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

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Abstract

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

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

Introduction

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

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

In contrast, a historically more data-rich situation for KRFC supported the development of a fully age-structured CR applied to both the hatchery- and natural-origin components of the stock (Goldwasser et al. 2001, Mohr 2006). Conditional on assumed rates of natural mortality after the first year in the ocean, and assumptions about release and drop-off mortality that are combined with empirical estimates of size-at-age and fishery size limits to estimate total fishing mortality from landed mortality, the CR estimates the full ocean abundance by month and age for the hatchery-origin component of KRFC, along with age-specific maturation rates and fishery impact rates. Once the hatchery component has been reconstructed, conditional on the assumption that natural-origin fish have the same age-specific ocean impact rates, natural-origin cohorts are reconstructed based on estimates of age-specific natural-origin river run size informed by scale age data from unmarked fish. This approach may have been reviewed as part of the Salmon Methodology Review of a draft Klamath Ocean Harvest Model (KOHM) in 2001 (SSC 2001), and the CR component of the KOHM was specifically reviewed by the Center of Independent Experts (CIE) in 2006 (Bradford 2006, Goodman 2006, Pawson 2006).

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

In this report, we fully document the CR algorithms and provide the results of applying them to brood years (BY) 2007-2016 and run years (RY) 2011-2019 of SRFC, for which both CWT and scale age data are available. Results for BY 2016 are somewhat incomplete since age-5 fish from that cohort are not included, but age-5 or older fish are rarely observed in SRFC. There was a gap in sampling of ocean fisheries for CWT in early 2020 that also has a small effect on BY 2016 estimates, and lack of scale reading data (along with low mark/tag rates for hatchery fish prior to BY 2007) precluded full analyses for years earlier or later than those analyzed here, although we do present CR results for just tagged hatchery-origin fish for BY 1998-2006. We do not include BY prior to 1998 because natural-area spawners were not sampled for CWT prior to 2000.

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

Methods

Study system

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

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

Data

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

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

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[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.

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

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

Age-Specific Escapement and Fishery Impacts

Escapement to the spawning grounds of each tributary can include 1) marked and CWT tagged hatchery-origin fish, 2) unmarked and presumably untagged hatchery-origin fish, and 3) unmarked natural-origin fish. CWT recoveries were used to estimate the age-specific abundance of hatchery-origin fish spawning in the river. For each tag recovered, the number of tags present but unrecovered *k* was estimated by drawing from a negative binomial distribution (Michielsens et al. 2006) where Θ equals the sampling fraction of the survey and probability of recovering the tag (obtained as the inverse of the "estimated_number" reported in RMIS for each tag recovery). This was done 1000 times for each tag to characterize uncertainty from sampling.

$$k \sim NB(1, \Theta)$$

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

Natural-origin escapement to each tributary's natural spawning grounds and to each hatchery was estimated by subtracting the age-specific hatchery-origin escapement at that site from total escapement. We used the scale ages of unmarked fish recovered from each site to estimate the age composition of unmarked escapement. Scale samples were bootstrapped for each return year by redrawing samples with replacement 1000 times to evaluate sampling uncertainty. The age distribution of returning spawners for each iteration was then estimated using an iterative algorithm to account for bias in scale aging (Kimura and Chikuni 1987). The algorithm used a confusion matrix composed of estimated age from scales to known age from CWTs from the same tributary (or group of tributaries). Estimates of unmarked hatchery-origin fish at each age were then subtracted from the total unmarked escapement at each age to estimate natural-origin escapement at age. In some instances, estimated escapement of natural-origin fish at an age would have been negative because unmarked hatchery-origin fish estimates exceeded total unmarked fish, potentially due to sampling error or the aging and aging bias correction process. This occurred in three percent of all iterations across tributaries, ages, and years. In these cases, ages-specific escapement was set to zero when escapement estimates were negative. For tributaries with hatcheries (Battle Creek, Feather River, and American River), abundance estimates of natural-origin spawners recovered in the hatchery were combined with abundance estimates in-river to estimate total natural-origin escapement to the tributary.

