Chapter 23
Effects of Hatchery Releases and Environmental Variation on Wild-stock Productivity: Consequences for Sea Ranching of Pink Salmon in Prince William Sound, Alaska

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Abstract

In Prince William Sound (PWS), Alaska, the total run of pink salmon, *Oncorhynchus gorbuscha*, for the years 1990–2001 averaged 31 million fish per year. Sea ranching from a system of large hatcheries produced over 75% of the run. The degree to which hatchery production actually may have replaced, rather than enhanced, wild stock production is controversial. To examine if hatchery releases have reduced wild stock productivity, we used a generalized linear version of the Ricker spawner-recruit model to analyse the relationship of wild stock productivity with the number of hatchery juveniles released and an array of other environmental variables. Three time periods of wild stock spawner-recruit data were analysed; the time periods were defined by the availability of the associated environmental data. For all time periods, indices of conditions in the marine environment best explained the variability in wild stock production in PWS. No significant effect of hatchery releases on productivity was observed for the 1980–1998 brood years (with the most comprehensive set of environmental variables) or for the 1960–1998 brood years (with the longest time series for spawner-recruit data and for some of the environmental variables). For the time period for the 1975–1998 brood, hatchery releases were identified as affecting wild stock productivity, but did not explain as much of the variability as did an index of density-independent marine survival conditions. Based on these results and a simulation model for the time period in which a detectable hatchery effect was identified, we estimated for return years 1990–2000 that the annual loss in wild production due to displacement by hatchery fish was 0–4.6 million pink salmon, and that the commensurate annual net gain in total returns was 20.6–25.3 million pink salmon. Thus, sea ranching of pink salmon in PWS has provided large net benefits to the salmon fisheries of the region.

Introduction

Sea ranching of salmon is the practice of artificial rearing and release of juvenile salmon to migrate to marine waters to grow and subsequently return as adults available for harvest (Heard 1996). This practice is widespread, occurring in both Pacific and Atlantic Oceans; in North America, Alaska is the geographic region that produces the largest number of salmon, from both wild systems and sea ranching (Mahnken *et al.* 1998). A large portion of the Alaska sea ranching production is from Prince William Sound (McNair 2001).

Prince William Sound (PWS) is a large, semi-enclosed body of water in South Central Alaska, adjacent to the northern Gulf of Alaska (Fig. 23.1). A system of four large hatcheries produce hundreds of millions of juvenile pink salmon with the purpose of increasing the total run of fish returning to PWS for exploitation by commercial, recreational, and subsistence fisheries. Sea ranching of pink salmon in PWS started in 1975. The numbers of juveniles released increased rapidly until the mid-1980s (Fig. 23.2); 500–600 million juvenile pink salmon have been released annually since then (Johnson *et al.* 2002). These releases have produced large numbers

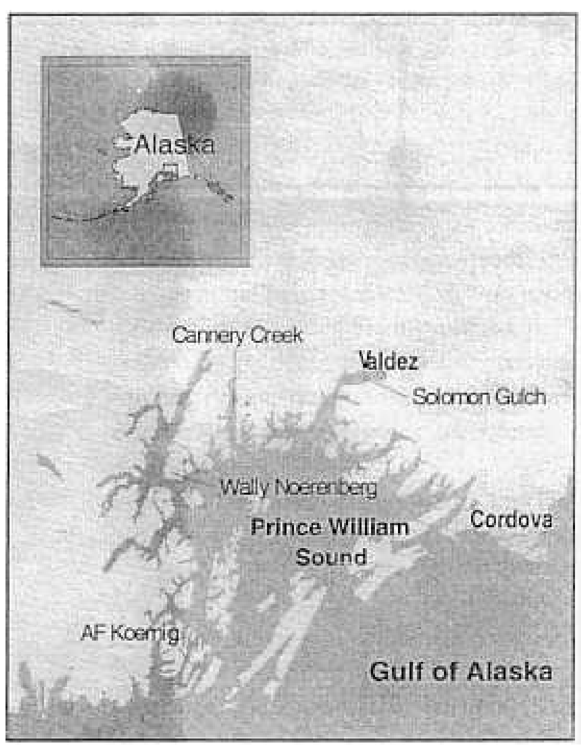

Fig. 23.1 Prince William Sound, Alaska, and the locations of principal towns (Cordova and Valdez) and of the four major pink salmon hatcheries in the region.

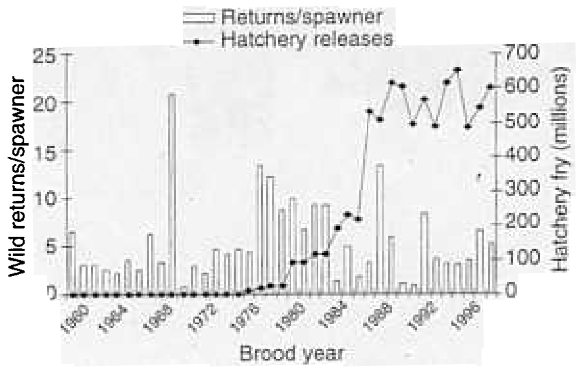

Fig. 23.2 Number of hatchery juveniles released and wild stock returns per spawner in Prince William Sound, Alaska, for brood years 1960–1998.

of returning adults (Fig. 23.3); hatcheries returns have averaged 23.7 million fish annually from 1990 to 2000 (Johnson *et al.* 2002), providing large benefits to the region (Pinkerton 1994, Smoker & Linley 1997).

Concurrent with increasing hatchery production, however, total abundance of wild pink salmon (Fig. 23.3) in PWS has declined from record high levels in 1979–1985, and productivity (returns per spawner) of wild pink salmon has generally declined (Fig. 23.2). Hilborn & Eggers (2000) argued that these declines were not coincidence, but were a result of hatchery production displacing wild stock salmon from the PWS ecosystem. They noted that pink salmon returns in recent years had increased not only in PWS, but also in other regions of Alaska where sea ranching was not an important component of the production. They used a population dynamics model to show an apparent depressive effect of hatchery fry releases on

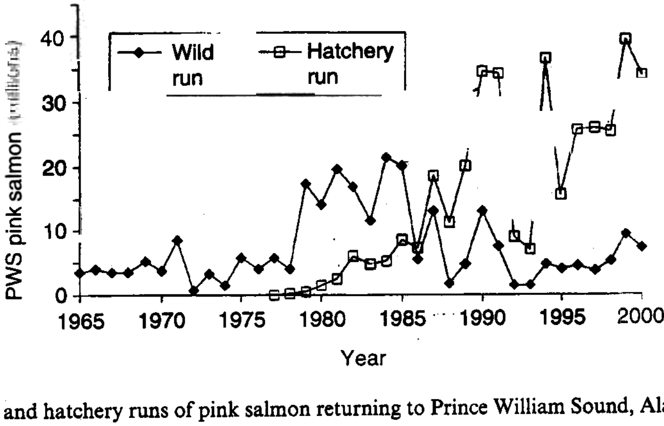

Fig. 23.3 Wild and hatchery runs of pink salmon returning to Prince William Sound, Alaska, 1965–2000.

wild stock productivity, and they used the model to simulate the production of wild fish in the absence of hatchery releases. Based on this model, they concluded "... there is little if any increase in total abundance due to the hatchery program in PWS. Our best estimate is 2 million fish per year."

