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

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Models

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

1. Southern resident killer whale presence model We fit separate a hierarchical model to each pod (J, K, L), as well as a hierarchical model to all SRKWs pooled together. We estimated the occurrence probability (Pr(z=1)), as a smooth function of day of year, s(day), fitted via a thin plate regresion spline basis using the programming language `Stan` (Carpenter et al., 2017) (`www.mc-stan.org`), accessed via the `brms`(BÃijrkner, 2017, 2018) package in R (R Development Core Team, 2019), version 3.6.2. We assessed model performance through Rhat (all were close to 1) and high neff, as well as visual consideration of chain convergence and posteriors (Gelman et al., 2014).

   We included years as groups in our hierarchical model, and allowed the smoothed effect of day of year on presence to vary across year:
   -Add equation

2. Fraser River Chinook salmon abundance index model

   This model can be described by the following equations:
   -Add equation
   where CPUEi is catch per unit effort on dayi, mu(dayi) is the overall mean phenology function predicted by day of year across all years, v(day) is the year's deviation from that mean function (also assumed to be a smooth function of time) and XXi is an error process, assumed to be normally distributed. Mu(day) and v(day) were parameterized with smoothing splines and fit `Stan` (Carpenter et al., 2017) (`www.mc-stan.org`), accessed via the `brms`(BÃijrkner, 2017, 2018) package in R (R Development Core Team, 2019), version 3.6.2. We ran four chains simultaneously, each with 4 000 sampling iterations (1 000 of which were used for warm-up). We assessed model performance through Rhat (all were close to 1) and high neff, as well as visual consideration of chain convergence and posteriors (Gelman et al., 2014).

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

   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 links the observations (i.e., the number of sightings of the pod per day per site) to the state model. Our hierarchical occupancy model can be described by the following equations:

-Add equation
Observation model: Y(area,yr,day) Binomial (Tyr,day,area,Zyr,day*Parea,yr)
State model: zyr,day   Bernoulli(Psiyr,day)

in which occupancy probability (Psiyr,day) was modeled as a semi-parametric, smooth function of day of year (âĂŸdayâĂŹ), using flexible thin-plate spline regression modelling, and year (âĂŸyrâĂŹ) as a level (Strebel et al., 2014). The number of sightings in which the pod was detected (yarea,yr,day) among the total number of sightings made in the area, year, and day (Tyr,day,area) was modeled as a binomial random variable. The number of successful sightings (y) depended on the product of the state of occurrence (zyr,day) and of detection probability (parea,yr). We assumed zyr,day to be a Bernoulli random variable for which 0 signifies absence and 1 is presence. We modeled detection probability (parea,yr) as a year- and area-specific probability between 0 and 1.

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 (R Development Core Team, 2019), 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 Rhat (all were close to 1) and high neff, as well as visual consideration of chain convergence and posteriors (Gelman et al., 2014). 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, Table S4.)

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 both reveal declines in SRKW presence in recent years, across all three pods (Fig. S4). This consistently collected dataset also suggests that SRKWs have shifted the timing of their activity in the area (Fig.S5.

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.S2). This shift in effort complicates interpretations of trends in the number of whale days over time (Fig. S3) 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.S8A), 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.S8B). 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

BÃijrkner, P.-C. 2017. brms: An R package for Bayesian multilevel models using Stan. Journal of Statistical Software 80:1–28.

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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.

R Development Core Team. 2019. R: A Language and Environment for Statistical Computing. R Foundation for Statistical Computing, Vienna, Austria.

