

Southern Resident Killer Whale Population and Status Update

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Abstract

This document is intended to provide an overview and status update of the Southern Resident population following the most recent summer census in 2019. Many of the analyses and figures presented below are described in more detail elsewhere, particularly the most recent Status Review (NMFS 2016) and recent technical reports following the 2011 - 2012 bilateral workshops (Hilborn et al. 2012; Ward et al. 2013). In particular, these analyses are meant to describe recent changes in population size and age structure, change in demographic rates over time, and an updated projections of population viability.

Recent births and deaths

Since 2014, the following animals have been born in the SRKW population and lived:

animal	birth	sex
J51	2015	M
J53	2015	F
L121	2015	M
L122	2015	M
L123	2015	M
J56	2019	F
L124	2019	Unk

The following whales have died since 2014. Their deaths are also included in this table,

animal	death	sex	age_death
L27	2015	F	50
J14	2016	F	42
J28	2016	F	23
J31-neonate	2016	Unk	0
J34	2016	M	18
J54	2016	M	1
J55	2016	Unk	1
L95	2016	M	20
J2	2017	F	106
J52	2017	M	2
K13	2017	F	45
J35-neonate	2018	F	0
J50	2018	F	4

animal	death	sex	age_death
L92	2018	M	23
J17	2019	F	42
K25	2019	M	28

Sex ratio at birth

During the 2011-2012 bilateral workshops (Hilborn et al. 2012; Ward et al. 2013), a comparison between NRKW and SRKW sex ratios at birth was presented, with calves being approximately 55% female in the NRKW population and 45% female in the SRKW population. This difference was assumed to be due to chance, and there was no evidence for a significant trend. As the proportion of males in the SRKW population has increased over time, it is worth re-examining the evidence supporting any trend.

To evaluate support for a trend, we fit Bayesian logistic regression models (GLMs with a binomial family and logit link function), to SRKW birth data over the period 1977-present. In recent years, since 2016, there have been 0 male births and 3 female births. This analysis highlights that the probability of a positive trend is approximately 72.7% (Fig. 1).

