

1 **Cohort Reconstruction for Sacramento River Fall Chinook salmon and Comparison with**
2 **the Sacramento Index**

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7

8 **Abstract**

9 We conducted cohort reconstruction (CR) analysis for Sacramento River Fall Chinook (SRFC)
10 hatchery and natural-origin fish and compared cohort-based, age-specific assessments to the
11 current age-aggregated index of abundance, the Sacramento Index (SI), which currently serves as
12 both an index of adult (age-3+) ocean abundance at the start of the fishing season and of
13 potential adult escapement in the absence of fishing. Comparing estimates for run years 2010-
14 2019, the CR consistently estimated higher ocean abundance (by 16-79% with median 48%) and
15 lower potential escapement in the absence of fishing in the current management year (by 0.7-
16 24% with median 12%). The exploitation rate calculated using the SI ($1 - \text{Escapement}/\text{SI}$) was
17 higher than the terminal-year spawner reduction rate (SRR_y , calculated reduction in escapement
18 compared to the escapement expected if there was no fishing during the management year in
19 question) every year (with the first 10 years of the CR reflecting hatchery-origin fish only).
20 Primary drivers of this mismatch are likely the inability of the SI to account for non-landed
21 fishing mortality, natural mortality, and unharvested adult fish that are on a trajectory remain in
22 the ocean for another year or more before spawning. The SI calculation excludes ocean harvest
23 occurring north of Cape Falcon and only considers harvest occurring in the current management

24 year; for consistency this was also done in the initial comparison of the CR against the SI.
25 Including the ocean harvest north of Cape Falcon increased estimates of ocean harvest by 4.8%,
26 ocean impacts by 4.9%, and SRR_y by 2.3%. Considering the cumulative effects of ocean fishing
27 at younger ages increased SRR estimates by 11% and potential escapement by 19%. The SI does
28 not include any consideration of uncertainty, for the CR we employed bootstrapping routines that
29 account for the uncertainty associated with sampling for CWT and scales. Uncertainties that
30 remain unquantified include assumptions about natural mortality after the first year in the ocean,
31 release and dropoff mortality, ocean departure timing, and the equivalence of age-specific ocean
32 impact rates for hatchery- and natural-origin fish.

33

34 **Introduction**

35 Based on historical data limitations ([Buttars 2010](#), [Bergman et al. 2012](#)) related to
36 insufficient sampling and a low and variable marking (adipose fin clip) and tagging (coded-wire
37 tag, CWT) rates of hatchery-origin Sacramento River Fall Chinook (SRFC), along with some
38 hatchery release groups going completely unmarked and untagged, the Sacramento Index (SI)
39 was developed to inform its management ([O'Farrell et al. 2013](#)) in the absence of a full cohort
40 reconstruction (CR). The SI is intended to serve as an index of both adult ocean abundance at the
41 start of the fishing season and potential adult escapement in the absence of fishing in the current
42 management year, where “adult” is defined as any fish age-3 or older. The SI is calculated by
43 summing estimates of adult escapement of SRFC (to hatcheries and natural-areas combined,
44 anywhere in the Sacramento Basin but excluding strays out of the system), adult river harvest,
45 and adult ocean harvest. Consistent marking and tagging of hatchery releases (since 2007) and
46 collection of scale samples from spawner carcasses (since 2010) significantly improved the data

47 availability, and allow for the potential to estimate adult ocean abundance and potential
48 escapement using cohort-based, age-specific methods.

49 In the SI calculation, non-landed ocean fishing mortality is not accounted for except in
50 special cases involving coho-only fisheries or non-retention genetic sampling. The SI also does
51 not account for adult fish that spend more than one year in the ocean without either returning to
52 spawn or being harvested, nor does it account for natural mortality. In the SI calculation, ocean
53 harvest of SRFC is estimated indirectly via a multi-step process (see [O'Farrell et al. 2013](#) for full
54 details). The approach assumes that all ocean harvest of Chinook south of Point Arena that
55 cannot be assigned to other tagged hatchery stocks or natural-origin Klamath River Fall Chinook
56 (KRFC) is catch of SRFC, to derive a ratio of total SRFC ocean harvest south of Point Arena to
57 SRFC ocean harvest tag recoveries south of Point Arena. This ratio is applied to tag recoveries
58 between Point Arena and Cape Falcon to estimate ocean harvest of SRFC in those areas. Ocean
59 harvest occurring north of Cape Falcon is not included in the SI calculation. An SI-derived
60 exploitation rate is calculated as $ER=(SI-Escapement)/SI$ to capture an estimate of the
61 proportional reduction in escapement relative to potential escapement in the absence of fishing.

62 In contrast, a historically more data-rich situation for KRFC supported the development
63 of a fully age-structured CR applied to both the hatchery- and natural-origin components of the
64 stock (Goldwasser et al. 2001, Mohr 2006). Conditional on assumed rates of natural mortality
65 after the first year in the ocean, and assumptions about release and drop-off mortality that are
66 combined with empirical estimates of size-at-age and fishery size limits to estimate total fishing
67 mortality from landed mortality, the CR estimates the full ocean abundance by month and age for
68 the hatchery-origin component of KRFC, along with age-specific maturation rates and fishery
69 impact rates. Once the hatchery component has been reconstructed, conditional on the

70 assumption that natural-origin fish have the same age-specific ocean impact rates, natural-origin
71 cohorts are reconstructed based on estimates of age-specific natural-origin river run size
72 informed by scale age data from unmarked fish. This approach may have been reviewed as part
73 of the Salmon Methodology Review of a draft Klamath Ocean Harvest Model (KOHM) in 2001
74 ([SSC 2001](#)), and the CR component of the KOHM was specifically reviewed by the Center of
75 Independent Experts (CIE) in 2006 ([Bradford 2006](#), [Goodman 2006](#), [Pawson 2006](#)).

76 [Chen et al. \(2023\)](#) described application of the CR approach to hatchery- and natural-
77 origin Sacramento River Winter Chinook (SRWC) and added the capability to quantify the
78 uncertainty associated with sampling for CWT and scales. We confirmed that the hatchery-origin
79 component of the [Chen et al. \(2023\)](#) CR yielded equivalent results to the CR used in annual
80 management of that stock ([O'Farrell et al. 2012](#)) that was endorsed in a Salmon Methodology
81 Review in 2011 ([SSC 2011](#)). The CR offered here differs in two key conceptual ways from the
82 SRWC CR that was reviewed previously. First, it includes a natural-origin component. The
83 methodology used to reconstruct the natural-origin component is similar to that used for KRFC
84 (Mohr 2006). In addition, our approach is a substantial advance over both Mohr (2006) and
85 [O'Farrell et al. \(2012\)](#) in that it quantifies the uncertainty associated with sampling, as
86 recommended in the CIE review of the KRFC CR ([Goodman 2006](#), [Pawson 2006](#)).