In a dissenting view, we, and our colleague T. Joyce (Wertheimer *et al.* 2001) argued that comparisons of present and historical abundances of salmon in four pink salmon producing regions of Alaska showed that pink salmon returns had increased to a much greater extent in recent years in PWS relative to the other regions. We estimated that net hatchery benefit in added catch was 17.5–23.7 million pink salmon per year. We argued that Hilborn & Eggers (2000) population model was unrealistic, and may have overstated the effect of hatchery fry on wild stock productivity because no other environmental variables were considered in the statistical analysis. Increasing fry releases may have simply been concurrent with the response of wild stocks to a changing environment. To examine this possibility, our objective in this chapter was to evaluate the relationship of wild stock returns per spawner to a wide suite of environmental parameters or indexes, including the number of hatchery fry released.

Methods

Data sources

Productivity (returns per spawner) of wild pink salmon in PWS was evaluated in relation to the size of the spawning population and 11 measures or indexes of environmental conditions over time. The variables used are listed in Table 23.1; a short description of the parameters and the sources of the data are given below.

Wild stock spawners and returns by brood year The numbers of wild stock pink salmon harvested in PWS and spawning in PWS streams are estimated annually by the Alaska Department of Fish and Game (ADFG). Data were available for the 1960–1998 broods of pink salmon (Johnson *et al.* 2002). Because pink salmon have an obligatory 2-year life cycle (Heard 1991), returns (catch plus escapement) in a given year can be assigned entirely as the production from the brood year 2 years prior to the return year.

Winter air temperatures Winter air temperatures (WinterAir, Table 23.1) in Cordova, Alaska, were used as an index of physical environmental conditions affecting the freshwater incubation of wild stock embryos in PWS. Winter air temperatures have been shown to explain significant variability in the returns of pink salmon in Southeast Alaska (Jaenicke 1995). Monthly average air temperatures for Cordova were retrieved from climate statistics summarized by the US National Weather Service, Alaska Region (www.wrcc.dri.edu/summary/climsmak.html). Annual winter temperature indices were computed as the average of the monthly averages for November through March. Productivity of pink salmon of brood year

Table 23.1 Measures or indices of environmental variation examined for correlation with variation in the productivity of Prince William Sound (PWS) wild stock pink salmon. Years of data for each environmental variable are listed relative to the available spawner/recruit data for PWS wild pink salmon (1960–1998 brood years). Rationale and data sources for environmental variables are given in Methods.

Variable name	Description	Years available (relative to brood year)
WinterAir	PWS Winter Air Temperatures	1960–1998
SpringAir	PWS Spring Air Temperatures	1960–1998
Zooplankton	PWS Spring Zooplankton Index	1980–1998
Herring	PWS Herring Biomass	1980–1998
GulfSST	Summer sea surface temperatures (SST) in the Gulf of Alaska (GOA)	1960–1998
GulfWind	Summer wind stress in the GOA	1960–1996
PDO	Pacific Decadal Oscillation (PDO) winter average prior to juvenile ocean residency	1960–1998
PDO-1	PDO winter average, adult ocean residency	1960–1998
GulfPinks	Index to pink salmon abundance in the GOA	1960–1998
MSI	Marine survival index (MSI) for pink salmon originating from PWS	1975–1998
HatchFry	Releases of juvenile pink salmon from PWS hatcheries	1960–1998

y was examined for association with the winter temperature index for November of year y through the following March.

Spring air temperatures Spring air temperatures (SpringAir, Table 23.1) in Cordova, Alaska, were used as an index of sea surface temperature (SST) conditions affecting initial marine rearing of juvenile pink salmon in PWS. Air temperatures were used because no time series of SST observations for near shore habitats in PWS was available that extended back prior to the 1990s, and because air temperatures in coastal areas have been shown to be closely related to the surface layer temperatures of nearby estuaries (Bruce *et al.* 1977). Monthly average air temperatures for Cordova were retrieved from climate statistics summarized by the United States National Weather Service, Alaska Region (www.wrcc.dri.edu/summary/climsmak.html). Annual spring temperatures were computed as the average of the monthly averages for April, May, and June in a given year. Productivity of pink salmon of brood year y was examined for association with the spring temperature index in year $y+1$.

Spring zooplankton abundance Settled volumes of zooplankton sampled at a station near the Armin F. Koerning Hatchery in PWS were used as an index of food availability during initial marine rearing of juvenile pink salmon in PWS (Zooplankton, Table 23.1). This is the only sampling station in PWS with continuous annual sampling for zooplankton extending back prior to the 1990s. Samples were taken using a 0.5 m, 243-micron net towed vertically through the upper 20 m of the water column. All samples taken at the station in April and May of a given year were averaged for the annual index. Productivity of pink salmon of brood year y was examined for association with the zooplankton index in year $y+1$ (R.T. Cooney, University of Alaska Fairbanks, Fairbanks, Alaska, for calendar years 1981–1990 pers. comm.; D. Reggiani, Prince William Sound Aquaculture Association, Cordova, Alaska, for calendar years 1991–1999 pers. comm.).

Herring biomass Herring have been identified as potential competitors and important predators of juvenile pink salmon in PWS (Willette *et al.* 1999). The post-spawning biomass of age three and older herring in PWS, estimated using an age-structured population model (Johnson *et al.* 2002), was used as an index to herring abundance during initial marine rearing of juvenile pink salmon in PWS (Herring, Table 23.1). Productivity of pink salmon of brood year y was examined for association with the post-spawning biomass of herring in year $y+1$.

Gulf of Alaska summer SST Summer SST in an area of the Gulf of Alaska (GOA) adjacent to PWS were used as an index of temperature conditions affecting PWS pink salmon juveniles after they migrated from PWS into the GOA (GulfSST, Table 23.1). Temperature records for the area lying between 58° and 60° north latitude and 146° and 149° east longitude were extracted from the Comprehensive Ocean–Atmosphere Data Set (COADS; Mendelssohn & Roy 1996) for 1961–1997 (affecting brood years 1960–1996); and from the Global Telecommunication System Data Base (www.pfeg.noaa.gov) for 1998–1999 (affecting brood years 1997 and 1998). Annual summer temperature was computed as the average of the temperature records for July, August, and September in a given year. Productivity of pink salmon of brood year y was examined for association with the summer SST index in year $y+1$.

