Addendum to SRWG Reports for Peer Review Panel

Although the Sacramento River Fall Chinook (SRFC) Work Group (SRWG) had limited time to meet between the adoption of peer review Terms Of Reference (TOR) and the document deadline for the peer review itself, the SRWG did identify a few minor corrections to make to the reports submitted in November 2025 and has generated a small amount of new material that may be relevant to topics raised in the peer review TOR.

Specifically, the November 2025 progress reports took as a given the Council's direction to derive a natural-area S_{MSY} based on the formula $S_{MSY}=F_{MSY}xS_{MP}$ and therefore did not describe the background and rationale for that approach, which are briefly summarized in this addendum. The SRWG also provided some small refinements to its discussions of some data sources, and given attention in the TOR to issues around temporal coverage the SRWG added some discussion of temporal patterns in residuals in the dataset with the longest temporal coverage and explored sensitivity to a model formulation with autocorrelated process error.

Further description of the need for an indirect approach to S_{MSY}

As noted by the SRWG (June 2024, particularly Appendix A of that report) and Scientific and Statistical Committee (SSC, June 2024), the theoretical basis for S_{MSY} calculation can only strictly apply to a natural stock free of hatchery influence. This is not a novel observation, for example the environmental analysis for Amendment 16 to the Fishery Management Plan (FMP, PFMC/NMFS 2011, p. 56) stated "stock/production relationships and MSY concepts that are fundamental to the management of natural stocks do not apply to hatchery stocks" and the Salmon Technical Team (STT 2005) explicitly stated in their derivation of S_{MSY} for Klamath River Fall Chinook (KRFC) that their approach required the assumption "Estimates of spawning stock and recruitment are representative of a natural stock that can be considered independent of hatchery influences." While this assumption does not hold strictly true for KRFC, the overall ratio of hatchery versus natural production in KRFC is generally substantially lower than for SRFC, and hatchery-origin KRFC are less likely to spawn in natural areas due in part to the absence of release practices that increase straying in SRFC (Sturrock et al. 2019), meaning that the effects of hatchery-origin fish on natural-area escapement and production are much lower in that system[1].

Fundamentally, S_{MSY} is a theoretical concept that requires a closed system in equilibrium[2]. While elaborations exist that allow for consideration of stochasticity and/or age

[1] For instance, the estimated proportion hatchery-origin on the Klamath River mainstem between Iron Gate Dam (in place at the time) and the Shasta River confluence from 2001-2019 ranged from 1%-48% with mean 26% (Gough et al. 2020), and hatchery-origin spawners made up <1%-39% with mean 6% of natural-area spawners on the Shasta River for 2002-2023 (Giudice and Kang 2024). This compares to summed natural-area escapements for SRFC as a whole for 2010-2021 ranging from 53%-78% with mean 69% hatchery-origin (Satterthwaite 2023, his Appendix A, calculation restricted to natural-area spawners rather than basin totals including hatchery returns).

[2] While even purely wild salmon populations have some degree of straying, natural strays typically do not make up a major fraction of escapement in populations distinct enough to be managed as "stocks".

structure, applying MSY theory to a Pacific salmon life history fundamentally assumes that spawners, recruits, and yield can be defined in such a way that S_{MSY} spawners will produce R_{MSY} recruits, of which $Y_{MSY}=F_{MSY}xR_{MSY}$ can be harvested (broadly defined to include non-landed fishing mortalities) leaving an escapement of $(1-F_{MSY})xR_{MSY}=S_{MSY}$ spawners in the next generation, allowing this closed-loop cycle to repeat indefinitely.

In the case of SRFC, this logic breaks down for (at least) two reasons. SRFC consists of a mix of natural-origin fish spawning in natural areas, natural-origin fish entering hatcheries and lost to natural spawning, hatchery-origin fish spawning in natural areas, and hatchery-origin fish returning to hatcheries. By definition, natural-area spawners produce natural-origin recruits. However, not all unfished natural-origin recruits will become natural-area spawners, because some natural-origin spawners will enter hatcheries and be lost to the natural spawning population. In addition, many hatchery-origin spawners will stray into natural areas. This means that simple closed-loop calculations and derivations cannot apply. Similarly, yield will be heavily influenced by harvest of hatchery-origin fish.

The SRWG is unaware of any model formulations that would allow incorporation of hatchery dynamics into a theoretically sound derivation of a natural-area S_{MSY}, noting that Council direction indicated S_{MSY} should be expressed in natural-area spawners[3]. Even if hatcheries could somehow be directly incorporated into a new theoretical model, hatchery dynamics are not driven by natural-area spawners (though are unlikely to be completely independent, as low total escapements may mean inadequate egg availability at hatcheries), and are especially difficult to model in a system like SRFC where there are ongoing and planned changes in hatchery practices (e.g. increased production of enhancement smolts, variable use of trucking, and greatly increased fry releases [Anonymous 2024, particularly Section 4]) whose implementation into the future are uncertain and whose effects cannot be predicted from available data at this time.

Further description of the choice of a Ricker and $S_{MSY}=F_{MSY}xS_{MP}$

The Council's November 2024 Decision Summary specifically instructed the SRWG to "use the F_{MSY} value adopted under Agenda Item F.2 Salmon Methodology Review to derive an updated S_{MSY} value per the formula described in Agenda Item F.2, Attachment 2". The referenced formula is $S_{MSY}=F_{MSY}xS_{MP}$, an analytical result that can be derived from the mathematical formulation of a Ricker as applied to a semelparous organism that is harvested prior to spawning (e.g., Pacific salmon).