87 In this report, we fully document the CR algorithms and provide the results of applying
88 them to brood years (BY) 2007-2016 and run years (RY) 2011-2019 of SRFC, for which both
89 CWT and scale age data are available. Results for BY 2016 are somewhat incomplete since age-
90 5 fish from that cohort are not included, but age-5 or older fish are rarely observed in SRFC.
91 There was a gap in sampling of ocean fisheries for CWT in early 2020 that also has a small
92 effect on BY 2016 estimates, and lack of scale reading data (along with low mark/tag rates for

93 hatchery fish prior to BY 2007) precluded full analyses for years earlier or later than those
94 analyzed here, although we do present CR results for just tagged hatchery-origin fish for BY
95 1998-2006. We do not include BY prior to 1998 because natural-area spawners were not
96 sampled for CWT prior to 2000.

97 We compare the outputs of the CR to the SI for metrics of preseason ocean abundance,
98 potential escapement in the absence of fishing, and the exploitation rate (proportional reduction
99 in escapement compared to the escapement that would have been expected in the absence of
100 fishing). For consistency with the SI, we performed these calculations excluding ocean harvest
101 north of Cape Falcon and only considering ocean fishing impacts that took place during the year
102 of return. As sensitivity analyses, we also documented the effects of including ocean fishery
103 impacts north of Cape Falcon and the effects of considering ocean fishing impacts earlier in
104 ocean residency. We also present estimates of vital rates that cannot be estimated from the SI
105 approach, namely age-specific ocean impact rates, comparisons of landed versus non-landed
106 fishing mortality, maturation rates (separately for hatchery- versus natural-origin fish), and early
107 life survival of hatchery-origin fish (survival from release until the start of ocean age-2); and
108 note a correlation between maturation rate estimates and performance of the SI forecast. For
109 estimating these biological rates that are not used directly in management, we included data on
110 harvest north of Cape Falcon in the interest of accuracy.

111

112 **Methods**

113 Study system

114 SRFC is composed of multiple populations spawning in natural spawning areas, such
115 as the upper Sacramento River, Feather River, American River, Yuba River, Battle Creek, Clear
116 Creek, and other minor tributaries of the Sacramento River, and three hatcheries: the Coleman

117 National Fish Hatchery, Feather River Hatchery, and Nimbus Fish Hatchery ([Yoshiyama et al.](#)
118 [1998](#)). SRFC is a hatchery dominated stock; the proportion of fall-run fish returning to spawning
119 grounds in the Central Valley that are of hatchery-origin averaged 76% for the 2010-2019 return
120 years ([Satterthwaite 2023](#)).

121 Data

122 Coded-wire tags (CWTs) are batch tags that have been used extensively for West Coast
123 salmonid management. CWTs have been used for hatchery-produced SRFC and recovered in
124 fisheries along the coast and at some Central Valley hatcheries since the 1970s. Surveys that
125 recovered CWTs on the spawning grounds in the Sacramento Basin began in 2000. For hatchery
126 releases in 2007-2021, all batches of hatchery fish were marked (adipose fin clip) and CWT-
127 tagged at a rate of at least 25%, and spawner surveys have become more robust, so it is possible
128 to obtain accurate estimates of escapement and harvest abundance ([Bergman et al. 2012](#))¹. Fish
129 that are implanted with a CWT have their adipose fin removed (“marked”) to denote the
130 presence of a tag. The release and recovery information of coded-wire tagged fish are reported to
131 the Regional Mark Information System (RMIS) database provided by the Regional Mark
132 Processing Center ([RMPC 2024](#)). We queried the database for recoveries of 1998-2016 brood
133 years (BY) from Coleman National Fish Hatchery, Feather River Hatchery, and Nimbus Fish
134 Hatchery.

135 In addition to coded-wire tags, scales have been collected from marked and unmarked
136 spawner carcasses during surveys and at hatcheries and aged by the California Department of

¹ Beginning in release year 2022 (brood year 2021), unmarked fry releases have taken place. Tissues have been collected from the parents of these unmarked fry releases, in theory their offspring should be identifiable via future genetic sampling of returning fish. Estimates for future years will be possible if there is sufficient genetic sampling of unmarked fish to recover parentage-based “tags” from unmarked fry releases whose parents were genotyped, or if unmarked fry releases are discontinued. Note that brood year 2021 has already been compromised by unsampled returns in 2023 and unsampled ocean harvest north of California in 2023 and 2024.

137 Fish and Wildlife since 2010. Scales were aged by an individual experienced reader. Sex and
138 length were considered only after the initial aging by the reader. Samples from CWT-tagged,
139 hatchery-origin fish with known age were read to assess for aging bias. The known age from the
140 CWT and the read age from the scale reads were used to develop a confusion matrix to adjust for
141 potential aging bias ([Kimura and Chikuni 1987](#)), so only samples from hatchery-origin fish with
142 CWTs composed the confusion matrix. Samples were grouped by tributary except for natural-
143 origin fish returning to Cow Creek, Cottonwood Creek, Mill Creek, Butte Creek, and Deer
144 Creek, which were aggregated because of limited sample sizes. These tributaries have smaller
145 abundances and generally lower hatchery presence. Scale samples were not collected in Battle
146 Creek so scale samples from unmarked escapement at Coleman National Fish Hatchery were
147 assumed to represent unmarked escapement for the entire subbasin.

148 Estimates of total SRFC escapement to major rivers and tributaries were obtained from
149 GrandTab, compiled by the California Department of Fish Wildlife ([Azat 2024](#)). Rivers with
150 escapement estimates for the years of our study were the Sacramento River, Feather River,
151 American River, Yuba River, Clear Creek, Battle Creek, Cottonwood Creek, Butte Creek, Mill
152 Creek, Deer Creek, and Cow Creek. Minor tributaries with infrequent sampling (e.g., Paynes
153 Creek, Bear Creek) were not included in the analysis.

154 Age-Specific Escapement and Fishery Impacts

155 Escapement to the spawning grounds of each tributary can include 1) marked and CWT
156 tagged hatchery-origin fish, 2) unmarked and presumably untagged hatchery-origin fish, and 3)
157 unmarked natural-origin fish. CWT recoveries were used to estimate the age-specific abundance
158 of hatchery-origin fish spawning in the river. For each tag recovered, the number of tags present
159 but unrecovered k was estimated by drawing from a negative binomial distribution ([Michielsens](#)

160 [et al. 2006](#)) where Θ equals the sampling fraction of the survey and probability of recovering the
161 tag (obtained as the inverse of the “estimated_number” reported in RMIS for each tag recovery).
162 This was done 1000 times for each tag to characterize uncertainty from sampling.

163
$$k \sim \text{NB}(1, \Theta)$$

164 For each recovery, $k + 1$ equaled the estimated number of marked fish from a particular
165 release group present per tag. The number of marked hatchery fish from each release group was
166 then expanded to include unmarked hatchery fish from that same release group based on the
167 CWT tagging rate of the batch. Maturing CWT fish may also return to a hatchery or be captured
168 by in-river fisheries. Escapement to the hatchery and in-river harvests were estimated using the
169 same expansion methods as natural spawning ground escapement estimates. Hatchery-origin
170 escapement was grouped by source across all hatchery and spawning ground recovery locations.