GOA summer wind stress Summer wind observations in an area of the GOA adjacent to PWS were used as another index of oceanographic conditions affecting PWS pink salmon juveniles after they migrated from PWS into the GOA (GulfWind, Table 23.1). Wind stress (wind speed cubed) records for the area lying between 58° and 60° north latitude and 146° and 149° east longitude were extracted from the Comprehensive Ocean–Atmosphere Data Set (COADS; Mendelssohn & Roy 1996) for 1961–1997 (affecting brood years 1960–1996). Annual summer wind stress was computed as the average of the wind stress observations for July, August, and September. Productivity of pink salmon of brood year y was examined for association with the wind-stress index in year $y+1$.

Pacific decadal oscillation (PDO) The PDO is an index of temperature changes in the North Pacific Ocean that has been related to basin-scale changes in the abundance and productivity of fishes in the North Pacific and GOA, including Pacific salmon (Mantua *et al.* 1997). Because the average PDO during winter is thought to affect growth and survival conditions influencing salmon populations in the subsequent spring and summer (Mantua *et al.* 1997), the annual PDO index was calculated as the average of the monthly averages for November of a given year, y, through March of the following year, $y+1$. Monthly PDO index values were extracted from data maintained by N.J. Mantua, University of Washington (ftp.atmos.washington.edu/mantua/pnw_impacts/INDICES/PDO.latest). This annual winter PDO index was examined for association with the productivity of pink salmon of brood year y as a measure of the effect of basin-scale temperature changes on juvenile PWS pink salmon.

PDO-1 Productivity of pink salmon of brood year $y - 1$ was also analysed for association with the annual winter PDO index to determine if basin-scale temperature conditions during the adult ocean life-history phase affect the returns per spawner of PWS wild stock pink salmon. We identified this use of the PDO as an explanatory variable as PDO-1 (Table 23.1).

GOA pink salmon abundance The average annual catch of pink salmon in regions of Alaska adjacent to the GOA was used as an index of pink salmon abundance in the GOA (GulfPinks, Table 23.1) to examine if density-dependent interactions in the GOA affected the productivity of PWS pink salmon. Catch data were compiled from Byerly *et al.* (1999) and from ADFG (2000).

Marine survival index (MSI) Average annual survival rates of hatchery juveniles released in PWS (Johnson *et al.* 2002) were used as an index of marine survival conditions (Table 23.1) affecting wild stock survival and productivity.

Hatchery releases The number of hatchery juveniles released into PWS in year $y + 1$, where y is the brood year, was used as the measure of the impact of sea ranching on wild stock productivity (HatchFry, Table 23.1). Release numbers were from Johnson *et al.* (2002).

Time periods of data

Returns per spawner data for PWS pink salmon were available for the 1960–1998 brood years; however, data were not available for this entire time series for all the environmental variables (Table 23.1). We analysed the relationship of wild stock productivity to the other parameters over three time series, which were defined by the availability of the data. The time series were: (1) 1980–1998 broods, for which all parameters were used, (2) 1975–1998 broods, for which the indexes for zooplankton and herring biomass were not available for the entire time series, and (3) 1960–1998 broods, for which the MSI was also not available for the entire time series. The first time series contained the broadest number of potential explanatory variables, but excluded the first five brood years of the hatchery program, when hatchery releases were low and wild stock returns were generally strong. The second time series incorporated the full extent of hatchery releases, but with the loss of some of the information on environmental variability. The third time series included a relatively extensive number of years when there was no hatchery influence on returns per spawner, and the variation in productivity of the pink salmon population was due entirely to other environmental factors. By analyzing each of the time series, we were able to examine the sensitivity of the relationship between wild stock productivity and a suite of indexes of environmental and ecological conditions without *a priori* judging the importance of a specific index relative to increased information on the variability of wild stock productivity over time.

Analytic approach

The association of wild stock productivity with environmental variability (including hatchery releases) was examined using simple correlation analysis and stepwise regression. The environmental variables were first standardized by subtracting the average of the variables for the time series. Thus, anomalies from the average of each variable were the values analysed. Wild stock productivity was defined as Ln (R_{y+2}/S_y), where R is the return, S is the spawning escapement, and y is the brood year.

We used the generalized linear version of the Ricker model (Quinn & Deriso 1999) to consider the suite of environmental variables we had compiled for each time series of data,

$$\mathrm{Ln}(R/S) = a + \beta S + \gamma_1 X_1 + \cdots + \gamma_n X_n$$

where a is the natural log of the Ricker productivity parameter α, β is the Ricker density-dependence parameter, and γ is the coefficient for the environmental variable X. We used forward–backward stepwise regression (Minitab 2000) to identify the environmental variables that best explained the variability in wild stock productivity over time. A variable could enter the regression model at each step only if its coefficient was significantly different from zero at $p < 0.1$ (forward step); a variable already in the regression model would be dropped if its coefficient is not significantly different from zero at $p < 0.1$ after the addition of a new variable (backward step). The exception was annual number of spawners, S, which was kept in the regression model regardless of the p value for β.

Because wind stress data were not available for the 1997 and 1998 brood years (Table 23.1), the regression analysis of the three time series was initially run from the beginning of the series through the 1996 brood. In all cases, wind stress did not enter the regression models. The regression analysis for each time series was then run through the 1998 brood year, without including the wind stress variable. Correlations reported in the results are through 1996 brood for wind stress, and through the 1998 brood for all other environmental variables.

Testing for density-dependence of MSI

The effect of hatchery releases on wild stock productivity could be masked by the MSI. Larger hatchery releases could cause density-dependent reduction in both hatchery and wild survival in the marine environment. We tested whether MSI was density-dependent by examining the correlation of hatchery survivals with the magnitude of hatchery releases. We also tested whether MSI masked the *hatchery* effect by recalculating the stepwise regression model for 1980–1998 broods without the MSI data to determine if hatchery releases would be identified as significant in the absence of the MSI variable.

Simulation of hatchery effect

Hilborn & Eggers (2000) used a Ricker model with an auxiliary variable for hatchery releases to show a statistical association of releases with variation in wild stock productivity, and to simulate wild stock runs in PWS in recent years in the absence of hatchery releases. They first fit the data for the 1977–1985 brood years to the model:

$$R_{y+2} = \alpha S_y e^{-S\beta} e^{\gamma(fry_{y+1} - \overline{fry})} \tag{23.1}$$

where fry is the number of hatchery juveniles released in year $y+1$, with y the brood year, and $\overline{fry}$ is the average number of juveniles released over the time series. Parameters from the fit model were then used to estimate recruitment in the absence of hatchery fry, but with the annual hatchery fry release in each year set to zero:

$$R_{y+2} = \alpha S_y e^{-S\beta} e^{\gamma(-\overline{fry})}. \tag{23.2}$$

The auxiliary variable thus becomes a constant, increasing the wild stock productivity parameter. In their simulations, the recruitment in a given year from Equation (23.2) was adjusted by multiplying it by the ratio of the observed recruitment divided by the predicted recruitment from Equation (23.1) (the exponent of the log residual). This adjustment was done as an estimate of the "environmentally-induced deviation in that year" (Hilborn & Eggers 2000), resulting in simulated annual returns that mirrored the pattern of strong and weak returns of pink salmon to PWS over time.

