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Article

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Abstract.

Southern Resident killer whales (SRKW) is a population of fish-eating killer whales that inhabits the Salish Sea and eastern Pacific nearshore environment from Southern Alaska to Monterey Bay, California. Since the mid-2000s they have been listed as endangered under the ESA due to declining population numbers. Their primary prey is Chinook salmon many populations of which also are listed under the ESA. SRKW also suffer from environmental factors including inadequate numbers and size of Chinook salmon, pollutants, vessel noise and traffic, and inbreeding in a subset of reproductive aged individuals. I develop a simple population viability analysis (PVA) that helps highlight the critical importance of Chinook abundance in the context of limiting factors that have negative effects on population growth rates. I developed a novel index of Chinook salmon abundance in Pacific Salmon Treaty AABM fisheries that accounts for over-and under-harvest of annual allowable catch limits, thereby providing an index of the ecologically effective abundance of Chinook in AABM fisheries. The PVA employs a Bayesian logistic regression approach coded in stan. The analysis shows that increases in numbers of Chinook available to SRKW will achieve positive population growth rates in the context of the several negative limiting factors.

Key words. Southern resident killer whales. Population viability analysis. Chinook salmon harvest. Limiting factors. Abundance index.

Introduction.

Southern Resident killer whales (SRKW) is a population of fish-eating killer whales that inhabits the Salish Sea and eastern Pacific nearshore environment from southern Alaska to Monterey Bay, California. The population spends most of the months from June to October foraging in and near the Salish Sea, which consists of the Strait of Georgia and the northern half of the Strait of Juan de Fuca and the southwest corner of Vancouver Island in southern British Columbia, Canada, and the southern half of the Strait of Juan de Fuca and Puget Sound in Washington State. SRKW are obligate predators of Chinook salmon, in particular the largest and oldest Chinook which are the most lipid rich and energy dense species of Pacific salmon (Healy 1991, Ford and Ellis 2006, Ford et al 2010, Nelson et al. 2024, Williams et al 2024, Raincoast 2025). The population has been listed as 'endangered' under the US Endangered Species Act (ESA) and Canada's Species at Risk Act (SARA) since the mid-2000s. Lack of quantity and quality (caloric content) of prey (mainly Chinook salmon) has been identified as the primary factor limiting the recovery of the population. Other important limiting factors are vessel traffic volume and sound levels and high body burdens of PCBs and other persistent organic pollutants (POPs) and levels of inbreeding and potential inbreeding depression (fitness reduction) in a select number of whales as determined by Kardos et al (2023). Despite the development and implementation of recovery plans by both NOAA Fisheries and Canada's Department of Fisheries and Oceans (DFO) shortly after listing, the SRKW population has failed to increase in numbers, but rather has continued a slow decline (Figure 1, Table 1; Williams et al.2024 and references therein; Nelson et al. 2024; Raincoast 2025).

The SRKW demographic data for census years 1999 to 2025 are shown in Table 1. The population trajectory from 1975 to 2025 is shown in Figure 1. As of July 1st, 2026, the southern resident killer whale population in 2025 consisted of 76 total members. This is an increase from the 2025 census number of 74 in 2024. (Center for Whale Research (CWR) 2026 (https://www.whaleresearch.com/orca-population). (Note: The Center for Whale Research publishes annual SRKW census for years ending December 31 in July of the year following December 31. So, for example, the July 2000 census report is for the year ending December 31, 1999).

Table 1. SRKW census data for years 1999 to 2025 and instantaneous annual population growth rate $Ln(N_t - N_{t-1})$, where Ln is the natural logarithm.

Census Year	**SRKW Census**	**GR**
1999	82	-0.036
2000	78	-0.050
2001	79	0.013
2002	82	0.037
2003	83	0.012
2004	88	0.058
2005	89	0.011
2006	86	-0.034
2007	85	-0.012
2008	85	0.000

2009	86	0.012
2010	87	0.012
2011	84	-0.035
2012	82	-0.024
2013	78	-0.050
2014	81	0.038
2015	83	0.024
2016	77	-0.075
2017	75	-0.026
2018	73	-0.027
2019	72	-0.014
2020	74	0.027
2021	73	-0.014
2022	75	0.027
2023	73	-0.027
2024	74	0.014
2025	76	0.027

61

62

63 Insert Figure 1 here.

Recent population viability analyses (PVA) using the Vortex PVA model (Lacy et al 2017; Murray et al 2021; Williams et al 2024) have shown that annual SRKW population growth rates are the result of interactions between prey (primarily Chinook) abundance, vessel noise in the Salish Sea and POP body burdens, but note that Chinook abundance is the primary factor (Raincoast 2025). Williams et al. 2024 employ a Chinook abundance index that is based on the average annual abundance of select Pacific northwest coast populations for SRKW census period 1973 to 2023.

The objective of this paper is to provide a simplified PVA analysis of annual SRKW population growth rates for census years 1999 to 2025 that highlights the importance of the annual estimated abundance of Chinook salmon in the Pacific Salmon Treaty (PST) Aggregate Abundance Based Management (AABM) fisheries. The AABM regime was implemented beginning in 1999, which is close to the beginning of a period in which SRKW declined from a high of 98 individuals in 1995 to recent lows in the lower- and mid-70s (Figure 1). The AABM fisheries consist of Chinook fisheries in three regions of the Northeast Pacific Coast: Southeast Alaska (SEAK), North and Central British Columbia (NBC), and the West Coast of Vancouver Island (WCVI).

I employ a new abundance index for Chinook salmon managed under the AABM regime, which properly accounts for years in which the aggregate AABM fisheries over- or under-fish the Treaty-specified total allowable catch (TAC) corresponding to the abundance index (AI) that corresponds to the estimated total AABM Chinook abundance. The new index is based on the number of Chinook that are uncaught when each fishery catches exactly its treaty-specified total allowable catch (TAC) for a given AI. The new index thus indexes the number of Chinook available to the marine ecosystem for each index of total AABM Chinook

abundance when the fisheries catch exactly their treaty-specified TAC. I call this new index the "ecologically effective (Chinook) abundance index", EEAI.

