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Historical Scale Growth of Bristol Bay and Yukon River, Alaska, Chum Salmon (*Oncorhynchus keta)* in Relationship to Climate and Inter- and Intra-Specific Competition

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Growth is a key factor affecting survival of Pacific salmon (e.g. Healey 1986; Ruggerone et al. 2007; Martinson et al. 2008). Faster growing salmon are able to avoid predators and survive when prey availability is low (Beamish and Mahnken 2001). Salmon growth has been shown to co-vary with climate (Ruggerone et al. 2005, 2007; Farley et al. 2007), and the North Pacific Ocean has experienced climate shifts during this study (Mantua et al. 1997; Hare and Mantua 2000). Another factor affecting growth and productivity of salmon may be interactions with pink salmon (*Oncorhynchus gorbuscha*), which are abundant (Ruggerone et al. 2010). Intraspecific competition may lead to density-dependent growth (Ishida et al. 1993; Peterman et al. 1998; Ruggerone et al. 2003), and increased hatchery chum (*O. keta*) production possibly caused reduction in growth of Asian chum salmon (Ishida et al. 1993; Kaeriyama et al. 2007).

We used salmon scales to determine whether marine growth of chum salmon varied with climate and interspecific competition. We examined annual growth using scales collected from Bristol Bay (age-0.3, 1965-2006; age-0.4 1966-2006) and Yukon River (age-0.3, 1965-2006; age-0.4, 1967-2006) chum salmon (Fig. 1). We compared the growth data with climate indices, abundance of Asian chum salmon, and the odd- and even-year abundance pattern of pink salmon.

Generalized least squares regression was used to compare relationships among environmental variables, Asian pink and chum salmon abundance, and growth of western Alaska salmon because analyses indicated there was autocorrelation among residuals. The number of model parameters was reduced by stepwise regression, and the Akaike Information Criterion (AIC) was used to determine the best model.

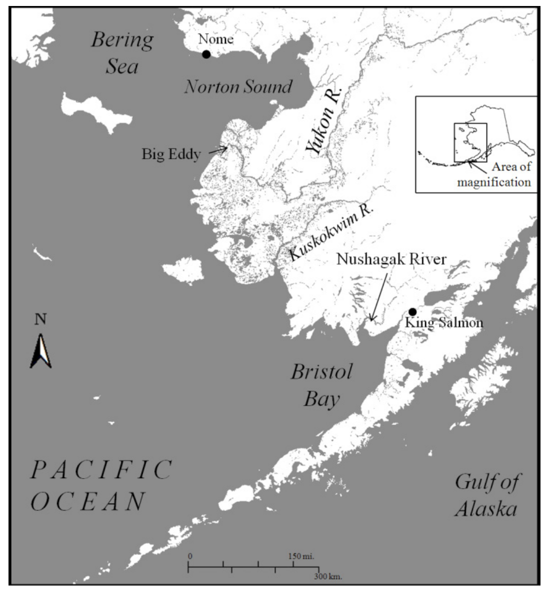

Fig. 1. Location in western Alaska where chum salmon scale samples were collected annually in Bristol Bay and the Yukon River, 1965-2006. Scales were collected during commercial chum salmon fisheries in the Nushagak District, which were conducted at the mouth of the Nushagak River. Yukon River chum salmon scales were collected at the river mouth during commercial and test fisheries at Flat Island and Big Eddy.

Full model - First year at sea (SW1): age-0.3 and -0.4 fish

$$\begin{aligned} SW1\ growth = \alpha + \beta_1(local\ SST_t) + \beta_2(ALPI_t) + \beta_3(NPI_t) + \\ \beta_4(May\ Mix_t) + \beta_5(Ice\ Cover_t) + \beta_6(local\ Air\ Temp_t) + \varepsilon_t \end{aligned} \quad (1)$$

where local SST_t is the local sea surface temperature (SST), $ALPI_t$ is the Aleutian Low Pressure Index, NPI_t is the North Pacific Index, $May\ Mix_t$ is the wind mixing index from St. Paul Island, Alaska, $Ice\ Cover_t$ is the ice cover index from the northern Bering Sea, and $local\ Air\ Temp_t$ is air temperature at Nome or King Salmon, Alaska.