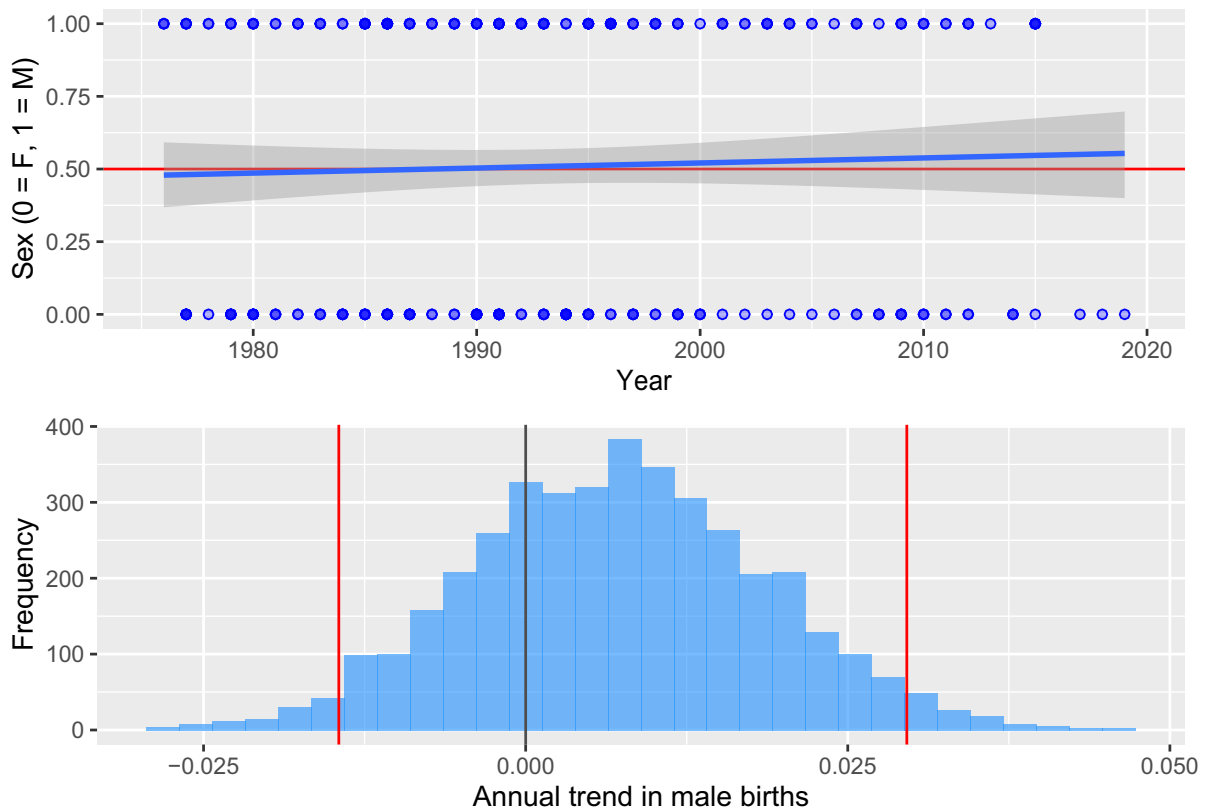


Figure 1: Trends in sex ratio at births for Southern Resident killer whales. Shown are all births (with GLM best fit) and the posterior distribution of the coefficient for the year term (trend). Positive values of the coefficient would support an increasing trend through time. The red line on the top panel represents the 50:50 sex ratio, and red lines on the histogram represent the 95% CIs.

Changing Population Structure

One of the objectives of the recovery goals (NMFS 2008, 2011) was an age and sex distribution that is more similar to the Northern Resident population (at the time of ESA listing). The Southern Resident population has undergone a number of shifts in age and sex, and because the population is so small, the age or sex composition are more sensitive to individual births and deaths. Previous status reviews based these targets from 1973-1996 (Olesiuk, Ellis, and Ford 2005):

Stage	
Juveniles	47 %
Reproductive females	24 %
Post-reproductive females	11 %
Adult males	18 %

We can re-evaluate these targets, both for the Northern and Southern Resident populations, using the most recent years of data available (2018 for Northern Resident, 2019 for Southern Resident). There are some small differences between life stages used in Olesiuk et al. 2005, and more recent work (Ward et al. 2013). First, Olesiuk assumed animals to not be mature to 15.5 (whereas Ward et al. 2013 assumed females to be mature at age 10). Second, Olesiuk et al. (2005) defined post-reproductive animals to be animals who hadn't given birth in 10 years (Ward et al. 2013 used a cutoff of 42 years). For these calculations, we define age at maturity to be 10 years, and 42+ as the age of reproductive senescence.

	SRKW 1979	SRKW 2019	NRKW 1979	NRKW 2018
Juveniles (< 10)	37 %	19 %	32 %	30 %
Adult males (10+)	18 %	35 %	32 %	25 %
Adult females (10-42)	27 %	39 %	31 %	36 %
Post-reproductive females (42+)	19 %	7 %	4 %	9 %

Reproductive females

The number of reproductive aged females was at its lowest point in the late 1970s, in part because of the prior harvesting that occurred into the early 1970s (Fig. 3). Though the overall number of reproductive females has been fluctuating between 25-35 for most of the last 40 years, there have been contrasting changes by pod, with declines in L pod females and increases in J pod (Fig. 3). At the start of the survey in 1976, the distribution of females was skewed toward younger ages with few older, post-reproductive females. The distribution in recent years is more uniform across female ages (in other words, more females in their 30s, Fig. 2).

For comparison, we can also look at the aggregate number of reproductive females in the NRKW population. This shows a nearly linear growth over time (Fig. 4).

Changing demographic rates

Increased evidence of declining fecundity

There are several methodological changes from the projections done previously (Hilborn et al. 2012; Ward et al. 2013). First, because we don't have indices of salmon abundance available to whales (and none of the existing metrics of salmon abundance have been found to correlate with killer whale demography; PFMC Draft Report 2019), the estimation model was switched from a GLM to a GAM, which allows a smoother

