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Forecasting Pink Salmon Harvest in Southeast Alaska from Juvenile Salmon Abundance and Associated Environmental Parameters: 2008 Returns and 2009 Forecast

by

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Abstract

The Southeast Alaska Coastal Monitoring (SECM) project has been sampling juvenile salmon (*Oncorhynchus* spp.) and associated environmental parameters in northern Southeast Alaska (SEAK) since 1997 to better understand effects of environmental change on salmon production. A pragmatic application of this effort is to forecast the abundance of adult salmon returns in subsequent years. Since 2004, juvenile peak salmon catch per unit effort (CPUE) from SECM, modified by other environmental parameters as appropriate, has been used to forecast harvest of adult pink salmon (*O. gorbuscha*) in SEAK. The forecast of 16.1 million fish for 2008 was within 2% of the actual harvest of 15.9 million fish. This represents the fourth forecast over the period 2004-2008 which was within 11% of the actual harvest. In 2006, however, the harvest was substantially different from the forecast. Although a simple CPUE model did indicate a downturn in harvest for 2006, the forecast was nonetheless 200% higher than the actual 2006 harvest. These results show that the CPUE information has great utility for forecasting year class strength of SEAK pink salmon, but additional environmental data are needed to avoid "misses" such as the 2006 return. Since 2007, the forecast model was developed using stepwise multiple regression, jackknife hindcast analysis, and bootstrap confidence intervals. A four-parameter model was selected as the "best" forecast model for 2009. Juvenile pink salmon CPUE in northern SEAK accounted for 82% of the variability in annual harvest of SEAK pink salmon over the 1997-2008 time period. The amount of variability explained was improved to 99% when the May 20-m integrated sea water temperatures and mixed-layer depths (from the SECM strait habitat) and the El Niño Southern Oscillation (ENSO) Index were included in the four-parameter multiple regression model. The 2009 forecast from the four-parameter model, using data collected in 2008, is 44.4 million fish, with an 80% bootstrap confidence interval of 37-52 million fish. Juvenile pink salmon peak CPUE collected in southern SEAK from 2005-2007 was highly correlated ($r = 0.99$) with the peak CPUE from northern SEAK in those years, and was not correlated ($r < 0.01$) with the residuals from the forecast model. Because the pattern of juvenile abundance was similar for the two areas, no additional variation in the harvest was explained by including the southern region data. However, that time series includes only three years of data; more years may provide additional information on regional variation in pink salmon year-class strength, especially for years when the two areas have distinctly different environmental conditions.

Introduction

The Southeast Alaska Coastal Monitoring (SECM) project has been sampling juvenile salmon (*Oncorhynchus* spp.) and associated environmental parameters in northern Southeast Alaska (SEAK) since 1997 to better understand effects of environmental change on salmon production (Orsi et al. 2008). A pragmatic data application of this effort is to forecast the abundance of adult salmon returns in subsequent years. Mortality of juvenile pink (*O. gorbuscha*) and chum (*O. keta*) salmon is high and variable during their initial marine residency, and is thought to be a major determinant of year-class strength (Parker 1968; Mortensen et al. 2000; Willette et al. 2001; Wertheimer and Thrower 2007). Sampling juveniles after this period of high initial mortality may provide information that can be used with associated environmental data to forecast abundance.

Pink salmon provide a good test species to determine the utility of indexes of juvenile abundance in marine habitats for forecasting because of their short, two-year life cycle from spawning to recruitment. Sibling recruit models are not appropriate for this species because no leading indicator information exists (i.e., only one age class occurs). However, spawner/recruit analyses have also performed poorly for predicting pink salmon returns, due to high uncertainty in estimating spawner abundance and high variability in marine survival (Heard 1991, Haeseker et al. 2005); instead, predictions from an exponential smoothing model for the time series of annual harvests have provided more accurate forecasts of SEAK pink salmon than spawner/recruit analyses (Plotnick and Eggers 2004; Eggers 2006). Wertheimer et al. (2006) found a highly significant relationship between juvenile pink salmon catch per unit effort (CPUE) from the SECM sampling and the SEAK harvest. Juvenile pink salmon CPUE has subsequently been used to produce improved forecasts for SEAK pink salmon either as auxiliary data to improve the ADFG exponential smoothing model (Heinl 2008) or as direct indicators of run strength when modified by associated environmental data (Wertheimer et al. 2008). This paper reports on the efficacy of using the SECM data for forecasting the 2008 SEAK pink salmon harvest and on the development of a prediction model for the 2009 forecast.