171 Natural-origin escapement to each tributary’s natural spawning grounds and to each
172 hatchery was estimated by subtracting the age-specific hatchery-origin escapement at that site
173 from total escapement. We used the scale ages of unmarked fish recovered from each site to
174 estimate the age composition of unmarked escapement. Scale samples were bootstrapped for
175 each return year by redrawing samples with replacement 1000 times to evaluate sampling
176 uncertainty. The age distribution of returning spawners for each iteration was then estimated
177 using an iterative algorithm to account for bias in scale aging ([Kimura and Chikuni 1987](#)). The
178 algorithm used a confusion matrix composed of estimated age from scales to known age from
179 CWTs from the same tributary (or group of tributaries). Estimates of unmarked hatchery-origin
180 fish at each age were then subtracted from the total unmarked escapement at each age to estimate
181 natural-origin escapement at age. In some instances, estimated escapement of natural-origin fish
182 at an age would have been negative because unmarked hatchery-origin fish estimates exceeded

183 total unmarked fish, potentially due to sampling error or the aging and aging bias correction
184 process. This occurred in three percent of all iterations across tributaries, ages, and years. In
185 these cases, ages-specific escapement was set to zero when escapement estimates were negative.
186 For tributaries with hatcheries (Battle Creek, Feather River, and American River), abundance
187 estimates of natural-origin spawners recovered in the hatchery were combined with abundance
188 estimates in-river to estimate total natural-origin escapement to the tributary.

189 Coded-wire tags recovered from fisheries sampling were used to estimate the impact of
190 ocean fisheries I on CWT fish. Total impact includes landed fish F and non-landed mortalities,
191 including fish that were hooked but dropped off without being brought on board and fish that
192 were caught and released because they were of sublegal size that died due to injury and stress, D
193 and R respectively.

$$I = F + R + D$$

195 F was estimated using the same expansion methods as escapement and in-river fisheries
196 estimates, applied to CWT recoveries from dockside sampling of the landed catch.

197 Release mortality, R , was estimated from the number of released fish and the release
198 mortality rate r .

$$R_{a,t} = \left(\frac{F_{a,t}}{h_{g,b,a,t}} - F_{a,t} \right) \times r_{g,b,t}$$

200 Releases equaled the number of fish contacted (landed harvest divided by the proportion legal-
201 sized [see below] for the cohort) minus the landed fish. Harvestability, h , or the proportion of the
202 cohort that is greater than the size limit and can be kept, depends on the size distribution of the
203 cohort at the time and the size limit for the fishery type g , area b , and time t . We estimated the
204 size distribution of cohorts each month using maximum likelihood estimation methods based on
205 truncated normal distributions as described in [Satterthwaite et al. \(2012\)](#). The size distribution of

206 individuals in each cohort was assumed to be normally distributed and the total lengths
207 (converted from reported fork lengths) of recovered fish represent the subset of fish above the
208 size limit. We estimated the size distribution (mean and standard deviation) specific for each
209 cohort for each month-age-year combination when more than 20 samples of fork length were
210 collected. In month-age-year combinations when less than 20 samples were collected for the
211 cohort, we used the estimated size distribution pooling recoveries across 2000-2016 for the
212 month-age combination. The release mortality rate, which varies by the fishery, area, and time,
213 was then applied to releases. r was 0.26 for commercial fisheries for all areas and times and
214 ranged between 0.14 and 0.39 for recreational fisheries depending on fishing techniques in the
215 region and time (STT 2000).

216 Additionally, fish that were hooked but not brought on board may still become
217 mortalities. We applied a drop-off mortality rate of 0.05 to all contacted fish to estimate this
218 drop-off mortality (STT 2000).

219
$$D_{a,t} = \frac{F_{a,t}}{h_{g,b,a,t}} \times d$$

220 Analysis of Past Cohorts

221 We estimated vital rates (e.g., maturation, impact) for hatchery cohorts from BY 1998-2016 and
222 natural cohorts from BY 2008-2016 (scale data was not available to inform natural-origin age-
223 specific escapement prior to 2010, and a lack of natural-area escapement sampling for CWT
224 prior to 2000 precluded reconstructing hatchery-origin cohorts prior to BY 1998). For each of the
225 1000 iterations, cohort abundances over time were calculated by reconstructing abundances
226 every month, starting with the last month that an individual from the cohort was recovered.
227 Abundance N at each age a at each time step t is equal to abundance at the next time step and
228 individuals during the current time step that were natural mortalities V , fishing mortalities I , or

229 matured M . Ages are assigned using 1-based indexing (i.e., fish are age one in their first year of
230 life, and the numerical value of ocean ages match the age a fish would be at its next spawning
231 opportunity).

$$232 \quad N_{a,t} = N_{a+1,t+1} + V_{a,t} + I_{a,t} + M_{a,t}$$

233 Natural mortality was modeled to occur after maturation and fishing mortality every month. V at
234 each time step was calculated by multiplying the number of surviving fish and the proportion of
235 fish that were mortalities given a mortality rate v .

$$236 \quad V_{a,t} = N_{a+1,t+1} \times \frac{v_{a,t}}{1 - v_{a,t}}$$

237 We used monthly natural mortality rates that accumulated to annual natural mortality rates of 0.5
238 at age two and 0.2 at ages three, four, and five for v , rates used for analyses of other Chinook
239 salmon stocks in California ([KRTT 1986](#); [O'Farrell et al. 2012](#)).

240 Cohort abundance was calculated from when fish first turn age two on September 1 (after
241 entering the ocean earlier that year, one year after their parents matured) to the last month that an
242 individual from the cohort was recovered. For hatchery cohorts, year-one survival (i.e., from
243 release to age two) was calculated by dividing cohort abundance at age two by number of
244 hatchery fish released. For natural-origin cohorts, we estimated productivity by calculating
245 recruits (age-2 fish) per spawner.

246 We calculated annual ocean impact rates i for hatchery-origin cohorts at each age. Annual
247 impact was grouped from when fish turn the next age in September to August the following year
248 and impact rates were calculated using

$$249 \quad i_a = I_a / N_{a,t=9}$$

250 Note that under this formulation, the denominator is ocean abundance at the start of the age even
251 though abundance decreases over the course of the year due to natural mortality, and possibly
252 fishing mortality as well. Thus, an impact rate of 100% is theoretically impossible.

253 Data to directly estimate ocean and in-river harvest of natural-origin SRFC do not exist,
254 and so age- and year-specific impact rates estimated for hatchery-origin component were
255 assumed to apply to natural-origin fish during cohort reconstructions.

256 We modeled maturing fish as leaving the ocean on August 31 before they turn the next
257 age. Maturation rates m at each age equaled matured fish that escaped to spawning grounds or
258 hatcheries or were harvested by the in-river fishery divided by the cohort's ocean abundance at
259 the end of August. To evaluate changes in maturation rates over time, we conducted weighted
260 Mann-Kendall tests to assess for monotonic trends using the R package *wdm* ([Nagler 2023](#)). We
261 considered the degrees of certainty in maturation estimates across years by using the mean
262 estimates of the maturation rate across the 1000 iterations and weighing each estimate inversely
263 proportional to its variance across iterations ([da Graça 2010](#)). We tested for a trend over time in
264 the age-2 and age-3 maturation rate of the hatchery and natural-origin components.

