels typical of the fall migration period, beginning in September and concluding in November, would produce a robust estimate of detection efficiency. The total number of radiotelemetry tags in the system will need to be monitored and limited, because signal collisions can increase when too many tag transmissions are being received simultaneously by a radiotelemetry receiver (i.e. the receiver cannot identify the individual tag IDs when there are too many colliding signals). PIT-only marked fish can also provide information on detection efficiency of the first array, given they are detected at the second array. Additionally, radio tags can be recovered from adults that return to the hatchery and subsequently reused, which will reduce the total number of radio tags to be purchased.

Although the in-field number of PIT and radio tags used may be difficult to predict, using several goals and assumptions can provide an estimate of the number of tags that should be available for use. First, the target is that 150 PIT tags will be applied each week for 6 weeks in a row, approximately 50 every 2-3 days to capture any changes in flow. Transporting approximately 50 fish per day is also based on logistical capacity (e.g., available transportation vehicles). Assuming PIT tags are not reused, 900 PIT tags will be required. Second, only half of the PIT tagged fish will have radio tags (75 per week) to reduce collisions and overall cost. Therefore, a minimum of 450 radio tags will be required to support this study design.

Acknowledgments

We would like to thank Dr.s C. Schwarz and L. Cowen for reviewing the document and providing feedback that improved the study design and to D. Ramos-Espinoza and S. Anglea for consulting on PIT technology and application in the Chilliwack River. We would also like to thank our collaborators in the Salmon Enhancement Program, J. Sandher, J. Mothus, and J. Smith, for facilitating this multi-departmental program.

3 References

Arnason AN, Kirby CW, Schwarz CJ, Irvine JR (1996) Computer analysis of data from stratified mark-recovery experiments for estimation of salmon escapements and other populations. Can tech Rep Fish Aqu Sci 2106:vi + 37 p.

Bennett, Sean (1999) Summary of the 1998 Fraser River Tooth Test Net Fishing Results. Habitat Conservation Trust Fund. Report No. 910-606.

Bonner SJ, Schwarz CJ (2011) Smoothing population size estimates for time-stratified mark-recapture experiments using Bayesian P-splines. Biometrics 67:1498–1507.

CTC (Chinook Technical Committee). 2013. Catch and escapement of Chinook salmon under Pacific Salmon Commission jurisdiction 2012. Pacific Salmon Commission, Report TCCHINOOK (13)-1. Vancouver, BC.

Connolly PJ, Jezorek IG, Martens KD, Prentice EF (2008) Measuring the Performance of Two Stationary Interrogation Systems for Detecting Downstream and Upstream Movement of PIT-Tagged Salmonids. North Am J Fish Manag 28:402–417.

Browner WS, Newman TB, Cummings SR, Hulley SB (2001) Estimating Sample Size and Power: The Nitty-gritty In Hulley SB, Cummings SR, Browner WS, Grady D, Hearst N, Newman TB (Eds). *Designing clinical research: an epidemiological approach*, *Second Editio*n (pp. 65-94); Lippincott Williams and Wilkins. New York, NY.

McElreath, R. (2018). Missing Data and Other Opportunities In R. McElreath, *Statistical Rethinking: A Bayesian course with examples in R and Stan* (pp. 423-440). New York, NY. Chapman and Hall/CRC.

MEW (Model Evaluation Workgroup) (2008) Fisheries Regulation Model (FRAM) Technical Documentation for Coho and Chinook v. 3.0. (Document prepared for the Council and its advisory entities). Pacific Fishery Management Council, 7700 NE Ambassador Place, Suite 101, Portland, Oregon 97220-1384

PSCSSC (Pacific Salmon Commission Sentinel Stocks Committee) (2018). Pacific Salmon Commission Sentinel Stocks Committee Final Report 2009-2014. Pacific Salmon Comm. Tech. Rep. No. 39: 167 p.

Petersen CGJ (1896) The yearly immigration of young plaice into the Limfjord from the German Sea, etc. Rep Danish Biol Stn 6:1–48.

R Core Team (2019). R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. https://www.R-project.org/.

Schwarz CJ, Taylor CG (1998) Use of the stratified-Petersen estimator in fisheries management: estimating the number of pink salmon (*Oncorhynchus gorbuscha*) spawners in the Fraser River. Can J Fish Aquat Sci 55:281–296.

Schwarz CJ (2020) SPAS: Stratified-Petersen Analysis System. R package version 2020.1.1.

Seber GAF (1982) The estimation of animal abundance, 2nd ed. The Blackburn Press, Griffin, London.

USFWS (2007) Proceedings of the Inter-Agency PIT Tag Detection Workshop. Vancouver, WA.

Appendix A

Nicomen Slough Southern Boundary Fund Proposal

Overview

Currently, Coho escapement to the Lower Fraser River (LFC) MU (management unit) is an important requirement of FRAM but is estimated with unknown and substantial uncertainty. Low recoveries of CWTs (coded-wire tags) from the current hatchery indicator stock (Inch Creek) have resulted in imprecise estimates of survival, exploitation, and escapement for the MU. This proposed project would augment the Inch Creek CWT releases into Nicomen Slough by tagging Coho which are already clipped and released into Norrish Creek (a tributary of Nicomen Slough). This effectively doubles the CWTs available to sample and will increase the precision of the escapement estimates to Nicomen Slough and also improve estimates of survival and exploitation rates for the LFC MU. Additionally, this project will contribute to the estimation of the total escapement of LFC when the project's results are used in conjunction with the results from a newly proposed assessment fishery conducted near New Westminster, B.C. (DFO, LGL and LFFA SBF 2019 submission), Chilliwack Coho PIT tag mark-recapture (DFO, LGL, and LFFA SBF 2019 submission), and a project estimating Lillooet Coho escapement (LGL SBF 2019 submission). However, estimation of Nicomen Slough Coho escapement cannot be performed until the first CWT Norrish Coho return to spawn in 2022 which requires the study to occur over multiple years.

While this project provides added benefit to several other proposed programs, this project also has value that stands alone. This work would reduce uncertainty of exploitation and survival rate estimates for the hatchery LFC MU indicator through increased CWT releases and subsequent fisheries and escapement sampling efforts. This would better inform backward FRAM ER estimates and improve forecasts for use in forward FRAM, which would improve the information used to plan bilateral fisheries.

Norrish CWT and Nicomen Slough natural escapement will be estimated using data collected from the following activities:

1. The application of CWTs to brood year 2019 Coho smolts which are scheduled to be tagged and clipped in 2020, and released in Norrish Creek in 2021;
2. The improved recovery of Inch and Norrish creek CWTs in preterminal fisheries and the terminal sport fishery in Nicomen Slough via increased Creel survey efforts (occurring over the duration of the program); as well as,
3. representative, random sampling of Coho spawners and carcasses in tributaries of the Nicomen Slough including Norrish Creek to collect mark rate and stray CWT samples (beginning in 2021).

The project aims to estimate the escapement of hatchery-origin Norrish Creek Coho, improve the accuracy of the Lower Fraser Coho MU survival and exploitation rate estimates, and generate an estimate of natural-origin escapement to Nicomen Slough. It will also be an integral project aligned with an assessment fishery and Lillooet CU SONAR which will be used to estimate the return of Coho to the entire Lower Fraser MU.

Methods

CWT Application and Creel

In the fall of 2020, we will apply CWTs to 100,000 Norrish Creek Coho at Inch Creek Hatchery (see Figure A1) to achieve our objective to double the number of CWTs to represent exploitation and survival rates of Nicomen Slough Coho. Inch Creek Hatchery currently produces 100,000 Norrish Creek Coho smolts which are adipose-clipped but not CWT'd. The additional information provided by the added CWT's in Nicomen Slough will improve the accuracy and precision of our estimates of survival and exploitation rates in this region as precision relies heavily on the number of recovered CWTs and a large number of CWT Coho are needed to achieve recoveries in recreational fisheries that have both low exploitation rates and low CWT sampling rates.

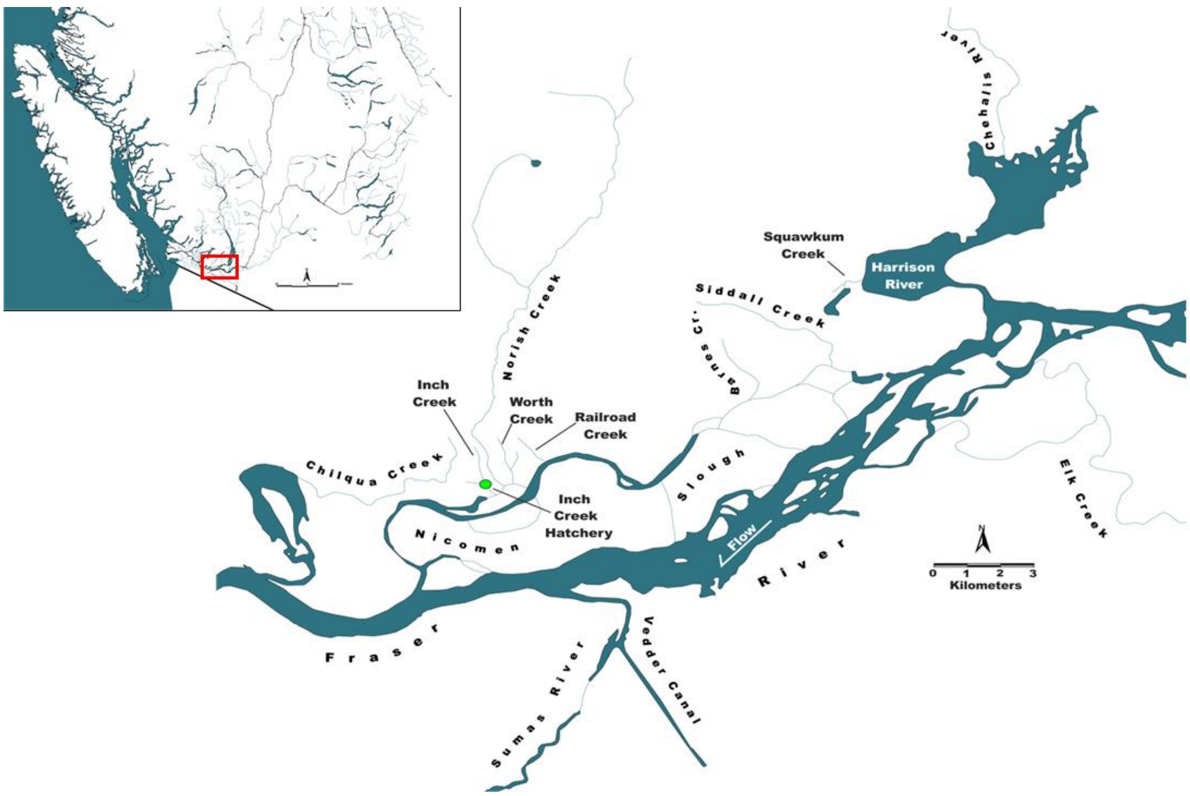


Figure A6. Location of Nicomen Slough in the context of Southern British Columbia

Since 2013 the CWT head sample rate from the Nicomen Slough Creel program has averaged 12.3% which is well below the PSC CWT Work Group minimum standard of 20%. The addition of one creel surveyor to the Nicomen Slough Creel program will effectively double the spatial-temporal coverage in this area and improve the CWT sample rate in this fishery. Traditionally, the creel program has spanned from the Friday before the Thanksgiving weekend until December 1 and operated on a full time schedule of on average 5 days per week which included shift work to cover weekends, early mornings and evenings.

Recreational fishing effort in Nicomen Slough has historically varied with water level patterns and has tended to be more concentrated in Norrish Creek later in the season (J. Tadey, pers. comm.). We propose to extend the Creel survey program from October 1 until December 15 to improve the representation of recreational fishing effort and recovery of CWT head samples in the Nicomen Slough and to improve accuracy of the CWT statistics. The extension of the Creel survey would be re-evaluated prior to the expected return of CWT Norrish Creek Coho in 2021 to determine if the extension will achieve the intended objective.

Estimation of Terminal Run and Spawners by CWT Stock

The Creel harvest estimates will directly feed into the estimates of terminal run size and escapement by CWT Stock (Norrish and Inch; Figure A2).

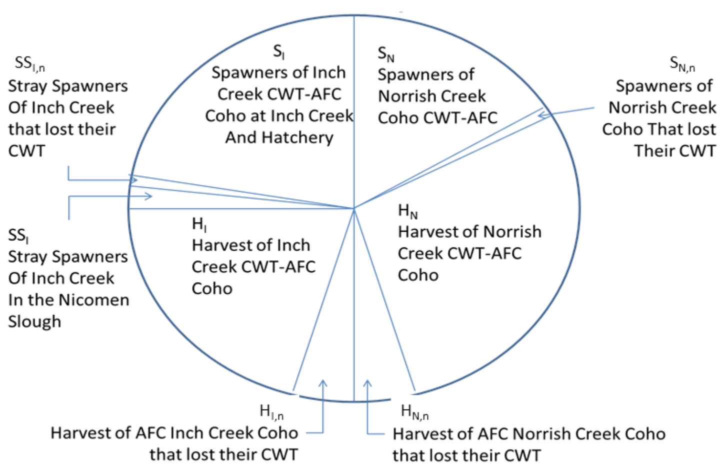


Figure A7. Terminal Run Composition for Inch and Norrish Creek Coho at the mouth of the Nicomen Slough.

Terminal run size estimates can be generated by the equation:

(A1) $$T_S = H_S + H_{S,n} + S_S + SS_S + SS_{S,n}$$

where T_S is the terminal run size for CWT stock *S*, H_S is the total recreational harvest of stock *S*, $H_{S,n}$ is the harvest of the stock that has no-pin despite exhibiting an adipose fin clip, S_S is the number of spawners of stock *S,* and SS_s and $SS_{S,n}$ represent the stray spawners from each CWT stock and the stray spawners with no-pin respectively. Harvest variables will be determined from the Creel survey and the salmon head recovery program. $H_{S,n}$ can be split into Inch and Norrish components by using the release production ratio (*P)* of Inch (*I*) and Norrish (*N*) Coho (equation A2).

(A2) $$H_{N,n} = H_n \times \left(\frac{P_N}{P_N + P_I}\right)$$

Inch Creek spawners are estimated by Inch Creek Salmonid Enhancement Program (SEP) and while Norrish Creek spawners can be estimated through escapement programs in the Nicomen Slough, there are concerns regarding the accuracy of current estimates. Norrish Creek terminal run (T_N) can be estimated using the CWT release ratio (*x*) of Inch and Norrish Coho releases for the brood year of the adults (equation A3). The preterminal fishery ratio of Inch to Norrish CWT's can also be used in the case that there may be differential survival to Nicomen Slough between stocks.

(A3) $$T_N = xT_I$$

Equation A3 allows us to substitute xT_I for T_N letting us calculate spawners of Norrish (S_N) by subtracting the harvest of Norrish from the terminal run estimate. Spawners in Nicomen Slough and the tributaries of Nicomen Slough are represented by AFC and unmarked fish (Figure A3).

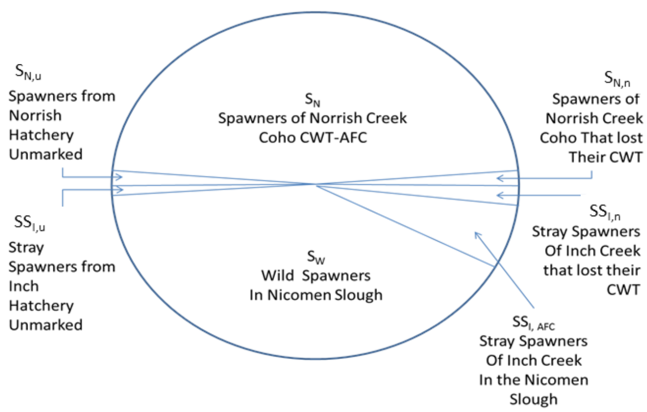


Figure A8. Spawning ground composition in the Nicomen Slough.

Dead pitch escapement surveys of carcasses by Coho Stock Assessment will provide us with mark-rate estimates which we can then use to calculate the natural origin spawners (S_w). Estimates of mark-rate cannot be generated through the Creel program because the recreational fishery on Coho in the Lower Fraser River is a mark selective fishery which would lead to a different mark rate in the terminal run vs. spawning grounds. Mark rate (*MR*) can be calculated as:

(A4) $$MR = \frac{S_{AFC}}{S_{AFC} + S_u}$$

where the subscripts *AFC* and *u* represent the adipose fin clip and unmarked portions of the population. Mark-rate can be estimated through the dead pitch program assuming we have random and representative collection of samples throughout all the spawning areas (equation A5). *D* represents the carcasses collected from the spawning grounds for all strata and subscript *w* represents the component of unmarked fish (*u*) that are wild.

(A5) $$MR = \frac{D_{N,AFC} + D_{I,AFC} + D_n}{D_{N,AFC} + D_{I,AFC} + D_n + D_w}$$

We can rearrange equation A4 and use the mark rate (*MR*) estimated from equation A5 to estimate the number of unmarked spawners:

(A6) $$S_u = S_{AFC}\left(\frac{1}{MR} - 1\right)$$

The seven components that represent spawners in the Nicomen Slough are represented by the following equations:

(A7) $$S_{AFC} = S_N + S_{N,n} + SS_I + SS_{I,n}$$

(A8) $$S_u = S_w + S_{N,u} + SS_{I,u}$$

Unmarked Norrish ($S_{N,u}$) and the unmarked stray spawners of Inch ($SS_{I,u}$) are estimated using the associated production of unmarked releases from the CWT release data which can be accessed from the Regional Mark Information System (RMIS) database. S_w can be estimated from escapement programs throughout the Nicomen Slough but quality is poor and there are concerns surrounding the accuracy of the estimate (C. Parken, pers. comm). In this project, we will generate this estimate analytically using equations A6 and A8. If spawning ground samples are sufficient, estimates of CWT spawners of each stock (*S*) with no pin ($S_{S,n}$ and $SS_{S,n}$) can be determined from field surveys. However, we can estimate these values using equation A10 and an adjustment factor if necessary (equation A9).

(A9) $$F_S = \left(\frac{H_{S,n} + H_S}{H_S}\right) - 1$$

(A10) $$S_{S,n} = F_S \times S_S$$

Stray spawners of Inch Creek in the Nicomen Slough (SS_I) can be estimated iteratively, by using solver for example, from the observed CWTs and a sampling rate (SR) calculated from dead pitch (equation A11) of

Norrish Creek Coho. The sampling rate needs to be calculated from Norrish Creek Coho because the number of Inch Creek CWT carcasses sampled in the dead pitch is expected to be small (< 5).