One concern about the application of the SECM juvenile data for forecasting SEAK regional harvest is the limited geographic scope of the juvenile sampling, which has been focused in northern SEAK (Orsi et al. 2008; Wertheimer et al. 2008). In response to this concern, the SECM project included sampling in southern SEAK in 2005-2007. The utility of incorporating southern SEAK juvenile pink salmon data into current forecast models is also examined in this paper.

Methods

Study Area

This paper focuses on forecasting the harvest of adult pink salmon in SEAK, using information on juveniles and their associated biophysical data from the prior year. Spawning aggregates of pink salmon in the SEAK region originate from over 2,000 streams (Baker et al. 1996). Data on juvenile pink salmon abundance, size, and growth, and associated environmental parameters have been collected by the SECM project since 1997; detailed descriptions of the sampling locations and data collection have been reported in a series of NPAFC documents (e.g., Orsi et al. 2006, 2007, 2008). The SECM data used in the forecasting model were from eight stations along two transects in the strait habitat of northern SEAK, sampled from 1997 to 2008, and for eight stations along two transects in the strait habitat of southern SEAK, sampled from 2005 to 2007 (Figure 1).

Data Descriptions and Sources

Parameters considered for the forecasting models included pink salmon harvest as the response parameter (ADF&G 2008) and 15 biological and physical variables that were either collected by SECM or were indexes of broad-scale environmental conditions that influence temperature and productivity in the Gulf of Alaska. The biophysical parameters examined for forecasting harvest are listed in Table 1. Two indexes of juvenile pink salmon abundance in northern SEAK were evaluated. One was the average Ln (CPUE+1) for catches in either June or July, whichever month had the highest average catches in a given year (Peak CPUE, Table 1). This parameter has been previously identified as having the highest correlation with harvest and providing the best performance among potential CPUE metrics for forecasting harvest (Wertheimer et al. 2006; Orsi et al. 2006; Wertheimer et al. 2008). The second measure was the average Ln (CPUE+1) for August in northern SEAK (August CPUE, Table 1). This parameter was included as a possible indicator of delayed migratory timing through northern SEAK that could be associated with low year-class strength (Wertheimer et al. 2008).

Three measures of juvenile pink salmon growth and condition in northern SEAK were considered as indicators of biological variation that could affect survival of pink salmon. These were: 1) growth of juvenile pink salmon in terms of change in average lengths from June to July (June-July apparent growth, mm/day; Table 1); 2) a weighted average size of juvenile pink salmon, (Pink Salmon Size July 24, mm; Table 1); and 3) the average annual residuals for observed Ln weight of individual fish in a year in relation to the regression relationship derived from all paired Ln weights and Ln lengths for pink salmon collected during SECM sampling from 1997-2007 (Condition Index, Table 1).

Two measures of zooplankton standing crop were evaluated as indicators of secondary production that could influence pink salmon year-class strength. These were 1) May and June average NORPAC 20-m settled volume, an index of upper water column zooplankton (May-June Average Zooplankton 20 m, Table 1); and 2) May and June average 333-bongo displacement volume as an index of integrated zooplankton to 200-m depth (May-June Zooplankton Total Water Column, Table 1).

Eight measures of physical conditions were evaluated for their influence on pink salmon harvests in SEAK. Six of the physical parameters were measures of local conditions that occur during the SECM sampling period in Northern SEAK. These were: 1) May 3-m water temperature; 2) July 3-m water temperature; 3) May upper 20-m integrated average water temperature; 4) June upper 20-m integrated average water temperature; 5) June average mixed-layer depth (MLD, June Mixed-layer depth); and 5) July 3-m salinity (Table 1).