The paper consists of three parts. The first part consists of a logistic population model designed to estimate an aggregate parameter that constitutes a proxy for environmental and genetic conditions that are expected to negatively affect annual SRKW population growth rates, and two parameters measuring the effects on annual population growth of EEAI values for the current and previous census year and which are expected to positively affect annual growth rates. The second part consists of projections of population size over 100 years applying parameter values estimated by the logistic population model. The third part consists of estimates of annual growth rates for census years 1999 to 2025 based on values of EEAI under an AABM regime in which the total allowable catch in the three-region AABM aggregate is reduced by half of the allowed TAC under the 2009 PST renewal. Details on the calculations for each part are provided in the Methods.

RESULTS.

Part I. The logistic population model and estimation of the model parameter for census years 1999 to 2025 (annual population growth from 2000-to-2001 to 2024-to-2025).

As explained in Methods, the model consists of two time-varying intercepts for census years t and t-1, and non-time-varying parameters for the values of EEAI for census years t and t-1. Table S1 shows the summary results of the Bayesian time-varying linear regression of the annual population growth rates of SRKW for census years 1999-2000 to 2024-2025 on the Chinook abundance index at lags 0 and 1 (i.e., alpha[t-1], alpha[t], AI[t-1] and AI[t], for t = 1999 to 2025). Parameter estimation was conducted in stan, using rstan. Convergence was excellent based on

the Rhat statistic, the number of effective posterior samples per parameter (neff), and the low standard errors of the means of the parameters.

The regression model equation (further described in Methods) is shown in equation 1 below:

$$GR[t] = alpha[t-x] + beta*AI[t-x], \quad [1]$$

Where GR[t] is the instantaneous population growth rate from time (year) t-1 to time t, alpha[t-x] is the time varying (dual) intercept, for x = 0 and 1, that accounts for the (negative) impact of unmeasured covariates on GR[t]. Included in alpha[t] are the joint effects of limiting factors that include: vessel noise and disturbance, POP loads in individual whales, the effects of inbreeding and inbreeding depression (fitness reduction due to the accumulation of deleterious alleles in homozygous state at loci affecting individual survival and/or reproduction), and possibly other as-yet unidentified limiting factors.

The annual population growth rate, lambda[t] is then exp(GR).

Table S1 displays the main results of the Bayesian regression. Figure 2 displays a scatter plot of four primary parameters for years 1999 to 2025, and Figures 3 and 4 display histograms of betalag1 and betalag0, respectively.

Insert Figure 2 here.

Insert Figure 3 here.

Insert Figure 4 here.

Most alpha parameters are normal or nearly normal as is the mean of the annual SRKW population growth rates, rwmn. The two constant Chinook abundance coefficient parameters, betalag1 and betalag0, have means that are slightly greater than the medians, indicating a slight but noticeable right-skew to the posterior distributions (Figures 3 and 4). Therefore, to hedge in a conservative direction in forward projections (part two below) I used the median values of betalag1 and betalag0 rather than their slightly larger mean values.

The results are informative of the interaction between the limiting factors aggregated in the time-varying alpha values, and the coefficients betalag1 and betalag0 that characterize the effect of annual Chinook abundance indexed by EEAI. The median values of betalag1 and betalag0 are 0.0230 and 0.0142, respectively (Table S1), indicating the EEAI in the previous census year (t-1) has a moderately greater effect on GR from t-1 to t than EEAI in the current year (t).

The alpha values range from a low (high negative impact on GR[t]) of -0.0397 in 2017 (alpha[18]) to a high (low negative impact on GR[t]) of -0.0126 in year 2004 (alpha[6]) (Table S1). The time trajectory of alpha is shown in blue in Figure 2. Notably, from census years 2011 to 2025, alpha values were below -0.03 (high negative impact on GR[t]) in 11 of the 15 years. These values were lower than any in the period from 1999 to 2010, indicating that there was an increase in the average negative effects of the limiting factors on GR[t] beginning in or around 2011.

Figure 2 shows some of the main results of the regression analysis. The regression-estimated SRKW growth rate (black broken line) broadly follows the trajectory of the census growth rate (sold black line), though the absolute magnitude is smaller than the census rate. This is expected as the regression estimate is taking account

of all of the data in estimating the “best” (mean) point of each year. Further, given the small size of the SRKW population, an increase or decrease of a few individuals between one year and the next will show up as a relatively large value. For example, from 2003 to 2004 the population grew from 83 to 88 which yields a growth rate of Ln(88/83) = 0.058. But the population was clearly not capable of sustaining such a growth rate.

As expected, the estimated population growth rate closely follows the trajectory of the Chinook abundance index, EEAI. Census year 2006 is of interest. The abundance index in year 2005 was the among the lowest in the time series (0.675) and was followed in year 2006 by a similarly low EEAI of 0.643. These produced a large dip in both the actual and the estimated growth rate. This dip was not as great as it might have been due to the relatively high (less negative) alpha values in the two years (-0.018 and -0.019, respectively (blue line)).

Beginning in or around 2011-2012, the growth rates decline and were negative in nine of fourteen years from 2011 to 2024. This occurred despite there being eight years in which the EEAI values ranged from 1.25 to 2.25. This was due to values of alpha remaining at or below -0.03 in seven of the years. This dramatically demonstrates the interaction between Chinook abundance, measured by EEAI, and the unmeasured co-variate factors indexed by alpha.

The time trajectory of EEAI (red line) and the regression-estimate SRKW population growth rate GR-hat (black line) shows that the estimated growth rate closely tracks the Chinook abundance index (Pearson correlation coefficient 0.45), as expected despite the confounding unmeasured negative factors (indexed by alpha), if Chinook abundance is positively related to SRKW growth potential.

