Agenda Item E.1.a
SRWG Report 1***(Electronic Only)***
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Sacramento River Fall Chinook Ad-hoc Workgroup Report

May 2024

Pacific Fishery Management Council
Sacramento River Fall Chinook Ad Hoc Workgroup

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LIST OF ACRONYMS

CDFW	California Department of Fish and Wildlife
ER	Exploitation Rate
ESA	Endangered Species Act
ESU	Evolutionarily Significant Unit
FMP	Fishery Management Plan
HCR	Harvest Control Rule
KRFC	Klamath River Fall Chinook
MSA	Magnuson-Stevens Act
MSST	Minimum Stock Size Threshold
MSY	Maximum Sustainable Yield
NMFS	National Marine Fisheries Service
NOAA	National Oceanic and Atmospheric Administration
NWFSC	(NMFS) Northwest Fisheries Science Center
ODFW	Oregon Department of Fish and Wildlife
OY	Optimum Yield
PFMC	Pacific Fishery Management Council
SHM	Sacrament Harvest Model
SI	Sacramento Index
SRFC	Sacramento River fall Chinook
SSC	(Council's) Scientific and Statistical Committee
STT	(Council's) Salmon Technical Team
SWFSC	(NMFS) Southwest Fisheries Science Center
TOR	Terms of Reference
TRH	Trinity River Hatchery
WCR	(NMFS) West Coast Region
WG	Workgroup

1 EXECUTIVE SUMMARY

The Sacramento River Fall Chinook (SRFC) Workgroup (WG) is guided by the Terms of Reference (TOR) document developed to outline the tasks and products needed for the Pacific Fishery Management Council (PFMC or Council) consideration when reviewing the management and stock assessment tools currently in place for SRFC. The WG has discussed multiple topics, including the current management framework, stock status, abundance estimation and forecasting, fisheries, harvest estimation, and models associated with SRFC. The WG also discussed environmental variables that may affect SRFC along with the accuracy and stability of management models.

Consistent with the TOR, the WG has identified areas of potential improvement for SRFC assessment and management through evaluation of the management measures currently in use (reference points, conservation objective, harvest control rule, see Section 10). Potential improvements to the current methods used to characterize abundance and harvest (the Sacramento Index, SI), and forecast abundance (the SI forecast) were also identified. The WG also noted recent poor performance of the model used to determine the exploitation rate (ER) resulting from proposed fisheries (the Sacramento Harvest Model, SHM), but did not identify alternative approaches and thinks other bodies are better suited to that task. The WG noted the importance of environmental effects on productivity, and the varying predictability of different environmental drivers, and discussed how environmental effects could be incorporated into models and/or management measures.

The WG acknowledges that the potential improvements identified thus far vary in their complexity, data requirements, and likely timelines for investigation. In addition, some explorations would benefit, and likely require, additional resources and expertise not currently represented on the WG to investigate the task. Examples of this include improving the SHM, developing a life cycle model for SRFC, and fully evaluating benefits to the fishery under different scenarios.

In some cases, identifying the best alternatives will require clarity on conflicting guidance in the FMP with respect to maximizing yield versus production, and perhaps careful consideration of overall goals and how (or whether) to apply the theory behind maximum sustainable yield (MSY) or Optimal Yield (OY) for a stock that is neither entirely natural- nor entirely hatchery-origin. (see Appendix A).

In terms of guidance sought from the Council at this meeting, the WG highlights the questions posed in Section 8 of the Report and the needs for Resources and Expertise identified in Section 9.

2 OUTCOMES OF FIRST WORKGROUP MEETING

The Sacramento River Fall Chinook (SRFC) Workgroup (WG) held its first meeting online January 30-31, 2024. Will Satterthwaite (National Marine Fisheries Service [NMFS], Southwest Fisheries Science Center) was elected Chair and Colin Purdy (California Department of Fish and Wildlife [CDFW], North Central Region) was elected vice-Chair. The meeting brought together representatives from CDFW, Oregon Department of Fish and Wildlife (ODFW), NMFS (both the Regional Office and Science Centers). The meeting was well attended by the public and additional employees of agencies with and without representation on the WG. Public comment was taken at designated periods, and input was welcomed during specific agenda items. WG discussions started to collectively identify the most important issues, data availability, gaps, and potential for future improvements.

WG members gave presentations on the current management framework (including reference points and their theoretical basis, the conservation objective, and the harvest control rule [HCR]), current stock status and trends, ocean and inland fisheries, abundance estimation, abundance forecasting, harvest estimation, harvest prediction/planning, spawner distribution and run timing, and environmental variables (freshwater and marine) relevant to population dynamics of SRFC and/or the accuracy and stability of management measures and associated models.

The WG discussed the draft TOR and is recommending no changes to the document. The WG focused on Purpose 1.a.“*evaluating the management measures currently in place and their robustness to environmental variability”* and Purpose 1.b. “*Provide the Council with a workplan/timeline to: i) develop alternate management measures as needed, and ii) design new or update existing abundance forecast methods and harvest models to incorporate age-structure information, as is done for Klamath River Fall Chinook”*. The WG made progress on identifying potential alternatives to current management measures under 1.a, and discussed potential improvements to the abundance forecast model, recognizing that additional expertise and close coordination with other models used for California stocks will be needed to fully accomplish the task under Purpose 1.b. ii.

The WG also discussed the timelines and data needs for each of the potential alternative approaches and made preliminary assessments of data availability and gaps and assigned tasks to further inventory the available data. The WG discussed data streams that are not currently available but might be useful in the future, and emphasized the need to continue to collect data in ways that would provide needed inputs for current and future models. The WG identified several points where it could benefit from Council guidance on priorities and discussed the resources and additional expertise that could lead to higher quality WG products and outcomes.

3 EVALUATION OF CURRENT MANAGEMENT MEASURES

This section evaluates the management measures currently in place. While it notes areas of concern with the current approaches, this section does not provide recommended solutions. A range of alternatives to address some or all of these concerns are presented in Section 4.

3.1 Reference Points

Informed discussion of reference points and associated management measures requires an understanding of their theoretical basis and the management objectives they are intended to achieve. The Pacific Coast Salmon FMP (PFMC 2022, p. 13) states that the goal of PFMC salmon fishery management is to achieve Optimum Yield (OY), where:

> *Optimum yield (OY) means the amount of fish that will provide the greatest overall benefit to the Nation, particularly with respect to food production and recreational opportunities, and taking into account protection of marine ecosystems. It is prescribed on the basis of the maximum sustainable yield (MSY) from the fishery, reduced by any relevant economic, social, or ecological factors, and provides for rebuilding of an overfished stock, taking into account the effects of uncertainty and management imprecision.*
>
> *MSY is a theoretical concept that, for the purposes of the Magnuson-Stevens Act, is defined as the largest long-term average catch or yield that can be taken from a stock or stock complex under prevailing ecological and environmental conditions and fishery technological characteristics, and distribution of catch among fleets. In Council management of naturally spawning salmon stocks, MSY is usually approached in terms of the number of adult spawners associated with this goal (S_{MSY}). Often, data are insufficient to directly estimate S_{MSY}. In these cases, the Council may use MSY proxies derived from more general estimates of productive capacity and implement harvest strategies that may be expected to result in a long-term average catch approximating MSY.*

In discussing the theoretical derivation of the models typically used to estimate S_{MSY} for Council-managed fisheries, the WG noted challenges in interpreting and applying the models to a stock that consists of a mix of natural- and hatchery-origin individuals and where a large number of hatchery-origin fish spawn in natural areas (see Appendix A). Discussion of the theoretical derivation of S_{MSY} also highlighted the distinction between yield and production (also discussed further in Appendix A), which becomes particularly relevant given the FMP's stated goals for California salmon fisheries (PFMC 2022, p. 51):

> *With respect to California stocks, ocean commercial and recreational fisheries operating in this area are managed to maximize natural production consistent with meeting the U.S. obligation to Indian tribes with federally recognized fishing rights, and recreational needs in inland areas.*

S_{MSY} is the first reference point identified in the FMP. For many Council-managed stocks, S_{MSY} is estimated from a spawner-recruit relationship, but a proxy may be used if data are insufficient for a direct estimate. The S_{MSY} proxy for SRFC is equal to the lower bound of the conservation objective. "This objective is intended to provide adequate escapement of natural and hatchery (emphasis added) production for Sacramento and San Joaquin fall and late-fall stocks based on habitat conditions and average run-sizes" (PFMC 2022, p. 21). Due to the proxy nature of the current S_{MSY} value and its direct link to the conservation objective, the WG's full evaluation of the current S_{MSY} value is presented along with the evaluation of the conservation objective.

F_{MSY} is the exploitation rate (proportional reduction in spawning escapement compared to the escapement that could have been achieved in the absence of fishing) corresponding to MSY. As noted for S_{MSY} values, a proxy may be used if data are insufficient for a direct estimate. For SRFC, F_{MSY} is a proxy value of 0.78, which is the mean value of F_{MSY} estimates for a set of stocks with available data and deemed appropriate when the reference points were adopted in the FMP (PFMC and NMFS 2011, p. 171). The current F_{MSY} proxy value is based on the average of estimates made for 20 stocks spanning from California to Washington in a 2011 analysis (PFMC and NMFS 2011, p. 173). Although this analysis excluded studies that were "very old" (PFMC and NMFS 2011, p. 171), it included data from brood years as early as 1947, and included stocks that may differ substantially in their productivity from present-day SRFC. The WG also noted that hatchery-and natural origin fish may be capable of sustaining differing exploitation rates (Kope 1992) as might populations on different tributaries within the Sacramento Basin.

MSST (Minimum Stock Size Threshold) sets a floor for the three-year geometric mean escapement, below which the stock is considered overfished and a rebuilding plan is required. MSST is generally defined as $0.5*S_{MSY}$ or $0.75*S_{MSY}$, although there are some exceptions (PFMC 2022, p. 17). For SRFC, MSST = 0.75 x S_{MSY}. The reasoning behind the values of the multipliers used in the MSST equation does not appear to be well documented.

F_{ABC} (exploitation rate corresponding to acceptable biological catch) reflects a reduction from the F_{MSY} value to account for uncertainty. The degree of the reduction depends on whether F_{MSY} is directly estimated (0.95) or a proxy value is used (0.90). For SRFC, F_{ABC}= 0.90 x F_{MSY} (PFMC 2022, p. 29). However, the reasoning behind the values of the multipliers used in the F_{ABC} equation does not appear to be well documented.

3.2 Conservation Objective

The SRFC conservation objective is expressed as a range of 122,000-180,000 adult (age-3 or older) spawners in natural areas and hatcheries combined throughout the Sacramento basin, regardless of origin. The original derivation of this objective range is described in PFMC (1984, p. 3-16 to 3-19). The upper bound is the sum of stated escapement goals for the three Sacramento Basin fall Chinook hatcheries and mean natural-area escapements during a reference period for the Upper

Sacramento, Yuba River, Feather River, and American River. While the FMP (PFMC 2022, p. 21) and some text in PFMC (1984, p. 3-16) state that a 1953-1960 reference period was used for all four areas, text later in PFMC (1984, p. 3-17) suggests that a 1971-1981 reference period was used for the Yuba River. Regardless of the time frame used for each river, a literature review performed during the PFMC's 2022 Salmon Methodology Review could not reproduce the reported averages or their sum. The sum of the escapement goals for the Sacramento hatcheries and the mean natural area escapements to the four natural areas from the literature review resulted in an upper bound value of over 300,000 fish compared with the upper bound of 180,000 escapement in the FMP (Satterthwaite 2022, p. 11).

The inclusion of fish returning to hatcheries in the conservation objective was originally explained (PFMC 1984, p. 3-19) as follows:

> *The separation of hatchery and natural fish in these units is artificial. Returns to the hatcheries on the American and Feather rivers have exceeded hatchery capacities in recent years. Once capacity is reached, the ladders are closed and fish that would have returned to the hatchery remain in the river and are counted as natural spawners. Also, naturally-produced salmon commonly return to the hatchery, thus becoming hatchery fish. In 1982 Coleman Hatchery took 7,200 fish in excess of its goal and greatly exceeded hatchery capacity. Had these fish not been taken, they would have become natural spawners.*
>
> *The distinction between hatchery and natural stocks has become lost in these portions of the river. Natural spawners are those that spawn in the wild regardless of their origin. The only major tributary with a truly natural run is the Yuba River. Runs in this river have been remarkably stable from 1971-81, averaging about 10,000 adults. The run increased sharply in 1982 to 23,000. The stability of the Yuba River escapement suggests that present and past management practices have not reduced the productivity of natural stocks.*

Information currently available indicates that many of these conditions may no longer apply. Escapements entering some hatcheries have routinely exceeded their stated goals (PFMC 2024a, Table B-1), especially in more recent years. In addition, the WG noted that while there is evidence for substantial genetic introgression and homogenization among SRFC (Williamson and May 2005), evidence for some genetic differentiation and adaptation remains (Meek et al. 2020). In addition, recent data show that escapement to the Yuba River is not entirely or even majority natural-origin in many years, and Yuba River escapements did not remain stable around 10,000 after 1981 (Satterthwaite 2022).