265 We evaluated the fishing impact on the population by estimating potential escapement in
266 the absence of fishing, E' . To estimate E' , ocean abundance in the absence of fishing N' was first
267 calculated at every time step starting from the earliest age of reconstructed abundance by
268 applying only natural mortality and maturation over time. E' was then estimated by applying the
269 estimated maturation rate for the cohort to N' at the end of each August. The spawner reduction
270 rate, SRR, is the reduction of spawning abundance due to all fishing impact and was calculated
271 for each run year.

272
$$SRR = 1 - \frac{E}{E'}$$

273 Because the SI only considers fishing impacts in the year of return, we also calculated a
274 year-specific version of the SRR and potential escapement E , denoted SRR_y and E'_y , that look at
275 the reduction in escapement due to the current year's fishing compared to the escapement that
276 could have occurred with no fishing in the current year, but still considering the reductions in
277 potential escapement that resulted from fishing in previous years. $E'_y < E'$ because E' is the
278 potential escapement if there had not been fishing on the cohort at any point whereas E'_y is the
279 potential escapement after accounting for the effects of prior year's fishing.

280 We compared the similarity of our estimates of cohort-based, age-specific metrics to the
281 current index of abundance and metrics of exploitation, based on SI values obtained from the
282 most recent Preseason Report I ([PFMC 2024](#)). Because the SI is used to represent both potential
283 escapement and age 3+ ocean abundance at the start of the season, we compared the SI to
284 potential escapement if no fishing had occurred in the current year and to age 3+ ocean
285 abundance in September the previous fall. For metrics of exploitation, we compared the ocean
286 harvest component of the SI (south of Cape Falcon) to ocean harvest south of Cape Falcon and
287 impact we estimated for fish age 3+. Additionally, we compared the exploitation rate derived
288 from the SI, which includes in-river and ocean harvest ([PFMC 2024](#)), to SRR_y .

289 Source-specific vital rates were estimated for each of the hatcheries that produced
290 Sacramento River Fall Chinook (Coleman National Fish Hatchery, Feather River Hatchery, and
291 Nimbus Fish Hatchery) by conducting separate cohort analyses for each hatchery. Cohorts of
292 natural-origin fish in six tributaries with consistent monitoring and scale collection and aging
293 (Sacramento River, Feather River, American River, Yuba River, Clear Creek, Battle Creek) were
294 also analyzed independently. Natural-origin fish returning to other tributaries (Butte Creek,

295 Cottonwood Creek, Mill Creek, Cow Creek, and Deer Creek) were aggregated into a single
296 cohort and evaluated due to small sample sizes.

297 Code Availability

298 Code to perform the cohort reconstructions, excluding data on harvest taking place north
299 of Cape Falcon, is available at [https://github.com/echenfishbitch/SRFC-cohort-reconstruction-](https://github.com/echenfishbitch/SRFC-cohort-reconstruction-noNF)
300 [noNF](https://github.com/echenfishbitch/SRFC-cohort-reconstruction-noNF). Code that includes data on harvest taking place north of Cape Falcon is available at
301 <https://github.com/echenfishbitch/SRFC-cohort-reconstruction-wNF>.

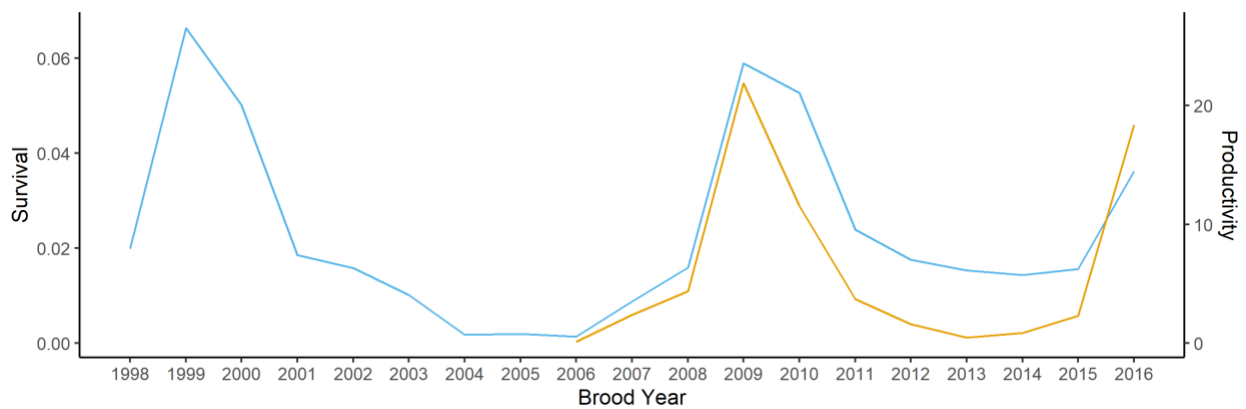
302

303 **Results**

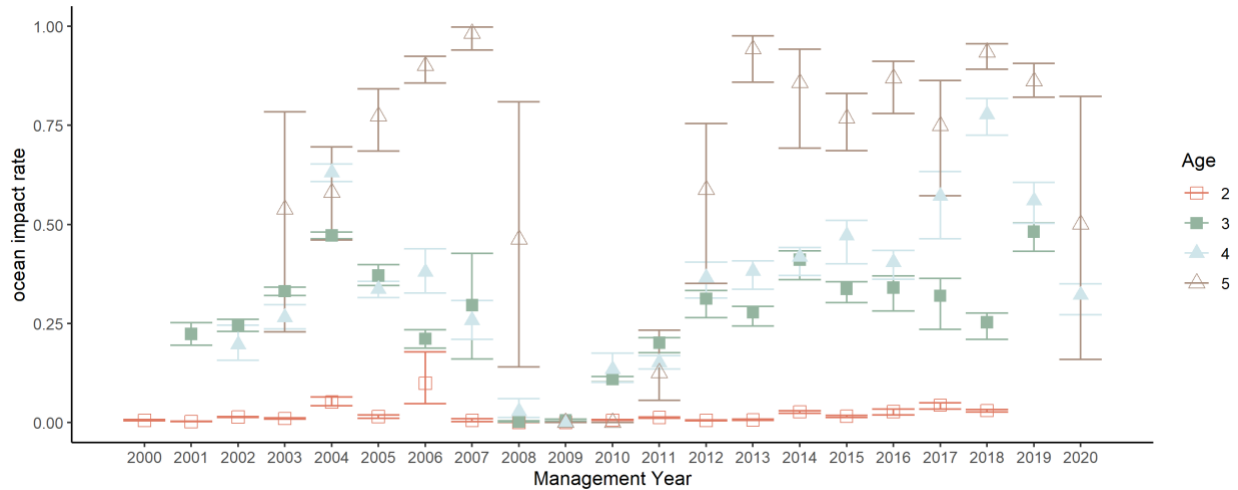
304 Analysis of Past Cohorts

305 From 1998 to 2016, the average number of fall-run hatchery Chinook released every
306 year from hatcheries in the Sacramento Basin and reported on the RMIS database was
307 22,361,802 fish (SD = 4,437,241 fish). Release information of fish from Nimbus Fish Hatchery
308 was not available in 1998, 1999, 2002, 2004, and 2005 even though releases occurred these
309 years, and significant proportions (>10 percent) of releases from Feather River Hatchery for
310 1998-2001 brood years and Nimbus Fish Hatchery for 2001 and 2003 brood years were not
311 reported in the RMIS database that were reported in [Huber and Carlson \(2015\)](#). These cohorts,
312 and all cohorts prior to 2008 when natural-origin data were unavailable, were not included in
313 comparing the cohort-based, age-specific methods to the Sacramento Index. Coleman National
314 Fish Hatchery released the most fish (mean = 12,516,003), followed by Feather River Hatchery
315 (mean = 9,368,277, excluding 1998-2001) and Nimbus Fish Hatchery (mean = 4,066,443,
316 excluding 1998-2005).