Figures 3 and 4 show the range and relative probabilities of the values of betalag0 and betalag1. Recalling that the mean and median values of betalag0 = 0.0241 and 0.0230 and of betalag1 = 0.0162 and 0.0142, respectively, we see that one-half of the posterior densities occur at values greater than the median values and more than 40% occur at values greater than the mean values. While the probability mass of betalag0 is concentrated at values less than the median, a large proportion of the mass nonetheless occurs at values between the median of 0.0142 and about 0.040. The bulk of the probability mass of betalag1 is also concentrated at values less than the median of 0.0230, but a large proportion of the posterior mass also occurs between values of the median of 0.0154 and 0.055. So, applying the values of the medians of betalag0 and betalag1 in the post-regression analyses appears to be reasonably conservative and likely also risk-averse.

Interpretation of alpha.

As noted above, the regression intercepts alpha estimate the effect on the annual population growth rate (GR) of SRKW of all factors known to negatively affect SRKW population growth rates, and therefore excluding the coefficients (betalag0 and betalag1) of Chinook abundance in the three AABM fisheries (indexed by EEAI). There are (at least) two useful ways to interpret alpha.

First, and strictly speaking, alpha[t] (the value of alpha for census year t) is the expected value of GR in year t if the Chinook abundance index were zero. For example, in year 2012 the mean value of Alpha (alpha [14]) was -0.036 (Table S1). If in that year the value of EEAI were 0, the expected (instantaneous) growth rate of the SRKW population from 2012 to 2013 would be -0.036, and the value of lambda (exp(GR) would be exp(-0.036) = 0.965. If the size of the SRKW

212 population in 2012 were 100, the expected value in 2013 would be 97. If the
213 population in 2012 were 74, the expected value in 2013 would be 71.

214 More generally, equation [3] (see Methods) can be employed with any actual
215 consecutive pair of values of the chosen abundance index, to calculate the expected
216 growth rate of the SRKW population from year [t-1] to year[t]. The index value of
217 1.0 may be an appropriate index to use for general assessment and for comparison
218 of potential SRKW population growth for other values of the index. The median
219 value of the regression coefficient betalag1, the coefficient for the abundance index
220 AI at lag-1, is 0.023. The mean value betalag0, the coefficient for the AI at lag-0, is
221 0.0142. Consider the values of alpha for years 2020 and 2021 (alpha [22] and [23]
222 in table S1) which are -0.0244 and -0.0266, respectively. If the values of EEAI for
223 the two consecutive years 2020 and 2021 were 1.0, the SRKW growth rate from
224 2021 to 2022 would be:

225 $-0.0244 + -0.0266 + 1 * -0.023 + 1 * 0.0142 = -0.051 + (1 * (0.023 + 0.0142))$

226 $= -0.051 + 0.0372 = -0.0138$, and the mean of the annual growth rate from 2021 to
227 2022, lambda, would be $\exp(-0.0138) = 0.986$.

228 If the SRKW population in 2021 was 100, the mean value of the population in
229 2022 would be 99. If the population in 2021 were 74, the mean value of the
230 population in 2022 would be 73.

231 The posterior distributions of the two regression coefficients beta are especially
232 significant. Both are significantly positive, with a majority posterior probability
233 mass greater than 0.01 (Table S1, Figures 3 and 4). This shows that, despite the
234 lack of specific covariates encompassed by the time-varying intercepts (alpha),
235 there is strong evidence that Chinook abundance (measured by the abundance

index, EEAI) has a significant positive influence on the SRKW population growth rate.

Importantly, if the value of alpha for two consecutive years were zero and the abundance index EEAI were 1.0 in both years, the instantaneous SRKW population growth rate from the first to the second year would be 0.0372 and lambda would be exp(0.0372) = 1.038! If the population in the first year were 74, in the following year the population would have grown to 78 individuals.

This clearly shows the significance of the unmeasured co-variates' (represented by alpha) negative impact on SRKW growth rate. It is also significant to note that, in contrast to the finding of Nelson et al. (2024), the analysis indicates that the coefficient of Chinook abundance in the prior year (t-1) is moderately greater than the coefficient in the current year (t) and consequently its effect on the growth rate of SRKW in the current year (t) is greater than the coefficient in the current year for the same level of the abundance index.

Applying the regression parameters to estimate AABM Chinook abundance required to achieve a given target SRKW GR.

Most important, the parameters from the regression can be used to estimate the level of the AABM Chinook abundance index required to achieve a given target SRKW GR, given a specific level of the intercepts alpha-lag0 and alpha-lag1, such as the mean of years 2000 to 2024. Assume the desired target GR level is 0.01, which would just get the SRKW population on a positive growth trajectory.

The average value of alpha for years 1999 to 2025 is -0.026 (from Table S1). Then,

GR = 2* -0.026 + 0.0372*AI. Solving for the AI that would achieve a GR of 0.01:

0.01 = -0.052 + 0.0372 *EEAI.

Thus, 0.0372*EEAI = 0.052 + 0.01 = 0.062, and

EEAI = 0.062/0.0372 = 1.67.

That is, given current conditions for the period 1999 to 2025 of limiting factors negatively affecting SRKW population growth, the Ecologically Effective Chinook abundance index would need to be 1.67, which is equal to an annual total AABM Chinook abundance of 1,272,000 Chinook under the assumption that exactly the total TAC is caught in the AABM Chinook fisheries.

The regression shows that the SRKW GR in the period analyzed results from the interaction of AABM Chinook abundance and one or more covariate factors unrelated to AABM Chinook abundance that negatively affect the annual SRKW population growth rate. Assuming that the median values of the posterior distributions of the beta parameters are reasonable, the regression shows that Chinook abundance is a fundamental factor in the SRKW population growth rate and that AABM Chinook abundance in particular is compromised in its effect on the GR by unaccounted covariate factors unrelated to AABM Chinook abundance. Importantly, as illustrated above, the results of the analyses of the simple logistic population growth model with time-varying intercept (alpha) provide a means of estimating the level of AABM Chinook abundance required to provide stable or increase SRKW population growth in the face of unaccounted factors that negatively affect SRKW population growth.