(A11)
$$SR = \frac{D_{N,AFC}}{S_N}$$

Currently creek walks by the Lower Fraser Coho extensive program survey the spawning grounds within the Nicomen Slough and the tributaries of the slough occur roughly 10 times per year beginning in late November and ending at the end of January. However these surveys have been opportunistic due to a lack of guaranteed funding. This project would fund three walks per week in the Nicomen Slough and tributaries and include the addition of creek walks in Norrish Creek which are not currently surveyed. The goal of these walks would be to recovery carcasses in order to determine the mark-rate on the spawning grounds.

The outputs of this work in conjunction with the estimate of Coho in the Lillooet watershed and a potential future assessment fishery will further our ability to generate estimates of escapement of LFC.

Appendix B

Lillooet River Sonar Southern Boundary Fund Proposal

Overview

Inconsistent, and sometimes absent, annual funding and a lack of resources to develop a Coho centric assessment program have resulted in DFO being unable to generate an estimate of Coho salmon escapement to the Lower Fraser River Management Unit (LFR MU) from observed data. The absence of reliable escapement estimates for Coho in the LFR MU and its three component Conservation Units (Lillooet, Boundary Bay and Lower Fraser) represents a critical information gap for Southern Boundary Coho salmon Management. In 2019 the PSC committed significant funding to the Lillooet ARIS project (LGL Limited and Lil'wat Nation) and the LFR Distant Fishery method (DFO, LGL Limited, LFFA) to support the development and testing of a program to estimate escapement of Coho to the LFR MU.

Coho returning to the Lillooet CU must transit first through the Lower Fraser River, then through the Harrison River and Lake system and then into the Lower Lillooet River, where a unique potential for a census-style assessment for much of the CU is created. Funding from the PSC in 2018 and 2019 enabled LGL Limited and the Lil'wat Nation to identify (2018) and establish (2019) an imaging sonar monitoring site on the Lillooet River at the mouth of Rogers Creek to assess escapement of Coho salmon to the Lillooet CU. Due to run timing of Coho to the Lillooet, the feasibility aspect of this project and the difficult working condition winter brings in the Lillooet watershed, operations in 2019 operated from October 17 through November 31.

Methods

Coho escapement to the Lillooet River CU will be estimated using an ARIS 1200 unit deployed in the Lillooet River mainstem near the mouth of Rogers Creek (Figure B1). PSC funding in 2018 helped identify the Rogers creek site as a suitable location for sampling with imaging sonar given the relatively narrow wetted width of the river at the site (approximately 42 m), absence of highly turbulent flows or large boulders that could degrade or obstruct the imagery, and ease of access from Lillooet River Forest Service Road.

The ARIS 1200 sonar head will be deployed using a rigid aluminum mount secured to the substrate immediately downstream of the mouth of Rogers Creek. To ensure safety of the equipment the mount will be designed to allow for quick demobilization during periods when river levels are anticipated to increase rapidly. The sonar head will be placed at an elevation just above the substrate, tilted slightly downward to allow beams to spread along the substrate throughout the extent of the range, and aimed to bisect the flow. Various tilt angles, sample window lengths and other system configuration parameters were tested to optimize data collection.

The ARIS was configured to view the nearest half of the river width for the first 30 minutes of each hour before viewing the distant half of the river for the latter half. This enables:

1. A more accurate length measurement of passing fish which will allow us to ascertain if co-migrating species are present (assuming size-separation), but also if resident fish (trout) are in the area, and;

2. Determination of where fish are migrating (near or distal to the ARIS) which will inform future configuration decisions to better optimize ARIS parameters. Flow conditions at the site indicate most migration will occur near-shore where flows are less turbulent and the water more clear.

The sonar system will consist of the sonar head, data transmission cable, ARIS command module, Ethernet cable, and laptop computer loaded with ARIScope data acquisition software. The system will be powered using a portable Honda generator maintained by onsite technicians. Electronic components will be housed in a weather-proof environmental enclosure located above the elevation of the high water line. Once the data collection parameters are optimized, the sonar system will be configured to collect continuous data throughout the 8-week study period. Data will be ported directly to 3-TB external hard drives in discrete 10-minute data files. Each day technicians will swap out external hard drives and backup the data to additional hard drives.

Imaging sonar data will be processed and reviewed using ARISFish software. Data will be subsampled by randomly choosing two 10-minute files per hour for each hour of data collection. Data review will entail playback of data files at two to three times the frame rate at which the data were collected. During data review technicians will record in data sheets the number of Coho salmon observed passing through the field-of-view in both upstream and downstream directions. Total upstream and downstream counts per 10-minute file will be entered into an Excel spreadsheet for post-processing. The mean counts across 10-minute files for each hour will be calculated and then expanded to estimate hourly counts. Net upstream hourly estimates will be calculated by subtracting downstream from upstream counts and plotted to assess diel movement patterns. Net upstream hourly counts will be summed for each day and plotted to assess run-timing throughout the study period. Total escapement through the study period will be estimated and presented with 95% confidence intervals.

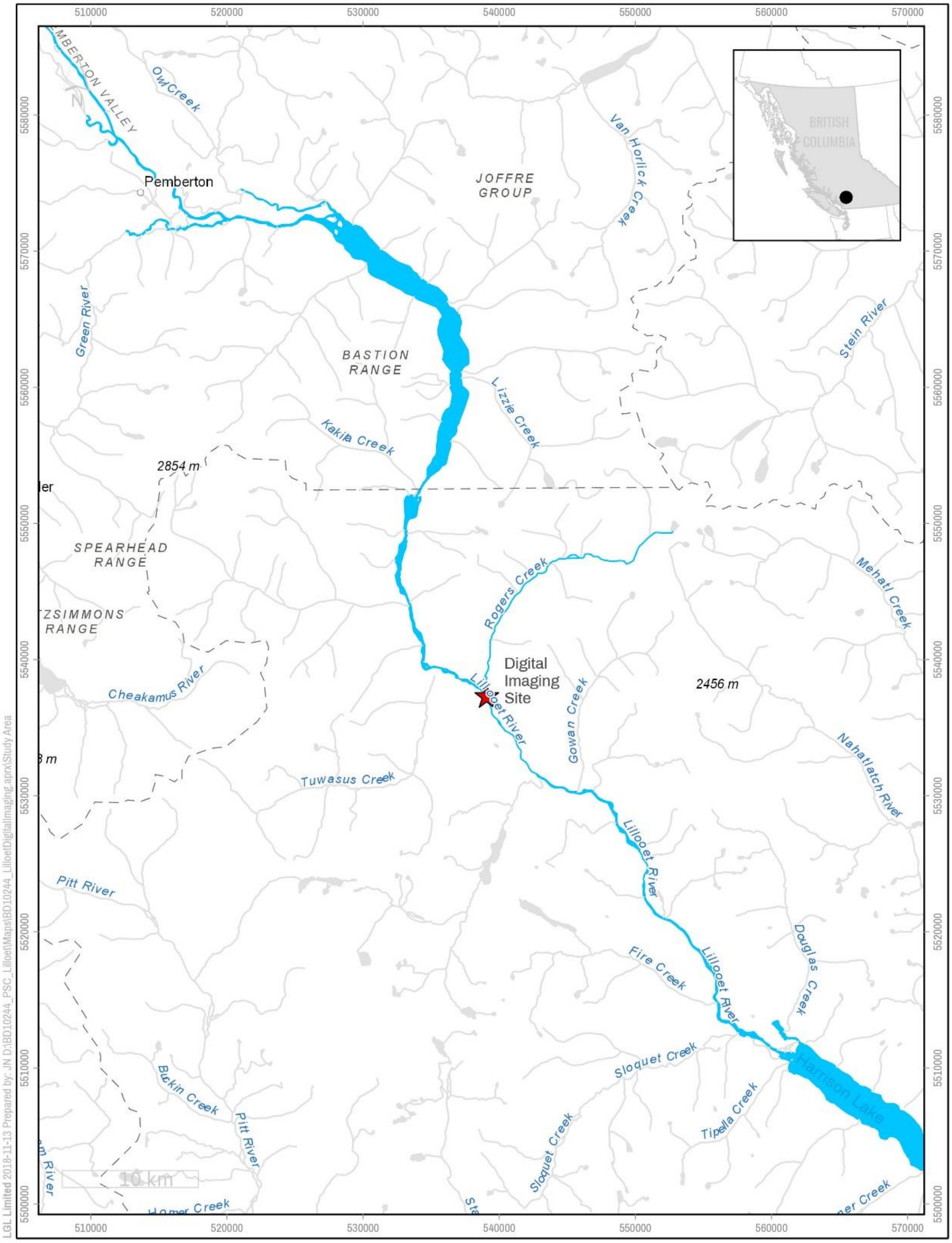


Figure B1 Map of Study area showing the site of the ARIS

Appendix C

Bootstrapped Variance estimate of reverse mark-recapture estimate

Theory & Methods

The Petersen estimator and it's stratified variants assume that the data that comprise them have no variance. However, the reverse-mark-recapture design uses several independent estimates that each have their own estimates of variance, usually in the form of a modelled standard error. The estimates that are expected to have a measurement of error are:

i) the marks (*M*), as they are estimates from three different methods *and* removals from fisheries, and
ii) the unmarked captures (*C*) and recaptures (*R*) may have some error due to measurement error in genetic stock identification, mark or tag losses, or observation error.

Here, a bootstrap method is proposed to re-sample point estimates from normal distributions that are determined by the point estimate's standard error. The re-sampled point estimates will be independent of each other and propagate uncertainty such that the variance in the model iterations will be relative to each estimate's magnitude and error (e.g. a large estimate with large error will produce greater variance in model iterations than a small estimate with small error).

The SPAS package (Schwarz 2020) developed for the R statistical computing environment (R Core Team 2019) is a stratified Petersen analysis system (SPAS) that will likely be used to estimate the total LFC return. The input data matrix for SPAS takes the form of an $s + 1$ by $t + 1$ matrix, where s is the number of application strata and t is the number of recovery strata. In the case of LFC, the application strata (s) coincide with the three populations that will have escapement estimates (Lillooet, Nicomen, and Chilliwack). The recovery strata (t) will correspond with different weeks of operation of the assessment fishery (e.g. weeks 1-2 would equal t_1, weeks 3-4 = t_2, etc.). The s x t matrix is the number of recovered marks (*R*) by application and recovery strata (e.g. at s = 1 and t = 3, the number of marked Lillooet fish caught in the test fisher between weeks 5-6 would be entered). The final column in the matrix, $t + 1$, is populated with the number of marked fish (*M*) per application strata that were not recovered. Therefore, only the escapement estimates (*E*) and fisheries removals (*F*) need to be added here, which is in slight contrast to Equation 2. Additionally, the Lillooet recaptures need to be removed from the marked-but-not-recovered cell because they will have been released at the assessment fishery, unlike the Chilliwack- and Nicomen-origin fish that would have had adipose fin clips and were sacrificed at the assessment fishery. Matrix C1 represents the input data matrix for the SPAS based on sampling from each cell's estimate and standard error from a normal distribution as *N*(mean = point estimate, variance = standard error of point estimate). The input matrix would be sampled 5000 times and run through the SPAS to produce a mean LFC system estimate and associated variance from the standard deviation of the samples.

Matrix C1:

$$\begin{bmatrix} N(\hat{R}_{Lil,1},\sigma^2{}_{Lil,1}) & N(\hat{R}_{Lil,2},\sigma^2{}_{Lil,2}) & N(\hat{R}_{Lil,3},\sigma^2{}_{Lil,3}) & N(\hat{R}_{Lil,4},\sigma^2{}_{Lil,4}) & N\left(\widehat{M}_{Lil,E},\sigma^2{}_{Lil,E}\right)+N\left(\widehat{M}_{Lil,F},\sigma^2{}_{Lil,F}\right)-\sum_1^t N(\hat{R}_{Lil,t},\sigma^2{}_{Lil,t}) \\ N(\hat{R}_{Nic,1},\sigma^2{}_{Nic,1}) & N(\hat{R}_{Nic,2},\sigma^2{}_{Nic,2}) & N(\hat{R}_{Nic,3},\sigma^2{}_{Nic,3}) & N(\hat{R}_{Nic,4},\sigma^2{}_{Nic,4}) & N(\widehat{M}_{Nic,E},\sigma^2{}_{Nic,E})+N(\widehat{M}_{Nic,F},\sigma^2{}_{Nic,F}) \\ N(\hat{R}_{Chi,1},\sigma^2{}_{Chi,1}) & N(\hat{R}_{Chi,2},\sigma^2{}_{Chi,2}) & N(\hat{R}_{Chi,3},\sigma^2{}_{Chi,3}) & N(\hat{R}_{Chi,4},\sigma^2{}_{Chi,4}) & N\left(\widehat{M}_{Chi,E},\sigma^2{}_{Chi,E}\right)+N(\widehat{M}_{Chi,F},\sigma^2{}_{Chi,F}) \\ N(\hat{C}_{u,1},\sigma^2{}_{u,1}) & N(\hat{C}_{u,2},\sigma^2{}_{u,2}) & N(\hat{C}_{u,3},\sigma^2{}_{u,3}) & N(\hat{C}_{u,4},\sigma^2{}_{u,4}) & - \end{bmatrix}$$

Where $\hat{R}$, $\hat{C}$, and $\widehat{M}$ indicate the marked recoveries, unmarked recoveries, and marked-and-not-recovered point estimates, respectively, for each population (Lil = Lillooet, Nic = Nicomen, Chi = Chilliwack, u = unmarked). The marked ($\hat{R}$) and unmarked ($\hat{C}$) recoveries are also separated by recovery period (t). The marked-and-not recovered ($\widehat{M}$) point estimates are a combination of escapement estimates (E) and fisheries removals (F), and in the case of Lillooet, also the sum of the marked recoveries that were released back into the river are also removed. Each point estimate also has an associated standard error that is used as the variance in the normal distribution (σ^2).

This method was tested using simulated data. The expected catches of marked ($\hat{R}$) and unmarked ($\hat{C}$) LFC in the assessment fishery were produced using the methods outlined in Appendix D. The expected catches were then randomly distributed over time into three recovery strata, which is the minimum number of recovery strata that the SPAS input can use if three application strata are used (i.e. $t \geq s$) (Schwarz 2020). The point estimates of population size (the marked and not recovered estimates) were determined using the average expected population ratios (Figure 1) and a range of LFC return estimates. To reduce the number of simulation permutations, the marked portion of fish removed by fisheries was not simulated separately from the escapement estimate; however, it was highly acknowledged that careful accounting of marked and unmarked fish for each input is integral for producing an unbiased estimate (C. Schwarz, pers. comm. 2020).

Investigation of the behavior of the bootstrapping method used a "base case." A target CV to each population estimate or fishery sample was assigned based on a final system return of 50,000. We determined that 50,000 was a reasonable system return based on the range of returns of Chilliwack River hatchery-origin returns (Table F1 in Appendix F) and the average proportion they make up in the Decay Model. The base case applied a CV of 15 % to each of the population estimates and a CV of 10 % to each of the fisheries samples; each of these CVs represent expected or targeted ceilings for the respective estimates. The initial investigation also investigated the robustness of the bootstrapped system CV to the amount of effort put into the assessment fishery, measured as "boat days" over a six week interval based on outputs from Appendix D (The Catch Forecast). The CV associated with each estimate was then varied individually to identify the sensitivity of the bootstrap estimate's precision to each input.

Results & Discussion

The bootstraps behaved as expected and produced population estimates that followed a normal distribution (Figure C1). The coefficient of variation was robust to the number of days spent sampling (boat days) once there were around 10 or more days (Figure C2) during the base case (see description above). If the catch forecast is correct and CV targets of estimates are made, then this simulation also indicates that reaching a 15 % CV of LFC returns is possible with the planned number of boat days in the assessment fishery. Finally, the bootstrapped CV was most sensitive to the CVs of the unmarked captures in the assessment fishery, and the Chilliwack and Lillooet marked and recapture inputs (Figure C3). The Nicomen marked and recapture inputs did not affect the system CV much.

The results of this simulation are dependent on our assumptions of the relative proportion that each population makes of the total return and our predicted catch forecast. An alternative method may be required if sample sizes are small or input CVs are high (C. Schwarz, pers. comm. 2020). A Bayesian framework could facilitate smaller sample sizes and high CVs. Additionally, a Bayesian framework could re-estimate the input estimates and their associated errors by applying their original CVs as a normally distributed prior with their own estimate as the mean (McElreath 2018).

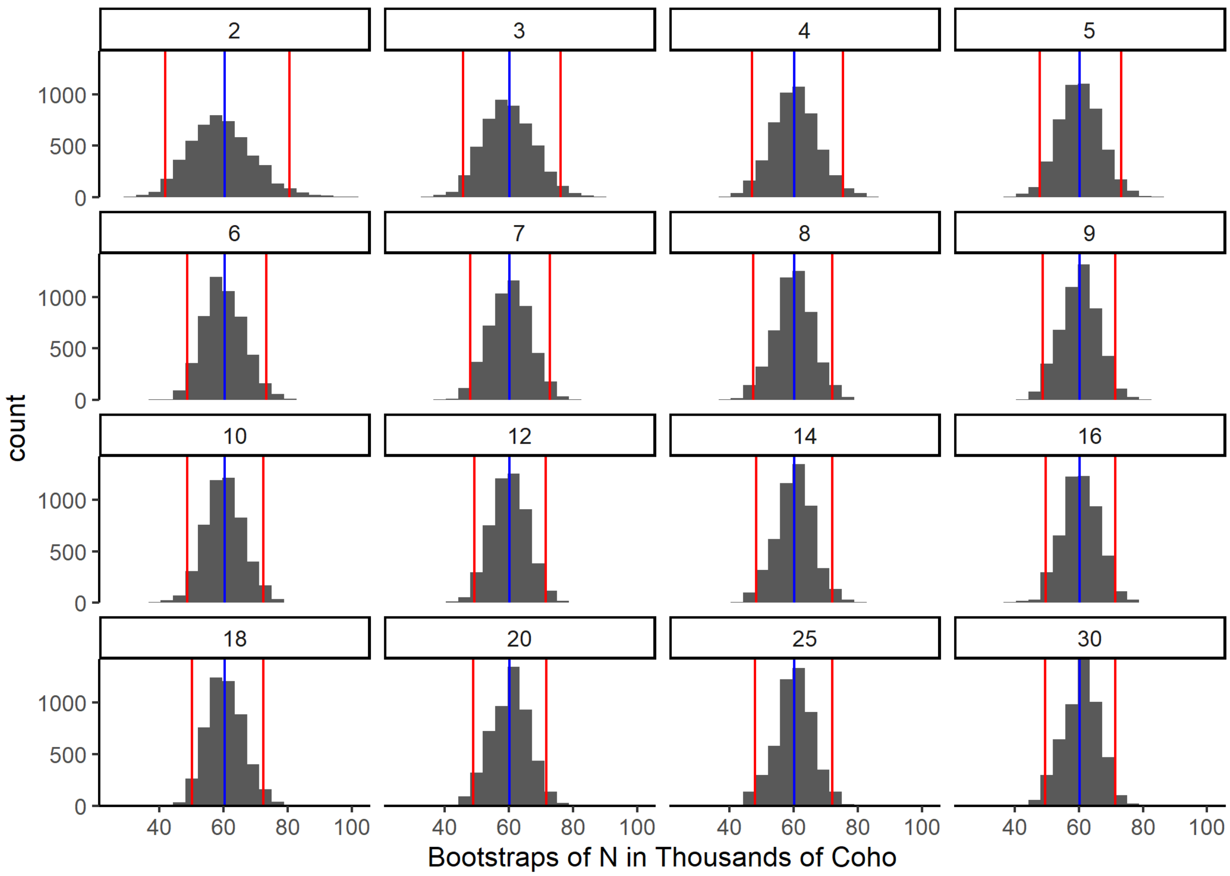


Figure C1. Histograms of system estimates (N) of Lower Fraser Coho from 5000 bootstrap samples of the input data, separated by the number of boat days (indicated in each panel title). The blue line is the median estimate and the red lines are the 25th and 75th quantiles.