[3] Specifically, the second bullet point under "Sacramento River Fall Chinook Workgroup Progress Report and Recommendations" in the November 2024 decision summary document stated that S_{MSY} should be expressed in natural-area spawners. Further, p. 6 of the FMP states (*emphasis added*): "Stocks designated as hatchery stocks rely on artificial production *exclusively*, while those designated as natural stocks have at least some component of the stock that relies on natural production, although hatchery production and *naturally spawning hatchery fish may contribute to abundance and spawning escapement estimates*."

The SRWG's initial report (June 2024) described the challenges to defining S_{MSY} for a composite hatchery-natural stock and presented many potential alternatives for defining an escapement goal, with some discussion of the relative merits and drawbacks of each approach. The SSC's (June 2024) comments on that report stated:

The SSC recommends the S_{MSY}, F_{MSY}, conservation objective, and other reference points for SRFC be developed for natural-origin fish only. In the interim, some updates can be completed in a short period of time. The SSC recommends that the currently used proxy value for F_{MSY} be updated using recent data from other Chinook stocks that are representative of the SRFC stock under current conditions. The SSC also recommends that S_{MSY} and the CO be updated using one of the indirect approaches proposed by the WG.

The STT (June 2024) recommended "refocusing on management measures that are based on MSY but take into account other factors to achieve OY, consistent with the National Standard 1 guidelines" and recommended against a natural-origin objective because implementing one could be difficult. The STT (June 2024) agreed with the SRWG that available data sources could allow estimation of the natural-area escapement maximizing natural-origin production and stated that it was "supportive of identifying a reasonable ratio between S_{MSY} and S_{MSP} to inform a data-based estimate of S_{MSY}" but did not define what a reasonable ratio was or how it should be determined.

In a progress report update (SRWG November 2024a), the SRWG noted that under a Ricker spawner-recruit relationship, the ratio between S_{MSY} and S_{MP}[4] is F_{MSY}, and separately the SRWG proposed a path to updating the proxy value for F_{MSY} that is used for SRFC. The observation that $S_{MSY}=F_{MSY}xS_{MP}$ for a Ricker is not a novel insight by the SRWG (and in fact it serves as the basis for the Grays Harbor coho S_{MSY} and likely explains the ratio between the undocumented conservation objective and S_{MSY} for Willapa Bay Fall Chinook [PFMC 2024]), however it does seem to be somewhat under-appreciated by U.S. West Coast salmon managers[5]. The SRWG produced a mathematical proof re-confirming this relationship (SRWG November 2024b), under a Ricker spawner-recruit relationship. The same ratio would not necessarily hold under an alternative spawner-recruit formulation, and not all spawner-recruit formulations even have discrete maximum values to apply a ratio to as "supported" by the STT.

The SRWG (November 2024a) noted that a Ricker is not the only plausible form to a spawner-recruit relationship, and the available data gave little support either way for choosing between a Ricker versus the most common alternative, a Beverton-Holt; and other functional forms are also plausible (e.g. Munsch et al.[2020] took a nonparametric GAM approach). The

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[4] The S subscript for sustainable is needed for yield Y but not production P, thus S_{MSP}, S_{MP}, and S_{MAX} all refer to the escapement that maximizes production in different documents.

[5] When asked about this, a salmon stock assessment scientist and professor from Alaska replied "In general, while I would think salmon SRA folks generally know this is the case, I can't think of a single publication that states this explicitly."

SRWG (November 2024a, pp. 2-3) noted that "this challenge of choosing among functional forms for spawner-recruit relationships is not unique to SRFC, and particularly welcome[d] insight from the SSC into the scientific merits of alternative approaches to this challenge, and from the STT on the precedents for how this challenge has been addressed for other stocks." Neither advisory body provided a direct response to this query. The SSC[6] (November 2024a) reiterated that "concepts such as S_{MSY} and F_{MSY} are not applicable to a composite stock because production may be largely or entirely decoupled from spawning abundance" but "S_{MSY} and F_{MSY} do have a sound theoretical basis for the natural-origin component of the stocks, and the SSC supports the SRWG's efforts to estimate these quantities (or appropriate proxies, see Agenda Item F.2.a Supplemental SSC Report 1). Available data for SRFC limit the ability to identify spawners of natural-origin and therefore the SSC supports the SRWG proposals to measure S_{MSY} in terms of natural-area spawners." Separately, the SSC (November 2024b) endorsed an updated F_{MSY} proxy for SRFC and its application within the equation $S_{MSY}=F_{MSY}xS_{MP}$ and the STT (November 2024) also recommended adoption of the updated F_{MSY} proxy.

Since there was no direct response to the SRWG's query about how the problem of choosing an appropriate functional form was approached for other PFMC-managed stocks, the SRWG conducted a literature review of Chinook salmon S_{MSY} reference points and their justifications as reported in Table 3-1 of the FMP (PFMC 2024) and possibly updated in the most recent Table A-1 of Preseason Report 1 (PFMC 2026), summarized in Table 1 below. Given questions around sample sizes and appropriate year ranges to inform reference points, the SRWG also compiled the range of years for the data informing each Chinook salmon reference point.