Ages of reproductive – aged female SRKW

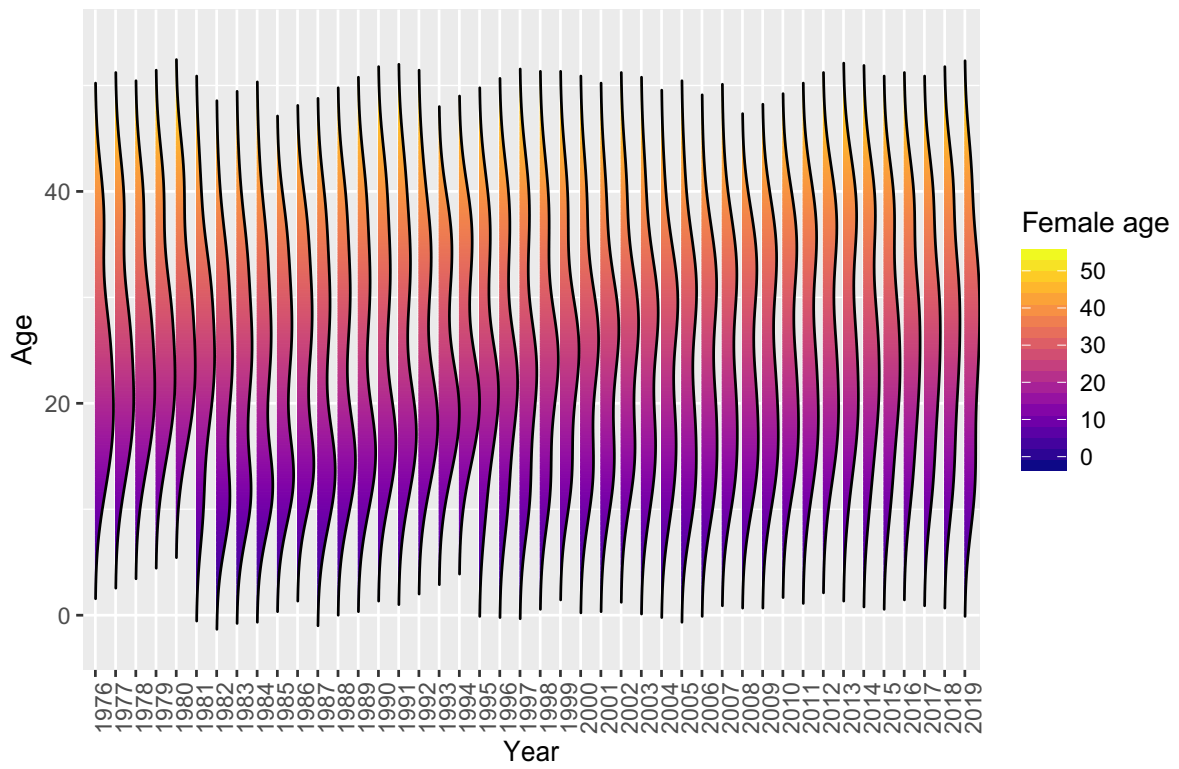


Figure 2: Distribution of ages of reproductive age females (10-42, inclusive) for Southern Residents by year since 1976.

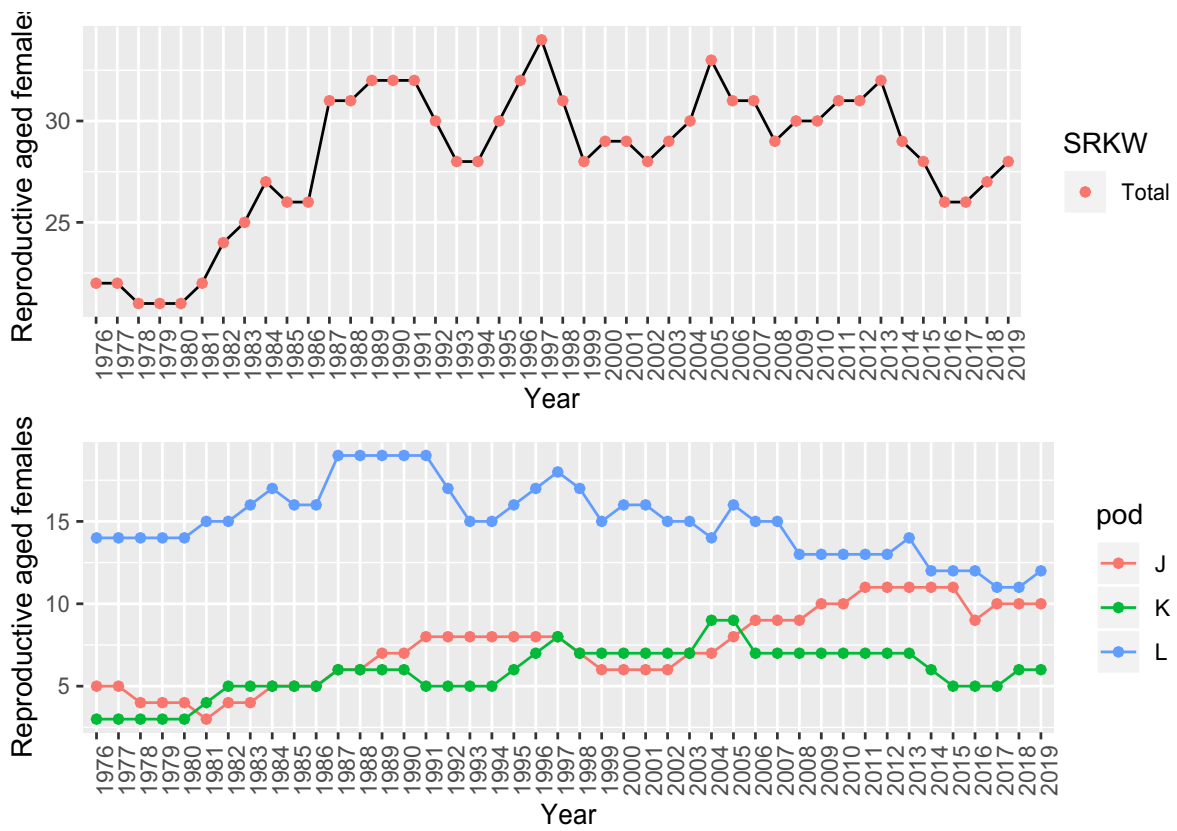


Figure 3: Time series of reproductive age females (10-42, inclusive) for Southern Residents by year since 1976.