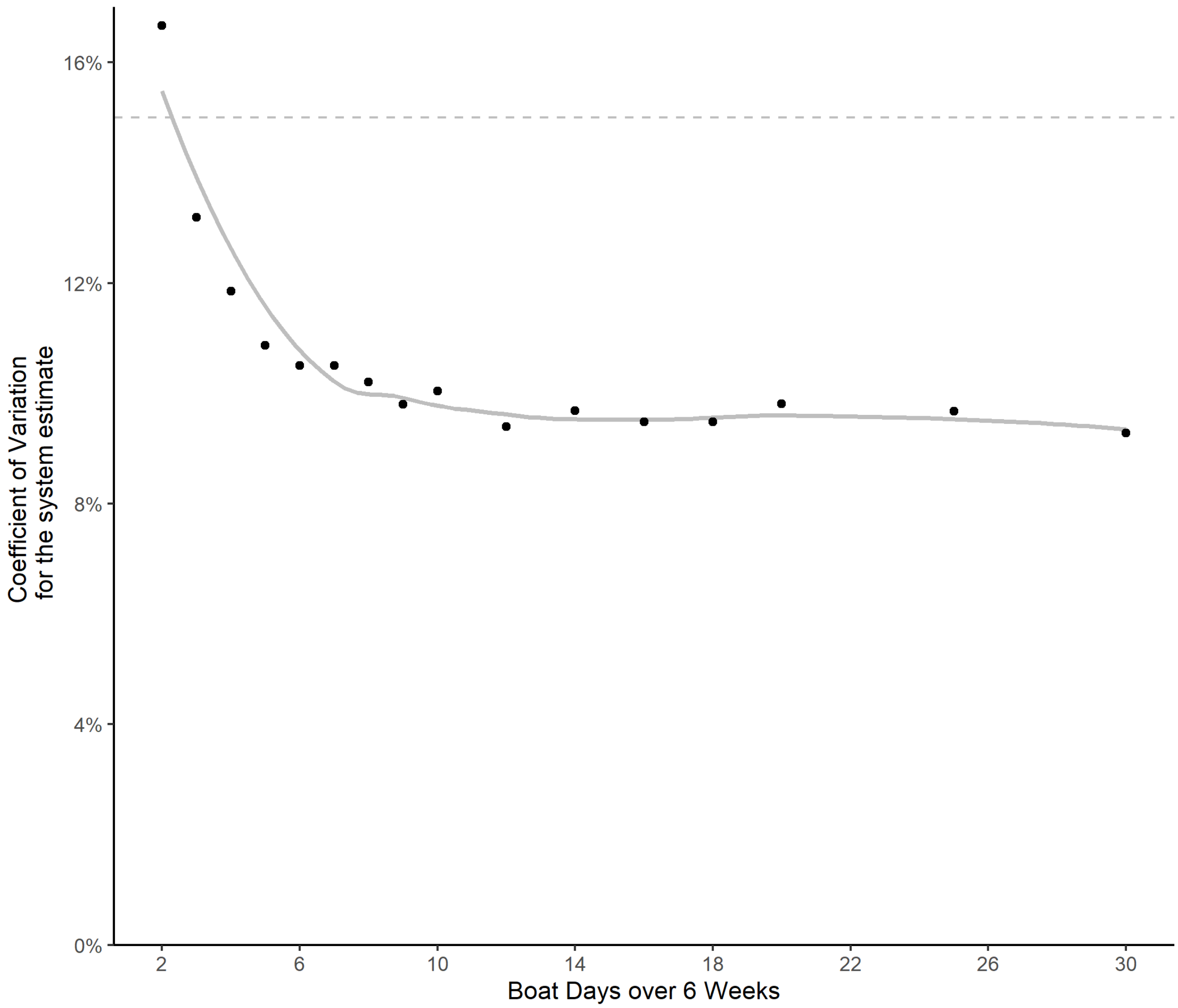


Figure C2. Changes in the system estimate's coefficient of variation (CV) based on 5000 bootstrap samples where the input values change by the number of boat days in the assessment fishery if it were operated for six weeks. The gray dashed line is the ceiling target system CV (15 %). The solid gray line is a smoothed fit of the points using locally weighted linear regression.

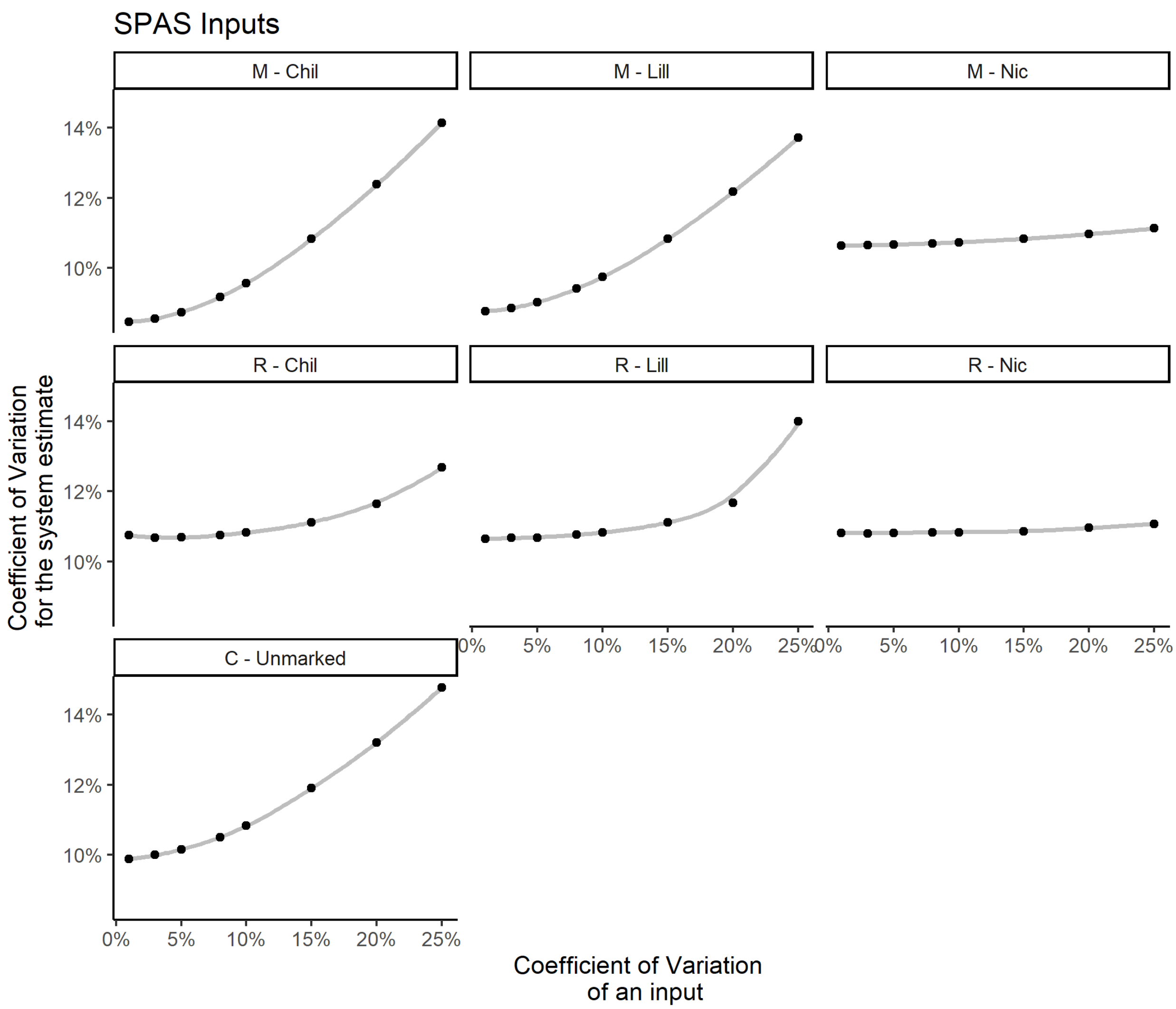


Figure C3. Changes in the system estimate's coefficient of variation (CV) based on 5000 bootstrap samples where the coefficient of variation (CV) for one input value is changed at a time while the other input CVs are held at the base case values. Each panel corresponds to which input value's CV is changing. The solid gray line is a smoothed fit of the points using locally weighted linear regression.

Appendix D

Catch Forecast

Overview

Coho catch was predicted for a given sampling design based on a multistep process employing observed empirical relationships occurring within four distinct data sources (*Figure D1*). The four data sources used employed to create the forecasts, the sources include:

1. Pacific Salmon Commission (PSC) and Albion gillnet test fisheries;
2. Bennett (1999) tangle net study;
3. Fisheries and Oceans Canada (DFO) Lower Fraser genetic stock identification (GSI) data which included a daily breakdown between Interior Fraser Coho (IFC) and Lower Fraser Coho (LFC) stocks, as well as a yearly breakdown of stocks within the IFC and LFC; and
4. Chilliwack hatchery data indicating yearly clipped to unclipped proportions.

Briefly, the PSC and Albion gillnet assessment fishery data were used to generate empirical models that permitted forecasts of run-timing peak dates and daily catch, including the manner with which catch declines on either side of the run-timing peak. These empirical models provided a range of predictions of total future daily Coho Salmon catch, in gillnet equivalents, which included allowances for random stochastic processes. The gillnet equivalents were then converted to tangle net equivalents by comparing Coho Salmon catch between the Albion fishery and the Bennett 1998 study. The daily and total Coho Salmon catches for a given sampling design (i.e., total effort and sampling dates) were determined and apportioned between LFC and IFC designatable Units (DUs) based on an empirical relationship derived from DFO daily Lower Fraser GSI data. Then, the total LFC catch was apportioned among four stock aggregates (i.e., Chilliwack, Nicomen, Lillooet, and Other) based on DFO Lower Fraser GSI data that apportions yearly catch among the known stocks. Finally, the clipped return rates for hatchery fish were forecasted for Chilliwack and Nicomen stock aggregates based on the adipose clipping rates observed at the Chilliwack Hatchery.

Empirical models provided estimates of both sampling and process error, which were considered in the Coho Salmon catch forecasts. Because run timing, catch, and stock composition can be expected to be vary among future sampling years, a Monte Carlo approach must quantify the impact of these stochastic processes on the forecasted catch by providing a range of potential anticipated catches for a given sampling design. For each given simulation iteration, different values were used for run-timing, catches, stock proportions, and clipping rates (*Figure D1*), all generated from empirically-derived distributions, thus producing a range of forecasted catches for a given forecast day. Differing designs were then applied against the distribution of predicted daily catches in order to determine the distribution of forecasted catches for a given design.

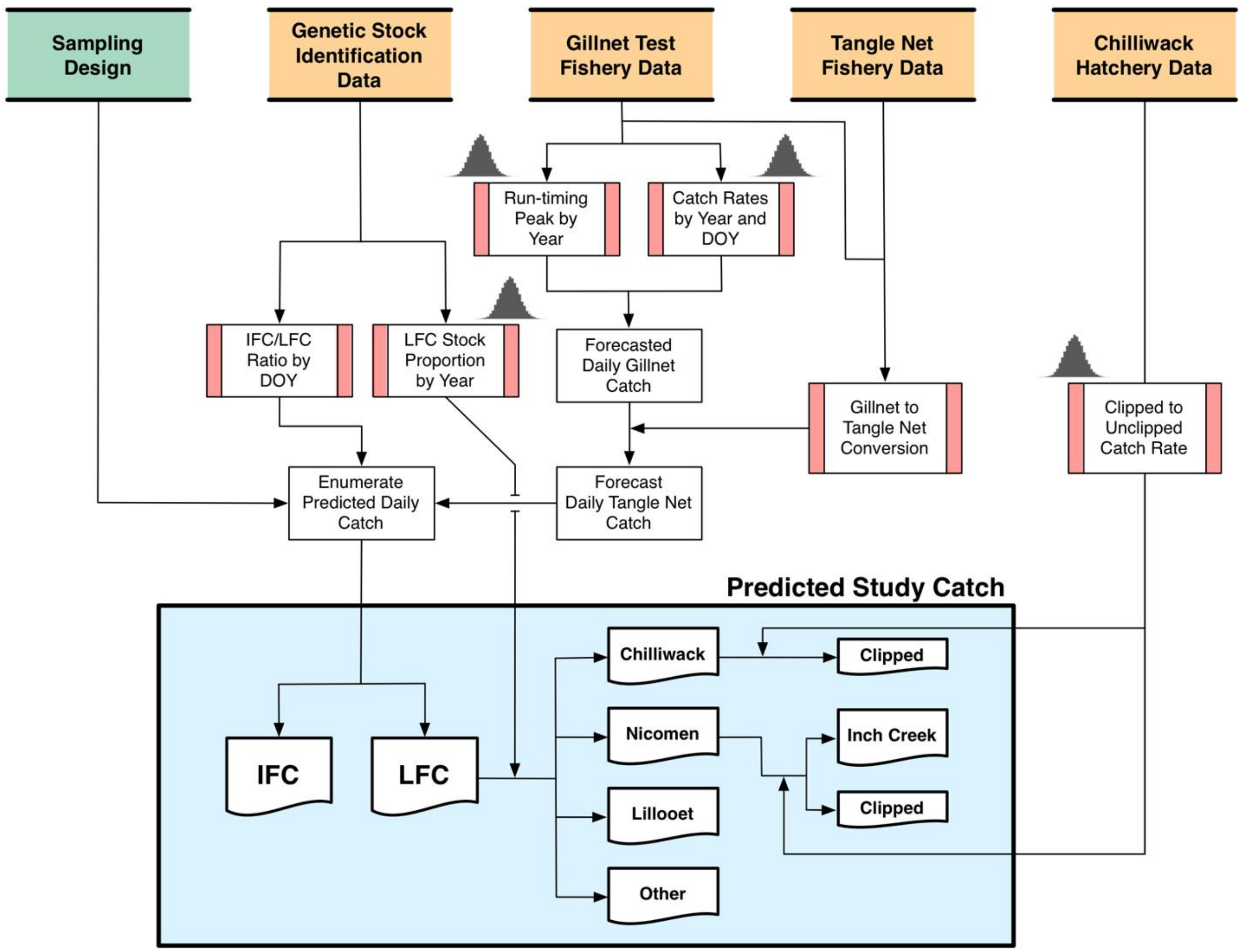


Figure D1. Flow diagram indicating data sources and analyses used to make catch by effort forecasts. Orange strip indicate processes using empirical based prediction models. Empirical process steps with histograms indicating prediction models that produce stochasticity in the final catch prediction calculations. Abbreviations: DOY – Day of Year; IFC – Interior Fraser Coho; LFC – Lower Fraser Coho.

Forecasting Coho Salmon Run-timing

The Cottonwood and Whonnock PSC gillnet test fisheries (i.e., 2002-2018) were combined with the Albion gillnet assessment fishery (i.e., 1984-2018) to create a catch by date timeline from 1984 through to 2018 (*Figure D2*). Other than 1985, 1993, 1997, 2006, and 2015, all years showed clear peaks in Coho Salmon catch.

The date associated with yearly peak Coho Salmon catches were estimated by fitting second-order polynomial curves to each year independently. A linear mixed effect model was used (nlme package; Pinheiro et al. 2018) where log transformed daily catch per unit effort (i.e., catch of Coho Salmon per gillnet set) in a given year ($C_{y,d}$) was modelled as having a second-order polynomial relationship with the day-of-year (DOY). Fixed effects were used to represent overall differences between test fisheries, and random year effects were used to represent systematic differences in catch per unit effort among years. The full model was defined as,

$$\log(C_{y,d}) = \beta_0^{\text{daily}} + \beta_{0,a}^{\text{daily}} A + \beta_{0,w}^{\text{daily}} W + \beta_{1,y}^{\text{daily}} \cdot \text{DOY} + \beta_{2,y}^{\text{daily}} \cdot \text{DOY}^2 + \text{Year}(R). \quad \text{Equation D1}$$

where the coefficients $\beta_{1,y}^{\text{daily}}$, and $\beta_{2,y}^{\text{daily}}$ represented the fixed second-order polynomial regression parameters, estimated separately for each year. The β_{0}^{daily} term was the global intercept representing the Cottonwood fishery average, and $\beta_{0,a}^{\text{daily}}$ and $\beta_{0,w}^{\text{daily}}$ represented offsets from the global intercept for the Albion and Whonnock fisheries, with A and W representing dummy variables indicating whether observations came from the respective fisheries. Finally, the $\text{Year}(\text{R})$ term was a random effect component, representing year-to-year differences in overall catch per unit effort (i.e., random intercept), which represents process errors such as environmental stochasticity. Because the test-fishery sampling occurred on a daily basis, we expected observations closer in time to be more correlated than observations further apart in time. To accommodate this potential auto-correlation, the residual errors within a given year were assumed to follow an AR(1) process (i.e., autoregressive with a lag of 1).

Overall, the linear mixed effect model (Equation D1) provided a good fit to the observed data (*Figure D3*), with residual errors in one day being approximately 42% correlated with the previous day (95% CI: 37-46%). Because of the breadth of the assessment fishery sampling window, only dates with non-zero Coho Salmon catch were included in the analysis.

