Using Salmon Survey and Commercial Fishery Data to Index Nearshore Rearing Conditions and Recruitment of Alaskan Sablefish

Authors: Yasumiishi, Ellen M., Shotwell, S. Kalei, Hanselman, Dana H., Orsi, Joseph A., and Fergusson, Emily A.

Source: Marine and Coastal Fisheries: Dynamics, Management, and Ecosystem Science, 7(7) : 316-324

Published By: American Fisheries Society

URL: https://doi.org/10.1080/19425120.2015.1047070

Marine and Coastal Fisheries: Dynamics, Management, and Ecosystem Science 7:316–324, 2015
Published with license by the American Fisheries Society
ISSN: 1942-5120 online
DOI: 10.1080/19425120.2015.1047070

ARTICLE

Using Salmon Survey and Commercial Fishery Data to Index Nearshore Rearing Conditions and Recruitment of Alaskan Sablefish

Ellen M. Yasumiishi,* S. Kalei Shotwell, Dana H. Hanselman, Joseph A. Orsi, and Emily A. Fergusson
National Marine Fisheries Service, Alaska Fisheries Science Center, 17109 Point Lena Loop Road, Juneau, Alaska 99801, USA

Abstract
We examined physical and biological indices from Pacific salmon *Oncorhynchus* spp. surveys and commercial fisheries to index nearshore rearing habitats used by age-0 and age-1 Sablefish *Anoplopoma fimbria* in the eastern Gulf of Alaska and as indicators for their recruitment to age2 during the period 2001–2013. The best-fitting general linear model used to estimate age-2 Sablefish recruitment included chlorophyll-*a* concentration during late August and an index of juvenile Pink Salmon *O. gorbuscha* abundance during the age-0 stage of Sablefish. The model and biophysical indices from 2012 and 2013 produced a forecast of 23 million age-2 Sablefish for 2014 and a forecast of 8 million Sablefish for 2015. This study highlights the opportunity to use proxies for direct ambient physical and biological observations of rearing habitats in estimating groundfish recruitment to older ages.

Environmental forcing during early life stages often plays a critical role in determining the survival of marine fish (Cushing 1969; Houde 1987). Sablefish *Anoplopoma fimbria* in Alaska have had several high recruitment events during periods of low observed spawning biomass; therefore, recruitment does not appear to be closely related to the level of spawning biomass and is more likely related to environmental effects on survival during early life stages (Hanselman et al. 2013). Sablefish recruitment was positively correlated with the intensity of the winter Aleutian low-pressure system (hereafter, Aleutian Low; McFarlane and Beamish 1992) and associated conditions, such as cooler-than-average winter sea surface temperatures (SSTs) in the central North Pacific and warmer-than-average summer sea temperatures in the Gulf of Alaska (GOA; Sigler et al. 2001; Shotwell et al. 2014). One hypothesized mechanism is an increase in primary productivity (PP) from phytoplankton blooms and the subsequent effects on survival of and prey availability for Sablefish in nearshore rearing habitats (Shotwell et al. 2014). In the present study, we explore the value of using salmon survey and commercial fishery data from Southeast Alaska (SEAK) to index nearshore rearing conditions and recruitment of Alaskan Sablefish.

The Sablefish is a long-lived, deep-dwelling, oily fleshed species of commercial importance. Sablefish are distributed across the North Pacific Ocean from northern Mexico to the Bering Sea, but the bulk of the Alaskan population is primarily located in the GOA, where they are subject to a major commercial fishery (Hanselman et al. 2013). Of the six major

Subject editor: Donald Noakes, Vancouver Island University, Nanaimo, British Columbia

*Corresponding author: ellen.yasumiishi@noaa.gov
Received November 6, 2014; accepted April 10, 2015

groundfish groups in Alaska, Sablefish ranked fourth in ex-vessel value at US$120.3 million and sixth in catch at 13,900 metric tons during 2012, but the price per pound (1 lb = 0.4536 kg) of Sablefish was highest at $4.18 ($9.22 per kg), in comparison with less than $0.30 ($0.66 per kg) for the other groundfish groups (Fissel et al. 2013).

Alaskan Sablefish are typically encountered at depths of 200–1,000 m along the continental slope, in shelf gullies, and in deep-sea canyons (Wolotira et al. 1993). They are thought to spawn at depths of 300–500 m along the upper continental slope during winter (Mason et al. 1983). Eggs and yolk sac larvae are initially found at depths greater than 200 m; the larvae then migrate to the surface and are neustonic for the remainder of the age-0 stage, being present in the central and eastern GOA during spring and summer (Mason et al. 1983; Moser et al. 1994; Sigler et al. 2001). During mid- to late summer, age-0 Sablefish are advected onshore by currents and settle out in bays and inlets along the coast, where they spend the next 1–2 years (Rutecki and Varosi 1997; Maloney and Sigler 2008). Consequently, the coastal waters of Alaska are important rearing habitats for age-0 and age-1 Sablefish.

Quantifying the conditions associated with nearshore rearing habitat used by age-0 and age-1 Sablefish may help in predicting the success of incoming year-classes to the fishable population at age 2 and older ages. Assessments of the Alaskan Sablefish population are based on catches of Sablefish during annual fishery surveys using longline gear along the upper continental slope from the southern tip of SEAK to 60°N in the Bering Sea (Lunsford and Rodgveller 2013). Information on catch, effort, age, length, weight, and maturity is used to estimate the abundance of age-2 and older Sablefish (Hanselman et al. 2013). Indexing of the nearshore rearing habitat used by age-0 and age-1 Sablefish may provide an early indication of the strength of the incoming year-class.

Observations of juvenile Sablefish in pelagic surveys of nearshore habitats are typically rare (Rutecki and Varosi 1997; Orsi et al. 2013b). This may be due to the settlement of age-0 Sablefish into bays, their diel vertical migrations (Wing and Kamikawa 1995), and their ability to evade capture via the standard surface-trawl survey techniques used to sample juvenile fishes in nearshore habitats—specifically, by vertically migrating to deeper depths below the trawl or by inhabiting non-strait habitats and shallower waters (Orsi et al. 2013b). Thus, a time series of juvenile Sablefish abundance is not available from surveys; however, information on co-occurring species and nearby strait habitats might provide a usable substitute for Sablefish rearing conditions.