Other than SRFC, a total of 16 Chinook salmon stocks have S_{MSY} values defined for use in PFMC management. For four Washington Coastal spring/summer Chinook stocks, no explanation or citation was provided[7] for the S_{MSY} value. For Central and Northern Oregon Chinook, S_{MSY} is expressed in fish per mile rather than a total escapement. Hoko Summer/Fall Chinook have an S_{MSY} value that was derived by multiplying miles of stream used by a redds per mile value from coastal Washington streams and an assumption of 3 fish per redd (Ames and Phinney 1977[8]). Of the remaining ten stocks, nine used a Ricker (two cases using one or two covariates, seven cases without covariates). For the cases where a Ricker was used, in a few instances there was some comparison with a Beverton-Holt and in one case also a Shepherd formulation, with some quantitative and/or qualitative explanation of the decision to use a Ricker, but in most cases a Ricker was the only formulation presented. The last case, Willapa

[6] Although the chair of the SRWG is currently a member of the SSC, as reported in the November 2024 SSC minutes, he was recused from the SSC's review of both the SRWG progress report and SRWG materials reviewed in the Salmon Methodology Review.
[7] The SRWG recommends reaching out to current and former STT members, SAS members, Salmon Amendment Committee members, and Council salmon staff officers to obtain documentation of these reference points before the institutional memory of how they were derived is permanently lost.
[8] This document is cited in the FMP but does not appear to be available online. A pdf copy was obtained from STT vice-chair Jon Carey.

Bay Fall Chinook, has a conservation objective of 4,350 but no explanation or citation for that conservation objective is provided in the FMP beyond it being the "WDFW spawning escapement objective". That stock uses a proxy value of 0.78 for F_{MSY}, and its S_{MSY} value is 3,393. 3,393 is exactly 78% of 4,350. Thus, the SRWG strongly suspects, but cannot confirm, that 4,350 was likely treated as an estimate of S_{MP} and then the logic that $S_{MSY}=F_{MSY}xS_{MP}$ was applied, similar to how it was directly stated (assuming F_{SMY} is a typo for F_{MSY}) to be used for Grays Harbor coho (PFMC 2024).

Given this extensive precedent for the use of Ricker spawner-recruit relationships for Chinook salmon within the PFMC's salmon FMP, and the lack of strong support for an alternative formulation, the SRWG deemed it appropriate to use a Ricker to implement the Council's direction to apply a formula that was derived from a Ricker.

Table 1. Basis of Chinook salmon S_{MSY} values used in PFMC management (for stocks other than SRFC).

Stock	Method	Years Used to inform S_{MSY} estimate
Klamath River Fall Chinook	Ricker with early life survival covariate	Brood years 1979-2000 (STT 2005). Note that a more recent spawner-recruit analysis was performed by the Klamath River Fall Chinook Work Group (KRWG 2024) but this more recent information is not used to inform the reference points in use.
Southern Oregon Chinook	Ricker with survival and flow covariates	Brood years 1980-2004 (Confer and Falcy 2014[9]).
Central and Northern Oregon Chinook	Fish per mile in index streams	Unknown, but cited source documents (which could not be found) were published in 1982 or earlier (Thopmson 1977, McGie 1982).
Willapa Bay Fall Chinook	Not directly stated why, but S_{MSY}=0.78 x conservation objective. 0.78 is the F_{MSY} proxy. Basis of conservation objective is not provided.	Unknown, no explanation or citation provided.
Grays Harbor Fall Chinook	Ricker*	Brood years 1986-2005 (QDNR and WDFW 2014).
Queets Fall Chinook	Ricker	Brood years 1968ish to 1977ish, Cooney (1984)[10] describes "years" used but does not specify brood years vs return years vs other definitions.
Hoh Fall Chinook	Ricker	Brood years 1968ish to 1977ish, Cooney (1984) describes "years" used but does not specify brood years vs return years vs other definitions.
Quillayute Fall Chinook	Ricker	Brood years 1968ish to 1977ish, Cooney (1984) describes "years" used but does not specify brood years vs return years vs other definitions.

[9] This document is not cited by the FMP, but was the source of the S_{MSY} value adopted as a result of the 2014 Salmon Methodology Review.

[10] This document is cited in the FMP but does not appear to be available online. A pdf copy was obtained from Chuck Tracy, retired PFMC staff.

Hoko Summer/Fall Chinook	23.6 miles x 12 redds per mile x 3 fish per redd*	Unknown, but source document was published in 1977 (Ames and Phinney 1977[11]).
Grays Harbor Spring Chinook	Unknown	Unknown, no explanation or citation provided.
Queets Sp/Su Chinook	Unknown	Unknown, no explanation or citation provided.
Hoh Spring/Summer Chinook	Unknown	Unknown, no explanation or citation provided.
Quillayute Spring/Summer Chinook	Unknown	Unknown, no explanation or citation provided.
North Lewis River Fall Chinook	Ricker	Brood years 1964-1982 (McIsaac 1990 as cited in CTC [1999])
Columbia Upper River Bright Fall Chinook	Ricker (inferred due to inclusion in PFMC/NMFS [2011] compilation of alpha values from Rickers)	Although source document (Langness and Reidinger 2003[12]) could not be located, is based on brood years 1964-1991 according to PFMC/NMFS (2011).
Columbia Upper River Summer Chinook	Ricker [AR(1) variant]	Brood years 1979-1995 (CTC 1999).

* Note that the descriptions given in FMP Table 3-1 do not match the cited documentation for Grays Harbor Fall Chinook or Hoko Summer/Fall Chinook. The methods reported here match the cited source documents.

[11] This document is cited in the FMP but does not appear to be available online. A pdf copy was obtained from STT vice-chair Jon Carey.

[12] This document is cited in table 3-1 of the FMP but does not appear in the FMP's list of references cited. It is cited in PFMC/NMFS (2011) with bibliographic information provided there. The SRWG was unable to obtain a copy.