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

$$I = F + R + D$$

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

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

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

Releases equaled the number of fish contacted (landed harvest divided by the proportion legal-sized [see below] for the cohort) minus the landed fish. Harvestability, h, or the proportion of the cohort that is greater than the size limit and can be kept, depends on the size distribution of the cohort at the time and the size limit for the fishery type g, area b, and time t. We estimated the size distribution of cohorts each month using maximum likelihood estimation methods based on truncated normal distributions as described in Satterthwaite et al. (2012). The size distribution of individuals in each cohort was assumed to be normally distributed and the total lengths (converted from reported fork lengths) of recovered fish represent the subset of fish above the size limit. We estimated the size distribution (mean and standard deviation) specific for each cohort for each month-age-year combination when more than 20 samples of fork length were collected. In month-age-year combinations when less than 20 samples were collected for the cohort, we used the estimated size distribution pooling recoveries across 2000-2016 for the month-age combination. The release mortality rate, which varies by the fishery, area, and time, was then applied to releases. r was 0.26 for commercial fisheries for all areas and times and ranged between 0.14 and 0.39 for recreational fisheries depending on fishing techniques in the region and time (STT 2000).

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

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

Analysis of Past Cohorts

We estimated vital rates (e.g., maturation, impact) for hatchery cohorts from BY 1998-2016 and natural cohorts from BY 2008-2016 (scale data was not available to inform natural-origin age-specific escapement prior to 2010, and a lack of natural-area escapement sampling for CWT prior to 2000 precluded reconstructing hatchery-origin cohorts prior to BY 1998). For each of the 1000 iterations, cohort abundances over time were calculated by reconstructing abundances every month, starting with the last month that an individual from the cohort was recovered. Abundance N at each age a at each time step t is equal to abundance at the next time step and individuals during the current time step that were natural mortalities V, fishing mortalities I, or matured *M.* Ages are assigned using 1-based indexing (i.e., fish are age one in their first year of life, and the numerical value of ocean ages match the age a fish would be at its next spawning opportunity).

$$N_{a.t} = N_{a+1.t+1} + V_{a.t} + I_{a.t} + M_{a.t}$$

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

$$V_{a.t} = N_{a+1.t+1} \times \frac{v_{a.t}}{1 - v_{a.t}}$$

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

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

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

$$i_a = I_a / N_{a.t=9}$$

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

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

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

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

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

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

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

Source-specific vital rates were estimated for each of the hatcheries that produced Sacramento River Fall Chinook (Coleman National Fish Hatchery, Feather River Hatchery, and Nimbus Fish Hatchery) by conducting separate cohort analyses for each hatchery. Cohorts of natural-origin fish in six tributaries with consistent monitoring and scale collection and aging (Sacramento River, Feather River, American River, Yuba River, Clear Creek, Battle Creek) were also analyzed independently. Natural-origin fish returning to other tributaries (Butte Creek, Cottonwood Creek, Mill Creek, Cow Creek, and Deer Creek) were aggregated into a single cohort and evaluated due to small sample sizes.

Code Availability

Code to perform the cohort reconstructions, excluding data on harvest taking place north of Cape Falcon, is available at https://github.com/echenfishbitch/SRFC-cohort-reconstruction-noNF. Code that includes data on harvest taking place north of Cape Falcon is available at https://github.com/echenfishbitch/SRFC-cohort-reconstruction-wNF.