The other two physical parameters were basin-scale indexes of physical conditions that affect the entire Gulf of Alaska and North Pacific Ocean. One was the annual November to March average of Pacific Decadal Oscillation (PDO) during the winter prior to the juvenile pink salmon rearing period (Pacific Decadal Oscillation, Table 1), which has been identified as an indicator of environmental conditions affecting juvenile salmon in their first year at sea (Mantua et al. 1997). The second was the annual average multivariate El Niño Southern Oscillation (ENSO) index (NCDC 2007) that occurred the year before pink salmon were harvested. Due to the lag in the influence of ENSO on conditions in the Gulf of Alaska, this index was used as an indicator of conditions encountered by pink salmon in their winter and final spring at sea.

Forecast Model Development

A four step process was applied to identify the "best" forecast model for predicting pink salmon harvest in SEAK. The first step was to develop a regression model of harvest and juvenile salmon CPUE, with physical conditions, zooplankton volumes, and pink salmon growth indices considered as additional parameters. The potential model is

$$\mathrm{Ln(Harvest)} = \alpha + \beta(\mathrm{Ln(CPUE)}) + \gamma_1 X_1 + \ldots + \gamma_n X_n + \varepsilon,$$

where γ is the coefficient for environmental variable *X.* Backward/forward stepwise regression with an alpha value of $P < 0.1$ was used to determine whether an environmental variable is added or retained in the model.

The second step was to calculate the Akiake Information Criterion (AIC) for each significant step of the stepwise regression, to prevent over parameterization. The AIC was corrected (AIC_c) for small sample sizes (Shono 2000).

The third step was a jackknife approach to evaluate "hindcast" forecast accuracy over the entire SECM time series. This procedure generated forecast model parameters by excluding a year of data, then used the excluded year to "forecast" harvest for the associated harvest year; this process was repeated so that each year in the time series was excluded and used to generate a forecast. The average relative forecast error was then calculated for each model.

The final step in developing the model was to compare bootstrap confidence intervals (CIs) to the regression prediction intervals for the forecasts to examine the effect of process error and measurement error on the forecasts. For the bootstrap approach, juvenile pink salmon catches for each month in each year y were randomly re-sampled n_{my} times, where *n* is the number of hauls in month *m* in year *y*, and then the re-sampled catches for each month and year were averaged. Average simulated catches for years 1997-2007 were used to construct the regression models with SEAK harvest as the dependent variable, and the appropriate averages of the simulated catches for 2008 were used to forecast 2009 harvests. This process was repeated 1000 times, generating 1000 forecasts for each model. The forecasts were ordered from lowest to highest, and the lowest 10% and highest 10% were removed to define the 80% bootstrap CIs. These results were then compared to the prediction CIs for the regression model based on the observed annual average catches.

Data on juvenile pink salmon abundance were available for southern SEAK 2005-2007 (Wertheimer et al. 2008). The Peak CPUEs for juvenile pink salmon from southern SEAK were evaluated for relationships with northern SEAK Peak CPUEs and with the deviations between the observed and predicted harvests of SEAK pink salmon for 2006-2008. A significant correlation would indicate that information on abundance from the southern area could improve the forecast model based on indexes of juvenile abundance from the northern area.

Results

Forecast Efficacy

In 2008, the SECM forecast of 16.1 million pink salmon was within 2% of the actual 2008 harvest of 15.9 million fish (Table 2). Including the 2008 results, four of the five SECM forecasts since 2004 have been within 11% of the actual harvest (Figure 2). Only in 2006 was the harvest substantially different from the forecast; in that year, the actual harvest was well outside the 80% confidence interval of the forecast (Figure 2).

The inclusion of SECM Peak CPUE data also improved the ADF&G 2008 forecast based on an exponential smoothing model of harvest data. The ADF&G forecast that incorporated the juvenile data was for 19 million pink salmon; without modifying the forecast with the juvenile data, the forecast would have been 30 million pink salmon (Table 2, Heinl 2008).