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Full model - Third year at sea (SW3): age-0.3 and -0.4 fish

$$SW3\ growth = \alpha + \beta_1(Pinks_t) + \beta_2(Asian\ Chums_t) + \beta_3(GOA\ Annual\ SST_k) + \beta_4(NPI_k) + \beta_5(Pinks_t{*}Asian\ Chums_t) + Gender + \varepsilon_t \quad (2)$$

where $Pinks_t$ represents total abundance of Russian pink salmon, $Asian\ chums_t$ is a four-year moving average of Asian chum abundance (Ruggerone et al. 2010), and $GOA\ Annual\ SST_t$ represents annual average SST of the Gulf of Alaska.

Normalized plots of Bristol Bay SW1 and SW3 age-0.4 growth by year provide an example of the data and the lack of visible odd- and even-year pattern related to the abundance of Asian pink salmon (Fig. 2). Plots showed changes in growth around 1976/77, or the regime shift associated with the Pacific Decadal Oscillation (PDO) and changes in SST.

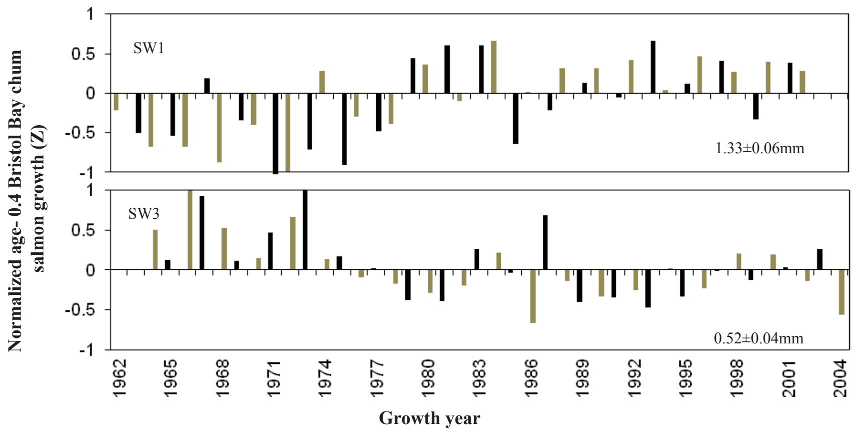

Fig. 2. Mean annual growth of age-0.4 Bristol Bay chum salmon during their first (SW1) and third (SW3) year at sea is plotted against time, 1961-2006. Un-weighted mean ± 1 SD during each life stage is shown.

Bristol Bay first-year growth: For age 0.3 chum salmon, local SST and ice cover showed a significant positive relationship with first year growth (Table 1). For age 0.4 fish, the local SST and NPI showed a significant positive relationship with first year growth, and the ALPI, May mixing index, and ice cover showed a detectable negative relationship with first year growth.

Table 1. Generalized least squares models (GLS) comparing growth during the first (SW1) and third (SW3) year at sea for age-0.3 (1965-2006) and age-0.4 chum (1966-2006) salmon caught in commercial fisheries at the mouth of the Nushagak River in Bristol Bay. AIC=Akaike Information Criterion; AR = autocorrelation function; Int = intercept.

				Model coefficients				
Model variables	AIC	AR	Int	V1	V2	V3	V4	V5
SW1 growth								
Age-0.3								
SST + Ice Cover	-120.3	3	1.349	0.075	0.016			
				<0.001	0.070			
Age-0.4								
SST + ALPI + NPI + May Mix + Ice Cover	-128.1	0	0.541	0.200	-0.017	0.033	-0.770	-0.024
				<0.001	0.022	0.055	0.005	0.032
SW3 growth								
Age-0.3								
Pinks + Asian chums + Pinks*Asian chums + Gender	-236.4	1	0.629	2.3E-4	-0.071	2.7E-4	-0.050	
				0.040	0.002	0.027	<0.001	
Age-0.4								
Pinks + GOA SST + Gender	-239.2	4	0.641	2.4E-4	-0.012	0.051		
				0.024	0.037	0.028		

Bristol Bay third-year growth: For age 0.3 chum salmon, Asian chum salmon abundance showed significant negative effects on third year growth; whereas, pink salmon abundance and the interaction term (Pinks*Asian chums) showed a significant positive relationship with third-year growth (Table 1). For age 0.4 chum salmon, GOA SST showed significant negative effects, and pink salmon abundance had a significant positive relationship with third year growth. For both ages, females showed significantly less third-year growth than males.

Yukon River first-year growth: For age 0.3 chum salmon, first-year growth was significantly negatively correlated with the May mixing index, and positively correlated with Nome annual air temperature (Table 2). For age 0.4 chum salmon, the best model indicated that there was a significant positive relationship of local sea surface temperature, ALPI, and the May mixing index with first-year growth.