317 Early life survival of 1998 – 2016 hatchery cohorts (i.e., survival from release to age 2)
318 had a mean of 0.023 (median 0.016; SD = 0.020). For the natural-origin component from 2008-
319 2016 brood years, productivity was a mean of 7.2 recruits (ocean age-2 fish on September 1) per
320 spawner (median = 3.7; SD = 8.1). These metrics of year-1 production have a correlation of 0.89
321 between the hatchery and natural-origin component (Figure 1). Impact rates increased with age.
322 The mean impact rate was 0.020 (SD = 0.024) at age two, 0.27 (SD = 0.13) at age three, 0.35
323 (SD = 0.20) at age four, and 0.64 (SD = 0.31) at age five (Figure 2). Unless otherwise noted,
324 cohort reconstruction results excluded harvest north of Cape Falcon.
325



326
327 **Figure 1.** Year-1 survival (i.e., from release to age-2) of hatchery cohorts (gold) and productivity
328 (age-2 recruits per spawner) of natural-origin broods (blue).

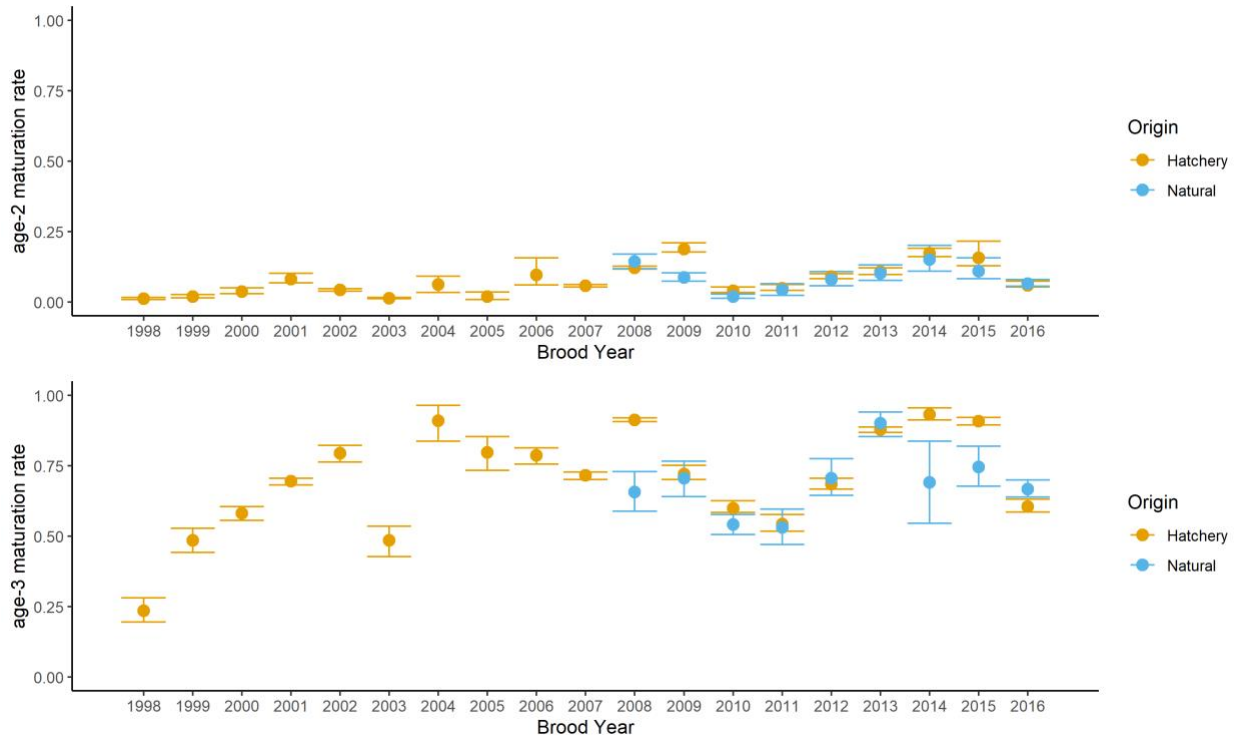


329

330 **Figure 2.** Age-specific ocean impact rates every combination of age and harvest year where
 331 hatchery-origin cohorts could be fully reconstructed. Points indicate the mean while error bars
 332 indicate the 95% credible intervals from resampling.

333

334 The mean age-2 maturation rate of the entire natural-origin component for 2008 – 2016
 335 brood years was 0.089 (SD = 0.044), while the mean for the entire hatchery-origin component
 336 during the same period was 0.109 (SD = 0.055) (0.075 for BY 1998 – 2016) (Figure 3). The
 337 mean age-3 maturation rate was 0.683 (SD = 0.110) for the natural-origin component in 2008-
 338 2016 BY and 0.754 (SD = 0.155) for the hatchery-origin component during the same period
 339 (0.698 for BY 1998 – 2016). Maturation rates appeared to show an increasing trend from 1998-
 340 2016, but this was only statistically significant for hatchery-origin fish at age-2 (Kendell’s τ
 341 – correlation coefficient = 0.62, $p = 0.050$). An apparent trend in the age-3 maturation rate for
 342 hatchery-origin fish from 1998 to 2016 was not statistically significant ($p = 0.46$), nor were
 343 trends in natural-origin age-2 maturation rate ($p = 0.72$) or age-3 maturation rate ($p = 0.60$) from
 344 2008 to 2016. Age-specific maturation rates for each tributary and hatchery population are
 345 shown in Figure A1 and Figure A2.



346

347 **Figure 3.** Maturation rate at age two (top) and age three (bottom) for Sacramento River Fall
 348 Chinook salmon from hatcheries (gold) and natural production (blue). Points indicate the mean
 349 while error bars indicate the 95% credible intervals from resampling.

350

351 The Sacramento Index was highly correlated ($r=0.99$) with potential escapement of age
 352 3+ fish absent fishing in the current management year but exceeded potential escapement in all
 353 years. Potential escapement in the absence of fishing in the current management year was an
 354 average of 12.9% lower than the SI (Table 2). Compared to the SI, the ocean abundance of age
 355 3+ fish on September 1 was 48% greater and had a correlation of 0.99 with the SI. The ocean
 356 harvest component (south of Cape Falcon) of the Sacramento Index had a correlation of 0.97
 357 (Table 1). Ocean harvest calculated using cohort reconstructions was on average 5.5% (median =
 358 4.3%) lower than the ocean harvest calculated for the SI. Impact, which considers non-landed
 359 mortality like release mortality and drop-off mortality, was slightly greater than harvest and had

360 a correlation with the SI's ocean harvest of 0.97 and was on average 1.5% greater (median 3.1%)
 361 than the SI's ocean harvest. The exploitation rate calculated from the SI was always higher than
 362 SRR_y (Figure 4).