Additional Discussion of Datasets in 'Sacramento River Fall Chinook Workgroup Progress Report From November 2025 As Updated and Streamlined For S_{MSY} Peer Review Panel'

RBDD Passage dataset

There is an additional subtlety to interpretation of the Red Bluff Diversion Dam (RBDD) passage dataset as a metric of natural-origin production that should be acknowledged. For brood years 2006-2020, the effects of releases from Coleman National Fish Hatchery could be fully accounted for by expanding the number of marked hatchery-origin fish recovered to account for the expected number of unmarked hatchery-origin fish from that same release group, based on a known marking rate. Prior to brood year 2006, this calculation was not performed. However, in most years the majority of Coleman National Fish Hatchery releases passing RBDD fell within the spring run length-at-date category (Voss and Poytress 2022), and so this is a more significant issue for estimates of spring run RBDD passage than for fall run, and brood years back to 2002 were considered appropriate to include in the spawner-recruit analysis reported in the SRFC rebuilding plan (PFMC 2019). Nevertheless, the SRWG wishes to acknowledge this confounding of the earlier years included in the RBDD dataset. If the RBDD spawner-recruit fitting exercise with flow covariate is repeated with brood years 2002-2005 excluded, the information from the two highest escapement years is lost, the estimate of S_{MP} is reduced from 393,544 to 358,262 and is outside the range of the input data (Figure 1).

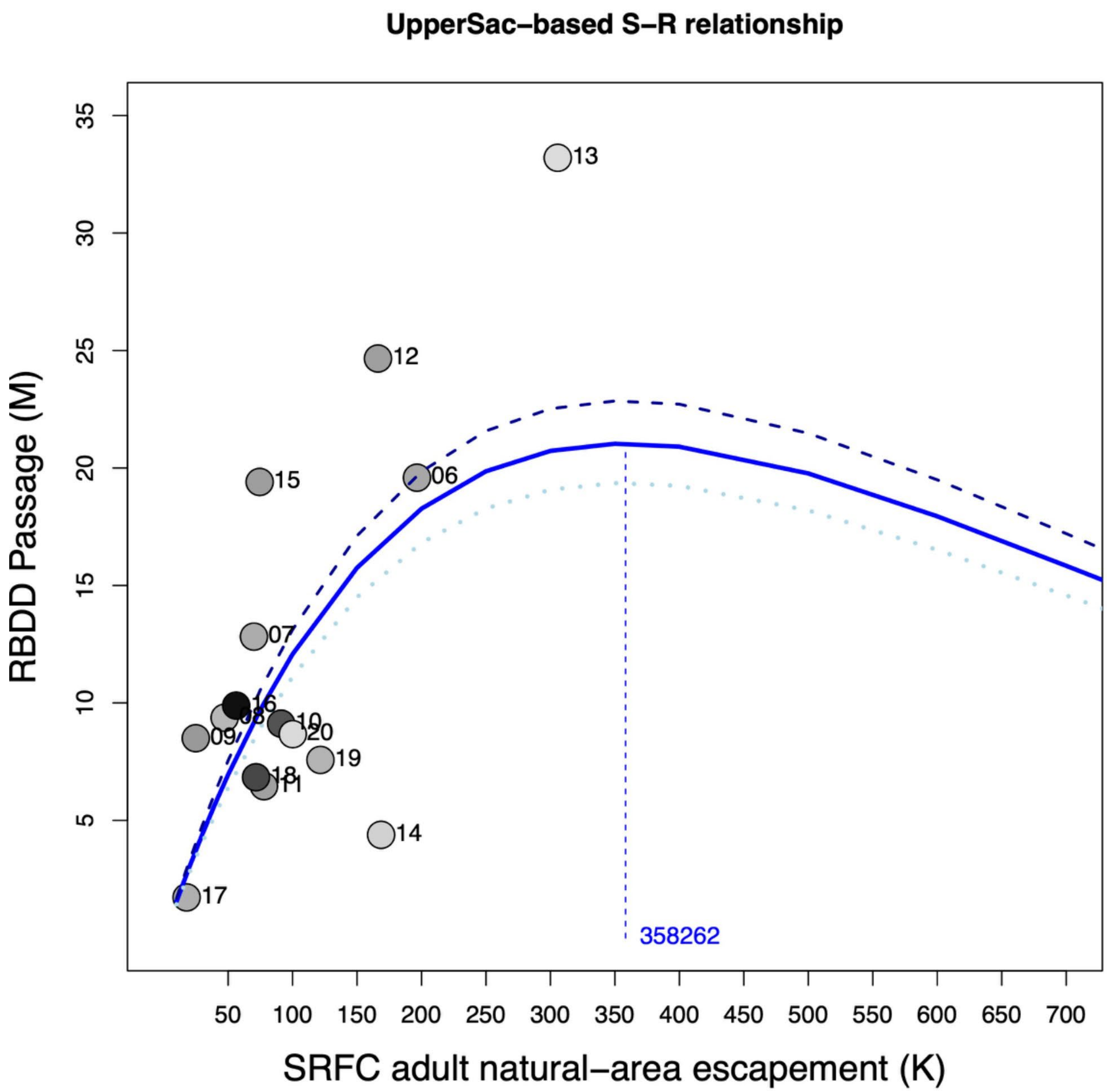

Figure 1. Spawner-recruit relationship for the Upper Sacramento juvenile abundance index, brood years 2002-2005 excluded. The solid curve represents the fitted relationship at the mean value of the flow covariate, dotted curves represent relationships when the flow covariate is one standard deviation above or below its mean. Annual values are labeled by brood year, darker shading indicating a higher value of the flow covariate.