Yukon River third-year growth: For both ages of chum salmon, Asian chum salmon abundance and GOA SST showed a significant negative relationship with third-year growth; whereas, pink salmon abundance and the interaction term (Pinks*Asian chums) showed a significant positive relationship with third-year growth (Table 2). Females grew significantly less in the third year than males.

Table 2. Generalized least squares models (GLS) comparing growth during the first (SW1) and third (SW3) full year of growth at sea for age-0.3 (1965-2006) and age-0.4 (1967-2006) chum salmon caught in commercial and test fisheries at the mouth of the Yukon River. AIC=Akaike Information Criterion; AR = autocorrelation function; Int = intercept.

				Model coefficients				
Model variables	AIC	AR	Int	V1	V2	V3	V4	V5
SW1 growth								
Age-0.3								
MayMix + local Air Temp	-131.8	4	1.071	-1.131	0.010			
				0.061	<0.001			
Age-0.4								
SST + ALPI + May Mixing	-126.8	4	1.289	0.021	0.016	0.014		
				0.002	0.022	0.053		
SW3 growth								
Age-0.3								
Pinks + Asian chums + GOA SST +	-246.9	1	0.604	2.6E-4	-0.060	-0.015	2.5E-4	-0.060
Pinks*Asian chums + Gender				0.020	0.005	0.047	0.027	<0.001
Age-0.4								
Pinks + Asian chums + GOA SST +	-263.3	1	0.469	2.5E-4	-0.053	-0.019	2.4E-4	-0.034
Pinks*Asian chums + Gender				0.016	0.004	0.002	0.016	0.008

Overall, we found that warmer regional temperatures, NPI, and less ice cover significantly enhanced the first-year growth of chum salmon in Bristol Bay and Yukon River. We also found that third-year growth was significantly affected by Asian chum salmon abundance for all but Bristol Bay age 0.4 fish. In contrast to our hypothesis that cooler temperatures in the Gulf of Alaska would have inhibited growth, we found that warmer large-scale SSTs from the Gulf of Alaska were associated with reduced growth in the third year at sea.

We hypothesized that cooler temperatures in the Gulf of Alaska would inhibit the marine growth of western Alaska chum salmon and that Gulf of Alaska temperatures would significantly affect marine growth of both ages of Bristol Bay and Yukon River chum salmon, but the model coefficients were negative. Thus, we found opposite effects, contradicting our hypothesis. Although this appears counterintuitive, Ruggerone et al. (2011) found that adult length-at-age was negatively correlated with sea surface temperature, rather than positively correlated as they had hypothesized. They suggested that this unexpected result was due to density-dependent effects involving abundance of hatchery chum salmon. Perhaps the abundance of hatchery chum salmon overwhelmed the favourable growing conditions associated with warm SSTs.

Pink salmon abundance appeared to inhibit growth of western Alaska chum salmon during the third year of growth, but the effect was much less than that observed for Asian chum salmon abundance. Researchers suggested that chum salmon change their spatial distribution in years when pink salmon abundance was high (Azumaya and Ishida 2000). If pink salmon abundance increased, and chum salmon moved into the Gulf of Alaska where sea surface temperatures were also warmer, it is possible that growing conditions were good for both species. Thus, improved SST might explain improved growth of pink and chum salmon in recent years. Chum salmon have unique gut architecture, allowing them to "prey switch" and forage on lower quality prey (Davis et al. 2004). This ability to survive on a variety of prey species perhaps allowed chum salmon to increase in abundance if prey productivity was high even though pink salmon abundance was also high.

The abundance of Asian chum salmon negatively affected the growth of both ages of Yukon River and age-0.3 Bristol Bay chum salmon. Age-0.3 is the predominant age group of Asian chum salmon, thus it is possible Yukon River and Bristol Bay age-0.3 chum salmon would be affected to a larger degree by increased abundance of Asian chum salmon because competition for prey among conspecifics would likely be greater among fish of the same age group.

The North Pacific Ocean is part of a dynamic ecosystem, and many of the explanatory variables in the models overlap, or are autocorrelated. Thus, we found the complexity of the ecosystem created problems in our analysis as noted by the importance of the multiplicative effects in the models. Do these multiplicative effects create spurious results, or do they indicate important interactions among the components of a complex ecosystem? Overall, it appears that several factors, notably, sea surface temperature, abundance of pink salmon, and abundance of Asian chum influence growth of Bristol Bay and Yukon River chum salmon during their first and third year at sea.

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