Forecasting Pink Salmon Production in Southeast Alaska Using Ecosystem Indicators in Times of Climate Change

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Abstract: Researchers in Alaska have provided accurate pre-season annual forecasts of pink salmon harvest to resource stakeholders of Southeast Alaska (SEAK) in times of climate change. Since 1997, the Southeast Alaska Coastal Monitoring project has collected biophysical data associated with seaward migrating juvenile salmon from May to August, and it has used these data along with larger basin-scale indexes to forecast SEAK pink salmon returns via regression and ecosystem metric models. In nine of the past eleven years (2004–2014), predictions from linear regression models ranged 0–17% of actual harvests, an average absolute forecast deviation of 10%. The primary explanatory variable was juvenile pink salmon peak catch. In some years, models included secondary variables to improve fit. A supplemental modeling approach was tested recently to better inform stakeholders. This approach incorporated both an annual rank score forecast outlook based on ecosystem metrics, and a visual stoplight color-code graphic. Accurate pre-season salmon forecasts and descriptive outlooks from this applied research has increased economic efficiency of the fish processing industry, enabled managers and resource stakeholders to anticipate harvest with more certainty, helped promote resource sustainability, and provided insight into ecosystem mechanisms related to pink salmon production in a changing climate.

Keywords: pink salmon, production, ecosystem indicators, Southeast Alaska, climate change

INTRODUCTION

Reliable predictions of recruitment into commercial fisheries are a hallmark of successfully applied science to fisheries management. To achieve this goal in marine fisheries, a robust understanding of life history and ecology is needed from the period of hatching (or ocean entry) until fishery recruitment. This understanding requires information and monitoring of key biological factors associated with fish stock abundance, migratory behavior, and trophic interactions, as well as physical factors driven by climate. In the case of Pacific salmon (*Oncorhynchus* spp.), the transition from fresh water to salt water via estuaries is important, as the early ocean migration period is thought to have a critical influence in overall salmon survival. This is particularly true for salmon species entering the ocean as small fish soon after emerging from their riverine redds (nests), such as pink salmon (*O. gorbuscha*) and chum salmon (*O. keta*). Early marine mortality and growth of these species strongly influence year-class strength (Parker 1968; Pearcy 1992; Bradford 1995; Karpenko 1998; Mortensen et al. 2000; Wertheimer and Thrower 2007; Fukuwaka et al. 2010). As juvenile pink salmon grow and migrate further offshore, later ocean conditions can also impact growth and/or survival through trophic interactions with predators, prey, or competitors (Willette et al. 2001; Moss et al. 2005; Armstrong et al. 2008; Sturdevant et al. 2009).

In addition to ecological factors influencing salmon recruitment, physical and spatially-explicit factors are also important to consider. For example, compared to simple models based on juvenile abundance only, environmental correlates may contribute significantly in explaining fish recruitment variation (Stige et al. 2013). Also, larger ocean basin-scale factors reflective of climate, such as the El Niño Southern Oscillation (ENSO) and the Pacific Decadal Oscillation (PDO) multivariate indexes, may also affect salmon production (Beamish and Bouillon 1993; Hare and Francis 1995; Mantua et al. 1997; Francis et al. 1998; Hare et al. 1999). Moreover, the spatial scale of salmon survival appears to operate on a localized scale within 500 km (Mueter et al. 2002a, b; Pyper et al. 2005; Malick et al. 2009; Sharma et al. 2013). This suggests both climate

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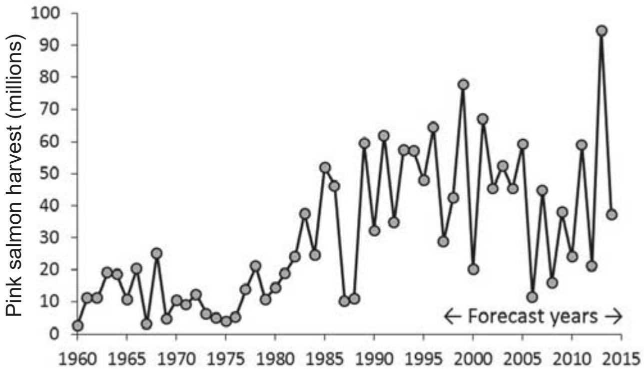

Fig. 1. Historical variability in annual pink salmon harvest (millions of fish) in Southeast Alaska, and the years used in developing preseason forecast models for harvest, 1997–2014.

and spatially-explicit factors play an important role in establishing year-class strength. Furthermore, because the response of salmon stocks to global climate change varies regionally (Fukuwaka et al. 2011), identifying such controlling mechanisms to regional salmon production is important. This is particularly true for pink salmon, which have been identified as a key indicator species in the study of climate impacts in marine ecosystems in the North Pacific Ocean (Riddell and Beamish 2003). Thus, for pink salmon, a logical approach in developing forecast models predicting production should include a spatially explicit time series of ecosystem metrics associated with the seaward migration of pink salmon.

Historically, pink salmon returns have been notoriously difficult to predict in many regions due to limited pre-season fishery information, complicated stock dynamics with odd- and even-year cycles, and highly variable rates of annual adult returns (Adkison and Peterman 1999; Adkison 2002; Haeseker et al. 2005; Shevlyakov and Koval 2012). Pink salmon, which are the smallest, most abundant Pacific salmon species, also have the simplest overall life history, spending only one winter at sea before returning to spawn (Heard 1991). As a result, adult pink salmon lack leading indicator cohort information from earlier returning age components such as "jacks" or other younger sibling precursors of strong year-class strength. This poses a problem for fish managers on how to best anticipate upcoming