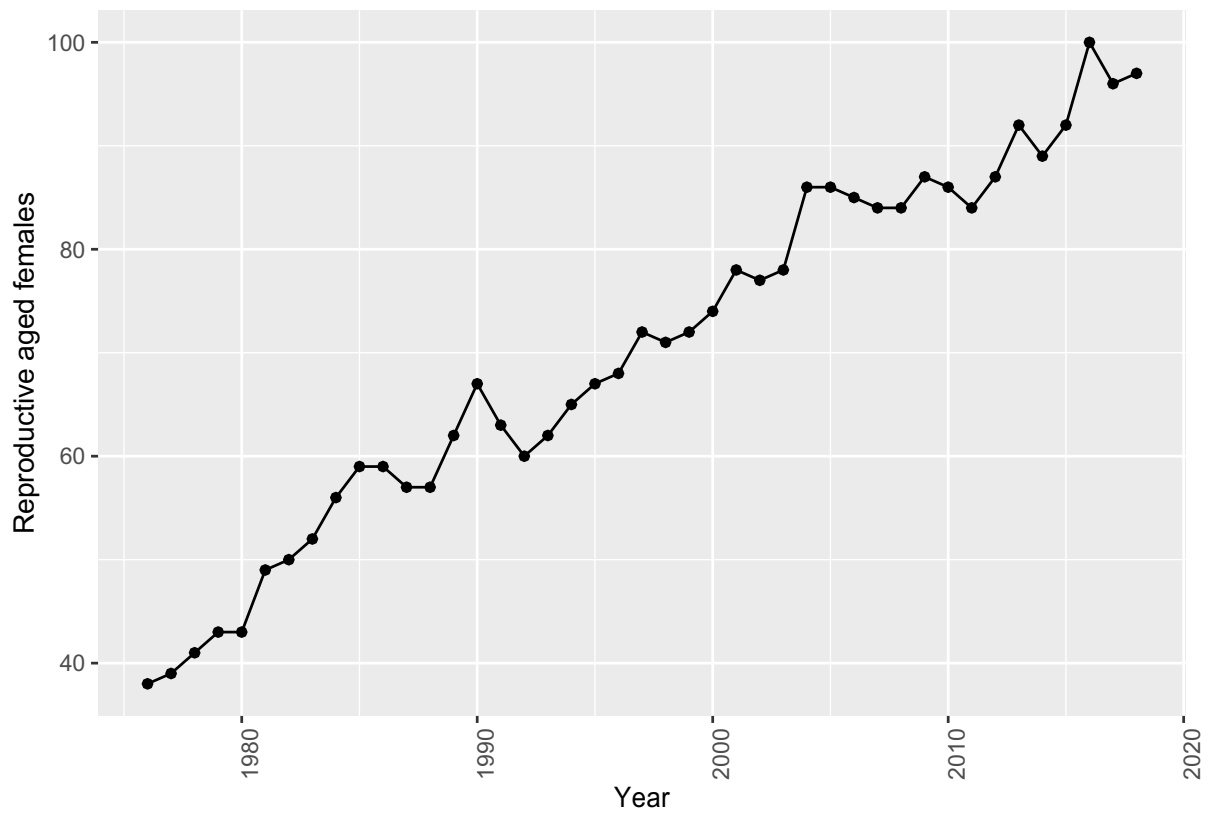


Figure 4: Time series of reproductive age females (10-42, inclusive) for Northern Residents by year since 1976.

over year effects. In terms of interpretation, these smooth terms represent annual variation that may be driven by processes (prey, disease, etc) or changes in data quality or detectability (particularly for birth rates, which are partially a function of things like the fraction of time that particular social groups spend in inland waters where they're more likely to be seen). To evaluate changes in survival or fecundity rates over time, we can examine survival rates estimated using data through 2010, versus estimates using data through 2019. For both instances, we can fit generalized additive models (GAMs) that include the effect of age (separate splines by sex) and optionally a spline term over time. To not introduce bias, we did not allow animals born < 1970 to be included in the estimation (only the projection). For this sensitivity analysis, the SRKW and NRKW data are combined into a single model, with population as an estimated offset (Ward et al. 2013).