Pink Salmon *Oncorhynchus gorbuscha* also inhabit the coastal waters of Alaska during their seaward migration and on their return to spawn in freshwater (Heard 1991). Therefore, rearing conditions for and the abundance of juvenile Pink Salmon may serve as suitable indices for age-0 Sablefish survival. Pink Salmon are considered juveniles from the time of seawater entry in the spring and summer to the end of December; they are considered adults from January 1 to the time of freshwater entry for the spawning migration. Pink Salmon inhabit nearshore waters during the spring and summer of their juvenile stage; they move offshore during the fall, remaining there during winter and spring, and then return to nearshore waters during summer. Age-0 Sablefish and juvenile Pink Salmon reach a similar size and feed on similar prey (Sigler et al. 2001). Age-0 Sablefish (<200 mm SL) initially feed primarily on euphausiids and pelagic tunicates but later become more piscivorous as they increase in size (Laidig et al. 1997; Sigler et al. 2001). Juvenile Pink Salmon (<300 mm FL) primarily feed on amphipods, euphausiids, fishes, and copepods in northern waters of SEAK. Adult Pink Salmon feed upon and compete with Sablefish; they are known to feed on age-0 Sablefish and their prey (Kaeriyama et al. 2000). Age-0 and age-1 Sablefish also feed on salmon eggs and tissue that are washed out from rivers into saltwater (Coutré 2014). The catch of juvenile Pink Salmon in nearshore surveys acts as a valuable pre-season forecasting tool for the commercial harvest of adult Pink Salmon in SEAK during the following year (Orsi et al. 2013a; Wertheimer et al. 2013). Indices of juvenile Pink Salmon abundance may be useful as proxies for growth and survival of age-0 Sablefish and as indicators of Sablefish recruitment to age 2.

We hypothesized that physical and biological indicators from fisheries and oceanography surveys that target juvenile Pink Salmon would be useful for understanding relationships between the two co-occurring species and for predicting Sablefish recruitment. We employed a generalized linear model to evaluate the importance of summer conditions during the Sablefish age-0 stage for the subsequent recruitment of Sablefish to age 2 by using Pink Salmon returns and biophysical indices from a survey conducted in nearshore strait habitats during late July and late August. In addition, our model and biophysical data were used to forecast age-2 recruitment 2 years in advance. These conditions included (1) summer SST; (2) summer PP, as measured by chlorophyll-*a* concentration; (3) abundance of juvenile Pink Salmon; and (4) abundance of adult Pink Salmon. We expected that Sablefish recruitment to age 2 would be (1) positively related to the nearshore summer SST and PP measured during the Sablefish age-0 stage, (2) positively related to juvenile Pink Salmon (indicator species) abundance during the Sablefish age-0 stage, and (3) negatively related to adult Pink Salmon (predator and competitor) abundance during the Sablefish age-0 stage. Possible mechanisms for increased Sablefish survival included favorable ocean conditions for growth and feeding (warm nearshore summer SST), increased ocean productivity (higher chlorophyll-*a* concentration), and greater survival of co-occurring species (juvenile Pink Salmon) during the Sablefish age-0 stage; and reduced predatory and competitive interactions between adult Pink Salmon and age-0 Sablefish.

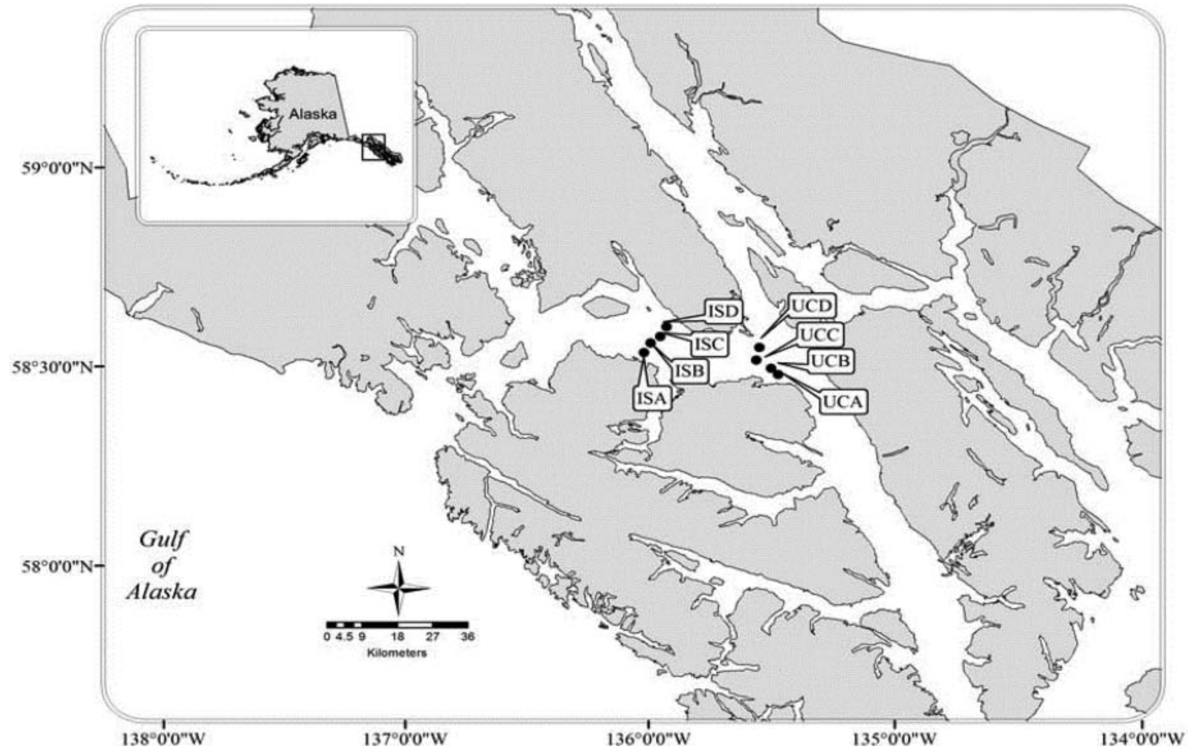

FIGURE 1. Northern waters of Southeast Alaska, where sea surface temperature, primary productivity, and juvenile Pink Salmon abundance were sampled along two transects. Sampling occurred at four stations per transect: Icy Strait stations A–D (ISA, ISB, ISC, and ISD) and Upper Chatham Strait stations A–D (UCA, UCB, UCC, and UCD).