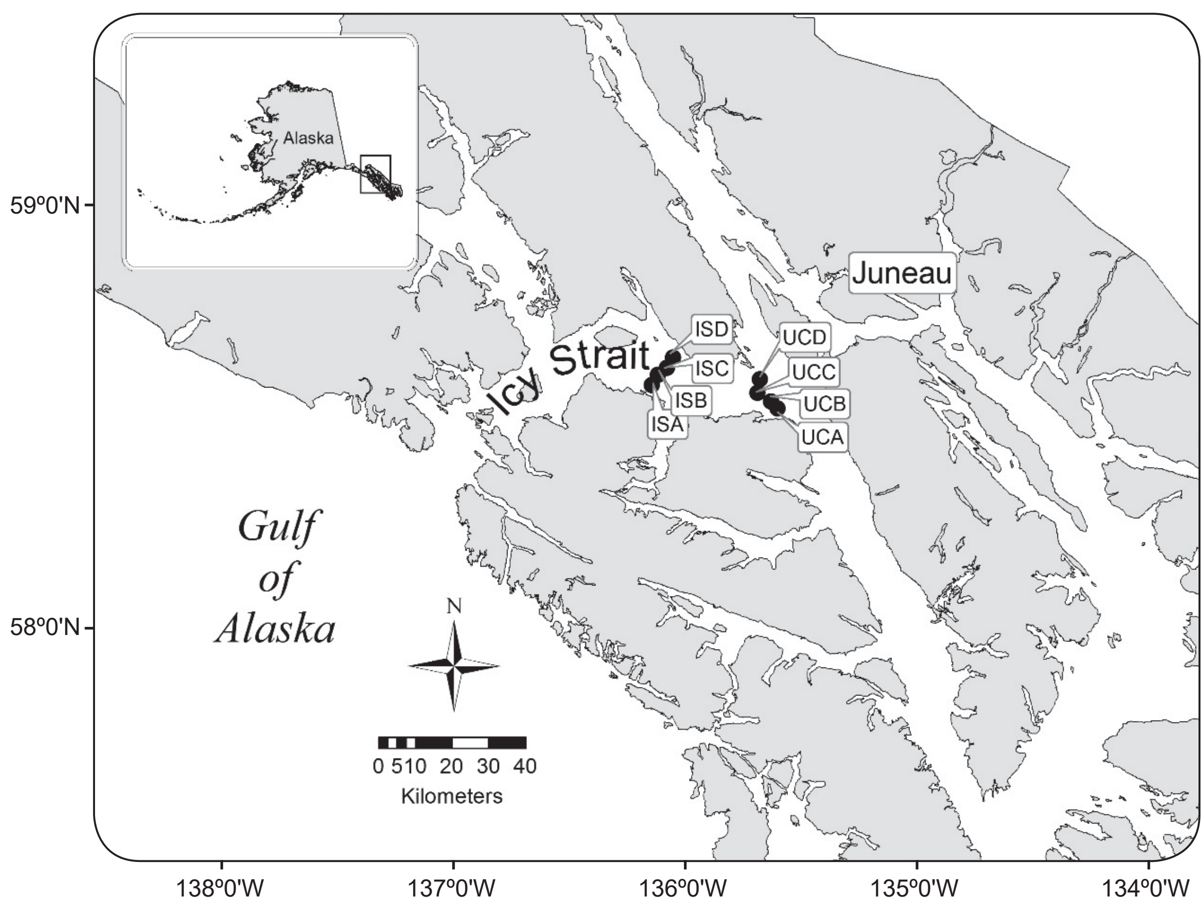

Fig. 2. Stations sampled by the Southeast Coastal Monitoring (SECM) project each month for juvenile pink salmon and ecosystem metrics in Icy Strait, Southeast Alaska, May–August, 1997–2014.

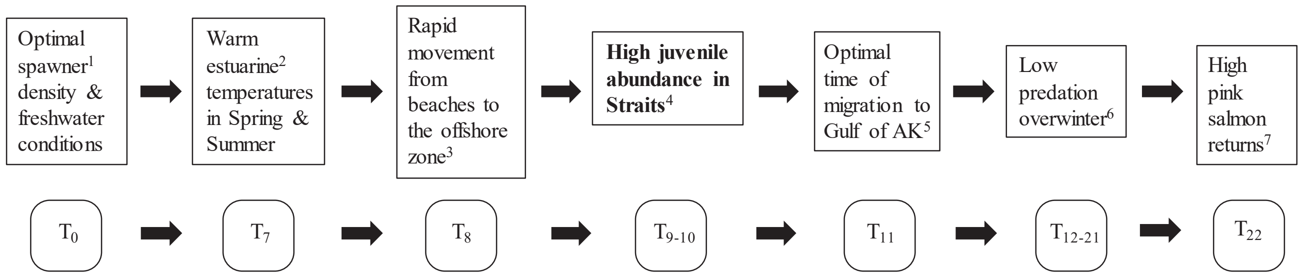

Fig. 3. Conceptual model of key sequential life-history events conducive to high pink salmon production in Southeast Alaska. Approximate spatial monthly time lags are shown below from adult spawning (T_0) to adult harvest period (T_{22}).

harvests. Furthermore, annual pink salmon harvests to regions such as Southeast Alaska (SEAK) fluctuate wildly, with harvests that have ranged from 3–95 M fish annually from 1960 to 2014 (ADF&G 2015; Fig. 1). Consequently, planning for a highly variable adult pink salmon return is a major challenge to managers, fisherman, and the fish processing community. This uncertainty in the magnitude of upcoming pink salmon harvests puts resource stakeholders at a distinct economic disadvantage for planning infrastructure for the upcoming year and also requires mangers to rely upon in-season management to optimize harvest and ensure a sustainable pink salmon fishery. Accurate pre-season pink salmon forecast models would be a practical tool that would benefit both managers and regional resource stakeholders.

The pink salmon resource in SEAK is valuable both from a commercial and an ecological standpoint. From 2001 to 2013, the ex-vessel value of the SEAK commercial pink salmon harvest averaged approximately $42 M U.S., commanding the highest value compared to any other salmon species in nearly half the years (ADF&G 2015). In 2013, when the commercial harvest of pink salmon reached a historical peak in SEAK, over 94 M fish were harvested in common property fisheries, worth an ex-vessel value of $125 M U.S. Pink salmon return to some 2,500 natal stream systems in SEAK, with 97 per cent being of wild stock origin. In addition, they provide important annual sources of marine nutrients to terrestrial ecosystems (Piston and Heinl 2013, 2014). Thus, accurately assessing year-class strength prior to upcoming fisheries is vital to the region to help ensure the sustainability of the wild pink salmon resource.

Since 1997, researchers from NOAA's Southeast Alaska Coastal Monitoring (SECM) project have collected monthly (May to August) coastal ocean ecosystem metrics in the vicinity of Icy Strait, SEAK. The SECM research has used this time series data to describe seaward marine habitat use of migrating juvenile salmon, their ecological interactions, growth, and subsequent production, in the context of a changing climate (Orsi et al. 2000, 2004, 2007; Sturdevant et al. 2012; Fergusson et al. 2013). A high profile outcome of the SECM research project has been the ability to use coastal ocean metrics associated with juvenile pink salmon to construct pre-season pink salmon forecast models to benefit SEAK resource stakeholders (e.g. Wertheimer et al. 2014). As a result, these pre-season pink salmon forecast models have been tested annually since 2004, and reported in previous documents, presentations, and website postings (Orsi et al. 2005, 2006a, 2013c; www.afsc.noaa.gov/ABL/EMA/EMA_PSF.htm; Wertheimer et al. 2006, 2008, 2009, 2010, 2011, 2012, and 2013). Most recently, an ecosystem metric approach using ranks and multiple indicators was developed to provide a qualitative pink salmon harvest outlook. This use of multiple ecosystem indicators (oceanographic and ecological) has been described previously to forecast returns of other salmonids such as Chinook salmon (*O. tshawytscha*) and coho salmon (*O. kisutch*) in the Pacific Northwest in multivariate or "stoplight" chart approaches (Logerwell et al. 2003; Burke et al. 2013; Peterson and Burke 2013).

This study reports pre-season pink salmon forecast accuracy of models predicting pink salmon harvest in SEAK using coastal ocean ecosystem metrics. The three objectives of this study are to: (1) review pre-season pink salmon forecast model accuracy performances over each of the past eleven years (2004–2014) using a step-wise linear regression approach, (2) describe a new annual rank

[1]Optimal pink salmon escapements to Southeast Alaska stream systems & good freshwater conditions
[2]Warm temperatures in the littoral nearshore zone conducive to rapid fish growth
[3]Rapid offshore migration, fry reach threshold size (~60 mm), minimizes nearshore predator interactions
[4]Icy Strait abundance index of juvenile salmon
[5]Peak entry period into Gulf of Alaska from Icy Strait in June or July
[6]Open ocean residence period of about 8–9 months
[7]Pink salmon total harvest after in-season monitoring of catch and sex ratios

Table 1. Pre-season forecast models developed using coastal ocean metrics associated with seaward migrating juvenile pink salmon (year 1, 2003–2013) compared to adult harvest (harvest year, 2004–2014) in Southeast Alaska. The standard vessel-calibrated catch per trawl haul model ($CPUE_{cal}$) was used in all years and the catch per trawl track distance ($CPUE_{ttd}$) and ecosystem rank models were tested against the $CPUE_{cal}$ model outcome with actual harvest in 2014 and the predicted harvest* in 2015.