Results from these models indicate that of female survival, male survival, and female fecundity, fecundity rates have changed the most since 2010 and have declined (particularly for older ages, Fig. 5). Time series of estimated fecundity rates also indicate low rates in recent years (this is not surprising, as there have been very few successful births). Since 1980, there have been several periods associated with high fecundity (late 1980s, mid 2000s, Fig. 6). In contrast, estimated survival rates have been relatively flat (Fig. 6), with the exception of low survival prior to the population being listed (SRKW reached a peak of 98 animals in 1995, and then dropped to 82 animals in 2003).

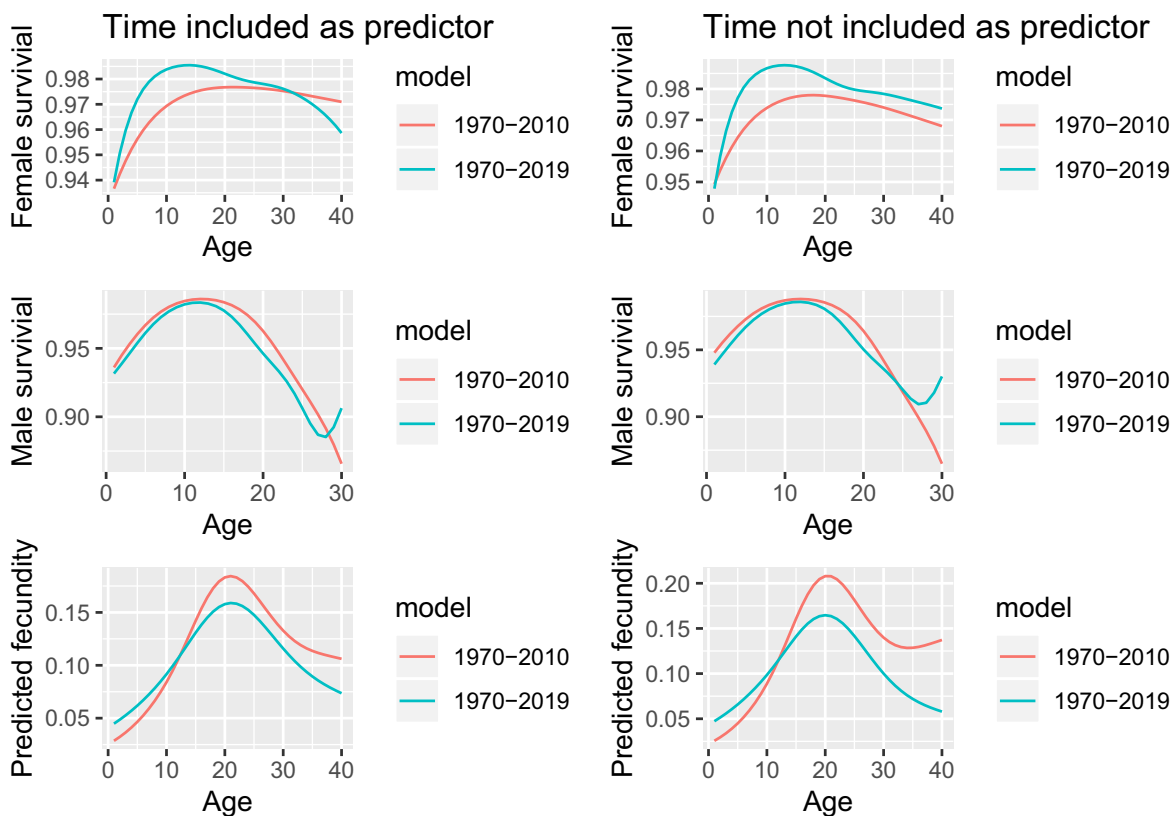


Figure 5: Sensitivity analysis, showing how adding data since 2010 changes Southern Resident Killer whale demographic rates. Models with time and age as predictors include smooth terms fit independently over each predictor; models without time only include the age effect. All models support the inclusion of year effects (not shown). Across rates, these models illustrate little change in survival rates, and a decline in fecundity rates since 2010.

