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Phenological shifts and mismatch with marine productivity vary among Pacific salmon species and populations

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1.0 Timeline sensitivity analysis

1.1 Sensitivity of rate of peak shift to length of time series

Our analysis includes six salmon species with diverse life histories, which could respond at different rates to climate change. Pacific salmon have a range in age to maturity with pink salmon reaching maturation at ~2 years of age, sockeye at ~ 4 – 5 years, coho at ~ 2 – 5 years, chum at ~2 – 7 years, Chinook at ~5 – 7 years, and steelhead reaching maturity anywhere between ~3 – 7 years of age[44]. As a result of the difference in lengths of the life cycle it is possible that it could take some species longer to exhibit phenological shifts. We chose a minimum time series of 20 years as this length of time was long enough to observe shifts in even the most long-lived species.

To demonstrate that 20 years of data was long enough to observe phenological shifts, if present, we completed a sensitivity analysis. We ran the hierarchical state-space model used to predict the rate of change in peak migration beginning with only the most recent five years of data. We successively ran the model each time adding a sequential year, moving backwards in the time series and re-estimating the rate of peak change until the end of the time series. For example, for the Auke Creek pink salmon population we first ran the model with five years of data from 2015 – 2019. We ran the model again with six years of data from 2014 – 2019 and continued until all data was included (40 yrs, 1980 – 2019).

Results for each species and population are plotted in Extended Data Fig. 1. In general, the trend in peak change stabilized after ~15 years of data for pink and chum salmon, ~12 – 20 years for sockeye salmon, ~8 – 20 years for coho salmon, ~10 – 18 years for Chinook salmon, and ~8 – 15 years for steelhead trout. This shows that 20 years is a long enough time series to detect a change in phenology, if present.

1.2 Sensitivity of model results to time period observed

Since populations ranged in the length of the time series with a minimum of 20 years and a maximum length of 59 years, we analysed our data to determine if our analysis was robust to differences in observation period. For example, since climate change is non-linear, longer time series could be biased with longer time series having decreased mean rate of change. We completed three sets of analysis. We A) modeled the shift in peak outmigration timing using the hierarchical state-space model, but included only years 1999 – 2019, B) ran a weighted linear model of time series length on rate of shift in peak outmigration date, C) re-analysed geographic, environmental, and biological variables for truncated datasets including data from 1999 – 2019 only, to determine if the length and years when smolts were counted could possibly impact the rate of phenological change.

1.2.1 Analysis A: Shift in peak outmigration timing for truncated dataset 1999 – 2019

We re-analysed smolt count data using only years 1999 – 2019 as this period of time includes the rapid warming effects of recent climate change. To complete this analysis, we used only contemporaneous datasets that collected at least 10 years of data during the 1999 – 2019 period. Our time series analysis showed that 10 years is the minimum amount of time to detect a change in phenology, albeit with increased uncertainty due to the short time period. Of the original populations included only 60 datasets had greater than 10 years of data collected between 1999 – 2019, as we included present and historic smolt datasets in our data collection.

The analysis of the 60 remaining populations showed that rate of shift in peak migration during the period of 1999 – 2019 closely matched those of the longer time series, except in a few cases (Extended Data Fig. 5). The populations with the largest discrepancies were Warm Springs and Clackamas Chinook, Bingham steelhead, and Chignik sockeye. In general, this shows that our conclusions are robust to the time period of observation.

1.2.2 Analysis B: Effect of the time series length on rate of change in peak migration timing

We determined the effect of the time series length on rate of change in peak migration timing using a weighted linear model, where weight was assigned based on the inverse square of the variance. We included an interaction between number of years and species to allow the effect of time series length to vary with species. All terms had confidence intervals that spanned zero and therefore the length of the time series did not have a significant effect on the rate of shift in peak migration timing (Extended Data Table 3).

1.2.3 Analysis C: Effect of geographic, environmental, and biological variables on peak change for truncated datasets

As with the full datasets we compared geographic, environmental, and biological variables with the rate of peak change to determine if there were any strong predictors of peak change for the truncated datasets (1999 - 2019). We used weighted linear models, where weight was assigned based on the inverse square of the variance of peak change. We compared 59 models of combinations of independent and non-correlated predictor variables and found that the top model included only latitude. This model was the only model in the top model set ($< 2\ \Delta$AIC).

Our findings for the truncated dataset differed from the model results of the full dataset. In model selection for the full model, the top model included species and trap elevation. The significant terms were coho, chum, log trap elevation and an interaction between steelhead and trap elevation. Model comparison of the truncated model set did not show species as an effect, possibly because only one chum population was included in the truncated model results. Instead, only latitude was included in the top model, and though the effect was significant, the relationship between latitude and shift in peak migration was weak (Extended Data Table 4).