Model approach	Years tested as a pre-season model	Remarks
Linear stepwise regression, multiple biophysical variables (1–4) used as terms in models with peak juvenile catch $CPUE_{cal}$, in June/July using vessel calibration metric	11	Standard approach, $CPUE_{cal}$ metric, and up to 3 additional parameters. Simple single parameter model had best "jackknife" fit in 4 years
Simple regression, only $CPUE_{ttd}$, peak juvenile catch in June/July, using trawl track distance metric	2*	New, considered if CPUE is high, more accurate in detecting high return years
Average rank score of six ecosystem indicators significantly correlated with harvest, with annual rank regressed with prior harvests	2*	New, incorporation of average ranks of six significant bivariate ecosystem metrics over the SECM time series

score forecast outlook approach based on ecosystem metric scores and a qualitative stoplight color-code graphic, and (3) provide insight to linkages among coastal ecosystem processes, climate, and future salmon production based on previous model outcomes.

METHODS

Study Area and the Pink Salmon Resource

Southeast Alaska is a temperate rainforest region in the southern panhandle of Alaska and supports a multitude of anadromous salmon streams that contribute to viable commercial, subsistence, and sport fisheries. This rugged, remote, pristine region is comprised of a network of over 1,000 islands comprising a 175 × 500 km long strip of the Alexander Archipelago off the coast of Alaska bounded eastward by the Coast Mountains of North America and westward by the Gulf of Alaska. Pink salmon spawning aggregates are reported to originate from 2,000–2,500 coastal streams throughout the SEAK region (Baker et al. 1996; Zadina et al. 2004). Pink salmon are harvested in common-property fisheries by many users groups, with purse seining the primary commercial fishery method in SEAK (Piston and Heinl 2011).

The pink salmon fishery is managed by the Alaska Department of Fish and Game (ADF&G) with annual information shared post-season among researchers and stakeholder groups. Pink salmon are managed on a sustained yield basis, driven largely by in-season management as the fishery progresses. Harvesting generally occurs from July to September of both early and late runs of pink salmon: mainland spawning stocks that return early and coastal spawning stocks that return later in the fall. Typically, the fishery begins with test seine sets, then monitoring of fishery performance (catch rates per vessel) each statistical week (time period), followed by surveying escapement in index streams and monitoring sex ratios in the commercial catch as a surrogate of the run time progression (a 50:50 male to female ratio indicates the returns are half over). The intensity of harvest in a particular year is gauged by these in-season performance metrics, and fishing effort is adjusted to reflect the relative abundance of the returns. At the end of each harvest season, there is a Purse Seine Management Task Force process where current escapements are reviewed by the ADF&G, the public and industry share fishing performance information, and pre-season forecasts are reported (Davidson et al. 2013). The pre-season harvest forecasts reported at this meeting enable managers and regional stakeholders to anticipate the magnitude of the upcoming harvest. The annual harvest of pink salmon in SEAK can be substantial, but varies tremendously, with

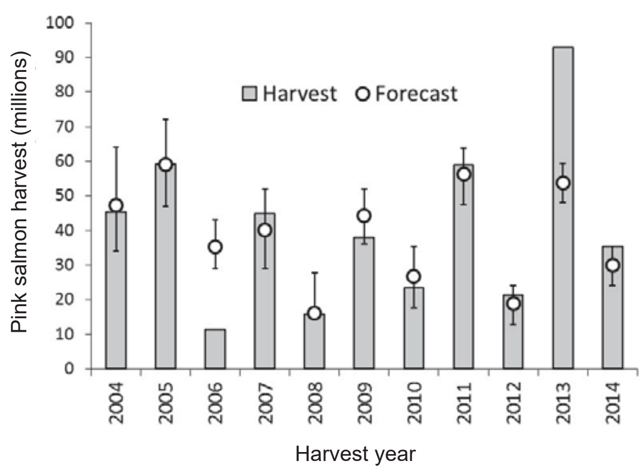

Fig. 4. Annual pre-season pink salmon harvest (millions of fish) forecast model estimates compared to the actual harvests in Southeast Alaska, 2004–2014. The 80% bootstrap confidence intervals are identified with the line and bars. All models were based on a forward/backward step-wise regression using peak juvenile catch in June/July calibrated for vessel ($CPUE_{cal}$); additional model terms beyond a single term $CPUE_{cal}$ model were used in seven of the eleven years.

Table 2. Historical pre-season pink salmon forecast models used from 2004 to 2014 and actual harvest outcomes (millions of fish). Potential model parameters include: (1) $CPUE_{cal}$ = vessel-calibrated peak June or July juvenile pink salmon average catch per haul (*Ln* [CPUE + 1]), (2) $ISTI_{MJJA}$: Icy Strait integrated upper 20-m water column monthly temperatures from May to August, (3) $Temp_M$ = Icy Strait upper 20-m water column temperatures in May, and (4) MLD = Mixed layer depth in June.

Harvest year	Model type and number of parameters	Predicted harvest (million)	Actual harvest (million)	Deviation (million)	Absolute deviation	Absolute deviation discounting the high* and low* deviations
2004	$CPUE_{cal}$	47	45	2	(4%)	(4%)
2005	$CPUE_{cal}$	59	59	0	(0%)	(0%)
2006	$CPUE_{cal}$	35	12	23*	(209%)	---
2007	$CPUE_{cal}$ + $Temp_M$	38	45	-7	(10%)	(10%)
2008	$CPUE_{cal}$ + $Temp_M$	18	16	2	(1%)	(1%)
2009	$CPUE_{cal}$ + $Temp_M$ + ENSO + MLD	37	38	-1	(17%)	(17%)
2010	$CPUE_{cal}$ + $Temp_M$ + ENSO	31	23	8	(15%)	(15%)
2011	$CPUE_{cal}$	55	59	-4	(5%)	(5%)
2012	$CPUE_{cal}$ + $Temp_M$	17	21	-4	(12%)	(12%)
2013	$CPUE_{cal}$ + $ISTI_{MJJA}$	48	95	-47*	(43%)	---
2014	$CPUE_{cal}$ + $ISTI_{MJJA}$	30	35	-5	(15%)	(15%)
Average				-3	30%	10%

production increasing since 1980s, and a recent divergence between odd and even broodline abundances since the mid-2000s (Piston and Heinl 2011).

Pink Salmon Production Response Variables and Ecosystem Metrics

The production response variable chosen for this study is the total number of pink salmon commercially harvested annually in SEAK. Harvest is commonly used as a historical index of regional productivity because it is highly correlated with total return (i.e., harvest plus escapement (Jaenicke 1995; Jaenicke et al. 1998)) and is estimated with high accuracy and precision relative to escapement estimates. Our production response variable for this study was the total number of fish in the annual commercial harvest of pink salmon in all of SEAK, minus a small portion harvested in Yakutat in the extreme northeastern portion of the region. These harvest data were provided by the ADF&G (S. Heinl, steve.heinl@alaska.gov, pers. comm.).