We used the same type of model to simulate wild stock production for the time series (1975–1998 broods) during which hatchery releases were indicated to be a significant variable in the linearized Ricker model. However, we included in the simulation model the MSI, the variable that explained the greatest amount of variability in the spawner/recruit relationship:

$$R_{y+2} = \alpha S_y e^{-S\beta} e^{\gamma_{MSI}(MSI_y - \overline{MSI})} e^{\gamma_{fry}(fry_{y+1} - \overline{fry})}.$$

Parameters were estimated for this model from the data. The model with the fit parameters was then used to simulate wild stock production in the absence of hatchery fry by again setting to zero the annual hatchery fry release in each year:

$$\hat{R}_{y+2} = \alpha S_y e^{-S\beta} e^{\gamma_{MSI}(MSI_y - \overline{MSI})} e^{\gamma_{fry}(-\overline{fry})}. \tag{23.3}$$

For the simulation, observed values were used for S and MSI.

Results

1980–1998 brood years

Data were available for all 11 environmental variables for the 1980–1998 broods (Table 23.1). Releases of hatchery juveniles during this time period of pink salmon were 91–230 million for the first seven years, then increased to around 500–600 million annually (Fig. 23.2). Variables relating to conditions in the marine environment were the most highly correlated with wild stock productivity (Table 23.2). The MSI and GulfSST had r values relative to wild stock productivity of 0.78 and 0.69, respectively, and were significant at $p = 0.001$. SpringAir had an r of 0.42, and was significant at $p = 0.077$. HatchFry was negatively correlated with wild stock productivity, with $r = -0.24$, but the correlation was not significantly different from zero ($p = 0.320$).

When the generalized linear Ricker model was fit to the environmental data available for this time period, indexes of ecological conditions in the marine environment were identified as statistically significant in explaining variability in wild stock productivity (Table 23.3). The MSI was the first environmental variable to enter the regression model, and explained 62% of the variation in wild stock productivity. Also significant were the Gulf SST and Zooplankton variables. When the three environmental variables were included in the spawner/recruit model, the R^2 for the full model was 80% (Table 23.3). No significant effect of the number of hatchery juveniles released (HatchFry) was detected in the model for this time period.

The cross-correlation matrix for the explanatory variables for this time series is shown in Table 23.4. Some of the variables were significantly correlated with each other; correlation between variables affects which variables do and do not enter or remain in the stepwise regression model. Of interest in this regard was the association between HatchFry and the other variables, particularly MSI; substantial correlation

Table 23.2 Correlation of environmental variables and numbers of spawners with the productivity of Prince William Sound wild pink salmon over three time series of data. Productivity was defined as Ln(R/S), where S is the wild stock spawning escapement for a brood year, and R is the wild stock return (catch and escapement) for that brood year. Environmental variable names are described in Table 23.1. Listed are the correlation coefficient r, and the probability (p) that r is significantly different from zero. Numbers in bold were significant at $p < 0.1$.

Variable	Time period 1: 1980–1998 Broods		Time period 2: 1975–1998 Broods		Time period 3: 1960–1998 Broods	
		(p)		(p)		(p)
Spawners	−0.172	(0.295)	−0.207	(0.331)	−0.172	(0.295)
WinterAir	−0.063	(0.797)	−0.125	(0.561)	0.204	(0.213)
SpringAir	**0.416**	**(0.077)**	0.308	(0.144)	**0.333**	**(0.039)**
Zooplankton	0.384	(0.104)	NA	NA	NA	NA
Herring	−0.029	(0.905)	NA	NA	NA	NA
GulfSST	**0.685**	**(0.001)**	**0.499**	**(0.013)**	**0.535**	**(<0.001)**
GulfWind[a]	−0.365	(0.150)	−0.348	(0.113)	−0.214	(0.203)
PDO	0.109	(0.658)	0.028	(0.898)	**0.287**	**(0.085)**
PDO-1	−0.105	(0.668)	−0.119	(0.580)	0.065	(0.702)
GulfPinks	0.109	(0.656)	−0.061	(0.777)	0.104	(0.540)
MSI	**0.780**	**(<0.001)**	**0.611**	**(0.002)**	NA	NA
HatchFry	−0.241	(0.320)	**−0.377**	**(0.069)**	−0.140	(0.408)

[a] Correlation for wind stress is through the 1996 brood for each time series.

Table 23.3 Results of forward–backward stepwise regression fit of the generalized linear version of the Ricker model to spawner/recruit data and associated environmental variables for Prince William Sound pink salmon, brood years 1980–1998. The regression coefficients, the associated probability (p) that a coefficient is significantly different from zero, and adjusted R^2 (the coefficient of determination adjusted for degrees of freedom) are shown for each step of the regression. Spawners were always included in the model, other variables could enter or remain in the model if $p < 0.1$. The model was fit first considering all 11 environmental variables listed in Table 23.1; then the model was fit with MSI excluded from the analysis.

Variable	Step 1	Step 2	Step 3	Step 4
MSI Included				
Constant (Ln(α))	1.78 (0.001)	1.82 (<0.001)	1.67 (<0.001)	1.87 (<0.001)
Spawners	2.2*E^{-7} (0.379)	−2.3*E^{-7} (0.138)	−1.4*E^{-7} (0.256)	−2.7*E^{-7} (0.057)
MSI		32.9 (<0.001)	26.2 (<0.001)	24.1 (<0.001)
GulfSST			0.47 (0.004)	0.40 (0.010)
Zooplankton				1.90 (0.078)
R^2(adjusted)	0.0	61.8	76.6	80.1
MSI Excluded				
Constant (Ln(α))	1.78 (0.001)	1.56 (<0.001)	1.90 (<0.001)	
Spawners	2.2*E^{-7} (0.379)	−0.8*E^{-7} (0.379)	−2.9*E^{-7} (0.379)	
GulfSST	0.75 (0.002)	0.75 (0.002)	0.60 (0.010)	
Zooplankton			0.21 (0.072)	
R^2(adjusted)		40.9	49.6	

could indicate density-dependence of MSI with hatchery juveniles released, which could mask detecting a direct effect on wild stock productivity. HatchFry was negatively correlated with most (10 of 12) of the other variables, with significant ($p < 0.1$) negative correlation with Spawners, WinterAir, PDO, and PDO-1, and significant positive correlation with GulfPink (Table 23.4). The correlation of MSI and HatchFry for the 1980–1998 broods was negative, but was not statistically significant.