The lower bound of 122,000 was derived by PFMC (1984) due to concerns about lower than-recent returns to the Upper Sacramento and concerns that meeting their implied Upper Sacramento goal of 108,000 spawners (PFMC 1984, p. 3-18, 99,000 in natural areas and 9,000 at Coleman

National Fish Hatchery) would require "over-escapement" to the lower river, and the expectation that Upper Sacramento escapement (including hatchery returns) would stabilize at about 50,000 (PFMC 1984, p. 3-19). Therefore, an "interim" goal of 122,000 spawners was set "until such times as the problems caused by the Red Bluff Diversion Dam are rectified, and the full production of salmon in the Upper Sacramento River can be realized". Since the gates at Red Bluff Diversion Dam have been permanently opened starting in 2011 (Satterthwaite 2022), a revision to the spawner escapement goal may be warranted.

The WG discussed the original basis for the conservation objective and the differences between the circumstances when the objective was derived and circumstances today. The WG acknowledged that some data cannot be reproduced, some concepts are out of date, and other assumptions or predictions did not have come fully to fruition. In addition, changes in the distribution of escapement and mean natural-area escapements compared with the reference period for the Upper Sacramento, Yuba River, Feather River, and American River as described above indicate those assumptions that were foundational to the original derivation of the goal are no longer applicable. The WG further noted that setting a basin-wide goal equal to the sum of stated or implied sub-area goals is exceedingly unlikely to meet all sub-area goals simultaneously (Satterthwaite 2022), since fish will distribute themselves throughout the watershed in varying ways that are unlikely to exactly match the relative magnitude of the different sub-area goals.

The WG noted that a conservation objective and reference points based on total (hatchery and natural area) escapement is not directly linked to maximizing natural production consistent with page 51 of the FMP, nor with the theoretical basis for deriving S_{MSY} from a spawner-recruit relationship. The WG also noted that multiple analyses indicated that a higher escapement goal would be expected to yield greater natural production (PFMC 2019, Munsch et al. 2020, Satterthwaite 2023) and inland harvest (unpublished data presented at annual CDFW Salmon Information Meeting).

3.3 Harvest Control Rule

The harvest control rule for SRFC is defined in terms of the reference points F_{ABC}, MSST, S_{MSY}, and two levels of *de minimis* exploitation rates, F = 0.10 and F = 0.25. The maximum allowable exploitation rate, F, in a given year, depends on the pre-fishery ocean abundance in spawner equivalent units, N. At high abundance the rule caps the exploitation rate at F_{ABC}, at moderate abundance the rule specifies an F that would result in S_{MSY} spawners if forecasts and harvest model implementation were perfect, and at low abundance the rule allows for *de minimis* exploitation rates. The control rule describes maximum allowable exploitation rates at any given level of abundance. The Council may recommend lower exploitation rates as needed to address uncertainties or other year specific circumstances. When recommending an allowable *de minimis* exploitation rate in a given year, the Council is obligated to consider additional circumstances, and other considerations as appropriate (PFMC 2022, p. 32).

The WG discussed areas of potential improvement with the harvest control rule. Specific breakpoints in the control rule depend on the reference points, and thus the concerns raised in the previous sections regarding the current values of those reference points are relevant to the current implementation of the control rule and potential changes to the control rule to address them. The WG also acknowledged the utility in accounting for uncertainty in the preseason abundance forecast, uncertainty in S_{MSY}, and management imprecision.

3.4 Environmental variables and their implications for management measures

Studies on SRFC, and Chinook salmon more broadly, suggest that productivity and capacity are influenced by environmental variables experienced at different life stages (e.g., Martin et al. [2017], Wells et al. [2017], Friedman et al. [2019], and Munsch et al. [2019]). A number of these have been incorporated into the list of ecosystem indicators reported annually as stoplight tables in the California Current Ecosystem Status Report (Leising et al. 2024). Assessing the degree to which productivity of natural- and hatchery-origin cohorts tracks these indicators is complicated by uncertainty in data on SRFC stocks, including age structure and mixing of hatchery- and natural-origin in the SI. Nevertheless, a productivity index based simply on the SI and total outmigrants three years earlier was used in an analysis presented to the WG to examine the correlations of indicators with productivity, and the potential for these correlations to change over time.

As noted in the presentation on a potential productivity index, several indicators (outmigrant productivity, temperature during outmigration, water temperature during redd incubation, water flow, number of hatchery fish released, proportion of hatchery fish released outside natal rivers) exhibited relatively strong correlations with recruitment deviations from the SI-based productivity measure. Furthermore, correlations with most indicators exhibited strong nonstationarity, i.e. the strength of the correlation changed over time. For example, the correlation of recruitment deviations with temperature during outmigration was essentially 0 in the 1980s but has risen to >0.5 in recent years.

Much of the WG's discussion of the implications of environmental variables concerned their potential use in improving abundance forecasts (see below), their implications for the stability of reference points, and their utility in informing year-specific goals.

Given evidence for environmental changes, nonstationarity in the relationships between environmental factors and biological responses, and expected climate change, the most suitable values of reference points and objectives may change over time. At the same time, MSY is defined as a long-term average. This raises challenging questions about the appropriate temporal scope of datasets used to inform reference points and conservation objectives, while also deepening concerns about use of proxy values derived from analyses of other stocks many years ago or using historical average escapements as a basis for current objectives for SRFC. The FMP (PFMC 2022) anticipates periodic updates to reference points (p. 38), and conservation objectives (p. 20) as additional data becomes available.

In terms of year-specific goals, the WG noted that Munsch et al. (2020) suggested the escapement maximizing production might be fairly stable from year to year, but the benefits to production and thus to future yield would vary extensively, and could be partially predicted by flow during juvenile outmigration for the subsequent cohort. The WG acknowledged that other environmental factors were likely important as well, and some would be expected to affect capacity (and thus the escapement maximizing production) as well as productivity.

Notably, some environmental variables may have cumulative effects on the population and to recruitment and be poorly documented in their population level effects. For example, thiamine deficiency impacts salmon in multiple ways and at multiple freshwater life history stages with potential cumulative effects with other stressors (Mantua et al. 2021). For adult Chinook salmon, thiamine deficiency can decrease a fish's ability to handle stress such as due to high water temperatures and increase the susceptibility to disease which can increase prespawn mortality. Both these factors occur in the Sacramento Basin. Many pathogens become more virulent at high water temperatures. Hinch et al. (2021) suggested that stress may also lead to a male biased sex ratio in the spawning population of salmon as prespawn mortalities may occur at higher rates in females thereby decreasing fecundity in the population. For juvenile salmon, if thiamine deficiency does not result in mortality, it can lead to latent effects including impairment which increases juvenile susceptibility to disease and predation during rearing and emigration. This is particularly concerning in locations like the Feather River with documented high occurrences of *Ceratomyxa shasta* and predation.

The WG spent some time discussing which environmental factors could be predicted far enough in advance to inform setting year-specific escapement goals based on the expected benefits of greater escapement for parents in a particular spawning year. This topic will require further work, but the WG noted the strong effects of flow and the potential to at least partially predict flow and some other water conditions into the future based on expected reservoir carryover and water management practices. Given the definition of MSY reference points as long-term averages, and regulatory burdens associated with changes in conservation objectives, the WG's preliminary opinion is that if analyses supporting year-specific escapement goals could be developed or inform qualitative adjustments (i.e., similar to the stoplight charts [Leising et al. 2024]), the harvest control rule would probably be the most appropriate means for implementing these into management.

4 PRELIMINARY IDENTIFICATION OF POTENTIAL MANAGEMENT MEASURE ALTERNATIVES

This section of the report summarizes potential approaches for management measure alternatives identified by the WG, their pros and cons, and approximate timelines anticipated. Section 10 summarizes these points in tabular form. In all cases, timelines identified by the WG are preliminary and include only the estimated time required for the technical work, not the time associated with any required scientific review or administrative/regulatory actions.

4.1 F_{MSY}

4.1.1 *Updated proxy*

The quickest update to F_{MSY} for SRFC could be through an updated proxy value inferred from other Chinook stocks, with careful selection of stocks and time periods that are representative of the SRFC stock.

A literature review could search for new spawner-recruit analyses of relevance (e.g., Confer and Falcy [2014] estimated reference points for Rogue River Fall Chinook, and the Klamath River WG recently produced updated spawner-recruit curves for KRFC [KRWG 2024]). The literature review could also identify factors that might make particular stocks or studies more or less relevant to SRFC (e.g., similarity in life history characteristics, habitat conditions, and recency of data). F_{MSY} for SRFC could be based on the single proxy stock deemed most likely to be representative, or an average of the more representative studies.

This could lead to a value more representative of SRFC but would still require use of a proxy. The technical aspects of this work would likely require less than a year to complete if based on existing, published relationships; or could be extended to a multi-year effort updating relationships for other stocks based on more recent data and/or analyzing additional stocks for the first time. It is likely that the extra time spent on updating the analyses or analyzing new stocks would result in a better representation of present-day SRFC.

4.1.2 Spawner-recruit analysis based on abundance surrogate for natural area escapement

Similar to KRFC (STT 2005), if sufficient data were available, a spawner-recruit analysis for SRFC could be performed, using natural area spawners as the measure of spawner abundance and some metric of natural production as recruits. To parallel what is used for KRFC analysis, the estimates of recruits would be based on a cohort reconstruction. A cohort reconstruction for SRFC is not currently available; however, the WG is aware of a draft cohort reconstruction for SRFC that could be useful. A cohort-based alternative is discussed in the next section (4.1.3).

In the absence of an age-based cohort reconstruction, a possible surrogate for potential natural origin escapement in the absence of fishing would be the SI times the proportion of escapement that was of natural origin. The SI is the currently accepted index of potential escapement in the absence of fishing for SRFC and annual estimates are available back to 1983 (PFMC 2024b). Estimates of the proportion of escapement that is natural origin are available from 2010 (Kormos et al. 2012) through 2020 (Dean and Lindley 2023). It should be possible to extend these estimates to a few more recent years, acknowledging that the recent releases of unmarked fry (with parents genotyped) may prevent estimates for years without sufficient genetic sampling of returning spawners.

An analysis relating natural-area escapement for parent spawner years 2007-2017 to a natural-origin adjusted SI proxy for age-3 recruits in 2010-2020 could be completed in a matter of days. The time span of this dataset would provide for limited statistical precision and would not reflect the full range of environmental conditions reflected in a longer time series. Also, in addition to the limitations of the SI, the proportion of escapement that is natural origin may be difficult to estimate precisely and is generally low, such that small errors can be consequential proportionally. The composition of the escapement may not match the composition of the ocean harvest (e.g. if hatchery- versus natural-origin fish have different maturation schedules or vary in behaviors that expose them to fishing) and the assumption that recruitment occurs solely at age-3 (i.e., indexing recruitment as the SI 3 years after spawning) may be weaker for natural-origin fish. The SRFC escapement composition estimates are based on all age classes including jacks and may differ from the composition of adults alone. In addition, there may be some logical inconsistencies in relating natural-area escapement in the parent generation to natural-origin recruitment in the offspring generation while implicitly linking natural-origin recruitment to future escapement and potential long-term yield, since natural-origin fish are not the only source of natural-area spawners for SRFC. However, this does not impede an analysis of how natural area escapement affects subsequent natural-origin production, it only complicates the interpretation of sustainable yield.

Any spawner-recruit analysis would also depend on assumptions made about the form of the spawner-recruit relationship, and numerous statistical pitfalls need to be taken into consideration (Adkison 2022). However, these concerns apply to stocks beyond SRFC, so making the same assumptions as are commonly made for other stocks would make the derivation of recruitment metrics the main hurdle to implementing a comparable spawner-recruit analysis for SRFC.