Part II. Results of forward projection simulations of SRKW Population Size from the Bayesian regression analysis of SRKW population growth rates on PST EEAIs at lags 0 and 1 from census years 1999 to 2025.

I now apply the parameters of the regression model to a forward projection program that projects the SRKW population size forward for 100 years from a starting size of 75 for each of a number of values of the EEAI between 1.0 and 1.75 in increments of 0.05. The simulation was programmed in Matlab. 10,000 replicate simulations of 100 years were run for each value of EEAI. Each replicate simulation drew a constant value of the intercept parameter alpha from a normal distribution fit to the 27 annual values of alpha shown in Table S1. The results of the model provide a simplified population viability analysis of Southern Resident killer whales (SRKW) based on the population growth rates estimated for recent census years 2000 to 2025 (1999-2000 to 2024-2025).

Values of alpha for each year of each simulation were drawn from a normal distribution with mean of -0.0252 and standard deviation of 0.0081, based on the mean and standard deviation of the 27 values of alpha of the regression analysis.

The results are summarized an Excel worksheet (Supplementary File S2). The first column lists simulation years from 1 to 100. All simulations start from a SRKW population of 75 in year 1. Values reported in columns 2 to 14 are the mean annual values of the SRKW population across all 10,000 replicates for each of the 100 years (rows) in order of increasing values of EEAI.

A few summary results are of interest. All populations go extinct (n = 0) before year 100 for EEAI's less than or equal to 1.15. Quasi-extinction (defined as abundance declining to 30 or fewer individuals) occurs in less than 100 years for all EEAIs less than or equal to 1.35. Absolute extinction (SRKW population = 1) occurs before year 100 for AIs less than or equal to 1.35. For EEAIs of 1.4 to 1.5 population size in year 100 remains below the starting abundance of 75.

Importantly, the mean SRKW population size in year 100 does not exceed the starting population size of 75 at AIs of less than 1.55. Mean population size in year 100 is 83 at AI = 1.55 and 107 at AI = 1.60. The mean population size in year 100 does not attain the NMFS recovery plan target of 140 until the AIs exceed 1.65.

These results are consistent with the results reported from more richly parameterized recent PVAs conducted by Dr. Robert lacy and colleagues using the Vortex model (Lacy et al. 2017, Murray er al 2021, Williams et al. 2024.

Part III. SRKW Population growth under a reduction of the 2009 Treat TAC of 50% ("half-TAC").

Finally, I evaluated the effect on the calculation of the EEAIs of reducing the allowable AABM Chinook catches (TAC) specified in the 2009 Pacific Salmon Treaty Chinook renewal by 50%. To do this, for the abundance indices of each of the three AABM fisheries in Table 1of Chapter 3 of Annex IV of the 2009 PST (pages 63-64), I multiplied the specified TAC by 0.5, and summed them across the three fisheries to obtain the revised half-TAC for the three fishery AABM aggregate. For each AI then the number of uncaught Treaty Chinook at each aggregate TAC (equals AABM total Chinook abundance, N, minus the TAC). I then calculated the EEAIs for the 1999 to 2025 post-season Chinook abundances by looking up the post-season EEAIs of the 2009 Treaty renewal that correspond to the uncaught Chinook values of the half-catch regime, and then calculated the mean SRKW growth rates GR for the half-Tac EEAIs. The results are shown in Table 2 below.

Table 2. Ecologically effective AABM Chinook abundance indices for SRKW census years 1999 to 2025 for Half-TAC and the original 2009 Treaty renewal-post-season Abundance indices (AI). For values of the uncaught abundance greater than 613, 434 (post-season AI = 2.25), I took the conservative approach and set the EEAI to the maximum AI value of 2.25.

Year	Total Abundance	Total Half Catch	Total Uncaught	EEAI	SRKW Growth Rate
1999	628,844	160,853	467,991	1.731	X
2000	610,533	153,579	456,954	1.691	0.0136
2001	779,079	175,279	603,800	2.215	0.0283
2002	1,066,864	332,442	734,422	2.250	0.0482
2003	1,263,368	374,255	889,113	2.250	0.0526
2004	1,185,359	436,890	748,470	2.250	0.0568
2005	1,065,246	415,861	649,385	2.250	0.0536
2006	943,281	360,781	582,500	2.140	0.0457
2007	730,293	306,523	423,770	1.573	0.0352
2008	637,544	207,107	430,437	1.597	0.0246
2009	703,431	231,021	472,411	1.747	0.0288
2010	869,095	253,136	615,960	2.250	0.0315
2011	965,565	309,027	656,538	2.250	0.0272
2012	776,616	249,169	527,447	1.943	0.0114
2013	1,033,117	212,087	821,031	2.250	0.0060
2014	1,254,392	422,406	831,987	2.250	0.0178
2015	1,150,391	306,362	844,029	2.250	0.0138
2016	906,520	322,107	584,414	2.147	0.0039
2017	753,721	146,415	607,306	2.228	0.0089
2018	592,377	160,566	431,811	1.602	0.0139
2019	628,251	150,972	477,279	1.764	0.0111
2020	720,885	142,690	578,196	2.124	0.0232

2021	778,318	183,806	594,512	2.183	0.0289
2022	785,478	209,001	576,478	2.118	0.0233
2023	1,089,549	182,295	907,254	2.250	0.0157
2024	945,354	205,381	739,973	2.250	0.0170
2025	888,347	165,212	723,136	2.250	0.0213

The results of this exercise in conjunction with the results of the Bayesian analysis of SRKW growth rates from census years 1999 to 2025 (1999-2000 to 2024-2025) provides strong evidence that significantly reducing the allowable Chinook catch in each of the three AABM PST fisheries has a high probability of providing SRKW with access to enough Chinook annually to achieve a positive population growth rate under recent environmental conditions (1999 to 2025) affecting the abundance of Chinook that contribute to PST AABM fisheries. The exploratory modeling of a 50% reduction in the AABM TAC established in the 2009 PST renewal appears to provide robust assurance that such a management change would place the SRKW population on a strong positive population trajectory. Managers should explore other levels of TAC reduction in pursuit of a precautionary, risk-averse change in the management of AABM (and likely other west coast US Chinook fisheries).