The dates of yearly run-timing peaks were then determined based on fixed effect estimates from the second-order polynomial regression component. That is, peak-run timing day-of-year was estimated as a derived variable based on estimates of the $\beta_{1,y}^{\text{daily}}$, and $\beta_{2,y}^{\text{dilay}}$ parameters and the invariance property of maximum likelihood estimators. Taking the first derivative the yearly second order polynomial fixed effect curves (i.e., $\beta_{1,y}^{\text{daily}} \cdot DOY + \beta_{2,y}^{\text{daily}} \cdot \text{DOY}^2$), fixing to zero, and then solving for DOY, provides the following estimator for yearly peak run-timing date:

$$\text{Pe}\widehat{\text{akD}}\text{OY}_{\text{y}} = \frac{\widehat{\beta_{1,y}^{daily}}}{-2\widehat{\beta_{2,y}^{\text{daily}}}}. \qquad \text{Equation D2}$$

When estimates of yearly peak Coho Salmon run timing estimates were plotted against year, a distinct linear trend was noted suggesting a tendency towards overall earlier peak timing (*Figure D4*). This trend was estimated using a simple linear regression with the estimated peak run-timing date as the response:

$$\text{Pe}\widehat{\text{akD}}\text{OY}_{\text{y}} = \beta_0^{peak} + \beta_1^{peak} \cdot \text{Year}_{\text{y}} \qquad \text{Equation D3}$$

This represents a simple linear regression of the peak run-timing estimates (i.e., $\text{Pe}\widehat{\text{akD}}\text{OY}$) against year, where the trend was estimated excluding the years 1985, 1993, 1997, 2006, and 2015, which were identified earlier as not having clear peaks in run-timing. This formulation does not fully account for uncertainty in $\text{Pe}\widehat{\text{akD}}\text{OY}_{\text{y}}$ derived from the original $\beta_{1,y}^{\text{daily}}$, and $\beta_{2,y}^{\text{dilay}}$ parameter estimates. That said, the goals of the simulation, was to account for major sources of uncertainty and variability, as such this approximation should be fine.

Simulation Model Implementation

Coho Salmon peak run-timing observed in the Lower Fraser River was forecasted based on drawing predicted peak run-timing dates, with error, during each simulation iteration. On the Monte Carlo iteration s the run-timing peak observed in the Lower Fraser was predicted as,

$$\widehat{PeakDOY}_{y,s} = \widehat{\beta_0^{peak}} + \widehat{\beta_1^{peak}} \cdot \mathrm{Year}_y + \epsilon_{y,s}^{timing} \qquad \text{Equation D4}$$

where $\widehat{\beta_0^{peak}}$ and $\widehat{\beta_1^{peak}}$ were estimates from the simple linear regression (Equation D3) and $\epsilon_{y,s}^{timing}$ was normally distributed random error representing the prediction error. That is, $\epsilon_{y,s}^{timing} \sim N\left(0, \widehat{SE}_y^{timing}\right)$, where $\widehat{SE}_y^{timing}$ was the standard error for the prediction interval associated with forecast given the year (i.e., the outer band of *Figure D4* indicates the 95% prediction interval), which represents the uncertainty in predicting a new observation.

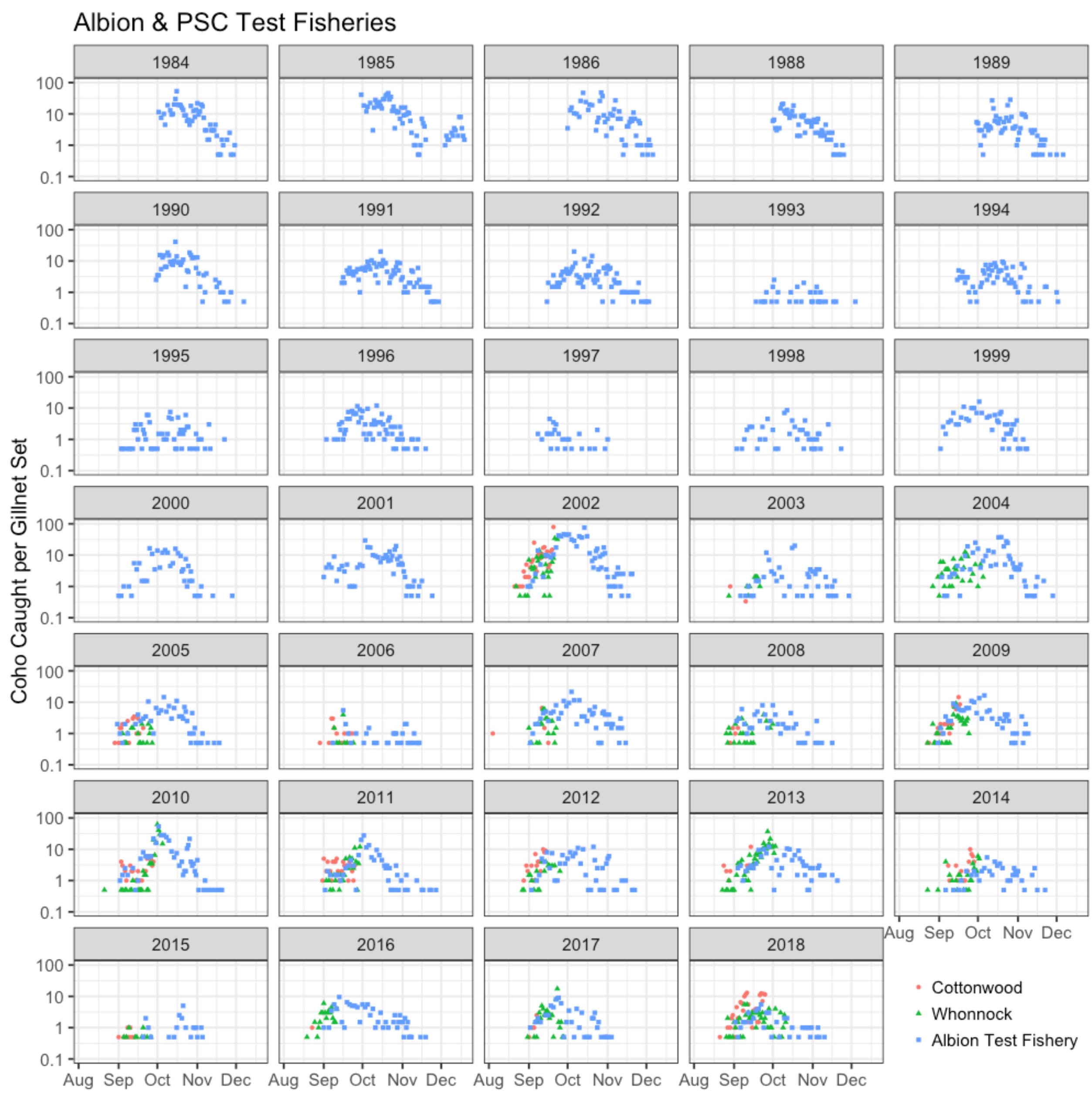


Figure D2. Coho Salmon catch per gillnet set, by day and year, for three gillnet test fisheries (i.e., Cottonwood (PSC), Whonnock (PSC), and Albion). Y-axis (i.e., catch per gillnet set) is displayed with logarithmic scaling.

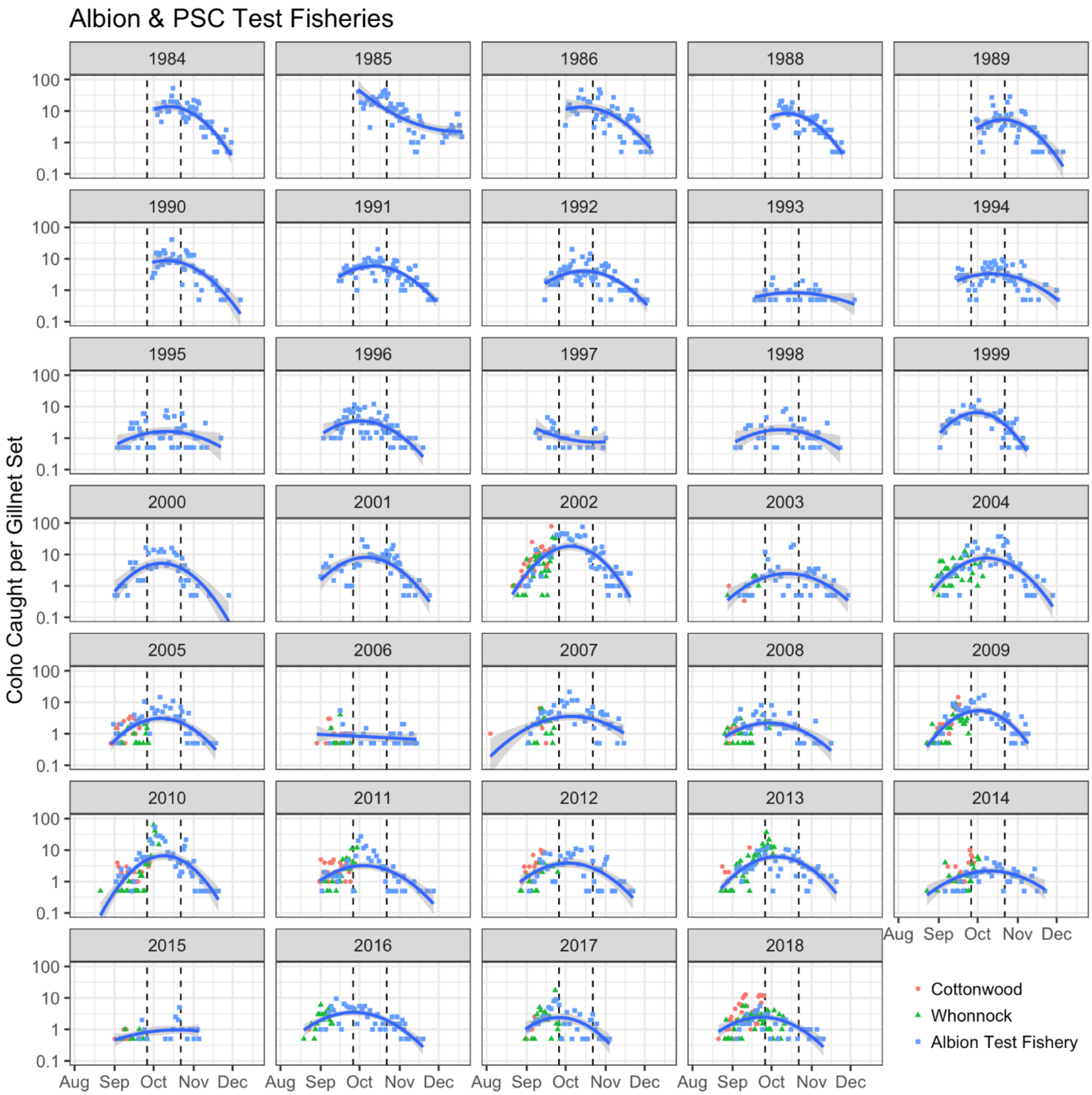


Figure D3. Average daily gillnet Coho Salmon catch per set, by date, for each year where sampling from at least one of three Lower Fraser test fisheries were available. The Y-axis uses a logarithmic scaling. Blue lines indicate second order polynomial regressions, with 95% confidence intervals represented by the pale blue shading. Dashed vertical lines indicate the range of estimated peak run-timing dates.

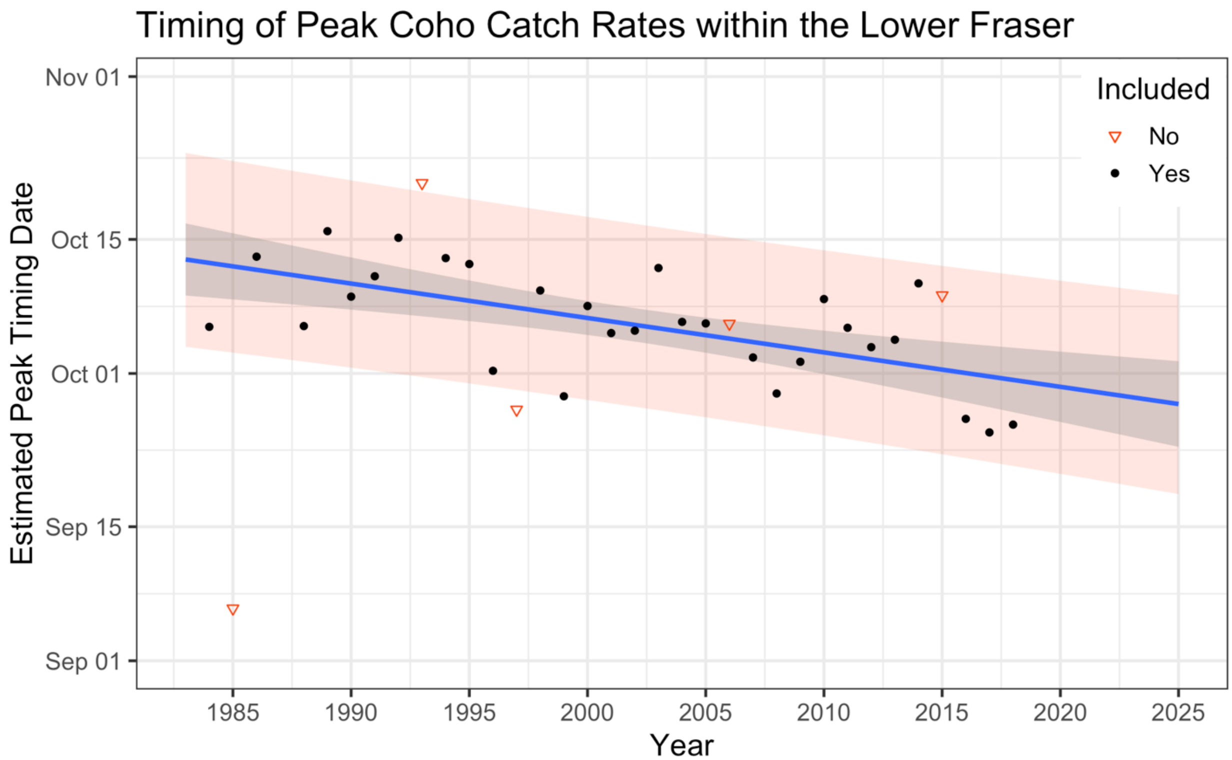


Figure D4. Estimated yearly peak timing dates by year with a simple linear trend indicating earlier peak run-timing dates. Inner shaded region indicates the 95% confidence interval for the linear regression line, with the outer shaded region indicating the 95% prediction interval for a new observation.

Forecasting Total Gillnet Catch

Generally, catch per unit effort is expected to decrease with temporal distance from the run-timing peak (*Figure D5*). The following linear mixed effect model was used (nlme package; Pinheiro et al. 2018) to predict daily gillnet catch per unit effort in a given year ($\mathrm{C_{y,d}}$) as a function of the temporal distance (i.e., number of days away) of the sampling event from the estimated run timing peak:

$$\log(\mathrm{C_{y,d}}) = Fishery + \beta_0^{catch} + \beta_1^{catch} \cdot D_{y,d} + Year(R) + D_{y,d}(R), \qquad \text{Equation D5}$$

where $D_{y,d}$ represents the absolute number of days from the center of the estimated run-timing peak (i.e., Equation D2 The model uses fixed effects (i.e., β_0^{catch} and $\beta_1^{catch} \cdot \mathrm{D_{y,d}}$) to represent the average linear relationship between catch and temporal distance from the run-timing peak, while the variable $Fishery$ was short-hand representing additional offsets for the average differences in catches per unit effort among the three gillnet test fisheries (i.e., $Fishery = \beta_{0,a}^{\mathrm{catch}} A + \beta_{0,w}^{catch} W$), where *A* and *W* are dummy variables indicating whether observations came from the Albion and Whonnock test fisheries. The random effects $\mathrm{Year(R)}$ and $\mathrm{D_{y,d}(R)}$ represent yearly variation in the intercept and slope of the average fixed linear relationship. Finally, because the test-fishery sampling occurs on a daily basis, we can expect observations closer in time to be more correlated than observations further apart in time. To accommodate this potential auto-correlation, the residual errors within a given year were assumed to follow an AR(1) process (i.e., autoregressive with a lag of 1).

Alternative models (other than the base model shown in Equation D5) were also considered (*Table D1*). In one alternative model, a linear year trend was included that represented a systematic change to catches per unit effort over time. In another alternative model, we included a 2nd order polynomial relationship with temporal distance from the run-timing peak. . Support for all models was assessed using the small sample-size corrected AIC ranking (AICc), keeping the same random effects terms the same as Equation D5; all models were fit using maximum likelihood estimation (*Table D1*).

Table D1. AICc model ranking for three models describing catch per unit effort vs temporal distance. Equation D5 was used as the base model. ΔAICc is the difference between the AICc score of a model relative to the top supported model, which will have a ΔAICc of zero. The AICc weight is the "model probability," which represents the level of support (i.e., weight of evidence) in favor of any given model being the most parsimonious among the candidate model set (Burnham and Anderson 2002). The cumulative AICc weight is the cumulative weight for the given and preceding models. The Log Likelihood is the maximum log-likelihood value of each model.

Model	**K**	**AICc**	**ΔAICc**	**AICc Weight**	**Cumulative AICc Weight**	**Log Likelihood**
Base + Year Trend	10	4217.67	0.00	0.85	0.85	-2098.78
Base	9	4222.04	4.37	0.10	0.95	-2101.97
Base + Poly(D, 2)	11	4223.29	5.62	0.05	1.00	-2100.57

The year trend model had assumed a general decline in overall catches per unit effort year-over-year and had the most support (i.e., ΔAICc = 0) with other models receiving only marginal or plausible support (i.e., ΔAICc between 2 and 7; Burnham and Anderson 2002). The lower support for the second order polynomial version of the model indicates that the decline in log catch with temporal distance appears to be better approximated by a linear trend as compared to more complex higher order forms.

Figure D5. Observed gillnet assessment fishery catch per set by number of days from estimated run-timing peak. Solid circles indicate sampling dates prior to the estimated run-timing peak, with solid triangles representing sampling dates after the estimated run timing peak.). Y-axis (i.e., catch per gillnet set) is displayed using a logarithmic scaling, solid lines indicate the a linear regression trend and shading indicates the 95% confidence region.

Simulation Model Implementation

On the Monte Carlo iteration s the daily gillnet equivalent daily catch was predicted with respect to the peak run-timing group with Equation D6:

$$\widehat{C_{y,d,s}^{gillnet}} = \exp\left(\widehat{\beta_0^{catch}} + \widehat{\beta_{0,a}^{\mathrm{catch}}} + \widehat{\beta_1^{catch}} \cdot D_{y,d,s} + \omega_{y,s}^{catch}\right) \qquad \text{Equation D6}$$

where $\widehat{\beta_0^{catch}}$ represented the global intercept, $\widehat{\beta_{0,a}^{\mathrm{catch}}}$ represented the average estimated difference associated with the Albion assessment fishery and $\widehat{\beta_1^{catch}}$ was the fixed effect estimate of the average linear relationship between catch and temporal distance from the run-timing peak after controlling for fishery. All estimates were derived from the top supported model (*Table D1*). The temporal distance (i.e., $\mathrm{D_{y,d}}$) was computed as the number of days from the predicted run timing peak within each Monte Carlo iteration (i.e., Equation D4). The term $\omega_{y,s}^{catch}$ represents a normally distributed random variable representing the year-to-year variation in average catch (i.e., $\omega_{y,s}^{catch} \sim N(0, \hat{\sigma}^{Year})$), where $\hat{\sigma}^{Year}$ was the estimated variability of the $\mathrm{Year(R)}$ random effect component. This component was interpreted as representing an estimate of process error.