In general, coastal ocean metrics were lagged one year prior to the subsequent pink salmon harvest to match the timing of fish encountering these conditions. Timely input parameters for the pre-season forecast model were needed so forecasts could meet the needs of fisheries managers and resource stakeholders. This resulted in variables only being considered if they could be compiled or accessed by the fall into first year of juvenile pink salmon ocean entry. Thus, the forecast model time frame necessitated that all samples be collected, processed, analyzed, or accessed by September so a pre-season forecast could be developed in October-November for the regional Southeast Purse Seine Task Force meeting in early December.

The coastal ocean ecosystem metrics for this study were mostly obtained from monthly surveys conducted by NOAA's Southeast Alaska Coastal Monitoring (SECM) project, 1997–2013 (Orsi and Fergusson 2014) and regional or basin-scale sources. The SECM survey collected data at eight stations along two transects across Icy Strait in the northern region of SEAK (Fig. 2). This survey data included coastal ocean biological metrics such as annual juvenile pink salmon abundance, size, growth, condition, and associated biological metrics such as zooplankton abundance (e.g., Fergusson et al. 2010, 2013; Orsi et al. 2011, 2012a, 2013a; Sturdevant et al. 2012). Physical coastal ocean ecosystem metrics for this study were obtained from SECM surveys and additional regional/basin-scale sources, such as river water discharge from the Mendenhall River (USGS 2013), the Multivariate ENSO index (MEI, NCDC 2013), the North Pacific Index (NPI, Trenberth and Hurrell 1994), and the PDO index (Mantua et al. 1997).

The monthly physical data collected by SECM included: water temperature, salinity, and mixed layer depth (MLD, m) from 1997 to 2013. Each month at all eight stations in Icy Strait, a Seabird SBE 19plus temperature-depth profiler (CTD) was deployed down to depths of 200 m or within 10 m of the bottom. The CTD profiles were used to determine the 3-m sea surface temperature (SST, °C) and

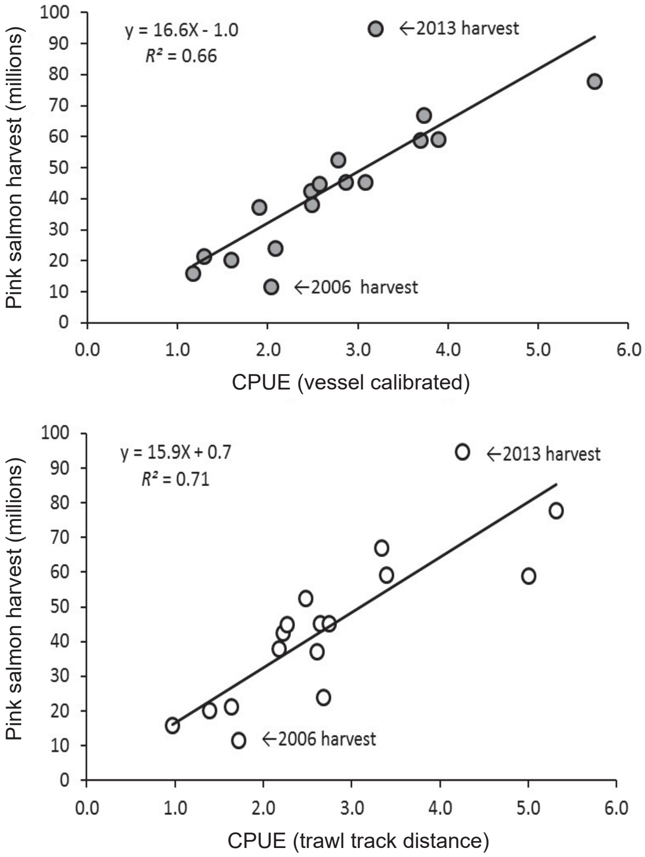

Fig. 5. Simple regression models of peak juvenile pink salmon catch in June/July (CPUE) compared to adult harvest (millions of fish) in Southeast Alaska. The top model uses the vessel calibration metric ($CPUE_{cal}$) and the bottom model uses the trawl track distance metric ($CPUE_{ttd}$). Both models compare juvenile pink salmon ocean entry years 1997–2013 to the harvest years 1998–2014.

salinity (PSU) readings, the average 20-m integrated water column temperature and salinity, and the MLD. The upper 20-m integrated water column temperature along all eight stations, over the four-month period (May–August) was averaged into an Icy Strait Temperature Index (ISTI). The ISTI has a strong association with the previous winter MEI climate signal (Sturdevant et al. 2012, 2013b). The annual ISTI metric represented the summer grand monthly average of the 20-m integrated water column temperature, using ≥ 160 temperatures taken at 1-m increments. The 20-m water column depth bracketed typical seasonal pycnoclines, the MLD, and the depth stratum fished by the surface trawl. The MLD established the active mixing layer and was defined as the depth where the temperature was ≥ 0.2°C colder than the water at 5 m (Kara et al. 2000).

Other physical data sources included a regional source of freshwater discharge and three ocean basin climate indexes. The regional freshwater discharge source was spring river flows from the Mendenhall River (MR, 58°26'N, 134°34'W) near Juneau, Alaska (USGS 2013). The MR watershed drainage is 220 km^2 and the gauge datum is at a height of 183 m above sea level. The MR is fed by both terrestrial and glacial icefield sources, and annual spring flows were calculated as the sum of the monthly average flows for March, April, and May during the year of juvenile pink salmon ocean entry. The three sources for ocean basin climate indexes were derived from online data sets of varied temporal periods for the MEI, the NPI, and the PDO. The MEI reflects conditions measured in the equatorial Pacific that reach Alaska at a later period, so MEI values were lagged about 6 months previous to reflect the potential timing of conditions influencing juvenile pink salmon entering the GOA as juveniles and later as overwintering adults. The MEI values used were the average monthly winter (November-March) values prior to the year of juvenile salmon ocean entry. The NPI is a measure of atmospheric air pressure thought to affect downwelling or upwelling events in the GOA, and spans over the 30°–65°N, 160°E–140°W region of the North Pacific Ocean. The time period chosen for the NPI index was summer (June to August) monthly average conditions in the same year of juvenile salmon ocean entry; a likely time and period that juvenile salmon migration time would intersect typical downwelling conditions that might be relaxed with higher NPI values, thus broadening the width of the Alaska Coastal Current. Because data from later periods would not be accessible in an adequate time for use in the forecast model, the NPI time period did not extend past August. The PDO, a long-term climate signal, represents monthly SST anomalies over the North Pacific Ocean. Average winter PDO values (November–March) were lagged to the ocean year prior to juvenile pink salmon ocean entry.