Additional year of escapement composition estimates

White et al. (2026) reported the estimated composition (hatchery- or natural-origin) of SRFC escapement in 2022, which would allow the addition of brood year 2019 to the natural-adjusted SI analysis (see Appendix G of November 2025 Progress Report) if it is assumed that all adult SRFC are either harvested or return to spawn at age-3. Adding brood year 2019 to the analysis would reduce the estimate of S_{MP} by 0.3%. Further extending this approach to more recent return years would only be possible in the presence of sufficient genetic sampling to characterize the contributions of unmarked fry releases beginning in brood year 2021 and thus first showing up as jacks/grilse in 2023.

Comparisons across recruitment datasets

As noted in the main text of the SRWG's November 2024 progress report (SRWG November 2024a), the correlation between the Munsch et al. (2020) fry index and the cohort reconstruction is modest (Figure 2). Some prominent outliers include brood year 2016 (estimated to be relatively more productive in the cohort reconstruction) and brood years 2013 and 2015 (estimated to be relatively less productive in the cohort reconstruction). According to the Habitat Committee's (HC 2023) assessment of conditions for these brood years, brood year 2016 was characterized by unusually good conditions in the Delta and high access to floodplain habitat (Figure 3). The former would be expected to result in more ocean abundance for a given level of fish leaving the main river, while the latter might be expected to reduce the proportion of outmigrants still within the "fry" size cutoff (<55mm) when sampled. Brood years 2013-2015 were characterized by unfavorable ocean conditions (particularly SSTarc, Figure 4) which may have reduced ocean survival in a way that may be unlikely to be driven by density-dependence solely among natural-origin SRFC.

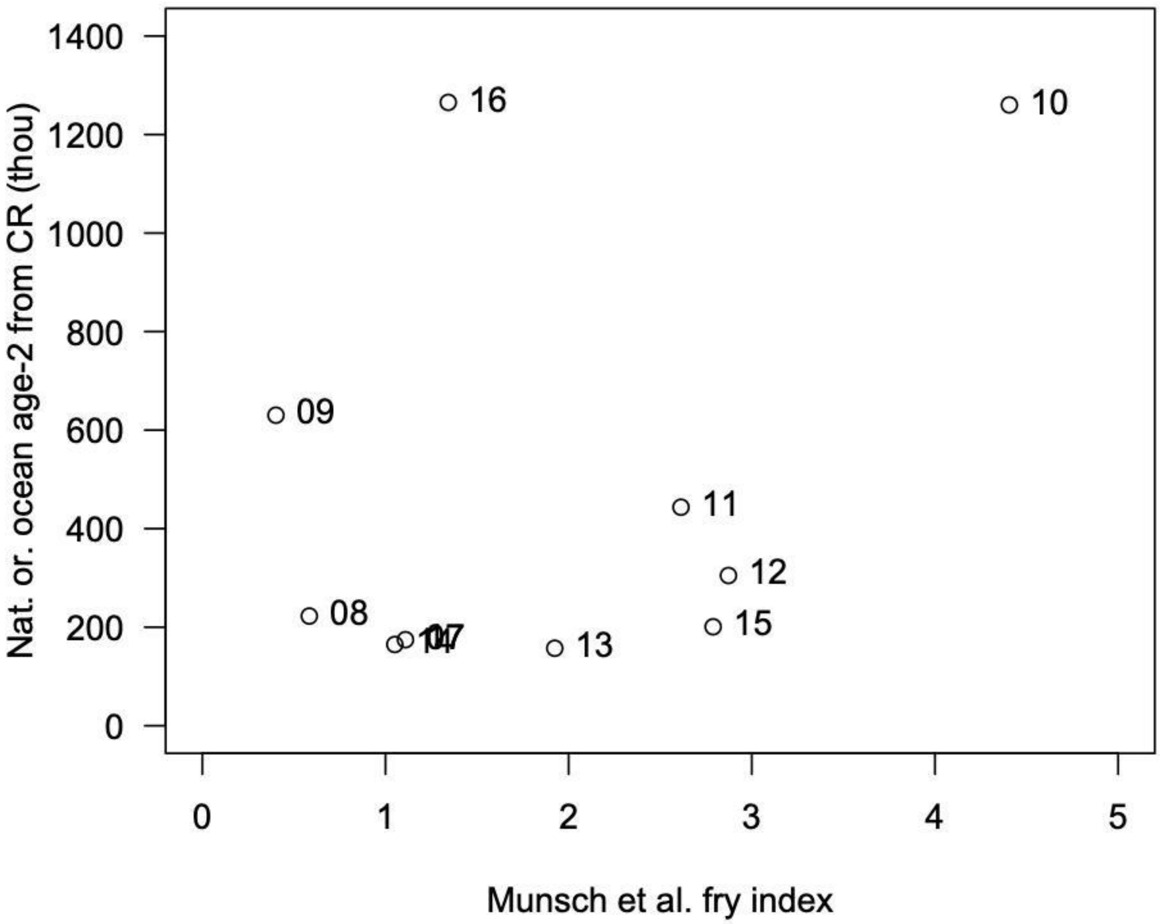

Figure 2. Correlation between estimated recruitment from the Munsch et al. fry index compared to natural-origin ocean age-2 abundance prior to fishing as derived from the cohort reconstruction, for brood years that could be analyzed using both methods. Points are labeled by brood year.