METHODS

We examined data from the Southeast Alaska Coastal Monitoring (SECM) project (National Marine Fisheries Service [NMFS]) in conjunction with commercial fisheries data to determine factors affecting Sablefish recruitment to age 2 in nearshore habitats. Surveys were conducted in Icy Strait and Upper Chatham Strait in the northern region of SEAK during late July and late August from 1999 to 2013 (Figure 1; Orsi et al. 2013b). Biophysical variables that were recorded during the SECM surveys and used in this study included SST, PP, and the CPUE of juvenile Pink Salmon. Information on commercial harvest and escapement was used to index juvenile and adult Pink Salmon abundances. Some age-0 Sablefish were captured, indicating that they can co-occur with juvenile and adult Pink Salmon in the survey area, but the Sablefish catches were not consistent over time and were too sporadic to be used in the time series analysis. A multiple regression model was used to examine the relationship between Sablefish recruitment and biophysical indices.

Response variable.—Abundance estimates for age-2 Sablefish in Alaskan waters were taken from the GOA Sablefish assessment (Figure 2; Hanselman et al. 2014). Fishery-independent information (annual longline and trawl surveys) included age and length compositions and survey abundance indices. Fishery-dependent information included foreign and domestic fishery catch, fishery age and length compositions, and CPUE.

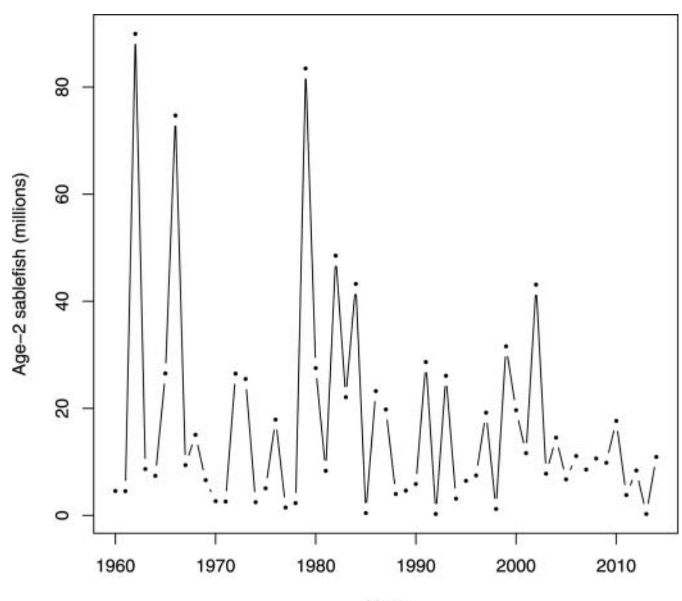

FIGURE 2. Age-2 Sablefish recruitment estimates from the stock assessment report by Hanselman et al. (2014). Years represent age-2 recruitment years, so age-0 Sablefish occurred 2 years earlier (i.e., age-2 Sablefish that recruited in 2001 were exposed to conditions as age-0 fish in 1999).

The Sablefish stock assessment model (Hanselman et al. 2013) estimates parameters simultaneously while allowing for missing data within a penalized maximum likelihood function; the model produces spawning stock biomass, recruitment, and fishing mortality estimates as well as projections of future harvest scenarios. Recruitment is computed as mean recruitment with annual recruitment deviations rather than as a stock–recruitment relationship (Hanselman et al. 2013). Sablefish recruits are defined as 2 year olds because this is the first age at which Sablefish are caught in traditional adult surveys. As age and length compositions for each year are added to the stock assessment model, the amount of information on year-class strength increases (i.e., estimates of age-3 fish in the next year adds information on the strength of age-2 fish in the prior year). Estimates of age-2 Sablefish recruitment were available from 1960 to 2014—the period over which (1) abundance data were available for use in the stock assessment model and (2) recruitment was reasonably well estimated (Hanselman et al. 2014). Initial estimates of age-2 Sablefish are uncertain, so as more demographic data are collected the estimates of year-class strength become more precise. To formulate our model, we used stock assessment model estimates of age-2 Sablefish recruitment for the years 2001–2013, as those estimates were more recent and more certain. The model coefficients and biophysical indices from 2012 and 2013 were then used to make predictions of age-2 Sablefish abundance for 2014 and 2015.

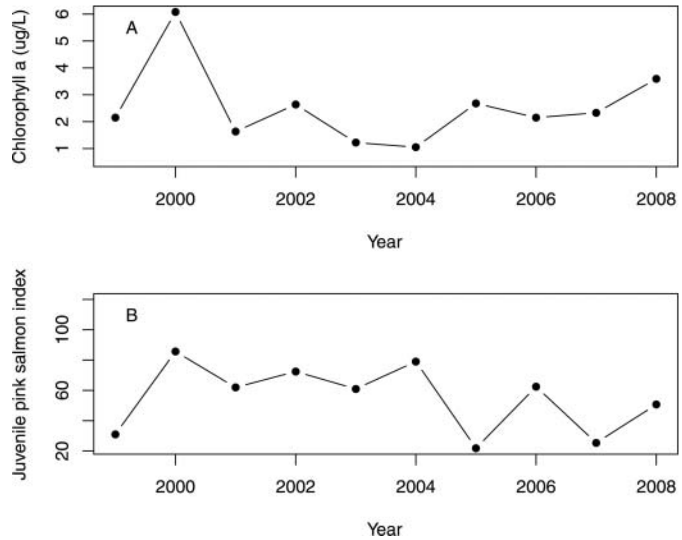

FIGURE 3. Statistically significant predictor variables and data used in estimation of model coefficients (2001–2013) and predictions (2014–2015) of Sablefish recruitment at age 2. Predictor variables are **(A)** maximum chlorophyll-*a* concentration at the Icy Strait stations during late August; and **(B)** juvenile Pink Salmon production based on Pink Salmon adult returns to Southeast Alaska. Year corresponds to the age-0 life stage of Sablefish (t – 2) that was related to age-2 Sablefish recruitment in year t.