Results

Analysis of Past Cohorts

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

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

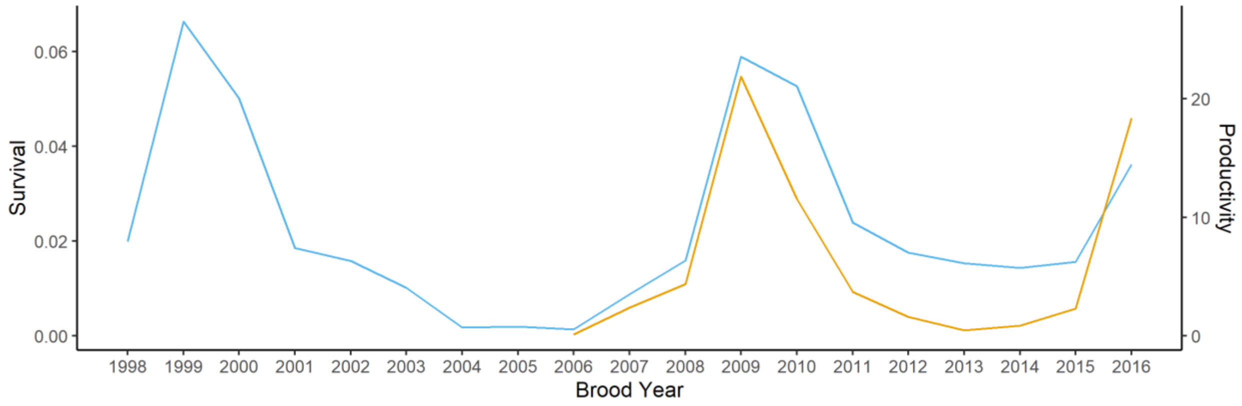

Figure 1. Year-1 survival (i.e., from release to age-2) of hatchery cohorts (gold) and productivity (age-2 recruits per spawner) of natural-origin broods (blue).

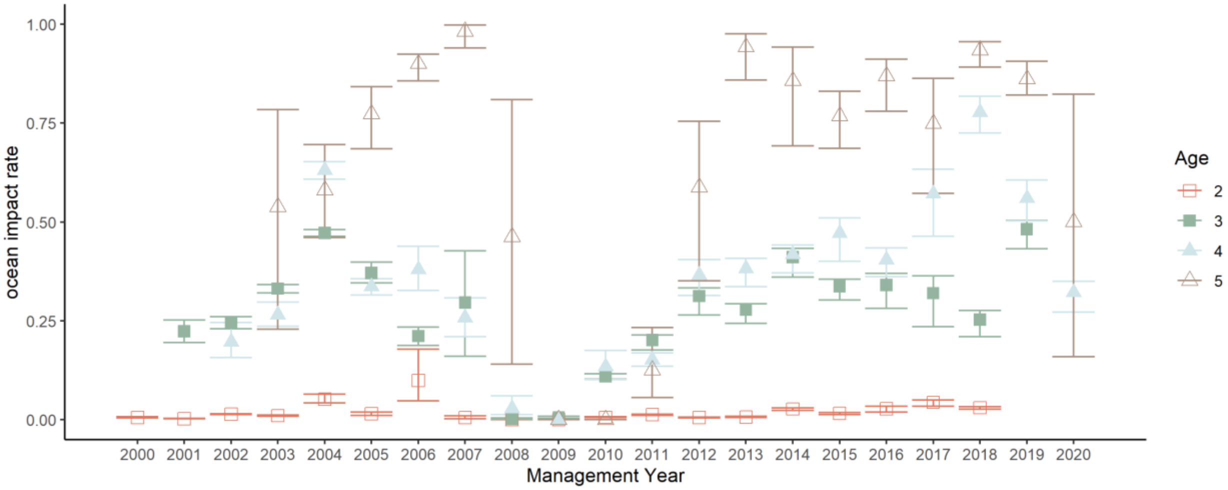

Figure 2. Age-specific ocean impact rates every combination of age and harvest year where hatchery-origin cohorts could be fully reconstructed. Points indicate the mean while error bars indicate the 95% credible intervals from resampling.