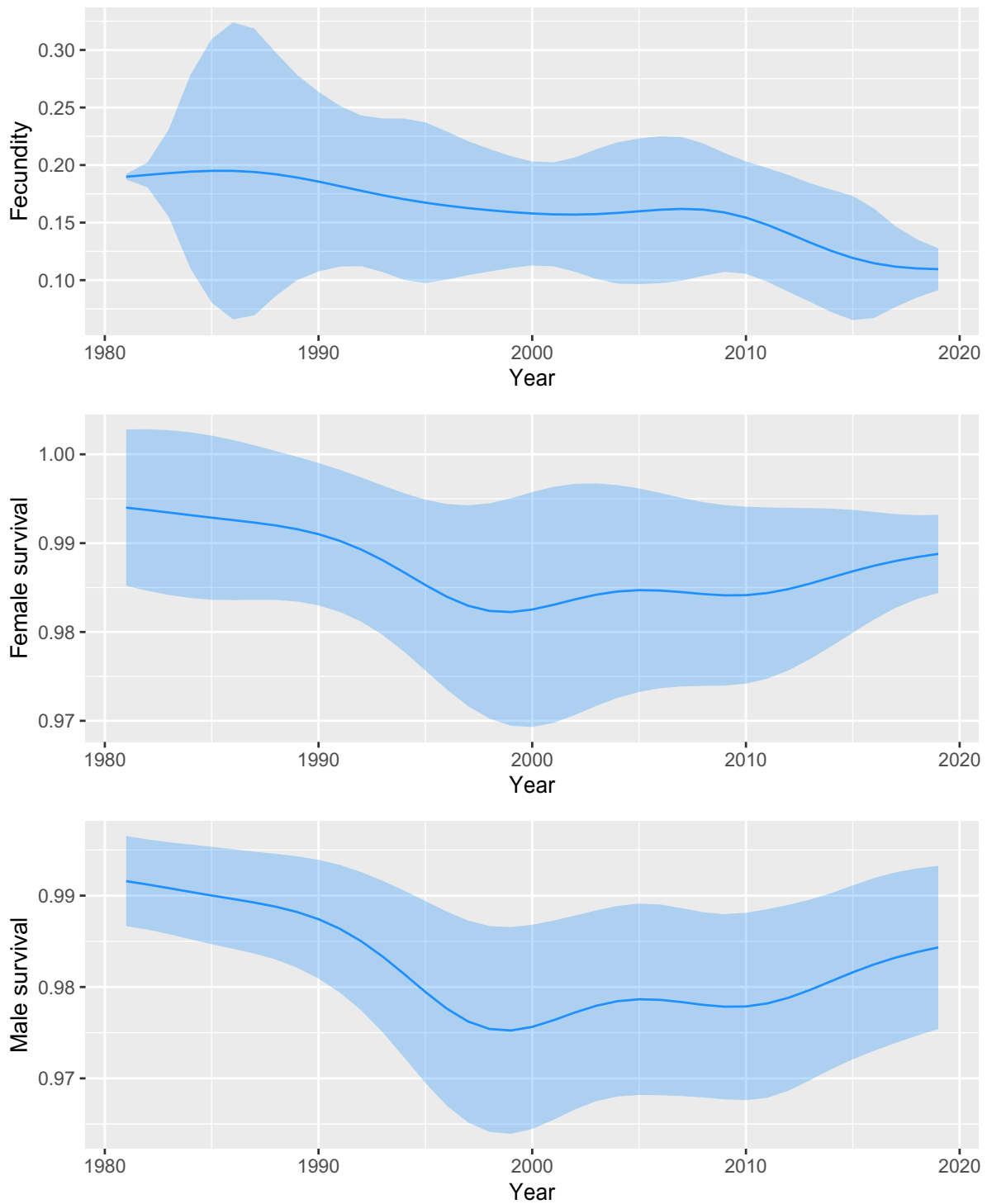


Figure 6: Time series of predicted fecundity rates for a 20-year old Southern Resident female killer whale and survival rates for a 20-year old female and male. Estimates are generated from the Bayesian logistic regression models, using priors from the NRKW population. Gray region represents ± 2 standard errors and the black line represents the mean.

Population projections

Given the current population age and sex structure, we performed a series of forecasts or projections, doing 1000 simulations of 25 years for each. Following previous work (Hilborn et al. 2012), projections beyond this time frame were not included, as longer term trajectories become negative, resulting in extinction or quasi-extinction. Following previous annual updates, we also used a sex ratio at birth of 55% male / 45% female, because of the historical skew in SRKW sex ratios at birth. Note that this differs from the previous reviews and published projections, which assumes a 50:50 sex ratio at birth (Hilborn et al. 2012; Ward et al. 2013).

The scenarios we considered were:

1. Projections using fecundity rates and survival rates estimated over the entire time series (this is done with estimation models ignoring time)
2. Projections using fecundity and survival rates estimated for the last 5 years, 2014 to 2019
3. Projections using the highest fecundity and survival rates estimated, in the period 1985-1989

Informative priors

Because this analysis was done in a Bayesian framework, we performed the analysis with and without informative prior distributions (scenarios without informative priors were based on Southern Resident data only). Data provided by DFO have updated the NRKW catalog from 2010-2011 to 2018. As such, we can (1) consider informative priors on the effect of age (for survival and fecundity rates), and (2) use informative priors on the effect of year. We included scenarios with just informative priors on age, or informative priors on the age and year terms (but not informative priors on just year alone).

