Supplemental materials for 'Shifting phenology of an endangered apex predator tracks changes in its favored prey'

March 17, 2021

Models

Southern resident killer whale presence and their prey at Lime Kiln Point State

1. Southern resident killer whale presence model

   We fit a separate hierarchical model to each pod (J, K, L), as well as a hierarchical model to all SRKWs pooled together. We estimated the presence, or occurrence probability (with presence when $Pr(\psi=1)$), as a smooth function of day of year, *s(day)*. Specifically, we assumed ψ to be a Bernoulli random variable dependent on day of year (as a smooth function, using thin plate regression spline basis), with a year-specific shape as well as a year-specific intercept (i.e., a random effect of year):

$$Pr(\psi_i = 1) = logit^{-1}(\alpha_{year[i]} + s(day)_{year[i]})$$

$$\alpha_{year} \sim N(\mu_\alpha, \sigma_\alpha)$$

2. Fraser River Chinook salmon abundance index model

   We modeled an index of Fraser River Chinook salmon abundance (y, the log of the daily catch per unit effort [CPUE] to which we added one prior to logging to avoid values of zero) as a smooth function of day of year (using thin plate regression spline basis), with a year-specific shape as well as a year-specific intercept (i.e., random effect of year):

$$y_i = \alpha_{year[i]} + s(day)_{year[i]}$$

$$\alpha_{year} \sim N(\mu_\alpha, \sigma_\alpha)$$

The above models for killer whales ad Chinook were fitted via thin plate regression spline basis using the programming language `Stan` (Carpenter et al., 2017) (`www.mc-stan.org`), accessed via the `brms`(Bürkner,

2018) package in R (**?**), version 3.6.2. For each model fit, we ran four chains simultaneously, each with 4 000 sampling iterations (1 000 of which were used for warm-up). Code for the above models is in Appendix 1. We assessed model performance through R_{hat} (all were close to 1) and high neff, as well as visual consideration of chain convergence and posteriors (Gelman et al., 2014).

Southern resident killer whales and salmon in the Central Salish Sea and Puget Sound Proper

1. <u>Southern resident killer whale occupancy models</u>

    We quantified pod-specific phenology for J, K, and L pods using occupancy models, which can estimate jointly species presence and detection probability (p, the probability of detecting at least one individual present at a site) by distinguishing true presence or absence, z (a latent, unobservable state), from observed presence. Occupancy models are composed of a state sub-model, which is the model for the ecological process of true presence or absence, and an observation sub-model, which in this case links the observations (i.e., the number of sightings of the pod per day per site) to the state model. We modeled occupancy probability ($\psi_{year,day}$) as a semi-parametric, smooth function of day of year (*'day'*), using flexible thin-plate spline regression modelling, and year as a level (Strebel et al., 2014). Thus, the sub-models are:

    - **State model**, in which we assumed $Z_{year,day}$ to be a Bernoulli random variable for which 0 signifies absence and 1 is presence:

    $$Z_{year,day} \sim Bernoulli(\psi_{year,day})$$

    - **Observation model**, in which the number of successful sightings (Y) in a particular fishing area on a particular day in a particular year, was modeled as a binomial random variable composed of the total number of sightings made in the area, year, and day ($T_{year,day,area}$), and the product of the state of occurrence ($Z_{year,day}$) and detection probability (P). We modeled detection probability as a year- and area-specific probability between 0 and 1 ($P_{area,year}$):

    $$Y(area, year, day) \sim Binomial(T_{year,day,area}, Z_{year,day} * P_{area,year})$$

    We fit separate occupancy models for each region (i.e., Central Salish Sea and Puget Sound proper) and season (spring/summer vs. fall/winter, since seasonal use varies by region) for each pod, and extracted estimates of annual arrival, departure, and peak occupancy dates with each model. We defined the arrival date as the earliest day within the season when occupancy probability exceeded 0.5; departure date was the latest day within the season when detection probability exceeded 0.5. Using a threshold probability between 0.2 and 0.5 did not qualitatively alter observed trends.) Pod-specific occupancy models were fit using `JAGS`, a program for analysis of Bayesian hierarchical models with Markov Chain Monte Carlo simulation (Plummer, 2019), accessed via the `R2jags` package (Su and Yajima, 2015) in R (**?**), version 3.6.2. We ran four chains simultaneously, each with 12 000 sampling iterations (4 000 of which were used for burn-in). We assessed model performance through R_{hat}, which were close to 1, and high neff, as well as visual consideration of chain convergence and posteriors (Gelman et al., 2014). Model code can be found in Appendix 2.

2. <u>Salmon abundance index models</u>

    To estimate the phenology of likely prey in the Central Salish Sea, we fit the hierarchical thin-plate regression spline models described above to the Albion Test Fishery data, from May through October (the full seasonal extent of the dataset), and from 1994 through 2017. To estimate the phenology of likely prey in Puget Sound, we fit the hierarchical thin-plate regression spline models separately to each of 13 Puget Sound runs (including three species across hatchery and wild salmon in 7 streams, Table S1) and used daily abundance index estimates to identify the day of year of first, peak, and last migration for each group in each year. We then used hierarchical linear models to identify trends over

time in phenology of salmon adult migration timing across Puget Sound proper. We fit separate multilevel linear models to each phenophase to estimate trends across years in the timing of adult salmon migration. The response variable, *day* is the day of year of the event (i.e., first, peak, or last date of migration in a given year) and the explanatory variable was year; we included group as a random effect to account for non-independence in timing at the group-level, as follows:

$$day_i = \alpha_{group[i]} + \beta_{year}$$

$$\alpha_{group} \sim N(\mu_\alpha, \sigma_\alpha)$$

See Appendices for model code.