363

364 **Table 1.** Indices of abundances estimated in the cohort analyses that excluded ocean harvest
 365 north of Cape Falcon versus the Sacramento Index (thousands of fish).

Year	Potential escapement ¹	Potential escapement ²	Sept 1 abundance ³	SI	Ocean Harvest ⁴	Ocean Impact ⁴	SI-based Ocean Harvest ⁴
2010	133.1	NA	213.2	149.8	22.2	23.7	22.8
2011	205.5	NA	304.9	207.0	55.7	59.7	69.5
2012	524.0	548.3	914.8	627.9	264.9	285.3	276.7
2013	686.8	766.7	1438.6	869.3	387.3	414.7	404.9
2014	440.5	577.7	820.8	551.2	318.4	340.8	303.0
2015	2353	334.0	410.7	254.9	143.4	155.3	124.6
2016	180.8	219.4	264.3	205.3	88.3	94.9	91.8
2017	121.1	144.0	197.1	137.1	62.8	68.1	70.7
2018	167.7	194.0	255.9	220.4	69.4	73.8	98.6
2019	464.9	507.6	908.8	507.1	405.5	438.1	323.0
2020	NA	NA	NA	352.5	138.0	147.2	195.5

366 ¹Potential escapement of fish age 3+ in the absence of fishing in the current management year

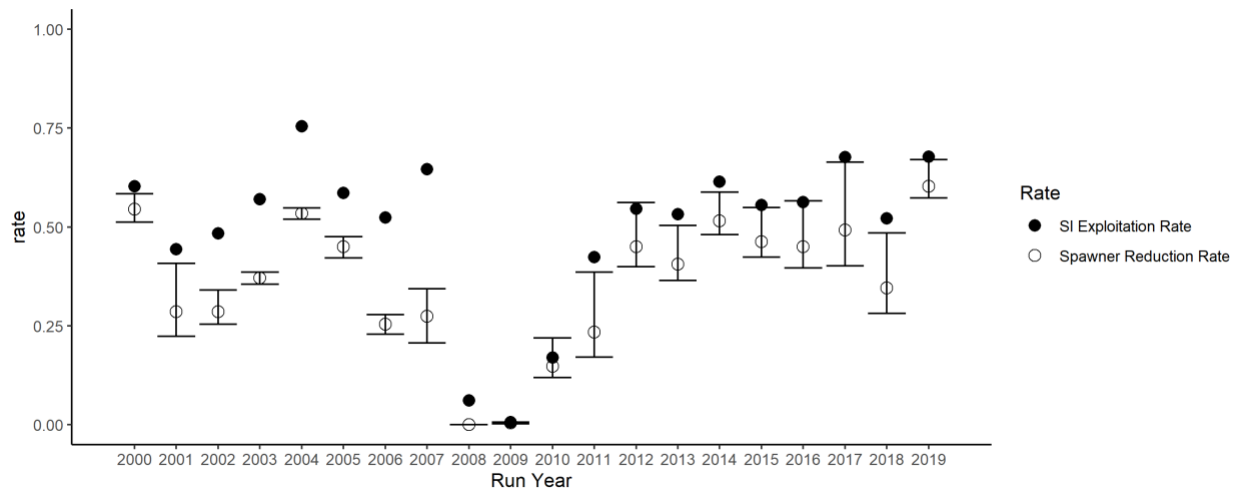
367 ²Potential escapement of fish age 3+ in the absence of fishing throughout ocean residency and
 368 return

369 ³Ocean abundance of age 3+ fish on September 1 the previous fall

370 ⁴South of Cape Falcon

371

372



373

374 **Figure 4.** Spawner reduction rate (SRR_y, open circle) and exploitation rate derived from the SI
375 (black circles) presented for every run year. For SRR_y, points indicate the mean while error bars
376 indicate the 95% credible intervals from resampling. Only point estimates were reported for the
377 SI-derived exploitation rate. Only impacts of ocean fishing during the current management year
378 are considered, and harvest north of Cape Falcon is excluded.

379

380 Including ocean harvest north of Cape Falcon increased estimates of ocean harvest by
381 1.6-13% (mean = 4.8%, median = 3.8%), ocean impact by 1.5-13% (mean = 4.9%, median =
382 3.8%), potential escapement by 0.5-3.5%, (mean = 1.5%, median = 1.2%), and ocean abundance
383 by 0.6-3.9% (mean = 1.9%, median = 1.9%) (Table 2). Including harvest north of Cape Falcon
384 increased SRR_y by 0.5-8.0% (mean 2.3%, median = 1.6%), while including the effects of ocean
385 fishing during earlier ocean residency increased SRR relative to SRR_y by 1.0-24% (mean = 11%,
386 median = 11%) if excluding harvest north of Cape Falcon or 1.3-24% (mean = 11%, median =
387 11%) if including it (Table 3). Including the cumulative effects of ocean fishing increased the

388 potential escapement absent fishing by 4.6-42% (mean = 19%, median = 15%) if excluding
 389 harvest north of Cape Falcon, or by 4.7-43% (mean = 19%, median = 15%) if including it.

390

391 **Table 2.** Indices of abundances estimated in the cohort analyses that include ocean harvest north
 392 of Cape Falcon versus the Sacramento Index (thousands of fish).

Year	Potential escapement ¹	Potential escapement ²	Sept 1 abundance ³	SI	Ocean Harvest	Ocean Impact	SI-based Ocean Harvest ⁴
2010	135.4	NA	217.4	149.8	25.2	26.8	22.8
2011	206.5	NA	306.7	207.0	57.0	61.0	69.5
2012	527.7	552.7	922.7	627.9	269.5	290.1	276.7
2013	694.9	776.8	1472.2	869.3	405.5	434.1	404.9
2014	448.0	593.7	838.8	551.2	330.5	353.7	303.0
2015	240.0	342.4	421.5	254.9	150.7	163.3	124.6
2016	187.1	228.2	274.7	205.3	95.8	103.1	91.8
2017	130.0	149.1	203.4	137.1	67.4	73.1	70.7
2018	169.2	196.3	258.5	220.4	71.1	75.7	98.6
2019	468.9	511.7	919.5	507.1	411.9	444.7	323.0
2020	NA	NA	NA	352.5	141.5	150.8	195.5

393 ¹Potential escapement of fish age 3+ in the absence of fishing in the current management year

394 ²Potential escapement of fish age 3+ in the absence of fishing throughout ocean residency and
 395 return

396 ³Ocean abundance of age 3+ fish on September 1 the previous fall

397 ⁴SI currently only considers ocean harvest south of Cape Falcon

398

399 **Table 3.** Annual SRR calculations that reflect only the effects of fishing during the current
 400 management year (SRR_y) versus consideration of ocean fishery impacts across the full period of
 401 ocean residency and return (SRR), as compared to the SI-derived exploitation rate (ER).