2009 Forecast

Bivariate correlations were computed between SEAK pink salmon harvests for 2004-2008 and the potential predictor variables are listed in Table 1. Only Peak CPUE was highly ($r = 0.89$) and significantly ($P = 0.001$) correlated with SEAK pink salmon harvest. None of the other parameters evaluated were significantly correlated with harvest.

In the stepwise regression analysis, a four-parameter model including Peak CPUE, May20-m temperature, ENSO, and June MLD explained 99% of the variability in the harvest data (Adjusted R^2), as compared to 82% for the simple linear regression with Peak CPUE (Table 3). The AIC_c decreased at each model step, and was lowest for the four-parameter model (Table 3), indicating that the full four-parameter model is also the most parsimonious and not over-parameterized.

The jackknife analysis indicated that including additional parameters with Peak CPUE in the forecast model could substantially improve forecasts for SEAK harvest (Table 4). Including the May temperature data decreased the average absolute percent deviation of the jackknife forecasts from the actual harvests for 1998-2008 from 31% to 21%. For 2006, the year in which the actual forecast by the simple Peak CPUE model was poor, including May temperature decreased the deviation of the jackknife forecast from the 2006 harvest from 188% to 84%. Adding ENSO data to the CPUE+May Temperature model further reduced jackknife forecast deviations for 1998-2008 to an average of 15%, and to 37% for 2006. The full four-parameter model resulted in a further decline to 8%, and effectively hindcast the 2006 harvest with a deviation of only 6%.

The 80% bootstrap CIs for the single- and multiple-parameter models for the 2008 forecast were compared with the 80% prediction intervals from the regression equations (Figure 3). The prediction intervals for the regression equations declined markedly as the number of parameters in the model increased, from a range of 25-50 million fish for the simple CPUE model to a range of 40-48 million fish for the full four-parameter model. The decreasing intervals reflected the improved model fit and the corresponding reduction in process error. However, the regression prediction intervals did not incorporate measurement error because the observations of CPUE are single averages for each sampling year. The bootstrap CIs incorporated the measurement error by randomly re-sampling the catches for 1000 iterations for each year. When measurement error was incorporated in this way, the CIs were narrowest for the simple CPUE model, 31-44 million fish (Figure 3). The CI increased for the two-parameter model to 38-55 million fish, but then became slightly narrower for both the three-parameter model (37-53 million) and the full, four-parameter model (37-52 million).

The full, four-parameter model was selected as the “best” SECM model for predicting the SEAK harvest in 2009, for several reasons. It had the best fit to the data, explaining 99% of the variability in harvest, the lowest AIC_c, and the lowest deviation in the jackknife analysis both overall and for the 2006 harvest. The bootstrap CI of the forecast from this model was only slightly wider than for the simple one-parameter model, and was actually narrower than for the two- and three-parameter models. Thus, at the SEAK Purse Seine Task Force meeting in Juneau in November, 2008, a forecast of 44.4 million was presented as the SECM prediction for the 2009 harvest.

Influence of Southern SEAK CPUE Data

The residuals from the forecast model for 2005-2007 had no correlation ($r < 0.01$) with the southern SEAK pink salmon CPUE for this time period. This was probably due to the similar pattern of abundance of juvenile pink salmon in the two areas. In both northern and southern SEAK, juvenile pink salmon CPUE was highest in June in 2005 and 2006, and in July in 2007 (Table 5). In the peak months, juvenile pink salmon CPUE was consistently higher in southern SEAK. Peak and overall average CPUEs were highest in both areas in 2006 and lowest in both areas in 2007. Average CPUE in the peak month was highly correlated ($r = 0.99$) between northern and southern SEAK over 2005-2007.

Discussion

The 2008 harvest of pink salmon was the second lowest in the past 20 years (ADFG 2008), but it was accurately forecast by both the SECM juvenile CPUE model and the ADFG model incorporating juvenile CPUE data. For four of the past five years, SECM juvenile models have forecast within 11% of actual harvest, demonstrating the utility of the juvenile salmon information for predicting year-class strength.