Comparing observed and modeled estimates of 'whale days' at Lime Kiln Point State Park, Washington, USA

We calculated annual total whale days quantified from the data directly (i.e., a whale-day was counted as a day on which Southern Resident Killer Whales (SRKWs) were observed) and quantified from model-estimated probabilities of whale presence (i.e., each days probability of whale presence was summed across the year). Model-estimated presence probabilities were obtained from occupancy models, which estimated daily and annual probabilities of presence of SRKWs at Lime Kiln Point State Park. The two calculations were similar, and both reveal declines in SRKW presence in recent years, across all three pods (Fig. S5). This consistently collected dataset also suggests that SRKWs have shifted the timing of their activity in the area (Fig.S6.

Effects of changes in effort on estimated phenological change

With increasing public awareness of SRKWs near urban areas (e.g. the Salish Sea), the number of public reports of whales and people contributing to sightings networks such as the OrcaMaster Database have increased since its inception (Fig.S3). This shift in effort complicates interpretations of trends in the number of whale days over time (Fig. S4) because an increase in the number of whale on which SRKWs were observed could be due to increased observer effort in a region, rather than due to increased whale activity in the region. To better understand how increased effort across the time-series (i.e., increased numbers of sightings over time) may affect estimates of trends in phenology, we simulated data sets of whale presence during two seasons equivalent to those in our data set (spring/summer, which was 1 May through 31 Sept, or 153 days, and fall/winter, which was 1 October through 1 Feb, or 123 days). We used whale presence probabilities that matched the mean observed probabilities for the Central Salish Sea and Puget Sound regions, separately, from 1978-2017 (Table S1). We kept them constant over 40 simulated years, respectively. We then created an observation data set, in which effort (the number of observations) varied. During the low effort time period (years 1-20), the number of observations had a mean of 15 per year for Puget Sound and 104 per year in the Central Salish Sea (matching the means for these regions from 1978-1997 in the OrcaMaster database). During the high effort time period (years 21-40 in our simulated data set), the number of annual observations had a mean of 39 for Puget Sound and 133 for the Central Salish Sea (matching those in the OrcaMaster database from 1998-2017). We then calculated first- and last- observations dates for each simulated year. We ran these simulations 100 times and calculated the difference between the low effort and high effort time

periods. We compared these to the mean differences in first- and last-observation dates across time periods in the OrcaMaster database, for each region, to understand whether observed changes may be due to changes in effort over time, rather than changes in killer whale activity. We conducted the same analysis across the recent time frame (2001-2017), as well, using region-specific estimates of presence probabilities and observer effort obtained from this time-period.

Our simulations indicate that, if SRKW activity did not change and only effort changed across the two time-periods, the first observation would be expected to shift earlier from 1978-2017, especially in Puget Sound (Fig.S9A), perhaps because the number of sightings was very low early in the time-series. Thus, the large increase in effort across this time period may affected trends in phenological shifts. However, the expected change due to increased effort opposes the patterns we observed in for the Central Salish Sea (i.e., we would expect earlier arrival and later departure). Further, focusing on 2001-2017 only, effects of changes in effort are likely to be minimal (Fig.S9B). Due to the presence only nature of the OrcaMaster Database, it is difficult to fully separate an absence of whales from an absence of observers. We therefore focus our interpretation on the recent time-period (2001-2017).

References

Bürkner, P.-C. 2018. Advanced Bayesian multilevel modeling with the R package brms. The R Journal 10:395–411.

Carpenter, B., A. Gelman, M. Hoffman, D. Lee, B. Goodrich, M. Betancourt, M. A. Brubaker, J. Guo, P. Li, and R. Allen. 2017. Stan: A probabilistic programming language. Journal of Statistical Software 76:10.18637/jss.v076.i01.

Gelman, A., J. B. Carlin, H. S. Stern, D. B. Dunson, A. Vehtari, and D. B. Rubin. 2014. Bayesian Data Analysis. 3rd ed. CRC Press, New York.

Strebel, N., M. Kéry, M. Schaub, and H. Schmid. 2014. Studying phenology by flexible modelling of seasonal detectability peaks. Methods in Ecology and Evolution 5:483–490.

Supplemental Tables

Table S1: **Salmon runs in Central Salish Sea and Puget Sound Proper** included in our analyses.

Region	Location	Species	Origin	Latitude	Longitude
Central Salish Sea	ALBION TEST FISHERY	Chinook	wild/hatchery	49.2104	-122.6228
Puget Sound Proper	CEDAR RIVER HATCHERY	Chinook	wild	47.3761	-121.9625
	CEDAR RIVER HATCHERY	coho	wild	47.3761	-121.9625
	GARRISON HATCHERY	chum	wild	47.1915	-122.5741
	GEORGE ADAMS HATCHERY	chum	hatchery	47.3013	-123.1818
	GEORGE ADAMS HATCHERY	Chinook	hatchery	47.3013	-123.1818
	HOODSPORT HATCHERY	chum	hatchery	47.407	-123.1399
	HOODSPORT HATCHERY	Chinook	hatchery	47.407	-123.1399
	MCKERNAN HATCHERY	chum	hatchery	47.3066	-123.203
	MINTER CR HATCHERY	chum	hatchery	47.3726	-122.7026
	MINTER CR HATCHERY	Chinook	hatchery	47.3726	-122.7026
	MINTER CR HATCHERY	coho	wild	47.3726	-122.7026
	MINTER CR HATCHERY	coho	hatchery	47.3726	-122.7026
	SOOS CREEK HATCHERY	chum	wild	47.3093	-122.1688