Things to add:

Table S4. Add table demonstrating that using a threshold probability lower than 0.5 did not qualitatively alter results (i.e., trends in first and last are consistent)

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
Puget Sound Proper	CEDAR RIVER HATCHERY	coho	wild	47.3761	-121.9625
Puget Sound Proper	GARRISON HATCHERY	chum	wild	47.1915	-122.5741
Puget Sound Proper	GEORGE ADAMS HATCHERY	chum	hatchery	47.3013	-123.1818
Puget Sound Proper	GEORGE ADAMS HATCHERY	Chinook	hatchery	47.3013	-123.1818
Puget Sound Proper	HOODSPORT HATCHERY	chum	hatchery	47.407	-123.1399
Puget Sound Proper	HOODSPORT HATCHERY	Chinook	hatchery	47.407	-123.1399
Puget Sound Proper	MCKERNAN HATCHERY	chum	hatchery	47.3066	-123.203
Puget Sound Proper	MINTER CR HATCHERY	chum	hatchery	47.3726	-122.7026
Puget Sound Proper	MINTER CR HATCHERY	Chinook	hatchery	47.3726	-122.7026
Puget Sound Proper	MINTER CR HATCHERY	coho	wild	47.3726	-122.7026
Puget Sound Proper	MINTER CR HATCHERY	coho	hatchery	47.3726	-122.7026
Puget Sound Proper	SOOS CREEK HATCHERY	chum	wild	47.3093	-122.1688

Table S2: **Salmon phenology has shifted earlier in Puget Sound Proper**, from 1997-2017, as quantified in the 13 runs included in our hierarchical model across coho, chum, and Chinook adult return data (see Table S1). ADD FRASER RIVER CHINOOK TRENDS TO THIS TABLE

phenophase	parameter	mean	25%	75%	2.5%	97.5%
first	intercept	1724.86	1442.52	2007.22	900.37	2549.48
	year	-0.73	-0.87	-0.59	-1.14	-0.32
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

Table S3: **Estimated linear trends in peak-, start-of-, and end-of-season SRKW phenology** in Puget Sound proper and the central Salish Sea, 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 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 and 95 percent uncertainty intervals are shown.NEED TO ADD 95 perceiles!

				1978-2017 trend			2002-2017 trend		
Pod	Region	Season	Phase	mean	25%	75%	mean	25%	75%
J	Puget Sound	Fall	peak	1.14	0.87	1.41	0.29	1.88	0.74
J	Puget Sound	Fall	first	0.54	0.08	0.99	-0.81	1.88	2.67
J	Puget Sound	Fall	last	0.97	0.52	1.40	-0.31	2.21	-0.95
J	Central Salish Sea	Summer	peak	1.03	0.65	1.43	-0.19	2.14	6.25
J	Central Salish Sea	Summer	first	-0.74	-0.89	-0.59	-1.19	-0.32	1.11
J	Central Salish Sea	Summer	last	1.11	0.94	1.26	0.68	1.62	0.50
K	Puget Sound	Fall	peak	1.79	1.50	2.10	0.88	2.66	1.72
K	Puget Sound	Fall	first	1.65	1.09	2.21	0.00	3.22	2.17
K	Puget Sound	Fall	last	2.67	2.10	3.25	1.08	4.15	1.38
K	Central Salish Sea	Summer	peak	0.97	0.68	1.26	0.06	1.84	1.37
K	Central Salish Sea	Summer	first	-0.35	-0.61	-0.10	-1.09	0.41	0.85
K	Central Salish Sea	Summer	last	0.68	0.45	0.88	0.12	1.38	-0.83
L	Puget Sound	Fall	peak	1.10	0.90	1.30	0.50	1.67	-0.38
L	Puget Sound	Fall	first	1.81	1.17	2.49	-0.30	3.72	1.66
L	Puget Sound	Fall	last	1.11	0.38	1.88	-1.13	3.12	-1.78
L	Central Salish Sea	Summer	peak	0.23	-0.04	0.50	-0.55	1.01	-1.12
L	Central Salish Sea	Summer	first	-1.79	-2.08	-1.51	-2.62	-0.90	0.54
L	Central Salish Sea	Summer	last	1.07	0.83	1.29	0.45	1.78	-0.19