However, in 2006 the pink salmon return and harvest was very poor (ADFG 2008), and was not accurately forecast by the simple juvenile pink salmon CPUE relationship (Wertheimer et al. 2008). Although the CPUE model forecast was high in 2006, it did indicate a decline relative to recent years, which was not apparent in the ADFG forecast that relies on average harvests (Eggers 2006). Drought conditions and high stream temperatures in the late summer and fall of 2004 may have contributed to the poor year-class strength of pink salmon (Beamish and Mahnken 2001; Moss et al. 2005). Periodic high mortality events at this stage would not be reflected by the juvenile salmon CPUE from the strait habitat in 2006. However, the juvenile CPUE should, conceptually, account for low recruitment of pink salmon from streams to the coastal marine environment. Return rates of pink salmon to the one large pink salmon hatchery in Southeast Alaska were 0.6%, well below the average return of 2.8% over the past 19 years (personal communication, Sam Rabung, Armstrong-Keta Inc., Juneau, AK), indicating that poor marine survival as well as adverse freshwater conditions affected the 2006 returns. The poor performance of the CPUE model in 2006 suggests that variable overwinter mortality after migration from the inside coastal habitat can affect survival and adult returns.

Information on environmental conditions that affect the juvenile pink salmon after they leave SEAK waters and enter the Gulf of Alaska could improve forecast accuracy for the juvenile pink salmon CPUE prediction model. The two-parameter CPUE models used for 2007 and 2008 forecasts were very accurate, and the multi-parameter models developed for the 2009 forecast greatly reduced the hindcast residual for 2006 (Table 4). The 2009 forecast included an ENSO index for conditions that influence pink salmon in their winter and subsequent spring at sea. Actual measures of conditions concurrent with the GOA conditions of the winter/spring following the first ocean summer might fit the data series better (e.g., winter PDO prior to adult spring/summer rather than juvenile spring/summer), but the data are not available in time for forecasting.

One caveat for the harvest forecast is that juvenile salmon CPUE should be an index of total run (harvest plus escapements to the spawning streams) rather than harvest alone. However, the escapement index of pink salmon in SEAK is not a precise or accurate estimate. Wertheimer et al. (2008) examined the incorporation of scaled escapement index data with harvest to develop an index of total run. This total run index did not improve model fit, because it was so highly correlated with harvest (r = 0.99). In addition, forecast of total run would require the assumption of an average exploitation rate to predict harvest. For these reasons, the use of accurate and precise harvest data as a proxy for total run is preferred.

The juvenile pink salmon CPUE data from southern SEAK for 2005-2007 did not explain any additional variation in the fit of the CPUE model that uses northern SEAK juvenile data only. This was because northern and southern SEAK CPUEs were very highly correlated for 2005-2007, supporting the assumption that the northern CPUE index reflects region-wide conditions. However, catches and escapements in northern and southern SEAK are not always synchronous in year-class strength (Byerly et al. 1999; ADFG 2008; Steve Heinl, Alaska Department of Fish and Game, personal comm.). Consistently sampling over broader geographic scope may provide insight into when and why asynchronous survival occurs within different areas of SEAK.

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Table 1.—Correlation coefficients of CPUE of juvenile pink salmon and associated biophysical parameters in year *y* for 1997-2007 with adult pink salmon harvest in Southeast Alaska in year *y* + 1. Parameters with statistically significant correlations are in bold text.