Fish and zooplankton collections followed established SECM methods documented by Orsi and Fergusson (2014). Juvenile pink salmon metrics from trawl catch samples included: abundance, seaward migration timing, relative catch proportion of the salmon catch, size, energetic content, and preferred prey. A standard measure of pink salmon abundance were catches from trawl hauls fished for 20 min at a speed of approximately 1.5 m/sec (3 knots), a distance of about 1.9 km (1.0 nautical mile). Station coordinates were targeted as the midpoint of the trawl haul, and current, swell, and wind conditions usually dictated the fishing direction. Up to 28 hauls were scheduled at the eight stations in Icy Strait per month. Trawl haul durations were sometimes shortened if survey catches were high or marine mammals were sighted in the vicinity while the trawl was fishing. In these instances, salmon catches were "time adjusted" to a standard 20-min haul. The seaward migration timing of pink salmon was also determined each year by recording the month at which catches were highest (June, July, or August). This metric gives insight to differences in the annual phenology of seaward migrating pink salmon. The catch proportion of juvenile pink salmon was also determined annually, to examine the relative abundance and frequency of juvenile pinks in the hauls. This annual catch proportion was determined by dividing

Table 3. Correlation coefficients for juvenile pink salmon biophysical parameters and ecosystem metrics in year *y* for 1997–2012 with adult pink salmon harvest in Southeast Alaska (SEAK) in year *y* + 1. Parameters with statistically significant correlations displayed in bold text; the probabilities were not adjusted for multiple comparisons. Parameters displayed in bold text were used in the ecosystem rank model.

Parameter	*r*	*P*-value
Juvenile pink salmon abundance and distribution		
$CPUE_{cal}$	**0.82**	**<0.00**
$CPUE_{ttd}$	**0.85**	**<0.00**
August CPUE	-0.10	0.70
Seasonality	**-0.63**	**0.01**
Percentage of juvenile pinks	**0.67**	**0.00**
Juvenile pink salmon growth, condition, predators		
Pink salmon size on 24 July	0.15	0.57
Condition index	0.12	0.65
Energy content	0.12	0.66
Zooplankton standing crop		
June/July average zooplankton total water column	0.09	0.73
June preferred prey	0.03	0.92
Predator index: adult coho harvest(M)/pink $CPUE_{ttd}$	**-0.81**	**0.00**
Local-scale physical conditions		
May 20-m integrated water temperature	0.05	0.85
June 20-m integrated water temperature	-0.25	0.35
Icy Strait temperature index (ISTI)	-0.21	0.44
June mixed-layer depth	0.07	0.81
July 3-m salinity	-0.01	0.98
Mendenhall River spring flow (March–May)	-0.13	0.63
PC1	-0.17	0.53
Basin-scale physical conditions		
Pacific Decadal Oscillation (PDO, *y* - 1)	0.02	0.95
Northern Pacific Index (NPI, June, July, August, [y])	**0.61**	**0.01**
ENSO Multivariate Index (MEI, Nov [*y* - *1*] - March [*y*])	0.25	0.34

the number of juvenile pink salmon caught in a haul by the total abundance of all juvenile salmon caught, averaged across all time periods.

Trawl catch per unit effort (CPUE) of juvenile pink salmon was calculated two different ways. The first method used catch calibrations between vessels (when available) and the second method used the trawl area swept. Wertheimer et al. (2010, 2014) documented methodology for determining vessel calibration to allow direct comparisons across the 18-yr SECM time series. The second CPUE method was based on the trawl area swept, where juvenile salmon catch data were adjusted using catches of fish per trawl haul divided by the over-ground GPS trawl track distance (ttd) between haul start and stop positions ($CPUE_{ttd}$). For each trawl haul, this catch metric was then transformed to a $CPUE_{ttd}$ by computing *Ln* (catch/ttd + 1). No vessel calibrations were needed because any differences in trawling speeds or durations would be reflected in the distance covered. This metric was newly developed in 2013 in an attempt to account for the discrepancy between forecast and harvest using the $CPUE_{cal}$ method in 2012 (Wertheimer et al. 2014).

A juvenile pink salmon predator index was also developed using adult coho salmon returns and an estimate of seaward migrating juvenile pink salmon abundance. Of all the potential juvenile salmon predator species identified and examined onboard during the annual SECM surveys, adult coho salmon have been the most consistent predator species encountered (Orsi et al. 2000; Sturdevant et al. 2012). Therefore, numbers of returning adult coho salmon were obtained from SEAK commercial harvests (M) and divided by the average catch of seaward migrating juvenile pink salmon in the research trawls (adult coho salmon SEAK harvest (M) yr1/juvenile pink salmon ($CPUE_{ttd}$) yr1). This predator index reflected the ratio of adult coho salmon to juvenile pink salmon each year; and the potential likelihood of predation occurring irrespective of other factors such as timing and distributions of either species and the availability of alternative prey resources.

Pink Salmon Forecast Models

A conceptual diagram of the major factors thought to contribute to high pink salmon production in SEAK can be described in a conceptual life-history flow chart (Fig. 3). These metrics are listed chronologically from the time of pink salmon spawning (0 month) to that of subsequent harvest of returning adults in the SEAK fishery (22 months). Each factor could potentially influence production, and all factors would be in alignment in years of maximum production. A more expanded list of ecosystem metrics, such as coastal ocean metrics associated with migrating juvenile salmon and biophysical conditions in a time-lagged format, are shown in Orsi et al. (2013b).

Forecast models were initially developed using linear regression models (Table 1). The primary step-wise model, which has been used over the past ten years, uses a several-step process with step-wise regressions (Orsi et al. 2005, 2006a, 2013a; Wertheimer et al. 2006, 2008, 2009, 2010, 2011, 2012, and 2013). This model generally uses a standard set of ecosystem indicators—modified slightly in some years—and compares them to the pink harvest in SEAK. This model has used vessel-calibrated catch in all years, with the final model selection criteria based on the model fit, Akaike information criterion (AIC), hindcast model performance, and prevailing ecosystem metric trends. Secondary model approaches have also been tested recently: one using the trawl track distance catch ($CPUE_{ttd}$) in lieu of vessel-calibrated CPUE, and another providing annual rank score forecast outlooks based on ecosystem metrics and a visual stoplight color-code graphic.

The process for selection of the "best" step-wise regression model for forecasting the SEAK pink salmon harvest follows Wertheimer et al. (2011):

Step 1: Develop a regression model of annual harvest and juvenile salmon $CPUE_{cal}$, with physical conditions, zooplankton measures, and pink salmon growth indexes considered as additional parameters.

$$\text{Harvest} = \alpha + \beta(Ln[\text{CPUE} + 1]) + \gamma_1 X_1 + \cdots + \gamma_n X_n + \varepsilon,$$

where γ is the coefficient for biophysical parameter *X*. Backward/forward step-wise regression with a significance level of $P < 0.05$ was used to determine whether a biophysical parameter was entered into the model.

Step 2: Calculate the Akiake Information Criterion (AIC) for each significant step of the step-wise regression, to prevent over-parameterization of the model. The AIC was corrected (AICc) for small sample sizes (Shono 2000).

Step 3: Perform 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 juvenile 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 sequentially and used to generate a forecast. The average relative forecast error was then calculated for each potential model identified in Steps 1 and 2.

Step 4: Compare bootstrap confidence intervals (CIs) for the regression prediction intervals (PIs) of the forecasts to examine the effect of process error and measurement error on the forecasts. For the bootstrap approach, monthly juvenile pink salmon catches for each year were randomly re-sampled *nmy* times, where *n* is the number of hauls in month *m* in year *y*. Then the re-sampled catches for each month and year were averaged. For example, the average simulated catches of juvenile pink salmon for the years 1997–2011 were used to construct the regression models with SEAK harvest as the dependent variable, and the appropriate averages of the simulated catches for 2012 were used to forecast the 2013 harvest. This process was repeated 1,000 times, generating 1,000 forecasts for each model. The forecasts were ordered from lowest to highest, and the lowest and highest 10% were removed to define the 80% bootstrap CIs. These results were then compared to the PIs for the regression model based on the observed annual average catches.