Table S2: **Salmon phenology has shifted** later in part of the Central Salish Sea (based on spring/summer Chinook in the Albion Test Fishery data, from 1995-2017) and earlier in Puget Sound Proper (based on 13 runs across coho, chum, and Chinook adult in Table S1, from 1997-2017).

region	phenophase	parameter	mean	25%	75%	2.5%	97.5%
Central Salish Sea	first	intercept	-2653.397	-3449.799	-1856.994	-5071.703	-235.091
		year	1.373	0.976	1.77	0.168	2.578
	peak	intercept	-4520.72	-5529.59	-3511.851	-7584.19	-1457.251
		year	2.365	1.862	2.868	0.838	3.892
	last	intercept	828.401	476.517	1180.285	-240.108	1896.909
		year	-0.267	-0.442	-0.091	-0.799	0.266
Puget Sound Proper	first	intercept	1706.47	1425.65	1987.32	886.42	2526.66
		year	-0.72	-0.86	-0.58	-1.13	-0.31
	peak	intercept	932.39	735.04	1129.77	356.14	1508.88
		year	-0.32	-0.42	-0.22	-0.61	-0.03
	last	intercept	1640.82	1447.50	1834.16	1076.32	2205.48
		year	-0.66	-0.75	-0.56	-0.94	-0.38

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Table S3: **Estimated linear trends in peak-, start-of-, and end-of-season SRKW phenology** in Puget Sound proper ('ps') during the fall/winter ('fall') and the central Salish Sea ('css') during the spring/summer ('sum'), from occupancy model estimates of presence probabilites. 'Peak' is the day of year with the maximum probability of presence (or the mean across day of year, if there are multiple days with the same peak probability of presence). To estimate the start of the season, we identified the earliest day of year with an estimated presence probility greater than 0.5. To estimate the end of the season, we identified the latest day of year with an estimated presence probility greater than 0.5. 50 percent, 75 percent, and 95 percent uncertainty intervals are shown.

| pod	region	season	phase	1978-2017 trend							2002-2017 trend						
				mean	25%	75%	12.5%	87.5%	2.5%	97.5%	mean	25%	75%	12.5%	87.5%	2.5%	97.5%
J	ps	fall	peak	1.17	0.91	1.47	0.71	1.61	0.33	1.93	0.45	-0.67	1.55	-1.41	2.38	-2.81	4.09
J	ps	fall	first	0.53	0.06	1.00	-0.25	1.28	-0.81	1.82	2.44	1.37	3.45	0.61	4.24	-0.59	5.51
J	ps	fall	last	0.95	0.49	1.40	0.20	1.73	-0.32	2.27	-1.23	-2.22	-0.28	-2.80	0.22	-3.60	1.09
J	css	sum	peak	1.01	0.60	1.43	0.26	1.71	-0.19	2.18	6.49	3.96	9.48	0.95	11.28	-4.05	14.90
J	css	sum	first	-0.76	-0.90	-0.61	-1.01	-0.51	-1.21	-0.32	1.10	0.94	1.21	0.86	1.31	0.70	1.79
J	css	sum	last	1.12	0.96	1.28	0.86	1.40	0.70	1.63	0.39	0.21	0.60	0.06	0.70	-0.13	0.90
K	ps	fall	peak	1.75	1.44	2.07	1.21	2.27	0.76	2.62	1.59	0.35	2.78	-0.44	3.75	-1.97	5.67
K	ps	fall	first	1.62	1.10	2.18	0.70	2.52	0.05	3.15	2.35	1.10	3.63	0.28	4.49	-1.40	6.04
K	ps	fall	last	2.75	2.21	3.31	1.80	3.69	1.21	4.20	1.27	0.64	1.83	0.39	2.33	-0.42	3.36
K	css	sum	peak	0.93	0.63	1.24	0.41	1.43	0.01	1.78	1.31	0.42	2.24	-0.24	2.83	-1.43	3.91
K	css	sum	first	-0.33	-0.58	-0.07	-0.78	0.11	-1.09	0.42	0.82	0.29	1.55	-0.36	1.89	-0.80	2.63
K	css	sum	last	0.65	0.42	0.85	0.28	1.02	0.09	1.30	-1.00	-1.57	-0.57	-1.76	0.14	-2.05	1.06
L	ps	fall	peak	1.07	0.87	1.29	0.71	1.43	0.41	1.65	-0.47	-1.03	0.03	-1.42	0.57	-2.21	1.58
L	ps	fall	first	1.62	0.95	2.32	0.44	2.81	-0.47	3.55	1.38	0.11	2.68	-0.70	3.59	-2.34	4.85
L	ps	fall	last	1.02	0.23	1.82	-0.30	2.28	-1.16	3.00	-1.82	-2.44	-1.17	-2.93	-0.75	-3.92	0.23
L	css	sum	peak	0.21	-0.04	0.48	-0.20	0.72	-0.52	0.99	-1.14	-2.16	-0.14	-2.80	0.55	-4.02	1.76
L	css	sum	first	-1.79	-2.07	-1.50	-2.26	-1.30	-2.63	-0.92	0.55	0.23	0.87	-0.20	0.96	-0.47	1.48
L	css	sum	last	1.09	0.85	1.30	0.70	1.43	0.47	1.81	-0.20	-0.40	0.02	-0.51	0.23	-0.88	0.38