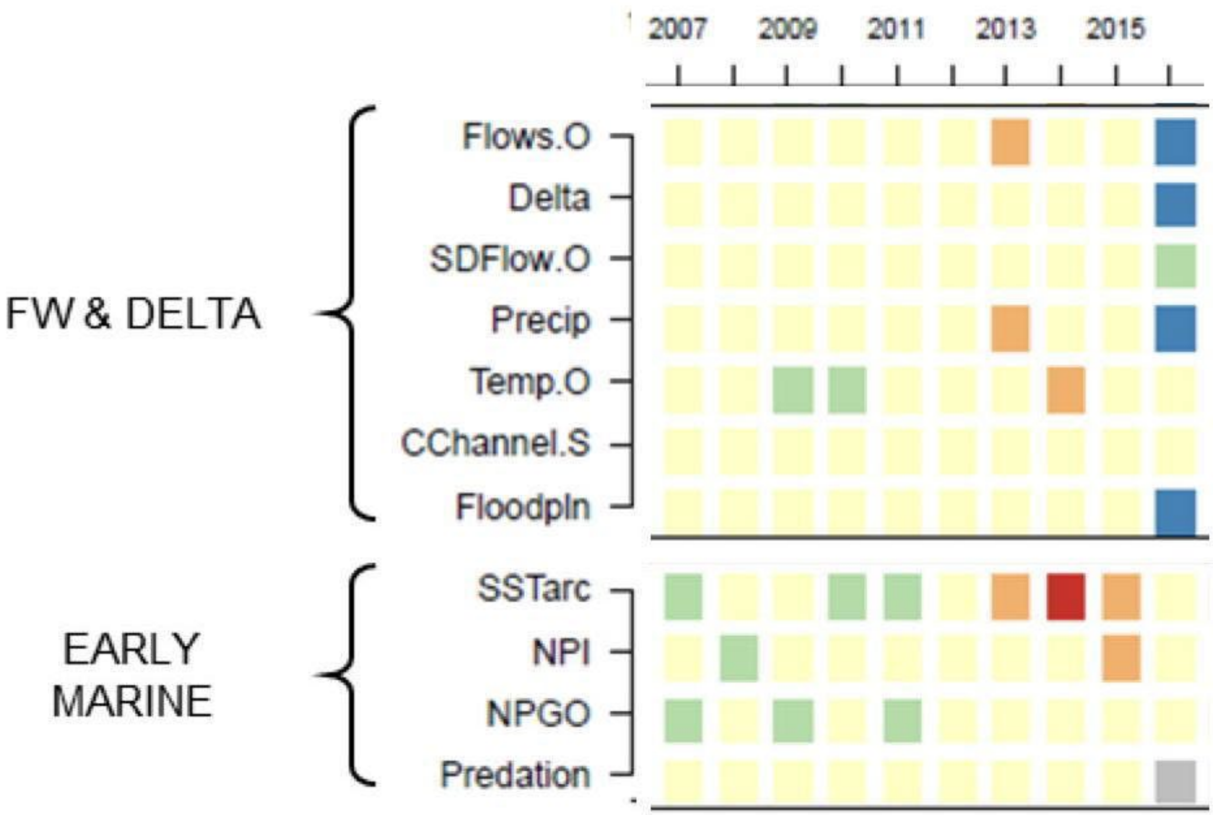

Figure 3. Habitat conditions hypothesized to affect SRFC productivity as reported in HC Report 1, March 2023. Columns are labeled by brood years. Yellow squares indicate near-average conditions, while green and blue represent increasingly favorable conditions while orange and red indicate increasingly unfavorable conditions. Grey indicates missing data. Note that the color scheme is based on standard deviations and thus may not do a good job of capturing low values from distributions that are highly skewed with the possibility of taking on very large values.

While the Munsch et al. fry index is based only on fry-sized (<55mm) fish, the RBDD juvenile index (Voss and Poytress 2022) includes juveniles of all sizes, with larger smolts adjusted to "fry equivalents" based on relative survival. Overall, the two indices gave broadly similar estimates of S_{MP} (at least relative to the uncertainty associated with any of these estimates, and in terms of being substantially larger than the S_{MP} suggested by the cohort reconstruction dataset) and gave year-specific estimates that were well-correlated in most years (Figure 4, overall r=0.63, r=0.77 with severe drought brood year 2013 excluded). In general, the two indices tended to diverge the most in low flow years, when the RBDD index seemed to indicate higher productivity than the Munsch et al. index. This is consistent with the pattern that would be expected from flow-dependent natural mortality during migration downstream from RBDD but before leaving the river system entirely. The SRWG could not identify a plausible hypothesis for why this apparent flow-related mortality would be density-dependent in a way that depends only on natural-origin fry abundance.

