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Southeast Alaska Pink Salmon Growth and Harvest Forecast Models

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Growth and harvest forecast models are used to provide insight into the role of temperature in the early marine ecology of Southeast Alaska (SEAK) pink salmon (*Oncorhynchus gorbuscha)*. The onset of the Gulf of Alaska marine heatwaves in 2014–2015 (Bond et al. 2015) has highlighted the importance of understanding the resilience of salmon to a warming climate as the frequency and magnitude of marine heatwaves are expected to increase with warming Arctic conditions (Di Lorenzo and Mantua 2016). Pre-season harvest forecasts using adult pink salmon data have been a persistent challenge due to the presence of a single adult age and high variation in spawner-recruit relationships. Juvenile models have been developed to assist harvest forecasts for SEAK pink salmon (Orsi et al. 2016; Wertheimer et al. 2018; Murphy et al. 2019) using data collected during Southeast Alaska Coastal Monitoring Survey (SECM) (Murphy et al. 1999; Orsi et al. 2016; Fergusson et al. 2019) and have become the primary tool used for pre-season harvest guidance in SEAK pink salmon fisheries. Temperature is an important environmental covariate in the harvest forecast model, but it is unclear how it contributes to the forecast performance (Murphy et al. 2019). Although environmental conditions are often used to account for changes in survival, they also play an important role in the distribution and migration of salmon. These two ecological processes are confounded within the harvest model as juvenile abundance is measured with catch-per-unit-effort (CPUE) data. Growth models are developed to provide ecological insight into the role of temperature in the early marine ecology of juvenile pink salmon. Otolith thermal mark recoveries of hatchery chum salmon are reviewed to provide insight into the overall migratory pattern of juvenile salmon in SEAK. Finally, run-size forecast models based on juvenile pink salmon abundance in the northern Bering Sea are included to add insight into critical periods in the marine survival of Alaskan pink salmon.

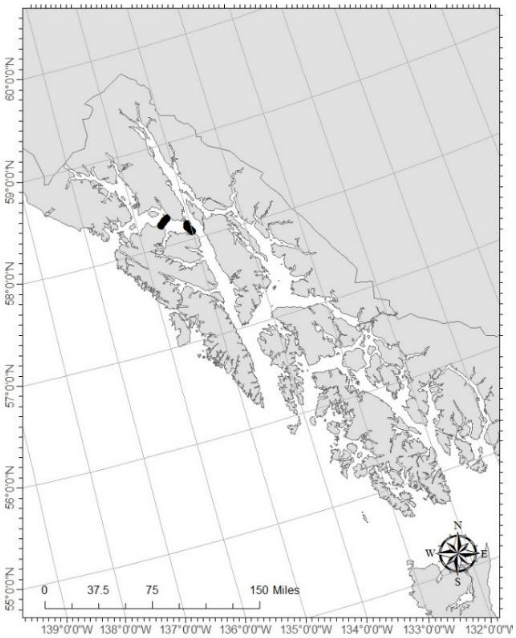

Fig. 1. A map of Southeast Alaska identifying the eight stations (black dots) within Icy Strait sampled by the Southeast Alaska Coastal Monitoring survey.

Data on juvenile salmon associated oceanographic and ecosystem indicators have been collected during SECM surveys since 1997 within the northern region of SEAK (Fergusson et al. 2019). Data from eight stations along two transects in Icy Strait (Fig. 1) are used in harvest and growth models of SEAK juvenile pink salmon.

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Oceanographic data collected at these stations consist of conductivity-temperature-depth (CTD) profiles of temperature (°C) and salinity (PSU), a water sample for chlorophyll-a (ug·L^{-1}), and a 60 cm bongo net tow for zooplankton. The overall average 20 m integrated water column temperature was used to estimate the Icy Strait Temperature Index (ISTI) (May–August and May–July). Fish were sampled at each station with a NETS Nordic 264 rope trawl fished for 20 min at each station at least once during June–August with tow speeds of approximately 1.5 m·sec^{-1} and typical fishing dimension of 18 m wide by 24 m deep.

Table 1. Average surface trawl catch-per-unit-effort (CPUE) in Icy Strait, the May–August Icy Strait Temperature Index (ISTI) and observed and predicted harvest of pink salmon in Southeast Alaska (SEAK), 1997–2017.