Supplemental Figures
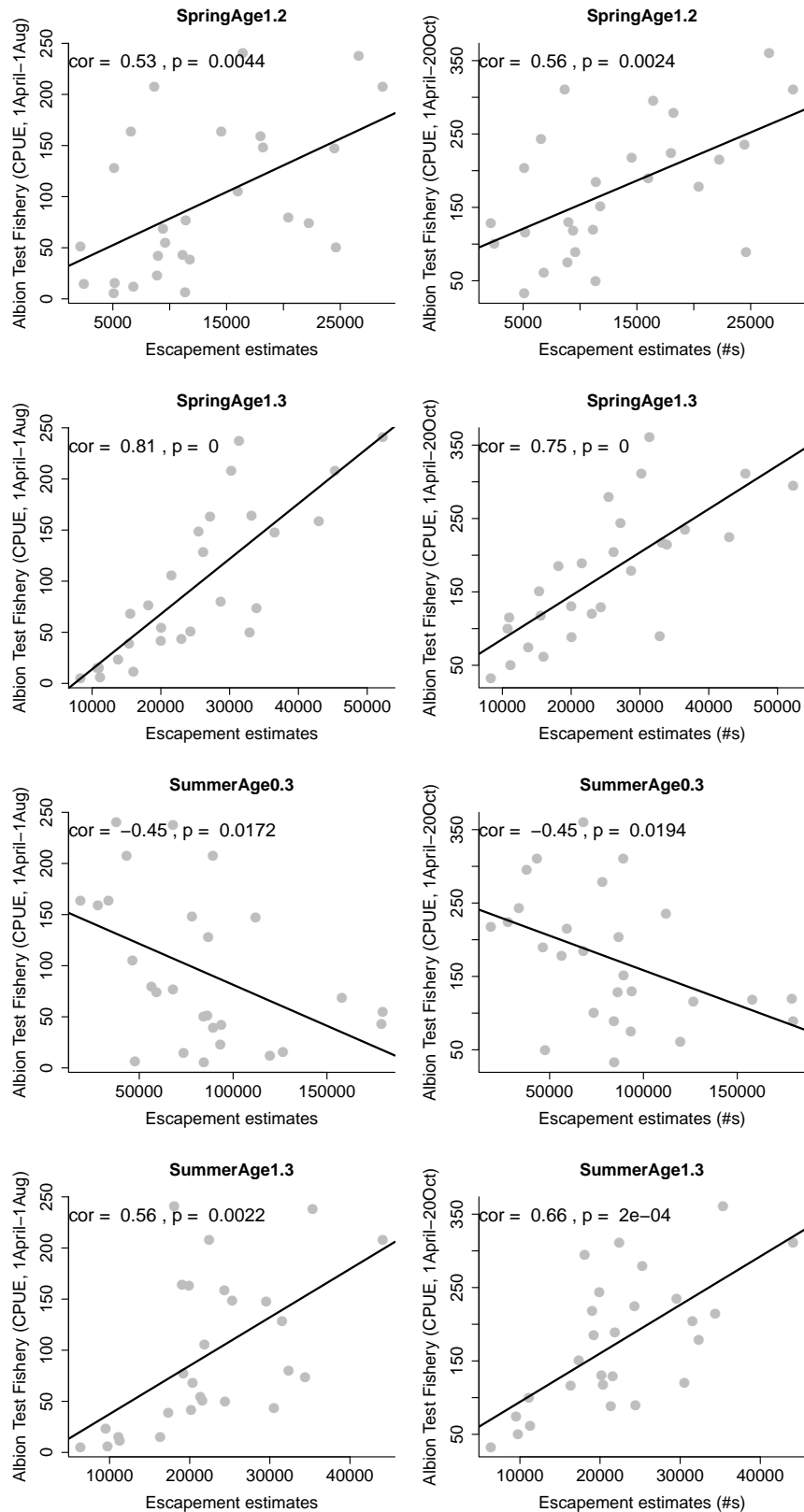
Figure S1: **Comparison of the abundance index from Albion test fishery CPUE (used in this paper) to alternative indices of abundance: total escapement from four index stocks used by the Pacific Salmon Commission (PSC 2018)**, from 1975-2018. Top row shows relationship between Albion Test Fishery CPUE to escapement estimates for four spring and summer index stocks assessed by the Pacific Salmon Commission in the Fraser River: Fraser Spring-Run 1.2, Fraser Spring-Run 1.3, Fraser Summer-Run 1.3, and Fraser Summer Run 0.3.
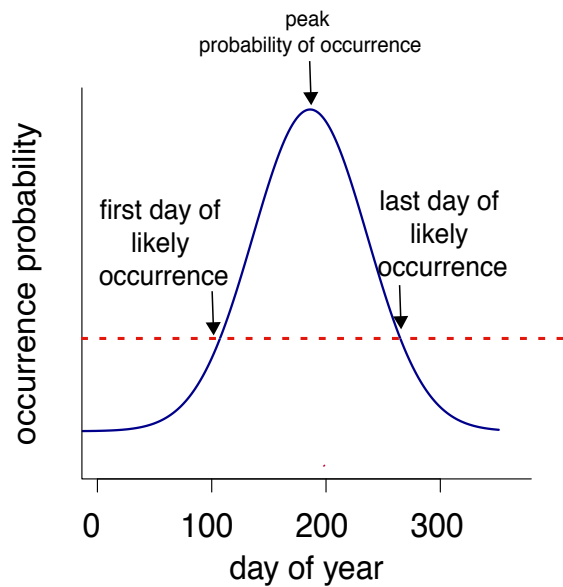
Figure S2: **The phenophases quantified in this study** included day of year of first and last occurrence, as well as day of year of peak occurrence probability for southern resident killer whales and peak abundance index for salmon.
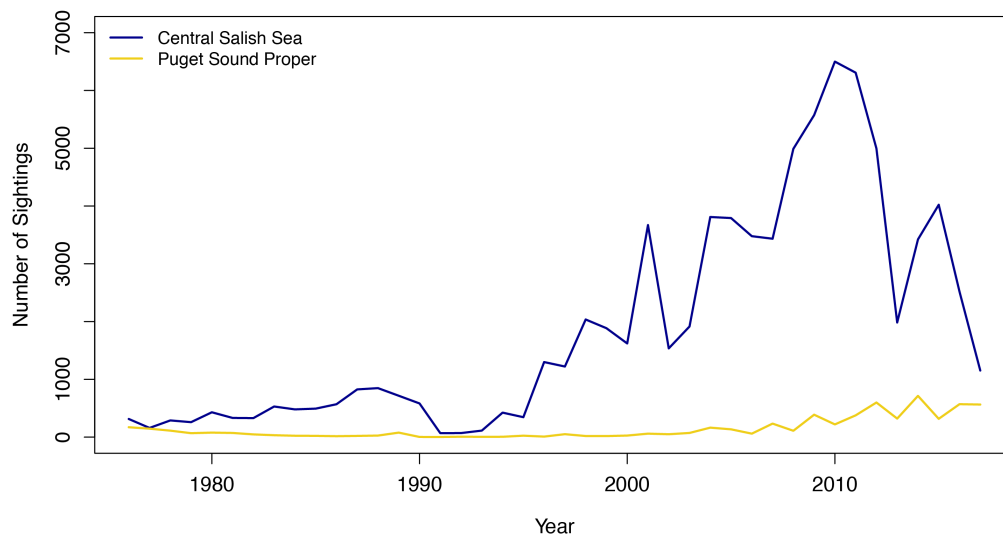
Figure S3: **Sightings of SRKWs from the OrcaMaster Database**, from 1978-2017.
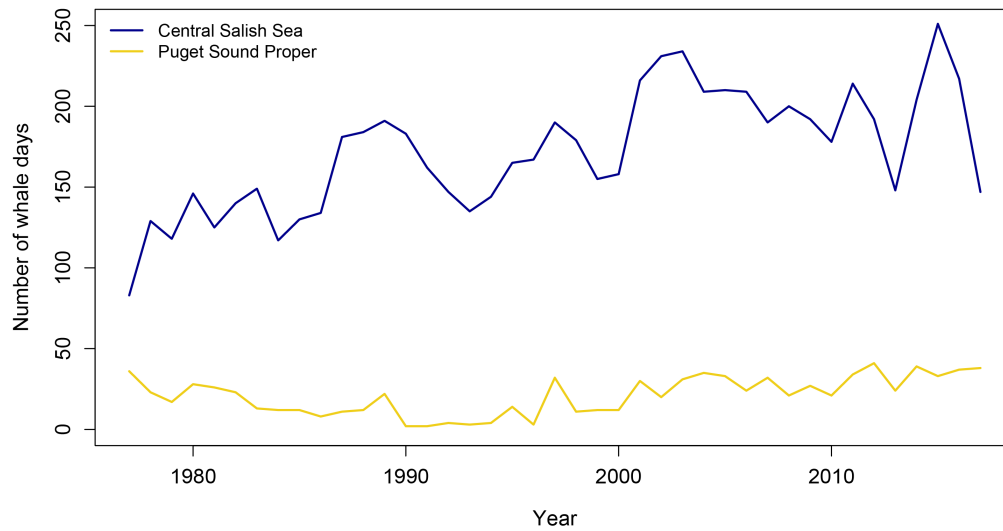
Figure S4: **Number of whale days from the OrcaMaster Database**, from 1978-2017.
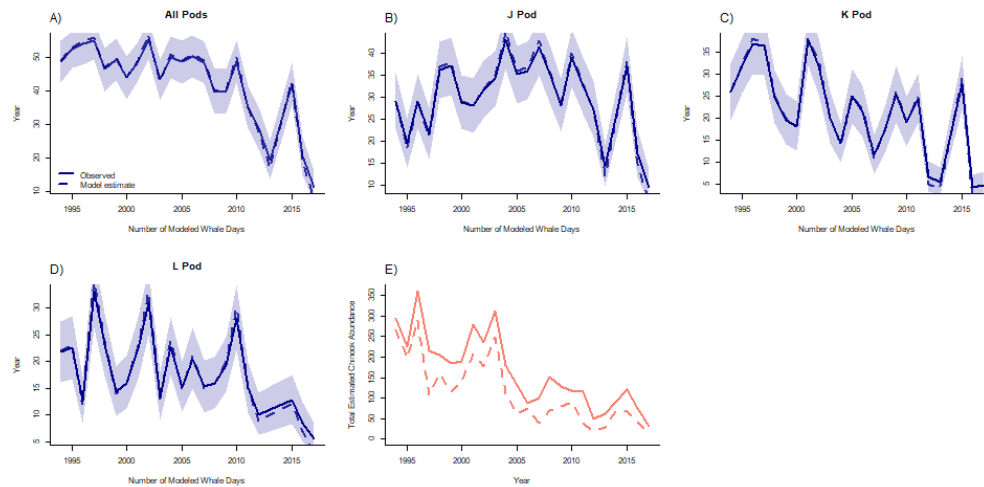