DISCUSSION and CONCLUSION.

The simplified analysis of the SRKW population growth rates in the first 26 years of the 21st century presented herein confirms the importance of Chinook abundance as indexed by the catch-adjusted post-season PST AABM index (EEAI) to the population growth rate of SRKW despite the confounding role of unspecified co-variate aggregates in the time-varying intercepts alpha. The primary unspecified

356 covariates at issue include the effects of vessel noise and persistent organic
357 pollutant (POP) loads in SRKW (particularly females that offload ~77% of their
358 PCB (and probably other POP) loads to offspring during gestation and lactation
359 through the first year of calf life) and inbreeding levels of individual SRKW.
360 Chinook abundance in fisheries occurring south of the AABM fisheries may also
361 contribute to SRKW demographic, but our analysis shows that AABM fisheries
362 have significant effects on SRKW population growth rates and that reductions in
363 the TACs in the three AABM fisheries alone can have significant positive effects
364 on SRKW demographics.

365 My approach appears to provide a relatively simple way to estimate increases in
366 Chinook abundance (in AABM fisheries) needed to achieve SRKW population
367 growth rates necessary to obtain a positive trajectory in the growth rate and thereby
368 to prevent the current rapid decline toward extinction (cf., Williams et al 2024) and
369 to achieve growth rates required to achieve recovery and eventual de-listing of the
370 population from the ESA and SARA. The analysis can likely also be used, in
371 conjunction with the AABM EEAIs, to track the success or failure of efforts to
372 reduce the impact of vessel noise and POPs.

373 Nelson et al. (2024) and Williams et al. (2024) estimated the relationship between
374 an index of Chinook salmon abundance in the West Coast Vancouver Island
375 (WCVI) AABM fishery on SRKW birth and survival rates. Both found positive
376 relationships between the WCVI index and both birth and survival rates. However,
377 due to the small number of births relative to the number of survivals, both found a
378 weaker effect of Chinook abundance on birth rates than on survival rates. The
379 WCVI AABM fishery index, like those for the other two AABM fisheries, do not
380 account for years in which the post-season catch is greater or lower than the
381 Treaty-specified total allowable catch (TAC). In such cases, the index does not

accurately indicate the number of Treaty Chinook that remain uncaught and potentially available to foraging SRKW. The Ecologically Effective Abundance Index presented in this paper corrects for this feature by providing for under- and over-harvest of the abundance-specified allowable catch and thereby providing a transformation of each AI into a direct index of the number of Chinook that remain uncaught when the TAC is neither over- nor under-fished and, hence, are potentially available to the marine ecosystem, including predators such as the SRKW. Our results employing this new abundance index to Chinook harvest in all three AABM fisheries from the beginning of the PST's AABM harvest regime in 1999 to the most recent abundance and catch data in 2025, show that levels of the uncaught Chinook abundance in both the current (lag0) and prior (lag1) years have positive effects on the annual SRKW population growth rate in the current year, which are modified by the negative effects of the primary limiting factors which are aggregated in the lag0 and lag1 alpha parameters. This approach enables a direct assessment of the AABM abundance index required to achieve various levels of potential annual SRKW growth given known or estimated levels of the two alpha parameters.

METHODS.

A harvest-adjusted ecologically effective PST AABM Chinook abundance index (EEAI) derived from the PST post-season abundance index (AI) and catch data.

The basic idea for deriving the new AI is to develop a lookup table of the number of Chinook that would remain uncaught (and hence potentially available to the ecosystem, including SRKW) at each PST post-season AI given the AI-determined "allowable catch level (ACL)" which we refer to henceforth as the TAC (total

allowable catch). For each year of interest (here, SRKW census year 1999 to 2025 I identify the PST post-season AI for which the annual post-season total AABM catch corresponds to the treaty-established TAC. That is, given a specific treaty-established AI and associated TAC (from Table 3 of Annex IV of Chapter 3 of a specific treaty renewal period), we look up the AI that would correspond to the case in which the actual post-season catch would have been equal to the TAC. Since the PST abundance index does not change between treaty renewals in 1999, 2009, and 2019, but the TAC associated each AI does, it is necessary to base the lookup table on a particular renewal period. For this analysis I chose the 2009 renewal.

I then looked at the AI and catch data for 1999 to 2024 as reported in TcChinook (2026)-02, section 2 (table 2.1, page 7). Table 2.1 lists the (post-season) AIs from 1999 to 2024 separately for each of the three AABM fisheries. I obtained the post-season AI and catch data for 2025 from the Pacific Salmon Commission Chinook Technical Committee (CTC) March 31, 2026 “Preseason abundance indices for 2026 and post-season abundance indices for 2025”. To obtain the (post-season) AI for the total of the three fisheries I first multiplied the annual AI for each AABM fishery by the 1979 to 1982 baseline value to obtain the estimated total Chinook abundance for each fishery. I then added the three estimates of total abundance to obtain the estimated total Chinook abundance for each year of interest, and then determined the AI for the three-fishery aggregate by consulting the AI-TAC table for the 2009 Treaty renewal, interpolating as necessary. Details are shown in an Excel file (Supplementary File S3). The new ecologically effective post-season AI (EEAI) derived from the total number of Treaty Chinook un-caught in the total of the three AABM fisheries aggregate in SRKW census years 1999 to 2025 are

shown in column S of the "calculate 2009 TACs" worksheet in Supplement File S3.

For the exploratory "Half-Tac" analysis of Part III below whereby the TACs specified in Chapter Three of the Chinook annex to the 2009 Treaty renewal, the details of the calculations of the total TAC and the EEAIs for SRKW census years 1999 to 2025 are shown in the "Calculate Half-TAC" worksheet in Supplement File S3.