Parameter	***r***	***P*-value**
Peak CPUE	**0.89**	**0.001**
August CPUE	-0.44	0.200
June-July Pink Salmon Apparent Growth	0.28	0.436
Pink Salmon Size July 24	0.54	0.108
Condition Index	-0.10	0.793
May/June Average Zooplankton Total Water Column	0.17	0.965
May/June Average Zooplankton 20-m	-0.06	0.876
May 3-m Water Temperature	-0.37	0.287
July 3-m Water Temperature	-0.04	0.903
May 20-m Integrated Water Temperature	-0.26	0.473
June 20-m Integrated Water Temperature	-0.29	0.411
June Mixed-layer Depth	-0.25	0.490
July 3-m Salinity	-0.24	0.505
Pacific Decadal Oscillation (Ocean Winter)	0.07	0.845
El Nino Southern Oscillation (Prior year annual average)	-0.03	0.943

Table 2.—Southeast Coastal Monitoring (SECM) and Alaska Department of Fish and Game (ADFG) forecasts for 2008 pink salmon harvest in Southeast Alaska (SEAK). The ADFG forecasts are from Heinl (2008). Na = not applicable.

	2008 SEAK Pink Salmon Harvest (millions of fish)	**Deviation from Actual Harvest**
SECM Forecast	16.1	1%
ADFG Forecast (w/ Peak CPUE data)	19.0	19%
ADFG Forecast (w/o Peak CPUE data)	30.0	189%
Actual Harvest	15.9	na

Table 3.—Regression models relating juvenile catch per unit effort (CPUE) of pink salmon in year *y* to adult harvest in Southeast Alaska in year *y* +1, for *y* = 1997-2007. R^2 = coefficient of determination for model; AIC_c = Akiake Information Criterion (corrected); *P* = statistical significance of regression equation. SEAK = total Southeast harvest.

Model	**Harvest Area**	**Adjusted R^2**	**AIC_C**	**Regression *P* -value**	**2009 Prediction (millions)**
Ln(PeakCPUE)	SEAK	82%	85.2	0.001	37.5
Ln(PeakCPUE) + May20-mTemp	SEAK	94%	75.8	<0.001	47.1
Ln(PeakCPUE) + May20-mTemp + ENSO	SEAK	96%	72.4	<0.001	45.3
Ln(PeakCPUE) + May20-mTemp + ENSO + MLD	SEAK	99%	58.2	<0.001	44.4

Table 4.—Average absolute percent deviation of jackknife forecasts to observed harvests for forecast models for 1998-2008 returns of pink salmon for the Southeast Alaska region and for the northern inside portion of that region. SEAK = total Southeast harvest.

Model	**Harvest Area**	**Average Deviation**	**2006 Deviation**
Ln(PeakCPUE)	SEAK	31%	188%
Ln(PeakCPUE) + May20-mTemp	SEAK	21%	84%
Ln(PeakCPUE) + May20-mTemp + ENSO	SEAK	15%	37%
Ln(PeakCPUE) + May20-mTemp + ENSO + MLD	SEAK	8%	6%

Table 5.—Catch per unit effort (CPUE) of juvenile pink salmon in northern (NSE) and southern (SSE) regions of Southeast Alaska in June and July, 2005-2007.

Year	Area	June CPUE	JulyCPUE	JJAverage
		Pink Salmon		
2005	NSE	24.8	5.2	15.0
	SSE	83.3	4.3	43.8
2006	NSE	45.0	41.2	43.1
	SSE	153.4	35.9	94.6
2007	NSE	0.8	6.2	3.9
	SSE	9.7	12.3	10.9