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Supplemental Figures

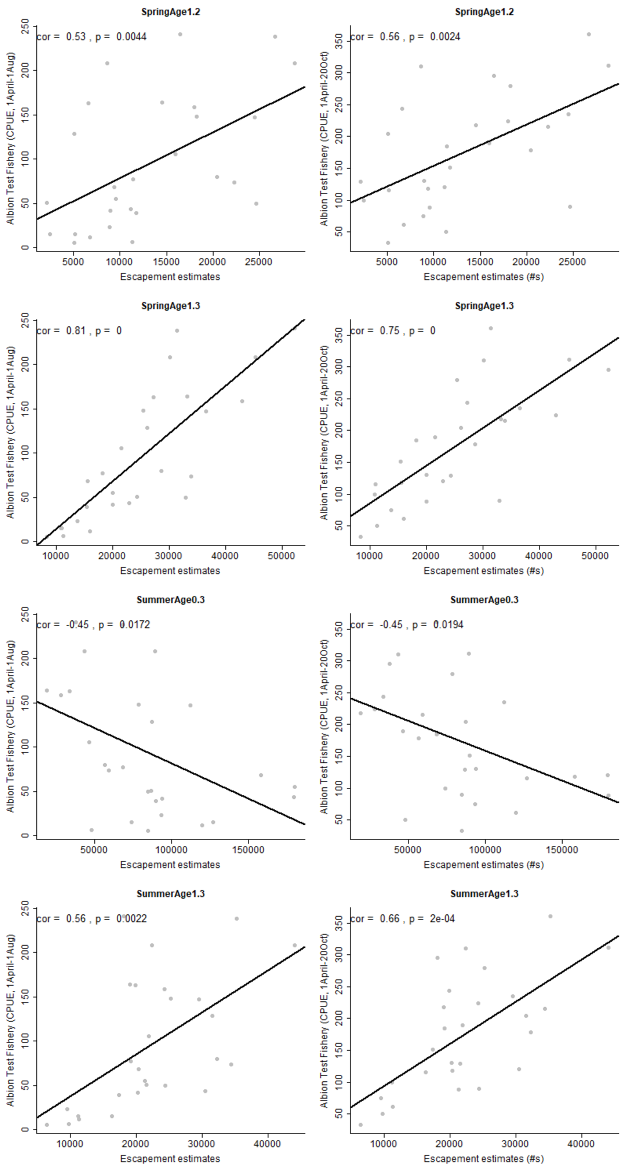

Figure S1: **Comparison of the abundance index from Albion test fishery CPUE (used in this paper) to alternative indeces of abundance: total escapement from four index stocks used by the Pacific Salmon Commission (PSC 2018)**, from 1975-2018. Top row shows relationship between Albion Test Fishery CPUE to escapement estimates for four spring and summer index stocks assessed by the Pacific Salmon Comission 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.