To test if density-dependence of MSI with HatchFry was masking the effect of HatchFry on wild stock productivity, we reran the regression model with MSI excluded from the environmental variables considered. In this case, only GulfSST and Zooplankton were identified as statistically significant in explaining variation in wild stock productivity, and no significant effect was indicated for HatchFry (Table 23.3). We also examined the correlation of MSI with hatchery releases for the entire suite of hatchery releases (1975–1998 broods). The correlation of MSI with hatchery releases was again negative but small, and was again not significantly different from zero ($r = -0.12; p > 0.5$; Fig. 23.4).

1975–1998 brood years

Data were available for 9 of the 11 environmental variables for the 1975–1998 broods; zooplankton data and herring biomass data were not available for the entire

Table 23.4 Cross-correlation matrix for environmental variables and numbers of pink salmon spawners that were considered as explanatory variables affecting the productivity of Prince William Sound wild pink salmon, brood years 1980–1998. Environmental variable names are described in Table 23.1. The correlation coefficient r is shown for each pairwise comparison. A number in bold indicates r is significantly different from 0 at $p < 0.1$ (unadjusted for multiple comparisons).

	Spawners	WinterAir	SpringAir	Zoop.	Herring	GulfSST	GulfWind	PDO	PDO-1	GulfPink	MSI	HatchFry
Spawners												
WinterAir	0.123	—										
SpringAir	**−0.699*****	0.143										
Zoop.	**0.451***	−0.350	−0.385									
Herring	0.342	0.099	−0.272	0.344	—							
GulfSST	−0.205	0.103	**0.619*****	0.223	−0.135							
GulfWind	**−0.743*****	−0.055	**0.685*****	**0.456***	0.248	−0.254	—					
PDO	0.229	**0.790*****	−0.113	−0.087	0.079	0.156	0.100					
PDO-1	0.384	0.237	−0.237	0.032	−0.061	0.072	0.126	0.345	—			
GulfPink	−0.296	0.178	**0.403***	−0.231	−0.218	0.271	−0.060	0.017	**−0.509****	—		
MSI	0.017	0.094	0.096	0.305	0.015	0.376	−0.144	0.321	0.132	−0.043	—	
HatchFry	**−0.556****	**−0.404***	0.366	−0.383	−0.281	−0.161	−0.200	**−0.537****	**−0.699*****	**0.514****	−0.343	

Bolded numbers with asterisks indicate significance level: * $0.05 < p < 0.1$; ** $0.01 < p \leq 0.05$; and *** $p < 0.01$.

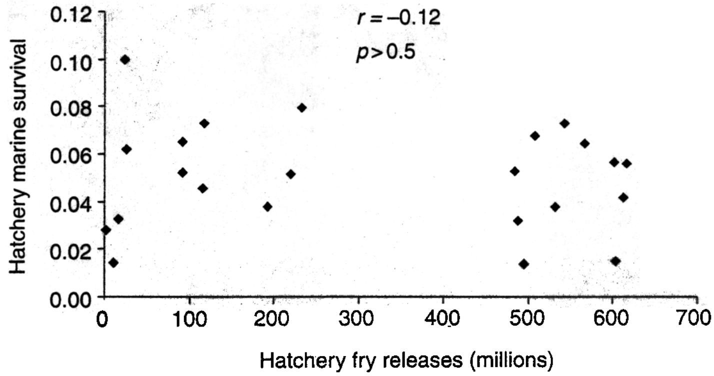

Fig. 23.4 Correlation of annual hatchery marine survival rates with annual number of hatchery pink salmon juveniles released into Prince William Sound, Alaska, for brood years 1975–1998.

period (Table 23.1). Releases of hatchery juveniles during this time period of pink salmon included the first 5 years of the hatchery programs. During these years, hatchery releases were small, ranging from 1 to 25 million, and wild stock productivity was generally high (Fig. 23.2). Variables relating to conditions in the marine environment were again the most highly correlated with wild stock productivity: MSI and GulfSST had r values, relative to wild stock productivity, of 0.61 and 0.50, respectively, significantly different from zero at $p = 0.002$ and $p = 0.013$, respectively (Table 23.2). For this time period, the negative correlation of HatchFry with wild stock productivity was stronger than for the 1980–1998 time period ($r = -0.377$), and the correlation was significantly different from zero at $p = 0.069$.

When the generalized linear Ricker model was fit to the environmental data available for this time period, five environmental variables were identified as significant in the full model (Table 23.5). The MSI was again the first environmental variable to enter the regression model, and explained 42% of the variation in wild stock productivity for this time period. HatchFry was the second environmental variable to enter the model, indicating a significant effect of the number of hatchery juveniles released in this period. Also significant were the GulfSST and PDO-1, measures of temperature conditions presumably affecting the juvenile and adult ocean-residency stages, respectively, of PWS pink salmon; and WinterAir, the measure of temperature conditions presumably affecting the embryonic stage of PWS pink salmon. When these five environmental variables were included in the spawner/recruit model, the R^2 for the full model was 79% (Table 23.5).

1960–1998 brood years

Data were available for 8 of the 11 environmental variables for the 1975–1998 broods; hatchery survival (MSI), zooplankton, and herring biomass data were not available for the whole period (Table 23.1). Releases of hatchery juveniles during this

Table 23.5 Results of forward–backward stepwise regression fit of the generalized linear version of the Ricker model to spawner/recruit data and associated environmental variables for Prince William Sound pink salmon, brood years 1975–1998. The regression coefficients, the associated probability (p) that a coefficient is significantly different from zero, and adjusted R^2 (the coefficient of determination adjusted for degrees of freedom) are shown for each step of the regression. Spawners were always included in the model, other variables could enter or remain in the model if $p < 0.1$.