Fecundity was modeled using a Bayesian GAM (Wood 2016; Plummer 2019), where

$$\text{logit}(p_{i,t}) = B_0 + f(\text{year}_{i,t}) + f(\text{age}_{i,t})$$

where p_i represents the probability of animal i giving birth at time t , B_0 is a population specific intercept, and smooth functions $f()$ are modeled over year and age. As in GAMs fit with maximum likelihood, the smooth functions can be written as $f(x) = \prod_{j=1}^J b_j z_j(x)$, where z_j are basis functions for the smoother, J is the dimensionality, and b_j are estimated coefficients. Additional details are provided in (Wood 2016).

Survival was also modeled using a logistic function, however we implemented a stage- rather than age-based model, following limitations of the data described in (Ward et al. 2013) and others. A primary concern for example is that ages of older animals at the start of the killer whale surveys were sometimes guessed based on reproductive histories, and potentially biased. The survival model predicting survival $s_{i,t}$ of animal i at time t can be written as

$$\text{logit}(s_{i,t}) = B_0 + B_{\text{stage}} + f(\text{year}_{i,t})$$

where B_0 is the population level offset, B_{stage} is a stage-specific effect (stages as described in (Ward et al. 2013)) and $f(\text{year}_{i,t})$ the smooth term over years.

The fecundity and survival models were first fit to the NRKW data, using weakly informative priors, 50000 Markov chain Monte Carlo (MCMC) iterations, and 3 parallel MCMC chains. Output from the posterior distributions of these models were used to generate multivariate normal prior distributions for the SRKW population models. The effects of age or stage and year were separated, and the posterior mean and variance-covariance matrix of each was summarized.

Projections done for the 2016 Status Review (NMFS 2016) also showed the population on a downward trajectory, and all three scenarios presented here provide further evidence of a declining population over the

next 25 years (Fig. 7). The most optimistic scenario, using demographic rates calculated from the 1985-1989 period, has a trajectory that increases and eventually declines after 2030. Additional runs for this scenario indicated a similar trajectory with a 50:50 sex ratio. Thus, this downward trend is likely driven by the current age and sex structure of young animals in the population, as well as the number of older animals. For example, there's currently 0 females younger than 25 – if all survive another 10 years, they will represent the majority of the reproductive females in the population and number fewer than the current population of reproductive females 2.

A first set of projections represents the SRKW population projected using the NRKW age/stage priors, but not including priors on the year terms (essentially letting each population have different patterns over time). This