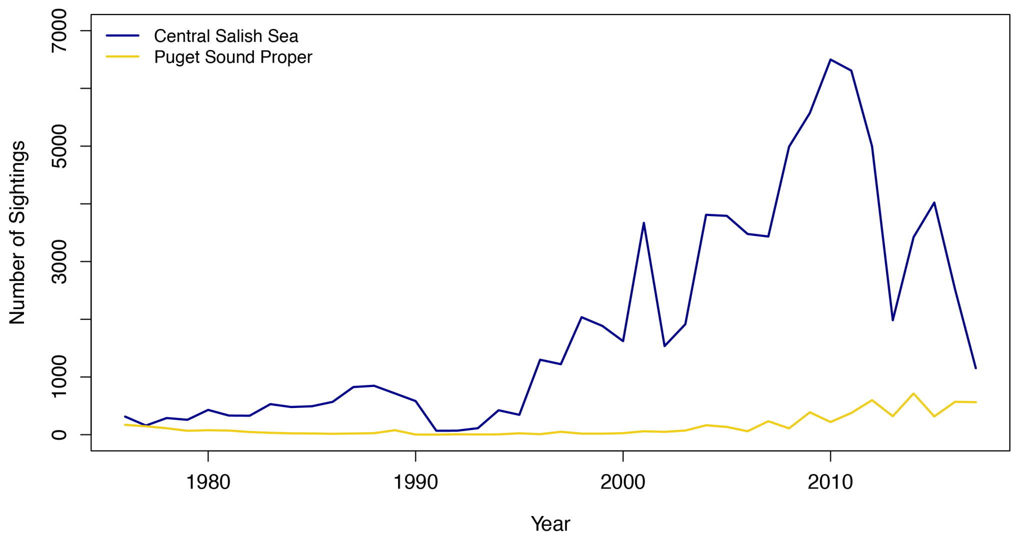

Figure S2: **Sightings of SRKWs from the OrcaMaster Database**, from 1978-2017.

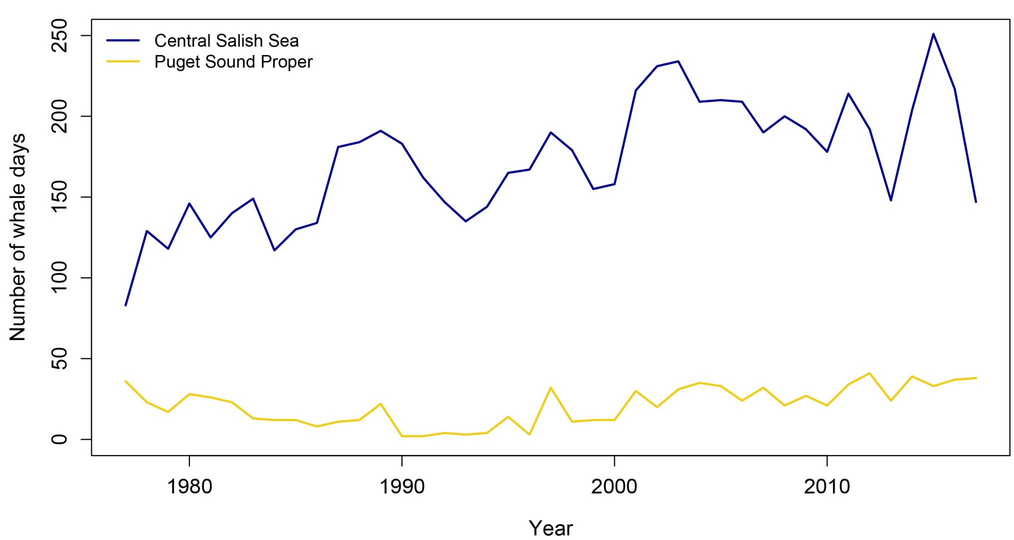

Figure S3: **Number of whale days from the OrcaMaster Database**, from 1978-2017.

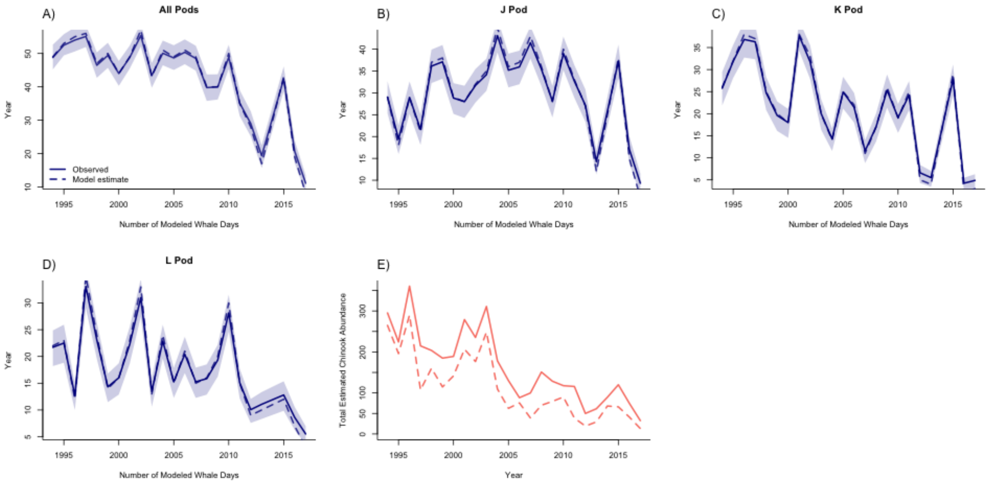

Figure S4: **Whale days and estimated Chinook abundance have declined at Lime Kiln State Park** since 1994. We show observed and modeled numbers of whale days from our Lime Kiln occupancy model, across all pods (A), J pod (B), K pod (C), and L pod (D), as well as estimated annual catch per unit effort (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.