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

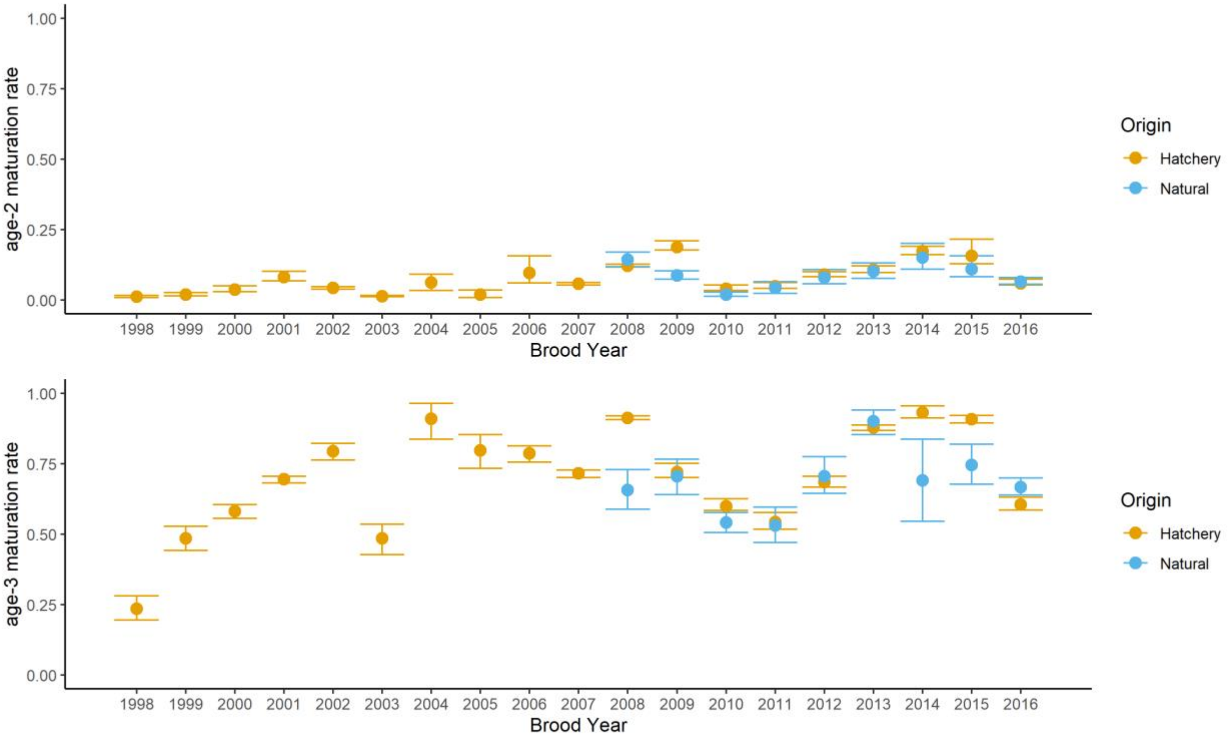

Figure 3. Maturation rate at age two (top) and age three (bottom) for Sacramento River Fall Chinook salmon from hatcheries (gold) and natural production (blue). Points indicate the mean while error bars indicate the 95% credible intervals from resampling.

The Sacramento Index was highly correlated (r=0.99) with potential escapement of age 3+ fish absent fishing in the current management year but exceeded potential escapement in all years. Potential escapement in the absence of fishing in the current management year was an average of 12.9% lower than the SI (Table 2). Compared to the SI, the ocean abundance of age 3+ fish on September 1 was 48% greater and had a correlation of 0.99 with the SI. The ocean harvest component (south of Cape Falcon) of the Sacramento Index had a correlation of 0.97 (Table 1). Ocean harvest calculated using cohort reconstructions was on average 5.5% (median = 4.3%) lower than the ocean harvest calculated for the SI. Impact, which considers non-landed mortality like release mortality and drop-off mortality, was slightly greater than harvest and had a correlation with the SI's ocean harvest of 0.97 and was on average 1.5% greater (median 3.1%) than the SI's ocean harvest. The exploitation rate calculated from the SI was always higher than SRR_y (Figure 4).

Table 1. Indices of abundances estimated in the cohort analyses that excluded ocean harvest 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