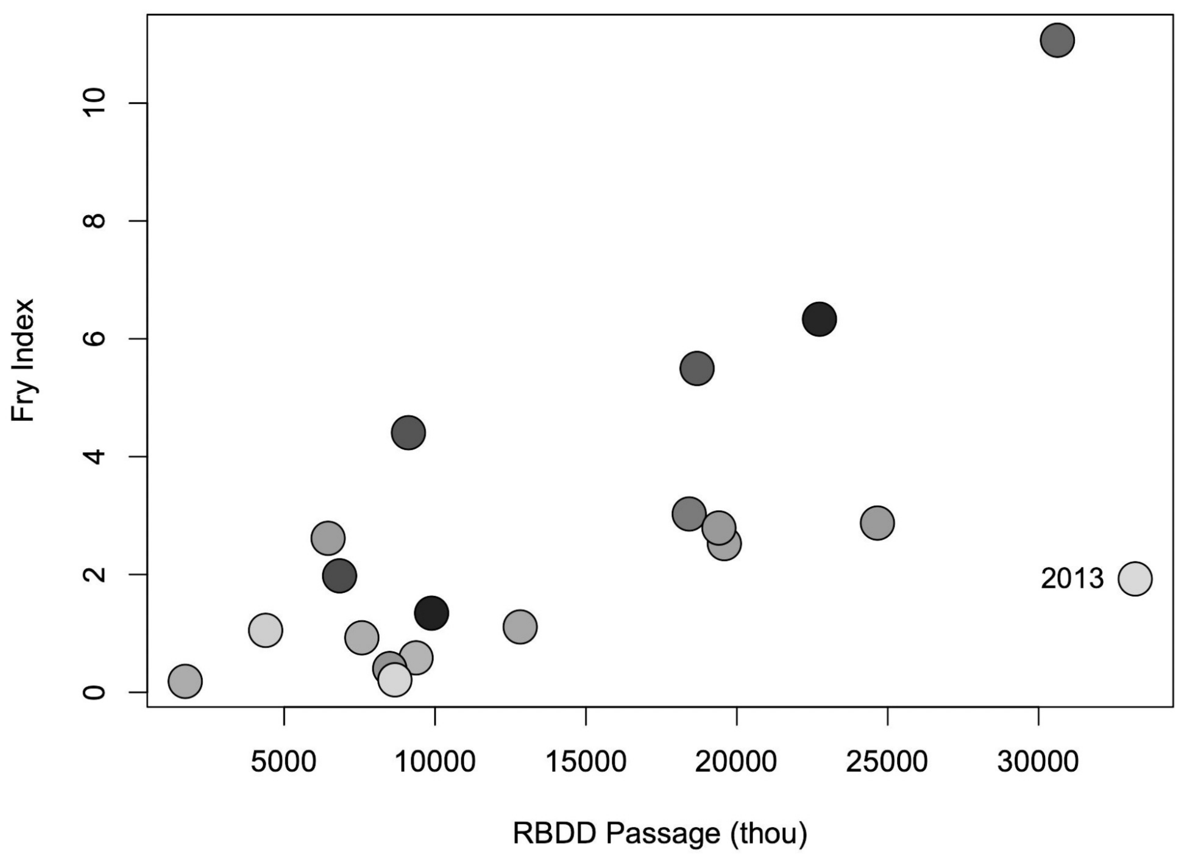

Figure 4. Munsch et al. fry index versus RBDD passage index for common brood years. Darker fill indicates higher flow conditions during outmigration. The point in the lower-right corner is brood year 2013, characterized by particularly low flow during outmigration.

Timeseries modeling approach to Spawner-Recruit fitting of Munsch et al. juvenile production index

Even after accounting for flow, there does seem to be autocorrelation in the residuals from the Munsch et al. model fit, but there does not appear to be a distinct, persistent step function as might be expected under a "regime shift" (Figure 5).

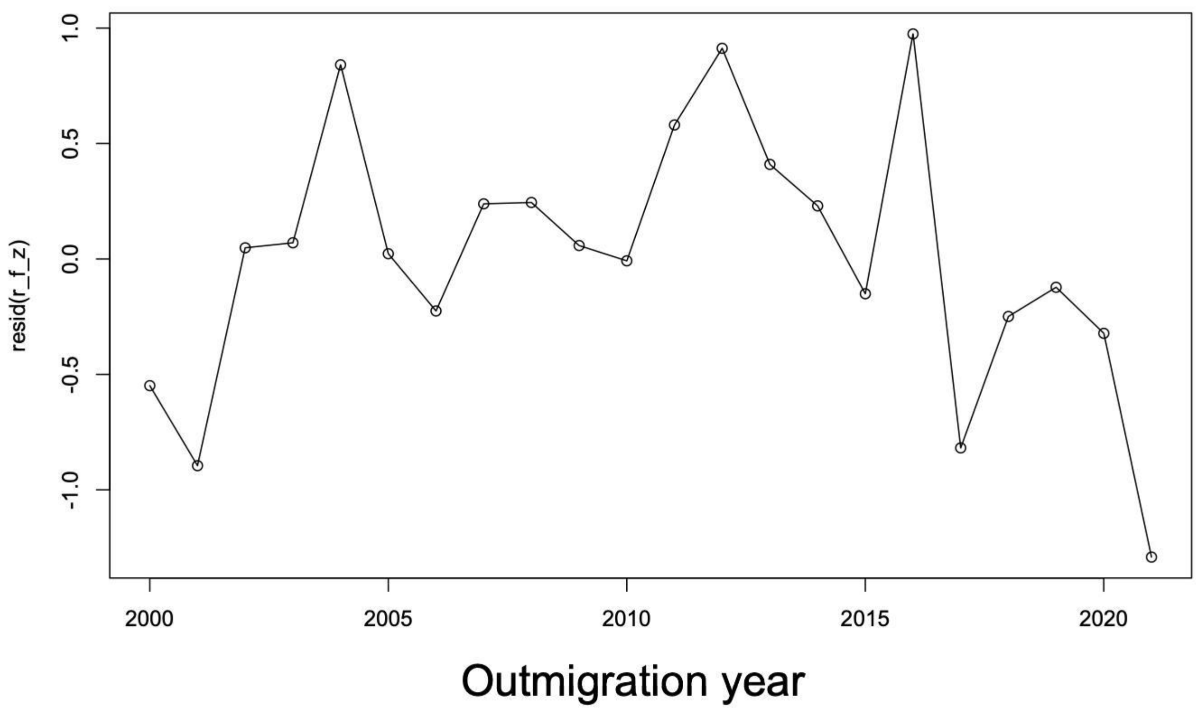

Figure 5. Residuals from Ricker fit to Munsch et al. fry index with flow covariate, by water year (outmigration year). Note indexing by water year, not brood year.