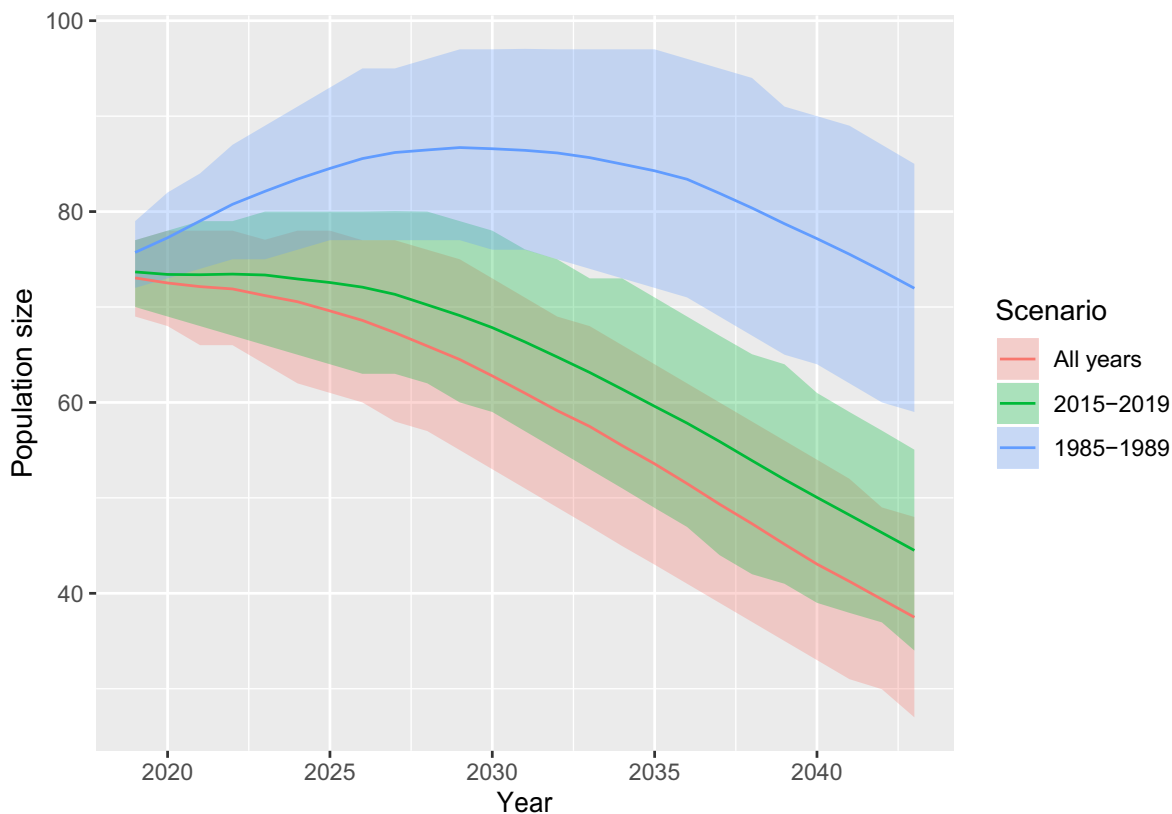


Figure 7: 25-year projections of the SRKW population, using the NRKW age and stage data as prior distributions for the SRKW parameters, but not including priors on the year effects estimated from the NRKW population

The sensitivity comparing the SRKW projections under different prior distributions illustrated that for most scenarios, there appeared to be little effect of using the prior on year effects, in addition to age. Perhaps the scenario that showed the largest effect was the most optimistic scenario, using survival and birth rates from the 1985-1989 period (Fig. 8).

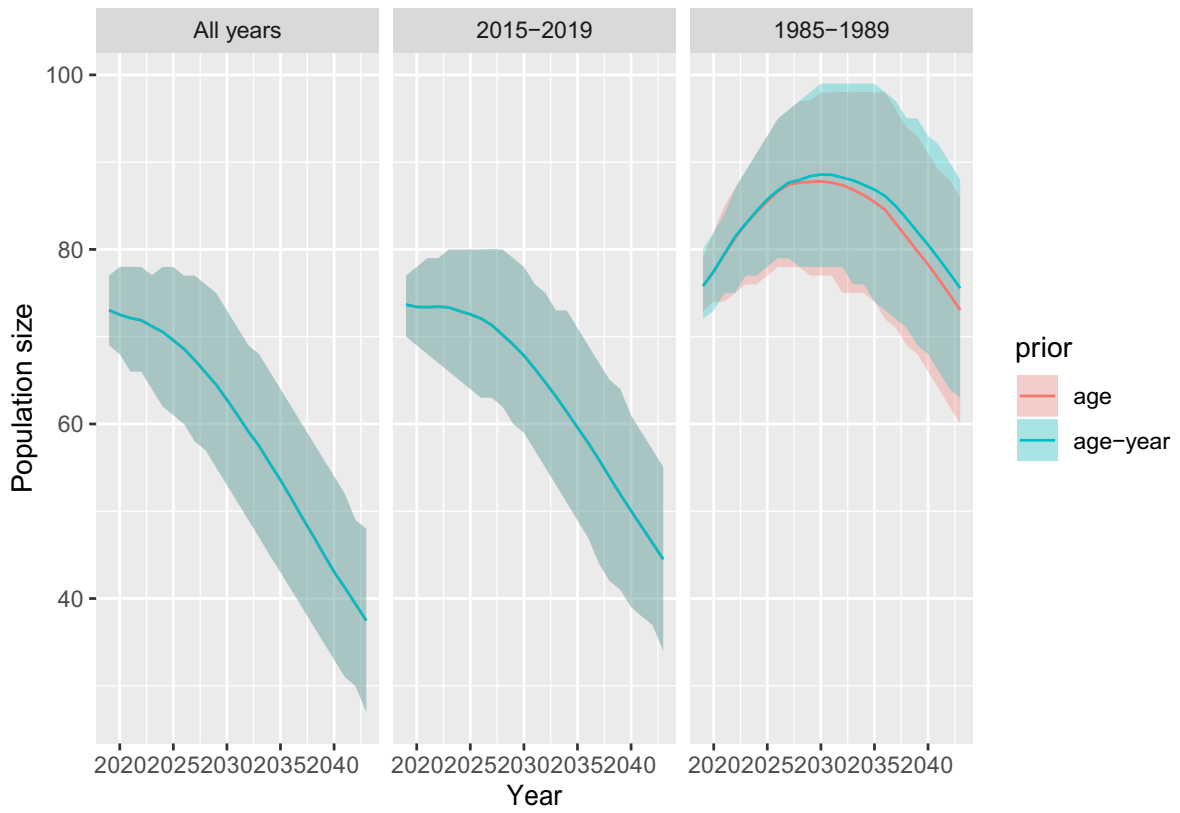


Figure 8: 25-year projections of the SRKW population, using the NRKW age / stage and year prior distributions for the SRKW parameters, estimated from the NRKW population

Acknowledgments

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