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

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

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

[4] South of Cape Falcon

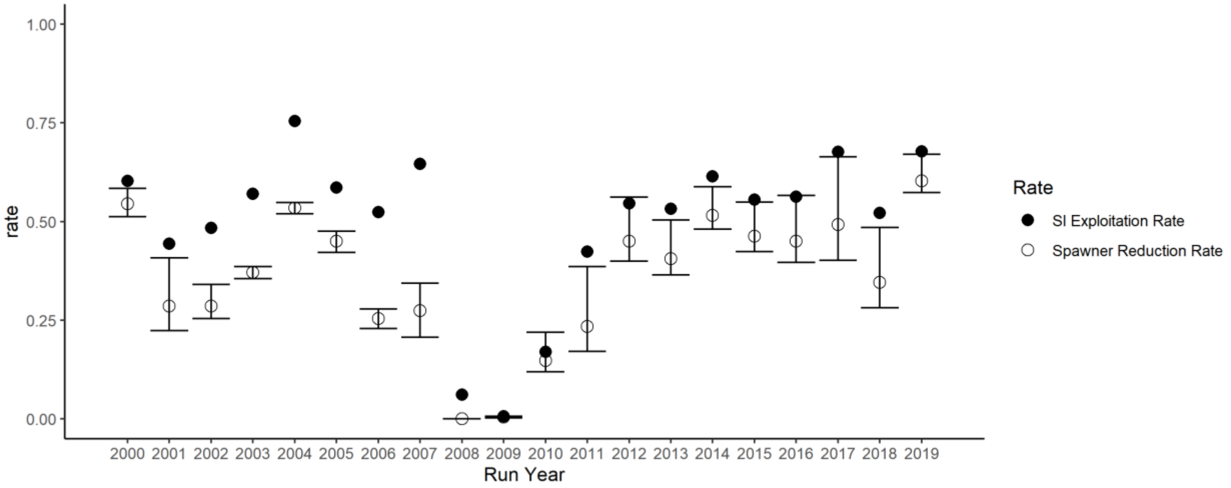

Figure 4. Spawner reduction rate (SRR_y, open circle) and exploitation rate derived from the SI (black circles) presented for every run year. For SRR_y, points indicate the mean while error bars indicate the 95% credible intervals from resampling. Only point estimates were reported for the SI-derived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

Including ocean harvest north of Cape Falcon increased estimates of ocean harvest by 1.6-13% (mean = 4.8%, median = 3.8%), ocean impact by 1.5-13% (mean = 4.9%, median = 3.8%), potential escapement by 0.5-3.5%, (mean = 1.5%, median = 1.2%), and ocean abundance by 0.6-3.9% (mean = 1.9%, median = 1.9%) (Table 2). Including harvest north of Cape Falcon increased SRR_y by 0.5-8.0% (mean 2.3%, median = 1.6%), while including the effects of ocean fishing during earlier ocean residency increased SRR relative to SRR_y by 1.0-24% (mean = 11%, median = 11%) if excluding harvest north of Cape Falcon or 1.3-24% (mean = 11%, median = 11%) if including it (Table 3). Including the cumulative effects of ocean fishing increased the potential escapement absent fishing by 4.6-42% (mean = 19%, median = 15%) if excluding harvest north of Cape Falcon, or by 4.7-43% (mean = 19%, median = 15%) if including it.

Table 2. Indices of abundances estimated in the cohort analyses that include ocean harvest 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	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

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

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

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

[4] SI currently only considers ocean harvest south of Cape Falcon

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

	Include NOF harvest		Exclude NOF Harvest		SI-derived
Year	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

Discussion

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

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

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

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

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

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

In addition to providing estimates of maturation rates, performing the CR allowed us to estimate early life survival, age-specific ocean impact rates, and SRRs that included the effects of fishing during the entire time fish spend in the ocean, not just fishing during the year of return. Estimates of early life survival may help inform identifying mechanistically-supported environmental indicators for consideration in future stoplight charts, forecast approaches, and/or risk tables (March 2024 Council direction to the EWG). Age-specific impact rate estimates could facilitate more informed consideration of the effects of changing size limits on SRFC fishery impacts. We were surprised that age-5 impact rate estimates were consistently higher than age-4 impact rate estimates, given that we expect nearly all fish to be legal-sized at age-4. Much of the "age-5" ocean impact took place in September or October the year fish turned ocean age-5, and we suspect many of these fish might have actually returned to spawn at age-4 had they not been harvested. This highlights the difficulty in unambiguously assigning a date that maturing fish leave the ocean (O'Farrell et al. 2010). Considering fishery impacts over the full lifecycle of a cohort rather than just the year of return is more consistent with how F_{MSY} values are typically estimated (e.g., STT 2005, Confer and Falcy 2014, KRWG 2024) based on total reduction in a cohort's escapement compared to what it would be in the absence of fishing.

The approach described here improves on previous CR methods by quantifying the uncertainty associated with sampling for CWT and scales, but numerous sources of uncertainty remain unaddressed, and the evaluation of sampling error assumes that sampling rates have been calculated and reported correctly and that the sampling process can be approximated as simple random sample with replacement. While we have explored modifying the CR to include harvest north of Cape Falcon in salmon-directed ocean fisheries, bycatch in other fisheries would take more work to incorporate and requires confidence in the available data sources. Similar to other CR used by the PFMC and Pacific Salmon Commission, we assumed fixed natural mortality rates after the first year in the ocean. These assumed natural mortality rates affect estimates of the other vital rates, and it may be possible to estimate them directly by combining information across years or cohorts (Allen et al. 2017). Our assumed values for drop-off mortality are shared with other CR but lack empirical support, while the release mortality rates are based on limited and dated information that may warrant updating (Lunzmann-Cooke et al. 2024); our estimates of released fish also depend on the assumptions that fish lengths-at-age are normally distributed, fish lengths are measured without error, and there is 100% fishery compliance with size limits. Our results are also sensitive to the ocean departure timing assumptions discussed earlier, and the assumption that age-specific ocean impact rates are the same for hatchery- and natural-origin fish.