Year	Include NOF harvest		Exclude NOF Harvest		SI-derived
	SRR	SRR _y	SRR	SRR _y	ER
2010	NA	15.9	NA	14.8	17.0
2011	NA	23.7	NA	23.5	42.4
2012	47.8	45.3	47.5	45.0	54.5
2013	47.6	41.3	46.9	40.6	53.2
2014	63.7	52.3	62.8	51.5	61.5
2015	61.9	47.2	61.0	46.3	55.5
2016	54.9	46.5	53.3	45.0	56.3
2017	55.6	50.4	54.3	49.2	67.6
2018	42.0	34.9	41.5	34.5	52.1
2019	63.8	60.6	63.5	60.3	67.7

402

403 **Discussion**

404 The current management framework for Sacramento River Fall Chinook salmon uses an
 405 aggregate age index of abundance, the SI, and including additional age structure information
 406 may improve retrospective assessments by addressing inherent limitations in the SI ([O'Farrell et](#)
 407 [al. 2013](#)). We found the SI tended to overestimate potential escapement and underestimate ocean
 408 abundance compared to potential escapement and ocean abundance estimated using cohort
 409 reconstructions.

410 The SI underestimated the age 3+ ocean abundance because the SI does not account for
 411 natural mortality and fish that neither mature nor are harvested and remain in the ocean. The
 412 ocean harvest component for the SI does not include non-landed mortalities as our analysis did,
 413 which contributes to underestimating ocean impact and ocean abundance.

414 The SI overestimated potential escapement in the absence of fishing because the SI
 415 includes ocean-harvested age-3 fish that would not have matured and contributed to escapement
 416 in the current year, and includes harvest of natural-origin fish from stocks other than SRFC

417 ([O'Farrell et al. 2013](#)). The natural-origin ocean harvest component of the SI is estimated by
418 subtracting harvest of other key stocks (e.g., KRFC, hatchery-origin fish from other stocks) from
419 total harvest south of Point Arena. However, not all contributing stocks are subtracted, and so the
420 harvest of other populations in the fishery (e.g., California Coastal Chinook, Southern Oregon
421 Northern California Chinook, natural-origin fish from other Central Valley stocks) leads to
422 upward bias in the estimate of the SI.

423 Performing the CR revealed that the age-2 maturation rate of hatchery fish has increased
424 over time, becoming more variable as it increased. We did not see a statistically significant
425 increase in the maturation rates of natural-origin fish, but the time series for the natural-origin
426 population was shorter (9 years for the natural-origin population vs. 19 years for the hatchery
427 population).

428 To evaluate whether changes in the age-2 maturation rate contributed to overestimates of
429 the Sacramento Index in recent years, we calculated the correlation between the age-2 hatchery-
430 origin maturation rate and forecast error, $\log(\text{SI}) - \log(\widehat{\text{SI}})$ where SI is the postseason estimate of
431 the SI and $\widehat{\text{SI}}$ is the SI that would have been produced under the current forecast approach
432 ([PFMC 2024](#)) using the data range that would have been available at the time. Increases in the
433 age-2 hatchery maturation rate are negatively associated with log error in the SI forecast ($r = -$
434 0.45), so high age-2 maturation rates correlated with over-forecasting the SI.

435 In addition to providing estimates of maturation rates, performing the CR allowed us to
436 estimate early life survival, age-specific ocean impact rates, and SRRs that included the effects
437 of fishing during the entire time fish spend in the ocean, not just fishing during the year of return.
438 Estimates of early life survival may help inform identifying mechanistically-supported
439 environmental indicators for consideration in future stoplight charts, forecast approaches, and/or

440 risk tables ([March 2024 Council direction to the EWG](#)). Age-specific impact rate estimates could
441 facilitate more informed consideration of the effects of changing size limits on SRFC fishery
442 impacts. We were surprised that age-5 impact rate estimates were consistently higher than age-4
443 impact rate estimates, given that we expect nearly all fish to be legal-sized at age-4. Much of the
444 “age-5” ocean impact took place in September or October the year fish turned ocean age-5, and
445 we suspect many of these fish might have actually returned to spawn at age-4 had they not been
446 harvested. This highlights the difficulty in unambiguously assigning a date that maturing fish
447 leave the ocean ([O’Farrell et al. 2010](#)). Considering fishery impacts over the full lifecycle of a
448 cohort rather than just the year of return is more consistent with how F_{MSY} values are typically
449 estimated (e.g., [STT 2005](#), [Confer and Falcy 2014](#), [KRWG 2024](#)) based on total reduction in a
450 cohort’s escapement compared to what it would be in the absence of fishing.

451 The approach described here improves on previous CR methods by quantifying the
452 uncertainty associated with sampling for CWT and scales, but numerous sources of uncertainty
453 remain unaddressed, and the evaluation of sampling error assumes that sampling rates have been
454 calculated and reported correctly and that the sampling process can be approximated as simple
455 random sample with replacement. While we have explored modifying the CR to include harvest
456 north of Cape Falcon in salmon-directed ocean fisheries, bycatch in other fisheries would take
457 more work to incorporate and requires confidence in the available data sources. Similar to other
458 CR used by the PFMC and Pacific Salmon Commission, we assumed fixed natural mortality
459 rates after the first year in the ocean. These assumed natural mortality rates affect estimates of
460 the other vital rates, and it may be possible to estimate them directly by combining information
461 across years or cohorts ([Allen et al. 2017](#)). Our assumed values for drop-off mortality are shared
462 with other CR but lack empirical support, while the release mortality rates are based on limited

463 and dated information that may warrant updating ([Lunzmann-Cooke et al. 2024](#)); our estimates
464 of released fish also depend on the assumptions that fish lengths-at-age are normally distributed,
465 fish lengths are measured without error, and there is 100% fishery compliance with size limits.
466 Our results are also sensitive to the ocean departure timing assumptions discussed earlier, and the
467 assumption that age-specific ocean impact rates are the same for hatchery- and natural-origin
468 fish.

469 We recommend immediate use of the CR for postseason estimates of the exploitation rate
470 for use in status determinations for all years where sufficient data to perform a CR are available,
471 and these estimates should consider all sources of fishing mortality that can be reliably
472 estimated, such as non-landed impact and impact north of Cape Falcon, during the full period of
473 ocean residency and river harvest. We understand that considering impacts north of Cape Falcon,
474 and impacts of ocean fishing in years prior to the return year, would be a departure from the
475 status quo and could pose practical challenges that should be evaluated prior to implementation
476 into the annual management process. We recommend re-parameterizing the Sacramento Harvest
477 Model (SHM, [Mohr et al. 2014](#)) based on estimates of harvest, impact, and exploitation based on
478 the CR as used in the Klamath Ocean Harvest Model (Mohr 2006) once estimates from a
479 sufficient number of years are available, and if necessary developing an offset to the preseason
480 planning models to account for harvest likely to take place north of Cape Falcon even if those
481 fisheries are not explicitly modeled within the SHM. Once a sufficiently large set of ocean
482 abundance estimates and age-specific escapements are available to both train and test a model,
483 and age-specific escapements from the most recent year are consistently available, we
484 recommend evaluation of a sibling-based forecast model similar to the one currently used for
485 KRFC ([PFMC 2024](#)). Once estimates of potential natural-origin escapement in the absence of

486 fishing are available for a sufficiently large number of cohorts that cover a wide range of parent
487 spawner abundances and environmental conditions ([SRWG 2024](#)), we recommend fitting
488 spawner-recruit relationships where spawners are measured as natural-area SRFC adult spawners
489 and recruits are measured as potential natural-origin SRFC escapement in the absence of fishing
490 derived from a CR. This could inform periodic updates to S_{MSY} and/or the conservation
491 objective.