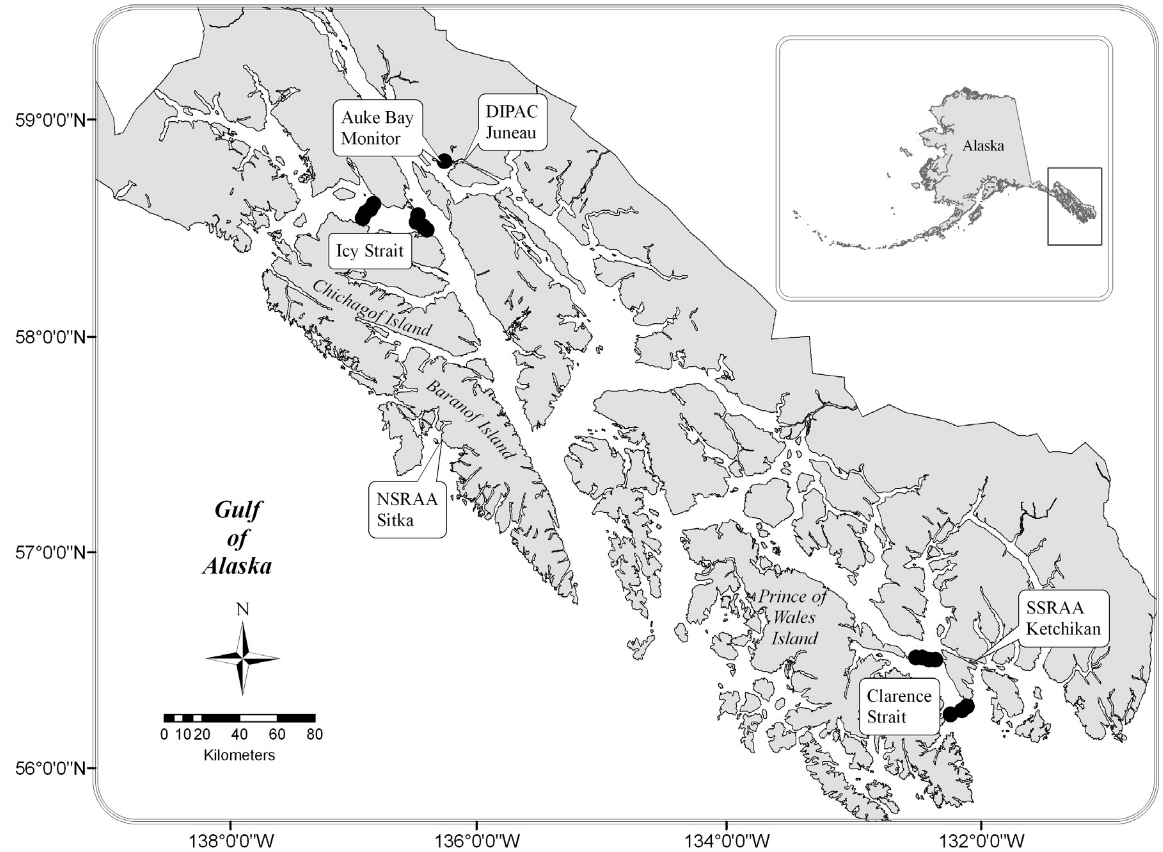

Figure 1.—Stations sampled for juvenile pink salmon along the Icy Strait and Clarence Strait transects in the northern and southern regions of southeastern Alaska for the development of pink salmon harvest forecasting models. Northern transects were sampled during May–August from 1997–2008 and southern transects were sampled during June–July from 2005–2007.