Forecasting Tangle Net Catch

Daily tangle net catch was predicted based on converting daily forecasted gillnet catch (i.e., Equation D6) to tangle net equivalents. Predicted gillnet catch was standardized to a single gillnet set, providing a catch per unit effort (CPUE) metric. Based on the fishing times reported in Bennett (1999), a full day of tangle net fishing translated to roughly 170 minutes of active fishing time, providing a way to adjust the Bennett (1999) data to a daily CPUE. A comparison of the two adjusted CPUE metrics (i.e., gill net vs. tangle net) showed good agreement for the Chum Salmon catch (another predominant catch component), but there was a clear difference for Coho Salmon catch, which likely indicated efficiency differences (*Figure D6*).

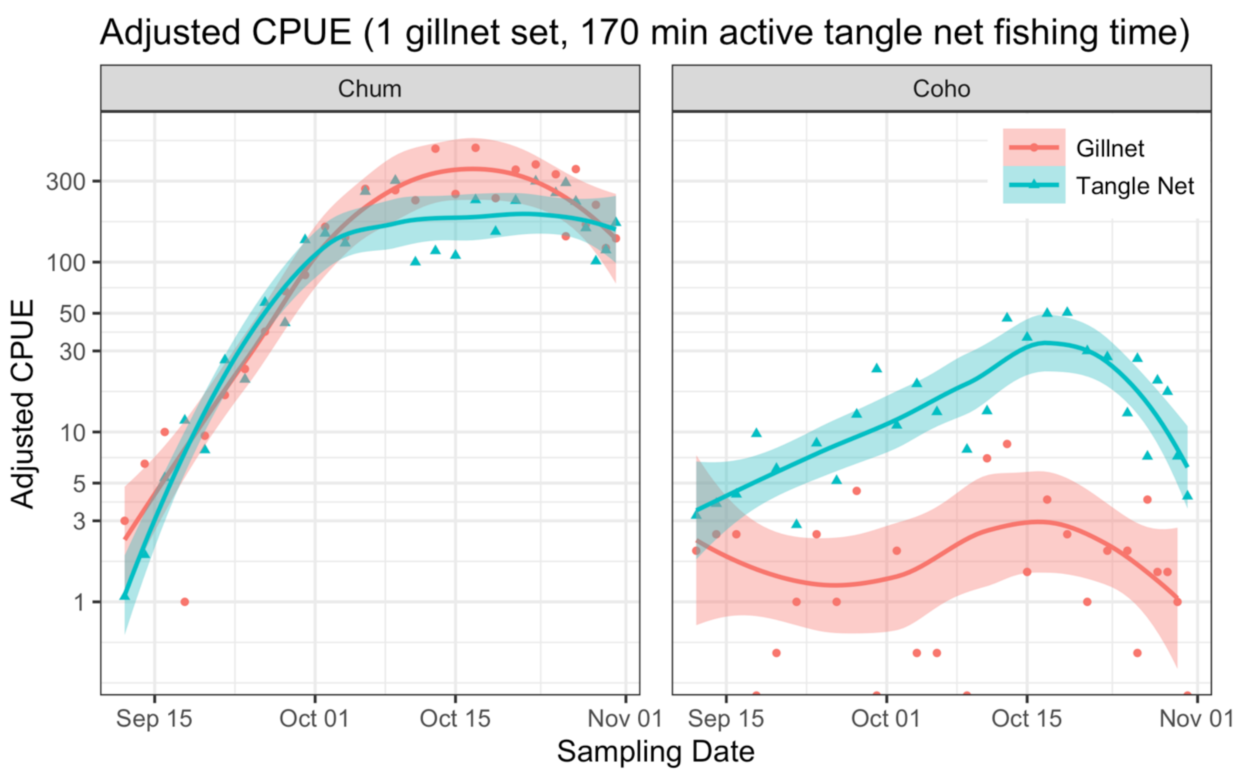


Figure D6. Comparison of 1998 Albion assessment fishery catch per gillnet set to tangle net data from Bennet et al. (1999). Coloured lines represent loess regression curves, and the shading shows the 95% confidence region. Adjusted CPUE (i.e., y-axis) is displayed using logarithmic scaling.

Because sampling days between the gillnet assessment fishery and Bennett (1999) did not always overlap, the ratio between adjusted CPUE was compared based on weekly averages (*Figure D7*). Weekly averages showed a constant ratio for Chum Salmon, but a variable ratio for Coho Salmon appeared to exhibit a linear in-season trend with day-of-year. As such, the tangle net to gillnet conversion ratio for Coho Salmon was modeled using a linear regression formulated as,

$$R_d = \beta_0^{\text{tangle}} + \beta_1^{\text{tangle}} \cdot DOY_d \qquad \text{Equation D7}$$

where R_d was the ratio of tangle net to gillnet adjusted CPUE values (i.e., *Figure D7*), with β_0^{tangle} and β_1^{tangle} terms represent the intercept and slope respectively.

Simulation Model

Daily tangle net Coho Salmon catch on Monte Carlo iteration s ($C_{y,d,s}^{tangle}$) was predicted for as:

$$\widehat{C_{y,d,s}^{tangle}} = \widehat{C_{y,d,s}^{gillnet}} \times \widehat{R_{d,s}},$$

where Equation D8

$$\widehat{R_{d,s}} = \widehat{\beta_0^{tangle}} + \widehat{\beta_1^{tangle}} \cdot DOY_d + \epsilon_{d,s}^{\text{tangle}}.$$

The term $\widehat{R_{d,s}}$ represented the forecasted tangle net to gillnet conversion ratio and $\widehat{C_{y,d,s}^{gillnet}}$ is the gillnet catch predicted in Equation D6. The estimates $\widehat{\beta_0^{tangle}}$ and $\widehat{\beta_1^{tangle}}$ used to predict the tangle net to gillnet conversion ratio were derived from Equation D7, with $\epsilon_{d,s}^{tangle}$ being a randomly distributed normal error term representing the prediction error associated with a given day of year and simulation iteration. That is, $\epsilon_{d,s}^{tangle} \sim N\left(0, \widehat{SE}_R^{tangle}\right)$, where $\widehat{SE}_R^{tangle}$ was the standard error for the prediction interval associated with the predicted conversion ratio.

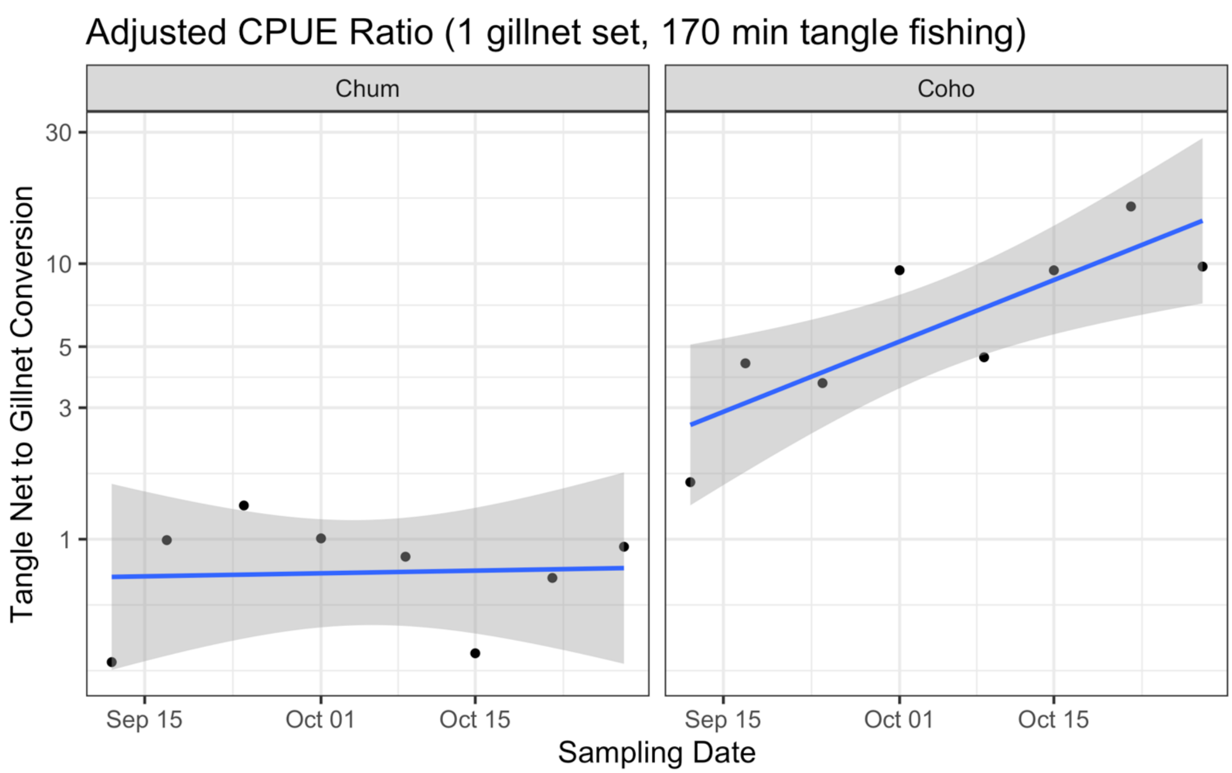


Figure D7. Tangle net to gillnet CPUE conversion ratio by day-of-year for Chum and Coho salmon test fisheries. Solid lines indicate log-linear trends, and the shading represents 95% confidence region for the regression line.

Forecasting LFC to IFC Proportions

Total predicted daily Coho Salmon catch for a given design was apportioned in aggregate between LFC and IFC depending on the dates of the proposed sampling design (*Figure D1*). Apportioning was based on an empirical model fit to 1997-2000 GSI data (*Table D2*) which provided daily estimates of the LFC to IFC proportions.

Table D2. Summary of daily GSI samples used in the LFC/IFC apportioning analyses.

Year	Gear	Area	Total Coho Samples	Date Range
1997	Tangle	New Westminster	643	Aug 08 – Nov 06
1998	Tangle	New Westminster	914	Sep 12 – Nov 15
1999	Tangle	New Westminster	626	Aug 26 – Nov 06
2000	Tangle	New Westminster	388	Aug 07 – Nov 09

Each sampled Coho Salmon was assigned a probability of belonging to the IFC aggregate, which tended to be distributed on either end of the probability scale (*Figure D8*). In order to assign individual observations to the LFC or IFC grouping, a conservative approach was taken, where fish with an estimated probability of belonging to the IFC aggregate was 0.5 or greater were assigned to the IFC aggregate; and those with scores less than 0.5 were assigned to the LFC aggregate.

The daily relationship between the LFC to IFC assignment counts were then modelled using a mixed effect general linear regression model assuming binomial errors (lme4 package; Bates et al. 2015). The probability of a sampled Coho Salmon belonging to the LFC aggregate on a given date within a year, was model as a linear function of day-of-year:

$$\text{logit}\left(\Pr\left(\text{LFC}_{\text{d,y}}\right)\right) = \beta_0^{LFC} + \beta_1^{LFC} \cdot \text{DOY}_{d,y} + \text{Year}(R) + \text{DOY}_{d,y}|\text{Year}(R) \qquad \text{Equation D9}$$

where β_0^{LFC} and β_1^{LFC} are a fixed effects that representing the intercept and slope for average linear relationship with day-of-year effect across all years. The random effects terms, $Year(R)$ and $\text{DOY}_{d,y}|Year(R)$ provide a random intercept and slope deviations from the average fixed effect relationship for each year. Here, the random effect can be interpreted as an estimate of process error (i.e., environmental stochasticity).

Results indicated that the average fixed effect relationship tended to fit the data well, as compared to the year-specific fits, which included the yearly random effect estimates (*Figure D9*). This suggests that the mean fixed effect relationship (i.e., dashed line; *Figure D9*) was doing a good job at capturing the general shift in composition between IFC and LFC stock components throughout the season.

Long-term trends in the DOY relationship were not considered given that only four years of sampling were available, and any trends estimated would need to be extrapolated over 20 years to be used in current catch forecasts.

Simulation Model Implementation

The average DOY trend represented by the fixed effect estimates (Equation D9) was used to predict the daily apportionment of forecasted catch between the LFC ($C_{d,y,s}^{LFC}$) and IFC ($C_{d,y,s}^{IFC}$) aggregates on each Monte Carlo simulation. Each quantity was computed as:

$$\widehat{C_{d,y,s}^{LFC}} = \widehat{C_{d,y,s}^{tangle}} \cdot \text{expit}\left(\widehat{\beta_0^{LFC}} + \widehat{\beta_1^{LFC}} \cdot \text{DOY}_d\right)$$

and Equation D10

$$\widehat{C_{d,y,s}^{IFC}} = \widehat{C_{d,y,s}^{tangle}} - \widehat{C_{d,y}^{\text{LFC}}},$$

where $\text{expit}(\mu) = 1/\exp(-\mu)$ and $\widehat{\beta_0^{LFC}} + \widehat{\beta_1^{LFC}} \cdot \text{DOY}_d$ represent the estimated linear in-season fixed effect trend. Given generally good fit between the observed data and the fixed effect estimate (*Figure D9*), we did not include estimates of the process error (i.e., random effects) in the Monte Carlo simulation to reduce the number of sources of variation considered in the forecasts.

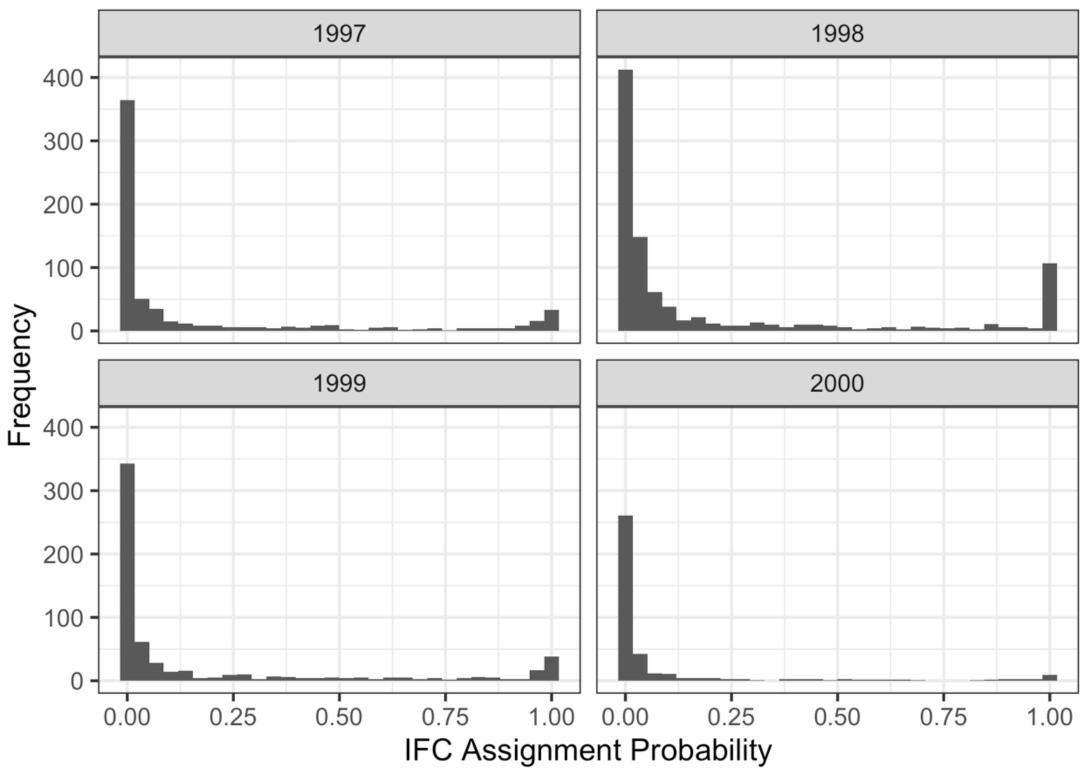


Figure D8. Histogram showing the distribution of IFC assignment probabilities by sampling year. A conservative threshold of 0.5 was used to apportion individuals to the IFC category.

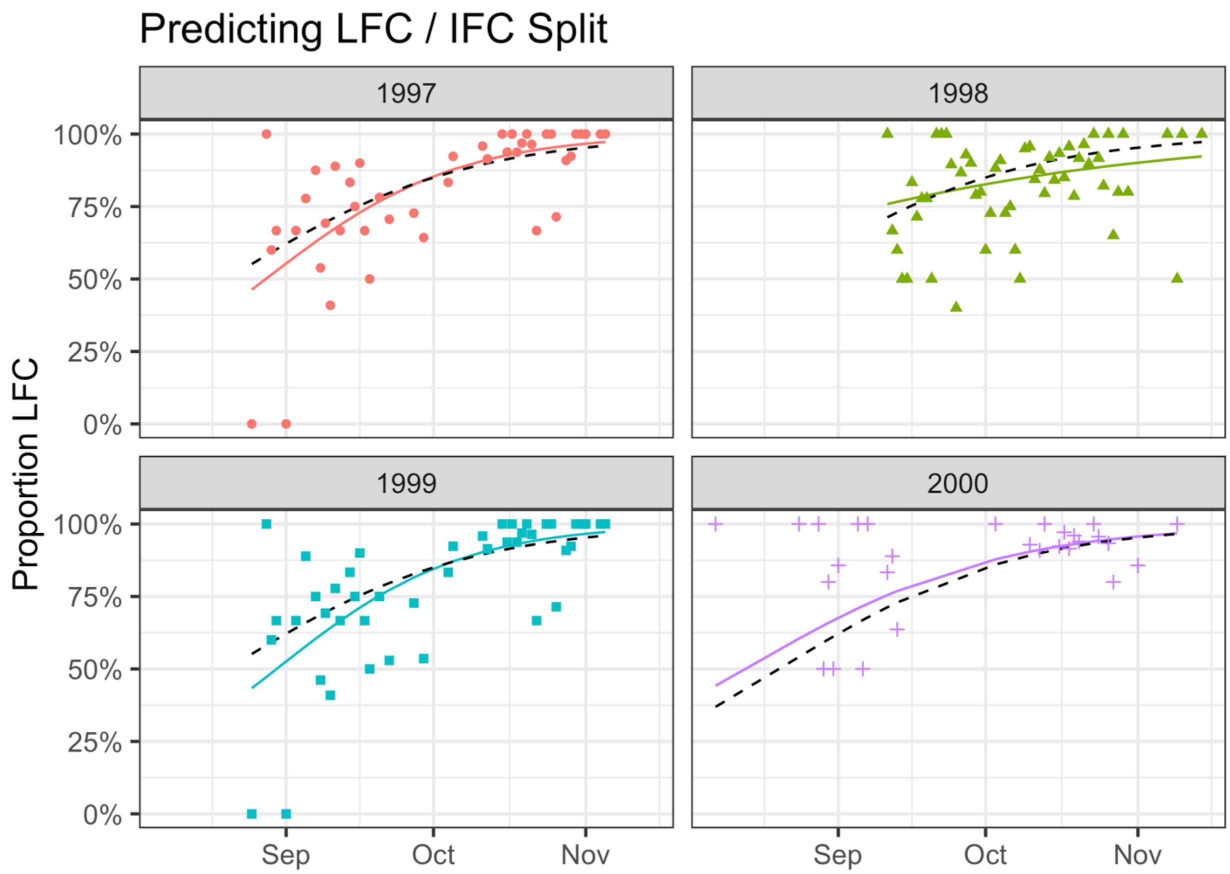


Figure D9. Daily LFC to IFC proportion by sampling date and year. Dashed line indicates the average relationship between date and the proportion of Coho Salmon returns belonging to the Lower Fraser aggregate. The solid lines indicate year specific estimated trend, while the dashed line indicates the average trend.