We recommend immediate use of the CR for postseason estimates of the exploitation rate for use in status determinations for all years where sufficient data to perform a CR are available, and these estimates should consider all sources of fishing mortality that can be reliably estimated, such as non-landed impact and impact north of Cape Falcon, during the full period of ocean residency and river harvest. We understand that considering impacts north of Cape Falcon, and impacts of ocean fishing in years prior to the return year, would be a departure from the status quo and could pose practical challenges that should be evaluated prior to implementation into the annual management process. We recommend re-parameterizing the Sacramento Harvest Model (SHM, Mohr et al. 2014) based on estimates of harvest, impact, and exploitation based on the CR as used in the Klamath Ocean Harvest Model (Mohr 2006) once estimates from a sufficient number of years are available, and if necessary developing an offset to the preseason planning models to account for harvest likely to take place north of Cape Falcon even if those fisheries are not explicitly modeled within the SHM. Once a sufficiently large set of ocean abundance estimates and age-specific escapements are available to both train and test a model, and age-specific escapements from the most recent year are consistently available, we recommend evaluation of a sibling-based forecast model similar to the one currently used for KRFC (PFMC 2024). Once estimates of potential natural-origin escapement in the absence of fishing are available for a sufficiently large number of cohorts that cover a wide range of parent spawner abundances and environmental conditions (SRWG 2024), we recommend fitting spawner-recruit relationships where spawners are measured as natural-area SRFC adult spawners and recruits are measured as potential natural-origin SRFC escapement in the absence of fishing derived from a CR. This could inform periodic updates to S_{MSY} and/or the conservation objective.

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

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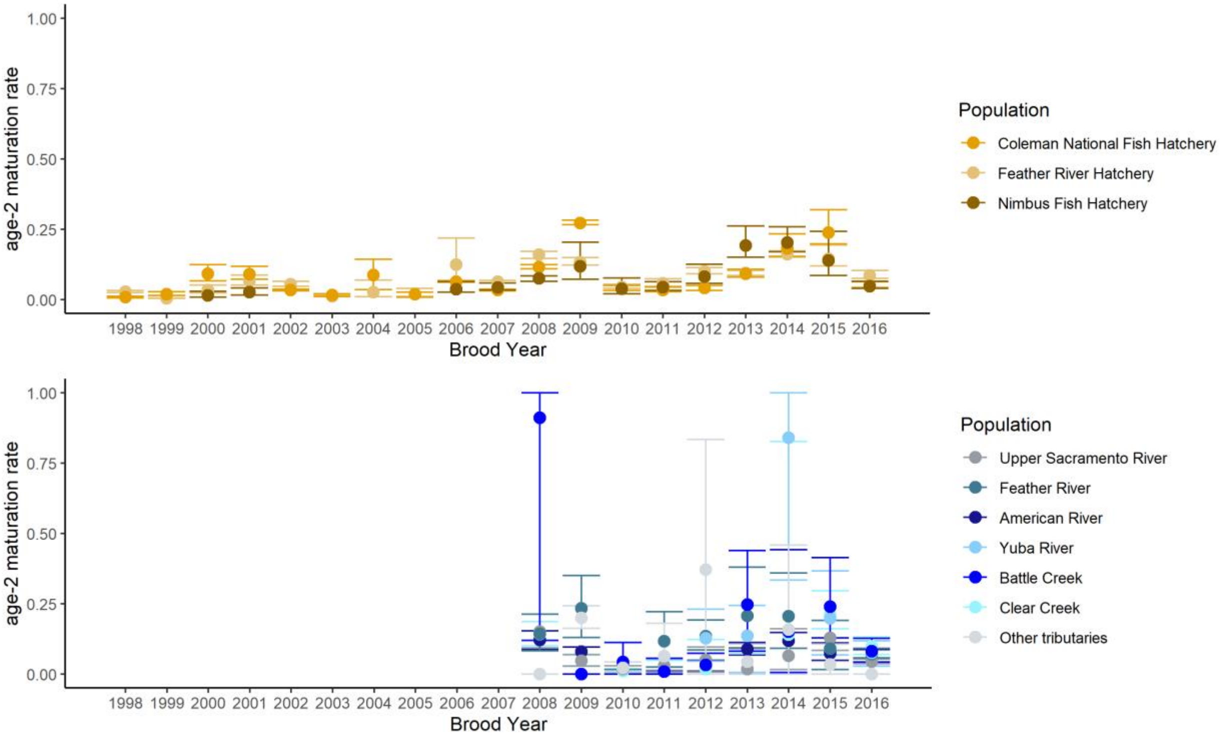