4.1.3 Spawner-recruit analysis based on cohort reconstruction for natural area escapement

To more closely match the spawner-recruit analysis performed for KRFC, a cohort reconstruction based on coded-wire tags (CWT) recovered from hatchery-origin fish and ages of unmarked fish derived from scale analysis (Mohr 2006, Chen et al. 2023) could be used to reconstruct the hatchery- and natural-origin components of SRFC cohorts, allowing estimation of the potential natural origin escapement in the absence of fishing for each cohort of SRFC with suitable data. CWT data from prior to the initiation of the constant fractional marking program may not be sufficiently reliable (Kormos et al. 2012), limiting the analysis to parent spawner years 2006 or later. As noted above, unmarked fry releases need to be accounted for when reconstructing natural-origin cohorts for recent, and potentially future, brood years. This requires genetic sampling that has not yet been implemented (see discussion Section 6.1). Scales have been collected from unmarked fish to allow for estimation of natural origin escapement at age, but this estimation is indirect since it requires subtracting the expected contribution of unmarked hatchery fish, which can lead to imprecise estimates for areas where the proportion hatchery-origin is high.

Preliminary efforts are currently underway at U.C. Berkeley (Emily Chen, public comment to WG) at reconstructing SRFC for years that have suitable data available. Thus, it could be possible to complete SRFC cohort reconstructions for a limited suite of years (as a one-time calculation) within a matter of months. The time span of this dataset would provide for limited statistical precision and would not reflect the full range of environmental conditions or escapement levels reflected in a longer time series.

Reasonably up to date CWT data are routinely available from the Regional Mark Information System (RMIS) and in databases maintained by CDFW, but at present estimates of escapement at age are only available for return years 2010-2018 (Dean et al. 2020) and still need to be adjusted for hatchery contributions to estimate natural-origin escapement-at-age. Scales have been collected, and in some cases read, for more recent years as well. While there would be advantages to using the most current data possible and setting up all of the infrastructure needed for routine updating of the analysis in a streamlined fashion, neither of these are required prior to a one-time spawner-recruit analysis for the purposes of informing updated SRFC reference points.

Beyond challenges posed by timely data availability, there may be some logical inconsistencies in estimating F_{MSY} and S_{MSY} by relating natural-area escapement in the parent generation to natural-origin recruitment in the offspring generation while implicitly linking natural-origin recruitment to future escapement and potential long-term yield, since natural-origin fish are not the only source of natural-area spawners for SRFC. However, this does not impede an analysis of how natural-area escapement affects subsequent natural-origin production.

4.1.4 Tributary-specific F_{MSY} values

The WG discussed the possibility that F_{MSY} values might vary among tributaries due to differences in habitat conditions and the amount of hatchery influence. It is not clear whether sufficient data exist to determine tributary-specific productivities, and tools do not currently exist to target different exploitation rates on stocks from different tributaries within the broader SRFC stock. Thus, while the WG expressed concerns about the implications of tributary-specific productivity for appropriate exploitation rates, it sees tributary-specific F_{MSY} determination as a multi-year, perhaps multi-decade, approach that would require additional expertise and resources.

4.1.5 Year-specific F_{MSY} values

The WG discussed the possibility of year-specific F_{MSY} values, but decided against pursuing this option further. Although productivity is expected to vary across years, MSY is defined as a long-term average, so the WG decided it was more appropriate to pursue year-specific management responses through the harvest control rule.

4.2 S_{MSY}

4.2.1 Eliminate "interim" value from PFMC (1984) approach

The WG discussed the possibility of eliminating the lower bound of the conservation objective (122,000) and retaining only the upper bound (possibly revised itself) given the "interim" nature of the lower bound of the conservation objective according to PFMC (1984), the permanent opening of the Red Bluff Diversion Dam gates, and post-1984 patterns in Upper Sacramento River returns highly inconsistent with the PFMC (1984) prediction of returns stabilizing around 50,000 (Satterthwaite 2022). However, the justification for the remaining upper bound of the PFMC (1984) conservation objective would remain unclear. It would lack any theoretical basis or link to actual estimates of production or yield as functions of escapement.

4.2.2 Update/revision to PFMC (1984) approach

As noted previously, attempts to reproduce the values reported in PFMC (1984) for each natural area's contribution toward the conservation objective (and thus S_{MSY}) based on mean escapements were unsuccessful (Satterthwaite 2022). Mean escapements from the reference periods identified in PFMC (1984) could be recalculated from current data for those years, or means could be calculated from a new set of years deemed to be more representative of current conditions. This analysis (for the previously identified set of years) was already done by Satterthwaite (2022), but available escapement estimates for the earliest years do not distinguish jacks from adults. A correction factor could be developed in less than a year. However, the justification for using mean escapements from these time periods would remain unclear. It would lack any theoretical basis or link to actual estimates of production or yield as functions of escapement.

4.2.3 Direct derivation from a spawner-recruit relationship

S_{MSY} could be derived directly from a spawner-recruitment relationship fit to data for SRFC, as described under and for F_{MSY} estimation, above. The same advantages, challenges, and timelines would apply. Note that this and other options would likely involve a shift from measuring and managing for S_{MSY} as a function of total escapement (hatcheries and natural areas combined) to measuring only natural-area escapement, perhaps also restricting to natural-origin. Changing the units for S_{MSY} or the escapement goal would require updating preseason forecasting tools to predict escapement in those same units. Alternatively, preseason planning could still be based on total escapement, with models similar to the one developed by Satterthwaite (2023) to determine the total escapement needed to achieve sufficient escapement at the desired scale.

As noted previously, there may be some logical inconsistencies in estimating F_{MSY} and S_{MSY} by relating natural-area escapement in the parent generation to natural-origin recruitment in the offspring generation while implicitly linking natural-origin recruitment to future escapement and potential long-term yield, since natural-origin fish are not the only source of natural-area spawners for SRFC. However, this does not impede an analysis of how natural-area escapement affects subsequent natural-origin production, and so would not impede identification of an S_{MSY} proxy based on a desired level of natural production.

4.2.4 *Indirect derivation from spawner-juvenile production relationship*

Although data to directly reconstruct adult abundance of SRFC by origin are lacking for many years, more extensive datasets are available for juvenile production (e.g. PFMC 2019, Munsch et al. 2020). For many salmon stocks, the escapement that maximizes yield is a fairly constant fraction of the escapement that maximizes production (Satterthwaite 2022). Although juvenile production metrics for SRFC as a whole may be lacking, such estimates are available for specific sub-areas (e.g. PFMC 2019) or for the entire basin but include other run timings (Munsch et al. 2020). Satterthwaite (2022) describes a method for identifying the escapement at one scale (e.g. on a specific tributary) that has a defined probability of achieving the desired production at another scale (e.g. for the whole basin), assuming the way that fish distributed themselves across the landscape is predictive of how they will be distributed in the future.

Much of the analysis needed to derive an S_{MSY} value by this method has already been completed (Satterthwaite 2023), although further analysis could be needed to identify a robust ratio between S_{MSY} and the escapement maximizing production. Satterthwaite (2023) also noted the potential benefits of exploring alternative models for how fish are distributed through the watershed as a function of total escapement. Such analysis would probably require less than a year.

4.2.5 *Proxy based on escapement maximizing production*

This would be a simpler version of the methods described in Section 4.2.2, with no need to identify a ratio between S_{MSY} and the escapement maximizing production. As such, complete analyses identifying the escapement that would maximize production already exist at various scales (measured either as total adult returns including hatcheries, returns only to natural areas, or returns only to natural areas above RBDD; Satterthwaite [2023]) and could be updated with additional data as available, though as noted there could be benefits in exploring alternative models of how fish are distributed across the watershed. This approach has the advantage of being easy to implement, having a clear theoretical basis, and meeting the stated goal of California fishery management in the FMP (page 51), but maximizing production would forego some yield compared to MSY.

4.2.6 *Proxy based on escapement optimizing production*

This would be analytically similar to the previous option, but rather than identifying the escapement that maximizes production (S_{MAX}), it would identify the escapement likely to achieve a target fraction of maximum possible natural production, which might approximate S_{MSY} even in a scenario where S_{MSY} cannot be estimated directly. An escapement less than that which maximizes production could allow for higher yield, and in cases where direct estimation of S_{MSY} is impossible, it may be easier to estimate S_{MAX} and identify a fraction of maximum production that is desirable from a policy perspective or is similar to the ratio between S_{MSY} and S_{MAX} in systems where the data allows estimation of both quantities. Policy discussions would be needed to identify the desired fraction of potential production, but once that target fraction was identified, complete analyses already exist (Satterthwaite 2023) and could be updated with additional data as available, though as noted there could be benefits in exploring alternative models of how fish are distributed across the watershed.

4.2.7 Proxy based on level of inland harvest opportunity

The WG evaluated historical data on inland harvest to examine the portion of the total Sacramento Index (adult escapement, adult ocean and inland harvest) made up by inland salmon harvest as well as the variation around the proportion of the total index over time. The relative proportional contribution of inland harvest makes the total Sacramento Index appear to be relatively stable over time. While harvest may vary and increase when more salmon are present in the valley, the proportion of the total index value made up by inland harvest doesn't appear to vary much as ocean harvest and adult escapement increased.

Assuming the past relationship between escapement and inland harvest persists into the future, identifying a desirable level of river harvest that could be used to derive a proxy estimate of S_{MSY} that would be expected to provide it. It is important to note this approach is based on policy decisions regarding allocation of harvest between ocean and inland areas (i.e., identifying a desirable level of river harvest). How this was taken into account in the original derivation of the SRFC objective in the context of the FMP language on p. 51 is unknown. The analysis relating escapement to inland harvest already exists and was presented to the WG, so the timeline for this approach would be driven by the identification of desired levels or inland harvest, which could involve protracted and complex policy discussions regarding allocation.

4.2.8 Proxy based on habitat

Salmon spawning habitat availability, while flow dependent, can be estimated and as a result of the number of adult spawners that can be supported by the available habitat within a given tributary and can be predicted across a range of flows. For example, weighted usable area curves were developed for salmon spawning habitat as part of Federal Energy Regulatory Commission relicensing for the Oroville facilities on Feather River, and found maximum habitat availability occurred at flows approaching 1,000 cubic feet per second in the Low Flow Channel of the Feather River (DWR 2005, Vol_V_App G). To maximize utilization of available habitat, habitat-based escapement goals could be developed relatively quickly but would require knowing the anticipated flow regime during spawning and that the flow regime assumed preseason would be implemented at the time of spawning, i.e., commitment by the water agencies. Additionally, these escapement goals would need to be revisited frequently for their applicability within and across years as a number of factors could affect utilization of the habitat and actual availability of habitat to support spawning. Factors affecting availability of habitat to support spawning include, but are not limited to, water temperatures in spawning reaches, permeability and quality of spawning gravel, movement between seasons of spawning gravel, and implemented habitat restoration projects occurring between seasons.

Depending on the scale at which habitat-based proxies are available, they might yield an S_{MSY} proxy directly, or allow for a set of sub-area goals that might or might not cover the entire basin. Even if they did cover the entire basin, simply adding them together would not be expected to meet all sub-area goals, given variation in how fish distribute themselves over the watershed. However, the approach described in Satterthwaite (2023) could accommodate sub-area goals into a framework based on the probability of a total escapement level meeting all of them, whether or not the individual sub-areas covered the entire basin. In addition, as noted previously, there could be benefits in exploring alternative models of how fish are distributed across the watershed.

4.2.9 Accounting for San Joaquin Fall and/or Sacramento Late-Fall

The WG discussed the merits of considering goals for the San Joaquin and/or late-fall runs. These could be treated as separate goals or rolled into a single Central Valley Fall Chinook Stock Complex goal. This accounting could better incorporate the contribution to fisheries from other stock components as well as other hatcheries (e.g., Mokelumne). In the case of a Central Valley Fall Chinook goal, considerations similar to the combination of sub-area goals would apply. Developing goals for these runs would likely be a multi-year effort.

4.2.10 Year-specific metrics based on expected conditions for upcoming cohort

The WG briefly discussed the merits of reference points that responded to year-specific conditions, noting that the production benefits from increased escapement would depend on environmental conditions faced by the offspring of the escaping run. However, given the definition of MSY as a long-term average, the WG did not consider S_{MSY} the best place to address year-specific effects.