Ecological predictors.—We used oceanographic indices (SST and PP) from Icy Strait due to the potential mixing of the water column at the Chatham Strait transect. Temperature was measured at 3-m depth by using an SBE 19plus SeaCAT CTD Profiler (Sea-Bird Electronics). Water samples taken from the surface were analyzed for chlorophyll-*a* concentration (μg/L) as an indicator of PP. Annual average and maximum values of SST and PP for July and August were calculated from the four stations at the Icy Strait transect.

A juvenile Pink Salmon abundance index, calculated as juvenile CPUE ($\text{Jpink}_{\text{CPUE}}$), was used as a proxy for ocean productivity and fish survival. Juvenile Pink Salmon were sampled with a Nordic 264 rope trawl that was modified to fish from the surface to 20 m directly astern of the trawl vessel (Orsi et al. 2013b). Station coordinates were targeted as the midpoint of the trawl haul; current, swell, and wind conditions usually dictated the setting direction. Several different vessels were used over time, and calibrations were made to standardize catch whenever possible (Wertheimer et al. 2010). The $\text{Jpink}_{\text{CPUE}}$ values for July and August were calculated as the average of juvenile Pink Salmon CPUEs at the eight stations.

An alternative index of juvenile Pink Salmon abundance ($\text{Jpink}_{\text{adults}}$) was constructed from returns (catch plus escapement) of adult Pink Salmon to SEAK (Figure 3B). The $\text{Jpink}_{\text{adults}}$ index was useful because the time series encompassed the outcome of conditions that influenced overwinter survival for juvenile Pink Salmon (i.e., from fall to the following summer) during the first year at sea, a proxy for overwinter survival of Sablefish from age 0 to age 1. Adult Pink Salmon abundance (Apink) in year t – 1 was used to represent juvenile Pink Salmon abundance in year t – 2.

Abundances of adult Pink Salmon during the age-0 stage of Sablefish were also indexed as adult Pink Salmon returns (catch plus escapement) to SEAK. Data were from the Alaska Department of Fish and Game (Piston and Heinl 2013).

Correlation analysis.—A correlation analysis using Pearson's product-moment correlation was used to examine the relationships between predictor variables. A Bonferroni correction factor was applied to the α-value ($\alpha = 0.05$). Correlated predictor variables were included separately in the Sablefish regression model. Statistical analyses were conducted in R version 3.0.3 (R Development Core Team 2014).

Recruitment model.—A generalized linear regression model was used to relate age-2 Sablefish recruitment to biophysical parameters,

$$\begin{aligned}\text{Sablefish}_t = {} & (\beta_1 \cdot \text{SST}_{t-2}) + (\beta_2 \cdot \text{PP}_{t-2}) \\ & + (\beta_3 \cdot \text{Jpink}_{t-2}) + (\beta_4 \cdot \text{Apink}_{t-2}) + e_t,\end{aligned} \quad (1)$$

where SST is sea surface temperature, PP is chlorophyll-*a* concentration, Jpink is juvenile Pink Salmon abundance, Apink is adult Pink Salmon abundance, β is the coefficient estimate, e is error, and t is year. Error was assumed to be normally

TABLE 1. Candidate biophysical indices (predictor variables) used in the model of age-2 Sablefish recruitment in northern waters of Southeast Alaska (SST = sea surface temperature; PP = primary productivity).

Predictor variable	Symbol
Oceanographic indices	
Mean SST at the four Icy Strait stations during late July (year $t-2$)	SST1
Maximum SST at the four Icy Strait stations during late July (year $t-2$)	SST2
Mean SST at the four Icy Strait stations during late August (year $t-2$)	SST3
Maximum SST at the four Icy Strait stations during late August (year $t-2$)	SST4
Mean chlorophyll-*a* concentration at the four Icy Strait stations during late July (year $t-2$)	PP1
Maximum chlorophyll-*a* concentration at the four Icy Strait stations during late July (year $t-2$)	PP2
Mean chlorophyll-*a* concentration at the four Icy Strait stations during late August (year $t-2$)	PP3
Maximum chlorophyll-*a* concentration at the four Icy Strait stations during late August (year $t-2$)	PP4
Indices of juvenile Pink Salmon abundance during Sablefish Age 0	
Mean juvenile Pink Salmon CPUE at Icy Strait and Chatham Strait stations during late July (year $t-2$)	Jpink1
Mean juvenile Pink Salmon CPUE at Icy Strait and Chatham Strait stations during late August (year $t-2$)	Jpink2
Southeast Alaska Pink Salmon production (harvest plus escapement of returning adults in year $t-1$)	Jpink3
Predator index	
Southeast Alaska Pink Salmon production during Sablefish age 0 (harvest plus escapement of returning adults in year $t-2$)	Apink

distributed, with a mean of zero and a constant variance. The SDs of the stock assessment estimates were added to the SEs of the fitted values from equation (1). Candidate predictor variables are listed in Table 1.

Selection of the best-fitting generalized linear regression model was based on cross-validation criteria and the Bonferroni correction factor. Cross validation was conducted to select the model with the best performance by using the "bestglm" package (version 0.34) in R. An additional penalty was imposed on the *t*-values of the significant predictor variables to account for the 12 possible predictors (at an α-value of 0.05) by using the Bonferroni correction factor ($P < \alpha$/[number of predictor variables]). Coefficients with *P*-values less than 0.004 (i.e., 0.05/12) were considered statistically significant at the 95% level. Summary statistics included the R^2, the *F*-statistic for R^2, and the *P*-value for the *F*-statistic. For each model, we tested the following assumptions: (1) homoscedasticity of the residuals (plot of absolute residuals versus fitted values; and a Goldfeld–Quandt test), (2) normality of the residuals (*Q*–*Q* plots; and a Shapiro–Wilk test), (3) absence of multicollinearity (Pearson's product-moment correlation), and (4) absence of autocorrelation in the residuals (correlograms of the autocorrelation function estimates).