Juvenile Year	Ln(CPUE+1)	ISTI (°C)	SEAK Harvest (millions)	Predicted SEAK Harvest (millions)
1997	2.48	9.48	42.45	34.39
1998	5.62	9.57	77.82	86.85
1999	1.60	8.97	20.25	28.43
2000	3.73	9.04	67.02	64.00
2001	2.87	9.44	45.32	41.80
2002	2.78	8.56	52.47	56.53
2003	3.08	9.78	45.31	39.11
2004	3.90	9.66	59.12	55.64
2005	2.04	10.26	11.61	12.53
2006	2.58	8.88	44.80	46.99
2007	1.17	9.31	15.90	14.88
2008	2.49	8.29	37.95	56.26
2009	2.09	9.61	24.03	25.19
2010	3.67	9.62	58.86	52.44
2011	1.35	8.90	21.25	25.52
2012	3.15	8.73	94.70	59.67
2013	1.91	9.16	37.20	30.48
2014	3.40	9.37	35.10	52.34
2015	2.19	9.86	18.40	22.42
2016	3.89	10.56	34.30	39.00
2017	0.31	8.93	7.65	7.04

Peak monthly (June and July) juvenile catch-per-unit-effort (CPUE) and associated environmental variables were used in a multiple linear regression model to forecast harvest based on the approach described in Wertheimer et al. (2006). CPUE was standardized to 20-minute trawl set and calibrated to the NOAA Ship *John N. Cobb* with fishing power coefficients for the vessels that have conducted SECM surveys over time (Wertheimer et al. 2010). The model was defined as:

$$Harvest = \alpha + \beta(\ln(CPUE + 1)) + \gamma_1 X_1 \dots \gamma_n X_n + \varepsilon,$$

where γ is the coefficient for environmental covariates X (e.g., water temperatures, climate indices, fish size and condition) and ε is the normally distributed error term. A backward/forward stepwise regression model selection procedure identified candidate models via Akaike Information Criterion (AIC) and small sample AIC (AICc). Mean and Median Absolute Percentage Error (MAPE, MEAPE) statistics from jackknife cross validations were used to define forecast accuracy of candidate models, and the harvest forecast was based on the 80% bootstrap confidence interval of the model with the highest forecast accuracy. A two-parameter model, including CPUE and the Icy Strait

Temperature Index (ISTI), has been the most consistently selected model over time and accounts for 78% (R^2) of the variability in harvest data (Fig. 2; Table 1). Temperature is a significant negative covariate in the model and partial residuals identify a negative linear relationship between temperature and harvest across the range of observed temperatures (Fig. 2). A linear relationship is more consistent with a simple ecological process such as temperature effects on juvenile distribution and migration; a threshold or non-linear relationship may be more likely if temperature is altering ecological rate processes.

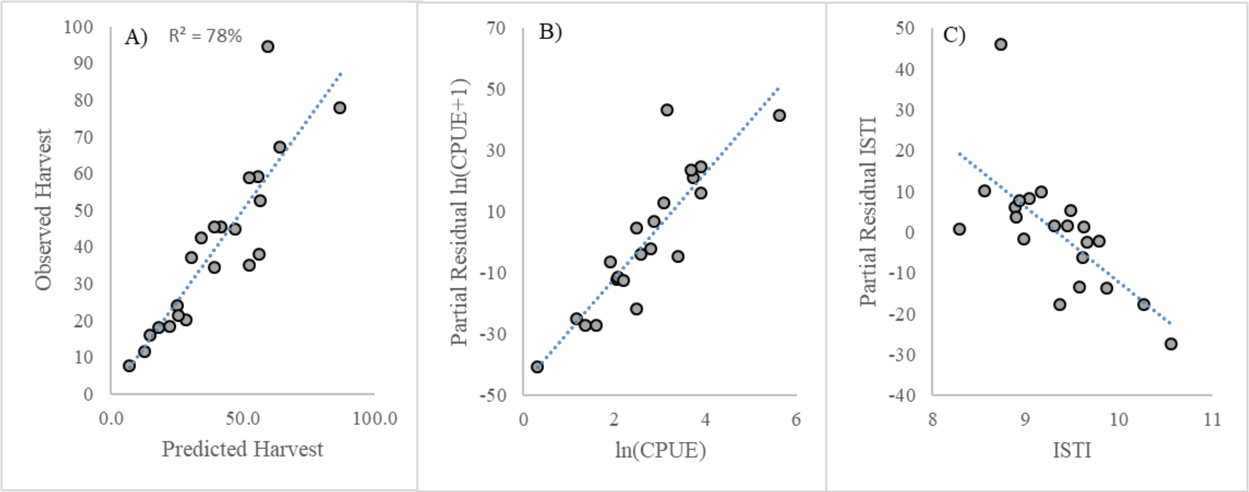

Fig. 2. The harvest forecast model for Southeast Alaska pink salmon, 1997–2018 juvenile years. Plots are: A) the relationship between predicted and observed harvest (millions of fish), B) the partial residuals for the peak monthly catch-per-unit-effort, ln(CPUE), of juvenile pink salmon in Icy Strait, and C) the partial residuals for the May–August Icy Strait Temperature Index (ISTI) (°C). The model explains 78% (R^2) of the variation in pink salmon harvest.