4.3 Minimum Stock Size Threshold (MSST)

If S_{MSY} were updated with any of the approaches described above, the MSST might need to be updated to remain at least 50% of S_{MSY} for consistency with FMP requirements. The updated MSST could continue to be 75% of the updated S_{MSY}, in which case the timeline would be driven by the approach for S_{MSY}. It might be possible to develop an alternate multiplier, but that would likely be a multi-year effort and there would likely be benefits to a consistent approach to deriving the multiplier across all stocks, not just SRFC. The WG would also require policy guidance to identify the criteria for determining an alternate multiplier. The WG discussed the idea of integrating genetic considerations into MSST, but the WG was not aware of existing analyses or datasets that would provide a good starting point, and this would be a multi-year effort.

4.4 Conservation objective

All of the potential approaches considered for S_{MSY} could be considered for the conservation objective as well. The WG also discussed the possibility of eliminating the lower bound of the conservation objective (122,000) and retaining only the upper bound (180,000, which could possibly be revised). Eliminating the lower bound of the conservation objective could be rationalized given the "interim" nature of the lower bound of the conservation objective according to PFMC (1984), the permanent opening of the Red Bluff Diversion Dam gates, and post-1984 patterns in Upper Sacramento River returns that are highly inconsistent with the PFMC (1984) prediction of returns stabilizing around 50,000 (Satterthwaite 2022). Escapement of SRFC to natural areas in the Upper Sacramento has not stabilized as expected, an average of over 150,000 were observed for 1996-2005 before the dam was decommissioned and the first- and second-lowest observed returns to the mainstem Sacramento River were realized after decommissioning (PFMC 2024a).

4.5 Harvest Control Rule

4.5.1 Updated reference points

The current control rule is parameterized based on the reference points S_{MSY}, MSST, and F_{ABC} (itself a function of F_{MSY}), and so updates to those reference points would implicitly update the control rule, while not changing its basic shape, with a timeline dependent on the approaches used to update any of the reference points.

4.5.2 Alternative escapement targets

The WG discussed whether the control rule should target year-specific escapements based on the environmental conditions that the offspring of returning spawners for a particular cohort would face. Identification of the best predictors could be a multi-year process that might be informed by the process employed for automated selection of environmental and biological covariates in the OPI-H coho forecast (Leeman et al. 2023). The WG also discussed whether the control rule should target an escapement other than (likely higher than) S_{MSY} such as the escapement maximizing natural production or that yields the desired level of inland harvest.

4.5.3 Alternative forms

The WG considered the merits of alternative control rule forms. Something simpler like the approach employed for most Pacific Salmon Treaty stocks (PFMC 2022, p. 34), which targets a single escapement as long as at least a minimum acceptable exploitation rate F_{DM} can be allowed, or allows F_{DM} otherwise could be more straightforward to implement and potentially less sensitive to forecast error. Eliminating *de minimis* fisheries (i.e. always targeting escapement of at least S_{MSY} or some other escapement target whenever possible) could offer conservation benefits, at the cost of losing minimal harvest opportunity in years of very low abundance. A matrix approach similar to that employed for Oregon Coast Natural coho (PFMC 2022, p. 35 as updated in Suring and Lewis [2013] and Suring [2017]) could allow incorporation of multiple metrics of abundance and environmental conditions. Identifying breakpoints in a matrix approach for SRFC would likely take about a year of analysis, but could benefit from existing work on indicators for this stock (HC 2023). In addition, methodologies for risk tables are under development for groundfish stocks (EWG 2024), and the Council supported examination of these approaches for CA salmon stocks at their March 2024 meeting.

4.5.4 Uncertainty buffers

The WG also discussed the potential to incorporate buffers against forecast error (Satterthwaite and Shelton 2023) and/or harvest planning implementation error (Satterthwaite 2023) into the control rule. The basic mathematics behind this approach have already been worked out, along with an approach for quantifying the error in current or updated forecasts (Satterthwaite and Shelton 2023) and harvest planning models (Satterthwaite 2023). The proposed approach is similar to the process used by the PFMC to separate scientific uncertainty and risk tolerance in determining buffers employed to implement management based on Coastal Pelagic Species and Groundfish stock assessments (Satterthwaite and Shelton 2023). The technical aspects of the work are essentially complete, and could complement work on risk tables (EWG 2024, HC 2024) or provide a quantitative pathway for their implementation, but it could take time to arrive at the PFMC's preferred level of risk tolerance (see also Potential Approaches to Analyze Alternatives, below).

4.5.5 Technical considerations for updating control rules

Specifying alternative control rules for these different goals or approaches would be straightforward and require little time (with the exception of identifying breakpoints in a matrix or identifying environmental predictors for time-varying escapement goals) but analyzing the costs and benefits could be more involved (see Potential Approaches to Analyze Alternatives, below).

5 WORKGROUP EVALUATION OF FORECAST AND HARVEST MODELS

5.1 Abundance and Harvest Estimation (SI)

The WG noted that the SI (O'Farrell et al. 2013) omits natural mortality after the juvenile stage, maturation spread over multiple age classes, and most sources of non-landed fishing mortality (e.g. sublegal-sized releases and dropoff mortality); it also has limitations in its estimates of landed fishing mortality, in particular in how the origin and age of unmarked fish are accounted for and does not account for bycatch in fisheries that are not directed at salmon. This reduces its ability to reflect the production from a specific cohort, and introduces bias that can vary with the harvest rate (i.e. all else being equal, the SI will be higher for a cohort experiencing a high harvest rate, because some fish counted in the harvest might not have shown up in the escapement if left unharvested since they might have died of natural causes or not returned to spawn that year). The WG also raised questions about the need to directly consider the abundance of San Joaquin and/or late-fall run Chinook.

5.2 Preseason Abundance Forecast (SI Forecast)

The WG noted that the SI forecast had over-forecasted the postseason estimate in seven out of the last ten years (now eight of the last eleven [PFMC 2024b]), and there was a strong tendency to over-forecast when abundance was low and forecast errors could be most consequential. Satterthwaite (2023) formally quantified statistical evidence for bias in the SI forecast, as well as its overall uncertainty (including imprecision). The WG noted that maturation rates have likely changed over time, and this would affect jack:adult ratios for different cohorts, a key driver of the current forecast method. The WG also noted that jacks straying into the Sacramento Basin from the San Joaquin Basin (in particular, Mokelumne River hatchery fish) likely had a higher jacking rate than Sacramento-origin fish and could contribute to over-forecasting.

5.3 Harvest Planning Model (SHM)

The WG noted that the SHM had under-predicted the postseason estimate of the SRFC exploitation rate in the most recent ten out of ten years (given the lack of fisheries in 2023, this was not updated for 2023). This reflected both under-predicting effort and under-predicting the harvest rate per unit effort, perhaps because of habitat compression leading to greater spatial aggregation and thus easier catchability of fish.

The WG discussed the planned Implementation of trip limits and inseason management for a total allowable harvest limit as adopted by the Council and transmitted to NMFS in November 2023 (NMFS 2023a, NMFS 2023b). This is a novel approach to fisheries management in the areas off the California coast that are most relevant to harvest of SRFC, which historically has made extensive use of time-area restrictions and very little use of catch quotas. Though mainly targeted at the KRFC harvest rate used as a proxy for managing impacts to California Coastal Chinook, these in-season caps would be expected to reduce the amount of under-prediction of SRFC harvest rates as well since fisheries in some time-area strata might close earlier than expected if catch rates are unexpectedly high. However, the WG noted that caps may still be set too high if abundance is over-forecasted, and this management approach has yet to be tested in ocean salmon fisheries off California.

6 PRELIMINARY IDENTIFICATION OF FORECAST AND HARVEST MODEL ALTERNATIVES

6.1 Abundance and Harvest Estimation

A KRFC-style cohort reconstruction (Mohr 2006, Chen et al. 2023) would allow estimates of ocean abundance and potential escapement by each age class for each cohort with suitable data, and would allow for incorporation of estimates of release and dropoff mortality in fisheries. Applying cohort reconstructions to tagged hatchery fish is relatively straightforward (e.g., O'Farrell et al. 2012) as long as a sufficient (and known) number of fish are marked and tagged, and comprehensive sampling for tags occurs in every relevant fishery and escapement stratum where fish from the stock of interest might be recovered. CWT data for brood years 2006 and later when the constant fractional marking program was initiated should be sufficient for cohort reconstructions of the hatchery-origin component (Kormos et al. 2012), although unmarked fry releases could confound estimates for recent and potentially future brood years without adequate sampling for genetic tags in all relevant recovery locations (CDFW 2023). Extending the cohort reconstructions to include natural-origin fish requires data on escapement-at-age for unmarked fish and a means of subtracting off the contribution of unmarked hatchery fish by applying appropriate expansion factors to tag recoveries.

As discussed under Section 4.1.3, preliminary cohort reconstructions for SRFC are underway but limited to years with sufficient CWT and scale-age data, and the timelines described there would apply here as well. However, routine application of a cohort reconstruction every year with updated data would require developing new workflows, as well as a commitment from responsible agencies to continue to collect, validate, and distribute the required data in a timely fashion. The STT (2019) indicated that this could take two years or longer.

The ability to use cohort reconstructions as a long-term tool for SRFC depends crucially on tagging a sufficient number of hatchery fish, with some representation of every release group with tagged fish, and a means of sampling to recover tags from all locations where tagged fish might be encountered. At the present time, the tag informing cohort reconstructions throughout the U.S. West Coast is the CWT, and sampling in California depends on the adipose fin clip to denote the presence of CWT to target fish for sampling. Efforts are underway to deploy parentage-based tagging (PBT) as a supplement or replacement to CWT, and it is crucial that PBT be deployed in a way that does not compromise the ability to perform cohort reconstructions if they are to be used to inform SRFC management (CDFW 2023).

Estimating the natural-origin component of cohorts depends on subtracting off hatchery-origin contributions to the escapement-at-age of unmarked fish. If all hatchery-origin fish were marked and/or tagged in a way that could be detected in all relevant sampling schemes, this would allow for more precise estimation of natural-origin escapement-at-age and thus more robust cohort reconstructions. 100% adipose fin clipping of hatchery production is one way to achieve this (CA HSRG 2012), but so is 100% tagging as long as tags can be detected in the absence of adipose fins (CA HSRG 2012). Even if less than 100% of hatchery production is marked/tagged, a mark/tag rate for production hatcheries higher than the current 25% mark/tag rate could increase the precision of natural-origin cohort reconstructions (Mohr et al. 2017). However, even a cohort reconstruction restricted to tagged hatchery releases, similar to the current approach for Sacramento River Winter Chinook (O'Farrell et al. 2012), would likely provide a more accurate measure of fishery impact rates than the current SI-based approach, while being less demanding in terms of data and analytical resources.

Following up on earlier discussion of the importance of Mokelumne River Chinook and other members of the Central Valley Fall Chinook stock complex beyond SRFC, the WG discussed the merits of approaches for tracking the abundance of these stocks as well, and/or a combined abundance index for the whole stock complex. The WG considered the prospects of reviving the Central Valley Index (CVI, O'Farrell et al. 2013) or an updated version that better accounted for ocean harvest and excluded Central Valley stocks outside the complex (i.e. winter and spring run). It would be relatively straightforward to expand the SI calculation to include late-fall run and San Joaquin fall run, but updating all the associated management models that are designed to use the SI to use an updated CVI in its place could require substantial work that could span multiple years.

6.2 Preseason Abundance Forecast

6.2.1 Updated SI forecast

Winship et al. (2015) compared the performance of thirteen model variants, including the current SI forecast model, based on data available at the time. Some of these model variants had additional subvariants using a range of environmental covariates. It would be relatively straightforward (likely less than a year) to update this comparison based on more recent data, and possibly include consideration of additional environmental covariates as identified in recent work (e.g., HC 2023). Approaches to incorporate the effects of jacks straying into the system, and/or error and uncertainty in how escapement surveys distinguish jacks from adults, could likely be developed within a year. Additional approaches could also be explored, for example the method recently adopted for OPI-H coho (Leeman et al. 2023) offers advantages in quantifying uncertainty and its dynamic nature for screening and selecting the best-performing model variants over time, as well as employing an ensemble approach that may be more robust to changes in the single best-performing model over time. Exploring a broader range of approaches could be a multi-year project, although it might be possible to develop something based on the OPI-H approach with at least a year of focused work.