492

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498 *CDFW collects data from various sources for fisheries management purposes, and data*
499 *may be modified at any time to improve accuracy and as new data are acquired. CDFW may*
500 *provide data upon request under a formal agreement. Data are provided as-is and in good faith,*
501 *but CDFW does not endorse any particular analytical methods, interpretations, or conclusions*
502 *based upon the data it provides. Unless otherwise stated, use of CDFW's data does not*
503 *constitute CDFW's professional advice or formal recommendation of any given analysis. CDFW*
504 *recommends users consult with CDFW prior to data use regarding known limitations of certain*
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511

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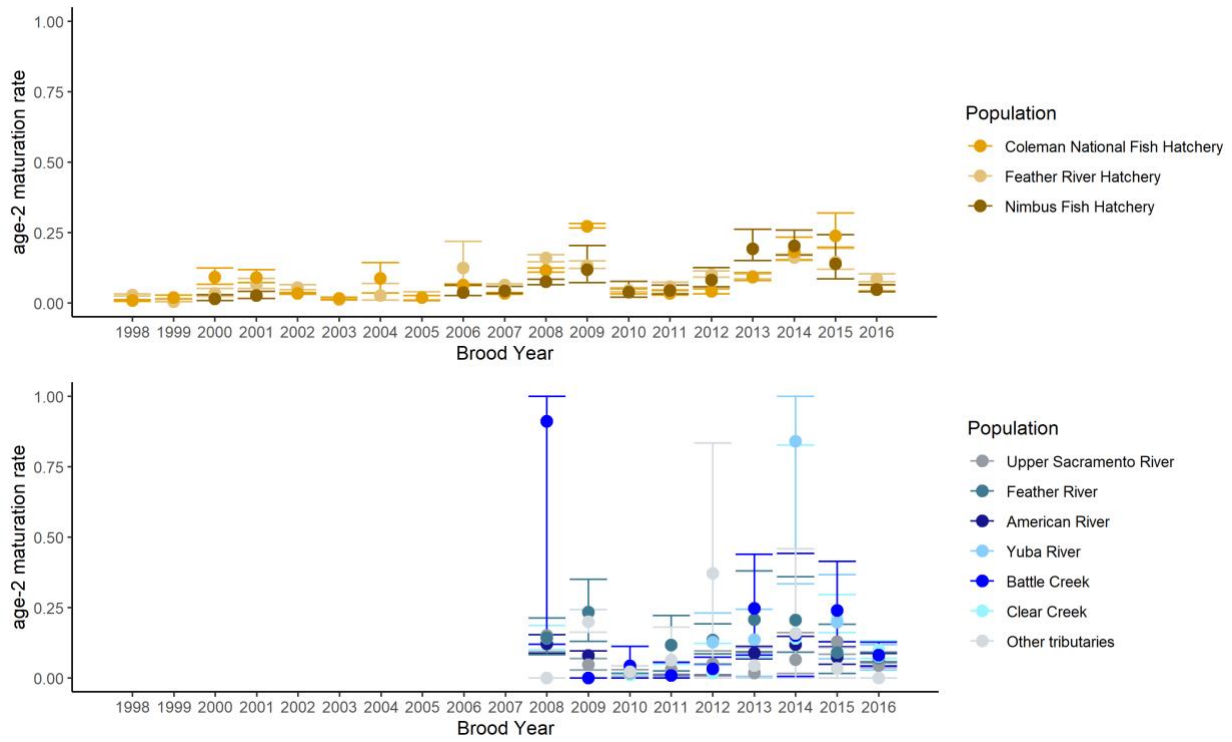
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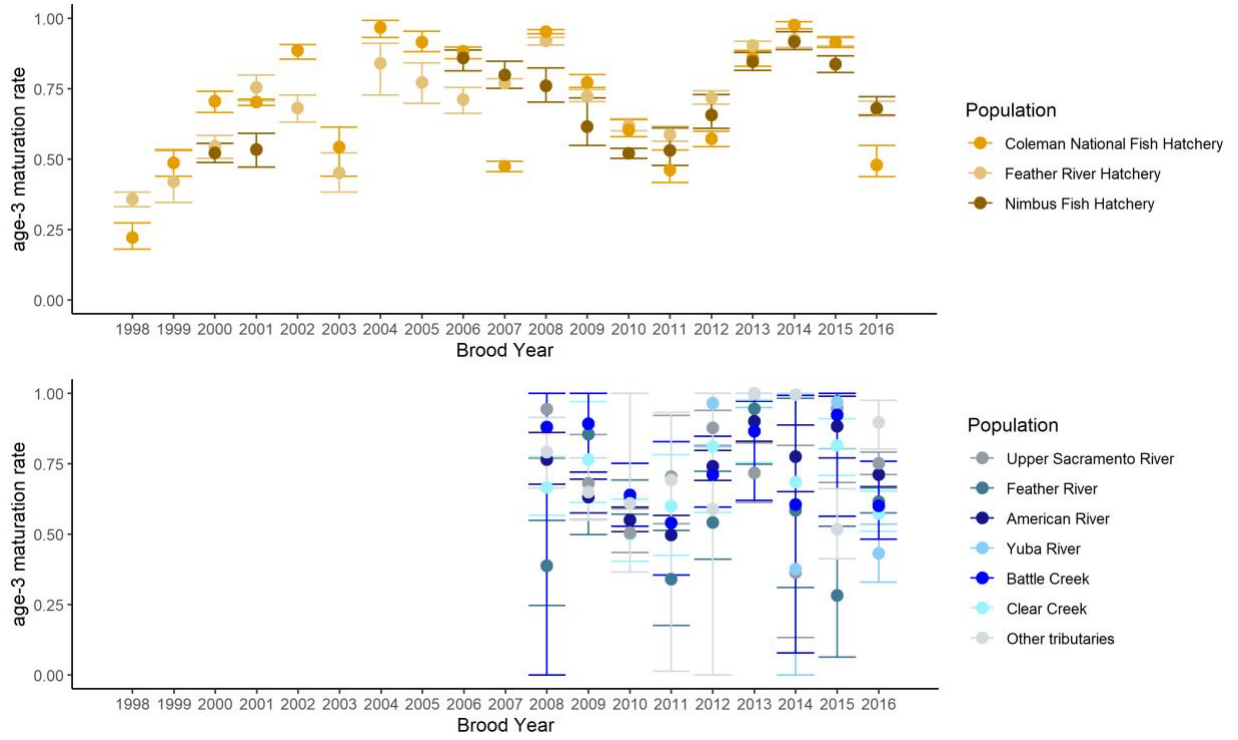
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637 **Figure A1.** Age-2 maturation rates for Sacramento River Fall Chinook salmon from hatcheries
638 (top) and natural production (bottom). Points indicate the mean while error bars indicate the 95%
639 credible intervals from resampling.

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645 **Figure A2.** Age-3 maturation rates for Sacramento River Fall Chinook salmon from hatcheries

646 (top) and natural production (bottom). Points indicate the mean while error bars indicate the 95%

647 credible intervals from resampling.

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