Figure S5: **Whale days and estimated Chinook abundance have declined at Lime Kiln State Park** since 1994. We show observed and modeled numbers of whale days from our Lime Kiln occupancy model, across all pods (A), J pod (B), K pod (C), and L pod (D), as well as estimated annual catch per unit effort (CPUE, catch per thousand fathom minutes), from our abundance model fit to Albion test fishery data from May though September across all Chinook. Shading shows 50 percentile uncertainty intervals.
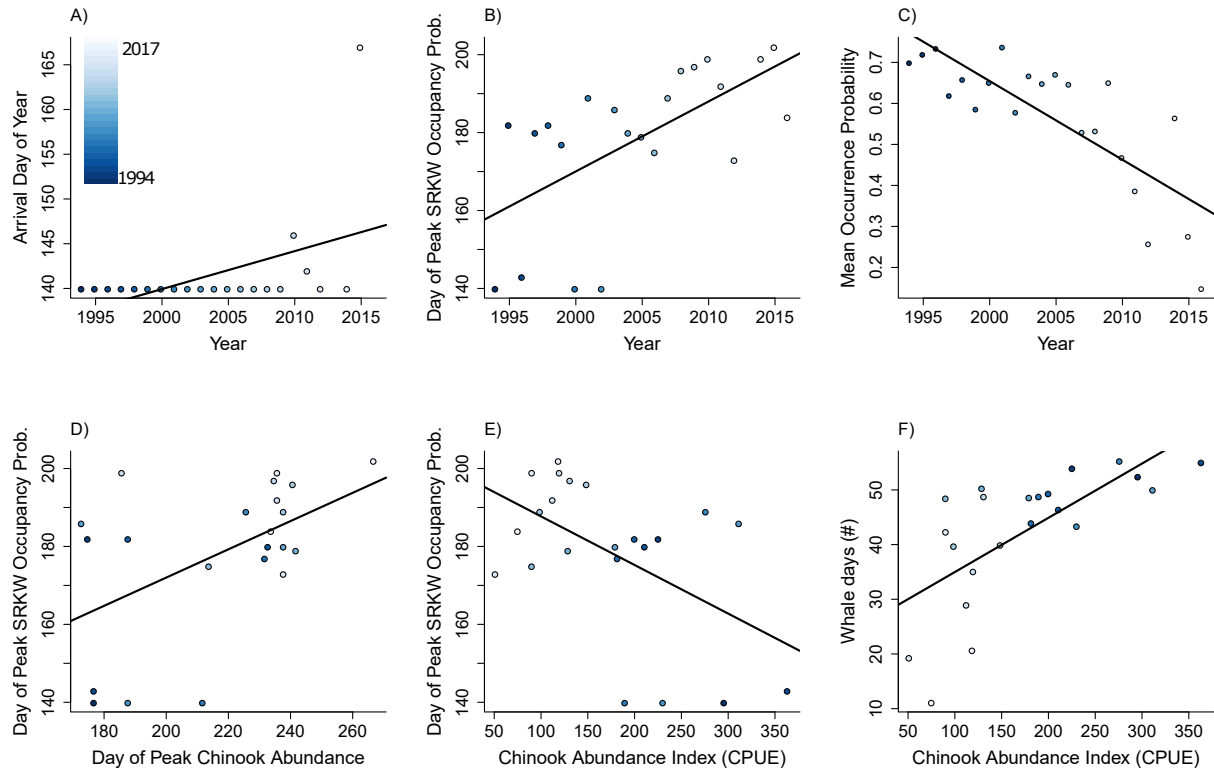
Figure S6: **SRKW phenology at Lime Kiln State Park is shifting**, with the likely arrival day of year (A, defined here as the first day of year when the occurrence probability is >0.20) and peak occurrence probability day of year (B) getting later, from 1994-2017. In addition, mean occurrence probability from May to August (the season when regular monitoring of SRKWs occurs at Lime Kiln) is declining during this time period (C). These trends are associated with a decrease in the amount of time SRKWs are spending near Lime Kiln (i.e., the number of days on which SRKWs were observed ("whale days") has declined since 1994 (Fig. S5) and are consistent with shifts in the timing of peak abundance (D) and abundance index (E,F) of their preferred prey, Fraser River Chinook Salmon. (See also Fig. 3 in the main text).