Exponential population growth model

A simple exponential population growth model with a time-varying intercept(s) was employed to evaluate the relationship between the annual population growth rate of Southern Resident killer whales (SRKW) for census years 1999 to 2025 and the new index (EEAI) of AABM Chinook abundance for the aggregate of the three AABM fisheries.

Let the annual population growth rate from time t-1 to time t (in years), λ (lamda) = N[t]/N[t-1], where N[t] is the census population size of SRKW in year t, and let the instantaneous population growth rate equal the natural log of lambda: Ln(N[t]/N[t-1]), which I will henceforth refer to simply as GR. Then, the time-varying logistic population growth model may be written as

GR[t] = alpha[t-x] + beta*AI[t-x]. [1]

GR is the (estimated) instantaneous population growth rate. Hence, the (estimated) annual growth rate lambda (λ[t]) is

Exp(alpha[t-x] + beta*AI[t-x]), [2]

where x is the lag in years from the current SRKW census year.

Here, alpha is the (time-varying) intercept of the linear regression of GR in census year t on the Chinook abundance index (EEAI) for one or more years of interest. Alpha accounts for all potential factors (covariates) affecting GR other than the index of AABM Chinook abundance. Based on the recent analysis by Nelson et al (2024) I evaluated the case in which the annual SRKW instantaneous population growth rate (GR) in year t was affected by Chinook abundance and other unmeasured factors in the current (year t) and preceding year (t-1). Lag values of 1 and 0 evaluate the hypothesis that values of the three main limiting factors (Chinook abundance, vessel noise and disturbance of SRKW foraging and other life-history functions, persistent organic pollutants (POPs) and levels of inbreeding in individual whales) in both the current and preceding years are most responsible for the observed SRKW growth rate in year[t].

Thus, I evaluated equations 3 and 4:

GR[t] = alpha[t-1] + alpha[t] + betaleg1*EEAI[t-1] + betalag0*EEAI[t]. [3]

Lambda[t] = exp(GR[t], [4]

where 'EEAI' is the new catch-adjusted AABM Chinook salmon abundance index.

In contrast to the time-varying character of the intercept alpha I assume that the two regression coefficients, betalag1 and betalag0, which estimates the slopes of the regression of annual SRKW population growth rate (GR) on the Chinook abundance index (EEAI) at lags 1 and 0 (respectively) are constant over the time period of the analysis.

Bayesian regression analysis in the program Stan (implemented with Rstan) was conducted on the annual instantaneous population growth rates of the SRKW

population from census year 1999 to 2025 based on the EEAI values for years 1999 to 2025. The parameters to be estimated were the regression intercepts (alpha) and the coefficients of the abundance index (betalag1 and betalag0). A total of 20,000 samples and 4 chains were run with a burn-in of 10000 each chain, resulting in a total posterior sample of 40,000.

Author contributions.

Nick Gayeski is the sole author of this paper and conceived the project and undertook all analyses reported in the Manuscript.

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Declarations

Competing interests

The author declares no competing interests.

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FIGURES

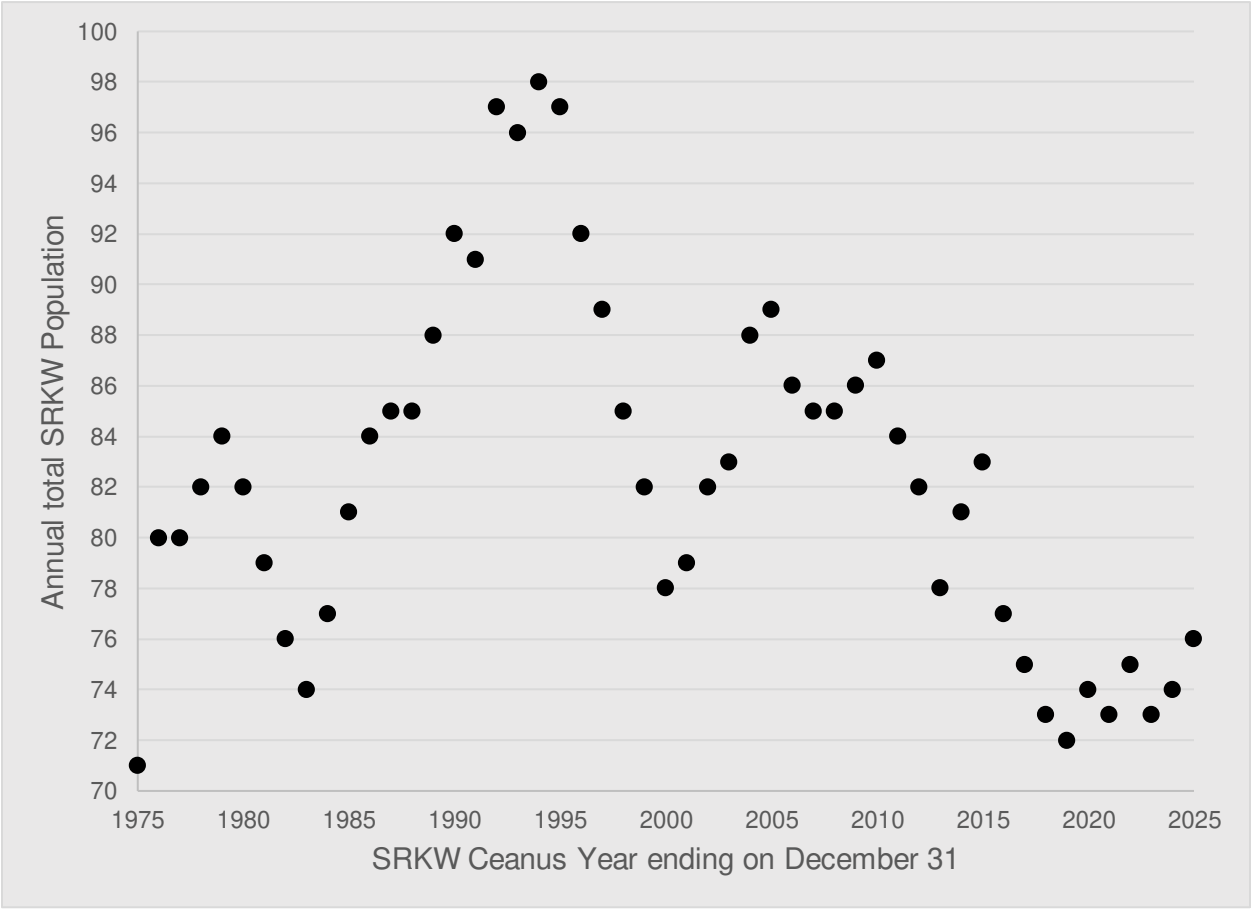


Figure 1. SRKW census population size 1975 to 2025 (census year ending December 31