Forecasting LFC Stock Aggregates

After total tangle net catch has been apportioned to IFC and LFC aggregates (see Forecasting LFC to IFC Proportions) the forecasted LFC catch was further apportioned among stocks (*Figure D10*) based on available yearly GSI data (*Table D3*). Lower Fraser stocks were apportioned into four main groupings: Chilliwack, Lillooet, Nicomen/Norrish, and Other (*Table D4*). The largest stock aggregate (i.e., Other) showed a general decline over time (*Figure D11*). Also, there are increasing odds over time of an LFC fish being a member of either the Chilliwack or Lillooet stock aggregates. The Nicomen/Norrish aggregate is following the same trend as the 'Other' stock aggregate (*Figure D12*).

Future stock proportions were forecasted using a two-step process. First, since the Other stock aggregate had the cleanest temporal trend, it was used as the reference category for Chilliwack, Lillooet, and Nicomen/Norrish. Yearly stock proportions for the Other stock aggregate was modelled using a generalized linear mixed model (lme4 package; Bates et al. 2015) on the stock count data, divided into either Other or 'Chilliwack + Lillooet + Nicomen/Norrish', using a binomial error model. The proportion of yearly catch that was apportioned to the Other category was modelled as:

$$\text{logit}\big(\Pr(\text{Other})\big) = \beta_0^{other} + \beta_1^{other} \cdot \text{Year} + \text{Year(R)}, \qquad \text{Equation D11}$$

where $\beta_0^{other} + \beta_1^{other}$ is a fixed effect that captures the linear trend in proportions over time (*Figure D11*). The $Year(R)$ term is a random effect, which can be viewed of as an estimate of the process error (i.e., environmental stochasticity).

For the second step, the remaining (i.e., not 'Other') yearly catch was apportioned between Chilliwack, Lillooet, and Nicomen/Norrish using a multinomial log-odds regression model (nnet package; Venables and Ripley 2002), where the log odds of being in a category relative to the reference category was modelled as having a linear association with year:

$$\log\left(\frac{\Pr(\text{Chilliwack})}{\Pr(\text{Other})}\right) = \beta_{0,1}^{\text{C}} + \beta_{0,2}^{\text{C}} \cdot \text{Year}$$

$$\log\left(\frac{\Pr(\text{Lillooet})}{\Pr(\text{Other})}\right) = \beta_{0,2}^{\text{L}} + \beta_{1,2}^{\text{L}} \cdot \text{Year} \qquad \text{Equation D12}$$

$$\log\left(\frac{\Pr(N\text{icomen/Norrish})}{\Pr(\text{Other})}\right) = \beta_{0,3}^{N} + \beta_{1,3}^{N} \cdot \text{Year}.$$

The two models (Equations D11 and D12) were combined to create an estimated stock aggregate proportion within the sampling period (i.e., 1997 – 2014; *Figure D13*). Overall, the Nicomen/Norrish and Other stock aggregates are forecasted to continue to decline over time, whereas the Chilliwack and Lillooet aggregates are forecasted to make up proportionately more of the LFC catch over time.

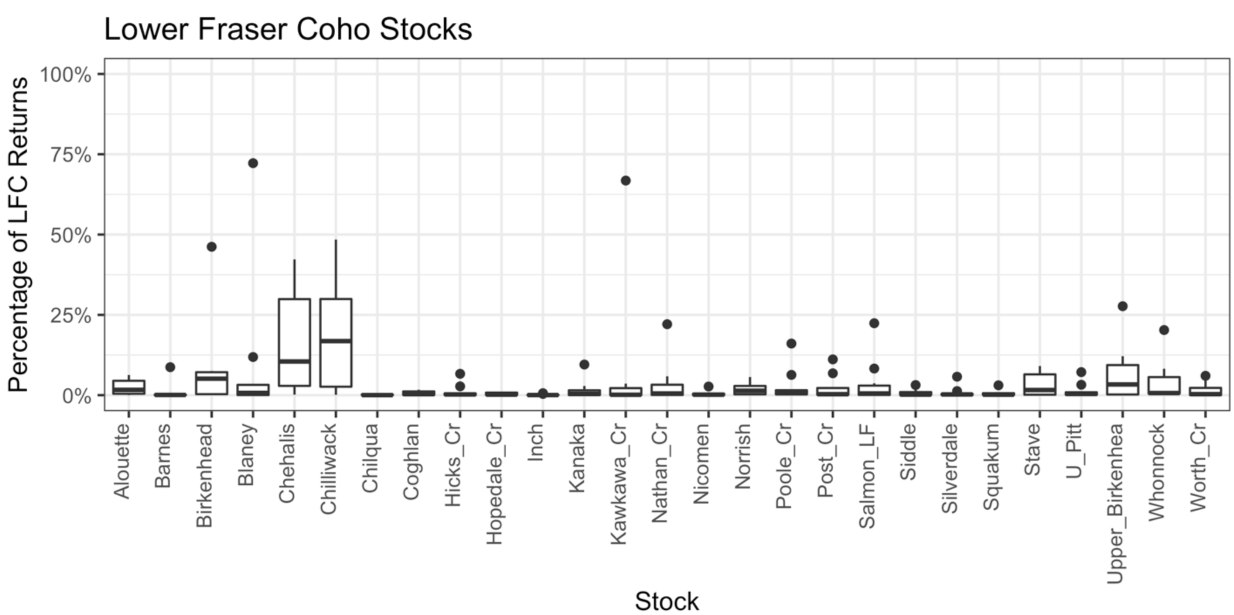


Figure D10. Box plots indicating the distribution of yearly stock proportion estimates by stock. Boxes enclose the 25th and 75th percentiles, with the center line indicating the median. Whiskers extend to 1.5 times the interquartile range (25th to 75th), with outlines indicated as individual points.

Table D3. Genetic Stock Identification data used to apportion migrating Coho to IFC and LFC stocks.

Year	Gear	Location	Sample Size	Date Range
1997	Gillnet	Albion	333	Aug 31 - Nov 14
1997	Tangle Net	Fraser	632	Jul 18 - Nov 06
1998	Tangle Net	Fraser	820	Sep 12 - Nov 15
1998	Troll	Cottonwood	48	Aug 26 - Sep 17
1999	Gillnet	LWFR_comm	82	Jul 18 - Jul 18
2000	Tangle Net	Fraser	385	Aug 08 - Nov 10
2010	Seine	Fraser_L	50	Jul 20 - Jul 20
2011	Seine	Fraser_L	78	Jul 20 - Jul 20
2013	Gillnet	Whonnock	448	Aug 27 - Oct 02
2014	Gillnet	FraserTest	64	Aug 24 - Oct 20

Table D4. Definitions of Lower Fraser Coho stock aggregates.

Stock Aggregate	n	Stock(s)
Chilliwack	1	Chilliwack
Nicomen/Norrish	6	Barnes, Nicomen, Norrish, Inch, Siddle, and Worth Creek
Lillooet	3	Birkenhead, Upper Birkenhead, and Poole Creek
Other	60	Post_Cr, Alouette, Blaney, Chehalis, Chilqua, Coghlan, Hicks_Cr, Hopedale_Cr, Kanaka, Kawkawa_Cr, Nathan_Cr, Salmon_LF, Silverdale, Squakum, Stave, U_Pitt, Whonnock, Bridge, Chilko, Gates_Cr, Mckinley, Seton_Cr, Albreda, Avola, Barriere, Birch_Island, Blue, Cook_Cr, Dunn, E_Barriere, Fennell, Finn, Lemieux, Lion, Louis, Mann, Pig_Channel, Raft, Reg_Christie, Tumtum_Cr, Bessette, Danforth, Duteau_Shwp, Eagle, Harbour_Cr, Harris_Cr, Ireland, LangChan_Shwp, McMomee, Mid_Shuswap, Momich, Salmon_SA, Senn, Sinmax, Wap_Cr, Bonaparte, Coldwater, Deadman, Spius, and Nahatlatch

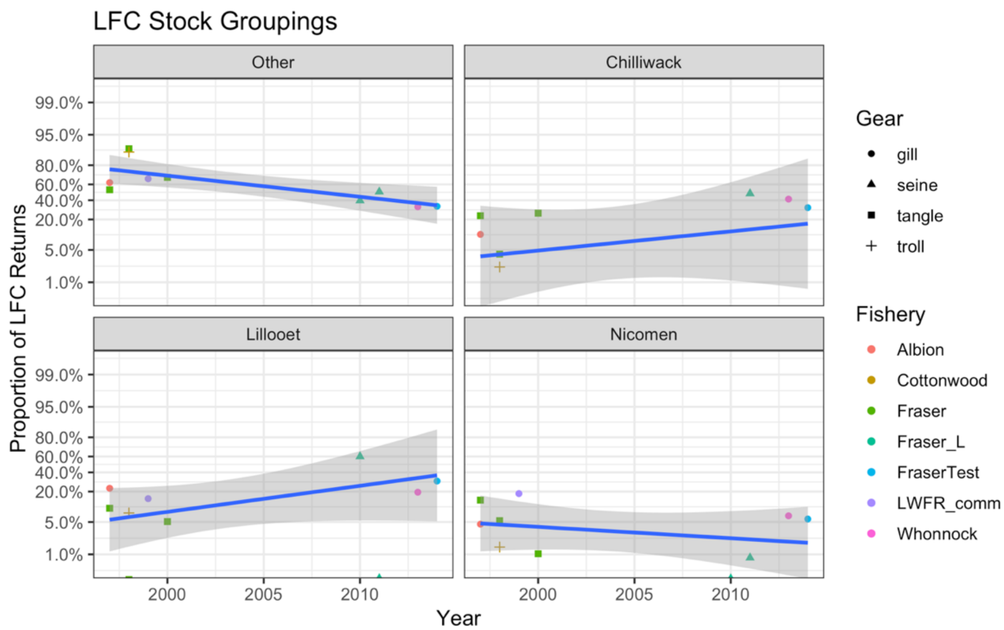


Figure D11. Yearly trends in estimated LFC stock aggregate proportions (see Table D4 for stock aggregate definitions). Solid lines indicate estimated regression trend, with shading representing the 95% confidence region for the regression line.

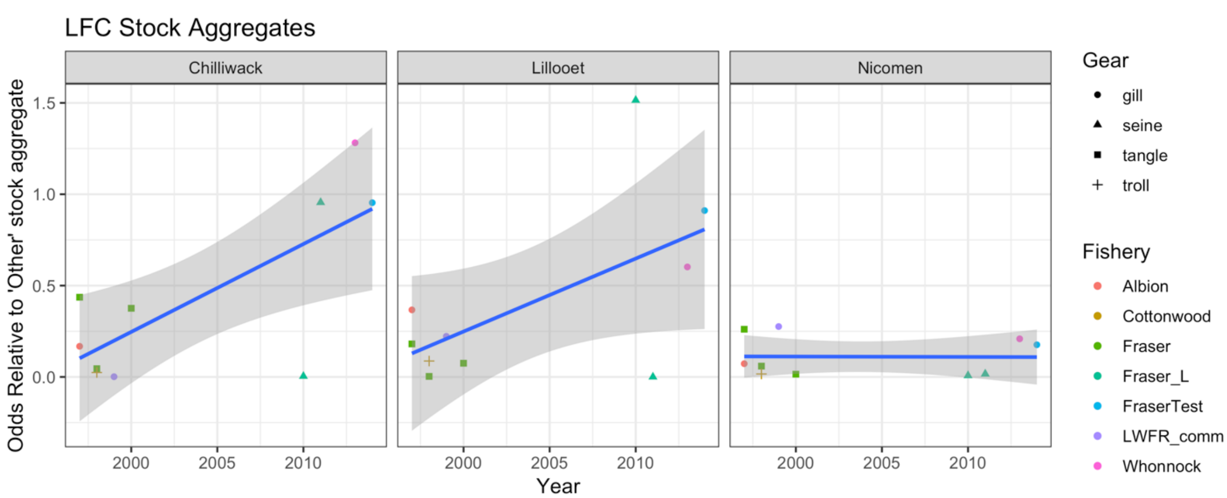


Figure D12. Odds a Lower Fraser Coho belongs to the Chilliwack, Lillooet, or Nicomen/Norrish aggregate relative to belonging to the 'Other' stock (see Table D3 for stock aggregate definitions). Solid lines indicate the estimated regression line, with shading indicating the 95% confidence region.

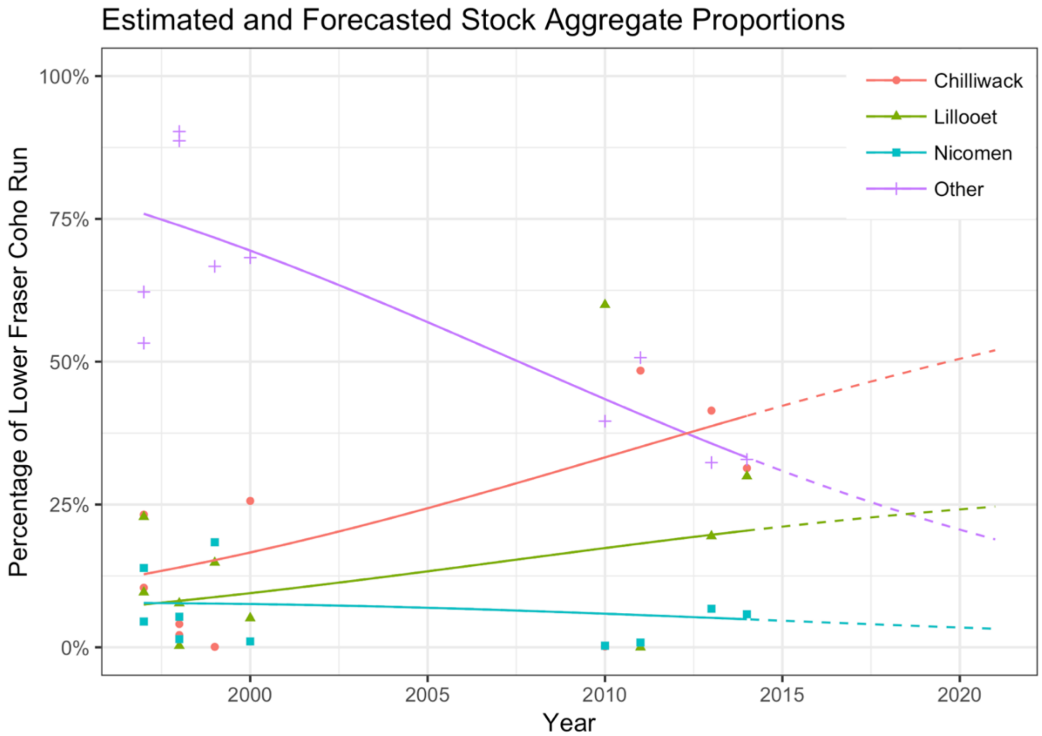


Figure D13. Solid lines indicate estimated trends, while dashed lines indicate forecasted trend.