A) J pod
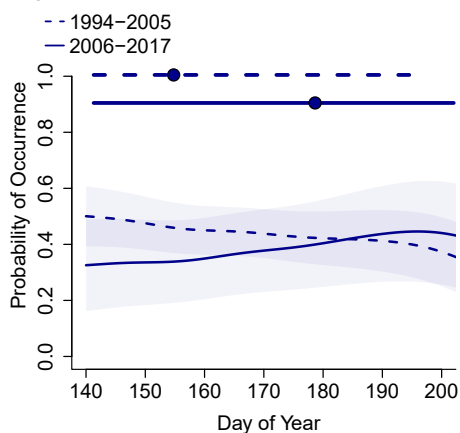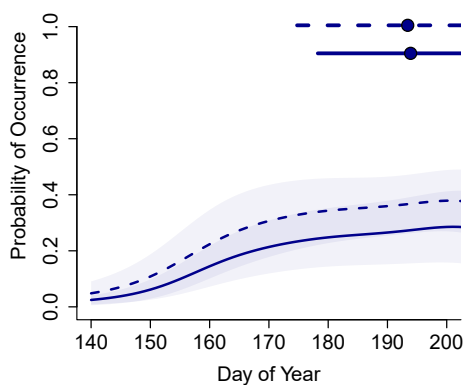