6.2.2 Changes to forecast methods if moving to cohort reconstruction in place of SI

Because cohort reconstructions yield estimates of ocean abundance-at-age and maturation rates, they could be collapsed into a single metric of potential adult escapement in the absence of fishing that could be used in the same way as the SI and would not require a move away from the SI forecast approach. However, a move to a cohort reconstruction would likely be accompanied by a move to an age-structured forecast as well. Adopting the sibling regression approach (Peterman 1982) used for KRFC would be computationally simple to implement and could be done within a year once cohort reconstructions for a sufficient number of brood years had been completed. However, there could be advantages to exploring age-specific forecasts that included additional predictors, as described in 6.2.1.

6.2.3 Incorporation of uncertainty buffers

The WG discussed the potential to build uncertainty buffers (e.g. Satterthwaite and Shelton 2023) into forecasts, but decided that the control rule was the more appropriate place to implement buffering. It would be straightforward to apply a buffer to the numeric value entered into the control rule to determine the allowable exploitation rate, while still using the unbuffered forecast for quota setting and other modeling uses requiring an unbiased forecast for optimal performance. However, bias correction methods (Satterthwaite and Shelton 2023) could be appropriate for building into forecasts, and internal estimates of forecast uncertainty (e.g., Auerbach et al. 2021) could inform the buffering implemented at the control rule stage.

6.2.4 Indicator-based forecasts

The WG discussed the potential to develop forecasts based on environmental indicators, building on the qualitative or categorical predictors already developed for SRFC (Habitat Committee 2023). Given agreement on what abundance index should be predicted, indicator-based forecasts could probably be developed within a year using the current suite of indicators, though there could be scope to explore additional indicators over a longer time frame as well.

6.3 Harvest Planning Model

The WG decided that its current membership does not have sufficient expertise to lead development of alternatives to the SHM. The WG also noted the need to coordinate changes to the SHM with changes to the harvest models used for other California stocks (KOHM and WRHM) and noted the challenges posed by using past performance to predict future results given the novel elements of the newly implemented California Coastal Chinook consultation standard. The WG highlighted the potential value of involving social scientists in revising models for predicting fishing effort. The WG notes that some of its potential alternatives for escapement reference points could change the units from total fish to fish returning to natural areas. Making this change would require accompanying changes to the Harvest Control Rule, and possibly changes to the harvest planning models to predict natural-area rather than total escapement.

7 POTENTIAL APPROACHES TO ANALYZING ALTERNATIVES

Most of the WG's discussion at its first meeting focused on understanding existing management measures and models, identifying areas of concern, and identifying potential alternative approaches. However, the WG did briefly discuss the methods that might be employed to analyze biological risks and fishery related benefits of alternative approaches.

Previous PFMC rebuilding plans have employed an analytical technique developed by O'Farrell and Satterthwaite (2021) to project harvest and escapement levels under alternative strategies. The methods developed were intentionally simple and limited in their data requirements, and assume no link between spawning escapement in one generation and recruitment in the next generation. This limits their suitability for exploring the effects of different strategies around natural-area escapement, especially over long time horizons. However, elements of the approach, and the metrics tracked, could be adapted to a model that accounts for the effects of natural-area spawning on future production. Or, analyses could focus on the consequences of different strategies as retrospectively applied for single years in the past, with an attempt to account for mixed-stock constraints (Satterthwaite and Shelton 2023).

To account for the effects of spawning escapement on future production, a lifecycle model approach would be preferred. A fully developed life cycle model for SRFC at the scale needed for this effort does not seem to currently exist, but elements could be borrowed from multiple existing models (e.g., Friedman et al. 2019, Peterson and Duarte 2020, Carvalho et al. 2023) and ongoing projects such as the Central Valley Project Improvement Act Science Integration Team, and lifecycle modeling efforts underway at the Northwest (e.g. Beechie et al 2022) and Southwest Fisheries Science Centers.

The WG would be best positioned to evaluate the risks and benefits associated with alternative approaches if it was provided with resources to pursue a comprehensive lifecycle modeling approach over multiple years. This could benefit from coordination (and perhaps pooling of resources) with the KRFC WG as it tackles similar tasks, and other groups working on Central Valley Chinook lifecycle models.

8 WORKGROUP QUESTIONS FOR COUNCIL

The WG has identified a range of options that vary in their timelines for completion, as well as the amount of novel work involved, which are summarized in Section 10. The WG appreciates both the immediate issues identified in its own and earlier reviews of the current management measures as well as the need to develop an approach that can be applied over the long term in the face of climate change and environmental variability. Hence, the WG is requesting feedback from the Council on the longevity of the WG and the prospects for developing longer-term approaches in addition to relatively short-term modifications.

Regardless of the expected timeline, the FMP presents conflicting guidelines for improving management alternatives. Addressing two major issues will help clarify some of these priorities.

1. When considering different options for S_{MSY} proxies and/or conservation objectives, the **WG noted apparently contrasting requirements in the FMP to focus on maximizing yield versus production (which cannot both be maximized simultaneously)**, and wondered about the literal intent to "maximize" production in some absolute sense as opposed to "optimize" the tradeoff between trying to achieve high levels of natural production without unduly constraining fisheries. The WG notes a potential parallel with language around "minimizing" bycatch, when in fact the goal is not to minimize bycatch (which could be set to zero by simply not fishing) but to keep bycatch at some acceptably low level while allowing fisheries to proceed. **The WG wonders if a similar optimal but not necessarily maximal level of natural production could be identified and serve as the basis of the conservation objective and possibly S_{MSY} proxy.**

2. The WG also noted confusion arising from the mix of hatchery and natural origin fish constituting the SRFC stock and the difficulty directly linking natural area escapement to future yield as a result (see Appendix A). **If the emphasis is on maximizing yield, should that be yield of natural-origin fish (analogous to the approach for KRFC) or yield of the hatchery-natural aggregate? If the emphasis is on natural production, how should consideration be given to the need for sufficient hatchery broodstock?** The WG notes that many other stocks in the FMP are defined separately for hatchery versus natural components, and FMP guidance speaks directly to hatchery stocks and natural stocks, leaving the approach for composite stocks somewhat unclear. While the FMP does include several salmon stocks that are managed on an aggregate basis, and/or managed for natural-area, or natural-origin escapement, SRFC appear to be unique in their management as the total escapement metric used also includes hatchery returns. The WG discussed the possibility of moving to a conservation objective and S_{MSY} reference point measured in terms of natural-area spawners, but also noted that it could be possible to still define these quantities in terms of total spawners while basing the total spawner numbers on more explicit consideration of what levels of natural-area escapement would be expected at those levels of total escapement. Natural production may be important to considerations beyond yield, such as population stability and predictability of fishing opportunity (Hilborn et al. 2003, Carlson and Satterthwaite 2011) as well as risk of changes in Endangered Species Act listing of SRFC and/or co-occurring stocks that could constrain fisheries if listing status worsened or increase fishing opportunity if listing status improved. The California Hatchery Scientific Review Group report (CA HSRG 2010) recognized the importance of incorporating naturally produced fish into hatchery broodstock to prevent hatcheries from exerting selective pressures on natural populations and in trying to function as integrated programs. The WG notes that despite this incorporation of naturally produced fish, hatchery production will have a very different recruitment rate to ocean fisheries compared to natural production due to different rearing and emigration experiences creating issues in evaluating natural area escapement as it relates to recruitment and in evaluating yield. Changes in hatchery production over time and subsequent hatchery origin representation relative to representation of natural origin fish on spawning grounds can exacerbate this.

Once the WG has clarity on these policy priorities, the WG can identify which alternatives are most consistent with achieving them. After identifying the alternatives that address policy preferences, the WG recommends moving forward with the shorter term alternatives and developing a workplan that bridges work toward longer term approaches

9 WORKGROUP NEEDS - RESOURCES AND EXPERTISE

WG discussions highlighted the value of lifecycle models, both in terms of potentially turning estimates of juvenile production into estimates of recruits to the fishery for better-supported derivation of S_{MSY} and/or conservation objectives, and in terms of evaluating the long-term consequences of changes in natural-area escapement levels for future production and yield. The WG encourages addition of expertise in lifecycle modeling, coordination with the KRFC WG, and coordination with external lifecycle modeling efforts such as the Central Valley Project Improvement Act Science Integration Team, and lifecycle modeling efforts underway at the Northwest and Southwest Fisheries Science Centers.

WG discussions highlighted the need for expertise in water management and prediction of future water conditions, carryover, and water release practices.

Some of the possible changes noted in this report will necessarily involve concurrence by the STT. Therefore, the WG encourages further coordination with the STT on reviews and changes of methodologies, including feedback on this report, especially on the potential alternatives provided in Section 10.

The WG notes that in March 2024, the "Ad Hoc Ecosystem Workgroup (EWG) was given direction to work with NMFS Science Center staff to further develop the methodological framework for risk tables. As part of developing the risk table methodology, their application should be broadened to include selected salmon stocks" suggests there could be benefits to coordination between the EWG and WG. Since this Council direction came after the WG's first meeting, the WG has not had the opportunity to fully discuss this topic and would look forward to a presentation from the EWG on elements of the risk table approach and the factors it considers, along with quantitative analyses associated with risk tables that might inform management measures or control rules.

10 SUMMARY TABLE OF POTENTIAL ALTERNATIVE APPROACHES

Section	Potential Alternative Approach	Timeline[a/]	Pros	Cons
		S_{MSY}		
4.2.1	Eliminate lower bound of conservation objective, setting S_{MSY} equal to sole remaining value	Short term: instant	Would address "interim" nature of lower bound, permanent opening of RBDD.	Does not address basis for upper bound.
4.2.2	Update the mean escapements and hatchery goals summed to derive the upper bound of the existing conservation objective	Short term: 1 month	Would address errors and non-reproducibility in existing values. Could update to more recent years.	Would still lack compelling scientific justification for approach (SSC 2022). Values prior to 1971 would require an adjustment factor for jacks.
4.2.3	Derive S_{MSY} from spawner-recruit (S-R) relationship (multiple sub-options)	Varies, see below	Would be consistent with FMP definition of S_{MSY}.	Theoretically coherent estimation of MSY (but not maximum production) is not possible with confounding by hatchery strays.
4.2.3, 4.1.2	Based on S_{MSY} from S-R analysis based on recruitment surrogate (SI-based)	Short term: (Satterthwaite unpublished)	Would be consistent with FMP definition of S_{MSY}. Less analytically demanding than cohort reconstruction. Scale age data not needed.	Theoretically coherent estimation of MSY is not possible with confounding by hatchery strays. Year-specific estimates of recruitment less accurate than those based on a cohort reconstruction. Would require shifting units to natural-area rather than total escapement, or an adjustment factor to retain current units of total escapement. Limited years with suitable data available, covering limited range of environmental conditions. Required data streams may not be available to update in future.
4.2.3, 4.1.3	Based on S_{MSY} from S-R analysis based on cohort reconstruction	Short term: 3 months	Would be consistent with FMP definition of S_{MSY}. Cohort reconstruction should provide best year-specific estimates of recruits.	Theoretically coherent estimation of MSY is not possible with confounding by hatchery strays. Limited years with suitable data available, covering limited range of environmental conditions. Required data streams may not be available to update in future
4.2.4	Based on S_{MSY} from S-R analysis based on expansion from juvenile production data	Long term: 1-2 years for lifecycle model/juvenile to adult expansion, remainder complete (Satterthwaite 2023)	Would be consistent with FMP definition of S_{MSY}. Juvenile production data available from more years and broader range of conditions than cohort reconstruction. Updating would be more robust to potential disruptions of data streams in future.	Theoretically coherent estimation of MSY is not possible with confounding by hatchery strays. Requires means for extrapolating adults recruits from juvenile production (e.g. lifecycle model). May require conversion from units of total escapement to escapement on scales matching juvenile production data.