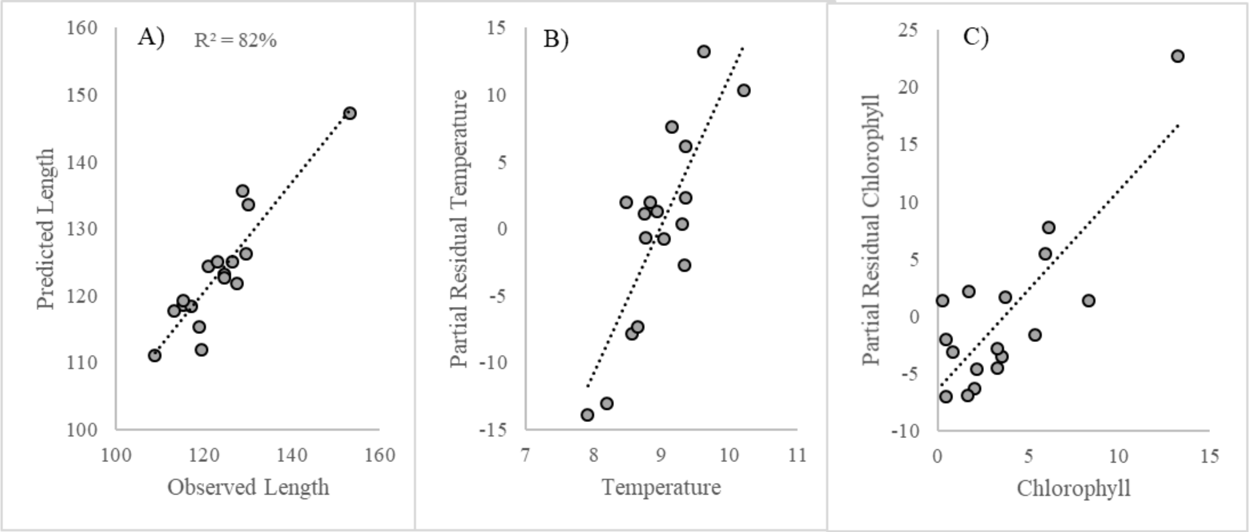

Fig. 3. The growth model for Southeast Alaska pink salmon in Icy Strait, 1999–2015 juvenile years. Figures included are: A) the relationship between observed and predicted lengths (fork length mm) of juvenile pink salmon on 24 July 24, B) partial residuals for the May–July Icy Strait Temperature Index (°C), and C) partial residuals for May chlorophyll ($\mathrm{ug \cdot L^{-1}}$). This model explains 82% (R^2) of the variation in the average length of juvenile pink salmon.

A similar stepwise model selection approach was used to identify environmental variables important to juvenile pink salmon growth. Year-to-year variation in juvenile pink salmon growth was approximated by their length (fork length) standardized to 24 July based on their apparent growth rate between the June and July SECM surveys. A two-parameter model including May chlorophyll ($\mathrm{ug \cdot L^{-1}}$) and the May–July ISTI index was identified as the best fitting model to average annual size of juvenile pink salmon. The model accounted for 71% (adjusted R^2) of the variability in the year-to-year variation in the average size of juvenile pink salmon, 1997–2018, and 82% of the variability from 1997–2015 (Fig. 3; Table 2). May chlorophyll data were not available in 2016 and 2017. The poor fit of the model in 2018 is likely due to the late outmigration timing of juvenile pink salmon (Scott Vulstek, personal communication), which highlights complications of modeling juvenile growth with size data. The essential point of this model is that temperature is a significant positive covariate in the growth of SEAK juvenile pink salmon. Reconciling the opposite effects of temperature in the growth and harvest models leads to the inference that growth and survival of pink salmon are not linked, or that ecological processes other than survival are contributing to the significance of temperature in the harvest model. The temperature effect in the harvest model may simply reflect changes in the migratory pattern of juveniles.