Step 5: Select the "best" forecast model in the context of auxiliary run strength indicators. Parameters that had significant bivariate correlation with the SEAK harvest or that were significant auxiliary variables in the step-wise regression model were ranked for each of the SECM data years and tabulated with ranks of the SEAK harvest by year. These parameters were considered to be indicators of ecosystem conditions that could contribute to salmon survival

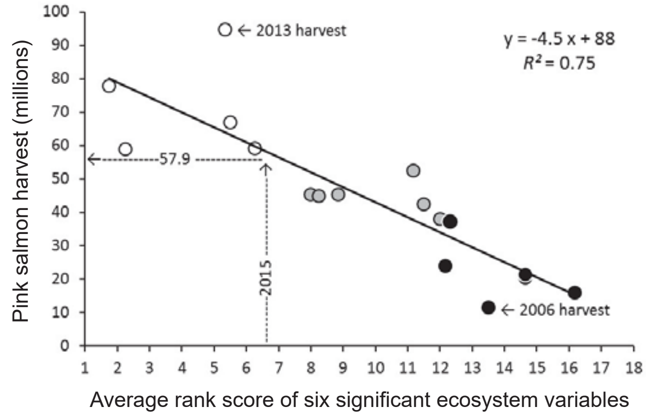

Fig. 6. Average rank score of six significant ecosystem indicators for pink salmon and subsequent harvest (millions of fish) over the harvest years 1998–2014. The six ecosystem metrics are identified in Table 3, and represent juvenile pink salmon CPUE metrics (vessel-calibrated and based on trawl track distance swept), peak juvenile migration month, seasonal proportion of juvenile pink salmon in the total catch, the adult coho salmon predation impact index, and the North Pacific Index in summer. The average rank score for the 2014 ocean year conditions (6.7) is projected forward to anticipate the harvest in 2015. Shading of the circles denotes the magnitude of the harvest outcomes: upper third = open, middle third = gray, and lower third = black.

(Peterson et al. 2012; Orsi et al. 2013c), and their relative ranks were considered for selecting the best regression model to forecast harvest.

The final forecast model approach, the ecosystem rank model, was used to develop a forecast outlook based on ecosystem metrics projected as a visual stoplight chart of annual rank scores. This approach used a suite of six ecosystem metrics and their average rank scores each year. These six ecosystem metrics have been significantly correlated with SEAK pink salmon harvest over the SECM time series, and include: (1) $CPUE_{cal}$, (2) $CPUE_{ttd}$, (3) peak migration month, (4) proportion of pinks in hauls, (5) adult coho predation index, and (6) the NPI. For each of these variables, an average rank score was assigned for each ocean year and ranked from "best" (lowest rank score) to "worst" (highest rank score). The annual rank score represented the strength of the combined variable correlations to the actual pink salmon harvest. A regression model was developed with SEAK pink salmon harvest as the dependent variable and the average rank score as the predictor variable. Annual estimates from this model were then compared to the actual harvest over the time series. It should be noted that the ecosystem metric rank model includes two measures of CPUE abundance ($CPUE_{cal}$ and $CPUE_{ttd}$), so this is not independent of the previous models based on $CPUE_{cal}$. This final forecast model determined a pre-season harvest (point estimate) that was compared to the actual 2014 harvest, and also projected to the 2015 harvest and compared to the other forecast models.

Communication of pre-season pink salmon forecast models are routinely provided to the resource stakeholders

Table 4. Pre-season salmon forecast model estimates and outcomes for predicting pink salmon harvest in Southeast Alaska in 2014 and 2015. The three forecast models tested were: (1) vessel-calibrated peak June or July juvenile pink salmon $CPUE_{cal}$ (*Ln* [catch + 1]), (2) trawl track distance peak June or July juvenile pink salmon $CPUE_{ttd}$ (*Ln* [catch + 1]), and (3) ecosystem rank model based on the relationship between the average rank of six significant bivariate variables and harvest. TBD means actual value is yet to be determined.

Harvest year	Model type	Auxiliary parameter(s)	Pre-season forecast (M)	Adjusted R^2	AIC_c	Actual harvest	Absolute deviation (M)
2014	$CPUE_{cal}$	Icy Strait temperatures May-Aug	29.9	77%	131.2	35.3	15.3%
2014	Ecosystem rank	$CPUE_{cal}$, $CPUE_{ttd}$, migration month, % pink in catch, predator index, & NPI	27.8	78%	NA	35.3	21.2%
2014	$CPUE_{ttd}$	Icy Strait temperature May	51.4	84%	125.6	35.3	45.6%
2015	$CPUE_{cal}$	Icy Strait temperatures May-Aug	54.5	74%	139.7	TBD	TBD
2015	Ecosystem rank	$CPUE_{cal}$, $CPUE_{ttd}$, migration month, % pink in catch, predator index, & NPI	57.9	75%	138.3	TBD	TBD
2015	$CPUE_{ttd}$	Icy Strait temperature May	71.5	81%	134.4	TBD	TBD

at meetings and in electronic formats. One such meeting is the annual SEAK Purse Seine Task Force (PSTF) meeting held each December and rotated throughout communities in SEAK. At the PSTF pre-season forecast, presentations have been given over the past 11 years. In the past two years, additional stoplight chart forecast outlooks using the ecosystem rank models were presented. After the PSTF meeting, information is posted electronically on a NOAA web site for public access (NOAA 2015).

RESULTS

The step-wise linear regression model provided accurate pre-season forecasts for SEAK pink salmon harvests for 9 of the past 11 years (2004–2014) (Fig. 4, Table 2). For the 9 years of "accurate" forecasts, the standard peak $CPUE_{cal}$ model had an overall average absolute deviation of 10% between the forecasts and actual harvests. For all years combined, however, the absolute deviation was 30%, due primarily to "misses" in two ocean years: a low ocean year 2005 (209% over forecast) and a high ocean year 2012 (43% under forecast). Secondary explanatory variables were used in 7 of the 11 years in the step-wise linear regression models to improve model fit and helped to better explain residual error between CPUE and harvest.

Over the 17-yr time series for all the ecosystem metrics, both the standard peak juvenile pink salmon $CPUE_{cal}$ and the peak juvenile pink salmon trawl-track-distance $CPUE_{ttd}$ had strong significant relationships with adult harvest (Fig. 5, Table 3). In each case, most of the variability in harvest (66–71%) was explained by CPUE alone. Similarly, of all the bivariate correlations of ecosystem metrics associated with pink salmon harvest, both CPUE metrics had the strongest positive correlations (Pearson correlations 0.82 and 0.85, $p = 0.00$). Of the other ecosystem metrics considered, four more were also significantly associated with harvest: predation index (Pearson correlation -0.81, $p = 0.00$), proportion of pinks in catch (Pearson correlation 0.67, $p = 0.00$), seasonality (Pearson correlation -0.63, $p = 0.01$), and the NPI (Pearson correlation, 0.61, $p = 0.01$). These six variables have substantial collinearity ranging from [r] = 0.51–0.90. Because of collinearity of the variables only one CPUE parameter is retained in the step-wise regression model.