Section	Potential Alternative Approach	Timeline[a/]	Pros	Cons
		S_{MSY} *(continued)*		
4.2.5	Based on escapement maximizing production (S_{MAX}) from spawner-juvenile production analysis	Short term: already complete (Satterthwaite 2023)	Would be consistent with p. 51 of FMP. Theoretically, coherent estimation is possible even with confounding by hatchery strays. Juvenile production data available from more years and broader range of conditions than cohort reconstruction. Updating would be more robust to potential disruptions of data streams in future.	Maximizing production does not maximize yield. If productivity is very low, the escapement that maximizes production may not be capable of self-replacement. May require conversion from units of total escapement to escapement on scales matching juvenile production data.
4.2.6	Based on escapement optimizing production from spawner-juvenile production analysis	Short term or unknown: 1-3 months to identify optimal fraction from literature review, unknown timeline for policy-driven optimum, remaining analyses complete (Satterthwaite 2023)	Consistent with p. 51 of FMP if "maximize" is interpreted as "come close to maximizing, while allowing for fishery considerations". Optimal fraction could be based on literature review of relationships between S_{MSY} and S_{MAX} for other systems where S_{MSY} can be robustly estimated.	Requires defining an optimal fraction of maximum production. May require conversion from units of total escapement to escapement on scales matching juvenile production data.
4.2.7	Proxy based on inland harvest opportunity	Long term: Analyses relating river run size to inland harvest already exist, policy aspects of defining desired inland harvest opportunity could be protracted	Consistent with additional considerations listed on p. 51 of FMP.	Requires defining a desired level of inland harvest.
4.2.8	Proxy based on habitat	Long term: multi-year	Numerous potential data sources and analyses to draw from.	Depends on proxy. Would require conversion from units of total escapement to escapement on scales matching habitat analyses.
4.29	Include consideration of San Joaquin and/or late-fall	Long term: multi-year	Mokelumne fish have made large contributions to harvest lately.	Increasing analytical needs, new preseason planning tools needed.
4.2.10	Year-specific estimates	not recommended	Some well-documented environmental effects on productivity, and highly plausible hypotheses for other effects.	MSY is defined as a long-term average. Would need to forecast environmental conditions that returning spawners from relevant cohorts would face.
		F_{MSY}		

Section	Potential Alternative Approach	Timeline[a/]	Pros	Cons
4.1.1	Updated proxy	Short term: 6 months based on existing literature, 1-2 years adding new analyses	More representative of SRFC and current conditions.	Still a proxy.
4.1.2	Spawner-recruit analysis based on abundance surrogate	Short term: 1 day to extract from an analysis that has already been done (Satterthwaite unpublished)	Would be consistent with FMP definition of S_{MSY}. Less analytically demanding than cohort reconstruction. Scale age data not needed.	Theoretically coherent estimation of MSY is not possible with confounding by hatchery strays. Year-specific estimates of recruitment less accurate than those based on a cohort reconstruction. Would require shifting units to natural-area rather than total escapement, or an adjustment factor to retain current units of total escapement. Limited years with suitable data available, covering limited range of environmental conditions. Required data streams may not be available to update in future.
4.1.3	Spawner-recruit analysis based on cohort reconstruction	Short term: 1-3 months	Cohort reconstruction should provide best year-specific estimates of recruits.	Theoretically coherent estimation of MSY is not possible with confounding by hatchery strays. Would require shifting units to natural-area rather than total escapement, or an adjustment factor to retain current units of total escapement. Limited years with suitable data available, covering limited range of environmental conditions. Required data streams may not be available to update in future.
4.1.4	Tributary-specific estimates	Long term multi-year	Tributaries and hatcheries likely differ in their productivities and thus harvest rates they can sustain.	Sufficient data to estimate may not exist. Limited ability of ocean fisheries to differentially exploit different tributaries.
4.1.5	Year-specific estimates	not recommended	Some well-documented environmental effects on productivity, and highly plausible hypotheses for other effects.	MSY is defined as a long-term average. Would need to forecast environmental conditions that returning spawners from relevant cohorts would face.
F_{ABC}				
3.1	0.90 x updated F_{MSY}	Short term: instant, once F_{MSY} updated	Required by FMP if F_{MSY} remains based on proxy	Basis of multiplier unclear
3.1	0.95 x updated F_{MSY}	Short term: instant, once F_{MSY} updated	Required by FMP if F_{MSY} estimated from SRFC-specific analysis	Basis of multiplier unclear
MSST				

Section	Potential Alternative Approach	Timeline[a/]	Pros	Cons
4.3	0.75 x updated S_{MSY}	Short term: instant, once S_{MSY} updated	Consistent with current MSST definition for SRFC	Basis of multiplier unclear
4.3	0.5 x updated S_{MSY}	Short term: instant, once S_{MSY} updated and multiplier consistent with FMP is decided upon	minimum allowed MSST under FMP	basis of multiplier unclear
4.3	Q x updated S_{MSY} where Q any value ≥0.5	Long term multi-year	consistent with FMP, multiplier could be based on quantitative analysis	-
Conservation Objective				
4.4	All the S_{MSY} options listed above apply here as well	see S_{MSY} options	see S_{MSY} options	see S_{MSY} options
Harvest Control Rule				
4.5.1	Effects of updated reference points	Short term: Instant upon any reference point update	Control rule uses S_{MSY}, MSST, and F_{ABC} as inputs, so changes to any of them would change numeric outputs of control rule	-
4.5.2	Year-specific escapement targets	Long term: multi-year	Some well-documented environmental effects on productivity, and highly plausible hypotheses for other effects.	Would require accurate forecasting of environmental conditions faced by offspring of returning spawners.
4.5.3	Alternative shapes to control rule		*De minimis* fisheries could be more or less frequently required if S_MSY was updated. Alternate forms could be less sensitive to forecast error. Could incorporate consideration of production or inland harvest, consistent with p. 51 of FMP.	Analytical burden deriving new shapes and analyzing potential consequences.
4.5.4	Incorporation of uncertainty-buffers	Varies: One approach has already been fully described, and the impacts of applying it to SRFC analyzed (Satterthwaite and Shelton 2023). Other approaches could involve multi-year efforts.	Consistent with p. 13 of FMP (definition of OY "taking into account the effects of uncertainty and management imprecision"). Consistent with Council action under Agenda Item H2 in March 2024. Reduced risk of overfishing or overfished status. Reduced duration of overfished status. Increased natural production. Reduced risk of future ESA-listing.	Reduced fishing opportunity in short-term, and possibly in long-term depending on effects of increased natural production

a/ Technical aspects only, approximate.

11 REFERENCES CITED

Adkison, M.D. 2022. A review of salmon spawner-recruitment analysis: The central role of the data and its impact on management strategy. Reviews in Fisheries Science & Aquaculture 30:391-427. https://www.tandfonline.com/doi/full/10.1080/23308249.2021.1972086

Auerbach, D., T. Buehrens, and N. W. Kendall. 2021. A proposed forecast methodology for natural-origin Willapa Bay Coho (*O. kisutc*h). Report to Pacific Fishery Management Council. https://www.pcouncil.org/documents/2021/10/f-1-attachment-3-a-proposed-forecast-methodolo-for-natural-origin-willapa-bay-coho-o-kisutch-electronic-only.pdf

[CA HSRG] California Hatchery Scientific Review Group. 2012. California hatchery review report. Prepared for the US Fish and Wildlife Service and Pacific States Marine Fisheries Commission. https://swfsc-publications.fisheries.noaa.gov/publications/CR/2012/2012California.pdf

Carvalho, P., W. H. Satterthwaite, M. R. O'Farrell, C. Speir, and E. P. Palkovacs. 2023. Role of maturation and mortality in portfolio effects and climate resilience. Canadian Journal of Fisheries and Aquatic Sciences 80:924-941. https://doi.org/10.1139/cjfas-2022-0171

[CDFW] California Department of Fish and Wildlife 2023. California Department of Fish and Wildlife Report on Salmon Methodology Review Final Topic Selection. Report to Pacific Fishery Management Council. https://www.pcouncil.org/documents/2023/08/c-2-a-supplemental-cdfw-report-1-2.pdf/

Chen E. K., W. H. Satterthwaite, B. J. Kormos, R. C. Johnson, C. C. Phillis CC, and S. M. Carlson. 2023. Age structure of natural versus hatchery-supplemented endangered Chinook Salmon and implications for fisheries management in California. Marine Ecology Progress Series 723:37-55. https://doi.org/10.3354/meps14446

Confer, T., and M. Falcy. 2014. Conservation Objective for Southern Oregon Coastal Chinook. Report to Pacific Fishery Management Council. https://www.pcouncil.org/documents/2014/11/f-salmon-management-november-2014.pdf/#page=123

Dean, A., B. Kormos, and P. McHugh. 2020. Scale Age Project Status Update. California Department of Fish and Wildlife Report, Marine Region, Ocean Salmon Project.

Dean, A., and C. Lindley. 2023. Recovery of Coded-Wire Tags from Chinook Salmon in California's Central Valley Escapement, Inland Harvest, and Ocean Harvest in 2020. Cal. Depart. Fish and Wildlife and Pacific States Marine Fisheries Comm. CDFW Ocean Salmon Project, 3637 Westwind Blvd Santa Rosa, CA 95403. https://www.calfish.org/Portals/2/Programs/CentralValley/CFM/docs/2020_CFM_CWT_Report.pdf

[DWR] California Department of Water Resources. 2005. G-AQUA2: Aquatic Resources Methodology. Oroville Facilities Relicensing FERC Project 2100. California Department of Water Resources, Sacramento, CA.

Friedman, W. R., B. T. Martin, B. K. Wells, P. Warzybok, C. J. Michel, E. M. Danner, and S. T. Lindley. 2019. Modeling composite effects of marine and freshwater processes on migratory species. Ecosphere 10(7):e02743. https://dx.doi.org/10.1002/ecs2.2743

[HC] Habitat Committee of the Pacific Fishery Management Council. 2023. Habitat indicators of Klamath and Sacramento salmon stocks: Stoplight tables for Sacramento River and Klamath River fall Chinook salmon. Report to Pacific Fishery Management Council. https://www.pcouncil.org/documents/2023/02/e-1-a-hc-report-1-habitat-indicators-of-klamath-and-sacramento-salmon-stocks.pdf/

Hinch, S. G., N,. N. Bett, E. J. Eliason, A. P. Farrell, S. J. Cooke, and D. A. Patterson. 2021. Exceptionally high mortality of adult female salmon: a large-scale pattern and a conservation concern. Canadian Journal of Fisheries and Aquatic Sciences 78:639–654. https://dx.doi.org/10.1139/cjfas-2020-0385

Kope, R. C. 1992. Optimal harvest rates for mixed stocks of natural and hatchery fish. Canadian Journal of Fisheries and Aquatic Sciences 49: 931-938. https://swfsc-publications.fisheries.noaa.gov/publications/CR/1992/9255.PDF

Kormos B, M. Palmer–Zwahlen, and A. Low. 2012. Recovery of coded-wire tags from Chinook Salmon in California's Central Valley escapement and ocean harvest in 2010. California Department of Fish and Game Fisheries Branch Administrative Report 2012–02. https://nrm.dfg.ca.gov/FileHandler.ashx?DocumentID=162355

[KRWG] Klamath River Fall Chinook Workgroup of the Pacific Fishery Management Council. 2024. Report to the Pacific Fishery Management Council on Klamath River Fall Chinook Interim Management Measures for Ocean Salmon Fisheries in 2024 and Potentially Beyond. Report to Pacific Fishery Management Council. https://www.pcouncil.org/documents/2024/02/agenda-item-c-4-a-supplemental-krwg-report-2-report-to-the-pacific-fishery-management-council-on-klamath-river-fall-chinook-interim-management-measures-for-ocean-salmon-fisheries-in-2024-and-potentia.pdf/

Leeman, C., S. Conley, M. Sorel, and T. Buehrens. 2023. An evaluation of preseason ocean abundance forecasts for Oregon Production Area hatchery Coho salmon. Report to Pacific Fishery Management Council. https://www.pcouncil.org/documents/2023/10/d-3-attachment-1-methodology-review-materials-electronic-only.pdf/#page=29

Leising, A., M. Hunsicker, N. Tolimieri, G. Williams, and A. Harley. 2024. 2023-2024 California Current Ecosystem Status Report. A report of the NOAA California Current Integrated Ecosystem Assessment Team (CCIEA) to the Pacific Fishery Management Council. https://www.pcouncil.org/documents/2024/02/agenda-item-h-1-a-cciea-team-report-1-2023-2024-california-current-ecosystem-status-report-electronic-only.pdf/

Mantua, N., R. Johnson, J. Field, et al. 2021. Mechanisms, impacts, and mitigation for thiamine deficiency and early life stage mortality in California's Central Valley Chinook salmon. North Pacific Anadromous Fish Commission Technical Report 17:92–93. https://npafc.org/wp-content/uploads/technical-reports/Tech-Report-17-DOI/28_Mantua-et-al.pdf

Martin, B. T., A. Pike, S. N. John, N. Hamda, J. Roberts, S. T. Lindley, and E. M. Danner, E.M. 2017. Phenomenological vs. biophysical models of thermal stress in aquatic eggs. Ecology Letters 20: 50-59. https://dx.doi.org/10.1111/ele.12705

Meek, M. H., M. R. Stephens, A. Goodbla, B. May, and M. R. Baerwald. 2020. Identifying hidden biocomplexity and genomic diversity in Chinook salmon, an imperiled species with a history of anthropogenic influence. Canadian Journal of Fisheries and Aquatic Sciences 77:534-547. https://dx.doi.org/10.1139/cjfas-2019-0171

Mohr, M. S.. 2006. Klamath River fall Chinook assessment: overview. Unpublished report. Santa Cruz (CA): National Marine Fisheries Service. Available from: Michael R. O'Farrell, National Marine Fisheries Service, 110 McAllister Way, Santa Cruz, CA 95060, USA.