Table 2. Average upper 20 m water column temperatures (May–July), May Chlorophyll-a concentrations, observed average length (estimated fork length on 24 July), and predicted average length of juvenile pink salmon in Icy Strait, 1999–2015.

Year	Temperature (°C)	Chlorophyll (ug ·L^{-1})	Length (mm)	Predicted Length (mm)
1999	8.56	3.54	115	119
2000	8.77	5.90	127	125
2001	9.03	0.45	117	118
2002	8.20	5.33	113	118
2003	9.31	2.03	121	124
2004	9.33	8.33	129	136
2005	10.21	1.66	130	134
2006	8.75	0.48	119	115
2007	8.94	3.71	125	123
2008	7.91	3.29	109	111
2009	9.36	2.16	123	125
2010	9.35	0.83	125	123
2011	8.65	3.26	115	119
2012	8.48	0.25	119	112
2013	8.83	6.13	130	126
2014	9.14	1.69	128	122
2015	9.62	13.23	153	147
2016	10.20	--	145	--
2017	8.56	--	121	--
2018	8.92	4.55	109	--

Table 3. Number of juvenile chum salmon hatchery otolith thermal marks recovered in Icy Strait by Southeast Alaska Coastal Monitoring surveys, 1997–2017.

Month	DIPAC[1]	NSEAK[2]	SSRAA[3]
June	3974	819	13
July	1611	2086	211
August	432	433	382

[1] Douglas Island Pink and Chum, Inc.
[2] Includes Northern Southeast Regional Aquaculture Association, Kake Nonprofit Fisheries Corp. and Armstrong-Keta Inc.
[3] Southern Southeast Regional Aquaculture Association.

Otolith thermal marks of juvenile chum salmon recovered during SECM surveys provide some insight into the migratory pattern expected for SEAK pink salmon (Table 3). Hatchery chum salmon origins vary by month with the stocks closest to Icy Strait (DIPAC) accounting for the largest proportion in June. Recoveries of thermal marks from other hatchery stocks in northern SEAK are highest in July. Thermal mark recoveries from stocks farthest away from Icy Strait (SSRAA) reach their peak in August. This highlights that some proportion of juvenile salmon from all regions of SEAK migrate through Icy Strait, and therefore change in juvenile migration patterns have the potential to alter the relationship between juvenile CPUE and abundance. The combination of trawl CPUE and temperature may be a more accurate measure of juvenile abundance than trawl CPUE data alone if the proportion of SEAK juveniles that migrate through Icy Strait (the northern migration corridor) increases in warm years. If true, this increases the importance of the initial or early marine life-history stage to the overall marine survival of SEAK pink salmon.

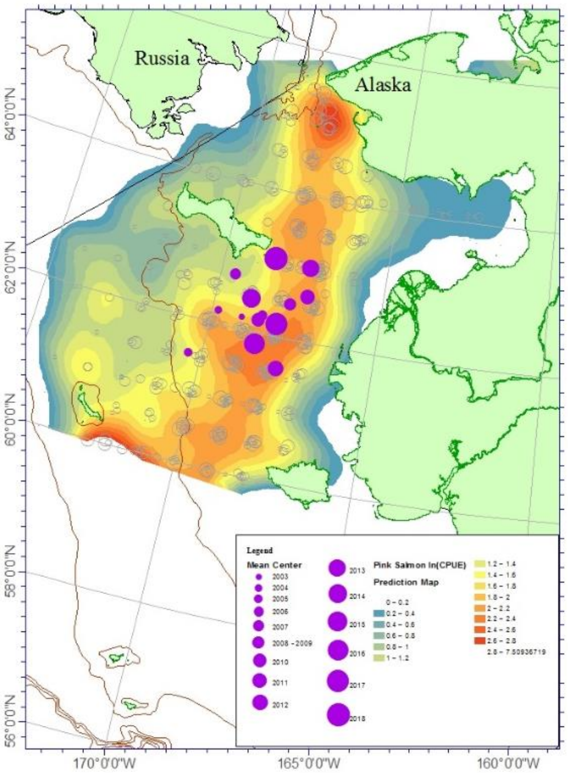

Fig. 4. Spatial distribution of juvenile pink salmon based on catch-per-unit-effort (CPUE) data from surface trawl surveys in the northern Bering Sea, 2003–2018. Color contours are from local polynomial prediction surface of ln (CPUE+1) (hollow circles) created using ArcGIS software from Esri, and filled circles identify the spatial center of juvenile pink salmon distribution and are scaled by year.