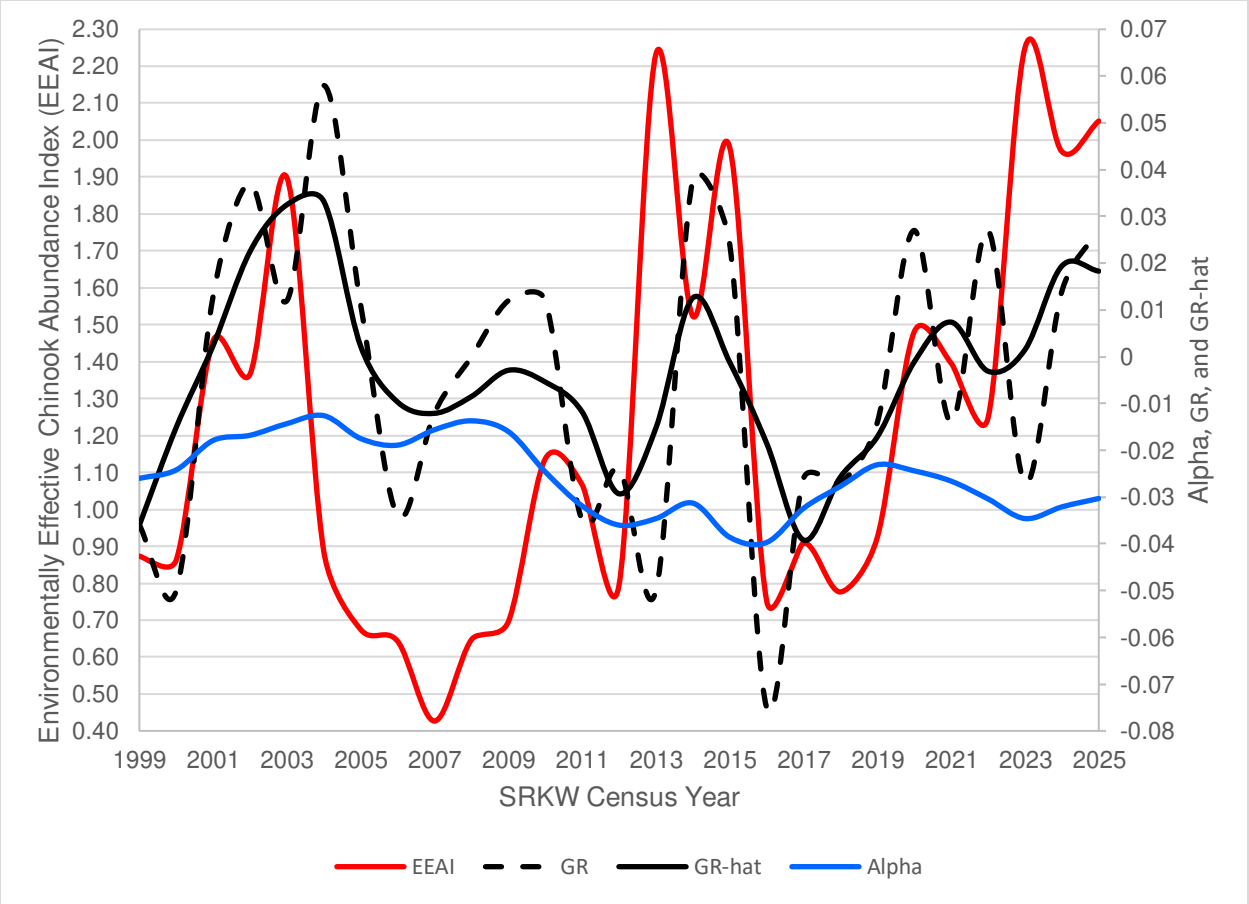


Figure 2. Chart of SRKW posterior parameters (Alpha, EEAI, Growth Rate (GR), and estimated Growth Rate (GR-hat) for census years 1999 to 2025. Pearson correlation coefficients for pairs of parameters (dfs = 25): [EEAI, GR] = 0.237; [EEAI, GR-hat] =0.475; [EEAI, Alpha] = -0.40; [GR, GR-hat] = 0.971; [GR, alpha] = 0.37; [GR-hat, Alpha] = 0.391.