Wor et al. (2025) note that models with time-varying productivity are generally more tractable than models with time-varying capacity, and note that estimation of productivity and capacity are not independent. When justified by a mechanistic hypothesis, they suggested consideration of models where productivity is modeled as time-varying, as this may improve the estimation of capacity. Time-varying productivity is functionally similar to a first-order autoregressive modification of the SRWG's previously used model since ε effectively acts as a density-independent multiplier:

$$log(R_t) = log\left(\alpha S_t e^{-\beta S_t}\right) + f z_t + \rho\varepsilon_{t-1} + \varepsilon_t$$

where R = recruits, S = spawners, α represents intrinsic productivity, β measures the strength of density dependence and is the inverse of capacity (i.e., recruitment is maximized at 1/β and so

S_{MP}=1/β), *f* is a parameter describing the effect of flow (larger *f* = stronger effects of flow), *z* is the flow index transformed to have mean 0 and standard deviation 1, and ε is an error term assumed to be normally distributed in log space with mean 0 and lag-1 autocorrelation ρ. Fitting this model to the Munsch et al. juvenile production index decreased the estimate of mean productivity (alpha) by 9%, decreased the log-scale flow effect from 0.523 to 0.465, and increased the estimate of S_{MP} from 496,980 to 539,932 with 95% confidence interval 259,661-infinity. The SRWG did not attempt fitting this model to datasets with shorter temporal coverage.

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Supplementary materials:

Input file for AR-1 model (save as "SRfitting_data.csv" in working directory)

```
Brood.Yr,Spawners,Recruits,flow,RPS
1999,357606,2.412794,0.446548,6.74707E-06
2000,369962,1.001467,-0.589387,2.70695E-06
2001,539376,3.477835,-0.08140015,6.44789E-06
2002,684226,5.496279,0.8542736,8.03284E-06
2003,414644,11.0676,0.6388201,2.66918E-05
2004,206230,3.026538,0.2577683,1.46755E-05
2005,214860,6.332354,2.098677,2.9472E-05
2006,196489,2.523694,-0.4478281,1.28439E-05
2007,70072,1.10913,-0.5456973,1.58284E-05
2008,47316,0.5842321,-0.7515642,1.23475E-05
2009,24948,0.4021344,-0.2010693,1.61189E-05
2010,91126,4.406087,1.028593,4.83516E-05
2011,77854,2.613268,-0.3551712,3.35663E-05
2012,166233,2.872366,-0.3232398,1.72792E-05
2013,305635,1.924141,-1.374569,6.29555E-06
2014,168667,1.050994,-1.193305,6.23118E-06
2015,74504,2.788777,-0.2794978,3.74312E-05
2016,56297,1.342855,2.218739,2.3853E-05
2017,17851,0.1851182,-0.6116502,1.03702E-05
2018,71689,1.976451,1.223834,2.75698E-05
2019,121629,0.92507,-0.6647328,7.60567E-06
2020,100169,0.2111811,-1.348141,2.10825E-06
```

R code for AR-1 model

```
library("nlme")

dat=read.csv("SRfitting_data.csv")


ar_sr_mod=gls(log(RPS)~Spawners+flow,data=dat,correlation=corAR1(0.5,form=~1))


ar_sr_mod


#Generalized least squares fit by REML

#  Model: log(RPS) ~ Spawners + flow

#  Data: dat

#  Log-restricted-likelihood: -32.87085


# Coefficients:

#  (Intercept)      Spawners          flow

# -1.096150e+01 -1.853940e-06  4.651818e-01


# Correlation Structure: AR(1)

# Formula: ~1

# Parameter estimate(s):

#      Phi

# 0.4170879

# Degrees of freedom: 22 total; 19 residual

# Residual standard error: 0.647266



summary(ar_sr_mod)


#Generalized least squares fit by REML

#  Model: log(RPS) ~ Spawners + flow

#  Data: dat

#       AIC      BIC    logLik
```

```
#  75.74169 80.46389 -32.87085

# Correlation Structure: AR(1)
# Formula: ~1
# Parameter estimate(s):
#      Phi
# 0.4170879

# Coefficients:
#                  Value  Std.Error   t-value p-value
#(Intercept) -10.961497 0.29242055 -37.48539  0.0000
#Spawners     -0.000002 0.00000102  -1.81934  0.0847
#flow          0.465182 0.12052144   3.85974  0.0011

# Correlation:
#         (Intr) Spwnrs
#Spawners -0.701
#flow      0.095 -0.120

#Standardized residuals:
#       Min         Q1        Med         Q3        Max
#-2.0012130 -0.2892963  0.1238749  0.4426721  1.6015586

#Residual standard error: 0.647266
#Degrees of freedom: 22 total; 19 residual


#confirm robustness to starting value of autocorrelationn
ar_sr_mod=gls(log(RPS)~Spawners+flow,data=dat,correlation=corAR1(0.8,form=~1))
#Coefficients:
#  (Intercept)      Spawners          flow
#-1.096150e+01 -1.853939e-06  4.651817e-01
```

#Correlation Structure: AR(1)

Formula: ~1

Parameter estimate(s):

Phi

#0.4170886

ar_sr_mod=gls(log(RPS)~Spawners+flow,data=dat,correlation=corAR1(0.1,form=~1))

#Coefficients:

(Intercept)   Spawners   flow

#-1.096150e+01 -1.853940e-06 4.651818e-01

#Correlation Structure: AR(1)

Formula: ~1

Parameter estimate(s):

Phi

#0.4170878

confint(ar_sr_mod)

2.5 %   97.5 %

#(Intercept) -1.153463e+01 -1.038836e+01

#Spawners   -3.851179e-06 1.433000e-07

#flow   2.289641e-01 7.013995e-01

1/3.851179e-06

259660.7