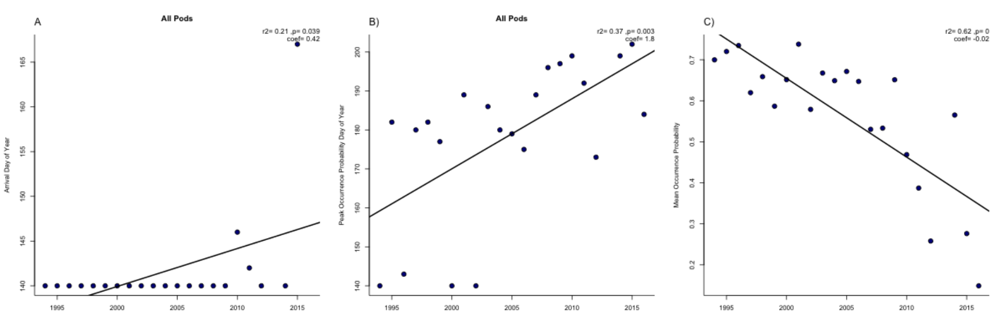

Figure S5: **SRKW phenology at Lime Kiln State Park is shifting**, with the likely arrival day of year (A, defined here as the first day of year when the occurrence probability is >0.20) and peak occurrence probability day of year (B) getting later, from 1994-2017. Mean occurrence probability from May to August (the season when regular monitoring of SRKWs occurs at Lime Kiln) is declining during this time period. 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. S4).

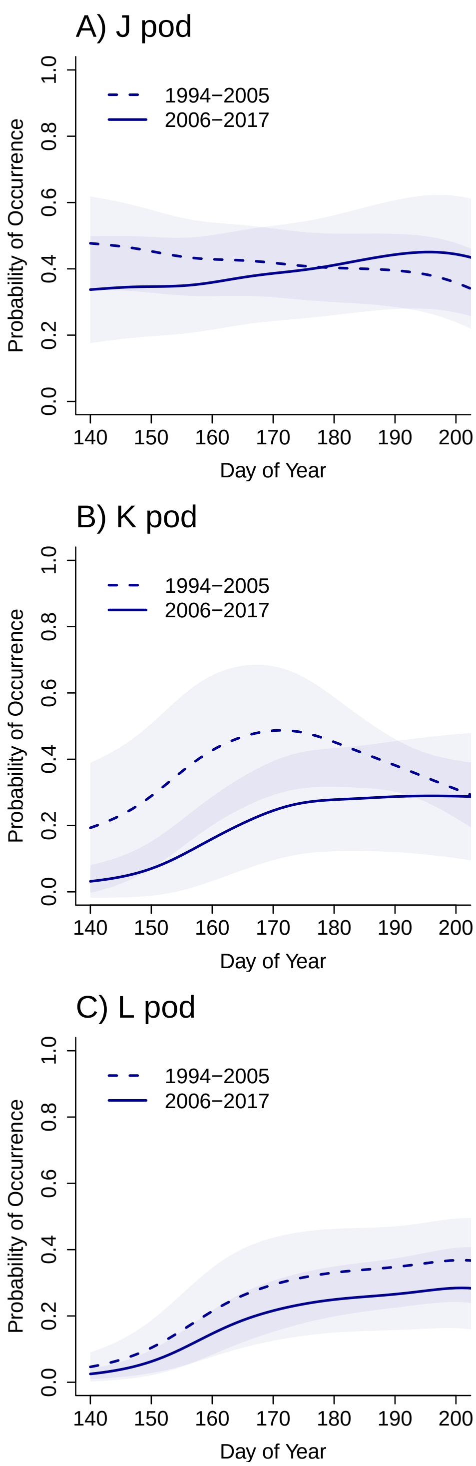

Figure S6: **SRKW phenology has shifted, in concert with shifts in Fraser River Chinook Salmon at one site with consistent observations in the Central Salish Sea**. K- and L-pod phenology (blue lines) is quantified from Lime Kiln Point State Park, SRKW phenology has shifted, with peak arrival dates delaying 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.