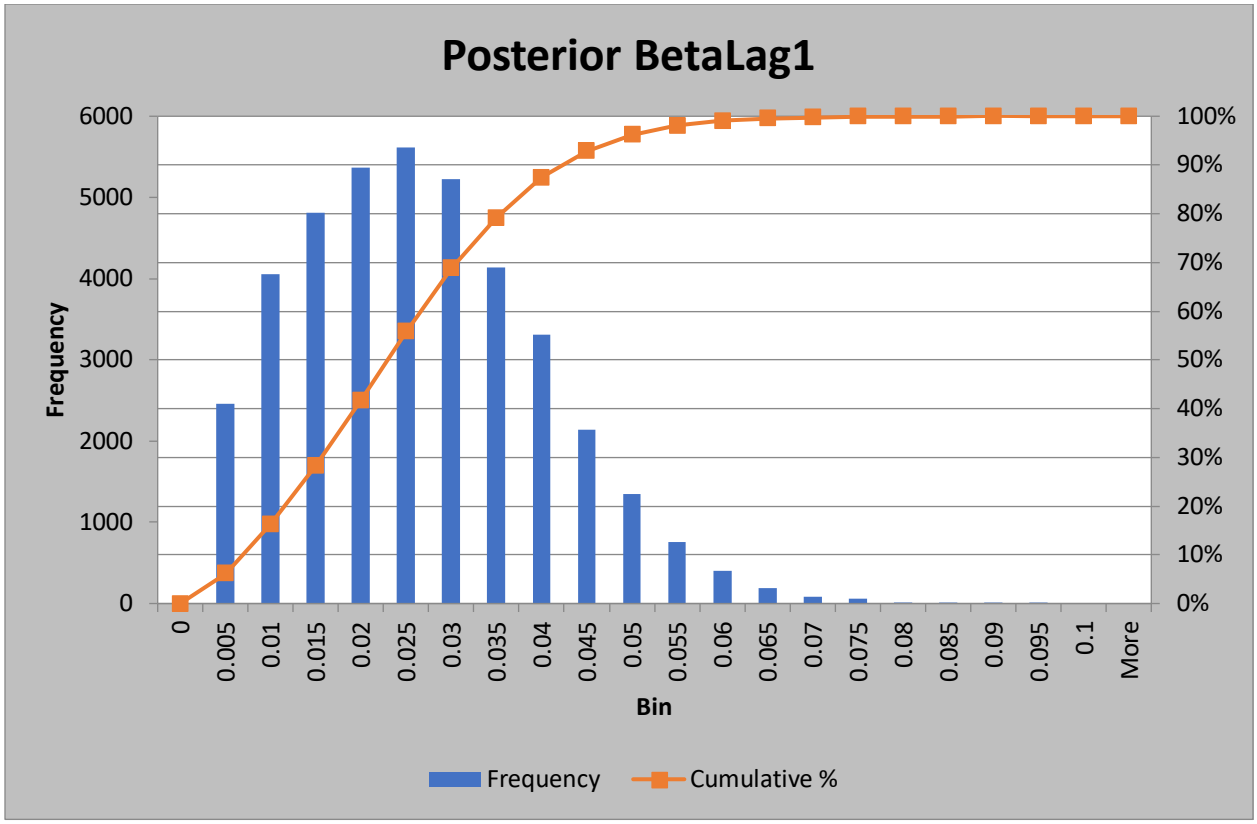


Figure 3. Histogram of posterior values of BetaLag1

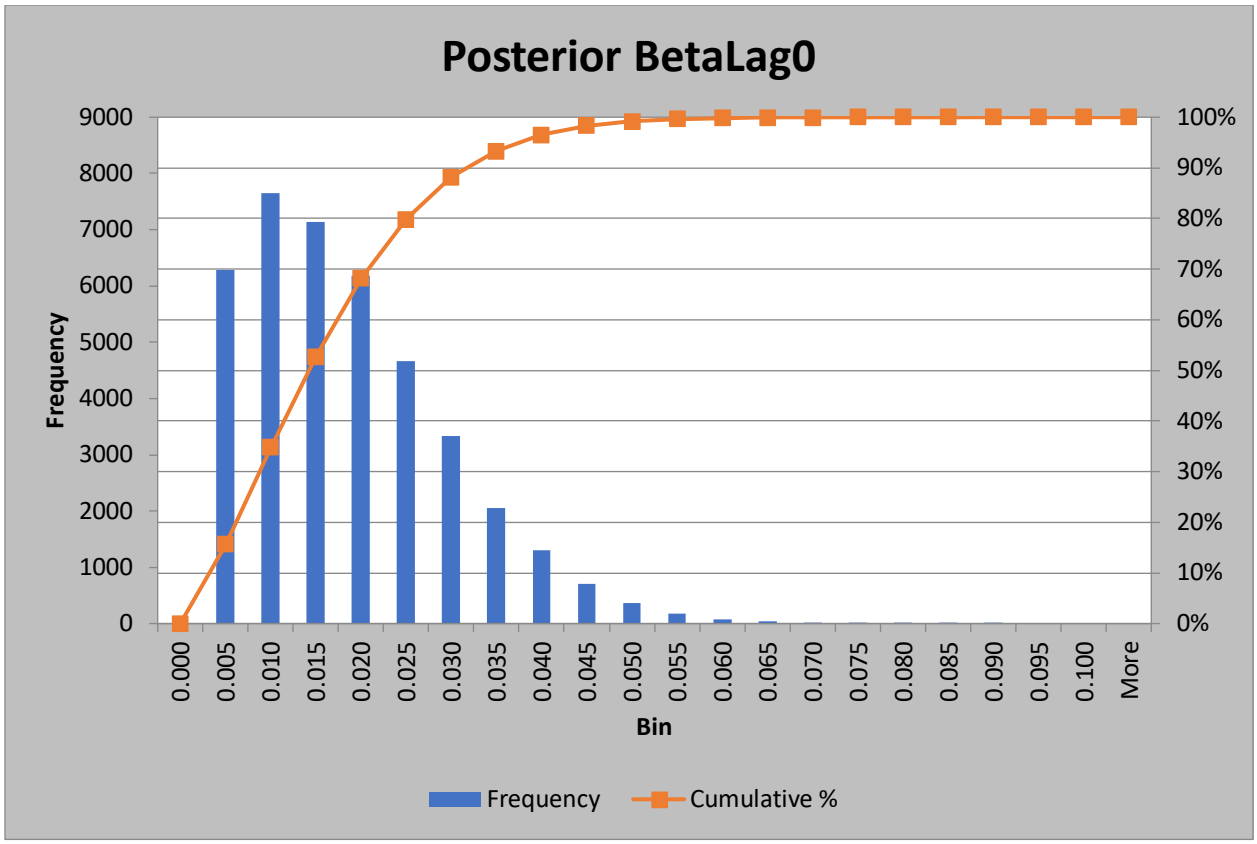


Figure 4. Histogram of posterior values of BetaLag0

Supplementary Files

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- SupplementFiles.zip