Predictions of Sablefish recruitment to age 2 were made by using the coefficient from the best-fitting model and biophysical indices. Biophysical indices from 2012 and 2013 were entered into the model to produce estimates of age-2 Sablefish recruitment for 2014 and 2015. Model predictions for 2014 were compared with stock assessment estimates of age-2 Sablefish recruitment in 2014.

RESULTS

Correlation Analysis

Pearson's product-moment correlation coefficients relating predictor variables used in the Sablefish model are given in Table 2. Significant correlations were found between mean and maximum values of SST and PP within each month, except between the mean and maximum PP index for August. Therefore, the mean and maximum values of SST and PP were added separately to the Sablefish model. Mean August PP was correlated with mean July PP, maximum July PP, and maximum August PP, so these variables were included in separate models. The $\text{Jpink}_{\text{CPUE}}$ index for July and the $\text{Jpink}_{\text{adults}}$ index were introduced separately in the Sablefish model.

Recruitment Model

The best-fitting generalized linear model identified by cross validation included 3 of the 12 possible variables: maximum SST during late August, maximum chlorophyll-*a* concentration (i.e., PP) during late August, and $\text{Jpink}_{\text{adults}}$. However, the SST coefficient was not significant after Bonferroni correction (Bonferroni-corrected $\alpha = 0.004$, but $P = 0.02$), so SST was removed from the model. The final model therefore included maximum chlorophyll-*a* concentration during late August and $\text{Jpink}_{\text{adults}}$ (Table 3). The model residuals were normally distributed (Shapiro–Wilk test: $W = 0.9625$, $P = 0.7924$), were homoscedastic (Goldfeld–Quandt test: GQ = 2.1155, $P = 0.2439$), and had no serial correlation. The biophysical indices captured 79% of the variability in stock assessment estimates of age-2 Sablefish recruitment.

TABLE 2. Pearson's product-moment correlation coefficients for the predictor variables used in the Sablefish recruitment model (codes for predictor variables are defined in Table 1). Values in bold italics represent significant correlations.

Predictor variable	SST2	SST3	SST4	PP1	PP2	PP3	PP4	Jpink1	Jpink2	Jpink3	Apink
SST1	***0.91***	0.49	0.50	−0.26	−0.13	−0.53	−0.22	−0.23	−0.39	0.09	0.28
SST2		0.43	0.46	−0.30	−0.16	−0.22	−0.18	−0.41	−0.23	0.06	0.37
SST3			***0.94***	−0.39	−0.34	−0.48	−0.32	−0.08	−0.15	0.05	0.33
SST4				−0.45	−0.37	−0.51	−0.41	−0.17	−0.14	−0.12	0.40
PP1					***0.90***	***0.76***	0.55	−0.29	0.47	−0.42	0.06
PP2						***0.76***	***0.66***	−0.25	0.56	−0.31	−0.02
PP3							***0.84***	−0.46	0.34	−0.35	−0.08
PP4								−0.09	0.34	0.04	−0.30
Jpink1									0.03	***0.65***	−0.45
Jpink2										−0.29	−0.12
Jpink3											−0.47

The final model and biophysical indices from 2013 and 2014 yielded a prediction of 22.8 million (SD = 4.54 million) age-2 Sablefish for 2014 and a prediction of 8.46 million (SD = 1.43 million) age-2 Sablefish for 2015 (Figure 4). Our 2014 estimate was high due to the large return of adult Pink Salmon in 2013, indicating favorable survival conditions for Sablefish from age 0 to age 1 in 2012–2013. The 2014 estimate from our model was two times higher than the stock assessment estimate of age-2 Sablefish recruitment for 2014. Future estimates of age-2 Sablefish abundance from the stock assessment model and based on survey data will help to determine the performance of these models for predicting recruitment.

DISCUSSION

Our study focused on the use of survey and fishery data to index environmental conditions during the age-0 stage of Alaskan Sablefish and predict their recruitment to age 2. Previous studies have primarily focused on environmental conditions during the winter prior to and during the age-0 stage (McFarlane and Beamish 1992; Sigler et al. 2001; Shotwell et al. 2014). We found that significant indicators for the estimated recruitment of age-2 Sablefish included late-summer SST, late-summer PP, and a juvenile Pink Salmon abundance index during age 0.

All of the relationships were positive. Higher recruitment of Sablefish to age 2 was associated with higher chlorophyll-*a* concentrations in nearshore areas during late summer of the Sablefish age-0 stage and with higher Pink Salmon productivity, possibly the result of increased storms during an intensified Aleutian Low. Previous studies support this relationship. For example, McFarlane and Beamish (1992) showed that Sablefish year-class strength in British Columbia during 1965–1980 was positively correlated with the Aleutian Low index ($R^2 = 0.53$, $P < 0.001$) and copepod abundance in the central Northeast Pacific at Ocean Station Papa ($R^2 = 0.45$, $P < 0.001$), indicating that stronger year-classes were associated with climate-related changes in prey abundances. At about 40 d posthatch (usually in March), larval Sablefish generally absorb their yolk sacs and begin feeding on copepods, the most abundant zooplankton in the water column (McFarlane and Beamish 1992). McFarlane and Beamish (1992) further hypothesized that the more intense Aleutian Low resulted in (1) greater upwelling of nutrients to the surface, which improved PP; and (2) greater wind transport of nutrients and plankton from offshore to nearshore waters, which in turn increased the survival of Sablefish by increasing the

TABLE 3. Best-fitting model describing age-2 Sablefish recruitment (year t) estimates (2001–2013) as a function of biophysical indices during the age-0 life stage (1999–2011; PP_{t-2}= primary productivity [chlorophyll-*a* concentration] during the Sablefish age-0 life stage [year $t-2$]; $Jpink_{adults,t-2}$ = juvenile Pink Salmon abundance index during year $t-2$ based on Pink Salmon adult returns to Southeast Alaska in year $t-1$). Coefficient statistics include the estimate, t-value, and associated P-value for the significant predictor variables in the generalized least-squares regression model of recruitment. Model statistics include the adjusted R^2, F-statistic, and associated P-value.