2.0 Temperature and peak phenology change

Our analysis of environmental, geographic, and biological variables did not reveal any strong relationships with change in peak outmigration. Yet water temperature and migration timing are closely related. Due to the highly adaptive nature of salmon populations, we suspected that the lack of relationship could be due to differences in the relationship between annual peak and temperatures.

We explored the relationships between annual peak and mean temperature three months before migration (the most parsimonious environmental predictor) for each population. We used a linear random effects model between annual peak, as estimated using the hierarchical state-space model, and mean temperature and precipitation three months prior to peak migration (estimated from latitude, longitude, and elevation using ClimateNA), where the random effect was year.

We found variability in the slope of the relationship between annual outmigration peak and annual mean temperature from three months before migration. The relationships between peak outmigration and temperature varied from strongly negative to positive across populations. For example, for every one degree Celsius increase in temperature, peak outmigration phenology advanced by 5.7 days for Bear Creek coho. On the other end of the spectrum, a one degree Celsius increase in temperature in Smith River, resulted in a 2.9 day delay in migration of steelhead trout (Fig. 4). Thus, similar changes in temperatures could result in diverse responses across salmon populations.

Table S1: Watershed descriptions for all smolt outmigration monitoring projects

Site Name	Latitude	Longitude	Species	Years (range)	Years (number)	Distance to ocean (km)	Elevation of trap (m)	Elevation (m) (min, max)	Watershed Area (km^2)	Hatchery Scale	Chlorophyll-a Section	Organization
Kvichak River	59.31	-155.94	sk	1972 - 2001	25	56	15	160 (0, 2163)	2648	sk = 0	NA	ADF&G
Auke Creek	58.38	-134.63	sk, pk, co	1980 - 2019	40	<1	21	235 (2, 583)	10	sk = 0, pk = 1, co = 0	13	ADF&G, NOAA
Tahltan Lake	57.98	-131.58	sk	1984 - 2016	33	273.5	811	1014 (808, 1632)	37	sk = 0	11	DFO
Chignik Lake	56.26	-158.73	sk	1995 - 2015	20	8	1	306 (0, 2505)	1623	sk = 0	26	ADF&G
Babine Lake	55.41	-126.68	sk	1961 - 2002	35	434.5	709	1057 (316, 2581)	10,449	sk = 1	NA	DFO
Chilko Lake	51.63	-124.14	sk	1951 - 2014	59	690.1	1174	1634 (735, 3238)	16,741	sk = 0	4	DFO
Keogh River	50.67	-127.35	co, sthd	1981 - 2015	35	<1	4	219 (3, 1190)	124	co = 0, sthd = 1	7	DFO, BCMoF
Black Creek	49.85	-125.10	co	1978 - 2016	34	<1	1	102 (1, 468)	65	co = 1	4	DFO
Cherry Creek	49.27	-124.78	co	1992 - 2013	28	2	61	212 (59, 577)	13	co = 1	4	DFO
Fraser River	49.13	-122.30	ch, pk	1966 - 2016	28	26.5	5	1188 (1, 3955)	231,524	ch = 0, pk = 0	4	DFO
Salmon River	49.12	-122.57	co	1986 - 2009	23	14	30	67 (1, 148)	85	co = 1	4	DFO
Carnation Creek	48.92	-125.00	co	1982 - 2015	34	<1	5	293 (3, 902)	113	co = 1	4	DFO, BCMoF

Table S1: Continued…

Site Name	Latitude	Longitude	Species	Years (range)	Years (number)	Distance to ocean (km)	Elevation of trap (m)	Elevation (m) (min, max)	Watershed Area (km^2)	Hatchery Scale	Chlorophyll-a Section	Organization
Upper Baker Lake	48.65	-121.69	sk, co	1989 - 2018	30	92	218	1103 (211, 3280)	19	co = 3, sk = 3	3	Puget Sound Energy
Lower Baker Lake	48.55	-121.74	sk	1989 - 2018	30	78	127	1010 (49, 3280)	8	sk = 3	3	Puget Sound Energy
Mannser Creek	48.53	-122.04	co	1994 - 2016	23	43.4	25	132 (23, 434)	6	co = 2	3	WDFW
Skagit River	48.44	-122.34	pk, ch, co, ck, sthd	1990 - 2019	30	17	1	1060 (0, 3280)	1172	pk = 0, ch =2, co =2, ck = 2, sthd = 2	3	WDFW
Snow Creek	47.98	-122.89	co, sthd	1978 - 2016	38	<1	6	386 (3, 1279)	60	co = 1, sthd = 1	3	WDFW
Chiwawa River	47.79	-120.66	ck	1999 - 2019	20	830.3	562	1330 (562, 2734)	488	ck = 3	2	WDFW
Bear Creek	47.67	-122.11	co, ck	1999 - 2019	20	48.6	13	106 (9, 192)	122	co = 1, ck = 1	3	WDFW
Little Anderson Creek	47.66	-122.76	co	1992 - 2019	24	<1	5	117 (5, 167)	12	co = 1	3	WDFW
Big Beef Creek	47.65	-122.78	co, sthd	1978 - 2019	42	<1	4	146 (2, 392)	32	co = 1, sthd = 1	3	WDFW
Seabeck Creek	47.64	-122.84	co	1993 - 2019	27	<1	5	114 (3, 184)	13	co = 1	3	WDFW
Stavis Creek	47.62	-122.88	co	1993 - 2019	27	<1	7	125 (4, 187)	16	co = 1	3	WDFW
Cedar River	47.48	-122.20	co, ck	1999 - 2019	20	34	10	589 (5, 1662)	483	co = 1, sthd = 1	3	WDFW
Bingham Creek	47.15	-123.40	co, sthd	1982 - 2013	32	66.3	76	170 (75, 869)	154	co = 1, sthd = 1	3	WDFW