Mohr, M. S., W. H. Satterthwaite, D. G. Hankin, P. A. Bisson, C. B. Grimes, S. Hamelberg, D. C. Hillemeier, S. T. Lindley, A. Low, M. L. Palmer–Zwahlen, S. Smith, and T. H. Williams. 2017. Evaluation of alternative marking/tagging systems for hatchery produced California fall-run Chinook salmon. NOAA Technical Memorandum NMFS-SWFSC-571. https://repository.library.noaa.gov/view/noaa/14328

Munsch, S. H., C. M. Greene, R. C. Johnson, W. H. Satterthwaite, H. Imaki, and P, L. Brandes. 2019. Warm, dry winters truncate timing and size distribution of seaward-migrating salmon across a large, regulated watershed. Ecological Applications 29(4):e01880. https://doi.org/10.1002/eap.1880

Munsch, S. H., C. M. Greene, R. C. Johnson, W. H. Satterthwaite, H/ Imaki, P. L. Brandes, and M. R. O'Farrell., 2020. Science for integrative management of a diadromous fish stock: interdependencies of fisheries, flow, and habitat restoration. Canadian Journal of Fisheries and Aquatic Sciences 77:1487–1504. https://doi.org/10.1139/cjfas-2020-0075

[NMFS] National Marine Fisheries Service. 2022. National Marine Fisheries Service Report, Fisheries Science Center Activities. Available from: https://www.pcouncil.org/documents/2022/03/d-1-a-supplemental-nmfs-report-1.pdf#page=4

[NMFS] National Marine Fisheries Service. 2023a. Relationship of the Management Framework for California Coastal Chinook Salmon (CC Chinook) to the Re-initiated ESA Consultation for CC Chinook. Report to Pacific Fishery Management Council. https://www.pcouncil.org/documents/2023/10/d-4-a-supplemental-nmfs-report-1-relationship-of-the-management-framework-for-california-coastal-chinook-salmon-cc-chinook-to-the-re-initiated-esa-consultation-for-cc-chinook/

[NMFS] National Marine Fisheries Service. 2023b. Draft Regulatory Language Implementing the California Coastal Chinook Management Framework.. Report to Pacific Fishery Management Council. https://www.pcouncil.org/documents/2023/10/d-4-a-supplemental-nmfs-report-2-draft-regulatory-language-implementing-the-california-coastal-chinook-management-framework.pdf/

O'Farrell, M. R., M. S. Mohr, A. M. Grover, and W. H., Satterthwaite. 2012. Sacramento River winter Chinook cohort reconstruction: analysis of ocean fishery impacts. NOAA Technical Memorandum NMFS-SWFSC-491. https://repository.library.noaa.gov/view/noaa/4474

O'Farrell, M. R., M. S. Mohr, M. L. Palmer-Zwahlen,and A. M. Grover. 2013. The Sacramento Index (SI). NOAA Technical Memorandum NOAA-TM-NMFS- SWFSC-512. https://repository.library.noaa.gov/view/noaa/4449

O'Farrell, M.R., and W. H. Satterthwaite. 2021. A rebuilding time model for Pacific salmon. Fisheries Research 238:105900 https://doi.org/10.1016/j.fishres.2021.105900

Peterson, J. T. and A. Duarte. 2020. Decision analysis for greater insights into the development and evaluation of Chinook Salmon restoration strategies in California's Central Valley. Restoration Ecology 28:1596–1609. https://doi.org/10.1111/rec.13244

[PFMC] Pacific Fishery Management Council. 1984. Framework amendment for managing the ocean salmon fisheries off the coasts of Washington, Oregon and California commencing in 1985. Pacific Fishery Management Council, 7700 NE Ambassador Place, Suite 101, Portland, Oregon 97220-1384. https://www.pcouncil.org/documents/1995/10/final-framework-amendment-for-managing-the-ocean-salmon-fisheries-off-the-coasts-of-washington-oregon-and-california-commencing-in-1985.pdf/

[PFMC] Pacific Fishery Management Council. 2019. Salmon Rebuilding Plan for Sacramento River Fall Chinook. Pacific Fishery Management Council, 7700 NE Ambassador Place, Suite 101, Portland, Oregon 97220-1384. https://www.pcouncil.org/documents/2019/07/sacramento-river-fall-chinook-salmon-rebuilding-plan-regulatory-identifier-number-0648-bi04-july-2019.pdf/

[PFMC] Pacific Fishery Management Council. 2022. Pacific Coast Salmon Fishery Management Plan for commercial and recreational salmon fisheries off the coasts of Washington, Oregon, and California as amended through Amendment 22. Pacific Fishery Management Council, 7700 NE Ambassador Place,
Suite 101, Portland, Oregon 97220-1384. https://www.pcouncil.org/documents/2022/12/pacific-coast-salmon-fmp.pdf/

[PFMC} Pacific Fishery Management Council. 2024a. Review of 2023 Ocean Salmon Fisheries: Stock Assessment and Fishery Evaluation Document for the Pacific Coast Salmon Fishery Management Plan. (Document prepared for the Council and its advisory entities.) https://www.pcouncil.org/documents/2024/02/review-of-2023-ocean-salmon-fisheries.pdf/

[PFMC] Pacific Fishery Management Council. 2024b. Preseason Report I: Stock Abundance Analysis and Environmental Assessment Part 1 for 2024 Ocean Salmon Fishery Regulations. (Document prepared for the Council and its advisory entities.) Pacific Fishery Management Council, 7700 NE Ambassador Place, Suite 101, Portland, Oregon 97220-1384. https://www.pcouncil.org/documents/2024/03/2024-preseason-report-i.pdf/

[PFMC and NMFS] Pacific Fishery Management Council and National Marine Fisheries Service. 2011. Environmental assessment for Pacific coast salmon plan amendment 16: classifying stocks, revising status determination criteria, establishing annual catch limits and accountability measures, and de minimis fishing provisions. Pacific Fishery Management Council, 7700 NE Ambassador Place, Suite 101, Portland, Oregon 97220-1384. https://www.pcouncil.org/documents/2011/12/salmon-fmp-amendment-16-environmental-assessment-and-regulatory-impact-review.pdf/

Poxon, B, and P. Bratovich. 202. 2020 Update Lower Yuba River Vaki Riverwatcher™ Chinook Salmon Passage and Run Differentiation Analyses. Prepared for Yuba Water Agency, 1220 F Street, Marysville, CA 950901.

SAC [Salmon Amendment Committee] 2009. Report of the Salmon Amendment Committee overview of scoping considerations for Salmon Fishery Management Plan Amendment 16. https://www.pcouncil.org/documents/2009/09/g-salmon-management-september-2009.pdf/#page=14

Satterthwaite, W. H. 2022. Literature Review for Sacramento River Fall Chinook Conservation Objective and Associated SMSY Reference Point. Report to Pacific Fishery Management Council. https://www.pcouncil.org/documents/2022/10/d-2-attachment-1-methodology-review-materials-electronic-only.pdf/#page=50

Satterthwaite, W. H. 2023. An approach to defining a Sacramento River Fall Chinook escapement objective considering natural production, hatcheries, and risk tolerance. San Francisco Estuary and Watershed Science 21(3):3. https://doi.org/10.15447/sfews.2023v21iss3art3

Satterthwaite W. H. and A. O. Shelton. 2023. Methods for assessing and responding to bias and uncertainty in US West Coast salmon abundance forecasts. Fisheries Research 257:106502. https://doi.org/10.1016/j.fishres.2022.106502

Satterthwaite, W. H., E. K. Chen, T. R. McReynolds, A. E. Dean, S. D. Allen, & M. R. O'Farrell. 2023. Comparing fishery impacts and maturation schedules of hatchery-origin versus natural-origin fish from a threatened Chinook salmon stock. San Francisco Estuary and Watershed Science 21(4):3. https://doi.org/10.15447/sfews.2023v21iss4art3

[SSC] Scientific and Statistical Committee of the Pacific Fishery Management Council. 2022. Scientific and Statistical Committee Report on Final Methodology Review. Report to Pacific Fishery Management Council. https://www.pcouncil.org/documents/2022/11/d-2-a-supplemental-ssc-report-1-4.pdf/

[STT] Salmon Technical Team of the Pacific Fishery Management Council. 2005. Klamath River Fall Chinook Stock-Recruitment Analysis. Report to Pacific Fishery Management Council. https://www.pcouncil.org/documents/2005/09/klamath-river-fall-chinook-stock-recruitment-analysis.pdf/

[STT] Salmon Technical Team of the Pacific Fishery Management Council. 2019.

Salmon Technical Team Evaluation of Recommended Changes to Sacramento River Fall Chinook Assessment and Management. Report to Pacific Fishery Management Council. https://www.pcouncil.org/documents/2019/09/agenda-item-f-2-a-supplemental-stt-report-2.pdf/

Suring, E. 2017. 2017 Technical Revision to the Marine Survival Forecast of the OCN Coho Work Group Harvest Matrix. Report to Pacific Fishery Management Council. https://www.pcouncil.org/documents/2017/11/agenda-item-d-2-attachment-1-2.pdf/

Suring, E. and M. Lewis. 2013. 2013 Technical Revision to the OCN Coho Work Group Harvest Matrix. Report to Pacific Fishery Management Council. https://www.pcouncil.org/documents/2013/11/c-salmon-management-november-2013.pdf/#page=15

Wells, B. K., J. A. Santorra, M. J. Henderson, P. Waryzbok, et al. 2017. Environmental conditions and prey-switching by a seabird predator impact juvenile salmon survival. Journal of Marine Systems 174:54-63. http://dx.doi.org/10.1016/j.jmarsys.2017.05.008

Williamson, K. S. and B. May. 2005. Homogenization of fall-run Chinook salmon gene pools in the Central Valley of California, USA. North American Journal of Fisheries Management 25:993-1009. https://doi.org/10.1577/M04-136.1

Winship, A. J., M. R. O'Farrell, W. H. Satterthwaite, B. K. Wells, and M. S. Mohr. 2015. Expected future performance of salmon abundance forecast models with varying complexity. Canadian Journal of Fisheries and Aquatic Sciences 72:557–569. https://doi.org/10.1139/cjfas-2014-0247

12 APPENDIX A - THEORETICAL BASIS OF MSY-ASSOCIATED REFERENCE POINTS

This appendix describes the theory behind the spawner-recruit analyses typically deployed for Council-area salmon stocks. This is meant to highlight the distinction between maximizing production and maximizing yield, and also to highlight the difficulties in interpreting MSY when significant numbers of hatchery-origin fish spawn in natural areas.