Figure A1. Age-2 maturation rates for Sacramento River Fall Chinook salmon from hatcheries (top) and natural production (bottom). Points indicate the mean while error bars indicate the 95% credible intervals from resampling.

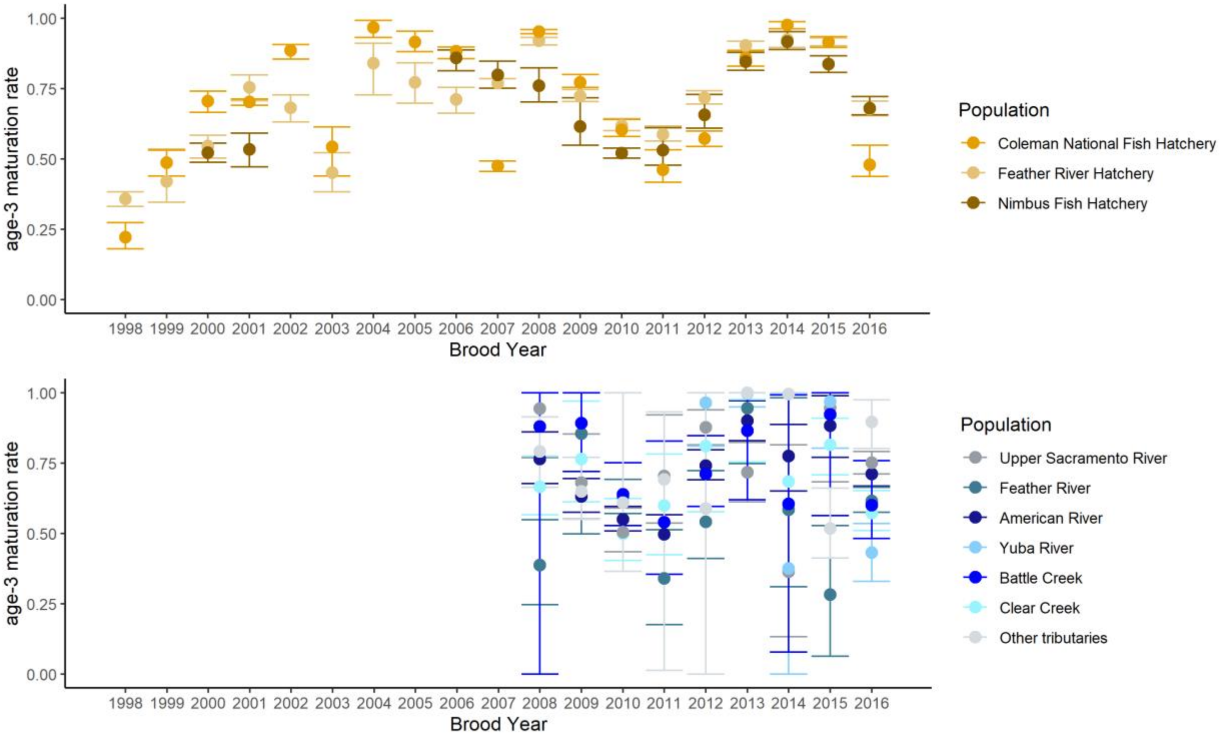

Figure A2. Age-3 maturation rates for Sacramento River Fall Chinook salmon from hatcheries (top) and natural production (bottom). Points indicate the mean while error bars indicate the 95% credible intervals from resampling.