The ecosystem rank modeling approach used the average rank scores of the six significant ecosystem metrics in Table 3 in order to incorporate a broader set of highly correlated variables that have been indicative of conditions leading to strong recruitment or year-class strength of pink salmon, recognizing there is substantial covariation amongst these variables. This model has performed well for the first two years tested. When regressed against harvest, this rank score forecast outlook predicted results consistent with that of the $CPUE_{cal}$ step-wise regression model in 2014 (Fig. 6). In both 2014 and 2015, the actual predictions based on the rank score regressions, were 6–7% of the standard step-wise regression model based on $CPUE_{cal}$: 27.8 M *vs.* 29.9 M in 2014, and 57.9 M *vs.* 54.5 M in 2015 (Table 4). Conversely, the step-wise regression model based on $CPUE_{ttd}$ differed considerably from average rank score and the $CPUE_{cal}$ step-wise regression model both in 2014 (51.4 M) and in 2015 (71.5 M). The qualitative stoplight chart provided enhanced forecasting communication to stakeholders (Fig. 7). Expressing the average rank score of the six significant bivariate correlations as an outlook and stoplight allowed stakeholders to readily see how the current year compared to others in the time series. For example, the ecosystem conditions in 2013 (2014 return year) ranked 14th of 18 and coded "red" in the bottom third of the ranks while the ecosystem conditions in 2014 (2015 return year) ranked 6th of 18 and coded "green" in the top third of the ranks. Also, the inclusion of additional correlations in the outlook, beyond juvenile salmon CPUE, added more ecosystem-based factors related to production over simple juvenile abundance that had mechanistic linkages, such as predation on salmon, juvenile salmon distribution and timing, and ocean physical conditions (NPI).

Brood year (BY)	Ocean entry year (BY lagged 1 yr later)	Juvenile peak pink (CAL) CPUE June or July	Juvenile peak pink (TTD CPUE June or July	Peak seaward migration month	Proportion of pink in trawl hauls in June-July-Aug	Adult coho predation impact Coho total #s/J-pink CPUE	North Pacific Index (June, Jully, Aug)	Outlook: annual rank score of combined variables		SEAK pink harvest year (BY lagged 2 yrs later)	Actual pink salmon harvest in Southeast Alaska (M)
Data source		*NOAA*	*NOAA*	*NOAA*	*NOAA*	*NOAA ADFG[1]*	*CGD*	↓			*ADFG[2]*
1996	1997	2.5	2.2	July	18%	1.5	15.6	Y	11	1998	42.4
1997	1998	5.6	5.3	June	46%	0.8	18.1	G	1	1999	77.8
1998	1999	1.6	1.4	July	9%	3.9	15.8	R	16	2000	20.2
1999	2000	3.7	3.3	July	28%	1.0	16.9	G	4	2001	67.0
2000	2001	2.9	2.6	July	30%	2.0	16.8	Y	8	2002	45.3
2001	2002	2.8	2.5	July	26%	2.5	15.6	Y	10	2003	52.5
2002	2003	3.1	2.7	July	20%	1.8	16.1	Y	9	2004	45.3
2003	2004	3.9	3.4	June	32%	1.4	15.1	G	5	2005	59.1
2004	2005	2.0	1.7	Aug	35%	3.3	15.5	R	15	2006	11.6
2005	2006	2.6	2.3	June	23%	1.9	17.0	Y	7	2007	44.8
2006	2007	1.2	1.0	Aug	17%	3.7	15.7	R	18	2008	15.9
2007	2008	2.5	2.2	Aug	24%	2.1	16.1	Y	12	2009	38.0
2008	2009	2.1	2.7	Aug	26%	1.7	15.1	R	13	2010	24.0
2009	2010	3.7	5.0	June	60%	0.9	17.6	G	2	2011	58.9
2010	2011	1.3	1.6	Aug	27%	4.1	15.7	R	17	2012	21.3
2011	2012	3.2	4.3	July	49%	1.1	16.7	G	3	2013	94.7
2012	2013	1.9	2.6	July	13%	2.8	16.0	R	14	2014	37.2
2013	2014	3.4	4.6	July	57%	2.1	15.8	G	6	2015	TBD

Outlook Indicator: G = Green Y = Yellow R = Red

Fig. 7. Ecosystem metrics considered for modeling a pre-season "outlook" of pink salmon harvest in Southeast Alaska, 1998-2015. Outlooks are based on the average rank score of six significant variables from 1997 to 2014, and grouped into three categories: BEST = white, AVERAGE = gray, and WORST = black. Pre-season harvest forecast for 2015 is a "BEST" outlook, with a rank of "6", corresponding to the 57.9 M fish harvest shown in Fig. 5, although actual harvest is yet to be determined (TBD). Data source contributors: ADFG[1] = Alaska Department of Fish and Game, L. Shaul; ADFG[2] = S. Heinl; CGD = Climate & Global Dynamics, J. Hurrell, www.cgd.ucar.edu/cas/jhurrell/indices.data.html and NOAA = Auke Bay Laboratories, Southeast Alaska Coastal Monitoring project.

DISCUSSION

This study demonstrates that pre-season forecast models based on coastal ocean ecosystem metrics can accurately predict SEAK pink salmon harvest in most years. The success of these models over the past decade suggests pink salmon production in SEAK is dependent on the proper sequence of favorable life-history events in the context of their early ocean abundance and distribution. In this study, significant relationships were found between juvenile pink salmon catches in summer (peak June or July) and adult harvest, which strongly supports the hypothesis that an early marine critical period related to survival exists prior to this summer period. This period would encapsulate favorable life-history events for pink salmon such as: (1) adequate numbers of fry entering marine nearshore habitats, (2) low levels of predator encounters both near shore and further offshore in strait habitats (Sturdevant et al. 2009, 2012), and (3) sufficient early marine growth to facilitate rapid offshore distribution into the Gulf of Alaska (GOA).

After juvenile pink salmon migrate seaward beyond their first critical period of a few months, they spend another ocean period lasting nearly a year that may also influence production. This second critical period involves overwintering, where inadequate energy stores may contribute to lower growth and size-selective predation resulting in poor survival (e.g. Beamish and Mahnken 2001). Furthermore, even low-level predation events over this period may have a large overall impact due to its relatively long time scale. Pink salmon also migrate extensively throughout the GOA and the North Pacific. When juvenile pink salmon migrate from Icy Strait (58°N) to the GOA they encounter the Alaska Coastal Current that flows northwestward to Kodiak Island (155°W), then southward to as far south as Oregon (44°N) before resuming a northward homeward migration (Takagi et al. 1981)—an overall ocean migration area of 2.26 M km^2. Ocean basin indexes such as the MEI, PDO, and NPI have also been implicated in controlling salmon production. Thus, understanding the ocean distribution of pink salmon and their trophic interactions is key to fully understanding factors affecting year-class strength and projecting accurate salmon forecasts.