B) K pod
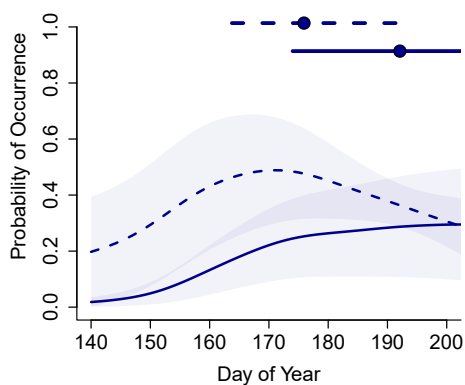
C) L pod

Figure S7: **SRKW phenology has shifted, in concert with shifts in Fraser River Chinook Salmon at one site with consistent observations in the Central Salish Sea**. K- and L-pod phenology (blue lines) is quantified from Lime Kiln Point State Park, SRKW phenology has shifted, with peak arrival dates delaying in recent (solid lines) compared with earlier (dashed lines) years. We show patterns for J-pod (A), K-pod (B), and L-Pod (C). Compare to Fig. 3 of the main text, which shows all pods together.
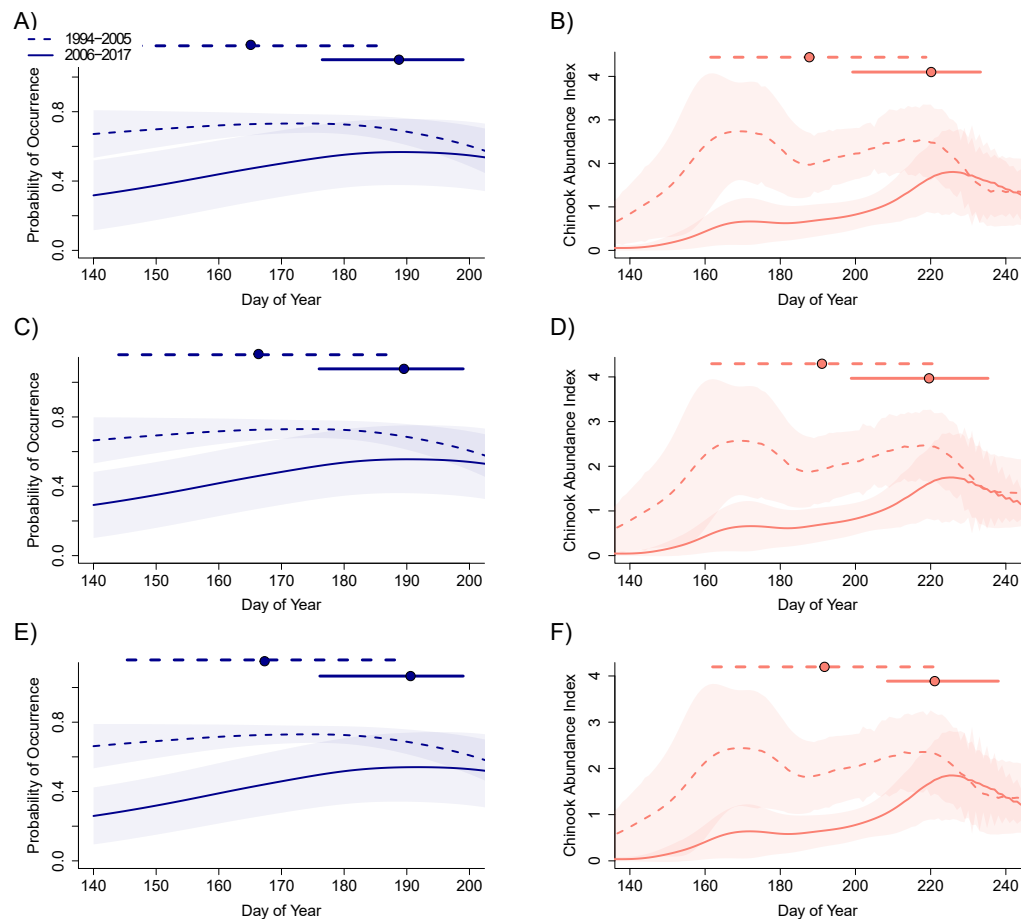
Figure S8: **Changing the break-point has little qualitative effect on patterns of shifts in SRKW phenology Fraser River Chinook**. We show patterns for all SRKW pods together (as in Figure 3 in the main text) with different breakpoints of 2005 (A,B), 2006 (C,D, as in Figure 3) and 2007 (E,F). SRKW phenology (blue lines, A,C,E) is quantified from Lime Kiln Point State Park; an index of adult Fraser River Chinook salmon (summed daily CPUE from April through August, pink lines) and SRKW phenology have shifted, with peak arrival dates delaying in recent (solid lines) compared with earlier years (dashed lines).
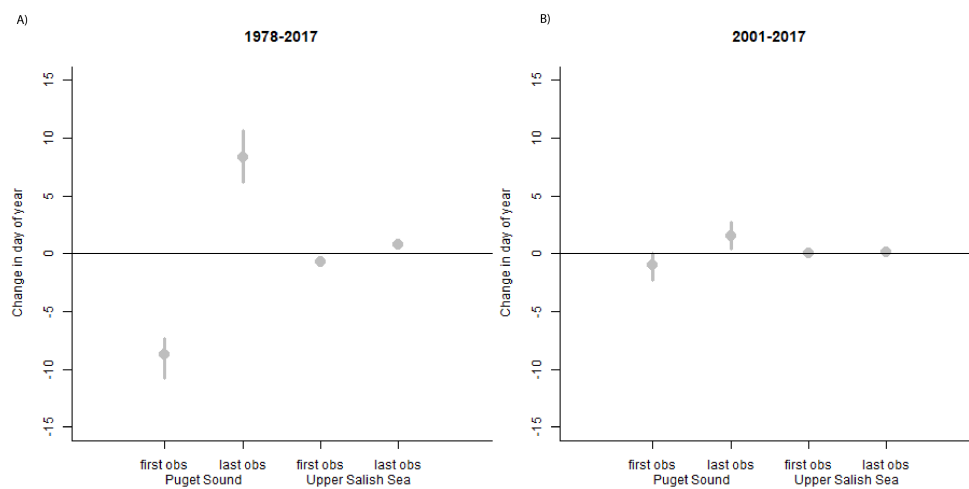