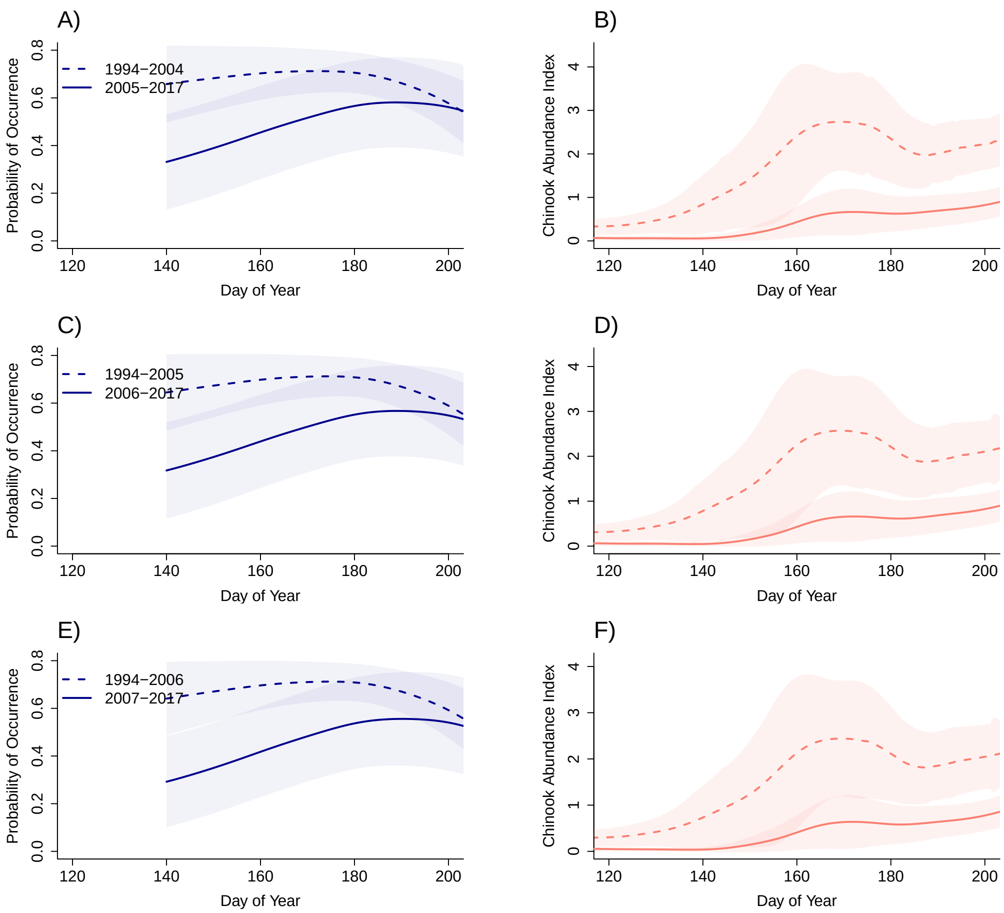

Figure S7: **Changing the break-point has little qualitative effect on patterns of shifts in SRKW phenology Fraser River Chinook**. We show patterns for all SRKW pods together (as in Figure 3 in the main text) with different breakpoints of 2005 (A,B), 2006 (C,D, as in Figure 3) and 2007 (E,F). SRKW phenology (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).