Simulation Model Implementation

The simulation model apportions the forecasted LFC catch (i.e., $\widehat{C_{d,y}^{LFC}}$, see Equation D10) to the four aggregate groupings by first apportioning total LFC catch to the Other category. For each forecasted year, the proportion attributed to the Other group on Monte Carlo iteration s was determined as:

$$\widehat{p_{y,s}^{other}} = \text{expit}\left(\widehat{\beta_0^{other}} + \widehat{\beta_1^{other}} \cdot \text{Year} + \omega_s^{yr}\right) \quad \text{Equation D13}$$

where $\widehat{\beta_0^{other}}$ and $\widehat{\beta_1^{other}}$ were the fixed effect estimates from Equation D11, and ω_s^{Year} was a normally distributed random error (i.e., $\omega_s^{yr} \sim N\left(0, \widehat{\sigma^{yr}}\right)$) based on the estimated yearly random effect. This allowed each simulation to have a slightly different yearly proportion attributed to the Other category, which was determined as:

$$\widehat{C_{y,d,s}^{other}} = \widehat{C_{d,y,s}^{LFC}} \cdot \widehat{p_{y,s}^{other}} \quad \text{Equation D14}$$

The remaining group aggregates (i.e., Chilliwack, Lillooet , and Nicomen/Norrish) were then attributed relative to the other category. First the remaining proportions were predicted based on the multinomial log-odds regression model (Equation D12), with each specific proportion predicted as:

$$\widehat{p_{y,s}^{G}} = \widehat{p_{y,s}^{other}} \cdot \exp\left(\widehat{\beta_{0,1}^{G}} + \widehat{\beta_{0,1}^{G}} \cdot \text{Year}\right) \quad for\ G \in \{C, L, N\}. \quad \text{Equation D15}$$

This generated the remaining stock aggregate proportions for Chilliwack, Lillooet, and Nicomen/Norrish (i.e., $\widehat{p_{y,s}^{C}}$ $\widehat{p_{y,s}^{L}}$ and $\widehat{p_{y,s}^{N}}$ respectively). To ensure all the stock proportions summed to one, the estimated proportions were normalized, that is,

$$\widehat{p_{y,s}^{G}} * = \frac{\widehat{p_{y,s}^{G}}}{\widehat{p_{y,s}^{C}} + \widehat{p_{y,s}^{\mathrm{L}}} + \widehat{p_{y,s}^{\mathrm{N}}}} \quad for\ G \in \{C, L, N\}. \qquad \text{Equation D16}$$

The final group-specific catch predicted for each Monte Carlo iteration made use of the adjusted probability (i.e., Equation D16) and the total predicted Lower Fraser catch (i.e., Equation D10). As such, the group-specific catch for a forecasted day and year within each Monte Carlo iteration was therefore determined as:

$$\widehat{C_{y,d,s}^{G}} = \widehat{C_{d,y,s}^{LFC}} \cdot \widehat{p_{y,s}^{G}} * \quad for\ G \in \{C, L, N\}. \qquad \text{Equation D17}$$

Forecasting Clipping Rate

The proportions of Coho Salmon returning to Chilliwack and Nicomen/Norrish that are forecasted to be clipped were determined based on the Chilliwack Hatchery data (*Figure D14*). Overall, the there was some indication of a linear trend, but the trend was non-significant (i.e., $p = 0.2$). Thus the clipped proportion returning to Chilliwack Hatchery each year was modelled as a simple intercept model, using the following simple mean only regression model:

$$\mathrm{logit}\left(p_{\mathrm{y}}^{\mathrm{clipped}}\right) = \beta_0^{clipped} \qquad \text{Equation D18}$$

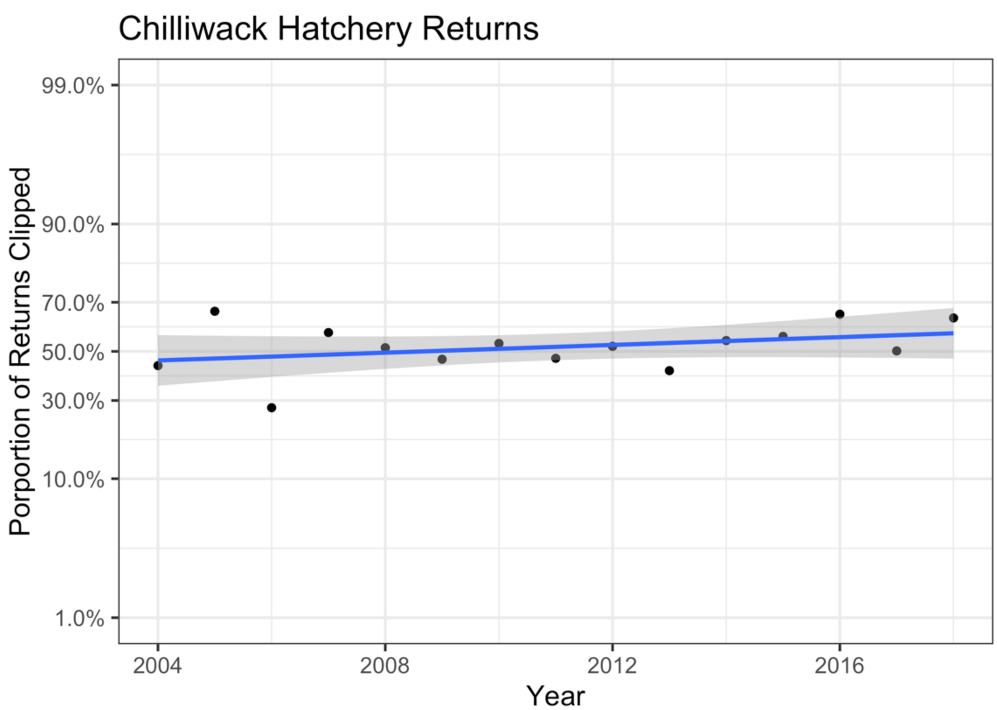


Figure D14. Proportion of Chilliwack Coho Salmon returns that were clipped from 2004 – 2018. Line indicates an estimated linear trend with shading indicating the 95% confidence region. Y-axis uses a logit scaling.

Simulation Model Implementation

Forecasted clipped returns for Chilliwack ($p_{y,s}^{\text{clipped}}$) were determined as a function of the estimate and an error term:

$$p_{y,s}^{clipped} = \text{expit}\left(\widehat{\beta_0^{\text{clipped}}} + \epsilon_{y,s}^{\text{clipped}}\right) \quad \text{Equation D19}$$

where $\epsilon_{y,s}^{\text{clipped}}$ was a normally distributed random error associated with each yearly forecast (i.e., $\epsilon_{y,s}^{\text{clipped}} \sim N\left(0, \widehat{\sigma^{\text{clipped}}}\right)$) and was based on the estimated residual variation (i.e., $\widehat{\sigma^{\text{clipped}}} = 0.42$) from the simple mean regression model (i.e., Equation D18).

The clipped rate for Nicomen/Norrish was set to 25% that of Chilliwack clip rate to match the anticipated returns from the future Nicomen/Norrish tagging studies (Chuck Parken, personal communication, 2019).

Assessing Sampling Designs

Sampling designs were assessed by applying a given design (i.e., boat-days of effort by date) to each simulation iteration. Total sampling effort from 5 to 25 boat days was considered, with the effort spread evenly across sampling windows from 1 to 6 weeks (*Figure D15*). The shorter sampling window would feature a higher sampling intensity on any given day than the wider sampling window. All sampling windows were centered on the mean forecasted sampling date (i.e., solid line, *Figure D4*), not the run-timing peak realized in each Monte Carlo iteration.

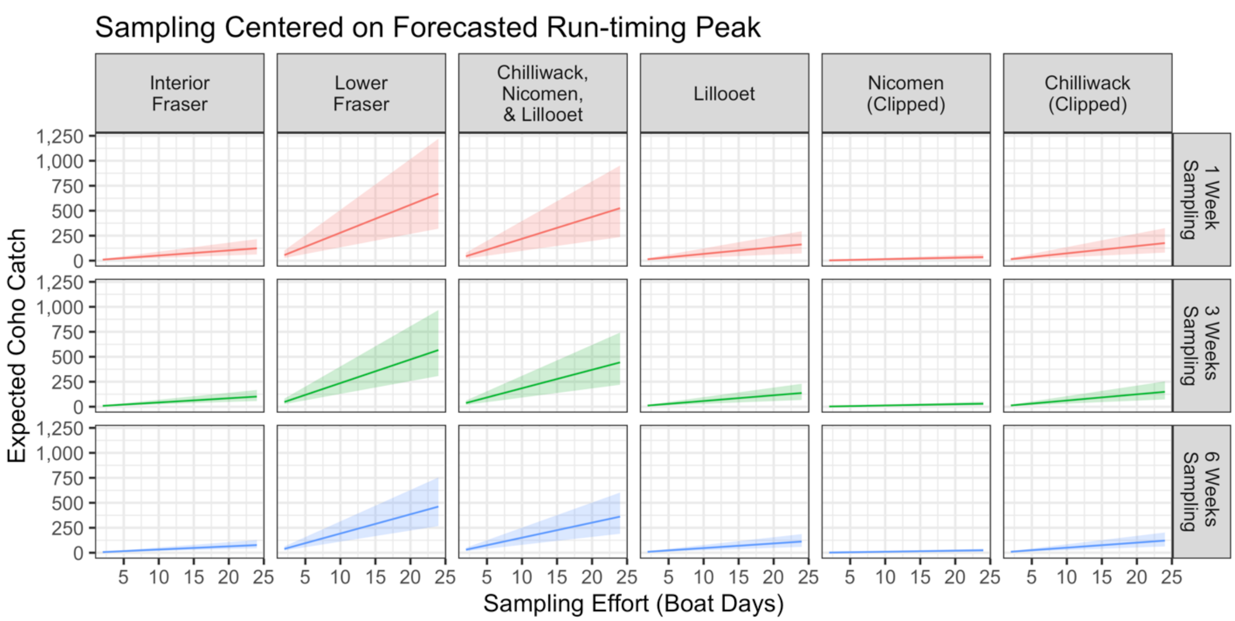


Figure D15. Forecasted Coho Salmon catch by sampling effort, partitioned across different stock constituents (columns), and by sampling window (rows). Solid lines indicate the mean catch computed across simulation iterations, while shading indicates the 2.5% and 97.5% percentiles.

Additional References

Bates, D., Maechler, M., Bolker, B., Walker, S. (2015). Fitting Linear Mixed-Effects Models Using lme4. Journal of Statistical Software, 67(1), 1-48. doi:10.18637/jss.v067.i01.

Burnham, K.P., and Anderson, D.R. 2002. Model selection and multi-model inference: a practical information-theoretic approach. In 2nd edition. Springer-Verlag, New York.

Pinheiro J, Bates D, DebRoy S, Sarkar D, R Core Team (2018). _nlme: Linear and Nonlinear Mixed Effects Models_. R package version 3.1-137, <URL: https://CRAN.R-project.org/package=nlme>

Venables, W. N. & Ripley, B. D. (2002) Modern Applied Statistics with S. Fourth Edition. Springer, New York. ISBN 0-387-95457-0

Appendix E

Forecasted bycatch in the assessment fishery

The impact of net configuration on bycatch was investigated based on a reassessment of the Bennett (1999) Appendix II, which lists catch by net position, sampling set and day. The Bennett study used a 30 fathom deep tangle net deployment hung at a 3:1 hang ratio. Most Coho catch occurred in the upper 2/3rd of the net (i.e., top and middle), while bycatch, which was dominated by Chum, tended to occur in the lower 2/3rd of the net (i.e., middle and bottom; Figure E1). There was also small amount of Sockeye bycatch that occurred in early September and a small scattering of Chinook bycatch throughout the sampling period (Figure E1). Steelhead catch was minimal (i.e., 16/639 = 0.3%) and there was no record of Pink bycatch in the tangle net assessment fishery (Table E1). These observed distributional difference in Coho and bycatch abundances by deployment depth provide an opportunity to improve the capture efficiency of Coho while reducing the abundance of bycatch. The tangle net configuration may be optimized for this study by modifying the deployment depths to correspond to the depths described as the top and middle portions in Bennett (1999) study.

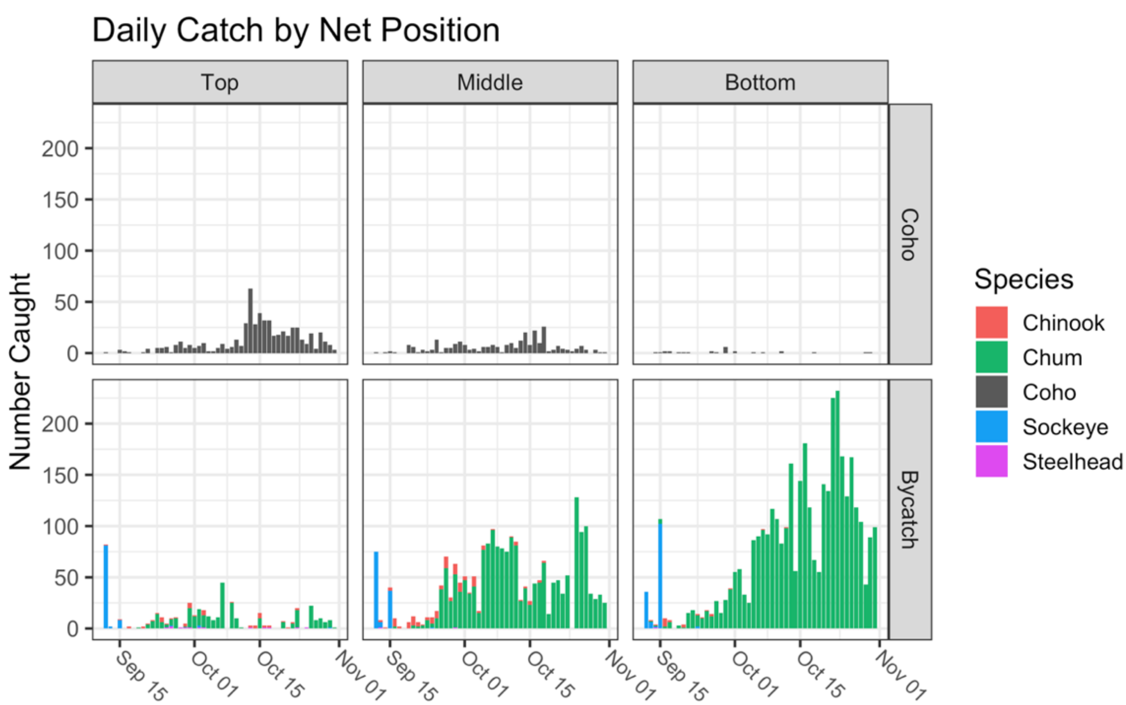


Figure E1. Daily Coho and bycatch quantities by date and net position.

Generally, any modifications that can increase the number of Coho caught and reduced the number of bycatch will be favourable to the study objectives. By modifying net deployments to shallower depths, not only will bycatch be reduced, but the amount of time associated with processing bycatch (i.e., pick time) will also be reduced, which could allow for additional tangle net sets, resulting in additional Coho catch for the given survey effort. To investigate the consequence of such a modification, we used a simulation experiment to determine the changes to Coho and bycatch based on the results from the Bennett study.

Table E1. Bycatch totals from the entire sampling season by species and net position from Bennett (1999).

Species	Top	Middle	Bottom	TOTAL
Chinook	51	127	23	201
Chum	315	1,917	3,581	5,813
Sockeye	95	118	147	360
Steelhead	13	2	1	16
TOTAL	474	2,164	3,752	**6,390**

General Approach

Sets from the from the Bennett study were resampled with replacement on a weekly basis to represent expected variability observed between tangle net sets. Coho and bycatch associated with upper portion of the net (i.e., top or top and middle) were retained and pick times were adjusted based on the empirical relationship observed between catch and pick times in order to determine the total number of sets that could be fished based on keeping the same total weekly effort as was used in the Bennett study (Table E2). This provided a distribution of expected Coho and bycatch by study week using a revised net deployment scheme focused on shallower deployments.

Table E2. Summary of weekly effort in the Bennett (1999) tangle net study.

Week	Start Date	End Date	Sets	Average Time (min)	Total Time (min)
36	Sep 12	Sep 13	27	18.0	486.1
37	Sep 14	Sep 20	83	21.7	1,799.5
38	Sep 21	Sep 27	81	22.3	1,806.1
39	Sep 28	Oct 04	65	23.7	1,542.5
40	Oct 05	Oct 11	69	22.9	1,582.5
41	Oct 12	Oct 18	69	22.9	1,577.2
42	Oct 19	Oct 25	70	22.9	1,604.1
43	Oct 26	Oct 31	66	23.0	1,517.3

Modelling Pick Times

The Bennett study recorded deployment, set and pick times for each of the 530 tangle net sets. Most sets used a 100 Fathom net length (i.e., 357/530 = 67%), a subset used shorter net lengths. Generally, pick times across the range of net lengths were positively associated with the total number of salmon caught for both groupings, and also appeared to show a similar per-unit-time gain per unit increase in catch (i.e., slope; Figure E2). This suggests that it should be possible to build an empirical model to predict the revised pick times associated with changes in catch that will result from changes in net deployments.

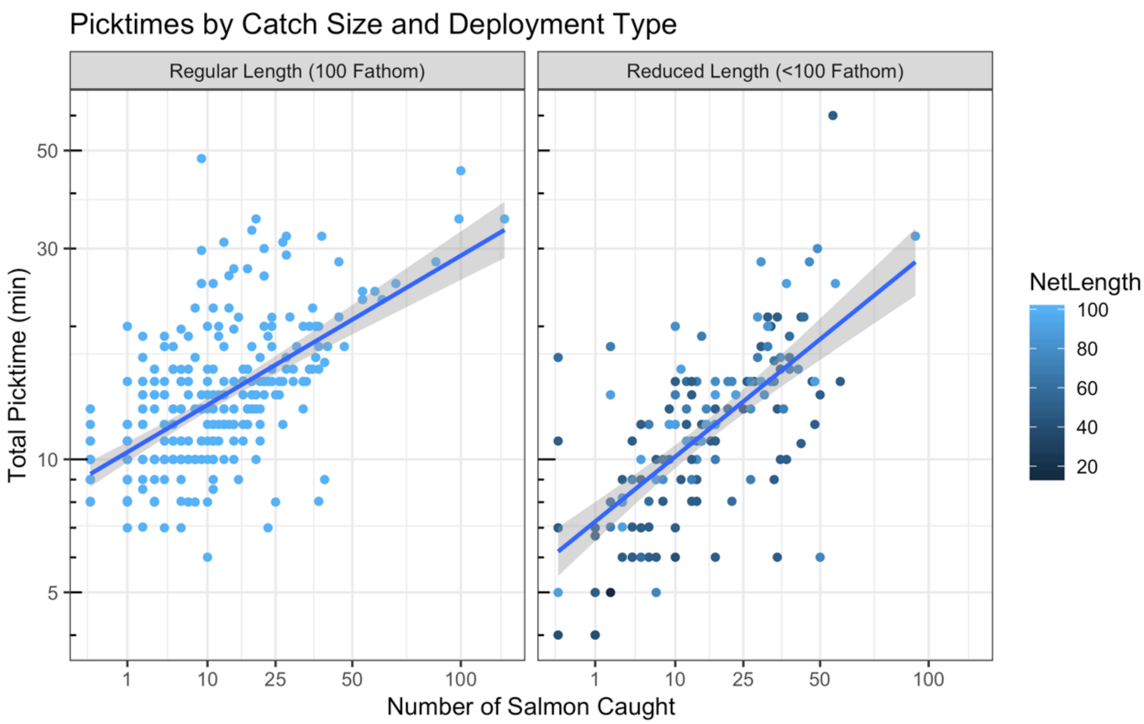


Figure E2. Linear regression of catch size and the recorded net pick times in Bennett (1999). Solid line indicates a simple linear regression line, shading indicates the 95% confidence region for the regression line. Pick times (i.e., y-axis) are displayed using a logarithmic scaling, while catch (i.e., x-axis) is displayed using a square root scaling.

The log-transformed pick time for a given set (i.e., $\log(PT_s)$) was modelled using a linear mixed effect model, with the base model having the form:

$$\log(PT_s) = \beta_0^{time} + \beta_1^{time}\sqrt{C_s} + Day(R), \quad \text{Equation E1}$$

where β_0^{time} and β_1^{time} are fixed effects representing the intercept and slope and $\sqrt{C_s}$ represents square root transformed catch for set s. The random effect $Day(R)$ represented day-to-day error in pick times that may be related to daily conditions. Finally, because sets within a day represent repeated measures the residual errors within a given day were assumed to follow an AR(1) process (i.e., autoregressive with a lag of 1).

Alternative models that also considered the effect of net length (L_s) were also considered, with support for each model was assessed using the small sample-size corrected AIC ranking (AICc; Table E3). All models used the same random effects terms and were fit using maximum likelihood estimation. Overall, the top supported model included net length as a continuous variable which acted as an offset adjustment to the overall intercept β_0^{time} for sets that shared the same net length. There was also support for including an interaction term, but for simplicity the top model was used to predict expected pick times for each simulation iteration.