	Coefficient statistics			Model statistics		
Predictor variable	Estimate	t	P	Adjusted R^2	F	P
PP_{t-2}	0.739	5.796	0.00012	0.79	25.3	0.000077
$Jpink_{adults,t-2}$	0.497	3.895	0.00249			

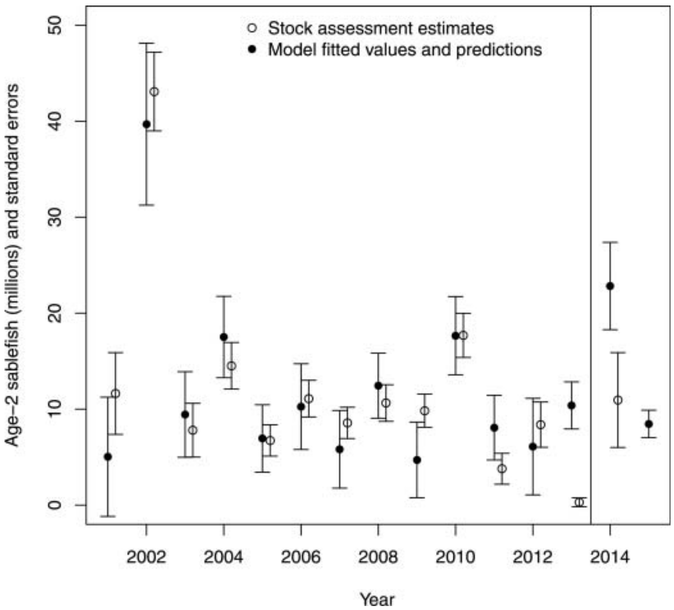

FIGURE 4. Estimates (±SE) of age-2 Sablefish recruitment from the stock assessment by Hanselman et al. (2014; open circles, 2001–2014); and estimates (solid circles, 2001–2013) and forecasts (solid circles, 2014–2015) from the generalized linear regression model describing age-2 recruitment as a function of the chlorophyll-*a* concentration and juvenile Pink Salmon abundance index during the Sablefish age-0 life stage (adjusted $R^2 = 0.79$, $P = 0.000077$).

production of copepods, their primary prey. Shotwell et al. (2014) developed a conceptual model of Sablefish recruitment (termed the ocean domain dynamic synergy [ODDS] model) that consisted of three linked mechanisms relating to intensification of the Aleutian Low. First, an increase in atmospheric and oceanic cyclonic circulation results in a match between the arrival of Sablefish larvae and the arrival of cool, productive water from the central North Pacific Ocean to the outer-shelf domain. Second, increased anti-cyclonic eddy activity in the mid-shelf domain entrains nutrients and prey that are used by Sablefish. Third, increased stratification along the coast due to warmer SSTs may result in an earlier spring phytoplankton bloom and enhanced zooplankton biomass, which could increase the growth of juvenile Sablefish in the nearshore zone and subsequently enhance survival. We explored conditions more associated with this third mechanism for their effects on the nearshore timing of Sablefish early life history and found that the late-summer SST and PP indicative of a late-summer phytoplankton bloom were particularly related to Sablefish recruitment.

Summer SST in nearshore waters during the Sablefish age-0 stage was not a significant predictor of age-2 Sablefish recruitment after we accounted for the number of predictors in our model. However, previous studies have shown that temperature can affect Sablefish recruitment via direct and indirect influences on motor activity, feeding, growth, and size (Sigler and Zenger 1989; Sigler et al. 2001). In adult Sablefish, feeding activity (number of squid consumed) was 33–71% greater at higher water temperatures (8°C) in comparison with colder water temperatures (2°C; Stoner and Sturm 2004). Higher temperatures also reduced the time required by Sablefish to attack, consume, and handle squid bait (Stoner and Sturm 2004). For Sablefish that were collected off the Oregon coast, the otolith-derived growth rate of late larvae and early juveniles was positively correlated with body size and temperature; furthermore, growth rate was positively correlated with recruitment except during the 1997 El Niño, when growth was high and survival was low—possibly due to poor feeding conditions in late summer (Sogard 2011). The late-summer maximum SSTs (10.7–14.5°C) observed during the years included in our study may have been within the optimum range favoring Alaskan Sablefish recruitment.

Late-summer PP in Icy Strait explained most of the variability in age-2 Sablefish recruitment over the 13-year time series. The two sporadic high-recruitment events for age-2 Sablefish in 2002 and 2010 corresponded with high PP levels for age-0 Sablefish in Icy Strait during late August of 2000 and 2008. A threefold increase in PP during late August suggests the occurrence of a late-summer phytoplankton bloom. We hypothesize that the high PP in late summer may increase the supply of nutrients and prey for age-0 Sablefish prior to winter, thereby increasing fish energy stores and, in turn, overwinter survival. The “critical size and critical period” hypothesis (Beamish and Mahnken 2001) states that if fish are larger and have higher energy density by fall, then they have an increased likelihood of surviving the winter. Long-term monitoring of late-summer PP and the feeding habits and whole-body energy of age-0 Sablefish could contribute to a better understanding of the influence of late-summer phytoplankton blooms on Sablefish recruitment.

Juvenile Pink Salmon abundance during the Sablefish age-0 stage, as indexed by returns of adult Pink Salmon ($\text{Jpink}_{\text{adults}}$), was a positive predictor of Sablefish recruitment to age 2. We found that $\text{Jpink}_{\text{adults}}$ was a better survival index than $\text{Jpink}_{\text{CPUE}}$. Returning adult Pink Salmon represent the portion of the population that survived the first winter at sea, whereas the CPUE of juvenile Pink Salmon represents the abundance of the population prior to overwintering mortality. The $\text{Jpink}_{\text{CPUE}}$ index is also just a snapshot of the juvenile population at one point in time and therefore may not be as accurate as juvenile abundance indices based on adult returns. Estimates of adult returns based on escapement and catch are also prone to error. As a postmortality index, the abundance of returning adult Pink Salmon provides an index of the Pink Salmon population closer to the time of Sablefish recruitment to age 2 and indicates additional survival conditions through the first winter of life. Furthermore, Pink Salmon juveniles may spend time on the continental shelf during late fall, near the area where age-0 Sablefish enter in late summer to rear and overwinter for up to 2 years. Our results indicate that the abundance of juvenile Pink Salmon is a reasonable proxy for growth and survival conditions experienced by age-0 Sablefish due to the similarity in size, growth rates, and diets between these two groups of fish.