Variable	Step 1	Step 2	Step 3	Step 4	Step 5	Step 6
Constant (Ln(α))	1.91	2.11	2.31	2.18	1.99	1.91
	(<0.001)	(<0.001)	(<0.001)	(<0.001)	(<0.001)	(<0.001)
Spawners	-2.3^*E^{-7}	-3.5^*E^{-7}	-4.8^*E^{-7}	-4.0^*E^{-7}	-2.8^*E^{-7}	-2.4^*E^{-7}
	(0.331)	(0.056)	(0.006)	(0.015)	(0.061)	(0.065)
MSI		23.7	22.2	22.4	20.8	19.3
		(<0.001)	(<0.001)	(<0.001)	(<0.001)	(<0.001)
HatchFry			-1.3^*E^{-9}	-1.7^*E^{-9}	-1.5^*E^{-9}	-1.6^*E^{-9}
			(0.010)	(0.001)	(0.002)	(<0.001)
PDO-1				−0.29	−0.30	−0.31
				(0.042)	(0.019)	(0.007)
GulfSST					0.33	0.44
					(0.024)	(0.002)
WinterAir						−0.06
						(0.014)
R^2 (adjusted)	0.0	42.	57.	63.8	71.5	79.0

time period included 15 years (1960–1974 brood years), when no hatchery juveniles were released into PWS (Fig. 23.2). Included in this period are the highest (20.8) and lowest (0.7) returns per spawner on record, which occurred in consecutive brood years, 1969–1970 (Fig. 23.2). Variables relating to conditions in the marine environment were again the most highly correlated with wild stock productivity (Table 23.2). In the absence of the MSI, GulfSST was the most highly correlated with wild stock productivity, $r = 0.54$ ($p < 0.001$). SpringAir and the PDO had r values of 0.333 and 0.287, significant at $p = 0.039$ and $p = 0.085$, respectively. HatchFry was again negatively correlated with wild stock productivity, $r = -0.14$, but the correlation was not significantly different from zero ($p = 0.408$) for this time period.

When the generalized linear Ricker model was fit to the environmental data available for this time period, only one environmental variable, GulfSST, was identified as statistically significant in explaining wild stock productivity (Table 23.6). No significant effect of the number of hatchery juveniles released (HatchFry) was detected in the model for this time period. Only 27% of the variability in wild stock returns per spawner was explained by the environmental data (Table 23.6).

Simulation of hatchery effect, 1975–1998 broods

For the 1975–1998 brood time period, in which hatchery releases were identified as a significant factor, the simulation model described in Methods was used to estimate

Table 23.6 Results of forward–backward stepwise regression fit of the generalized linear version of the Ricker model to spawner/recruit data and associated environmental variables for Prince William Sound pink salmon, brood years 1960–1998. The regression coefficients, the associated probability (p) that a coefficient is significantly different from zero, and adjusted R^2 (the coefficient of determination adjusted for degrees of freedom) are shown for each step of the regression. Spawners were always included in the model, other variables could enter or remain in the model if $p < 0.1$.

Variable	Step	Step 2
Constant (Ln(α))	1.72 (<0.001)	1.70 (<0.001)
Spawners	−2.0×E^{-7} (0.295)	−1.8×E^{-7} (0.268)
Gulf SST		0.49 (<0.001)
R^2 (adjusted)	0.3	27.2

the magnitude of the impact of hatchery releases. Equation (23.3) in Methods was fit to the data, with the result

$$\hat{R}_{y+2} = 10.1 \times S_y \times e^{(-4.8\times E^{-7})S_y} \times e^{22.2(MSI_y - 0.049)} \times e^{(-1.3\times E^{-9})(-3.26\times E^{8})}$$

which simplifies to:

$$\hat{R}_{y+2} = 15.3 \times S_y \times e^{(-4.8\times E^{-7})S_y} \times e^{22.2(MSI_y - 0.049)}.$$

Using observed values for S_y and MSI_y, this equation was used to simulate returns of wild stock for brood years 1975–1998 (Fig. 23.5). The simulated returns estimated by the model including MSI were higher than actual returns. However, these simulated returns were not nearly as high as returns estimated by Hilborn & Eggers (2000)

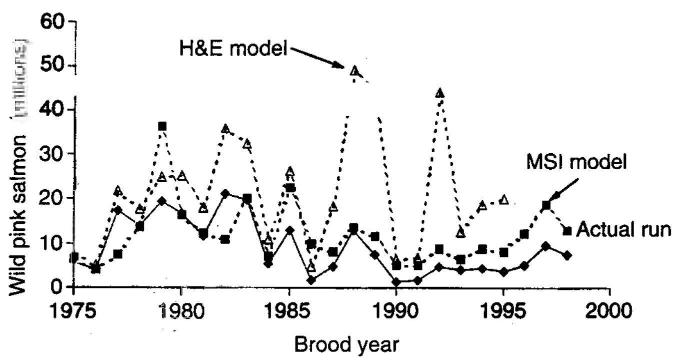

Fig. 23.5 Actual returns of wild stock pink salmon to Prince William Sound, Alaska, for brood years 1975–1998, and simulated returns using Ricker spawner/recruit relationships with an auxiliary variable for hatchery releases to estimate the wild stock return in the absence of hatchery fish. The H&E model uses hatchery releases as the only auxiliary variable for brood years 1977–1995, with annual returns adjusted by the annual residual (difference between predicted and observed) so that annual returns mirror the pattern of strong and weak returns of pink salmon to PWS over time (Hilborn & Eggers 2000). The MSI model includes the marine survival index as well as hatchery releases as auxiliary variables, for brood years 1975–1998.

(Fig. 23.5). The annual average yield (total return – spawning escapement) in recent years (1990–2000 return years) for the simulated returns (with MSI in the model) was 9.08 million pink salmon.

Discussion

For all three time periods of spawner/recruit data analysed, indices of conditions in the marine environment, rather than number of hatchery juveniles released, best explained the variability in wild stock productivity in PWS. No significant hatchery effect was observed for the1980–1998 brood years, with the most comprehensive set of environmental variables, or for the 1960–1998 brood years, with the longest time series of spawner/recruit data and measures of environmental change. For the time period encompassing the 1975–1998 brood, hatchery releases were identified as significantly affecting wild stock productivity, but did not explain as much of the variability as did the MSI. When MSI was included in a stock/recruit simulation model used to estimate the degree of hatchery impact indicated for this time period, predicted returns of pink salmon in the absence of hatchery fish were substantially less than those predicted considering only hatchery fry releases as an auxiliary variable in a stock/recruit simulation model (Fig. 23.5). These results strongly support the assertion of Wertheimer *et al.* (2001) that Hilborn & Eggers (2000) overestimated the impact of hatchery releases on wild stock productivity because increasing fry releases were concurrent with the response of wild stocks to a changing environment.

We did not consider the effect of measurement errors and uncertainty in our analyses. Measurement error in PWS escapement estimates is large for both observer counts and spawner stream-life (Bue *et al.* 1998). Total catch is measured with relatively little error, but the precision of the allocation of catch between hatchery and wild salmon in PWS is unknown for some years. Since 1987, tagging programs have been in place to estimate hatchery contributions to the catch (Peltz & Geiger 1990, Joyce & Evans 2002), but prior to 1987 allocation of catch was based on relative magnitude of returns to hatchery terminal areas and wild stock escapement, with unknown estimation error. The other biophysical parameters also have some degree of measurement error. Accounting for this measurement error was outside the scope of this chapter. Our objective was to examine the effects of relationship of wild stock productivity to a wide suite of environmental parameters or indexes, including the number of hatchery fry released, using a modeling approach similar to the one used by Hilborn & Eggers (2000) to attribute declines in wild stock productivity to the magnitude of hatchery releases. These authors also did not incorporate measurement error in their stock/recruit analysis, or attempt to estimate uncertainty of their model output. In our analyses, estimates of the relationship of wild stock productivity to the measures of ecological and environmental changes were sensitive to a confounded effect of the length of the time period evaluated and the variables for which data were available for a particular time period. Our use of a range of estimates of the degree of impact of hatchery releases does acknowledge substantial uncertainty in the outcomes of our analytical approach.