The ability to predict harvest from seaward migrating juvenile salmon and associated metrics suggests the later marine survival of pink salmon in the GOA is generally stable (low variance), with the exceptions of the forecast result anomalies in 2006 and 2013, over the past 17 years. However, these deviations of expected model outcomes also afford insight into the role of coastal ecosystem processes and climate on salmon production. The two ocean entry year outliers (2005 and 2012) suggest ensuing periods of intense (2005) and relaxed (2012) ocean mortality after migration from Icy Strait. The 2006 forecast over-estimated returns, while the 2013 forecast under-estimated returns. Ocean conditions in 2005 were anomalously warm, and Orsi et al. (2006b) found a suite of uncommon species (i.e., Humboldt squid [*Dosidicus gigas*], blue sharks [*Prionace glauca*], and Pacific sardines [*Sardinops sagax*]) offshore in the GOA in August which may have contributed to increased predation or competition for resources. Also, in warmer than normal conditions such as in 2005 (Sturdevant et al. 2012), juvenile salmon must consume relatively more prey to sustain growth and meet physiological requirements when temperatures are above optimal threshold. In contrast, ocean conditions in 2012 began warm and then cooled later in the fall to optimize early marine growth and migration. This was also a year of high fish condition residuals and fish diets were composed of high quality large copepods (E. Fergusson, emily.fergusson@noaa.gov, pers. comm.). Fish migrating to cooler GOA waters would also be less likely to encounter warm water predator/competitor complexes in summer and fall, and they could potentially expand their ocean distribution patterns farther south and occupy more habitat during "colder" winters. In addition to SEAK, pink salmon returns were also exceptional in 2013 both northward in Prince William Sound and westward in the Alaska Peninsula, further suggesting extremely favorable GOA ocean conditions in 2012 (Munro and Tide 2014).

A salmon forecast modeling approach should consider trophic interactions that include both "bottom-up" and "top-down" production controls in marine ecosystems (Miller et al. 2013). Seasonal and interannual changes occur in the abundance of planktivorous jellyfish in SEAK (Orsi et al. 2009), which are another potential competitor of juvenile salmon for prey. Thus monitoring jellyfish abundance may be an important indicator of potential "bottom-up" trophic interactions (Purcell and Sturdevant 2001), particularly during periods of environmental change (Brodeur et al. 2008; Cieciel et al. 2009). Companion studies in Icy Strait also indicated that food quantity can be more important than food quality for growth and survival of juvenile salmon (Weitkamp and Sturdevant 2008). As a result, monitoring the composition, abundance, and timing of zooplankton taxa with different life-history strategies may permit the detection of climate-related changes in the seasonality and interannual abundance of prey fields (Park et al. 2004; Coyle et al. 2011; Sturdevant et al. 2013a). In contrast, "top-down" predation events can also affect salmon year-class strength by piscivorous fish (Sturdevant et al. 2009, 2012, 2013b). In terms of competitive interactions, anthropogenic effects of developments such as salmon hatcheries may also impact nearshore habitats. For example, increased hatchery production of juvenile chum salmon has coincided with declines of some wild chum salmon stocks, suggesting a potential negative effect of hatchery stocks on wild ones (Reese et al. 2009). In SEAK, however, SECM and other studies have indicated that salmon growth is not food limited and that stocks interact extensively with little negative impact (Bailey et al. 1975; Orsi et al. 2004; Sturdevant et al. 2004, 2012). In coastal waters, zooplankton prey fields are more likely to be cropped by the more abundant planktivorous forage fish, including walleye pollock (*Gadus chalcogrammus*) and Pacific herring (*Clupea pallasi*) (Orsi et al. 2004; Sigler and Csepp 2007), than by juvenile salmon. These results stress the need to examine the entire epipelagic community in the context of trophic interactions (Cooney et al. 2001; Sturdevant et al. 2012) and to compare ecological processes, community structure, and life-history strategies among salmon production areas (Brodeur et al. 2007; Orsi et al. 2007; Orsi et al. 2012b, 2013b).

Pre-season pink salmon forecasts from this study benefit both fishery resource stakeholders and managers. In addition to informing stakeholders, the data used to model the pink salmon harvest in this study is shared with fishery managers for their pre-season pink salmon forecast models (Piston and Heinl 2013, 2014). The ADF&G uses exponential smoothing models based on brood-year harvest strength to forecast harvest two years later, and in recent years the models have been modified by the SECM juvenile pink CPUE from the prior year (Eggers et al. 2013). The NOAA forecast, as described in this paper, has used the step-wise regression model and is selected based on hindcast performance, AICc scores, and prevailing ecosystem metric trends (Orsi et al. 2005, 2006a, 2013c; Wertheimer et al. 2006, 2008, 2009, 2010, 2011, 2012, and 2013). The use of the SECM data has lowered the ADF&G forecast error. For example, over the 2007–2013 pink salmon harvest years in SEAK, the ADF&G exponential smoothing trend analysis without use of SECM juvenile pink CPUE data had an average forecast error of 32%, but after incorporating the juvenile pink salmon CPUE data into the models the error was reduced to 17% (Wertheimer et al. 2014).

Providing pre-season pink salmon forecasting information helps anticipate the upcoming SEAK pink salmon harvest and inform stakeholders, but developing new approaches to communicating outlooks and forecasts on an "ecosystem level" is also an important objective of this work. Maintaining a qualitative outlook in a visual format of a broad suite of the most important ecosystem metrics is useful to stakeholders so mechanistic factors related to production can be interpreted by a wide audience. The recognition of the role of trophic interactions and mechanistic processes in marine ecosystems is critical, as synergistic factors are influencing year-class strength. In this study, six ecosystem metrics were significantly correlated to SEAK pink salmon harvest over the time series: $CPUE_{cal}$, $CPUE_{ttd}$, peak migration month, proportion of pinks in hauls, adult coho predation index, and the NPI. Past pink salmon forecast models have included variables such as air temperature (Hofmeister 1994), Bayesian model averaging (Adkison 2002), or fall juvenile salmon data from trawl surveys (Shevlyakov and Koval 2012). For other species such as Chinook and coho salmon, ecosystem metrics have also been used to characterize ocean conditions in the northern California Current Large Marine Ecosystem (LME) to forecast these species (Burke et al. 2013; Peterson et al. 2012). Inter-specific relationships of salmon are also important factors to consider, as juvenile pink salmon abundance has been reported to serve as a predation buffer to larger salmon species such as coho salmon in SEAK (LaCroix et al. 2009; Weitkamp et al. 2011).

This study provided insight into linkages among coastal ecosystem processes, salmon production, and climate. The identification of six significant correlations of ecosystem metrics associated with migrating juvenile pink salmon and harvest in this study supports the hypotheses that : (1) early marine mortality is a strong factor determining year-class strength for pink salmon; (2) earlier ocean entry timing (phenology) is an advantage for juvenile pink salmon emigrating from Icy Strait; (3) a higher proportion of pink salmon juveniles relative to the total catch of juvenile salmon in Icy Strait is indicative of a strong pink salmon year class; and (4) pink salmon production is favored when the basin-scale NPI metric in summer (JJA) is high. The higher NPI may contribute to a widening of the Alaska Coastal Current, presumably through relaxed coastal down-welling, thus enabling fish to be transported further offshore along the productive continental shelf. We did not find a direct association between water temperatures in the upper water column and pink salmon run strength in SEAK. However, upper water temperatures were frequently an auxiliary parameter in the step-wise regression model, and indicated that while not the principal driver parameter, cooler spring/summer water temperatures resulted in somewhat higher survival of a given cohort of SEAK pink salmon. Continued observations and monitoring in SEAK will provide additional insight to linkages among climate, coastal ecosystem processes, and future salmon production, particularly during anomalous periods such as the "warm blob" event that occurred in the North Pacific during 2014 (Bond et al. 2015).

CONCLUSION

Results from this study indicate pink salmon forecast models using coastal ecosystem metrics can accurately predict SEAK harvest in most years, and provide a valuable management tool to benefit resource stakeholders, foster sustainable fisheries, and identify linkages among climate, coastal ecosystem processes, and salmon production.

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