



Pink salmon (*Oncorhynchus gorbuscha*) marine survival rates reflect early marine carbon source dependency

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ABSTRACT

Marine survival rate (the number of adult salmon returning divided by the number of salmon fry released) of pink salmon runs propagated by Prince William Sound, Alaska (PWS) salmon hatcheries is highly variable resulting in large year-to-year run size variation, which ranged from ~20 to ~50 million during 1998–2004. Marine survival rate was hypothesized to be determined during their early marine life stage, a time period corresponding to the first growing season after entering the marine environment while they are still in coastal waters. Based on the predictable relationships of $^{13}\text{C}/^{12}\text{C}$ ratios in food webs and the existence of regional $^{13}\text{C}/^{12}\text{C}$ gradients in organic carbon, $^{13}\text{C}/^{12}\text{C}$ ratios of early marine pink salmon were measured to test whether marine survival rate was related to food web processes. Year-to-year variation in marine survival rate was inversely correlated to $^{13}\text{C}/^{12}\text{C}$ ratios of early marine pink salmon, but with differences among hatcheries. The weakest relationship was for pink salmon from the hatchery without historic co-variation of marine survival rate with other PWS hatcheries or wild stocks. Year-to-year variation in $^{13}\text{C}/^{12}\text{C}$ ratio of early marine stage pink salmon in combination with regional spatial gradients of $^{13}\text{C}/^{12}\text{C}$ ratio measured in zooplankton suggested that marine survival was driven by carbon subsidies of oceanic origin (i.e., oceanic zooplankton). The 2001 pink salmon cohort had $^{13}\text{C}/^{12}\text{C}$ ratios that were very similar to those found for PWS carbon, i.e., when oceanic subsidies were inferred to be nil, and had the lowest marine survival rate (2.6%). Conversely, the 2002 cohort had the highest marine survival (9.7%) and the lowest mean $^{13}\text{C}/^{12}\text{C}$ ratio. These isotope patterns are consistent with hypotheses that oceanic zooplankton subsidies benefit salmon as food subsidies, or as alternate prey for salmon predators. Oceanic subsidies are manifestations of significant exchange of material between PWS and the Gulf of Alaska. Given that previously observed inter-decadal cycles of oceanic zooplankton abundance were climatically driven, exchange between PWS and the Gulf of Alaska may be an important process for effecting synoptic changes in marine populations of higher trophic levels, and thus an important consideration for climate-change models and scenarios.

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1. Introduction

Pink salmon (*Oncorhynchus gorbuscha*) is the most numerous Pacific salmon species and contributes to major fisheries. In Alaska, as of 2006, about 100 million pink salmon are caught annually, comprising ~80% of the state's salmon fishery (http://www.cf.adfg.state.ak.us/geninfo/finfish/salmon/salmon_harvest.php#forecasts).

Consequently, fluctuations in the size of pink salmon runs drive variability in the size of the total annual salmon harvest in Alaska.

The size of pink salmon populations returning to Prince William Sound (PWS) hatcheries in recent years has fluctuated by tens of millions (Table 1). Pink salmon populations in PWS are comprised of those that are artificially propagated and those that occur naturally at a ratio of approximately three to one (Wertheimer et al., 2004). Upwards of one half billion pink salmon are released into PWS each year by four hatcheries (Table 1). All pink salmon from hatcheries are identifiable from otolith thermal marks purposefully induced during their hatchery incubation (Hagen et al., 1995; Smoker and Linley 1997).

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Table 1
Production statistics of Prince William Sound hatchery pink salmon production during the 1998–2004 observation period

Cohort	AFK hatchery			Cannery creek hatchery			WN hatchery			Solomon Gulch hatchery			AFK+CCH+SGH+WNH			CCH+SGH+WNH		
	Fry released (millions)	Return (millions)	Marine survival (%)	Fry released (millions)	Return (millions)	Marine survival (%)	Fry released (millions)	Return (millions)	Marine survival (%)	Fry released (millions)	Return (millions)	Marine survival (%)	Fry released (millions)	Return (millions)	Marine survival (%)	Fry released (millions)	Return (millions)	Marine survival (%)
1998	106.0	8.7	8.25	137.6	8.1	5.87	103.7	9.5	9.13	195.2	14.9	7.65	542.4	41.2	7.60	436.4	32.5	7.44
1999	133.2	6.9	5.19	131.2	6.5	4.96	127.4	8.4	6.57	213.9	12.4	5.77	605.6	34.1	5.63	472.5	27.2	5.76
2000	142.5	4.8	3.37	132.2	2.1	1.60	116.1	7.2	6.19	195.8	16.1	8.24	586.6	30.2	5.15	444.1	25.4	5.73
2001	150.3	7.8	5.16	139.2	1.6	1.14	127.7	5.6	4.40	203.9	5.3	2.58	621.1	20.2	3.26	470.8	12.5	2.65
2002	156.0	7.1	4.53	138.6	8.3	5.98	106.2	17.8	16.80	202.6	17.3	8.56	603.4	50.5	8.38	447.4	43.5	9.72
2003	146.4	5.2	3.57	135.6	2.8	2.04	119.5	2.7	2.26	206.4	11.1	5.40	607.9	21.8	3.59	461.5	16.6	3.60
2004	174.4	10.1	5.80	136.3	13.5	9.90	109.6	9.2	8.36	222.5	17.8	8.02	642.8	50.6	7.87	468.4	40.5	8.64
Mean:	144.1	7.2	5.12	135.8	6.1	4.50	115.7	8.6	7.67	205.7	13.6	6.60	601.4	35.5	5.93	457.3	28.3	6.22