During the time periods for which it was available, MSI was the variable that best explained the variability in wild stock production. This variable, the annual survival rate of hatchery juveniles released in PWS, represents an integration of the effects of the various factors affecting pink salmon survival across their marine life history. The data indicate that these processes have been largely density-independent for PWS pink salmon; correlation of MSI with the magnitude of hatchery releases was small and statistically not significant.

The three overlapping time periods of data that we analysed spanned years during which two distinct climatic regime shifts have been identified in the North Pacific Ocean, occurring in 1977 and 1989 (Hare & Mantua 2000). Changes in climatic conditions can have large effects on the productivity of salmon populations (Adkison *et al.* 1996). We incorporated indices of environmental change to determine what factors were most associated with variations in productivity of PWS pink salmon. The measure of basin-scale effects we examined, the winter PDO index, has been shown to be associated with trends in Alaska salmon production (Mantua *et al.* 1997). However, Mueter *et al.* (2002) found that variability in survival indices of regional groups of pink salmon stocks was better explained by regional temperatures than by basin-scale variation in temperature indices. We also found that temperature in an area of the GOA adjacent to PWS (GulfSST) was more important in explaining the variation in productivity of PWS wild stock pink salmon than was the PDO. Only over the longest time interval, 1960–1998 broods, did the PDO have any significant correlation with returns per spawner in PWS. Also, Pyper *et al.* (2001) have shown that production trends have been much more correlated within regions and between adjacent regions than across all regions of the Northeast Pacific. Fluctuations in catch and productivity of PWS wild pink salmon have not been synchronous with fluctuations in other regions of Alaska (Hilborn & Eggers 2000, 2001, Wertheimer *et al.* 2001). Our results, and the findings of Pyper *et al.* (2001) and Mueter *et al.* (2002), suggest that this lack of synchrony has been due to regional-level environmental effects, rather than the scale of hatchery production (as proposed by Hilborn & Eggers 2000, 2001).

Although analyses of two of the three time series of spawner-recruit data did not identify a significant hatchery effect, we do not dismiss the possibility of reduced wild stock productivity due to large hatchery releases. Correlations between hatchery releases and wild stock productivity were uniformly negative, and the analyses of the 1975–1998 brood data did indicate a significant impact of hatchery releases on wild stock productivity. This could have been an artifact of lack of key environmental information (e.g. zooplankton abundance data) during years such as for the 1978 and 1979 broods, when hatchery releases were very small and wild stock productivity was high (Fig. 23.2). However, rather than choosing a particular time period as the *best* representation of the processes affecting PWS wild stock pink salmon, we used the results from the analyses of the three time periods to define a range of impacts in recent years on the wild stock return in PWS, and to assess the net gain from sea ranching to the total return of pink salmon to PWS.

We place the range of wild losses due to displacement from hatchery releases at 0–4.62 million pink salmon annually, and the net benefits from sea ranching operations at 20.6–25.3 million annually, for the 1990–2000 return years (Fig. 23.6). The average annual return of pink salmon to PWS for return years 1990–2000 (brood years 1988–1998) was 31.0 million (Johnson *et al.* 2002), of which 25.3 million were from hatchery releases and 5.7 million were from wild stocks. We set the impacts based on the significance of the hatchery releases in the spawner/recruit analyses, and on the simulation of the wild stock production in the absence of hatchery fish for the time period for which a significant effect was detected. Thus, the results for time period 1 and time period 3 indicated no significant impact on wild stocks, and we placed the minimum loss to wild stocks from displacement by hatchery production at zero. For time period 2, the simulation model indicated that wild stock yield could have been 9.08 million annually for these years. Actual wild stock yield for these years averaged 4.47 million pink salmon annually (Johnson *et al.* 2002), giving an estimated annual yield loss of 4.62 million wild pink salmon with this simulation.

Thus, we conclude that sea ranching in PWS has provided large net benefits to the region. Similarly, Wertheimer *et al.* (2001) estimated net benefits of 17.5 million to 23.7 million pink salmon annually, based on comparisons of present and historical catch levels for four pink salmon producing regions of Alaska. In contrast, Hilborn & Eggers (2000) estimated a net gain of only 2 million pink salmon annually from sea ranching in PWS. We have shown that Hilborn & Eggers's estimates of the degree of displacement impacts on wild stocks from hatchery are biased far too high. However, they have raised valid concerns about the degree to which sea ranching may negatively impact wild stock productivity in PWS. Indeed, our analyses identified a range

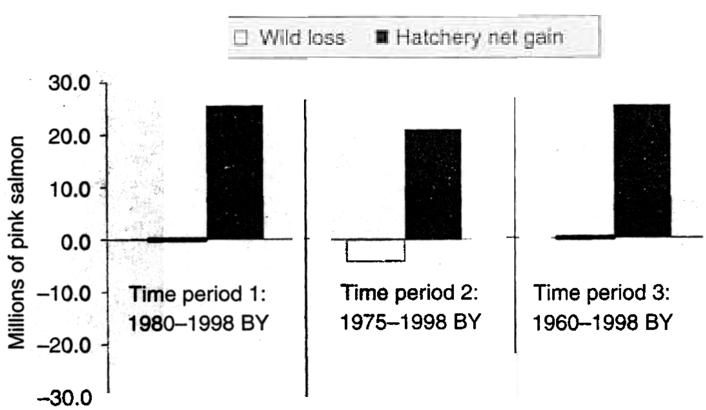

Fig. 23.6 Estimated annual loss in wild stock production, and annual net gain from hatchery production for return years 1990–2000, resulting from hatchery releases of pink salmon in Prince William Sound, Alaska, over three time periods.

of impacts, from zero to a 50% loss in yield from wild stocks for some years. The high end of this range is certainly not a trivial effect, but it must be considered in the context of the large benefits provided by sea ranching in this region.

The Alaska hatchery program is guided by policies, statutes, and regulations intended to ensure that sea ranching programs for salmon achieve their objectives of enhancing fisheries while protecting and maintaining the productive potential of wild stocks (Heard, 2003). As Blakenship & Leber (1995) have espoused, it is critically important to evaluate the success of sea ranching programs in relation to defined goals. We need to continue both retrospective analyses and empirical research examining the interaction of hatchery and wild fish in PWS, to better understand and quantify the impacts of hatcheries, and to refine hatchery strategies and regulation to minimize impacts when and where necessary. Our assessment is that the pink salmon program in PWS has been successful: wild stocks are highly productive in PWS, in relation to their historical performance and relative to the productivity of stocks in other regions of Alaska (Wertheimer *et al.* 2001), and the hatchery programs have increased total runs to the region by 3–6 times what we would expect under current environmental conditions.