Table S1: Continued…

Site Name	Latitude	Longitude	Species	Years (range)	Years (number)	Distance to ocean (km)	Elevation of trap (m)	Elevation (m) (min, max)	Watershed Area	Hatchery Scale	Chlorophyl-a Section	Organization
Chehalis River	46.80	-123.16	co, sthd	2000 - 2020	20	85	28	242 (27, 1165)	2545	co = 2, sthd = 2	3	WDFW
North Fork Nehalem	45.81	-123.74	co, sthd	1998 - 2017	20	20.6	88	271 (85, 737)	111	co = 3, sthd = 3	2	ODFW
Trout Creek	45.80	-121.93	sthd	1995 - 2016	20	266.5	330	716 (267, 1365)	88	sthd = 1	2	WDFW
Panther Creek	45.77	-121.84	sthd	1995 - 2016	20	251.8	181	705 (96, 1506)	107	sthd = 1	2	WDFW
Wind River	45.72	-121.80	sthd	1995 - 2016	21	245	25	702 (23, 1630)	581	sthd = 1	2	WDFW
Clackamas River	45.24	-122.28	co, ck, sthd	1959 - 2015	57	246	203	1028 (201, 2199)	1,727	co = 2, sthd = 1, ck = 2	2	USGS/Portland General Electric
Warm Springs River	44.87	-121.09	ck	1990 - 2016	33	462.1	409	951 (378, 1702)	1122	ck = 3	2	Confederated Tribes of Warm Springs
John Day River	44.84	-119.80	ck	1979 - 2017	23	574	535	1379 (556, 2759)	12,379	ck = 1	2	ODFW
Siletz/Mill	44.74	-123.79	co, sthd	1997 - 2019	23	110.8	50	337 (49, 953)	168	co = 1, sthd = 3	1	ODFW
Yaquina/Mill	44.57	-123.91	co	1997 - 2019	22	30.7	45	219 (43, 499)	10	co = 1	1	ODFW
Cascade Creek	44.32	-123.85	co	1998 - 2019	21	61.4	52	205 (52, 577)	14	co = 1	1	ODFW
Upper Mainstem Lobster	44.25	-123.64	co	1988 - 2019	31	65.6	195	433 (195, 670)	17	co = 1	1	ODFW
East Fork Lobster	44.25	-123.64	co	1988 - 2019	32	65.6	208	553 (210, 1042)	15	co = 1	1	ODFW

Table S1: Continued…

Site Name	Latitude	Longitude	Species	Years (range)	Years (number)	Distance to ocean (km)	Elevation of trap (m)	Elevation (m) (min, max)	Watershed Area	Hatchery Scale	Chlorophyl-a Section	Organization
Tenmile Creek	44.22	-124.11	sthd	1992 - 2016	25	<1	11	335 (3, 752)	60	sthd = 1	1	ODFW
West Fork Smith River	43.81	-123.77	co, sthd	1998 - 2019	22	56.8	58	285 (56, 867)	68	co = 1, sthd = 1	1	ODFW
South Umpqua River	42.98	-122.86	ck, sthd	1991 - 2016	24	308.8	350	989 (350, 2051)	630	ck = 1, sthd = 2	1	USFS

Species names are abbreviated as follows sk = sockeye, pk = pink, co = coho, sthd = steelhead, ch = chum, ck = Chinook salmon

Organization names are abbreviated as follows ODFW – Oregon Department of Fish and Wildlife, USFS = United States Forest Service, WDFW = Washington Department of Fish and Wildlife, DFO = Fisheries and Oceans Canada, BCMoF = British Columbia Ministry of Forests (formerly BC Ministry of Forests, Lands, and Natural Resource Operations and Rural Development), ADF&G = Alaska Department of Fish and Game, NOAA = National Oceanic and Atmospheric Administration, USGS = United States Geological Survey

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