Results of the present study demonstrate that indices of nearshore rearing habitats have potential as a means of forecasting Sablefish recruitment. The magnitude of late-summer PP and the survival of a co-occurring species were shown to correlate with Sablefish recruitment. Our present results contributed to ecosystem considerations within the Alaskan groundfish Stock Assessment and Fishery Evaluation Report (Zador and Aydin 2013). The report provides current ecosystem conditions and their impacts on fish populations. In the management of marine ecosystems, an ecosystem approach to fisheries involves incorporating ecosystem factors into fisheries stock assessments so as to support tactical management decisions (Link 2010; Idhe and Townsend 2013). Currently, our model only provides a qualitative measure of whether to expect above-average or below-average recruitment of Sablefish. A longer time series of ocean productivity will be necessary to match the time series of the stock assessment estimates; an evaluation of correlations between ocean productivity indices and uncertainty in stock assessment estimates of abundance is also needed.

There are several caveats to consider in the context of our study. First, the examined time series of biophysical indices was short (13 years) relative to the available time series of the age-2 Sablefish recruitment index (55 years, beginning in 1960). Second, we did not examine the relationship between biophysical indices and the uncertainty in recruitment estimates from the stock assessment model. Third, the present study was based on correlation analyses and was not supported by a process study directed at addressing Sablefish early life history. Although the significant correlations we identified were corroborated by previous findings in field research on Pink Salmon, the correlations do not necessarily equal causation. For example, Cooney et al. (2001) found that two co-occurring species—juvenile Pink Salmon and juvenile Pacific Herring *Clupea pallasii*—used different portions of the annual production cycle in the northern GOA. Cooney et al. (2001) also highlighted the importance of seeking mechanisms rather than a correlative understanding of complex marine ecosystems. The next logical step will be to develop a long-term monitoring project for sampling nearshore areas where age-0 Sablefish have historically occurred.

In summary, our study highlights the potential value of using fisheries and oceanography survey data and information from a commonly sampled species to index conditions experienced by a more elusive species when those species have shared rearing areas. Such data indicate status and trends in ecosystem pressures and can serve as early indicators of year-class strength for Alaskan Sablefish. Predictor variables can be useful in forecasting recruitment 2 years in advance to assist the stock assessment process. This study emphasizes the opportunity to use proxies for direct ambient physical and biological observations of rearing habitats and time series parameters in estimating groundfish recruitment to older ages.

ACKNOWLEDGMENTS

All co-authors contributed to the ideas presented in this article. We thank the anonymous reviewers for their valuable feedback; Jordan Watson (NMFS Alaska Fisheries Science Center) for assistance with R software; and Andy Piston (Alaska Department of Fish and Game, Ketchikan) for providing Pink Salmon harvest and escapement data. The findings and conclusions in this paper are those of the authors and do not necessarily represent the views of NMFS. Reference to trade names does not imply endorsement by NMFS.

REFERENCES

Beamish, R. J., and C. Mahnken. 2001. A critical size and period hypothesis to explain natural regulation of salmon abundance and the linkage to climate and climate change. Progress in Oceanography 49:423–437.

Cooney, R. T., J. R. Allen, M. A. Bishop, D. L. Eslinger, T. Kline, B. L. Norcross, C. P. McRoy, J. Milton, J. Olsen, V. Patrick, A. J. Paul, D. Salmon, D. Scheel, G. L. Thomas, S. L. Vaughan, and T. M. Willette. 2001. Ecosystem controls of juvenile Pink Salmon (*Oncorhynchus gorbuscha*) and Pacific Herring (*Clupea pallasi*) populations in Prince William Sound, Alaska. Fisheries Oceanography 10(Supplement 1):1–13.

Coutré, K. M. 2014. Feeding ecology and movement patterns of juvenile Sablefish in coastal Southeast Alaska. Master's thesis. University of Alaska, Fairbanks.

Cushing, D. H. 1969. The regularity of the spawning season of some fishes. ICES Journal of Marine Science 33:81–92.

Fissel, B., M. Dalton, R. Felthoven, B. Garber-Yonts, A. Haynie, A. Himes-Cornell, S. Kasperski, J. Lee, D. Lew, L. Pfeiffer, and C. Seung. 2013. Stock assessment and fishery evaluation report for the groundfish fisheries of the Gulf of Alaska and Bering Sea/Aleutian Islands areas: economic status of the groundfish fisheries off Alaska, 2012. North Pacific Fishery Management Council, Anchorage, Alaska.

Hanselman, D. H., C. R. Lunsford, and C. J. Rodgveller. 2013. Assessment of the Sablefish stock in Alaska. Pages 267–376 *in* M. Sigler and G. Thompson, editors. Stock assessment and fishery evaluation report for the groundfish resources of the Bering Sea/Aleutian Islands regions. North Pacific Fishery Management Council, Anchorage, Alaska.

Hanselman, D. H., C. R. Lunsford, and C. J. Rodgveller. 2014. Assessment of the Sablefish stock in Alaska. Pages 283–424 *in* Appendix B: stock assessment and fishery evaluation report for groundfish resources of the Gulf of Alaska. North Pacific Fishery Management Council, Anchorage, Alaska.

Heard, B. 1991. Life history of Pink Salmon (*Oncorhynchus gorbuscha*). Pages 119–230 *in* C. Groot and L. Margolis, editors. Pacific salmon life histories. University of British Columbia Press, Vancouver.

Houde, E. D. 1987. Fish early life dynamics and recruitment variability. Pages 17–29 *in* R. D. Hoyt, editor. 10th Annual larval fish conference. American Fisheries Society, Symposium 2, Bethesda, Maryland.