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References

ADFG (2000) Recent years harvest statistics. http://www.cf.adfg.state.ak.us/cf_home.htm.

Adkison, M.D., Peterman, R.M., Lapointe, M.L., Gillis, D.M. & Korman, J. (1996) Alternative models of climatic effects on sockeye salmon, *Oncorhynchu nerka*, productivity in Bristol Bay, Alaska, and the Fraser River, British Columbia. *Fisheries Oceanography*, **5**, 137–152.

Blakenship, H.L. & Leber, K.M. (1995) A responsible approach to marine stock enhancement. *Am. Fish. Soc. Symp.*, **15**, 167–175.

Bruce, H.E., McLain, D.R. & Wing, B.L. (1977) *Annual physical and chemical oceanographic cycles of Auke Bay, Southeastern Alaska.* NOAA Technical Report NMFS SSRF-712.

Bue, B.G., Fried, S.M., Sharr, S., Sharp, D.G., Wilcock, J.A. & Geiger, H.J. (1998) Estimating salmon escapement using area-under-the-curve, aerial observer efficiency, and stream-life estimates: the Prince William Sound example. *North American Anadromous Fish Commission Bulletin*, **1**, 240–250.

Byerly, M., Brooks, B., Simonson, B., Savikko, H. & Gieger, H. (1999) *Alaska commercial salmon catches, 1878–1997.* Regional information Report No. 5J99-05. Alaska Department of Fish and Game, Division of Commercial Fisheries. Juneau, AK 99801.

Hare, S.R. & Mantua, N. (2000) Empirical evidence for North Pacific [climatic] regime shifts in 1977 and 1989. *Prog. Ocanogr.*, **47**, 103–145.

Heard, W.R. (1991) Life history of pink salmon. In: *Pacific Salmon Life Histories* (eds C. Groot & L. Margolis), pp. 119–230. University British Columbia Press, Vancouver.

Heard, W.R. (1996) Ocean ranching: an assessment. In: *Principles of Salmonid Culture* (eds W. Pennell & B.A. Barton), pp. 833–869. Elsevier, New York.

Heard, W.R. (2003) Alaska salmon enhancement: a successful program for hatchery and wild stocks. In: *Ecology of Aquaculture Species and Enhancement of Stocks* (eds Y. Nakamura, J.P. McVey, K. Leber, C. Neidig, S. Fox & K. Churchill), pp. 149–170. Proceedings of the thirtieth US–Japan Meeting on Aquaculture. Sarasota, Florida, 3–4 December. UJNR Technical Report No. 30. Sarasota, FL: Mote Marine Laboratory.

Hilborn, R. & Eggers, D. (2000) A review of the hatchery programs for pink salmon in Prince William Sound and Kodiak Island, Alaska. *Trans. Am. Fish. Soc.*, **129**, 333–350.

Hilborn, R. & Eggers, D. (2001) A review of the hatchery programs for pink salmon in Prince William Sound and Kodiak Island, Alaska: response to comments. *Trans. Am. Fish. Soc.*, **130**, 720–724.

Jaenicke, M.J. (1995) *Variability of pink salmon returns to Southeast Alaska related to air temperature and precipitation.* M.S. Thesis, Juneau Center Fisheries and Ocean Sciences, University of Alaska.

Johnson, J., Sharp, D., Joyce, T. & Moffitt, S. (2002) *Prince William Sound management area 2000 annual finfish management report.* Alaska Department Fish Game Regional Information Report 2A02-02.

Joyce, T. & Evans, D. (2002) Using thermally-marked otoliths to aid the management of Prince William Sound pink salmon. *North Pacific Anadromous Fish Commission Technical Report*, **3**, 35–36.

Mahnken, C., Ruggerone, G., Waknitz, W. & Flagg, T. (1998) A historical perspective on salmonid production from Pacific Rim hatcheries. *North Pacific Anadromous Fish Commission Bulletin*, **1**, 38–53.

Mantua, N.J., Hare, S.R., Zhang, Y., Wallace, J.M. & Francis, R.C. (1997) A Pacific interdecadal climate oscillation with impacts on salmon production. *Journal Climatol.*, **8**, 241–253.

McNair, M. (2001) *Alaska salmon enhancement program 2000 annual report.* Alaska Dept. Fish and Game, Regional Inf. Rept. 5J01-01. Juneau, AK. 99802.

Mendelssohn, R. & Roy, C. (1996) *Comprehensive ocean dataset extraction's user guide.* U.S. Department of Commerce, NOAA Technical Memorandum NMFS-SWFSC-228.

Minitab (2000) *Minitab user's guide 2: data analysis and quality tools.* Minitab statistical software, release 13.

Mueter, F.J., Peterman, R.M. & Pyper, B.J. (2002) Opposite effects of ocean temperature on survival rates of 120 stocks of Pacific salmon (*Oncorhynchus* spp.) in northern and southern areas. *Can. J. Fish. Aquat. Sci.*, **59**, 456–463.

Peltz, L. & Geiger, H. (1990) *A tagging study of the effect of hatcheries on the 1987 pink salmon fishery in Prince William Sound, Alaska.* Alaska Department Fish and Game, Commercial Fisheries Division, Fishery Research Bulletin 90-2: 1–17.

Pinkerton, E. (1994) Economic and management benefits from the coordination of capture and culture fisheries: the case of Prince William Sound pink salmon. *North Am. J. Fish. Manage.*, **14**, 262–277.

Pyper, B.J., Mueter, F.J., Peterman, R.M., Blackbourn, D.J. & Wood, C.C. (2001) Spatial covariation in survival rates of Northeast Pacific pink salmon (*Oncorhynchus gorbuscha*). *Can. J. Fish. Aquat. Sci.*, **58**, 1501–1515.

Quinn, T.J. & Deriso, R.B. (1999) *Quantitative Fish Dynamics.* Oxford University Press.

Smoker, W.W. & Linley, T.J. (1997) Are Prince William Sound salmon hatcheries a fool's bargain? *Alsk. Fish. Res. Bull.*, **43**(1), 75–78.

Wertheimer A.C., Smoker, W.W., Joyce, T.L. & Heard, W.R. (2001) Hatchery pink salmon in Prince William Sound: enhancement or replacement? *Trans. Am. Fish. Soc.*, **130**, 712–720.

Willette, T.M., Cooney, R.T. & Hyer, K. (1999) Predator foraging mode shifts affecting mortality of juvenile fishes during the subarctic spring bloom. *Can. J. Fish. Aquat. Sci.*, **56**, 364–376.

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