Figure S9: **Expected change in phenology due to changes in effort alone, across Puget Sound and the Central Salish Sea regions**, from 1978-2017 (A) and from 2001-2017 (B).
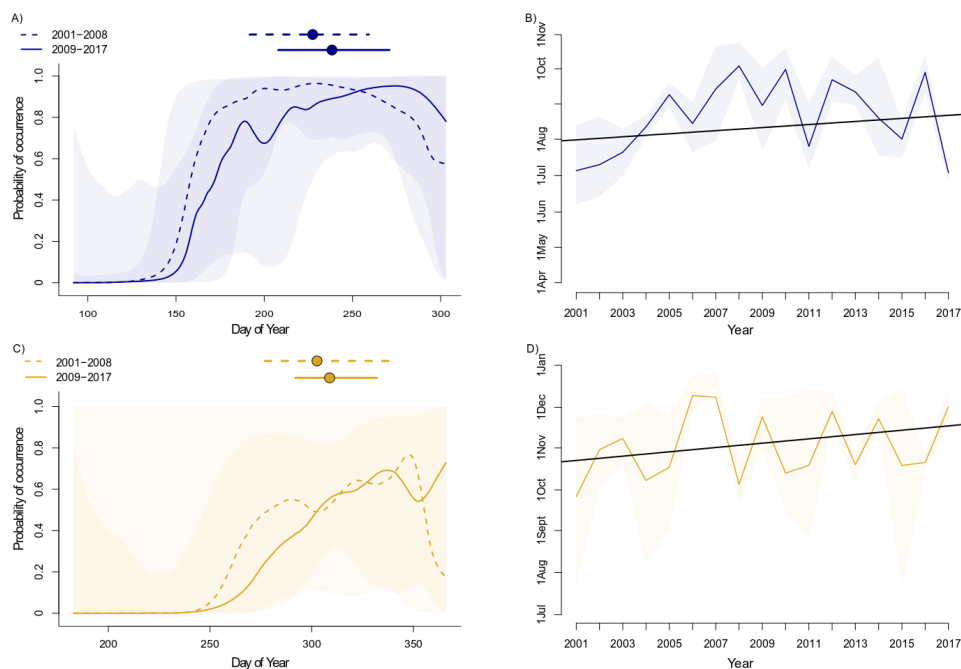
Figure S10: **K-pod activity varies seasonally in the Central Salish Sea (A) and Puget Sound proper (C).** This phenology has shifted later in recent years in the Central Salish Sea (B) and in Puget Sound (D). The shift toward later arrival in the central Salish Sea is evident the estimated probabilities of occurrence from the occupancy models for K-pod (A,C) as well as the linear trends in peak occurrence probability from 2001-2017 (B,D). Shading around lines represents 50% credible intervals.
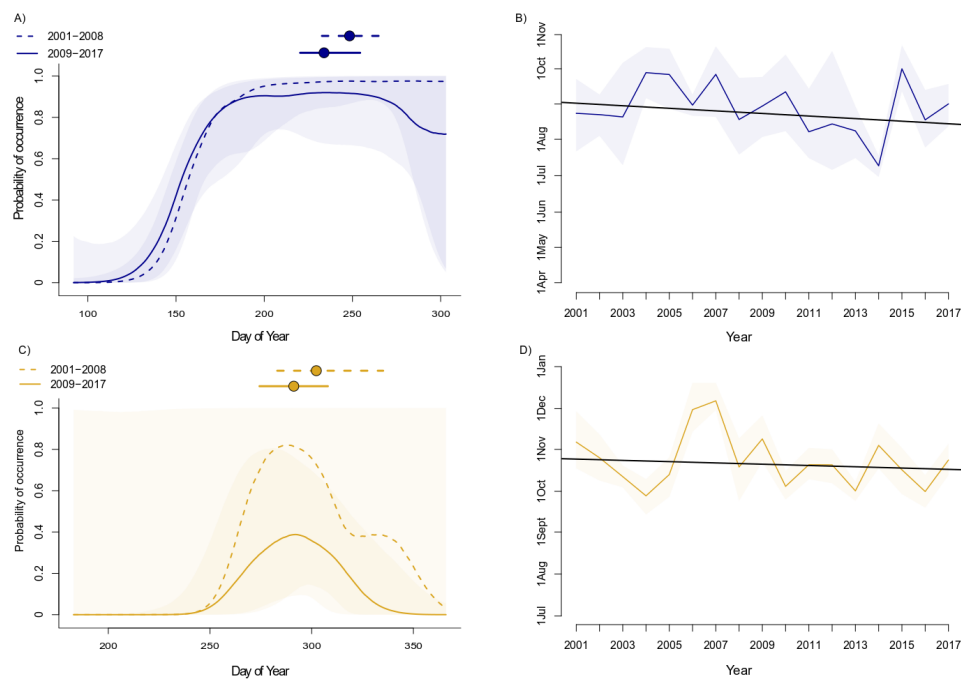
Figure S11: **L-pod activity varies seasonally in the Central Salish Sea (A) and Puget Sound proper (C)**. This phenology has shifted later in recent years in the Central Salish Sea (B) and in Puget Sound (D). The shift toward later arrival in the central Salish Sea is evident the estimated probabilities of occurrence from the occupancy models for K-pod (A,C) as well as the linear trends in peak occurrence probability from 2001-2017 (B,D). Shading around lines represents 50% credible intervals.