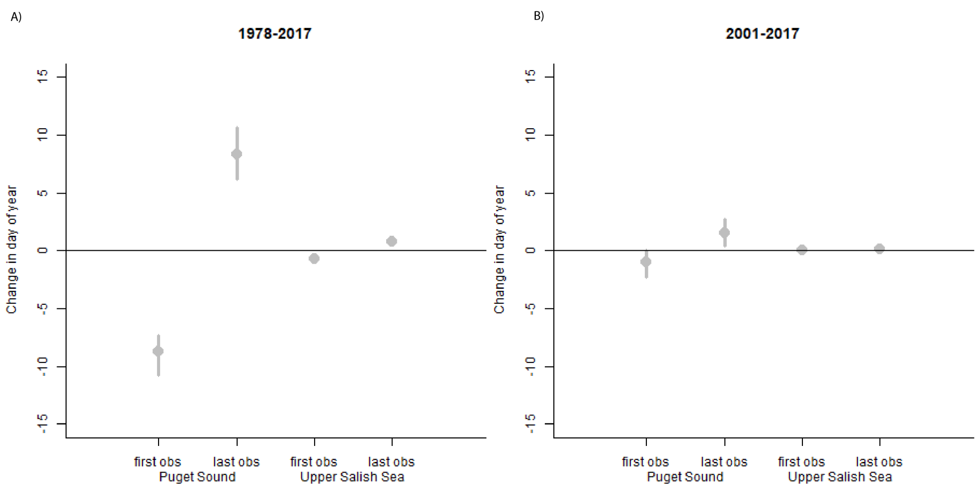

Figure S8: **Expected change in phenology due to changes in effort alone, across Puget Sound and the Central Salish Sea regions**, from 1978-2017 (A) and from 2001-2017 (B).