For the simulation model, the top ranked model (Table E3) was used to predict revised pick times associated with a net deployment corresponding with the upper portions of the net. Sets from each week were resampled, and pick times for a given simulation iteration (i), week (w) and set (s) pick time was modelled as,

$$PT_{i,s} = \exp\left(\widehat{\beta_0^{time}} + \widehat{\beta_1^{time}} \cdot \sqrt{C_{i,w,s}} + \widehat{\beta_2^{time}} \cdot L_{i,w,s} + \epsilon_{i,w,s}^{time}\right)$$ Equation E2

where, $\widehat{\beta_0^{time}}$, $\widehat{\beta_1^{time}}$, and $\widehat{\beta_2^{time}}$ are fixed effect estimates, $C_{i,w,s}$ is the revised catch corresponding to the altered deployment depths being considered, and $L_{i,w,s}$ was the net length associated with the resampled tangle net set. The error term $\epsilon_{i,w,s}^{time}$ was a randomly distributed normal error term representing the prediction error associated with the residual error term from the top model and represents how pick times can vary from set to set.

Table E3. AICc model ranking table comparing potential pick time models. Equation E1 was used as the base model (catch). ΔAICc is the difference between the AICc score of a model relative to the top supported model, which will have a ΔAICc of zero. The AICc weight is the "model probability," which represents the level of support (i.e., weight of evidence) in favor of any given model being the most parsimonious among the candidate model set (Burnham and Anderson 2002). The cumulative AICc weight is the cumulative weight for the given and preceding models. The Log Likelihood is the maximum log-likelihood value of each model.

Model	K	AICc	ΔAICc	AICc Weight	Cumulative Weight	Log Likelihood
Catch + NetLength	6	113.35	0	0.71	0.71	-50.58
Catch + NetLength + NetLength:Catch	7	115.17	1.82	0.29	1.00	-50.46
Catch	5	156.36	43.0	0.00	1.00	-73.11

Simulation Results

Coho catch and bycatch was predicted using net deployments corresponding with either the top portion only or top and middle portions of the Bennett study (Figure E3). Overall, restricting tangle net deployments to correspond to the top and middle portion of the status quo deployment resulted in an 9% increase Coho catch by the end of the season (95% CI: 3.2%, 15.3%), while bycatch was reduced by around 54% (95% CI: 51.1%, 57.0%) (Figure E3c). Restricting deployments to correspond to only the top portion resulted in a 19% decrease in Coho catch (95% CI: 11.9%, 25.5%) relative to the status quo and a 90.1% (95% CI: 88.7%, 92.8%) reduction in bycatch (Figure E3c). As such, the restricting tangle net deployments to correspond to the top and middle portion of the status quo deployment will in slight improvements of Coho catch, while greatly reducing bycatch. Further restricting deployment depth can further reduce bycatch, but will also notably reduce the Coho catch.

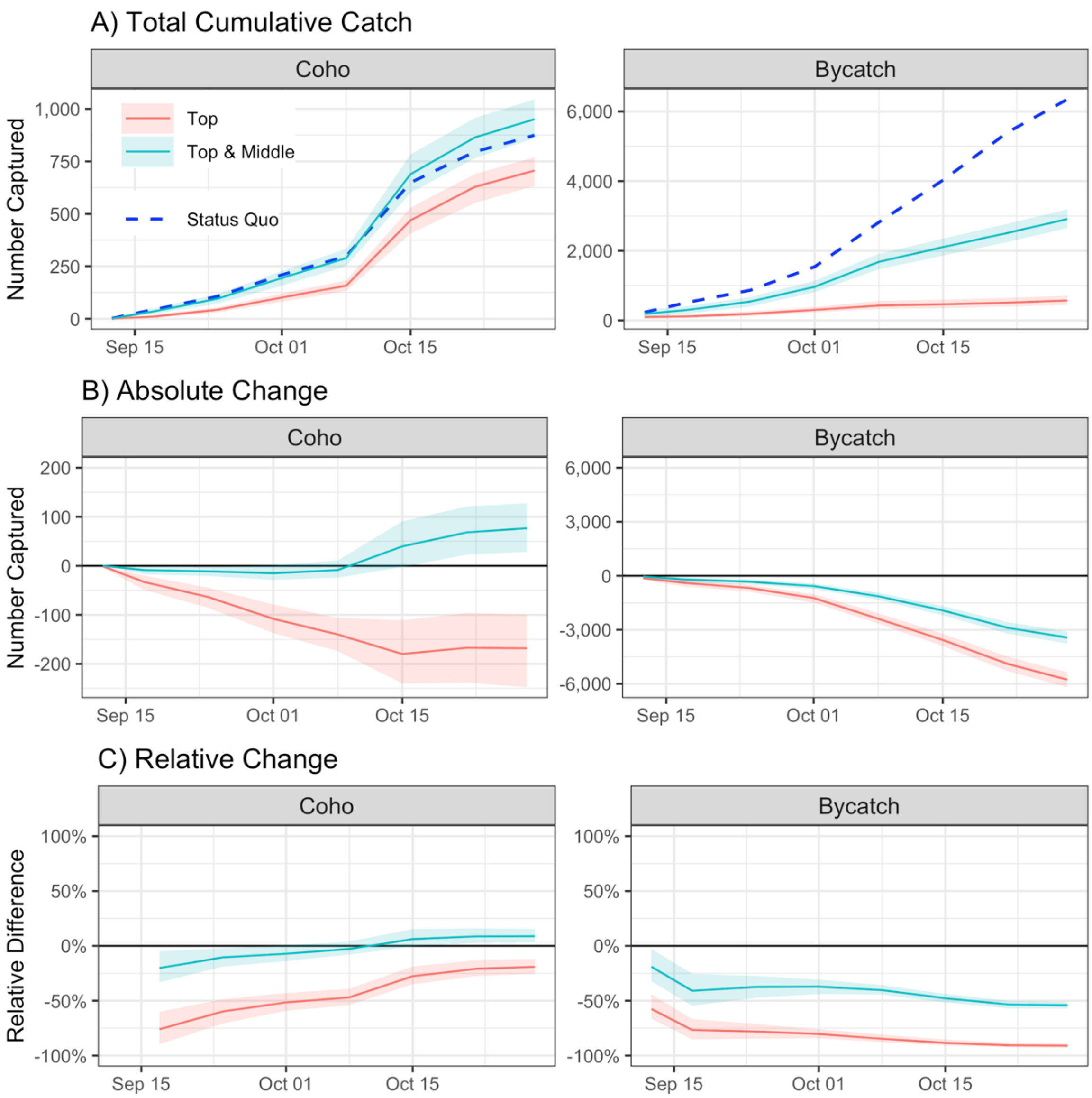


Figure E3. Predicted daily Coho and bycatch by date using revised net the full net deployment depth (i.e., "status quo") or using depths that correspond to the Top or Top and Middle portions of the Bennett (1999) deployment. Predicted catches were summarized as (A) total cumulative catch, (B) absolute change relative to the status quo deployment, and (C) percent change relative to the status quo deployment. Shading indicates the 95% confidence region.

Appendix F

Chilliwack River passive mark-recapture supplementary material

Estimating CV and target detection efficiencies

Estimating how CV changes over various detection efficiencies and straying rates can assist in developing target detection efficiencies that may guide array design and optimization. This exercise assumes that there is a 100 % detection efficiency at the second (hatchery) array, which is required to have an accurate population estimate. The two factors that we can most easily manipulate are the detection efficiency of the first array (subsequently referred to as array 1) and the number of PIT-tagged smolts released. Additionally, there is a large unknown in the proportion of hatchery fish that spawn in other tributaries and do not return to the hatchery (subsequently referred to as straying rate).

The data required to estimate CV are the expected number of PIT-tagged adults returning to the system, *m, c,* and *r.* The expected number of PIT-tagged adults returning can be estimated by the number of tagged smolts released multiplied by the smolt-to-adult survival rate (Coho Salmon that were not aged as 3_2 were removed from analysis). The smolt-to-adult survival rate can be estimated by calculating the average proportion of adult returns to the hatchery from the total smolt release (Table). It is assumed that PIT-tagged fish have the same survival and behaviour as non-tagged fish. The estimate of PIT tags in the system may be conservative (low) because not all fish are expected to return to the hatchery; therefore, the proportion of returned fish to the whole system is likely higher than the proportion that returned to the hatchery or were caught by the recreational fishery. Here, *m* is derived by multiplying the detection efficiency of array 1 by the number of expected PIT-tagged adults in the system from either a 10,000 or 20,000 tagged-smolts release. We calculated *r* by reducing *m* through the average recreational fisheries exploitation rate and a gradient of straying rates (0-0.99). lastly, *c* was the average number of hatchery swim-ins (Table).

A fully pooled (i.e., no stratification) Chapman's modified Petersen estimator was used to calculate the population size, variance (from direct hypergeometric equation), and subsequently the CV. Non-stratified data will typically result in a smaller CV, therefore, the results represent minimum target detection efficiencies or sample sizes.

Table F1. Hatchery releases of juveniles by brood year and their associated returns. Adult returns include all fish that entered the hatchery and would also represent n2, i.e., no fish below the swim-in channel were included in these counts. The recreational catch is the expanded total adult catch from creel surveys. The proportion returned is calculated by dividing the adult returns plus the recreational catch by the total releases. The expected PIT tags are a conservative estimate based on a release of 10,000 PIT-tagged juvenile releases multiplied by the proportion returned.

Brood Year	Total Releases	Adult Swim-ins (*c*)	Recreational Catch	Proportion Returned	Expected PIT tags
2007	1,182,421	28,465	6,363	0.0295	295
2008	1,240,041	26,304	8,749	0.0283	283
2009	1,268,080	34,997	11,577	0.0367	367
2010	1,141,748	40,944	14,972	0.0490	490
2011	969,477	26,716	6,171	0.0339	339
2012	839,984	10,606	5,956	0.0197	197
2013	836,291	17,866	7,872	0.0308	308
2014	798,351	13,789	2,869	0.0209	209
2015	863,557	39,980	8,178	0.0558	558
Average	1,015,550	26,630	8,079	0.0338	338

Results and Discussion

The general trend in CV is that it became less sensitive to changes in either detection efficiency of A1 or the proportion of adults returning to the hatchery (1- straying rate) if either was high (e.g., > 0.3; Figures Figure F1 and Figure F2). Biologically, it is expected that most of the hatchery Coho Salmon would return to the hatchery swim-in, so the target detection efficiency of array 1 can be focused on when the proportion of adults returning to the hatchery is larger than 0.5. When 10,000 PIT-tagged smolts are released and at least 50% of the run returns to the hatchery, a detection efficiency of 20% is required to obtain a CV of 15%. Conversely, when 20,000 PIT-tagged smolts are released and the hatchery return is 50%, the detection efficiency may only need to be 10% to obtain a CV of 15%. A more plausible scenario is that the proportion of adults returning to the hatchery is 80% or higher; in this scenario, detection efficiencies of only 8% and 4% are required to obtain a CV of 15% for releases of 10,000 and 20,000 PIT-tagged smolts, respectively.

These results can assist in decisions around purchasing array components and during field testing in 2020 to determine if subsequent adjustments will need to be made.

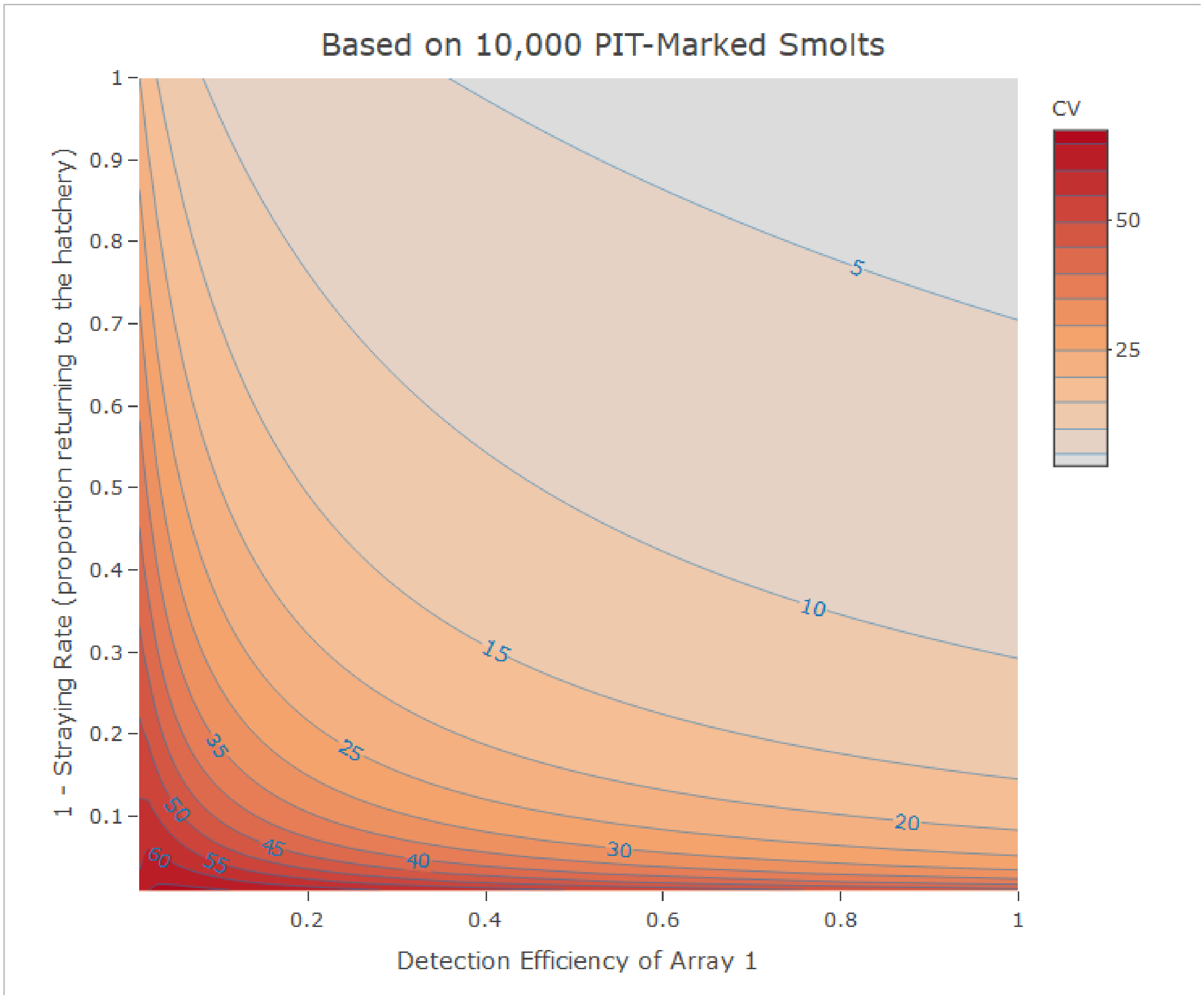


Figure F1. Contour plot of estimated average coefficients of variation (CV in %) at different detection efficiencies of array 1 and proportions of adult fish returning to the hatchery (as opposed to straying to other tributaries) for a PIT-tagged smolt release of 10,000.

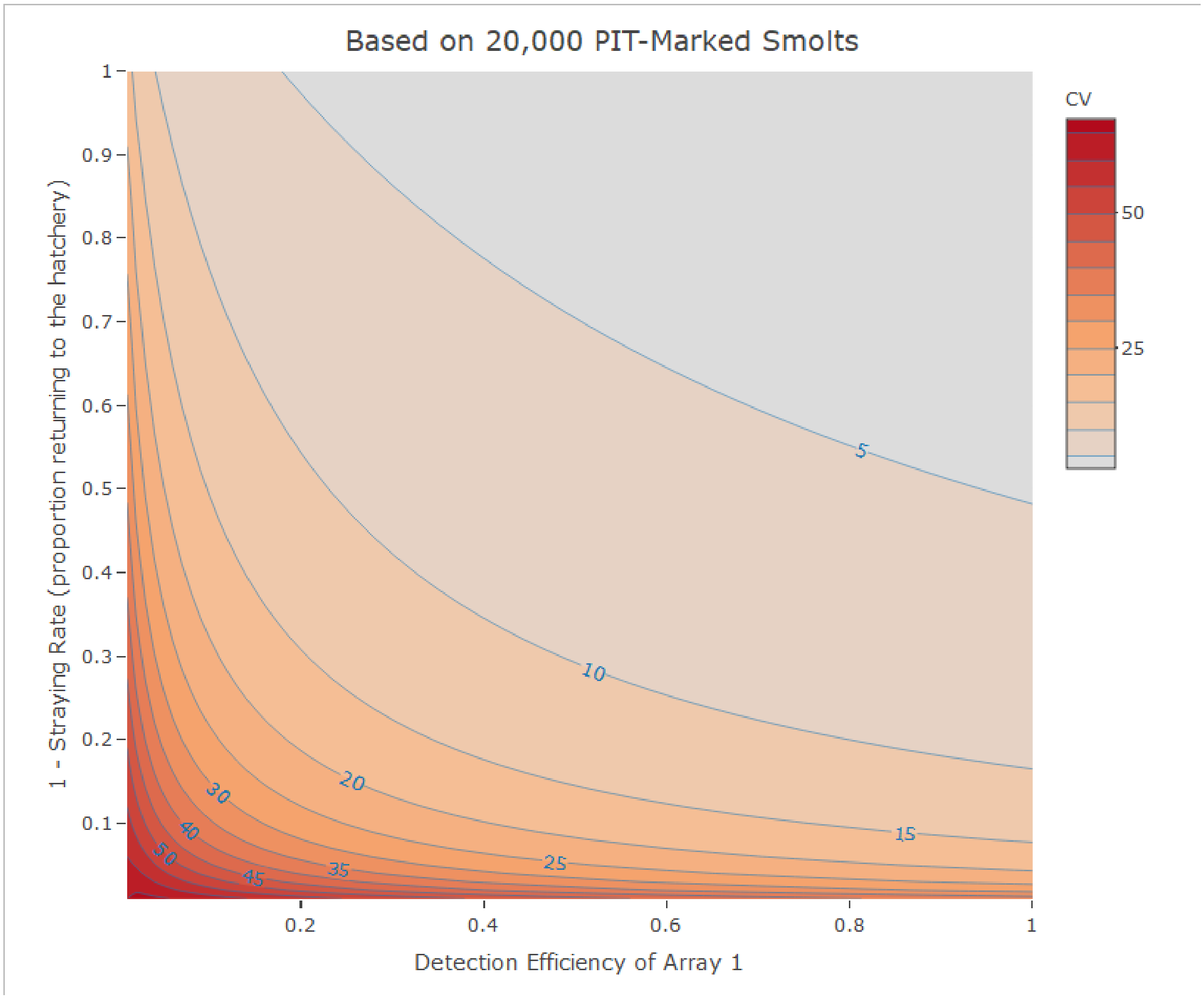


Figure F2. Contour plot of estimated average coefficients of variation (CV in %) at different detection efficiencies of array 1 and proportions of adult fish returning to the hatchery (as opposed to straying to other tributaries) for a PIT-tagged smolt release of 20,000.