Idhe, T., and H. Townsend. 2013. Interview with Jason Link. Fisheries 38:363–369.

Kaeriyama, M., M. Nakamura, M. Yamaguchi, H. Ueda, G. Anma, S. Takagi, K. Y. Aydin, R. V. Walker, and K. W. Myers. 2000. Feeding ecology of Sockeye and Pink salmon in the Gulf of Alaska. North Pacific Anadromous Fish Commission Bulletin 2:55–63.

Laidig, T. E., P. B. Adams, and W. M. Samiere. 1997. Feeding habits of Sablefish off the coast of Oregon and California. NOAA Technical Report NMFS 130:65–79.

Link, J. 2010. Ecosystem-based fisheries management: confronting trade-offs. Cambridge University Press, New York.

Lunsford, C., and C. Rodgveller. 2013. F/V *Ocean Prowler* cruise report OP-13-01: longline survey of the Gulf of Alaska and the eastern Bering Sea, May 26–August 28, 2013. Alaska Fisheries Science Center, Juneau.

Maloney, N., and M. Sigler. 2008. Age-specific movement patterns of Sablefish *Anoplopoma fimbria* in Alaska. U.S. National Marine Fisheries Service Fishery Bulletin 106:305–316.

Mason, J. C., R. J. Beamish, and G. A. McFarlane. 1983. Sexual maturity, fecundity, spawning, and early life history of Sablefish *Anoplopoma fimbria* off the Pacific coast of Canada. Canadian Journal of Fisheries and Aquatic Sciences 40:2126–2134.

McFarlane, G. A., and R. J. Beamish. 1992. Climatic influence linking copepod production with strong year-class in Sablefish, *Anoplopoma fimbria*. Canadian Journal of Fisheries and Aquatic Sciences 49:743–753.

Moser, H. G., R. L. Charter, P. E. Smith, N. C. H. Lo, D. A. Ambrose, C. A. Meyer, E. M. Sandknop, and W. Watson. 1994. Early life history of Sablefish, *Anoplopoma fimbria*, off Washington, Oregon, and California, with application to biomass estimation. California Cooperative Oceanic Fishery Investigations Reports 35:144–159.

Orsi, J., E. Fergusson, M. Sturdevant, and A. Wertheimer. 2013a. Forecasting Pink Salmon harvest in Southeast Alaska. Pages 131–134 *in* S. Zador, editor. Ecosystem considerations for 2013, appendix C of the Bering Sea/Aleutian Islands/Gulf of Alaska stock assessment and fishery evaluation report. North Pacific Fishery Management Council, Anchorage, Alaska.

Orsi, J. A., E. A. Fergusson, M. V. Sturdevant, E. V. Farley Jr., and R. A. Heintz. 2013b. Annual survey of juvenile salmon, ecologically related species, and biophysical factors in the marine waters of southeastern Alaska, May–August 2012. North Pacific Anadromous Fish Commission, Document 1485, Vancouver.

Piston, A. W., and S. C. Heinl. 2013. Pink Salmon stock status and escapement goals in Southeast Alaska. Alaska Department of Fish and Game, Special Publication 11-18, Anchorage.

R Development Core Team. 2014. R: a language and environment for statistical computing. R Foundation for Statistical Computing, Vienna.

Rutecki, T. L., and E. R. Varosi. 1997. Distribution, age, and growth of juvenile Sablefish, *Anoplopoma fimbria*, in Southeast Alaska. NOAA Technical Report NMFS 130:45–54.

Shotwell, S. K., D. H. Hanselman, and I. M. Belkin. 2014. Toward biophysical synergy: investigating advection along the Polar Front to identify factors influencing Alaska Sablefish recruitment. Deep-Sea Research Part II Topical Studies in Oceanography 107:40–53.

Sigler, M. F., T. L. Rutecki, D. L. Courtney, J. F. Karinen, and M.-S. Yang. 2001. Young-of-the-year Sablefish abundance, growth, and diet. Alaska Fishery Research Bulletin 8:57–70.

Sigler, M. F., and H. H. Zenger Jr. 1989. Assessment of Gulf of Alaska Sablefish and other groundfish based on the domestic longline survey, 1987. NOAA Technical Memorandum NMFS-F/NWC-169.

Sogard, S. M. 2011. Interannual variability in growth rates of early juvenile Sablefish and the role of environmental factors. Bulletin of Marine Science 87:857–872.

Stoner, A. W., and E. A. Sturm. 2004. Temperature and hunger mediate Sablefish *Anoplopoma fimbria* feeding motivation: implication for stock assessment. Environmental Biology of Fishes 61:238–246.

Wertheimer, A. C., J. A. Orsi, E. A. Fergusson, and M. V. Sturdevant. 2010. Calibration of juvenile salmon catches using paired comparisons between two research vessels fishing Nordic 264 surface trawls in Southeast Alaska, July 2009. North Pacific Anadromous Fish Commission, Document 1277, Vancouver.

Wertheimer, A. C., J. A. Orsi, E. A. Fergusson, and M. V. Sturdevant. 2013. Forecasting Pink Salmon harvest in Southeast Alaska from juvenile salmon abundance and associated biophysical parameters: 2012 returns and 2013 forecast. North Pacific Anadromous Fish Commission, Document 1486, Vancouver.

Wing, B. L., and D. J. Kamikawa. 1995. Distribution of neustonic Sablefish larvae and associated ichthyoplankton in the eastern Gulf of Alaska, May 1990. NOAA Technical Memorandum NMFS-AFSC-53.

Wolotira, R. J. J., T. M. Sample, S. F. Noel, and C. R. Iten. 1993. Geographic and bathymetric distributions for many commercially important fishes and shellfishes off the West Coast of North America, based on research survey and commercial catch data, 1912–1984. NOAA Technical Memorandum NMFS-AFSC-6.

Zador, S., and K. Aydin. 2013. Ecosystem assessment. Pages 1–235 *in* S. Zador, editor. Ecosystem considerations for 2013; appendix C of the Bering Sea/Aleutian Islands/Gulf of Alaska stock assessment and fishery evaluation report. North Pacific Fishery Management Council, Anchorage, Alaska.