Analyses of MSY in PFMC-managed salmon stocks have typically assumed a Ricker spawner-recruit relationship where the number of spawners (S) in the parent generation drives the number of recruits (R, potential spawners in the absence of fishing) for the next generation (Figure A1a, solid curve) as follows:

$$R = \alpha S e^{-\beta S}$$

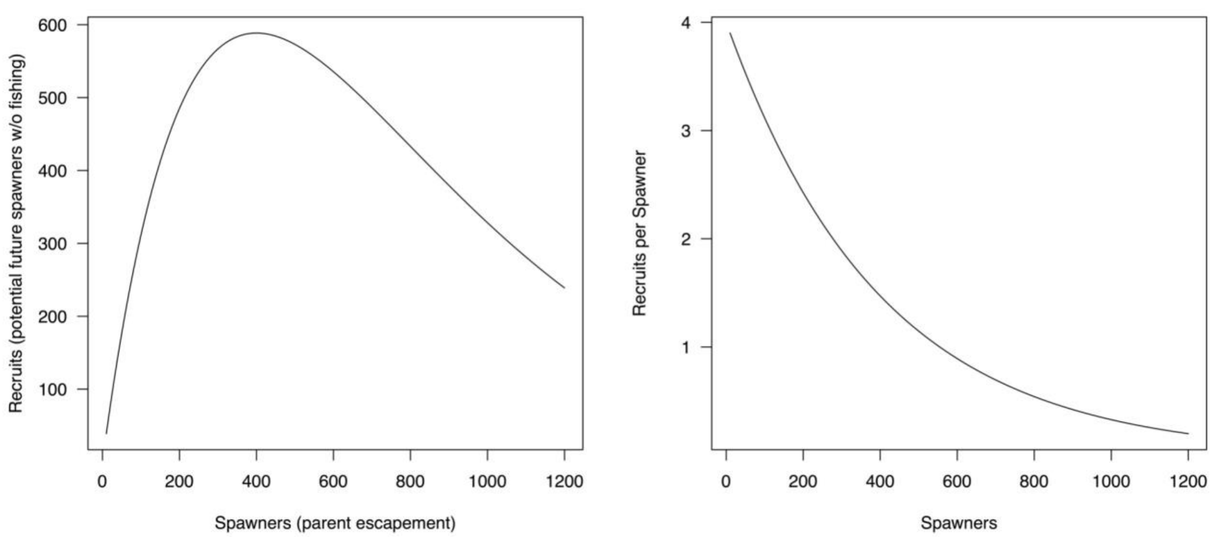

Figure A1. *Ricker spawner-recruit relationship at the population (a) or per spawner (b) level. The solid curve denotes the number of recruits (y-axis) predicted to be produced at any level of parent escapement (x-axis). The plotted curve is not driven by data for any stock and the values used for α and β were chosen arbitrarily for illustrative purposes.*

This formulation assumes that at very low spawner densities, competition with other spawners is minimal and recruits per spawner is at its maximum value, given by α. The β term drives how fast per capita production of recruits (Figure A1b) increases with increasing density, and maximum total production occurs at $\frac{1}{\beta}$ (denoted by the blue line in Figure A2). Note that other plausible formulations for the spawner-recruit relationship exist, and any model is a simplified abstraction (Adkison 2022),

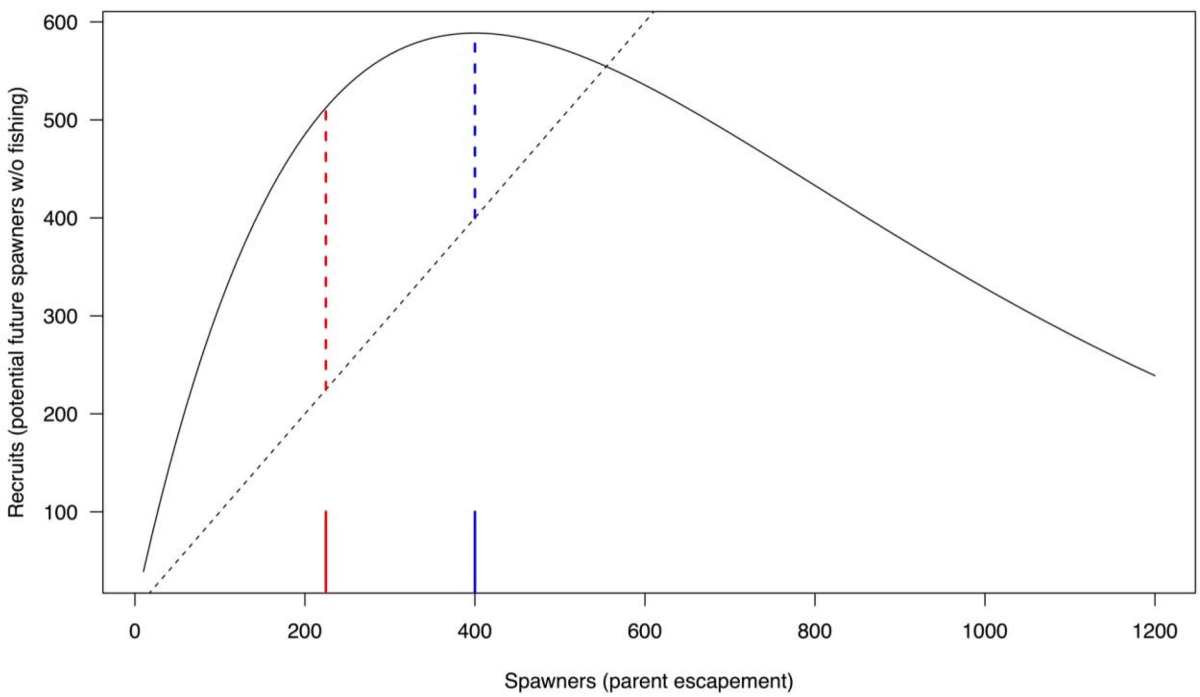

Figure A2*. Target escapement levels maximizing production or sustainable yield for a Ricker spawner-recruit relationship. The dotted line is the 1:1 line where spawners and recruits are equal. The solid blue line denotes the escapement maximizing production (S_{MP}) and the height of the dashed blue line denotes the expected yield from targeting escapement equal to S_{MP}. The solid red line denotes the escapement maximizing sustainable yield (S_{MSY}) and the height of the dashed red line denotes the yield expected from targeting escapement equal to S_{MSY} (maximum sustainable yield, MSY).*

The dotted diagonal line in Figure A2 is the 1:1 line where values on both axes are equal, and the point where the solid curve and dotted line cross is the predicted unfished equilibrium where the number of recruits expected is equal to the number of parent spawners. When the solid curve is above the 1:1 line, recruits are expected to exceed spawners and a sustainably fishable surplus is predicted to exist, with the amount of yield that can be sustained at a particular target escapement level given by the vertical distance between the solid curve and dotted line. Where the solid curve is below the 1:1 line, predicted recruits are less than the number of parent spawners and the population would be expected to decline toward the equilibrium, even in the absence of fishing.

Note that the yield at the escapement maximizing production (S_{MP}, blue line in Figure A2) is less than the yield at some lower escapements. The maximum sustainable yield (red line in Figure A2) occurs at S_{MSY}. The calculation of S_{MSY} is not as simple as calculating the escapement maximizing production, and historically S_{MSY} has often been determined using an approximate solution

(Hilborn 1985) or via numerical search algorithms, but an exact solution does exist (Scheuerell 2016).

If per capita productivity (α) changes while capacity or the strength of density dependence (β) is held constant, the value of the escapement maximizing production (S_{MP}) remains unchanged, but as per capita productivity (α) declines, S_{MSY} occurs at a smaller fraction of S_{MP} while the amount of yield at MSY decreases (Figure A3a). If capacity (β) changes while per capita productivity is held constant, S_{MSY}, S_{MP}, and MSY all increase as capacity increases or density dependence weakens (i.e., as β decreases, Figure A3b).

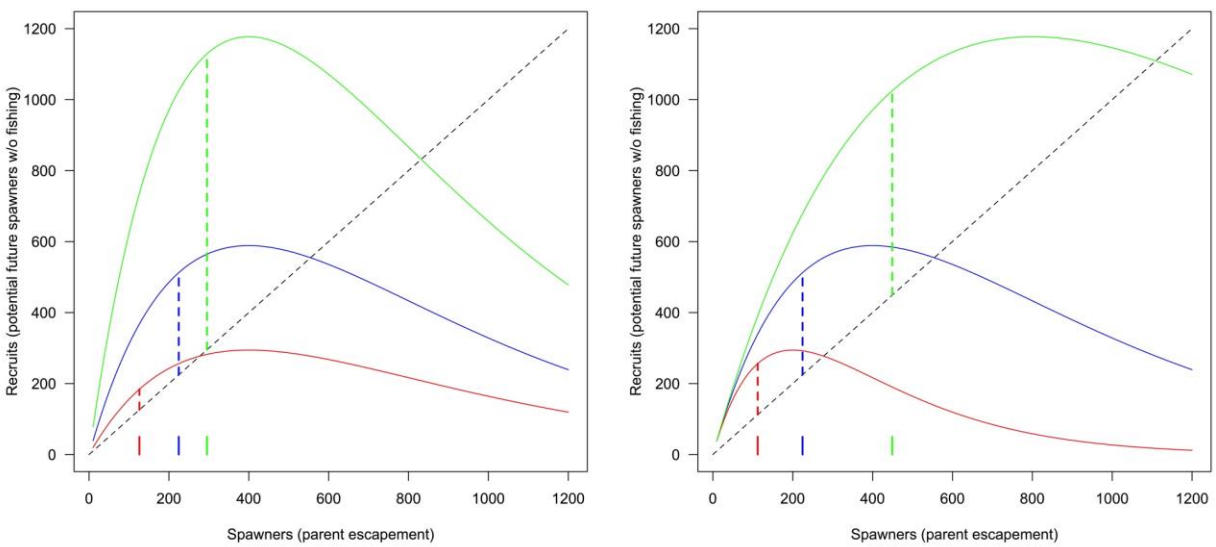

***Figure A3**. Effects of changing per capita productivity (α, left panel) or capacity/strength of density dependence (β, right panel) for a Ricker spawner-recruit relationship. In the left panel, the red curve has the lowest value for α and the green curve has the highest. In the right panel, the green curve has the lowest value for β and the red curve has the highest.*

Note that in any one year, harvest larger than the sustainable yield is possible, but is predicted to result in an escapement that leads to lower recruitment and thus lower potential yield in the future. Targeting S_{MSY} leads to the optimal tradeoff between current and future yield (assuming no discounting of future yield).

The logic behind calculating sustainable yield this way implicitly assumes that spawners are the only source of recruits that can provide for future yield. In the spawner-recruit analysis used to establish S_{MSY} for KRFC (STT 2005, p. 2), the Salmon Technical Team explicitly stated their analysis required the assumption that "[e]stimates of spawning stock and recruitment are representative of a natural stock that can be considered independent of hatchery influences." In a purely natural population, this assumption is sensible. In systems where few hatchery-origin fish stray into natural spawning areas, it is also probably approximately correct to consider natural-area spawners to be the primary source of recruitment of future natural-area spawners (as is done for KRFC, STT 2005). However, in a system (like SRFC) when a large number of hatchery-origin strays spawn in natural areas, juveniles produced from previous natural spawning events are not the only source of recruits and thus not the only drivers of potential yield and escapement. This may make interpretation of reference points from spawner-recruit relationships logically challenging unless both spawners and recruits are measured as natural-origin, natural-area spawners (or potential spawners in the absence of fishing in the case of recruits).

Note that interpretations of the natural-area escapement maximizing natural-origin production are not similarly challenged, since natural-area spawners are the only source of natural-origin production. However, if per-capita productivity is very low (e.g., red line in Figure A3a), it may be that the spawning escapement that maximizes production produces fewer recruits than are needed to achieve that same level of escapement in the next generation, even in the absence of fishing. Such a population would be expected to equilibrate at a size less than the escapement maximizing production (assuming no fishing and no hatchery supplementation).

References for Appendix A

Adkison, M.D. 2022. A review of salmon spawner-recruitment analysis: The central role of the data and its impact on management strategy. Reviews in Fisheries Science & Aquaculture 30:391-427. https://www.tandfonline.com/doi/full/10.1080/23308249.2021.1972086

Hilborn, R. 1985. Simplified calculation of optimum spawning stock size from Ricker's stock recruitment curve. Canadian Journal of Fisheries and Aquatic Sciences 42:1833-1834. https://doi.org/10.1139/f85-230

Scheuerel, M. D. 2016. An explicit solution for calculating optimum spawning stock size from Ricker’s stock recruitment model. PeerJ 4:e1623 https://doi.org/10.7717/peerj.1623

[STT] Salmon Technical Team of the Pacific Fishery Management Council. 2005. Klamath River Fall Chinook Stock-Recruitment Analysis. Report to Pacific Fishery Management Council. https://www.pcouncil.org/documents/2005/09/klamath-river-fall-chinook-stock-recruitment-analysis.pdf/