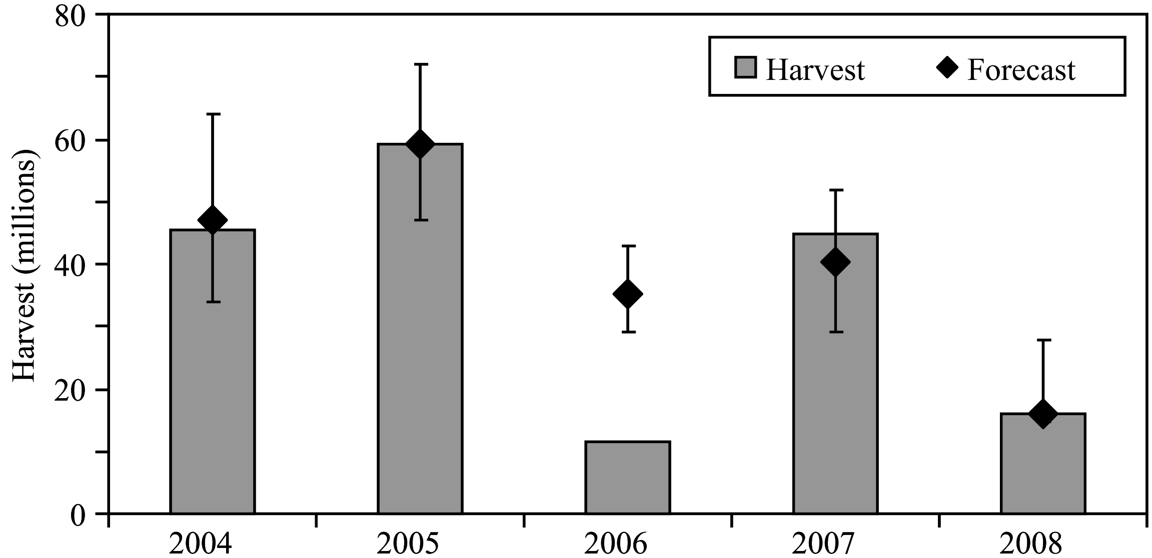

Figure 2.—Southeast Coastal Monitoring (SECM) pink salmon harvest forecasts for Southeast Alaska (SEAK; symbols), associated 80% confidence intervals (lines), and actual SEAK pink salmon harvests (colored bars), 2004-2008.

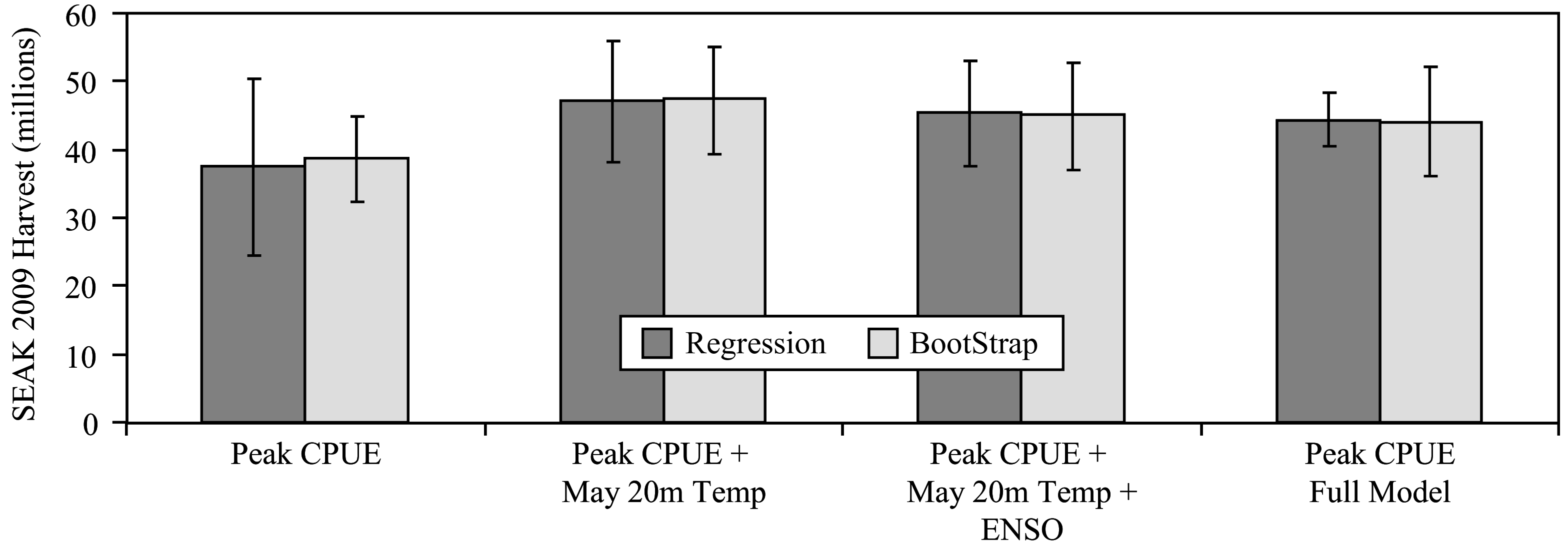

Figure 3.—Parametric regression and bootstrap 80% confidence intervals (lines) for predictions of SEAK pink salmon harvest in 2009 (colored bars) from four models incorporating juvenile Peak CPUE data in 2008. See text for descriptions of parameters included in models.