Juvenile abundance models from the northern Bering Sea provide insight into the importance of the early marine life-history stage of pink salmon to their marine survival. Surface trawl catch rates from the northern Bering Sea trawl surveys (Fig. 4) were used to construct an index of juvenile pink salmon abundance as:

$$Index = \frac{\sum_i^I \ln\,(CPUE_i + 1)}{I}\,\theta,$$

where $CPUE_i$ is the catch-per-unit-effort at station i, θ is the mixed-layer-depth (MLD) adjustment, and I is the total number of stations sampled by year. Effort is the area swept by the trawl in km^2, and the MLD adjustment, θ, is:

$$\theta = \frac{\sum_i^I C_i M_i}{\sum_i^I C_i},$$

where C_i is catch of juvenile pink at station i, $M_{i,}$ is the ratio of MLD to trawl depth when trawl depth is shallower than mixed layer depth, and 1.0 when trawl depth is below the mixed-layer depth, and I is the total number of stations sampled in that year (Murphy et al. 2017). This juvenile abundance index explains 73% (R^2 = 73%) of the year-to-year variability in adult returns to Norton Sound and the Yukon River (Fig. 5; Table 4), highlighting the importance of the early or initial marine life-history period to the marine survival of pink salmon in the northern Bering Sea.

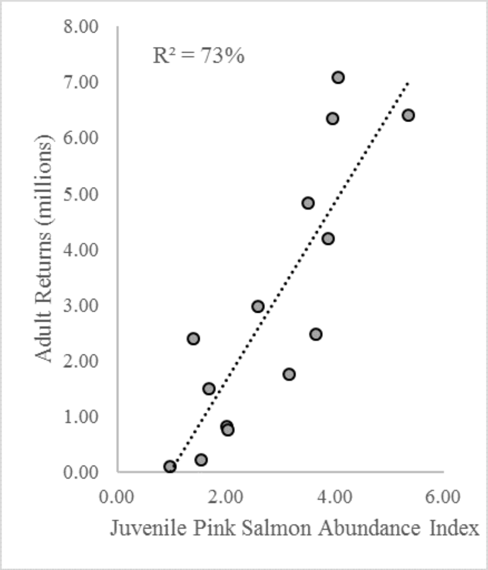

Fig. 5. The relationship between the juvenile pink salmon abundance index and adult returns to Norton Sound and the Yukon River for the 2004–2018 return years. This model explains 73% (R^2) of the variation in adult pink salmon returns to the northern Bering Sea.

Table 4. Average catch-per-unit-effort (CPUE), Mixed-Layer-Depth (MLD) adjustment, and abundance index for juvenile pink salmon in the northern Bering Sea, and adult returns to the Yukon River and Norton Sound, 2003–2017 (juvenile years).

Juvenile Year	Ln (CPUE)	MLD Adjustment	Juvenile Index	Adult Return
2003	2.65	1.49	3.95	6.35
2004	2.51	1.46	3.66	2.49
2005	1.96	1.79	3.52	4.84
2006	1.69	1.20	2.02	0.83
2007	3.22	1.20	3.87	4.19
2008	--	--		0.34
2009	1.38	1.01	1.39	2.39
2010	1.43	1.08	1.54	0.23
2011	1.47	1.15	1.69	1.50
2012	0.80	1.21	0.97	0.11
2013	3.10	1.02	3.17	1.76
2014	1.96	1.04	2.04	0.77
2015	4.25	1.26	5.35	6.39
2016	2.57	1.00	2.58	2.98
2017	3.94	1.03	4.05	7.08

Critical periods in the natural mortality schedule of salmon are important to our understanding of their underlying production dynamics and the scientific advice provided to fisheries management. The initial or early marine period of juvenile pink salmon has largely been believed to be the primary determinant of year-class strength (Parker 1968; Mortensen et al. 2000; Willette et al. 2001; Wertheimer and Thrower 2007) due to the high and variable mortality that occurs during this stage. The importance of the initial marine period to the survival of SEAK pink salmon increases and the negative influence of temperature on survival decreases if trawl CPUE and temperature are used together as an index of juvenile abundance. The inability to identify the origin of juvenile pink salmon limits attempts to test the role of temperature within the harvest forecast model; however, the data included here provide ecological support for considering temperature as a factor in abundance estimates of SEAK juvenile pink salmon.

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