AFK = Armin F. Koermig hatchery, WNH = Wally Noerenberg hatchery, CCH = Cannery Creek hatchery, SGH = Solomon Gulch hatchery.

Pink salmon have the shortest life cycle among the *Oncorhynchus*, reproducing at age two. Their life cycle can thus be described as consisting of three years: (1) the brood year, (2) the early marine year, and (3) the return year. The returning year creates the brood year of the next generation. This study focused on early marine year pink salmon because mortality occurring during the early marine year was hypothesized to determine survival from juvenile to adult stages (Parker 1968; Hartt 1980). Because of their short life history, pink salmon were expected to be particularly sensitive to year-to-year variability in oceanic forcing.

Survival rates of pink salmon from three of the four PWS hatcheries and PWS wild stocks have co-varied since their inception (1975–1985) to 1996 (Pyper et al., 2001). Furthermore, survival rates of wild PWS pink salmon and wild stocks over the northern Gulf of Alaska region spanning Kamishak Bay (Lower Cook Inlet) to Yakutat (northern Southeast Alaska) have co-varied over the previous ~ four decades (Pyper et al., 2001). These patterns of spatial co-variation in pink salmon survival rate were hypothesized by Pyper et al. (2001) to be driven by processes occurring during the coastal (i.e., early) phase of the marine life history of pink salmon. One such process that may affect salmon survival is diet and food availability.

One may infer the source of pink salmon prey in terms of space and time, rather than by taxon, using stable isotope analysis (SIA). Based on the predictable relationship between the stable isotopic composition of a consumer and its diet (reviewed by Michener and Schell, 1994), the stable isotope composition measured in a particle-feeding copepod such as *Neocalanus cristatus* reflects that of its low trophic level diet, which consists of phytoplankton and protozoa (Liu et al., 2005). Similarly, the stable isotope composition measured in pink salmon would reflect that of their zooplankton diet (Boldt and Haldorson 2002), which, in turn, reflects that of the diet of zooplankton, which consists of phytoplankton and protozoa.

A relatively high carbon stable isotope ratio cross-shelf gradient, but a relatively low nitrogen stable isotope ratio cross-shelf gradient exists in the study area (Kline, 1999). The carbon stable isotope ratio gradients were such that lower carbon stable isotope ratio values were diagnostic of carbon from outside PWS and used to infer oceanic subsidies, which were temporally variable and may contribute >50% of the carbon of PWS fish food webs (Kline, 1999; Kline and Willette, 2002). These isotopic gradients were based upon systematic observations of late feeding stage individuals of *N. cristatus* (a regionally ubiquitous copepod that comprises a significant part of the meso-zooplankton biomass during the spring bloom; Coyle and Pinchuk, 2003, 2005) and bulk net zooplankton samples (Kline, 1999). The *N. cristatus* data were more definitive than bulk samples because they provided a better statistical sample and avoided complications arising from the uncertain nature of bulk samples. Cross-shelf gradients were thus verified for this study period by comparing carbon stable isotope ratio values of individual *N. cristatus* from PWS with those from the adjacent Gulf of Alaska during the same years that pink salmon were sampled.

Pink salmon from three PWS hatcheries with a co-variation history (Pyper et al., 2001) were hypothesized to respond to a common forcing. Oceanic zooplankton subsidies were hypothesized to provide this common forcing. Oceanic subsidies were observed to vary between two local PWS hatchery pink salmon populations sampled in 1994 (Kline and Willette, 2002). Oceanic subsidies in PWS were observed to shift concordantly from one year to the next in juvenile herring (*Clupea pallasii*), juvenile pollock (*Theragra chalcogramma*), and diapausing (over-wintering resting phase) *Neocalanus* copepods (Kline, 1999). The goal of this study was to assess whether there was a relationship between such inter-annual shifts in oceanic subsidies, measured using carbon stable isotope ratios,

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