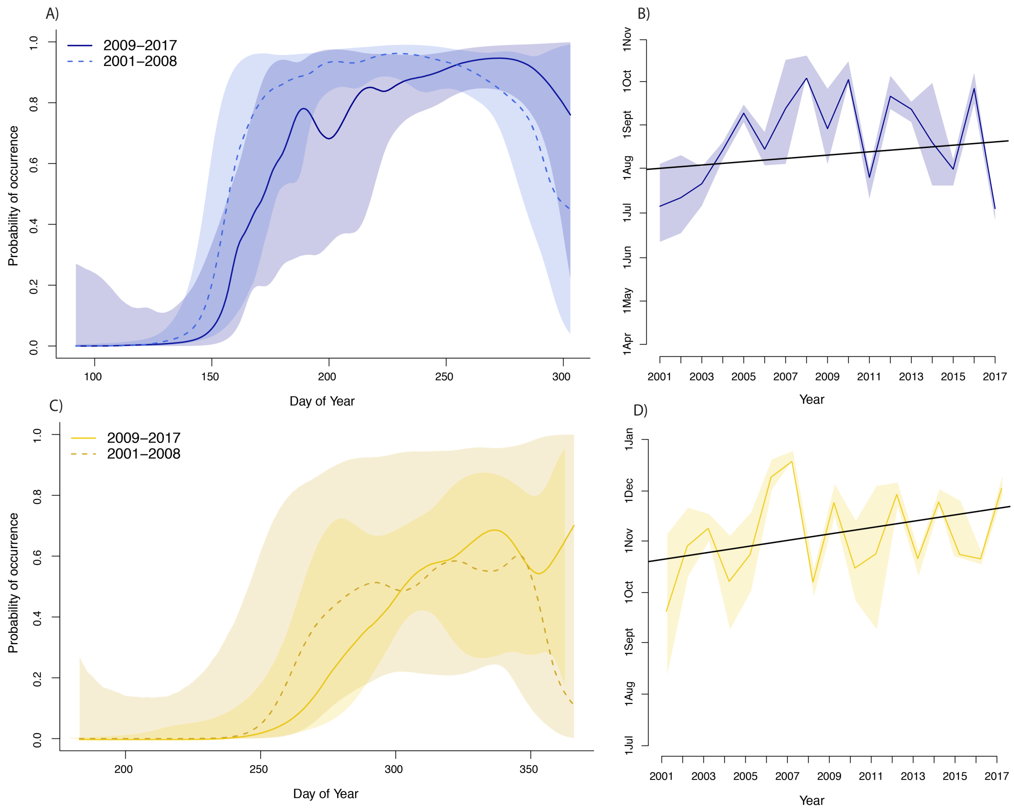

Figure S9: **K-pod activity varies seasonally in the Central Salish Sea (A) and Puget Sound proper (C).** This phenology has shifted later in recent years in the Central Salish Sea (B) and in Puget Sound (D). The shift toward later arrival in the central Salish Sea is evident the estimated probabilities 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 (95% credible intervals in Table SX).

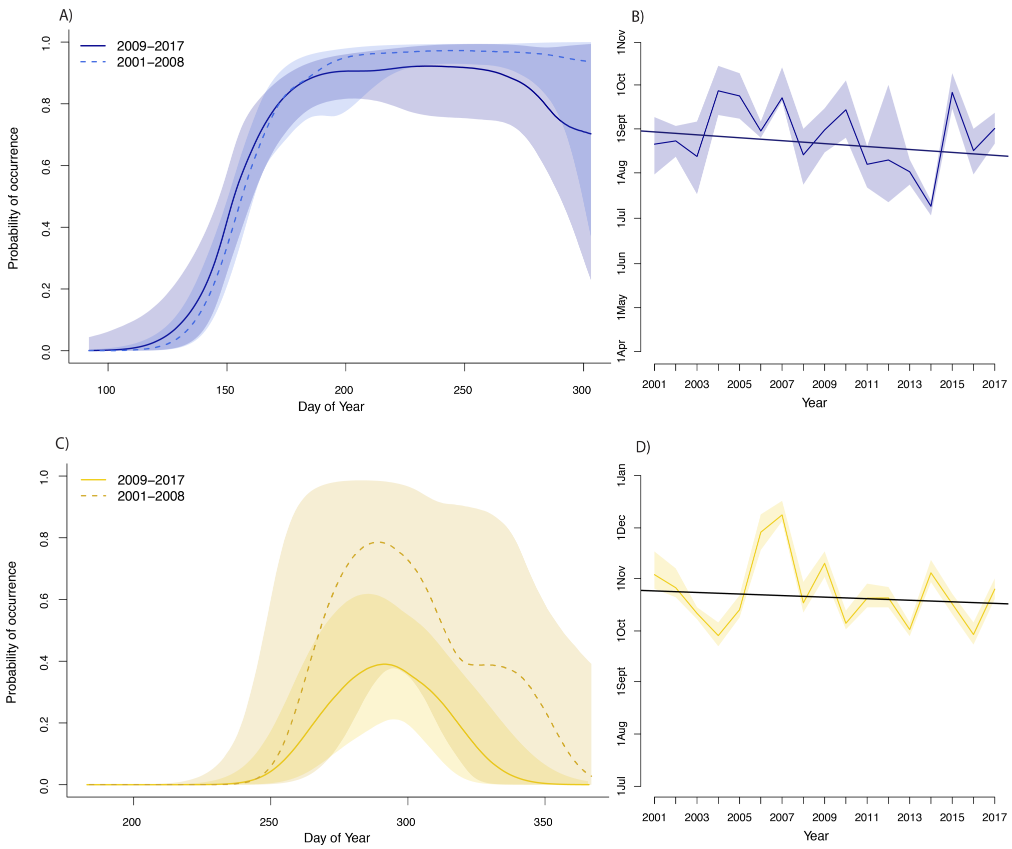

Figure S10: **L-pod activity varies seasonally in the Central Salish Sea (A) and Puget Sound proper (C)**. This phenology has shifted later in recent years in the Central Salish Sea (B) and in Puget Sound (D). The shift toward later arrival in the central Salish Sea is evident the estimated probabilities 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 (95% credible intervals in Table SX).